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EMC Antenna Fundamentals

Selecting the right antenna for the job can be a difficult task. In many cases, manufacturer terminologies and specifications are so varied that it is difficult to compare them. A firm grasp of the basic terminologies and their limitations is essential. The right antenna is an essential part of a test system. Depending on the specific application and the equipment used, one type of antenna may be better suited than another.

The discussion in this article is focused on antennas, which by definition are devices that convert time-varying voltages into a radiated electromagnetic field. The keyword here is “radiated.” Many field generating devices, such as TEM (or Crawford) cells, GTEM, parallel plates, or tri-plates (widely used in automotive component testing), are strictly speaking not antennas. Energies stay within the devices and are not radiated into space.

In EMC applications, antennas are primarily used for radiated emissions measurements, radiated immunity testing, site qualification testing (normalized site attenuation), or other applications such as exciting a reverberation chamber. In a specific application, one set of parameters may be more important than another. For example, the gain of an antenna may not be of any concern if it is used to excite a reverberation chamber.

Directivity And Gain

Passive devices, such as most of the antennas used in EMC, cannot amplify signals they receive, or radiate more energy than provided. Gain and directivity specify an antenna’s ability to concentrate a transmitted signal in a desired direction, or receive a signal from that direction.

Directivity describes how well an antenna concentrates radiation intensity in a certain direction, or receives a signal from this direction. This is in comparison to an omni-directional (isotropic) antenna. Note that an isotropic antenna is simply a theoretical model, and is not possible to construct one physically. A theoretical isotropic antenna has a directivity 0 dBi (“dBi” means dB over an isotropic source). A half wave dipole has a directivity of 2.14 dBi. This means a half wave dipole can concentrate 2.14 dB more energy in its maximum radiation direction than an isotropic source. Higher directivity is associated with narrower beamwidth.

Gain, by IEEE definition, is the product of the directivity and the ohmic efficiency (sometimes called ohmic loss factor). Most EMC antennas are made of aluminum or other highly conductive metals. In these antennas, the ohmic loss is insignificant; therefore, gain is the same as directivity. This is where confusion arises, since such a gain definition is rarely the one you encounter in an EMC application.

Gain in EMC applications typically includes an additional mismatch factor. To illustrate this, let us assume the antenna is in transmitting mode (the argument applies to receiving antennas as well). Note the IEEE definitions above are based on the net power delivered to the antenna. In reality, antennas are never perfectly matched to the source, and energies are reflected at the antenna port. The net power is the subtraction of the forward power and the reverse power (in dB terms).

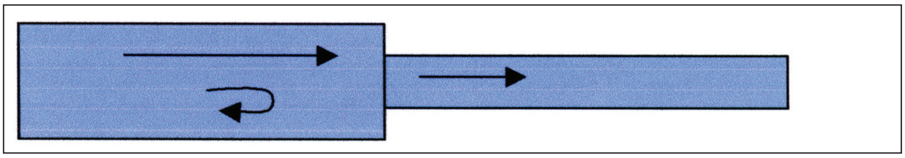


Figure 1

Although it is different from the IEEE definition, it is a practical one (this is sometimes referred to as apparent gain). For example, an antenna can have a very directive pattern but, if it is not close to 50 Ω in characteristic impedance, very small electric field levels will result when connected to a 50 Ω source (used for most instruments). In most EMC applications, gains published in the antenna catalogs include this mismatch factor.

An analogy: water (RF signal) flows through pipes with unequal diameters. Some of the water goes through and some is reflected (Figure 1).

Reflection Coefficient/VSWR/Return Loss

Reflection coefficient, VSWR and return loss all describe the same physical phenomenon as discussed in the last paragraph, that is, the mismatch factor. If a mismatch occurs, there is a standing wave established in a transmission line, the voltage ratio of the maximum to the minimum is called voltage standing wave ratio (VSWR). The closer the VSWR is to unity, the better the match is. Reflection coefficient is the ratio of the reflected voltage to the forward voltage. Reflection coefficient can be a complex number, as the reflected voltage does not always line up in phase with the forward voltage. The smaller the magnitude of the reflection coefficient, the better the match is. Return loss is simply the magnitude of logarithmic form of the reflection coefficient.

