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Interpreting Antenna Performance Parameters for EMC Applications: Part 2: Radiation Pattern, Gain, and Directivity

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This article is the second in a three-part tutorial series covering antenna terminology. As noted in the first part, a great deal of effort has been made over the years to standardize antenna terminology. The de facto standard is the *IEEE Standard Definitions of Terms for Antennas,* published in 1983. However, the EMC community has developed its own distinct vernacular which contains terms not included in the IEEE standard. In the first part of this series, we discussed radiation efficiency and input impedance match. In the second part of this series, we will discuss antenna field regions and antenna gain and how they relate to EMC measurements.

Geometrical Considerations

In order to quantitatively discuss radiation from antennas, it is necessary to first specify a coordinate system for describing the antenna and the associated electromagnetic fields. The most natural coordinate system for this task is the spherical coordinate system. This is because at a sufficient distance from an antenna (or any localized source of electromagnetic radiation), the electromagnetic fields must decay inversely with radial distance from the antenna (see references 1 and 2). Traditional spherical coordinates consist of a radial distance, an elevation angle, and an azimuthal angle as shown in Figure 1. The elevation angle is taken as the angle between a line drawn from the origin to the point and the z axis. The azimuthal angle is taken as the angle between the projection of this line in the x-y plane and the x axis. These spherical coordinates are analogous to the more familiar coordinates on a globe: azimuthal angle is equivalent to longitude; elevation angle is the complement of latitude (it is sometimes referred to as co-latitude).

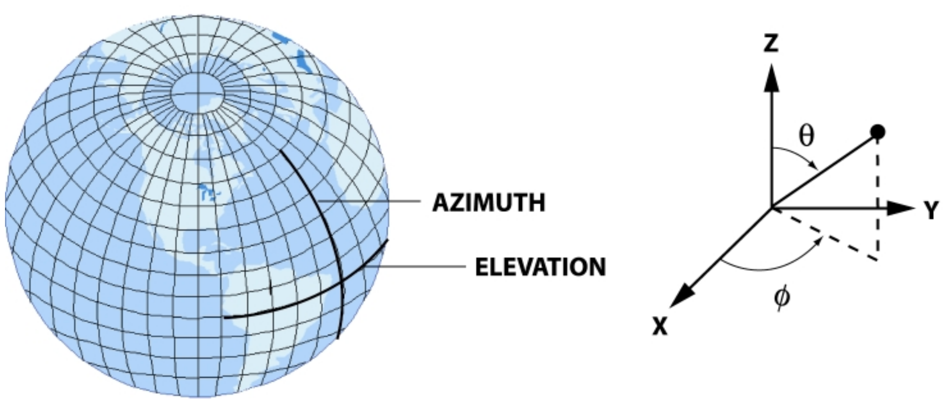

Figure 1: Spherical Coordinate System

In most antenna textbooks, the elevation angle is termed θ while the azimuthal angle is termed ϕ. Note that $\theta = 0$ corresponds to 90 degrees north latitude (the North Pole), while $\theta = 90$ corresponds to the equator. $\phi = 0$, on the other hand, corresponds to zero degrees longitude, the prime meridian (Greenwich, UK). Thus, the lines of constant θ are parallels and the lines of constant ϕ are meridians. The surfaces of constant θ are cones, hence θ is often referred to as the cone angle. The azimuthal angle is sometimes referred to as the clock angle since it corresponds to latitude and thus the progression of solar time. Finally, to completely specify the spherical coordinate system, the direction of increasing ϕ is taken the same way as increasing longitude. Looking down at the globe from above the North Pole the direction would be counter clockwise. This makes the coordinate system a *right-handed* or dextral coordinate system. While all these specifications may seem tedious, it must be understood before we can discuss antenna radiation patterns or quantitatively compare antennas.

