

Antennas for EMI Measurement

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Antennas for EMI Measurement

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Recent governmental EMI regulations in the USA and abroad have stimulated interest in radiated emissions testing. Considerable attention has been given to spectrum analyzer/receiver usage and test site construction. However, the radiated emissions measurement system consists of three major components:

- test site
- field strength meter
- antenna, matching network and transmission line.

Neither site characterization nor measurement accuracy can be trusted if the antenna performance is unknown. This article concentrates on the often overlooked measurements anomalies caused by antenna imperfections.

By custom and by virtue of its apparent simplicity, the dipole, used in an *open field* situation, is the standard measuring antenna. The dipole is a balanced antenna whose impedance at resonance averages 73 ohms. However, EMI measuring equipment is universally connected to antennas via 50 ohm unbalanced coaxial line. It is often assumed that the antenna balun affects the transformation from balanced source to unbalanced line and the impedance transformation in a nearly ideal fashion. This is rarely the case. If the antenna, through its balun, presents a high VSWR to the transmission line, the antenna factor and transmission line loss will not be accurately known. This will lead to the errors in signal measurement and site attenuation discussed below.

The Lessons of History

The FCC's experiences in setting up their test site provide valuable insight into these problems. As the agency charged with protecting communications, empowered to permit or forbid the production of any equipment emitting electromagnetic radiation, the FCC has enormous power and responsibility. The group within the FCC which measures equipment emissions is the laboratory division at Laurel, Maryland. Over 25 years ago, they sought to standardize their sites and equipment as part of their effort to take accurate measurements.

They started with a simple open field site, using the far field site attenuation model later published in FCC Docket 21371, and using the widely used and commercially available Empire DM-105 series dipole antennas. They ran into the following difficulties in their site attenuation measurements:

- At frequencies below 80 MHz, the site attenuation curve flattened out and turned up. The flattening was known to be due to near field effects, as it was more pronounced at closer distances; but the upturn was puzzling.

- At higher frequencies, significant deviations from the predicted values appeared. These deviations were cyclical with frequency.

Since the FCC was (and still is) *the* testing authority, these problems had to be resolved.

At that time, Willmar Roberts was Director of the laboratory and Assistant Chief Engineer for the FCC. He recognized that these results could be caused by an unexpectedly high degree of mismatch and loss in the Empire antenna baluns. The antenna set was tested for VSWR and balun loss.¹ The results are shown in Figs. 1 and 2. It is apparent that:

- At points of high VSWR the balun loss is also high. This would be expected of a large mismatch.
- The magnitude and frequency variation of the balun loss would explain the cyclical deviations from the theoretical values at high frequencies.
- The bottom end loss of the lowest frequency balun is sufficient to give an upward *tip* to the site attenuation curve in the 30-80 MHz range.

Roberts did not stop here, however. A new set of baluns was designed. It was found that a set of four antenna baluns was required to get the desired performance over the frequency range 20-1000 MHz. Each balun was useful over a frequency range of approximately 3 to 1. It is not commonly realized that to this day, the FCC laboratory and FCC Field Office Bureaus use four balun dipole antenna sets constructed to Roberts' specifications for their measurements. The VSWR and loss of these improved baluns are shown in Figs. 3 and 4.

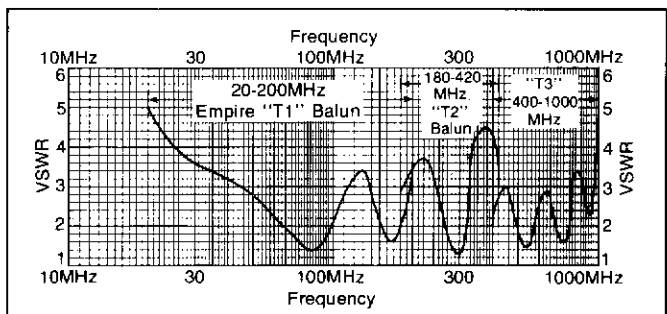


Figure 1—Empire DM-105 Antenna Set VSWR Measured by FCC.

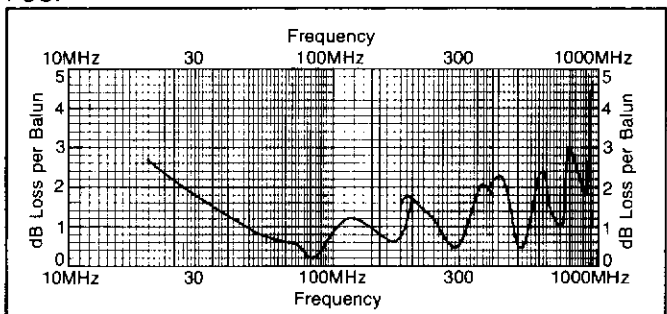


Figure 2—Empire DM-105 Set Back-to-Back Balun Loss Measured by FCC.

