USING THE BICONICAL DIPOLE ANTENNA IN THE FCC EQUIPMENT AUTHORIZATION PROGRAM

How biconical dipole antennas apply in EMI (electromagnetic interference) testing under the FCC Equipment Authorization Program, is the subject of this article. Although the authorization program dates back to 1938, with Part 15[1]* establishing performance requirements and test procedures for RF devices, herein we are concerned with the more recent emendations of Part 15, which sets certification requirements for radio and televion receivers (2/1/56).[2]

The authorization program has grown to include other types of devices, as further incidences of EMI were discovered. On October 1, 1983, the newer rules in Part 15 became effective requiring most kinds of computer-type equipment to be either certified or verified as meeting the technical standards in the FCC Rules and Regulations and labeled accordingly.

The information needed to certify or verify equipment as compliant includes data measurements which show levels of radio frequency emanations from prototypes or production samples of the equipment. These measurements are needed for computer-type equipment and RF devices as well, such as radio receivers, radio controls, wireless microphones, field disturbance sensors, and Class I TV devices. Radiated emanations from these devices must be measured at an open area test site, using a field strength or EMI meter and calibrated antennas.

Requirements for Antennas

Several sections of Part 15 cover measurement procedures and specify requirements for test antennas. (The most detailed is contained in MP-4, "FCC Measurement of Radio Noise Emissions from Computing Devices".[3]) Certain of these procedures are discussed in the following paragraphs, to illustrate the changing approach of the FCC toward the use of antennas. (Paragraph numbers refer to Part 15.)

Three voluntary standards may be used to measure radiation from receivers. Paragraph 15.75 lists the *IEEE Standard 187 (1951)*[4] *IEC Publication 106 (1959), and Supplement 106A (1962),*[5] and *EIA Standard RS-378 (1970).*[6] Although the IEEE Standard 187 and EIA RS-378 do not clearly specify the measuring antenna, the context of both documents plus the supplement to IEEE 187 indicate that the use of a dipole-type antenna was intended. Apparently, the writers of these documents assumed that a tuned dipole would be used, though they did not preclude the use of other linearly polarized antennas. By contrast, IEC-106 clearly specifies the use of a half-wave length dipole above 80 MHz.

Paragraph 15.141 states that, *"any procedure acceptable to the Commission may be used to measure the RF energy emitted by a low power communication device."* Paragraph 15.143 further requires the report of measurements to include either a detailed description of the measurement procedure or reference to the published standard that was applied. Two documents referenced in 15.141 contain the procedures used at the FCC laboratory: the *FCC Bulletin OCE 19,*[9] and *FCC Technical Report T-7001.*[8] OCE 19 calls for the use of a calibrated dipole antenna, while T-7001 calls for a "calibrated antenna." A tuned dipole antenna is probably intended by T-7001, since the context refers to the antenna as an accessory to a typical field-strength meter. At the time that OCE 19 and T-7001 were written, typical field-strength meters provided tunable dipole antennas as accessories.

For *Auditory Training Devices* operating in the 72-76 MHz and 88-108 MHz bands, *Paragraph 15.377* refers to FCC Bulletin OCE 19 for measurement of field strength of all emissions. These are the fundamental, harmonics, and other spurious emissions of the transmitter part of the system.

All of the above procedures are for measuring spurious radiation from radio receivers and transmitters at intentionally generated frequencies and their harmonics—that is, a relatively few frequencies that are all generally known prior to the test.

Paragraph 15.323 mentions using either a tuned dipole antenna or a linearly-polarized broadband dipole antenna for measurements of a *Field Disturbance Sensor* above 25 MHz. There is no preference indicated for either type of antenna. The procedure must be described in detail in the report of measurements, or a published standard must be used and referenced.

Paragraph 15.417 calls for the use of a dipole antenna for field strength measurements on frequencies above 30 MHz for the video modulated signals from a Class I TV Device, and permits the use of a dipole antenna down to 18 MHz. The context of this paragraph and paragraph 15.419 effectively specify a measurement distance varying from 1.6 m at 30 MHz, down to 1.0 m at 48 MHz and above. These paragraphs and the physical realities of the measurements strongly suggest the use of relatively short, broadband dipole antennas at frequencies below 300 MHz.