Since all these terms describe the same physical property, there is a one to one relationship among them. The simple equations are,

$$VSWR = \frac{1+|\Gamma|}{1-|\Gamma|}$$

$$|\Gamma| = \frac{VSWR-1}{VSWR+1} \quad ,$$

$$RL = -20 * \log|\Gamma|$$

where $|\Gamma|$ is the magnitude of the reflection coefficient, and *RL* is the return loss is dB. In terms of power relationship:

$$P_{net} = (1-|\Gamma|^2)P_{fwd} \,,$$

where P_{net} is the net power, and P_{fwd} is the forward power. For example, if an antenna has a VSWR=2:1, the magnitude of the reflection coefficient is 1/3, the return loss is 9.5 dB, and 11% of the power is reflected (or 89% net power is delivered to the antenna).

Antenna Factor

Antenna factor (AF) is another practical term for EMC engineers, and seldom used outside EMC applications. It provides a receiving antenna with the relationship between the incident electromagnetic field and the voltage on a 50 Ω load connected to the antenna. In equation form:

$$AF = \frac{E}{V} \,,$$

where E is the incident electric field, and V is the voltage on the 50 Ω load. AF has a unit of 1/m, or dB m^{-1}. Antennas with smaller AFs are more sensitive to the incident field. It is interesting to note that AFs generally increase with frequency. It comes as no surprise then that to measure the same field level, more sensitive receivers are needed for higher frequencies. AFs are normally provided by antenna manufactures or calibration labs. The accuracy of AFs directly affects radiated emissions measurement. It is recommended antennas be calibrated annually to minimize the measurement uncertainties.

Antenna Pattern And Beamwidth

Antenna pattern, in simple terms, is the response of an antenna as a function of viewing angle. In a strict sense, antenna pattern is a descriptor for the far field response. In practice, EMC measurements are often performed in the near field, and antenna pattern is taken quite liberally as well to include near field responses. Beamwidth is typically measured when power received has fallen half (3 dB down) of the boresight direction. This is called half-power beamwidth or 3 dB beamwidth. Beamwidth can be used to roughly estimate the size of a uniform field area in an immunity test. However, many other factors come into play for establishing uniform field, such as reflection from the ground or walls of a chamber. Moreover, patterns could be measured at a different distance than the one used in the immunity setup, thus the near field effect is different. Beamwidth is not a magic number that establishes the size of the uniform field plane.

Phase Center

A radiated wavefront has a curvature when in near field. In far field, the curvature is so large that it can be regarded as a plane wave. The apparent center of the curvature is the phase center. For many EMC antennas, such as biconical antennas or dipoles, the phase centers are quite obvious. For log periodic antennas, the phase center moves from the back to the front as frequency goes up. The measurement distance from the antenna to the device under test is unclear. In practice, a compromise has to be made for the distance.

Polarization

The polarization of a radiated wave has to do with the radiated vector field traced out as a function of time. It is beyond the scope of this article to explain the full meaning of polarization in all its detail. Fortunately, many EMC antennas are linearly polarized, such as dipoles, biconical antennas, log periodic dipole arrays, and horns. Linearly polarized antennas radiate vector field in a single direction which is less complicated than other polarizations. Any imperfections are measured by the cross-polarization ratio (the ratio of the field level in the intended direction to that of its orthogonal direction). Some antennas are circularly polarized for special applications, such as conical log spiral antennas as required by MIL-STD 461.

Balance

Coaxial cables attached to the antennas are inherently imbalanced, because they are asymmetrical with respect to ground. In other words, the cable shield to the ground is different from the center pin to the ground. Some antennas, such as biconical antennas, employ balun (short for *Bal*anced-to-*Un*balanced transformer) to overcome the imbalance. Basically, a balun provides low impedance or an easy pass through to the differential current, and high impedance to the common mode current. An unbalanced antenna has different responses depending on which side is up when polarized vertically. A large amount of common mode current exists between the shield of the feed cable and the ground plane. This causes large measurement uncertainties.

Bandwidth

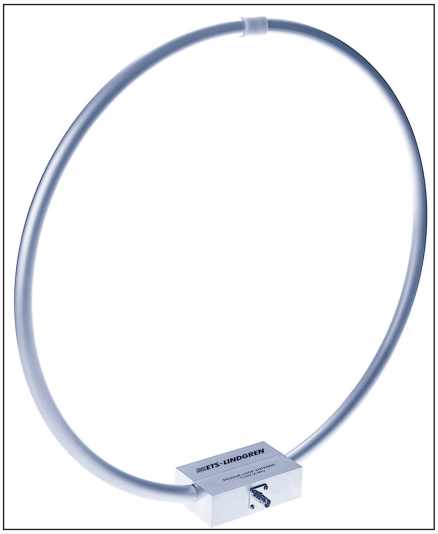
Bandwidth is "the range of frequencies within which the performance of the antenna, with respect to some characteristic, conforms to a specific standard" [1]. The definition is quite broad. It does not explicitly specify what the "characteristics" or "specific standard" are, so the term bandwidth is subjective. Depending on the application, the typical characteristics can include all or some of the terms discussed previously. Engineering judgments are needed to determine what is acceptable for your application.

