

HOW DO WE DEFINE THE FAR FIELD OF AN ANTENNA SYSTEM, AND WHAT CRITERIA DEFINE THE BOUNDARY BETWEEN IT AND THE NEAR FIELD? THE ANSWER DEPENDS ON YOUR PERSPECTIVE AND YOUR DESIGN'S TOLERANCES.

Near field or far field?

SEVERAL ENGINEERS, INCLUDING MYSELF, were sitting around talking one day when the question arose, "When does a product find itself in the far field of a radiation source?" One of the engineers, an automotive antenna expert, immediately stated that the far field began at a distance of 3λ from the source, with λ being the radiation wavelength. The EMC (electromagnetic-compatibility) engineer challenged this statement, claiming that "everyone knows" that the far field begins at

$$\frac{5 * \lambda}{2 * \pi}$$

A visiting engineer working on precision antennas got his 2 cents in with, "The far field begins at

$$\frac{50 * D^2}{\lambda}$$

where D is the largest dimension antenna." I happened to know the "correct" answer is

$$\frac{\lambda}{2 * \pi}$$

All of these guys are good engineers, and, as the debate went on, I wondered how such a seemingly simple question could have so many answers. After the discussion ran its course, we tried to make some sense of it. Could all of the answers be correct? This question led to several others, such as "where have all these definitions come from," "why do we need so

many definitions," and "why is it so important to know about the far field in the first place?" To begin to answer these questions, start with some basic information.

Because the far field exists, logic suggests the existence of a close, or near, field. The terms "far field" and "near field" describe the fields around an antenna or, more generally, any electromagnetic-radiation source. The names imply that two regions with a boundary between them exist around an antenna. Actually, as many as three regions and two boundaries exist.

These boundaries are not fixed in space. Instead, the boundaries move closer to or farther from an antenna, depending on both the radiation frequency and the amount of error an application can tolerate. To talk about these quantities, you need a way to describe these regions and boundaries. A brief scan of reference literature yields the terminology in **Figure 1**. The terms apply to the two- and three-region models.

USING AN ELEMENTAL DIPOLE'S FIELD

For a first attempt at defining a near-field/far-field boundary, use a strictly algebraic approach. You need equations that describe two important concepts: the fields from an elemental—that is, small—electric dipole antenna and from an elemental magnetic loop antenna. SK Schelkunoff derived these equations using Maxwell's equations. You can represent an ideal

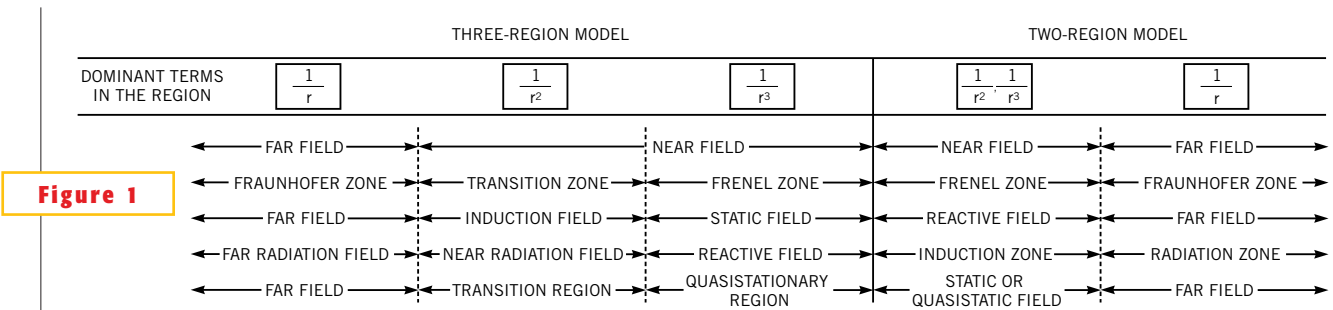


Figure 1

Two- and three-region models describe the regions around an electromagnetic source.

electric dipole antenna by a short uniform current element of a certain length, l . The fields from an electric dipole are:

$$E_{\theta} = \frac{I * l * \beta^3}{4 * \pi * \omega * \epsilon_0} \left[\frac{j * 1}{\beta * r} + \frac{1}{(\beta * r)^2} + \frac{-j}{(\beta * r)^3} \right] * \sin(\theta) * e^{-j * \beta * r} \text{ V/m}, \quad (1)$$

$$H_{\phi} = \frac{I * l * \beta^2}{4 * \pi} \left[\frac{-1}{j * \beta * r} + \frac{1}{(\beta * r)^2} \right] * \sin(\theta) * e^{-j * \beta * r} \text{ A/m}, \quad (2)$$

and

$$E_r = \frac{I * l * \beta^3}{4 * \pi * \omega * \epsilon_0} \left[\frac{j}{\beta * r} + \frac{1}{(\beta * r)^2} + \frac{-j}{(\beta * r)^3} \right] * \cos(\theta) * e^{-j * \beta * r} \text{ V/m}. \quad (3)$$

