Interpreting Antenna Performance Parameters for EMC Applications: Part 3: Antenna Factor

James McLean, Robert Sutton, Rob Hoffman, TDK RF Solutions Inc.

This article is the third in a three-part tutorial series covering antenna terminology. As noted, our intention is to discuss standardized antenna terminology as published in the *IEEE Standard Definitions of Terms for Antennas*, and how this terminology compares with the nomenclature that is commonly used in the EMC community. In the first part of this series, we discussed radiation efficiency and input impedance match. In the second part of this series, we discussed antenna field regions and antenna gain, and in this part we will discuss antenna factor and its importance to EMC measurements.

Antenna Factor

Antenna Factor (AF) is perhaps the most widely used device descriptor in the EMC area. However, it is one that is definitely not part of standard antenna terminology. Antenna factor reflects the use of an antenna as a field measuring device or probe. Succinctly stated, the antenna factor is the factor by which one would multiply the output voltage of a receiving antenna to obtain or recover the incident electric or magnetic field [1,2]. Thus, the electric field antenna factor is given by

$$AF^{electric} = \frac{E_{incident}}{V_{received}} \text{ 1/meter,}$$

and the magnetic field antenna factor is given by

$$AF^{magnetic} = \frac{H_{incident}}{V_{received}} \text{ Siemens/meter.}$$

The antenna factor is really analogous to a transfer function when the antenna is considered as a two-port transducer. Indeed, a complex antenna factor can be defined which provides the phase information for the incident field as well as the amplitude. The complex antenna factor has been used to a much lesser extent than its real counterpart. However, it has been clearly defined in the literature [3,4].

There is an ambiguity involved in specifying the antenna factor of an antenna or probe because the output voltage of an antenna is dependent on the load connected across the antenna's terminals (see Figure 1).

