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A primer on antenna near-field and far-field for the practical engineer

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For conformance and compliance, electromagnetic compatibility (EMC) and antenna performance testing, it is crucial to know the nuances of electromagnetic (EM) radiation from an antenna at given distances from the antenna aperture. This is important because the EM signal from an antenna behaves differently at various distances from the antenna, and if not properly accounted for, can result in substantial measurement errors. This is because there are three main regions where the EM radiation behaves differently as a function of distances away from an antenna: the reactive near-field (RNF), the radiating near-field/Fresnel Region and the far-field/Fraunhofer Region.

The majority of specifications are designed and written for testing an antenna in the far field, which requires a test engineer to know how far away from a given antenna the test antenna must be placed. Additionally, the different antenna types and sizes require different calculations to determine the boundary between these regions. Different applications present different methods of calculating when the far-field begins.

This paper aims to educate those new to the concepts of antenna field regions and help readers to understand the calculations involved in determining the boundaries between the various regions.

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What are antenna field regions?

When high frequency electrons pass through a conductor, EM radiation is emitted in the form of photons at the same frequency as that of the traveling electronics. This EM radiation has both an electric field and magnetic field component. However, these components are not orthogonal at every distance away from the radiator, or antenna. The phase of the magnetic field and electric field, as well as their alignment, depend on the type of antenna and the distance away from the radiator. At some distance from the radiator, the electric and magnetic fields become opposite in phase (180°) and the propagation of the wavefront becomes spherical, dropping off in power at a rate of 1/r, r being the radius of the spherical wavefront from the radiator.

It is important to note that the transitions between the three regions are not distinct but are instead gradual. Hence, determining the field region' boundaries has resulted in several different methods, mainly the electric dipole/elemental magnetic loop, wave impedance, antenna characterization method and wave's phase front method.

Near-field to far-field transformation

It is also possible to make antenna measurements in any of the regions, and with a sophisticated enough setup, even extrapolate the antenna's behavior given a precise enough measurement. A main use for this is to perform a near-field to far-field transformation that allows for measurements to be made in an antenna's near-field and calculate the far-field behavior from this measurement. This can be desirable if the size of the frequency of a given antenna, antenna size or available chamber are better suited for measurements being performed within the near-field. Near-field to far-field transformations are also often used in simulation results to predict the far-field behavior of an antenna within a limited simulation boundary region, and the computational resource requirements increase significantly with the size of the simulation region.

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A.H. SYSTEMS
9710 COZYCROFT AVE.
Chatsworth, CA. 91311
(818) 998-0223 (818) 998-6892
sales@AHSystems.com http://www.AHSystems.com
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There are a wide range of near-field to far-field transformation approaches and theories, which are beyond the scope of this paper.

Short note on measurement uncertainty

As with any metrology application, understanding the uncertainty of a measurement is crucial. With some measurements, such as near-field/far-field transformations, additional uncertainty is added compared to a properly performed far-field test as the calculations involve several variables in terms of positioning and phase relative to the radiating antenna. Generally speaking, maintaining precise physical distances in close proximity to a radiator may be more difficult and result in greater uncertainty than what could be attained with a well setup far-field measurement. In some cases, the increase in uncertainty may be acceptable.

Antenna field regions calculations explained

As stated earlier there are a few different ways of calculating the boundary between the near-field and far-field regions. In many cases, which method is chosen depends on a given application, certification, qualification, standard requirement or possibly customer requirements. The main reason there is a variation is due to the near-field and far-field boundaries not having any distinct physical separation, which allows for interpretations based on application requirements and user preferences.

Using an electric dipole and elemental magnetic loop

Using Maxwell's Equations to derive the electric field (E) and magnetic field (H) from an elemental electric dipole and an elemental magnetic dipole can be used to determine the divisions of the regions under ideal circumstances. Using a short uniform current element of a given length, the E and H fields of a magnetic loop can be derived as (SK Schelkunoff method):

$$E_\theta = \frac{I\beta^3 e^{-\beta j r} l \left(\frac{j}{\beta r} + \frac{1}{\beta^2 r^2} - \frac{j}{\beta^3 r^3}\right) \sin(\theta)}{4\pi\epsilon_0\omega}$$

$$H_\phi = \frac{I\beta^2 e^{-\beta j r} l \left(-\frac{1}{\beta j r} + \frac{1}{\beta^2 r^2}\right) \sin(\theta)}{4\pi}$$

$$E_r = \frac{I\beta^3 e^{-\beta j r} l \left(\frac{j}{\beta r} + \frac{1}{\beta^2 r^2} - \frac{j}{\beta^3 r^3}\right) \cos(\theta)}{4\pi\epsilon_0\omega}$$