Paragraph 15.840 refers to MP-4 for Computing Device test procedures, in which Paragraph 4.2.4 discusses antennas for measuring radiated emissions. While the balance of the paragraph details instruction for use, performance specifications are established at the outset: "A calibrated, tuned half-wave dipole antenna is preferred for measuring the level of radiated emissions. Other linearly polarized antennas are acceptable provided the results obtained with such antennas are correlatable to levels obtained with a tuned dipole." The following information can be gained from these three sentences alone:

1. The standard of comparison is a dipole antenna tuned to half-wavelength resonance and calibrated, and traceable to a national standard, establishing performance parameters.
2. The antenna used for record measurements must be linearly polarized—e.g., a broadband dipole or a planar log periodic antenna.

*Notations indicate reference material.

3. The calibration of the antenna used for record measurements must be suitable for the intended use of the antenna, so that field strength will be measured as equal to that of the reference tuned dipole antenna when one is substituted for the other in the same measurement geometry and the same electromagnetic field.

Paragraph 4.2.3 of MP-4, "Units of Measurement," helps in the understanding of the requirements for antennas. It tells that the measurements are of electric field strength at a specified distance and directs the use of appropriate conversion factors to convert the two-terminal voltage readings of the measuring instrument to field strength. This conversion factor is commonly called the Antenna Factor. The paragraph also permits the submission of data in the form of recorder charts from automatic measuring equipment or photographs of spectrum analyzer displays provided that the calibration levels in terms of electric field strength are shown on the charts or photographs. This suggests that the FCC is aware of and basically approves of the use of automated EMI test systems using broadband antennas.

In *Paragraph 32,* page 12 of the Report and Order under Docket 80-284[9] applications for several types of antennas are discussed.

> "Calibration of linearly polarized broadband antennas such as bi-conical and log periodic is such that measurement results can be related or correlated to those obtained using the half-wave dipole.Accordingly, biconical and log periodic broadband antennas may be used when properly calibrated."

The crux of the matter is the adequacy or validity of the antenna calibrations. Many broadband antennas and tuned dipole antennas are calibrated for use at a distance of one metre from the device being tested. The "calibration" of many tuned dipoles is calculated using oversimplified models, thus ignoring many real-world error-producing factors. It is important to include a correction factor to account for variations in the testing situation when using instruments calibrated to perform under specific conditions only. We can begin to see how the aforementioned Antenna Factor becomes a necessary step in making these adjustments.

Antenna Factor

The antenna factor for an EMI antenna is defined by Equation 1 showing the relationship between the loaded two-terminal output voltage (V_0) of the antenna and the strength of the electric field (E) in which it is immersed. The units are volts and volts-per-metre, respectively.

$$A.F. = E/V_0 \qquad \text{(Eq. 1)}$$

This deceptively simple factor may be analyzed as the product of several coefficient factors which describe mathematically how the antenna works. Each of these coefficients is the result of the functioning of some part of the antenna, so that the number of them included in the antenna factor and their values depend upon the design and construction of the antenna. Two coefficients are always included: the *conversion factor,* which converts from values of field strength to values of open-circuit antenna terminal voltage; and the *load correction factor,* which relates the voltage across the load circuit connected to the antenna, to the open-circuit antenna terminal voltage. In addition to these, there are usually a number of other coefficients to correct for impedance mismatches, transformations, and losses in the several parts of the antenna.

The *conversion factor* is the kernel of the antenna factor, having within it the effective height or length of the antenna, including gain and pattern effects. The conversion factor is usually given for the antenna pattern maximum, since that is how the antenna is generally used for EMI measurements. For dipole antennas, the conversion factor is the reciprocal of the effective length, while for more complex antennas it is proportional to the reciprocal of the square-root of the effective area. The gain and effective area of an antenna are always related to power transfer. Thus, the square-root of these quantities is used when they are related to the electric field strength or the terminal voltage, as is done in the antenna factor.