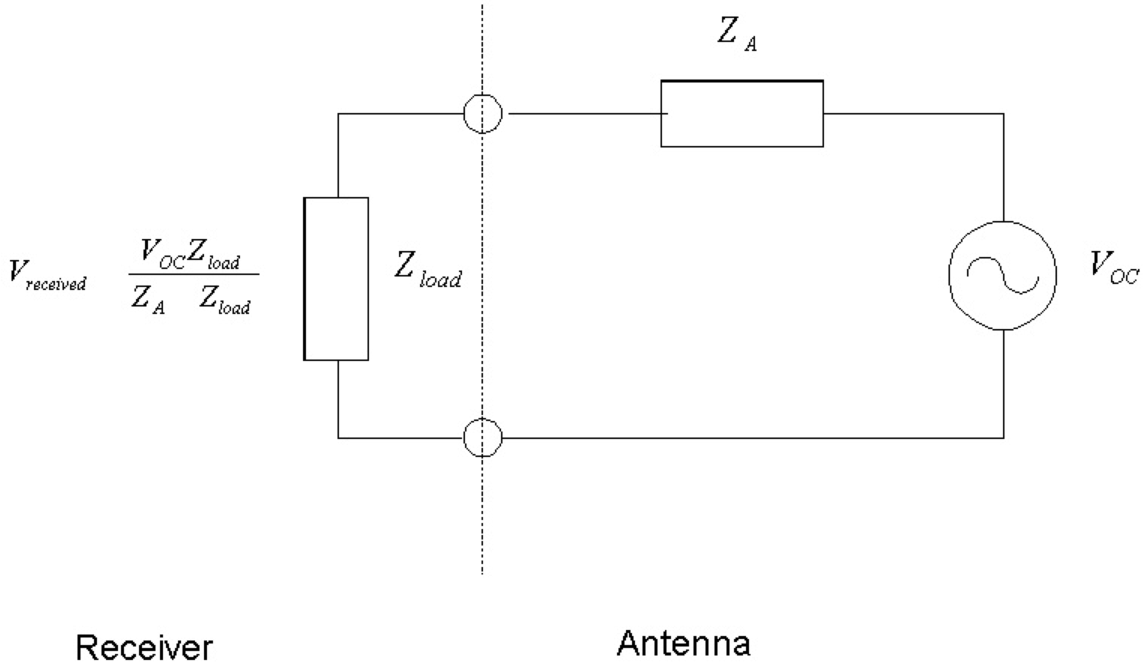

Figure 1: Diagram of Thévenin Equivalent Circuit Model for an Antenna

This is analogous to the ambiguity in defining the gain of a two-port network. Many definitions are possible depending on load conditions. Antenna factors are routinely defined for both open-circuit conditions and resistive load conditions. In Figure 1, the Thèvenin equivalent complex impedance for the antenna is Z_A while the complex input impedance to the receiver is Z_{load}. In the case in which the antenna is matched for maximum power transfer, the received voltage will then be one-half the open-circuit voltage. More often than not however, the antenna is not conjugately matched to the receiver. Most RF receivers including network analyzers and spectrum analyzers have 50 Ohm resistive input impedances. Therefore, most published antenna factors are defined assuming the antenna is connected to a 50 Ohm load.

Normally, the logarithmic scale of deciBels is intended for dimensionless quantities such as the voltage or current gain of an amplifier. However, unlike antenna gain or directivity, the antenna factor is not dimensionless; it has units of 1/m in the case of electric field antenna factor and units of S/m in the case of magnetic field antenna factor. In order to utilize a logarithmic scale, the antenna factor in dB is usually referenced to an antenna factor of 1 V/m per Volt or 1/m in the case of electric field antenna factor and 1 A/m per Volt or 1 S/m in the case of magnetic field antenna factor. This is in analogy to employing dBm where we are referencing a power to a specific power level, say one milliWatt, or describing the gain of a transimpedance amplifier as referenced to 1 S. Thus, electric field antenna factor is often expressed in dB (1/m) which must be taken to mean referenced to an antenna factor of 1/m. That is, an antenna with a published electric field antenna factor of 6 dB referenced to an antenna factor of 1/m will produce an output voltage of .5 volts for an incident field of 1 V/m. This is sometimes written as 6 dB 1/m. However, it is also sometimes written as 6 dB/m. Although this nomenclature departs from the standard procedure for displaying logarithmic values, it has historically been acceptable in the EMC community. Therefore, it is quite prevalent in the industry and the reader should be comfortable with it.

Note that the antenna factor includes losses and mismatch in the antenna and its associated equipment (such as a balun or matching transformer). However, it does not account for the use of an intervening transmission line (such as coaxial cable) to connect the antenna to the receiver. In most cases the characteristic impedance of the transmission line matches the resistive input of the receiver and thus the losses in the transmission line can be easily accounted for with a multiplicative factor. That is, for example

$$E_{incident} = V_{received} AF^{electric} C_A$$

where C_A is the loss factor of the transmission line. This relationship is usually stated logarithmically:

$$E_{incident}(dB\mu V/m) = V_{received}(dB\mu V) + AF^{electric}(dB1/m) + C_A(dB)$$

where the cable loss in dB is a *positive* number. That is $C_A = e^{\alpha l}$ where is α is the attenuation of the cable in nepers/m and l is the length of the cable in meters. For example, if a particular cable exhibited 3 dB insertion loss in a 50 Ohm system at a particular frequency and the cable were being used with a receiver with a 50 Ohm input impedance, the incident electric field would be obtained by adding 3 dB to the sum of the antenna factor and the received voltage.

The Relationship between Antenna Factor and other Fundamental Antenna Parameters

The electric field antenna factor for open-circuit conditions is essentially the reciprocal of the so-called effective length of an antenna [5]

$$h_e = \frac{V_{oc}}{E_{incident}}.$$

Note that in reference [5], a vector effective length is defined which includes polarization mismatch between the receiving antenna and the incident electric field. When effective length is given as a scalar quantity it is implicit that the polarization of the receiving antenna is aligned with that of the incident field. In reference [4] a complex, vector effective length is defined which includes phase information as well as polarization mismatch.

The term *effective length* is derived from the study of linear antennas [5-7]. An electrically-short dipole with a constant current distribution (constant along the length of the dipole) will exhibit an effective length equal to its physical length. The realization of a constant current distribution requires some sort of charge reservoir at the ends of the dipole. Practically, this can be implemented with top or end loading using capacitive plates. Thus, an electrically-short, end-loaded dipole will exhibit an effective length equal to its physical length of an (open-circuit) electric field antenna factor equal to the reciprocal of its physical length. This can be reasoned out physically, since the short dipole essentially forces the potential difference which occurs along its entire length to appear across its output terminals (in open circuit conditions). In contrast, an electrically-short linear dipole (no end loading) will exhibit an effective length of one-half its physical length [7].