Figure 1. FCC-4 dipole antenna. Source: AH Systems

Where I is the current in the wire, l is the length of the wire in meters, Beta is the electrical length of the dipole per meter of wavelength, ω is the angular frequency as radians per second, ε_0 is the permittivity of free space, μ_0 is the permeability of free space, Θ is the angle between the axis of the zenith wire and the point of observation, f is the frequency in hertz, c is the speed of light in free space, r is the distance between the source and observation point in meters, η_0 is the free-space impedance, and j is the complex number imaginary term designator commonly used by electrical engineers.

Similarly, the element magnetic loop can be derived as (SK Schelkunoff method):

$$E_\phi = -\frac{\mu_0\beta^2 e^{-\beta j r} j m\omega \left(-\frac{1}{\beta j r} + \frac{1}{\beta^2 r^2}\right) \sin(\theta)}{4\pi\eta_0}$$

$$H_r = \frac{\mu_0\beta^2 e^{-\beta j r} j m\omega \left(-\frac{1}{\beta^2 r^2} + \frac{j}{\beta^3 r^3}\right) \cos(\theta)}{2\pi\eta_0}$$

$$H_\theta = \frac{\mu_0\beta^2 e^{-\beta j r} j m\omega \left(\frac{j}{\beta r} + \frac{1}{\beta^2 r^2} - \frac{j}{\beta^3 r^3}\right) \sin(\theta)}{4\pi\eta_0}$$

Figure 2. SAS-563P loop antenna. Source: AH Systems

The definitions of the terms are the same as from Equations 1, 2 and 3. It can be observed that the terms in the above equations include 1/r, 1/r^2, and 1/r^3. From this, it can be concluded that while r<1 the 1/r^2 and 1/r^3 terms dominate, but as β*r exceeds 1, the value of these terms rapidly declines. Hence, in the near-field the 1/r^2 and 1/r^3 terms dominate in the field equations; however, the 1/r term is still present. This term then dominates the further away the observation point is from the radiator, for instance the far-field.

Hence, a boundary between the near-field and the far-field could be designated at points at which the 1/r^2 term and 1/r term are equal, noting that the 1/r term will be dominant at every distance further than this point.

$\frac{1}{\beta r} = \frac{1}{\beta^2 r^2}$ results in $r = \frac{\lambda}{2\pi}$, which is a commonly used definition for the near-field and far-field boundary. However, this is only one method of which several others exist for their utility in various applications.

Wave impedance method

Another approach is to use a method where the effectiveness of a shield can readily be determined. This would involve determining the impedance of a wave from an antenna and generating a ratio between the wave's impedance and the shield's impedance. This calculation assumes that at some point a wave's impedance becomes constant. Though not entirely true, a wave's impedance does eventually settle to near the impedance of free space after a certain distance from a radiator.

To calculate this, the ratio of Equation 1 to Equation 2 can be derived as:

$$Z_E = \frac{\eta_0 \left(\beta^2 j r^2 + \beta r - j\right)}{\beta r \left(\beta j r + 1\right)}$$

And the ratio of Equation 4 to Equation 5 can be derived as:

$$Z_H = -\frac{\eta_0 \beta r \left(\beta j r + 1\right)}{\beta^2 j r^2 + \beta r - j}$$

From these equations it can be observed that the two boundaries and three regions can be estimated. Therefore, these regions can roughly be designated as:

Near-field: $r < \frac{\lambda}{20\pi}$

Far-field: $r > \frac{2\lambda}{5\pi}$

However, the boundaries between these regions may change based on the designer's preferences and the demands of a given application.

Antenna characteristics method

Using an antenna's characteristics, it is possible to define the boundaries between the regions based on the phased front of the wave emitted from an ideal antenna (dipole). Though this method does not define a precise boundary, it allows for a boundary to be determined based on the amount of acceptable error for a given measurement. This at least provides a practical limitation to a measurement and boundary definition.