The FCC builds its own EMI antennas for its measurements. Here are the reasons why.

Impact on Site Attenuation

A photograph of the FCC's outdoor three meter open field site appears in Fig. 5. This is a simple site with no ground screen. The farther mast is three meters from the turntable. The FCC also has a covered three meter site consisting of a wooden wall with an inflatable canvas *bubble cover*. The covered site has a ground screen, but the uncovered one does not. The three meter site attenuation data for these two sites is shown in Fig. 6. These data were taken in 1976 using two of the four balun dipole sites designed by Roberts. Phil Inglis of the FCC was kind enough to release this information to the authors. These sites are not elaborate, yet their agreement with theory is impressive. This suggests the importance of the low loss baluns. If one were to add the extra loss for the old Empire baluns and the anticipated extra loss due to VSWR in 7.6 meters of RG-58 coax to the attenuation curve, the result would be quite different as shown by the dashed curve in Fig. 6. (VSWR effects are discussed below.)

The problem of antenna mismatch causing misleading site measurements is still with us today. Recently, one of the authors was shown the site attenuation curve of a modern test facility located on the West Coast. This was a physically magnificent site, consisting of a fiberglass building set on top of a ground plane some 12 meters square. All instrumentation was contained in a separate outbuilding about 25 meters distant. Figure 7 shows the three meter site attenuation for this site. These measurements were taken with three balun tuned dipole antenna sets. The deviations from the ideal are much larger than those measured by the FCC at their site.

Dipole Antenna Factors and Balun Measurement

There have been comments in the literature on the discrepancy between the antenna factors supplied by manufacturers and their actual value (e.g. reference 2). In the case of tuned dipole antenna sets, manufacturers usually supply a calculated antenna factor based on the effective area of a dipole matched to its load. This

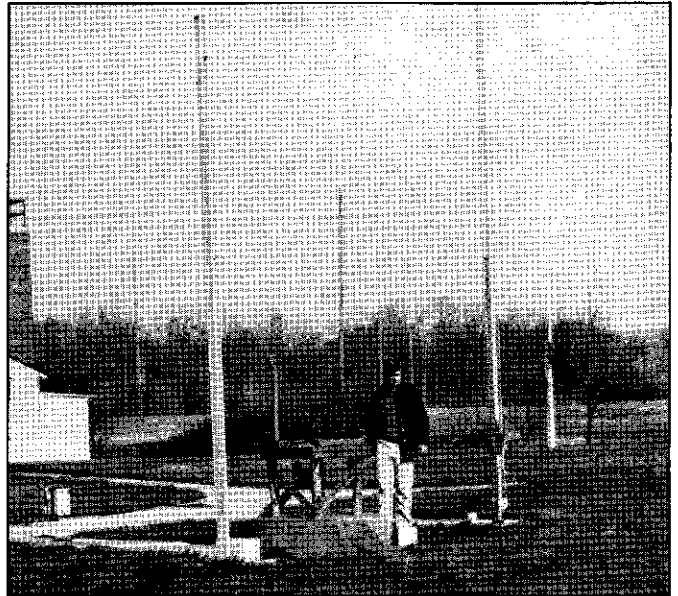


Figure 5—FCC Open Field Test Site.

This is the three meter site where many Class B computing and type approved devices receive their final test. The near mast, one meter from the table, is for set-up; the three meter mast is used for the actual measurement.

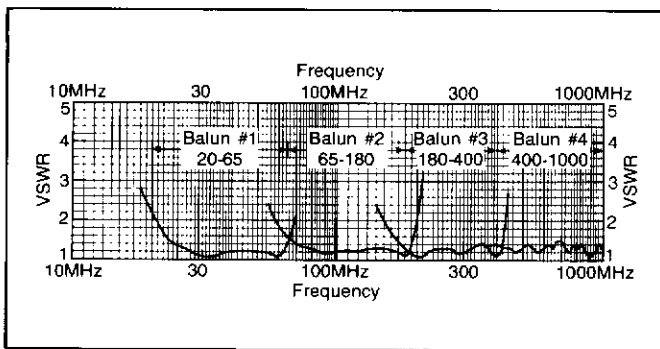


Figure 3—VSWR of Dipoles Currently Used by FCC.