In traditional antenna terminology, aperture or area is the term used to describe the power collecting capability of an antenna [7]. Note that several different definitions for this term are in use. For example the terminology in reference [7] is slightly different from that in [5]. When an antenna is connected as a receiving antenna, the power delivered to a load connected to the antenna can be found by multiplying the incident power density by the *aperture* [7].

$$A = \frac{P_{load}}{S_{inc}}$$

Naturally, the aperture of an antenna is a function of direction just as gain and directivity are. However, when no direction is specified, it is always assumed that the direction is that which gives the maximum value for aperture (or gain, directivity, etc.). Here the aperture includes the effects of mismatch as well as dissipation loss. The so-called *effective aperture* or effective area describes the antenna when the load is conjugately matched to the antenna for maximum power transfer:

$$A_e = \frac{P_{available}}{S_{inc}}$$

The IEEE definition for effective area of an antenna (in a given direction) is "In a given direction, the ratio of the available power at the terminals of a receiving antenna to the power flux density of a plane wave incident on the antenna from that direction, the wave being polarization matched to the antenna." The available power is obtained with a conjugate impedance match. The *maximum effective aperture,* A_{e0} [7] of an antenna describes the power collecting capability of the antenna when it is lossless and conjugately matched to the load. Thus,

$$A = \eta_{mismatch} A_e = \eta_{mismatch} \eta_{radiation} A_{e0}$$

where the mismatch and radiation efficiencies were defined in part two of this series.

We can express the electric field antenna factor in terms of the aperture:

$$AF = \frac{E_{incident}}{V_{received}} = \sqrt{\frac{\eta_0}{Z_{load} A}}$$

Where η_0 is the free space wave impedance. Note that this expression includes the effects of mismatch and loss in the antenna.

In order to derive an expression for antenna factor in terms of gain, it is necessary to relate the effective aperture of an antenna to its gain. There are several ways to do this. All either explicitly or implicitly invoke the Lorentz reciprocity relationship [8]. Using reciprocity, it is possible to show that ratio of the maximum directivity of a particular antenna to the maximum effective aperture of the antenna is the same for any linear reciprocal antenna. The value of this invariant ratio can be determined by evaluating the maximum directivity and maximum effective aperture for a specific antenna (for example, a short dipole). Interestingly enough, this is the *only* way this ratio can be determined [8]. The ratio is found to be:

$$\frac{A_{e0}}{D_0} = \frac{\lambda^2}{4\pi}$$

where A_{e0} is the maximum effective aperture of the antenna and D_0 is the maximum directivity of the antenna. When the antenna exhibits dissipative losses, we have:

$$A_e = \frac{\lambda^2}{4\pi} G_0$$

When impedance mismatch exists between the antenna and the load, we have (from the definition of gain including mismatch given in the second part in this series),

$$A = \frac{\lambda^2}{4\pi} G_0 \eta_{mismatch} = \frac{\lambda^2}{4\pi} G_0{}'$$

This equation relates the effective aperture of an antenna to its gain. By substituting the above equation into the expression for antenna factor and then choosing the load impedance to be 50 Ohms, we obtain the ubiquitous expression for antenna factor in terms of gain and wavelength.

$$AF = \frac{9.73}{\lambda \sqrt{G_0'}}$$

In deciBels, we have:

$$AF(\text{dB}) = 20\log_{10}\left(\frac{9.73}{\lambda\sqrt{G_0'}}\right).$$

There are several important points to notice about the above expression:

- *It applies only to far field situations (plane wave excitation).*
- *This expression is valid only for 50 Ohm system.*
- *The expression is only valid when the antenna and incident field are polarization matched.*
- *The effects of impedance mismatch are included.*

A good exposition on the limitations of the applications of published antenna factors is given in reference [9]. Antenna factors can be defined for near and far field conditions. Antenna factors can also be used to describe antennas as well as non-radiating devices such as TEM cells or near field probes. However, the above relationship between gain and antenna factor does not apply except under the limitations given above. Thus, it is crucial to understand the context in which the term is defined.