The *load correction factor* accounts for the ratio between the open-circuit voltage at the antenna terminals and the closed-circuit voltage across the load connected to the antenna. For a relatively simple antenna, such as a resonant dipole, this is often taken to be a factor of two (6 dB). This is based upon the idea that the load impedance matches the antenna feed-point impedance, e.g., approximately 73 ohms for an ideal half-wavelength resonant dipole antenna. Any mismatch between the load and the antenna impedance is accounted for by a separate "mismatch" factor.

If no impedance matching is provided between the antenna and load, then a coefficient to account for the "mismatch loss" must be included in the antenna factor. This "mismatch loss" is not energy dissipated as in a resistance; rather, it is energy reflected from the point of mismatch, the impedance discontinuity, back into the antenna to be reradiated.

A balanced antenna such as a dipole must be kept balanced if it is to perform correctly. Thus, if it is connected to the EMI meter by a coaxial transmission line (as is commonly done), it must contain a balanced-to-unbalanced transformer (BALUN). In some antennas this transformer may also perform an impedance transformation along with its balanced-to-unbalanced transformation. This BALUN may be realized as a lumped-element circuit, such as a set of tightly coupled windings of wire on a ferrite toroid, or as a distributed element circuit using pieces of transmission line. In any case, its transforming action and its losses must apear amongst the coefficients in the antenna factor, either implicitly or explicitly.

In some antennas, a carefully designed BALUN provides balancing for the antenna, but impedance matching is done by a resistive attenuator proportioned so that the antenna is matched, the transmission line is matched, and the entire loss is 10 dB. This makes the antenna factor larger, but both the antenna and its transmission line are properly terminated over a very wide band of frequencies. This allows for a much more accurate calculation of the antenna factor of the antenna from its physical properties, but such an antenna will still perform inaccurately if it is used improperly.

The above discussion has given a description of the antenna factor telling what it is and indicating how it might be found. However, except for certain antennas* finding the antenna factors by calculation from design parameters is fraught with many potential errors. For most antennas it is far better to measure the antenna factors by the careful use of a technically sound procedure.[10]

Four general approaches are available for making antenna factor measurements.

1. Measure the antenna gain under conditions that may simulate the actual use of the antenna.
2. Produce a standard field, and determine the antenna factor by placing the antenna directly in the field and calculating the ratio of field strength to measured output voltage.
3. Substitute the antenna to be calibrated with an antenna of known performance in a constant field; calculate the antenna factor by comparison.
4. Measure the attenuation between three pairings of three antennas on a standard test site; calculate the antenna factors for each from the proven propagation theory for the site.[10,11,12,13]

Less apparent than the applications of the antenna factor are the implications of its use. Note that in Equation 1, the units of the antenna factor are reciprocal metre. When the antenna factor is multiplied* by the two-terminal voltage measured at the output of the antenna, this voltage is converted from volts, millivolts, or microvolts to volts per metre, millivolts per metre, or microvolts per metre—terms of electric field strength. The strength of an electromagnetic field may be accurately measured by any antenna for which the antenna factor is accurately known. Herein lies the correlation between the tuned dipole antennas used at the FCC laboratory and any other antennas that might be used to measure the emanations from RF devices, providing the antennas are properly used and the antenna factors accurately determined.

Before proceeding with some of the measurement considerations, it will be helpful to understand which coefficient factors are common and which are unique to the tuned dipole and/or the biconical dipole antenna. Since antenna factors are usually given and used in decibels, it will help to first restate Equation 1 in dB, as shown in Equation 2.

$$AF = 20 \log E - 20 \log V_o \qquad \text{(Eq. 2)}$$

The antenna factor is in dB (m^{-1}). The values of 20 log E and 20 log V_o are usually used as dB (μV/m) and dB (μV). Common logarithms are used. A more specific relationship for dipole antenna factors is shown in Equation 3.

$$AF = 6 - 20 \log L_e + A_b + 20 \log [(Z_a + N^2 Z_L)/2NZ_L] \qquad \text{(Eq. 3)}$$

Figure 1 shows the circuit model of the dipole antenna used in this equation.

The symbols used in Equation 3 and Figure 1 have the following meanings:

L_e is the effective length of the antenna in metres;
Z_a is the impedance of the antenna as a source (feed-point impedance) in ohms;
Z_L is the impedance of the load connected to the antenna in ohms;
A_b is the loss (not including the effects of the transformation ratio, if any) in the BALUN in dB; and
N is the antenna-to-load voltage transformation ratio of the BALUN (usually either unity, N = 1, or scaled for impedance matching, $N = \sqrt{Z_a/Z_L}$).