Antenna Pattern and Radiation Pattern

The antenna pattern is defined in the IEEE standard as "*The spatial distribution of a quantity which characterizes the electromagnetic field generated by an antenna.*'' This is usually specialized to mean a representation of the angular distribution of one of these quantities. That is, in spherical coordinates, the distribution of the quantity over θ and ϕ for fixed R. The quantities that are generally of interest are:

- Power flux density
- Radiation Intensity
- Directivity
- Gain
- Phase
- Polarization
- Field Strength (Electric or Magnetic)

In particular, the *radiation* pattern is a representation of the angular distribution of radiated power density in the *far* field (please see below). That is, for sinusoidal steady state fields, it is a plot of the real part of the radial component of the Poynting vector:

$$W(\theta,\phi) = \frac{1}{2}\mathrm{Re}\left(\left[\vec{E}(\theta,\phi)\times\vec{H}^*(\theta,\phi)\right]\cdot\hat{a}_R\right) \text{ (W/m}^2\text{)}$$

where $\vec{E}$ and $\vec{H}$ are vector phasor representations of the electric and magnetic field, respectively. In the far field, the power flux density and the radiation intensity are identical; the Poynting vector is purely real and radially directed. Thus, the radiation pattern can be simply taken as representation of the tendency of an antenna to radiate electromagnetic energy as a function of direction in the far field region. However, even this interpretation of an antenna's radiation pattern can become problematic because of the three-dimensional nature of the information. The complexity of a three-dimensional pattern can sometimes obfuscate details. Because of the implicitly included viewing angle, a three-dimensional plot of a radiation pattern is of limited value in presenting quantitative information. This is analogous to mechanical drawing—two-dimensional cuts are generally what is required for fabrication. An assembly drawing might be a three-dimensional view but contains little or no metrical information. Thus, two-dimensional "cuts" of the radiation pattern are often presented. In particular, cuts in the so-called E and H-planes (again, see below) are often presented. However, it must be borne in mind that one or two cuts cannot fully describe an antenna's radiation characteristics.

Both the gain and the directivity are computed with knowledge of an antenna's radiation pattern. However, before we treat these quantities, we must digress to discuss the *field regions* surrounding an antenna. If we take an antenna pattern as the angular distribution of a particular quantity, we must choose the fixed value of R at which the pattern is taken. What we will find is that if we go far enough from the antenna, the angular distribution of these quantities will not depend on R.

The properties of phase and polarization are more difficult to discuss than radiation intensity and it is tempting to avoid them altogether. However, we will see that they are important in EMC testing situations and therefore warrant some discussion.

Field Regions

The volume surrounding an antenna is thought of as two or three distinct regions depending on the nature of the electromagnetic field produced by the antenna. At a sufficient distance from any antenna, only the radiated fields exist; this region is known as the *far* field. In communications systems, where antennas are generally always quite widely separated, it is sufficient to be concerned only with the far field of an antenna. However, the concept of field regions is quite important in the EMC testing area because of the extremely wide frequency range over which devices are tested. At the low end of this frequency range, standard test distances such as 1 and 3 meters sometimes dictate that devices under test (DUTs) are placed in the *near* field regions of the test antennas. Thus, some understanding of the near field physics is worthwhile.

The demarcation between field regions is necessarily somewhat vague. For the purpose of this article, field regions are divided into far field, reactive near field, and radiating near field.

▪ Far Field

The far field region of an antenna is the region surrounding an antenna which is sufficiently far from the antenna such that only the radiating field components are significant. The strict IEEE definition is "*That region of the field of an antenna where the angular field distribution is essentially independent of the distance from a specified point in the antenna region*." The far field region is sometimes termed the Fraunhoffer region in analogy with Fraunhoffer diffraction. Fraunhoffer diffraction can be thought of as interfering plane waves. In the far field, the field components are orthogonal. Equipartition of energy between electric and magnetic stored energy exists. The angular distribution of fields and power density is independent of distance. The electric and magnetic fields decay inversely with distance from the antenna and power density decays as the inverse square of distance. While most communications computations such as link budgets are performed using far field approximations, these approximations are often misleading to the EMC engineer as EMC testing is routinely performed at distances which place the DUT in the near field region of the test antenna, the test antenna in the near field region of the DUT, or both.