By omitting the 1/r^2 and 1/r^3 terms, then Equation 3 can be rewritten as:

$$E_r = \frac{I\beta^2 e^{-\beta j\left(r' - z\cos(\theta)\right)} jl}{4\pi\epsilon_0 \omega r}$$

Where r' is $r' = \sqrt{r^2 - 2rz\cos(\theta) + z^2}$ for the close case, and $r' = \sqrt{r^2 - 2rz\cos(\theta)}$ for the far away case. In the far-field, the term r'-zcos(theta) reduces to ~r, which results in a simplification of the preceding equation, with the exception of the r' term in the exponent, which represents the phase effect — very sensitive to small variations in separation distance. Choosing a phase difference that produces acceptable errors, sometimes given as pi/8 of the wavelength results in:

$$\frac{\beta * z^2}{2 * r} \leq \frac{\pi}{8} \text{ and } \quad r \cong \frac{2 * z^2}{\lambda} = \frac{2 * l^2}{\lambda}$$

Choosing the boundary definition in this case depends on the chosen references, or even MIL-SPEC — MIL-STD-449 and MIL-STD-462, specifically.

Wave's phase front method

Another approach is to use a comparison of phase of a wave front from two antennas that are parallel to each other and perpendicular to a line indicating the plane wavefront. This is shown in Figure 3.

Using Figure 3, the following equations can be derived from a triangle with hypotenuse = r+**Δ***r, adjacent side = r, and opposite side = z/2, where z = one half the antenna length of the receiving antenna, l.

Δr is typically chosen in terms of a fraction of a wavelength that produces phase errors at the minimum tolerance level for a given application. If a path difference of less than ⅛ the wavelength at a given frequency is chosen, or the highest applicable frequency as that would result in the lowest phase error, then the previous equation reduces to approximately the length of the receiving antenna divided by the wavelength. Using the Rayleigh Criterion for **Δ**r results in an r term approximated as two times the length of the receiving antenna divided by the wavelength, which is as derived previously in the antenna characteristics method.

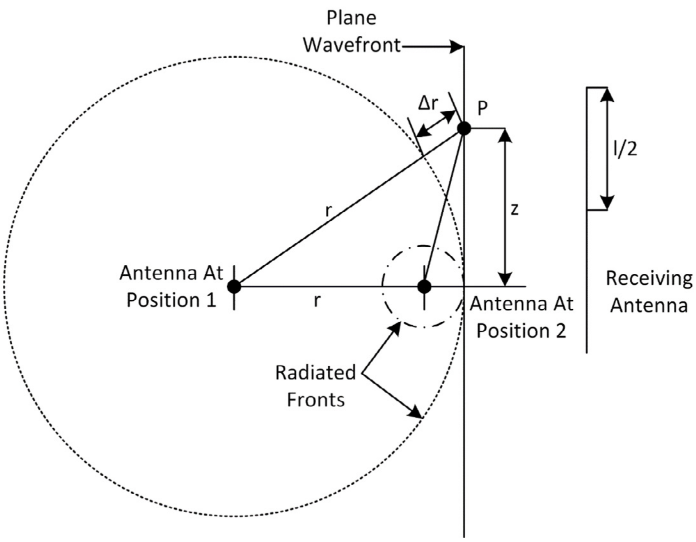

Figure 3. Two antennas are spaced apart and both perpendicular according to their wavefronts (Aligned along the z axis). At some point, P, the wavefront from antenna 1 can be approximated as a place wavefront with very small error. Where Δr is the difference in the path length between the distance r and the point P. Source: AH Systems

Conclusion

This paper discussed four common methods of determining the definitions for the near-field and far-field regions of an antenna and their boundaries. Which definition is used to determine the regions and boundaries generally depends on the use case, and the acceptable amount of error in calculating this definition and any conversions that may need to be performed. Ultimately, at some distance from an antenna relative to the wavelength, the 1/r^2 and 1/r^3 terms lose dominance and the 1/r term becomes dominant, which is the high-level determination of the far-field region.

Resources and links

- Antenna near-field and far-field distance calculator
- EMC formulas and equations
- Frequency and wavelength calculation
- Antenna terms and definitions
- Technical abbreviations and acronyms
- Electromagnetic waves and antennas, Sophocles Orfanidis, Rutgers ECE

A.H. SYSTEMS INC.

9710 Cozycroft Ave.
Chatsworth, CA 91311-4401
Tel: 818 998 0223

GLOBALSPEC

201 Fuller Road, Suite 202
Albany, NY 12203-3621
Tel: +1 518 880 0200