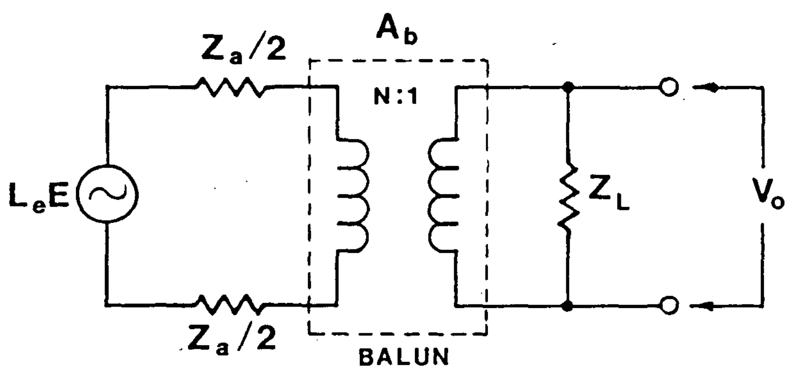

Figure 1. Simplified Circuit Model for a Dipole Antenna.

In the general case, the impedances are complex numbers, i.e., $Z_a = R_a + jX_a$ and $Z_L = R_L + jX_L$, and the BALUN does not provide a perfectly resistive transformation.*

Tuned Dipole Antennas that are in resonance at one-half wavelength are a special case of the general dipole antenna. Under the proper conditions, these "half-wave" resonant dipole antennas have certain theoretically predicable characteristics. The effective length, L_e, is λ/π when the antenna is

*The performance of antennas such as standard gain horns, and some electrically small electric and magnetic field sensors can be determined quite accurately and reliably as a function of their geometry.

*Usually the antenna factor is given in dB (m^{-1}) and it is added to the two-terminal antenna output voltage in dB (μV) measured by an EMI analyzer giving the field strength in dB (μV/m).

*These effects are usually ignored when the antenna factor is calculated on the basis of "theoretical" values, because they make the calculation much more cumbersome if included. However, ignoring them causes the calculated antenna factor to be incorrect.

immersed in a plane-wave field,[12] and the feed-point impedance, Z_a, is purely resistive if the antenna is far enough from ground or other obstacles. Z_a equals R_a which is about 73 ohms for an infinitely thin antenna, but is normally much less, ranging from 55 to 65 ohms, depending upon the length-to-diameter ratio for a physically realizable antenna. If the antenna is removed from free space conditions and brought close to the ground, it begins to couple to its image in the ground. This causes its feed-point impedance to vary cyclically above and below the free-space value, the variation increasing as it is brought closer to the ground. Finally, the impedance is reduced significantly when the antenna is near the ground.[13] This effect is most pronounced for horizontally polarized antennas and can cause the impedance to drop to a few ohms with the antenna less than one-tenth of a wavelength (one metre at 30 MHz) above the ground. This change in antenna impedance causes a commensurate change in the antenna factor used to determine the measured field strength.

The antennas used at the FCC laboratory usually have a Roberts BALUN,[14,15] providing an impedance transformation from 50 to 70 ohms. It is a very good wide-band BALUN, providing excellent balance, good impedance matching, and low losses.

Biconical Dipole Antennas are another special case of the general dipole antenna. The performance of the biconical dipole antenna is difficult to predict on the basis of theory; experimental or empirical work has been relied upon for performance determinations.[16] The coefficient factors that comprise the antenna factor for biconical dipole antennas are similar to those of the tuned dipole antenna, but with different values.

The effective length of the biconical dipole antenna is found according to its operating frequency range. At frequencies where its length is shorter than one-half wavelength, Equation 4[12] approximates its effective length.

$$L_e \cong (\lambda/\pi) \tan [(\pi/2)(L/\lambda)] \qquad \text{(Eq. 4)}$$

The length of the antenna, L, is the only new term in this equation. At frequencies where the biconical antenna is longer than one-half wavelength, its effective length can be estimated.[16,17] As with the tuned dipole antenna, the effective length is defined for fields which are planar across the dimensions of the antenna. The physically shorter the antenna, the closer it can be to the source of the field and the ground, while still satisfying the "planar" definition.