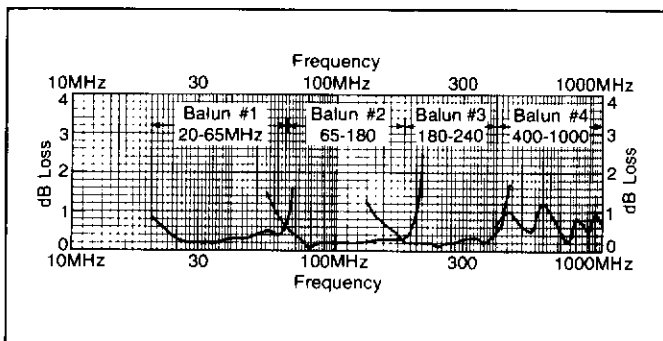


Figure 4—Back-to-Back Balun Loss of FCC Dipole Sets.

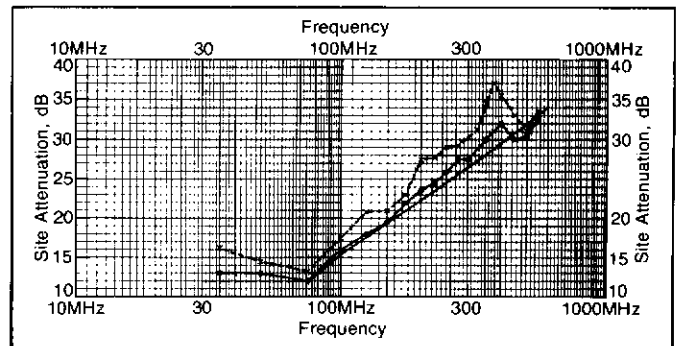


Figure 6—FCC Three Meter Site Attenuation Data for Covered Site (courtesy of Phil Inglis).

The upper dashed curve—X—was calculated by adding [2 · (DM-105-FCC Balun Loss) + VSWR loss in 25' of RG-58 Coax] to the covered—·—curve. This demonstrates how antenna VSWR can influence measurement. Effects are much worse with longer cables.

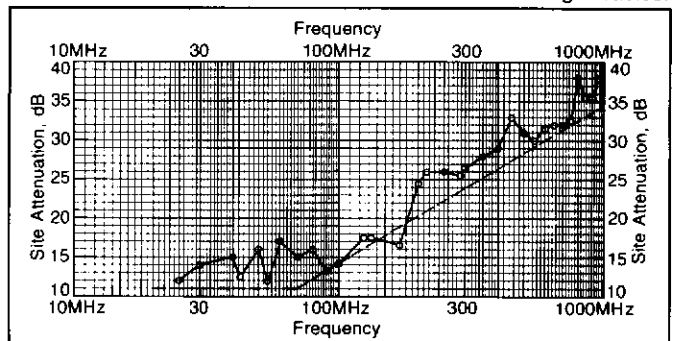


Figure 7—Site Attenuation at Modern Test Facility Utilizing Commercial Baluns and Long Cable Runs.

antenna factor, which relates ambient field strength to the voltage developed by the antenna into a 72 ohm load, is usually given as:³

$$\text{Antenna Factor} = \frac{\text{Field Strength (V/M)}}{\text{Antenna Output Voltage}} = \frac{2\pi}{\lambda} M, \quad (1)$$

$$\text{or } \frac{2\pi F}{C} M$$

$$\text{AF (dB)} = 20 \log \left(2\pi \left(\frac{F}{C} \right) \right) + 20 \log_{10} M,$$

where M is the attenuation factor for the antenna balun. Also M may include the presumed loss for a specified length and type of cable. The following should be noted about this factor:

- $2\pi F/c$ is the correct theoretical antenna factor for the dipole itself (if ground plane interaction effects on resonant impedance are neglected).
- The balun loss portion of the M term is almost always assumed by manufacturers to be a small and constant term. Unfortunately, it is not. Some manufacturers (and many EMC engineers) add 1 dB balun loss for vague and unstated reasons. Others assume the balun provides a perfect 1:1 balanced to unbalanced transformation from antenna to coaxial cable, but allow 1.7 dB for 73 to 50 ohm mismatch loss. Manufacturer supplied dipole antenna factor charts are always straight lines on a dB vs. log frequency plot, indicating that the actual loss has not been measured.
- Any included cable loss factor is added in as if the cable SWR is 1:1. As noted below, this poor assumption introduces additional inaccuracies when SWR is high.