▪ Reactive Near Field

In the reactive near field region of an antenna, the non-radiating field components dominate. The term *reactive* near field arises from the fact that for a non-resonant antenna such as an electrically-small dipole, reactive power circulates between the reactive near field and the source, an external matching network, or both. In the case of a resonant antenna such as a half-wave linear dipole, the reactive power circulates within the reactive near field. In either case, the reactive power is associated with the non-propagating, quasi-static field components which dominate in the reactive near field. The strict IEEE definition is "*That portion of the near-field region immediately surrounding the antenna, wherein the reactive field dominates*." Thus, for dipole-like antennas, the energy in this region is predominantly either electric or magnetic. For electrically-small antennas, the reactive near field is taken to extend to approximately a distance of

$$R \approx \frac{\lambda}{2\pi}$$

from the antenna. Of course, this line of demarcation is vague; the boundary of the reactive near field depends very much on the shape and details of the antenna. The value of

$$R \approx \frac{\lambda}{2\pi}$$

is derived from the gradual cutoff condition for spherical modes [Harrington]. It holds quite well for electrically-small electric or magnetic dipoles as the fields of these devices correspond quite closely to those of the TM_{01} and TE_{01} spherical modes respectively (the correspondence of fields is exact for infinitesimally small dipoles) [Harrington]. While it is difficult to give a very general guideline for the boundary of the reactive near field region, for antennas of appreciable electrical size the boundary is often stated to be approximately

$$R < 0.62\sqrt{\frac{D^3}{\lambda}}$$

where D is the largest dimension of the antenna. For an electric dipole, the electric field components dominate and the energy stored is predominantly electric. For a magnetic dipole, such as a loop, the magnetic field components dominate. Two antennas could have exactly the same maximum far field gain and produce exactly the same electric field intensities for a given input power at a point in the far field but exhibit drastically different electric and magnetic field intensities in the reactive near field. For example, at 30 MHz, with 10-meter wavelength, a 1-meter test distance is well within the boundaries of the reactive near field. A standard 1.37-meter biconical antenna is only .137 wavelengths long at this frequency and thus behaves very much like an electrically-small dipole. Therefore, its electric field is exceedingly large at 1 meter. However, this field is essentially a quasi-static field; it is maintained by energy circulating between the reactive near field of the antenna and the power amplifier. Unless narrow band conjugate matching is performed, very little power is radiated from the antenna. If such matching is performed (for instance, with an antenna tuner), exceedingly large near electric fields result; if high power is involved this often has catastrophic consequences. If the antenna's design is sufficiently robust, extremely intense electric fields can be generated at a 1-meter test distance. For example, the high power biconical in Figure 2 is capable of handling 3500W continuous forward power at 30 MHz and the attendant high voltages. Great care was taken to prevent electric field breakdown in this design.

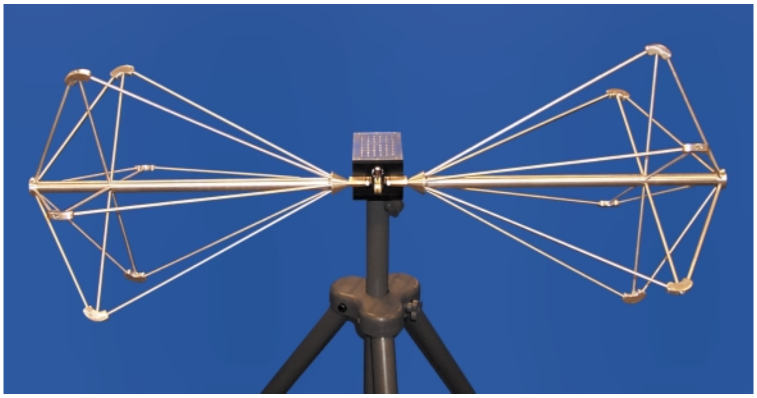

Figure 2: High Power Biconical Antenna
(Photo courtesy of TDK RF Solutions)

One consequence of the MIL-STD 1-meter test distance for radiated susceptibility testing between 30 and 100 MHz is that, at the lower end of this frequency range, when a 1.37-meter biconical antenna is used, the field to which the DUT is exposed is almost entirely electric. This is in stark contrast to a true free field measurement in which the electric and magnetic fields would be in ratio of

$$\eta_0 = 377\ \Omega .$$

One way to make a 1-meter measurement at 30 MHz and still retain the free space ratio of electric to magnetic field intensity is to use a transmission-line type field generator such as the one described in the previous article.