The fields for a magnetic dipole loop are:

$$E_{\phi} = -j * \frac{\omega * \mu_0 * m * \beta^2}{4 * \pi} \left[\frac{-1}{j * \beta * r} + \frac{1}{(\beta * r)^2} \right] * \sin(\theta) * e^{-j * \beta * r} \text{ V/m}, \quad (4)$$

$$H_r = j * 2 * \frac{\omega * \mu_0 * m * \beta^2}{4 * \pi * \eta_0} \left[\frac{1}{(\beta * r)^2} - \frac{j}{(\beta * r)^3} \right] * \cos(\theta) * e^{-j * \beta * r} \text{ A/m}, \quad (5)$$

and

$$H_{\theta} = j * \frac{\omega * \mu_0 * m * \beta^2}{4 * \pi * \eta_0} \left[\frac{j}{\beta * r} + \frac{1}{(\beta * r)^2} + \frac{-j}{(\beta * r)^3} \right] * \sin(\theta) * e^{-j * \beta * r} \text{ A/m}, \quad (6)$$

where I is the wire current in amps; l is the wire length in meters; β is the electrical length per meter of wavelength, or ω/c , $2 * \pi / \lambda$; ω is the angular frequency in radians per second, or $2 * \pi * f$; ϵ_0 is the permittivity of free space, or $1/36 * \pi * 10^{-9}$ F/m; μ_0 is the permeability of free space, or $4 * \pi * 10^{-7}$ H/m; θ is the angle between the zenith's wire axis and the observation point; f is the frequency in hertz; c is the speed of light, or $3 * 10^8$ m/sec; r is the distance from the source to the observation point in me-

ters; and η_0 is the free-space impedance, or 376.7Ω .

Equations 1 through 6 contain terms in $1/r$, $1/r^2$, and $1/r^3$. In the near field, the $1/r^3$ terms dominate the **equations**. As the distance increases, the $1/r^3$ and $1/r^2$ terms attenuate rapidly and, as a result, the $1/r$ term dominates in the far field. To define the boundary between the fields, examine the point at which the last two terms are equal. This is the point where the effect of the second term wanes and the last term begins to dominate the equations. Setting the magnitude of the terms in **Equation 2** equal to one another, along with employing some algebra, you get r , the boundary for which you are searching:

$$\left[\frac{1}{\beta * r} = \frac{1}{(\beta * r)^2} \right],$$

$$r = \frac{\lambda}{2 * \pi}.$$

Note that the **equations** define the boundary in wavelengths, implying that the boundary moves in space with the frequency of the antenna's emissions. Judging from available literature, the distance where the $1/r$ and $1/r^2$ terms are equal is the most commonly quoted near-field/far-field boundary. This result may seem to wrap up the problem rather nicely. Unfortunately, the boundary definition in reality isn't this straightforward.

ward. Examine **Table 1**, which contains a large set of far-field definitions from the literature. It's disconcerting to first make a point with a simple mathematical derivation, only to have reality disprove the theory.

Therefore, examine the boundary from two other viewpoints. First, find the boundary as the wave impedance changes with distance from a source, because this phenomenon is important to shield designers. Then, look at how distance from an antenna affects the phase of launched waves, because this phenomenon is important to antenna designers.

WAVE IMPEDANCE

Defining the boundary through wave impedance involves determining where an electromagnetic wave becomes "constant." (The **equations** show that the value never reaches a constant, but the value $\eta_0 = 377 \Omega$ is close enough.) Because the ratio of a shield's impedance to the field's impedance determines how much protection a shield affords, designing a shield requires knowledge of the impedance of the wave striking the shield.