Typical EMC Antennas

Several types of antennas can sometimes all satisfy the basic requirements of a measurement. The following list provides brief features, application notes and possible drawbacks of the typical EMC antennas to hopefully aid readers in selecting the best fit.

Loop And Magnetic Field Coil

Typically used in the frequency range from 20 Hz to 30 MHz for measuring magnetic fields. At these frequencies, measurements are in effect within the near field region. Unlike in the far field, in the near field region, electric fields do not relate to the magnetic field by 377 Ω. Magnetic field cannot be derived simply from the electric field. The designs of these antennas ensure they predominantly produce or respond to magnetic fields.

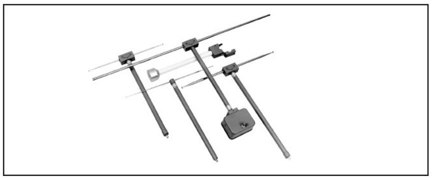


Rod Or Monopole Antennas

Rod antennas are the counterparts of loop antennas. They are designed to respond to electric fields from 30 Hz to 50 MHz. Since rod antennas are so small compared to the wavelengths (at 30 Hz, the wavelength is 10,000 km), amplifiers within the antennas are sometimes necessary for small signals. Rod antennas are typically required for the GR-1089-core standard for network telecommunications equipment (where radiated emission and immunity tests for electrical field at 10 kHz are required).

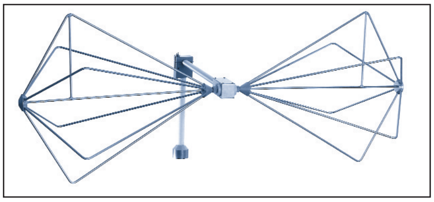
Dipole Antennas

Dipoles are tuned to specific frequencies, from approximately 30 MHz to a few GHz. They are narrow band. To cover a wide bandwidth, they need to be tuned manually. Dipoles are often used as reference antennas because the dipole elements performance can be theoretically calculated. Interestingly, Roberts' dipoles, which are specified in the ANSI C63.5, have balun designs that are difficult to characterize, so performance of the Roberts' dipoles is hardly calculable. Dipoles are seldom used in everyday measurements, due to the need for individual tuning at each frequency.



Biconical Antennas

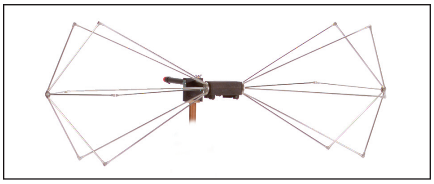
Biconical antennas typically cover the frequency range from 20 MHz to 300 MHz. All wire-cage biconical antennas on the market have similar size and shape (approximately 1.36 m wide). This is because they are based on MIL-STD-461 specifications from the 1960s, which has become the de facto standard. Due to the small electrical size at below 50 MHz, they have very high input impedance (high VSWR). Balun performance is crucial for biconical antennas. Common mode current can be easily induced on the feed cable (common mode impedance is no longer large compared to the input impedance of the antenna). Ferrite



beads are often used on the feed cable to suppress the common mode. In addition, feed cables should be extended out a meter or more horizontally before dropping vertically to the ground to reduce possible interference.

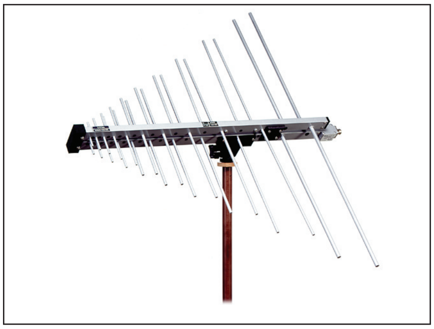
Calculable Biconical Antenna

Calculable biconicals combine the best elements of a biconical antenna and a dipole antenna in that they are theoretically calculable and broadband. They look very much like regular biconical antennas. The main differences are that the baluns can be entirely characterized with a network analyzer, the elements are precisely constructed, and their responses are numerically computed. These result in theoretically computed antenna factors that can be used for site validation testing or free space factors for radiated emissions testing. The accuracy of a calculable biconical antenna is actually better than those of a Roberts' dipole, because the balun performance is individually calibrated. The uncertainty is better than 0.25 dB for its antenna factor [2].