- **Radiating Near Field (Fresnel Region)**

In the radiating near field, the radiation fields predominate but the angular field distribution is dependent on the distance from the antenna. The strict IEEE definition is "*That portion of the near field region of an antenna between the far field and the reactive portion of the near field region, wherein the angular field distribution is dependent upon distance from the antenna*." Appreciable radial (non-radiating) fields may exist in the radiating near field region. If the antenna is large compared to a wavelength, the outer boundary of the radiating near field is taken to be

$$R \approx \frac{2D^2}{\lambda} .$$

Electrically-small antennas, for the most part, do not exhibit radiating near field regions; rather, the reactive near field transitions directly to the far field. Notice that for a sufficiently small antenna it is possible that

$$\frac{\lambda}{2\pi} > \frac{2D^2}{\lambda} \text{ and } \frac{\lambda}{2\pi} > 0.62\sqrt{\frac{D^3}{\lambda}} .$$

In order to exhibit a radiating near field, an antenna must be sufficiently large enough that interference between radiation from different points on the antenna is significant. At the upper end of its operating frequency range, 300 MHz, the 1.37-meter biconical antenna is 4/3 of a wavelength from tip to tip. Therefore, the Fresnel region extends to approximately 3.5 meters. A 1-meter test distance places the DUT in the radiating near field of the biconical antenna. In fact, a 3-meter test distance would still put a DUT in the radiating near field. Thus, the far field patterns of such an antenna are of limited use in determining how it will behave as an EMC test antenna. The radiating near field is termed the Fresnel region in analogy to Fresnel diffraction.

Polarization

Unfortunately, the vector nature of electromagnetic fields complicates the study of antenna behavior significantly. In contrast to a scalar field such as an acoustic pressure field, the electromagnetic field and hence the radiated fields from an antenna are vector quantities. That is, the electromagnetic field is a vector function of time and space. The steady state electromagnetic field can be represented by a vector phasor function [see reference 4, page 338]. The behavior of the vector nature of an electromagnetic field is often termed the polarization or polarization state. In the EMC area, almost all antennas are linearly polarized by design (with the notable exception of the tapered logarithmic spiral antenna—see the new MIL-STD 461). However, most antennas exhibit some slight departure in behavior from their designer's intentions. For example, even on the boresight, a log periodic dipole array (LPDA) antenna employing the over/under staggering scheme to provide phase transposition between elements (most LPDAs are made like this) exhibits *elliptical* polarization. That is, the radiation is polarized predominantly in one plane with a slight cross-polarization component which is not in phase with the principal component. Careful design can minimize this cross-polarization component, but cannot completely eliminate it. In Figure 3, a precision LPDA antenna is shown which covers the frequency range of 800 MHz to 3 GHz. The boresight radiation at 1.5 GHz is ever so slightly elliptically polarized with an axial ratio of 0.00370 and a tilt angle of –88.7 degrees (for definitions of these terms see reference 3]. The so-called cross-polarization rejection is actually greater than 32 dB, which is significantly better than most commercially available LPDAs. Nevertheless, to be completely rigorous, the electromagnetic field is elliptically polarized at this point in the far field pattern.

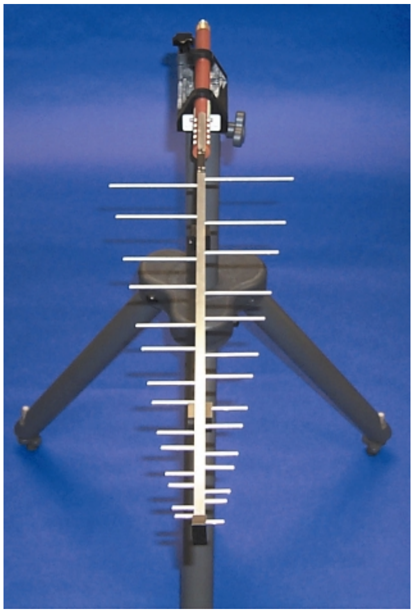

Figure 3: Log Periodic Dipole Array
(Photo courtesy of TDK RF Solutions)