The feed-point impedance of the biconical dipole antenna is a complex quantity that depends upon the cone angle and length of the antenna. It has been determined empirically by Brown and Woodward, and others.[16,17] Some typical values of the feed-point impedance of a biconical antenna are 2 − j240 ohms at the lower end, 48 + j10 ohms near the middle, reaching 240 + j12 ohms in the upper part, and dropping to 130 − j30 ohms at the upper end of the frequency range. These values are only examples for one particular biconical antenna design, and vary with the antenna parameters. One important characteristic of the biconical antenna is that its impedance is much less affected by its height above ground than tuned dipoles and other long, relatively thin antennas.[10,18]

The BALUN used in the typical biconical antenna is inherited from the empire Devices (Singer Metrics) DM-105-T1 antenna. This BALUN is specified in the U.S. Government drawing for the biconical antenna. Designed to be a 1:1 BALUN, it is made of sections of coaxial transmission line. Because of stray reactance effects, the voltage transformation ratio is different from 1:1 at many frequencies within the range of the biconical antenna.* This changes the performance of the antenna in such a way that its prediction by calculation is impracticable.

As indicated from the above discussion, a reliable measurement program is the practicable way to determine the biconical dipole antenna factors.[10]

Comparison of Antennas

The effective lengths, the antenna patterns, and the BALUN transformation ratios or mismatch losses of tuned dipole and biconical dipole antennas are compared below.

Only a quarter of the total antenna pattern is shown below in Figure 2, since the patterns of dipole antennas are symmetrical about the axis of the antenna.[12,17] Note that the pattern of the biconical dipole antenna is both broader at the low end and narrower at the high end of the frequency range than that of the tuned dipole antenna. This variation is usually too small to be significant.

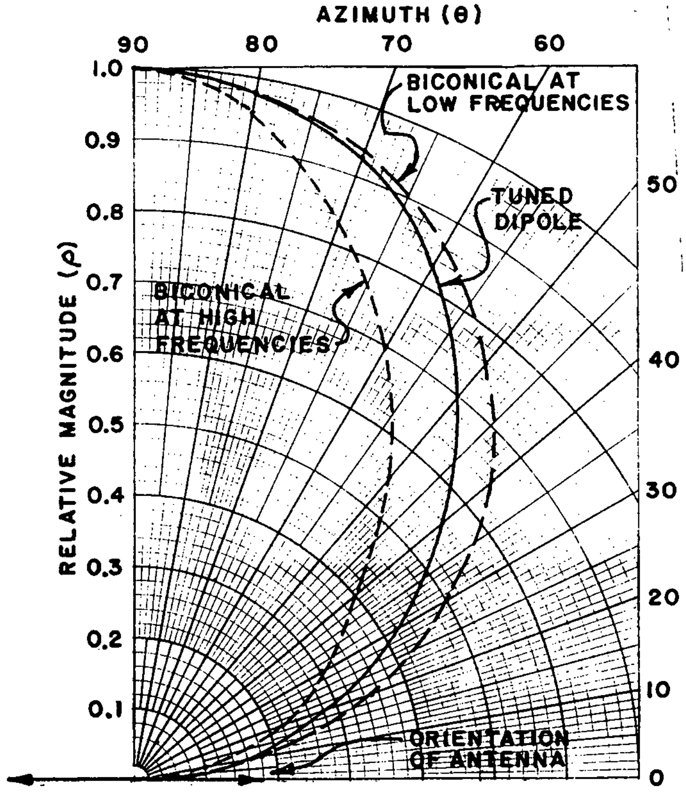

Figure 2. Comparison of Antenna Patterns.

*This problem has been at least partly corrected for Electro-Metrics' BIA-25 biconical dipole antennas starting with S/N 2427. Other activities to improve the BALUN of the BIA-25 are underway and will be reported in the future.