If you calculate the ratio of the electric and magnetic fields of an antenna, you can derive the impedance of the wave. The equations in **Figure 2** compute the impedance of the electric and magnetic dipoles, where Z_E is the ratio of the solution of **Equation 1** to the solution of

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lambda := 10      j := sqrt(-1)   eta_0 := 377      beta := 2 * pi / lambda
r := 0.80, 82..20

Z_E(r) := eta_0 * [ (1 + 1/(j*beta*r) + 1/(j*beta*r)^2) ] / [ (1 + 1/(j*beta*r)) ]
Z_H(r) := eta_0 * [ (1 + 1/(j*beta*r)) ] / [ (1 + 1/(j*beta*r) + 1/(j*beta*r)^2) ]
    
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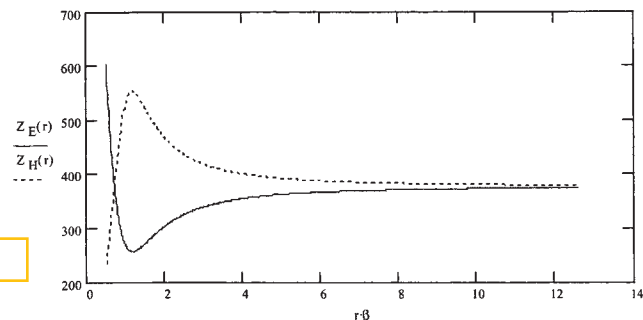


Figure 2

Equations and impedance plots describe elemental dipole and loop antennas.

Equation 2, and Z_H is the ratio of the solution of Equation 4 to the solution of Equation 5. The constants cancel each other out, leaving:

$$Z_E = \eta_0 * \frac{\frac{j}{\beta * r} + \frac{1}{(\beta * r)^2} - \frac{j}{(\beta * r)^3}}{\frac{j}{\beta * r} + \frac{1}{(\beta * r)^2}}$$

$$1 + \frac{1}{(\beta * r)} - \frac{j}{(\beta * r)^2}$$

$$1 + \frac{1}{(\beta * r)}$$

and

$$Z_H = -\eta_0 * \frac{\frac{j}{\beta * r} + \frac{1}{(\beta * r)^2}}{\frac{j}{\beta * r} + \frac{1}{(\beta * r)^2} - \frac{j}{(\beta * r)^3}}$$

$$\frac{1 + \frac{1}{(\beta * r)}}{1 + \frac{1}{(\beta * r)} - \frac{j}{(\beta * r)^2}}$$

Figure 2 also presents a MathCAD graph of the magnitudes of these two equations. The selected values for the wavelength, λ , and the step size, r , present the relevant data on the graph. Considering just the electric-field impedance in the near field, that is, $r * \beta \ll 1$, Equation 7 simplifies to:

$$Z_E = \frac{-j * \eta_0}{\beta * r}$$

As the distance from the source in-

creases, the ratio becomes constant, defined as $Z_E = \eta_0 = 377\Omega$.

This equation calculates the intrinsic impedance of free space. From the graph, you can see that the distance at which the intrinsic impedance occurs is approximately $5 * \lambda / 2 * \pi$, with $\lambda / 2 * \pi$ a close runner-up. Note that at $\lambda / 2 * \pi$, a local minimum (maximum) for an electric (magnetic) wave exists whose value is not 377Ω .

A more detailed way of describing the change in impedance is to identify three regions and two boundaries. Here, the boundaries come from eyeballing the impedance curves. The choices are close to what boundaries and regions appear in the literature. They are the near field, that is, the distance,

$$r < 0.1 * \frac{\lambda}{2 * \pi},$$

the transition region,

$$0.1 * \frac{\lambda}{2 * \pi} < r < 0.8 * \frac{\lambda}{2 * \pi},$$

and the far field,

$$r > 0.8 * \frac{\lambda}{2 * \pi}.$$

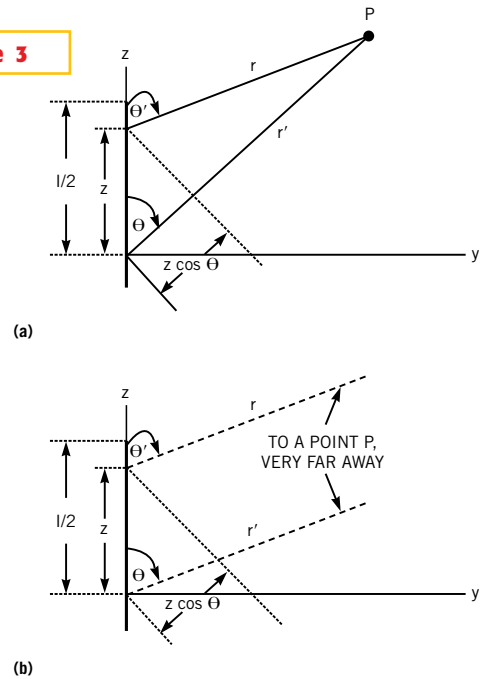
So, where is the boundary? In this case, you can't nail it down as precisely as you had previously. With this line of reasoning, you encounter a

real-world problem: how to define the boundary. The problem can change the boundary location, and the shield designer has to define the location.