The polarization of electromagnetic radiation and the measurement of it are not simple topics. Note that the *IEEE Standard Definitions of Terms for Antennas* gives numerous terms relating to the polarization of electromagnetic fields and waves as well as antennas. [see reference 3, the title of the previous edition of this book was *Polarization in Antennas and Radar*]. We do not wish to trivialize this subject with superficial explanations. Therefore, we will focus on *linearly polarized* antennas here, but keep in mind that practical situations can be more complicated. It is because of the pragmatic nature of the EMC testing area that linearly-polarized antennas are almost universally mandated by testing standards. In order to provide essentially perfect linear polarization, a precisely symmetric antenna such as precision dipole or precision biconical antenna as shown in Figure 4 is required. The precision dipole shown exhibits such low cross-polarization (80 dB) that specialized equipment is required to measure it.

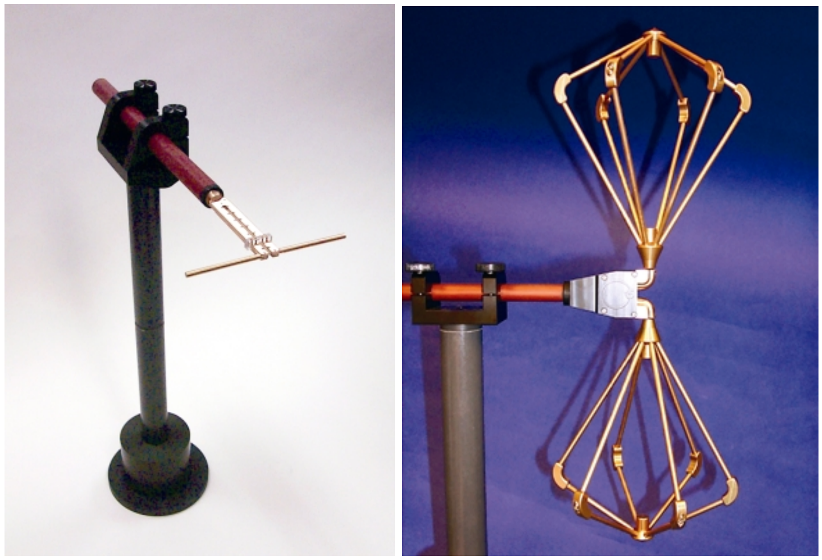

Figure 4: Precision Dipole Antenna and Precision Biconical Antenna (Photo courtesy of TDK RF Solutions)

It is generally true that the polarization state of an electromagnetic field at any point can be completely described by two orthogonal components. Moreover, these two orthogonal components carry power independently. Thus, while a complex DUT (for example a personal computer) might radiate elliptically polarized electromagnetic fields, the fields can be thought of as a superposition of two linearly polarized fields. Furthermore, if only radiated power is of interest, the phase between these two components is moot and it suffices to add the power in the two polarizations. Far away from any antenna only two field components can exist—those transverse to the direction of propagation, hence components in the θ and ϕ directions [see reference 1]. Thus, for a far field measurement of radiation intensity two orthogonally-polarized measurements are required. In the near field, three orthogonally-polarized measurements are required (see the isotropic field probe described below).

Gain

Gain is perhaps the most widely used descriptor for antenna performance. However, more than one definition or interpretation is in common use. Most antennas are passive devices and hence do not have power gain in the sense that an amplifier might exhibit power gain. But when viewed from the standpoint of some distant receiver, a particular antenna might radiate much more power in a given direction than an isotropic antenna. Thus, gain is defined as "*the ratio of the intensity, in a given direction, to the radiation intensity that would be obtained if the power accepted by the antenna were radiated isotropically. The radiation intensity corresponding to the isotropically radiated power is equal to the power accepted (input) by the antenna divided by* 4π."