Effective lengths, balun transformation and mismatch losses, and overall antenna factors are compared for three frequencies in Table I. The tuned dipole has a greater effective length at the low end of the frequency range than has the biconical dipole. However, the impedance and, thus, the antenna factor of the tuned dipole is more variable with height above ground at the lower frequencies than is the biconical dipole. (The data in Table I for the tuned dipole antenna are taken from references 12, 13, 15, 17, and 18, and calculations using Equations 3 and 4. Data from References 16, 17, and 18, and the program of measurements from Reference 10 have been used for the biconical dipole antenna.)

Antenna polarization does not cause difficulty when making horizontally polarized measurements, if the antenna is functioning properly. The antenna is basically uniform in the vertical plane, so pattern corrections are not needed when the antenna is raised or lowered while making horizontally polarized measurements. However, when making vertically polarized measurements, the antenna response varies with the vertical angle of arrival of the field being measured (See Figure 2). If the antenna is very far above the ground, the measured field strength must be corrected for the pattern, or the antenna must be tilted for maximum response to the field. (The vertically polarized emanations from most equipment being tested—EUT's—will be strongest near the ground.)

Table I. Comparison of Antennas.

Parameter	Frequency (MHz)	Tuned Dipole			Biconical		
Effective Length [m] (Free-space, plane-wave)	30		3.2		0.7		
	80		1.2		0.8		
	200		0.5		1.6		
Balun Trans & Losses [dB] (Free-space, plane-wave)	30		1.4		2.6		
	80		1.4		0.2		
	200		1.5		15.6		
Antenna Impedance [Ω] (Free-space, plane-wave)	30		62*		11401		
	80		62*		11351		
	200		62*		11601		
Height Above Ground [m]	—	∞**	2	1	∞**	2	1
Antenna Factor [dB (m^{-1})]	30	−2.6	−4.0	−5.8	11.2	10.9	10.9
	80	5.9	5.8	6.3	7.6	6.3	7.4
	200	13.5	13.9	13.1	17.0	16.1	17.4

*Typical for practical length-diameter ratios.
**The height above ground of ∞ indicates free-space, plane-wave conditions.

Making the Measurements

In this section we will summarize the inherent problems when making EMI measurements using either a tuned dipole or biconical dipole antenna, implied earlier. (For a more complete discussion of making EMI measurements on an open-area test site, see Reference 19.) Problem causes can be attributed to the effects of antenna polarization, the nearness of the antenna to the ground, and the transmission cable from the antenna.

However, some EUT's have emanations at high vertical angles because of unique constructional characteristics, so correction for the antenna pattern may be needed.

Nearness of the antenna to ground must be carefully considered if a tuned dipole antenna is being used. The impedance of a horizontally polarized antenna will be significantly affected at the lower frequencies, requiring correction to the antenna factor. Smith[18] gives a table of corrections to the antenna factor that can be used. The tip of the lower element of a vertically polarized antenna should be no closer than 25 cm to the ground (see paragraph 4.2.4.2 of Reference 3). At 30 MHz, this will cause the center of a tuned dipole antenna to be about 2.75 m above the ground. The same constraints applied to the biconical dipole antenna cause its minimum height to be about 1.0 m either horizontally or vertically polarized, needing no correction in the antenna factor.[10]

The transmission cable from the antenna can be problematic. If the shielded coaxial cable is not of good quality or if it has holes or breaks in the shield, the resulting antenna unbalance causes unquantifiable measurement errors. If care is not taken in placement, the cable may affect vertically polarized measurements unpredictably. Losses vary with the measurement frequency and physical condition. Also, the published antenna factors of some antennas include an allowance for cable loss while others do not. Electro-Metrics' BIA-25 biconical antenna factors, for example, do not include any cable loss allowance.

Summary

The biconical dipole antenna may be used in measurements to meet FCC requirements for computer-type equipment and many other EMI measurements in which a tuned dipole antenna has been traditionally used. The necessary correlation of the results using a biconical dipole antenna with those using a tuned dipole antenna comes from the proper calibration of the biconical antenna for the application intended. The importance of proper calibration of the biconical antenna is stated in the FCC docket [9]. The use of a tuned dipole antenna for EMI measurements does not necessarily assure correlation of results with those of the FCC (or other laboratories) unless the tuned dipole antennas used are exactly identical to those used by the FCC, calibrated in exactly the same way, and used under exactly the same conditions.

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