Finally, sometimes a so-called “equivalent electric field antenna factor” will be defined for a “magnetic” antenna such as a loop. Electrically-small loops can be thought of as responding primarily to magnetic fields; this is especially true for shielded loop antennas such as the one shown in Figure 2. Electrically-small linear dipoles, on the other hand, can be thought of as responding primarily to electric fields. However, the electric and magnetic fields are necessarily related by Maxwell’s equations (as far as we know). In a situation where the incident field is a plane wave, the electric and magnetic fields exist in a ratio equal to the intrinsic impedance of free space. Thus, the equivalent electric field antenna factor of a loop is simply the magnetic field antenna factor multiplied by 377 (or with 51.53 dB added). Conversely, an equivalent magnetic field antenna factor can be defined for an “electric” antenna such as a short dipole by dividing its electric field antenna factor by the intrinsic impedance of free space. These relations work perfectly well for far field conditions where the electric and magnetic field antenna factors provide the same information. However, under near field conditions, the relationship between the electric and magnetic fields of a radiating device is very complex. Nevertheless, the magnetic field antenna factor of a loop antenna measured under plane wave conditions can be used to measure the near magnetic fields of a device using the loop antenna. This is because, if the antenna is small enough, the magnetic field will be *locally uniform* across the antenna’s aperture. Likewise, a short electric dipole calibrated under plane wave conditions can be used to measure the near electric fields of a device.

Figure 2: Shielded Loop
(*Photo courtesy of TDK RF Solutions*)

In some regards, the antenna factor is a more difficult concept to grasp than gain. Note that if an antenna exhibits a gain which is perfectly flat with frequency, the antenna factor increases 6 dB/octave with increasing frequency. Also note that antenna factors, expressed in dB, can take on negative values. An antenna with 0 dBi gain possesses a 0 dB antenna factor at approximately 30.81 MHz. Thus a half-wavelength dipole has a zero dB antenna factor at 39.46 MHz. At 19.73 MHz, the antenna factor of a half wave dipole is –6 dB! These numbers are not commonly seen because full size antennas are rarely used for emissions measurements at these frequencies. It is interesting to point out that the frequency dependence of the antenna factor really stems from the frequency dependence of effective aperture. This is because the collecting aperture is closely related to the physical aperture or size of an antenna. In fact, for the gain to remain constant with frequency, the effective size of an antenna must diminish with increasing frequency. This is essentially true with frequency-independent antennas in that the size of the so-called “active region” decreases with increasing frequency. It might occur to one that antennas with relatively large or even nearly isotropic gains at lower frequencies must be capable of producing high voltages when exposed to moderate electric fields. This is true; in the lower HF range (say 10 MHz), full-size antennas such as half-wave dipoles (such as the suspended wire dipoles used by radio amateurs) can indeed develop very large voltages (10s of volts, RMS) across their terminals with only moderate incident electric fields (such as the ambient fields which exist in this frequency range).

Example of Antenna Factor

Perhaps the above concepts can be clarified with a practical example. In Figure 3, typical antenna factor data for an industry-standard 1.37-meter biconical antenna is shown. Experienced engineers can immediately recognize the “check mark” signature of the antenna factor. In fact, there are several mechanisms at work determining the antenna factor. In the lowest frequency range, the antenna factor increases precipitously with decreasing frequency. This behavior is due almost entirely to mismatch below the fundamental resonance of the antenna which occurs around 80 MHz. Between 80 MHz and 250 MHz, the antenna factor rises monotonically with frequency at fairly close to 6 dB per octave. This is because the antenna is well matched over this range. The antenna factor increases somewhat less than 6 dB/octave because the directivity of the antenna is increasing slightly with frequency over this range. At about 250 MHz, the antenna factor takes a marked increase in slope. This is because the directivity on the boresight begins to fall off with a frequency, a quasi null develops on the boresight above 300 MHz. The increasing frequency slope of the antenna factor of the 1.37 meter biconical antenna is not due to mismatch.