By definition isotropic means the same in all directions—iso means the same, tropic means direction. The isotropic antenna is a hypothetical device which radiates/receives power in/from all directions equally. The closest thing to an isotropic antenna is a small dipole which is, in fact, isotropic in one plane and exhibits a cosine (a "figure 8") pattern in the other. That is, the 3-dimensional radiation pattern looks like a doughnut as shown in Figure 5. This is in contrast to acoustic fields where monopole sources do exist; these exhibit isotropic patterns. We mention in passing here that, in the EMC area, so-called isotropic electric field probes are generally available. These probes actually consist of three orthogonal electric dipoles and three detectors. The key here is that three detectors are used. In order to provide isotropic reception, the outputs of the three dipoles must be *detected and then summed*. In this manner, the probe (detectors included) is sensitive to electric fields polarized in any direction. However, in general, there is no way to form a linear reciprocal antenna which exhibits a truly isotropic radiation pattern; the electrically-short dipole is the most fundamental source of electromagnetic radiation.

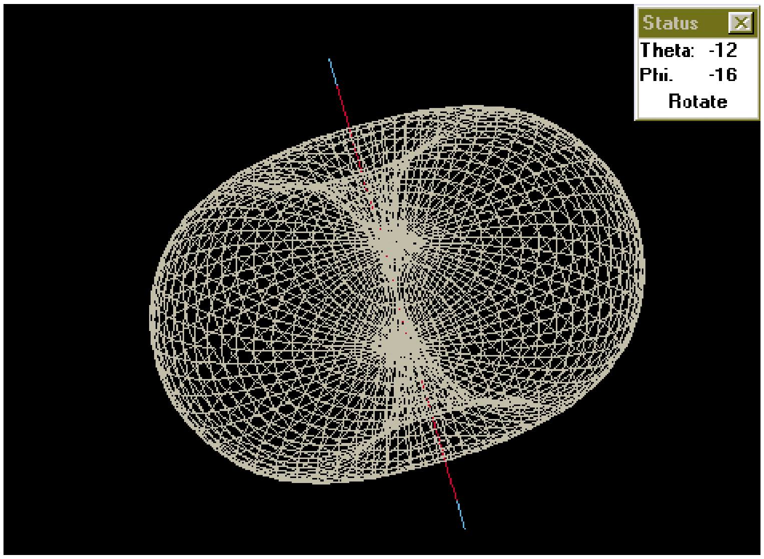

Figure 5: 3-D Pattern of linear dipole
(3-D graph courtesy of TDK RF Solutions)

Gain is sometimes referenced to something other than a hypothetical isotropic source. Most commonly, gain is referenced to a half-wave linear filamentary dipole. Gain is defined by the narrow viewpoint of a localized receiver—the gain is the ratio of input power required using a perfectly efficient (lossless) isotropic antenna to achieve a particular *intensity* at a specific location to that required when using the antenna in question. Thus, an antenna with 3 dB of gain in a particular direction would require half as much power as an isotropic source to achieve the same intensity. Thus, it can be seen that for the purposes of a link budget, the gain of an antenna can be treated the same as the gain of an active device such as an amplifier. Indeed, this can be seen from the Friis transmission equation [1]:

$$P_{received} = P_{transmitted} \frac{G_R G_T}{\left(\frac{4\pi D}{\lambda} \right)^2}$$

where $P_{received}$ is the received power, $P_{transmitted}$ is the transmitted power, G_T is the gain of the transmitting antenna, G_R is the gain of the receiving antenna, and D is the distance between source and receiver. Here we can see that doubling the gain of either the source or the receiver antenna is equivalent to doubling the transmitted power. Nevertheless, the gain of a passive antenna does not represent any real power gain. Thus, the gain of an antenna is the directivity multiplied by the radiation efficiency.

$$G(\theta,\phi) = \eta_{radiation} D(\theta,\phi)$$

In deciBels over isotropic (dBi), the gain is taken as 10 times the common logarithm of this quantity. Thus, a perfectly efficient isotropic antenna would have a gain of 0 dBi for all angles. Practical antennas (excluding high gain reflector antennas) not purposely employing lossy materials have gains ranging from 0 dBi to 30 dBi (see Table 1). Notice that the gain of an antenna is a function of direction. If no direction is specified, the gain is taken as that in the direction of maximum gain. In Figure 6, a 3-dimensional plot of gain for an LPDA is presented.