Log Periodic Dipole Arrays

Log periodic dipole arrays (LPDA) typically cover the frequency range of 80 MHz to a few gigahertz. As discussed previously, the phase center of a LPDA moves from the back of the antenna boom to the front as the frequency is increased. In ANSI or CISPR standards, emissions measurements are performed from the center of the log antenna boom. For immunity tests, EN61000-4-3 requires measurements be made from the tip of the log antenna. The gain of a LPDA is typically around 5 dBi, which provides a good compromise between beamwidth and sensitivity (or power and field strength requirement).



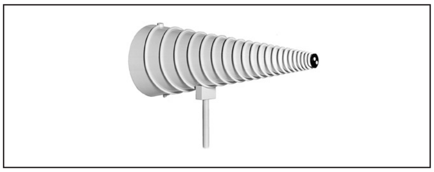
Bicon/Log Hybrid

Bicon/log hybrid antennas are sometimes referred to by their trade names, Biconilog or Bilog. The hybrid combines the frequency range of a biconical antenna and a log antenna, which is approximately 20 MHz to several gigahertz. They have become increasingly popular, as there is no band break during a test.

Just like biconical antennas at 20-50 MHz, hybrid antennas are electrically small. To increase the transmit efficiency, some hybrids employ end loading techniques to compensate for the size. They typically have T-shaped or L-shaped bowtie elements. These antennas should only be used for immunity testing. The coupling between the loading elements and their surroundings are very strong, and they introduce large measurement uncertainties for emissions testing [3]. If these antennas are to be used for both emissions and immunity testing, the end plates should be removable for emissions testing configurations.

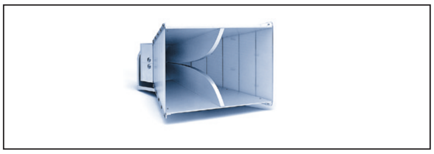
Conical Log-Spiral Antenna

The distinctive difference between the conical log spiral antenna and most other antennas is that the electric field is circularly polarized. The circularly polarized field eliminates the need for horizontal and vertical measurements separately. It is mostly used for MIL standard measurements. The frequency range is typically from 100 MHz to 1000 MHz. Note that when measuring the gain of a circularly polarized antenna with a linearly polarized one, the gain appears 3 dB lower because of the polarization mismatch.



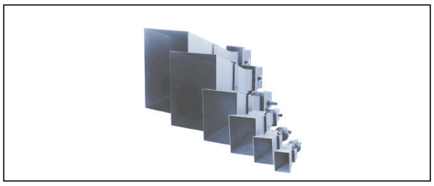
Broadband Ridged Waveguide Horn

These versatile and broadband ridged waveguide horns can cover 200 MHz to 40 GHz. The horns for low frequencies can be physically large. For example, the horn that covers 200 MHz to 2 GHz is approximately 37x39x29 inches. Since gain for these antennas are generally larger (around 10 dBi), the beamwidth is narrower. One should make sure that the beamwidth meets the measurement requirement.



Standard Gain Horn Antenna

These are very similar to dipoles or calculable bicons in that the gains can be theoretically computed. Compared to the ridged waveguide horn, they are narrow band. Many horns are needed to cover a broad frequency range.



Antenna Calibrations

There are several methods to calibrate an antenna. Much confusion exists for free-space antenna factors and antenna factors obtained in a specific setup (sometimes called geometry-specific antenna factors). Understanding how AFs are arrived is important in choosing the right antennas and their associated AFs.

Standard Site Method

The standard site method is specified in ANSI C63.5. This method is best suited for "dipole-like" antennas, such as dipole, bicon, log, and hybrid antennas. The site attenuation, or the insertion losses between the transmit and receive antennas, are measured. The basic setup for a standard site method includes a large, flat, and unobstructed conducting ground plane (made of metal). One antenna is set to be at a fixed height, while the other one is scanned from 1 to 4 m in height. The maximum response between the two antennas is recorded. Typically, three antennas are needed to perform such a calibration, and they are measured in three pairings. Calculations are then performed to derive the antenna factors. Although a ground plane is used, the aim of the C63.5 standard site method is to obtain free-space AF by theoretically removing the ground plane effect. The conducting ground plane is there to establish a repeatable calibration environment.