ANTENNAS AND THE BOUNDARY

An antenna designer would examine the boundary location with the parameters of a dipole antenna determining the

Figure 3



A geometry for an antenna and a receiver are "close" (a) as well as "far away" (b) from one another.

TABLE 1—DEFINITIONS OF THE NEAR-FIELD/FAR-FIELD BOUNDARY

Definition for shielding	Remarks	Reference
$\lambda/2\pi$	1/r terms dominant	Ott, White
$5\lambda/2\pi$	Wave impedance=377Ω	Kaiser
For antennas		
$\lambda/2\pi$	1/r terms dominant	Krause
3λ	D not $\gg \lambda$	Fricitti, White, Mil-STD-449C
$\lambda/16$	Measurement error<0.1 dB	Krause, White
$\lambda/8$	Measurement error<0.3 dB	Krause, White
$\lambda/4$	Measurement error<1 dB	Krause, White
$\lambda/2\pi$	Satisfies the Rayleigh criteria	Berkowitz
$\lambda/2\pi$	For antennas with $D \ll \lambda$ and printed-wiring-board traces	White, Mardiguan
$2D^2/\lambda$	For antennas with $D \gg \lambda$	White, Mardiguan
$2D^2/\lambda$	If transmitting antenna has less than 0.4D of the receiving antenna	MIL-STD 462
$(d+D)^2/\lambda$	If $d > 0.4D$	MIL-STD 462
$4D^2/\lambda$	For high-accuracy antennas	Kaiser
$50D^2/\lambda$	For high-accuracy antennas	Kaiser
$3\lambda/16$	For dipoles	White
$(D^2+d^2)/\lambda$	If transmitting antenna is 10 times more powerful than receiving antenna, D	MIL-STD-449D

boundary and as the phase front of a wave from an antenna. **Figure 3** shows an antenna with two lines, r and r' . Line r traverses from a point along the antenna at z to point P in space. Line r' goes from the midpoint of the antenna to point P . Somewhere along line r' , the near field ends, and the far field begins. The geometry of the diagram shows that r' is longer than r . The law of cosines shows the relationship between the variables is:

$$r' = \sqrt{r^2 + z^2 - 2 * z * r * \cos(\theta)} \quad (9)$$

If you now assume that point P is very far from the antenna, that is, $r \gg z$, then **Equation 9** reduces to:

$$r' = \sqrt{r^2 - 2 * z * r * \cos(\theta)} \quad (10)$$

Next, applying the Binomial Theorem, you expand **Equation 10**.

$$r' = r - z * \cos(\theta) + \frac{1}{r} * \left(\frac{z^2 * \sin^2(\theta)}{2} \right) + \frac{1}{r^2} * \left(\frac{z^3 * \cos(\theta) * \sin^2(\theta)}{2} \right) + \dots \quad (11)$$

You can truncate the expansion of **Equation 11**, beginning with the third term. The truncation means that you are dealing with a maximum error of

$$\frac{z^2}{2 * r}, \text{ with } \theta = \pi / 2.$$

You must deal with the error that occurs when you ignore the last term. The literature provides some help. Many antenna books provide evidence showing that a wave's amplitude has minimal effect on measurement error, but this situation is not the case with a wave's phase. The books say that phase differences with a maximum value of $\pi/8$ produce acceptable errors in antenna measurements. Thus:

$$\frac{\beta * z^2}{2 * r} \leq \frac{\pi}{8},$$

and

$$r \cong \frac{2 * z^2}{\lambda} = \frac{2 * l^2}{\lambda}$$

with $z=l$, where l is the maximum antenna length.

Any wave in the middle of the antenna must travel the additional distance

$z * \cos(\theta)$ to P with respect to a wave from z , or $r = r' - z * \cos(\theta)$. Traveling that extra distance means that a wave from the midpoint arrives at P attenuated, and with a phase difference, compared with a wave from z .