Table 1: Typical Gain of Common EMC Antennas

EMC Antenna	Typical Gain
Electrically-short dipole (lossless)	1.73 dBi
Half-wavelength dipole (lossless)	2.14 dBi
Optimum LPDA for communications applications	8-10 dBi
Reduced-size (compressed) LPDA typical for EMC applications	5-6 dBi
Horn	6-30 dBi

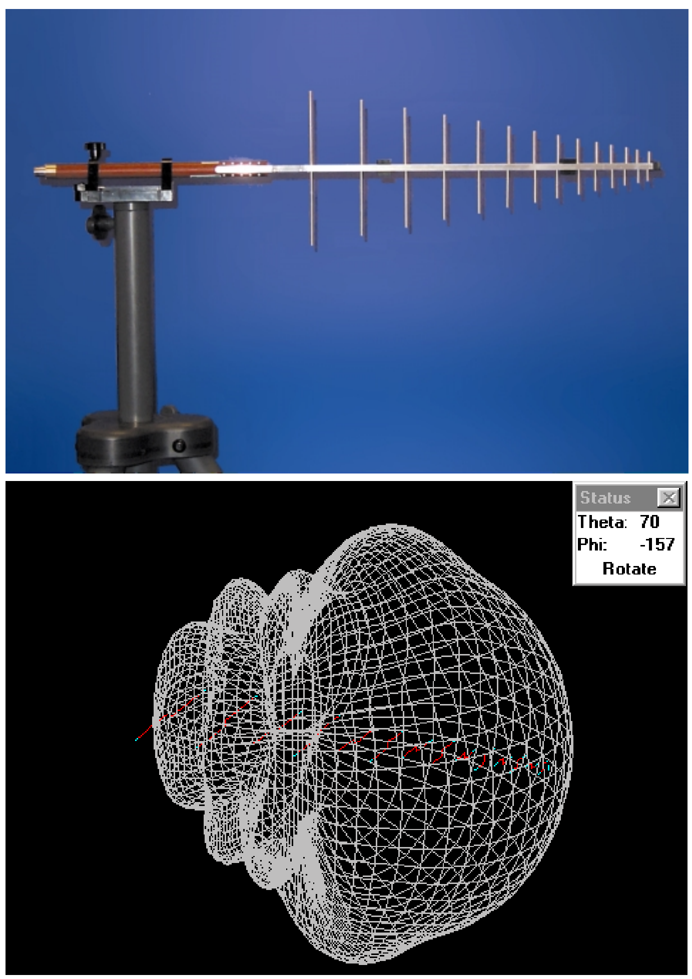

Figure 6: 3-D Pattern Magnitude of Gain of LPDA

It is important to understand the wording of the official definition. In particular, gain is defined in terms of "power accepted by the antenna." In a practical situation, not all of the so-called forward power is accepted by an antenna. Notice that the gain of an antenna implicitly includes the electrical efficiency. The measured gain published by most EMC test houses (gain derived from ANSI C-63.5 antenna factor measurements) actually is the true gain multiplied by the mismatch or reflection efficiency. While the electrical efficiency is typically quite good, say 90 percent or so, the mismatch efficiency is actually quite poor for some typical EMC antennas. We can define “gain with mismatch” as

$$G'(\theta,\phi) = \eta_{match} G(\theta,\phi) = \eta_{match}\eta_{radiation} D(\theta,\phi).$$

This is the definition of gain used in almost all manufacturers’ catalogs. While it differs from the IEEE standard definition, it is quite practical. The Friis equation modified to include mismatch loss [1] becomes simply:

$$P_{received} = P_{transmitted} \frac{G_R G_T}{\left(\frac{4\pi D}{\lambda}\right)^2} \sqrt{1-|\Gamma_T|^2} \sqrt{1-|\Gamma_R|^2} = P_{transmitted} \frac{G'_R G'_T}{\left(\frac{4\pi D}{\lambda}\right)^2}.$$