There are some important assumptions made in the standard site method. First, the calculation to remove the ground plane assumes the antennas under test have radiation patterns of a point dipole (i.e. a donut shape pattern - uniform in H-plane and figure "∞" in E-plane). Second, no coupling exists among antennas and the metal ground plane. And third, antennas are in the far field so that the physical size of an antenna has no effect, i.e. the antennas are immersed in a uniform field.

However, these simple assumptions are not always acceptable. The errors for a single bicon antenna factor derived from the standard site method can be as large as 2 dB [4]. This means if these AFs were used for normalized site attenuation test, the total error would be 4 dB (because an antenna pair is used for the site attenuation). A new ANSI C63.5-2000 draft standard addresses this limitation by providing correction factors. The correction factors are based on numerical simulations, and the baluns are assumed to be either 50 Ω or 200 Ω [4]. Note that this is not the perfect solution either, since some commercial antennas have balun impedances that vary drastically with frequency. Even a well-made one does not have a perfect match. The balun impedances have significant influences on the correction factor.

The best approach is probably to use the calculable biconical antennas. The baluns are individually calibrated, and no approximations are made regarding their electrical performance.

For log antennas, there is currently no correction table provided. These major factors contribute to errors:

- Non-stationary phase center with respect to frequency (distance between antennas is vague)
- Large deviation of the antenna pattern to that of a dipole (note that the gains are approximately 5 dBi or more)

It is not as straightforward to derive correction factors for log antennas as for bicons. The biconical antennas are similar in mechanical design while log antennas vary by make and model. Research is in progress to develop a new method, which is based on a complex fit normalized site attenuation scheme. Interested readers can refer to [5] for more details.

Reference Antenna Method

This is another method specified in ANSI C63.5. It is basically a substitution method. The responses between two known antennas are measured (specifically two Roberts' dipoles), and then one is replaced by the antenna under test. The antenna factor is derived from the difference. Mutual coupling between the two standard antennas and the antenna under test, as well as ground plane effects, can be significantly different, leading to significant errors.

Other Methods

There are other calibration methods, such as those used for loop antennas and rod antennas. Some labs use variations of the ANSI C63.5 method to calibrate log, dipole and bicon antennas, such as standard field method, or standard antenna method with precision dipoles etc. One important note is that, even if a perfect free-space antenna factor is obtained, one should still apply the correction factors provided by ANSI C63.5 for normalized site attenuation test. This is because normalized site attenuation (NSA) tests are not in free space. The correction factors are used to correct the influences from the test setup, i.e. the differences between free space and the specific geometry of an NSA setup.

Calibrations For High Gain Antennas

High gains, such as horn antennas, have narrow beamwidth. They do not see ground plane when placed in a close distance. In that case, the calibration is in free-space condition.

Use Of Antennas For Radiated Emissions Testing

Radiated emissions tests are defined in ANSI C63.4 in the US or the equivalent EN standards in Europe. The test setup is very similar to the antenna calibration setup. A large flat, unobstructed metal ground plane is used. The equipment under test is set on a low dielectric table, which is 80 cm high. The table is placed on a turntable, which can provide a full 360° scan. The receive antenna is scanned from 1 to 4 m for both horizontal and vertical polarization, and the maximum readings are recorded and compared to the standards.

For emissions measurements, it is recommended to use free-space antenna factor. This is despite the fact that the measurements are not performed in a free space environment. The true antenna factors in the specific test environment are height dependent. The free space AF provides a good compromise.

Use Of Antennas For Radiated Immunity Testing

Most immunity tests are performed per European standard EN 61000-4-3. It requires the establishment of a uniform field plane where the EUT would be. The typical setup is illustrated in Figure 2.

The antenna power handling capability is an important parameter in such a test. Many antennas are designed to have superior performance in balance and impedance matching, and not designed to handle high powers required in an immunity test. For an immunity antenna, the balance is not as important, since the purpose is to establish a known electromagnetic field. In the