You now rewrite **Equation 3** to account for the far-field effects:

$$E_r = \frac{I * l * \beta^2}{4 * \pi * \omega * \epsilon_0} \left[\frac{j}{r} \right] * e^{-j * \beta * (r' - z * \cos(\theta))} \text{ V/m} \quad (12)$$

Equation 12 omits the r^2 and r^3 terms, and the $r' - z * \cos(\theta)$ term in the denominator reduces to r because $r \sim r'$ in the far field. This method accounts for the attenuation effects. To account for the phase effects, modify the exponential phase term by $r' - z * \cos(\theta)$. In this case, you cannot replace $r' - z * \cos(\theta)$. Small differences in distance can greatly affect the exponential term.

You still have not precisely defined the boundary. However, you have defined a boundary determined by the amount of error that measurement can tolerate. The boundary definitions in **Table 1** show a variety of requirements.

THE BOUNDARY USING A WAVE'S PHASE FRONT

Finally, try to determine the boundary location from the perspective of a wave

from an antenna. **Figure 4** illustrates the situation. Here, you draw two antennas on the z axis perpendicular to a second line representing a plane wavefront. The circles represent waves from the antennas. The wavefront from the antenna in position 1 approximates the shape of the plane wave better than does the wavefront from the antenna in position 2. It should be obvious that, as the distance between the antenna decreases, a wavefront from the antenna approximates a plane wavefront with a decreasing amount of error.

You can describe this phenomenon using the labels in **Figure 4**. When r is very far away:

$$(r + \Delta r)^2 = \left(\frac{z}{2} \right)^2 + r^2$$

$$r^2 + 2 * r * \Delta r + \Delta r^2 = \frac{z^2}{4} + r^2$$

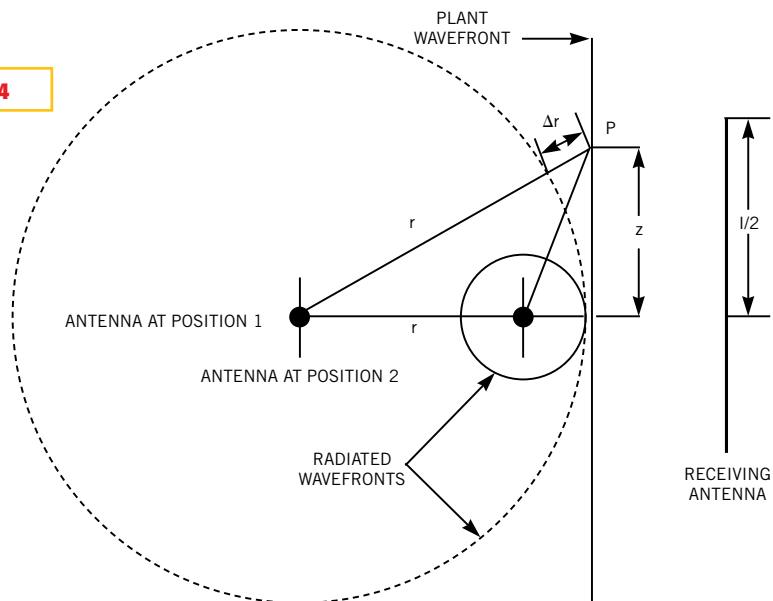
And

$$r = \frac{z^2}{8 * \Delta r} - \Delta r^2$$

$$r \cong \frac{z^2}{8 * \Delta r}$$

Now, Δr represents the difference in path length between the middle of the

Figure 4



One means of determining near field and far field uses the phase front of a wave.

phase front and point P on the phase front. This difference produces errors at a receiving antenna. The errors are mainly due to phase differences, with smaller errors due to amplitude differences. The criteria for selecting Δr is to express it in terms of that fraction of a wavelength that produces phase errors less than the maximum tolerable error for the problem at hand. Once you have determined that error, you have effectively defined the far field. The criterion previously used requires the path difference to be less than an eighth of a wavelength. This requirement means the far field begins at a distance of

$$r \cong \frac{z^2}{\lambda} = \frac{l^2}{\lambda},$$

when $z=l$, the length of the receiving antenna.

Sometimes, the literature cites the Rayleigh criterion for the path difference. This criterion has a phase error of one-sixteenth of a wavelength, which gives a far field at

$$r \cong \frac{2 * z^2}{\lambda} = \frac{2 * l^2}{\lambda}.$$

These last two values for the far-field location are the same as the value previously derived. □

AUTHOR'S BIOGRAPHY

Charles Capps is a senior EMC engineer with Delphi Automotive (Carmel, IN), where he has worked for 22 years. He obtained his BSEE from the University of California—Berkeley and his MSEE from the University of California—Santa Barbara. Capps is married with two children, and his hobbies include preparing to play basketball, playing basketball, and recovering from playing basketball by reading history and science fiction.

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