E and H-Plane Patterns

When discussing the radiation pattern of a linearly-polarized antenna, it is useful to define the so-called E and H-planes. The principal E-plane of an antenna is defined in the IEEE standard as “*For a linearly polarized antenna, the plane containing the electric field vector and the direction of maximum radiation*.” The E-plane pattern of an LPDA is shown in Figure 7. The principal H-plane is defined as “*For a linearly polarized antenna, the plane containing the magnetic field vector and the direction of maximum radiation*.” The H-plane pattern of an LPDA is presented in Figure 8. Thus, the principal E and H-planes are orthogonal planes. It is often sufficient to examine only E and H-plane cuts of the three-dimensional radiation pattern. These are termed the E and H-plane patterns. An advantage of discussing patterns in this manner is that the E and H-planes are referenced to the particular antenna under discussion and not a fixed coordinate system.

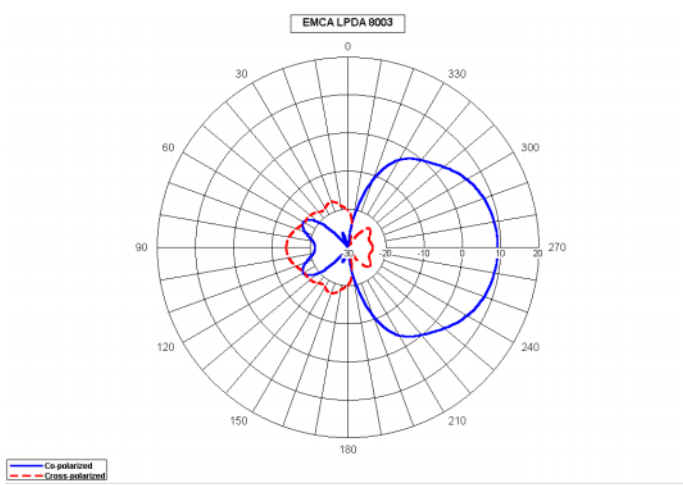

Figure 7: E-Plane Pattern and Cross Polarization for LPDA

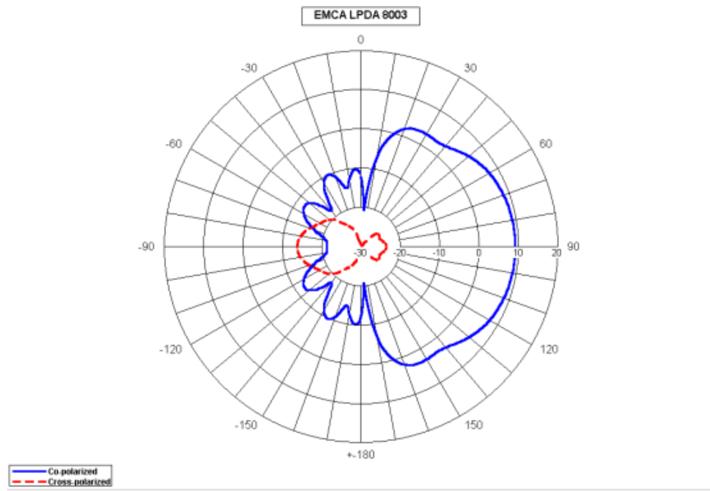

Figure 8: H-Plane Pattern and Cross Polarization for LPDA
(Photo and pattern graph courtesy of TDK RF Solutions)

Front-to-back ratio

The front-to-back ratio is the ratio of the gain of an antenna on its principal lobe to the gain in the opposite direction. A good LPDA will exhibit 20 dB or so of front to back ratio while a biconical antenna exhibits 0 dB.

Conclusion

The gain of an antenna is a crucial parameter in predicting its far field performance. It is essential to understand the difference between gain as defined in the IEEE standard and "gain with mismatch" as is almost universally used in EMC antenna manufacturers' catalogs. The mismatch can sometimes have a greater effect on the far field performance of an antenna than its directive nature. Finally, it is vital to understand the field regions surrounding an antenna so that one can know when to be cautious about estimating performance with far field quantities. The near field effects will be considered in detail in the next installment of this article in which we will discuss antenna factor and field generation capability.

References

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