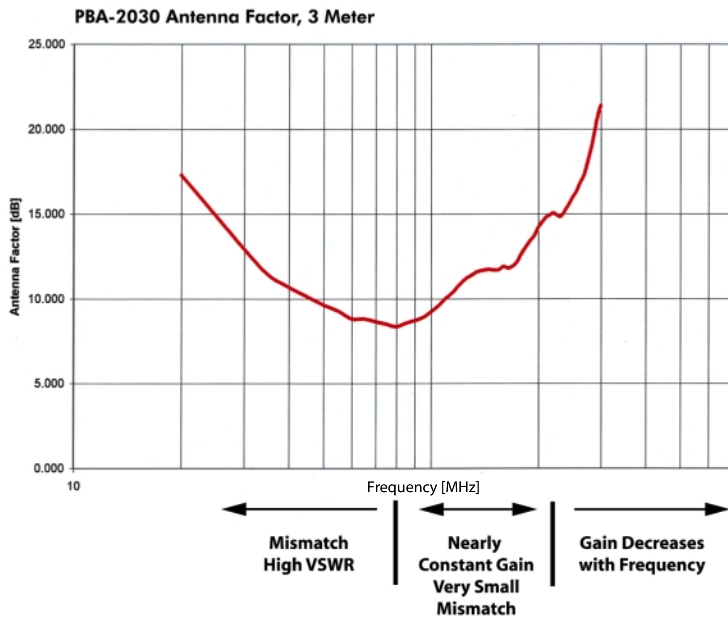

Figure 3: Antenna Factor for Typical 1.37 meter Biconical Antenna
(*Data and photo courtesy of TDK RF Solutions Inc.*)

This frequency characteristic is typical of a 1.37 meter biconical antenna employing a 4:1 balun transformer. Some commercially available biconical antennas utilize a 1:1 transformer. For these antennas, the overall impedance match is degraded, resulting in a less smooth antenna factor. The directivity of the biconical antenna is relatively constant over the entire operating frequency range (within a few dB). In fact, the gain as defined by the IEEE standard is also relatively constant over the entire operating frequency range. However, the gain including mismatch and the antenna factor are dramatically impacted by impedance mismatch below 80 MHz.

In Figure 4, the antenna factor of a typical LPDA antenna is shown. The antenna factor essentially increases monotonically at a rate of 6 dB per octave. Thus the gain of the antenna is essentially flat. The slight undulations are an artifact of the log-periodic design. At the high end of the operating frequency range, the antenna factor begins to increase at a slightly higher rate with frequency. This is due to unavoidable losses in the feeder coaxial transmission line, which increase as the square root of frequency. In some LPDA designs, the pattern of the LPDA becomes slightly distorted at the high end of the operating frequency range as the active region of the antenna nears the front end of the antenna.

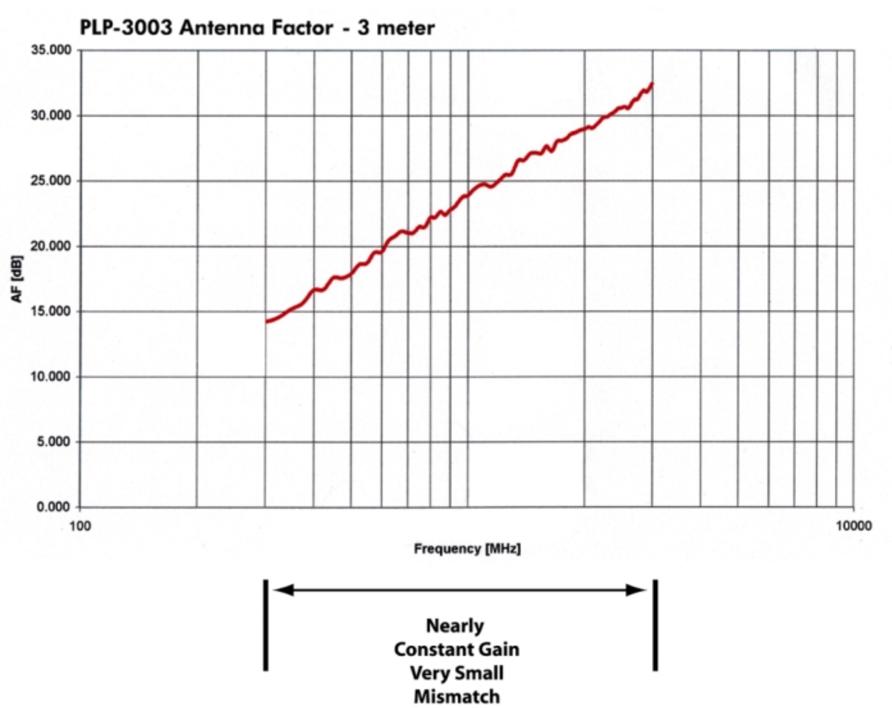

Figure 4: Antenna Factor for Precision Log Periodic Antenna
(*Data and photo courtesy of TDK RF Solutions Inc.*)