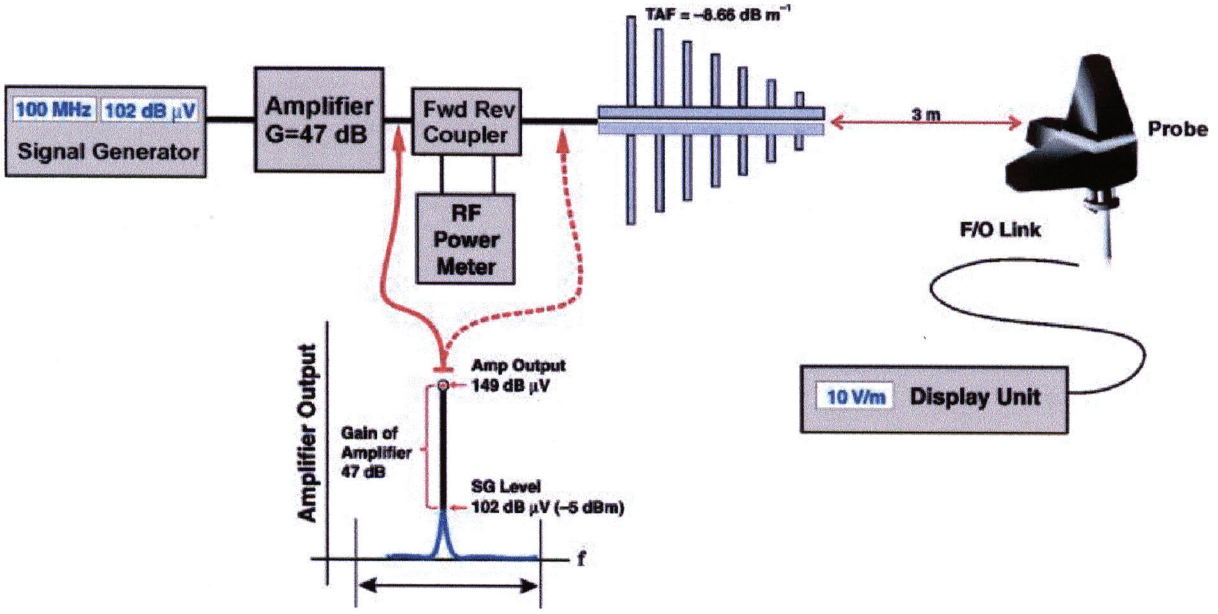


Figure 2

setup shown, the isotropic field probe is the key in setting up a calibrated field.

A field probe is a special kind of antenna. It consists of three independent broadband antennas, which are oriented orthogonally. The field levels are measured and reported digitally through a fiber optical link to a readout unit or a computer. The total field is summed as RMS values of the three axes:

A field probe is a broadband instrument. If more than one frequency component exist, a field probe responds to all of them. This is in contrast to antennas connected to a spectrum analyzer, where the analyzer discriminates between frequencies. It is thus critical to ensure the purity of the signal in an immunity testing setup, especially the harmonic field generated by a power amplifier.

Just as antenna factors are extremely important for emissions measurement, the calibrations of probe factors are vital for immunity tests. Calibration labs typically provide a frequency correction table for each probe. This corrects the reading for the specific frequencies. Another important factor is the linearity of a probe. This is a parameter that measures how faithful a probe measures at different field levels. Modern probes have internal adjustments for linearity, making sure probe readings are correct not only at the calibration field levels (e.g. 20 V/m). Not all probe calibrations are equal. When performing a probe calibration, a simple frequency response calibration without re-adjusting linearity is insufficient in most cases.

Conclusion

A broad range of topics have been discussed in this article, including the basic parameters of antennas, the common types of antennas used in EMC, their calibrations and applications in radiated emissions and immunity tests. Intentionally left out of this article are many detail theoretical discussions, equations and formulas found in other antenna papers in an attempt to make the points easier to understand. This is not meant to trivialize these topics. The reader can refer to [1,6] for more in-depth explanations on many important antenna topics. ■

References

[1] C. A. Balanis, “Antenna Theory Analysis and Design”, Second Edition, John Wiley & Sons, Inc., New York, 1997.

[2] Z Chen and A Cook, “Low Uncertainty Broadband EMC Measurement Using Calculable Precision Biconical Antennas,” 2000 IEEE International Symposium on Electromagnetic Compatibility, Washington, DC, 2000.

[3] Zhong Chen, “Understanding the measurement uncertainties of the bicon/log hybrid antennas”, ITEM 1999.

[4] Z Chen and M Windler, “Systematic Errors in Normalized Site Attenuation Testing,” Compliance Engineering 17, no. 1 (2000): 38–48.

[5] Z Chen and MD Foegelle, “An Improved Method for Determining Normalized Site Attenuation Using Log Periodic Dipole Arrays,” , 2000 IEEE International Symposium on Electromagnetic Compatibility, Washington, DC, 2000.

[6] J.D. Kraus, “Antennas”, Second Edition, McGraw-Hill, 1988.

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