Conclusion

This final component of our three part series on antenna performance parameters has focused entirely on antenna factor because of its importance in the EMC industry. The term antenna factor underscores the use of an antenna as a sensor or field measurement device. We have presented a discussion of antenna factor and have detailed its relationship with more traditional antenna parameters such as gain, directivity and aperture. Antenna factor has been shown to be essentially the reciprocal of the effective length of an antenna, which reflects the ability of an antenna to integrate an incident field to provide a potential difference at its output terminals. Some emphasis must be placed on proper use of antenna factor calibration data especially concerning ambiguities in the specification of load impedance and the limitations on the use of far field antenna factor calibration data in near field measurements. It is important to understand the limitations of the application of published antenna factor data. Free space antenna factor data can be used accurately when test conditions are sufficiently similar to free space. This is only true when proper attention has been paid to the test facility design. An example of an high-performance anechoic chamber is shown in Figure 5. Again the reader is referred to reference [7] for a detailed list of caveats involved in interpreting antenna factor data. Finally, we have presented a brief discussion of the behavior of the antenna factors of practical antennas. The references listed here, especially [2], can provide a great deal more information on this topic.

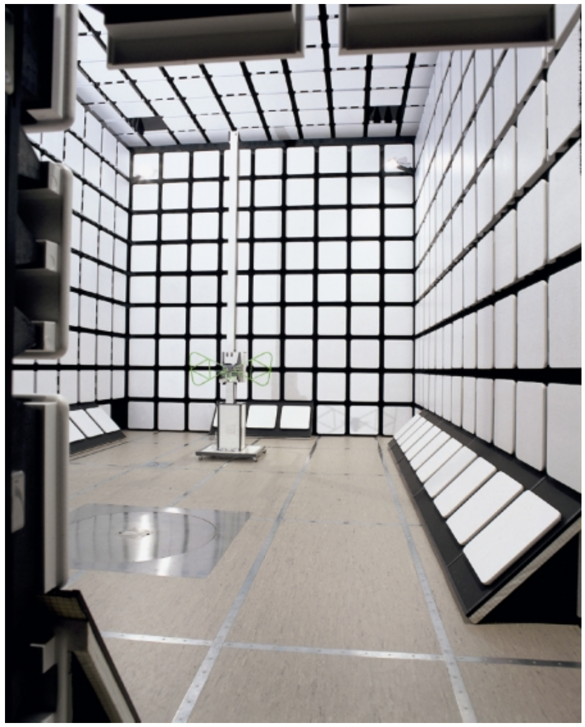

Figure 5: High-Performance Broadband Anechoic Chamber
(*Photo courtesy of TDK RF Solutions Inc.*)

Reference

1. A. A. Smith, Jr., "Standard-site method for determining antenna factors," IEEE Transactions on Electromagnetic Compatibility," Vol. 24, pp. 316-322, August, 1982.

2. Edward N. Skomal and Albert A. Smith, *Measuring the Radio Frequency Environment*, Van Nostrand Reinhold, 1985, pp. 187-189.

3. Shinobu Ishigami, Hitoshi Takashi, and Takashi Iwasaki, "Measurements of Complex Antenna Factor by the Near-Field 3-Antenna Method," IEEE Transactions on Electromagnetic Compatibility, Vol. 38, No. 3, August 1996, pp. 424-432.

4. René P. Mays, " A Summary of the Transmitting and Receiving Properties of Antennas," IEEE Antennas and Propagation Magazine, Vol. 42, No. 3, June 2000.

5. C. A. Balanis, *Antenna Theory Analysis and Design*, Second Edition, John Wiley & Sons, Inc., New York, 1997, pp 84-86.

6. J. D. Kraus, *Antennas*, McGraw-Hill, 1950, pp. 41-53.

7. J. D. Kraus, *Antennas*, Second Edition, McGraw-Hill, 1988, pp. 40-42.

8. Samuel Silver, Ed., *Microwave Antenna Theory and Design*, McGraw-Hill, 1949. pp 37-59.

9. Clayton R. Paul, *Introduction to Electromagnetic Compatibility*, Wiley Interscience, 1992, pp. 202-206

ANSI C-63.5 Standard.