The tunable dipole is a simple device. The telescoping rods and the matching balun are all that's there. The rods present a known antenna factor at resonance; the baluns are the variable element. The balun loss term should be supplied by the manufacturer but generally this is not done.* Fortunately, the balun loss is easily measured with equipment available in most EMC labs.

Figure 8 shows the test set up used by the FCC. To perform the test, connect two baluns of the same type back-to-back. It is best to remove the balanced ends from their housings to keep the connection as short as possible. This prevents losses due to the insertion of series lead inductance between the baluns or, at higher frequencies, due to radiation. Connect a 50 ohm impedance signal source to one balun via an attenuating pad (10 dB) and connect the second, again via a pad, to a 50 ohm power meter or spectrum analyzer. Measure the loss through the baluns and repeat with the connections reversed. Balun loss is considered to be one half of the average loss for the series connection. Perform this procedure at each frequency of interest.

Another indication of balun quality may be obtained by conducting a balun VSWR test in the manner described by Roberts: remove the balun from the housing, connect a 73 ohm resistor to the balanced ends to simulate the impedance presented by a resonant dipole, and measure the balun VSWR. These methods work very satisfactorily to about 500 MHz. For the highest frequencies, connection lengths become very important and can affect the ac-

*EDITOR'S NOTE: Credit should be given to a few antenna manufacturers who actually provide the antenna factor for each serial number, indicating that it includes x meters of coaxial losses plus balun loss. Some antenna manufacturers would be well inspired to read CISPR publication 16, Amendment 1, Section 13 which clearly requires a VSWR < 2, an accuracy of ± 3 dB on the antenna factor and a polarization discrimination ≥ 20 dB.

curacy of these measurements. Fortunately, at these frequencies nearly free space measurements can be made by assembling the dipoles and measuring radiated loss with a pair of antennas high in the air. A single antenna can be used for VSWR measurement. Roberts chose this method from 400-1000 MHz for the data in Figs. 1-4.

The Impact of VSWR

High antenna VSWR, even if known, leads to unpredictable performance. The extremes of measured voltage in a circuit where neither source nor load are matched to the connecting transmission line can be surprisingly high. The circuit of Fig. 9 shows the equivalent circuit for a receiving antenna and receiver. A similar equivalent circuit can be drawn for the signal source and transmitting antenna used in the site attenuation measurements. The load voltage⁴ is:

$$V = V_m \left(\frac{(1 - \Gamma_s)(1 + \Gamma_l)}{(1 - \Gamma_s \Gamma_l)} \right), \quad (2)$$

where Γ_s is the coefficient of reflection at the source (antenna) and Γ_l at the load (receiver). Γ_s and Γ_l are in general complex, and V_m is the matched voltage measured (when $\Gamma_s = \Gamma_l = 0$). Extreme values will occur for real values of reflection coefficient. The possible measured extremes of voltage are given by:⁵

$$\frac{(1 - |\Gamma_s|)(1 - |\Gamma_l|)}{(1 + |\Gamma_s \Gamma_l|)} \leq \frac{V}{V_m} \leq \frac{(1 + |\Gamma_s|)(1 + |\Gamma_l|)}{(1 - |\Gamma_s \Gamma_l|)} \quad (3)$$

As seen, balun induced VSWR can exceed 3:1 into a matched line. Many analyzers and receivers⁶ will operate with a 2:1 VSWR when running *wide open* into a matched line. The relation between $|\Gamma|$ and VSWR is:

$$|\Gamma| = \frac{\text{VSWR} - 1}{\text{VSWR} + 1} \quad (4)$$

For simplicity, assume the Γ 's approximate those that would occur if only the source or only the load were mismatched. Actual coefficients will vary about these values. For the figure given, we would have $\Gamma_s = 1/2$ and $\Gamma_l = 1/3$. This yields the extreme measurements estimate:

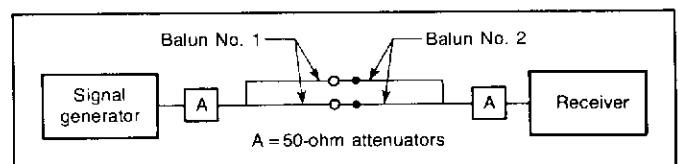


Figure 8—Set Up for Back-to-Back Balun Loss Test.

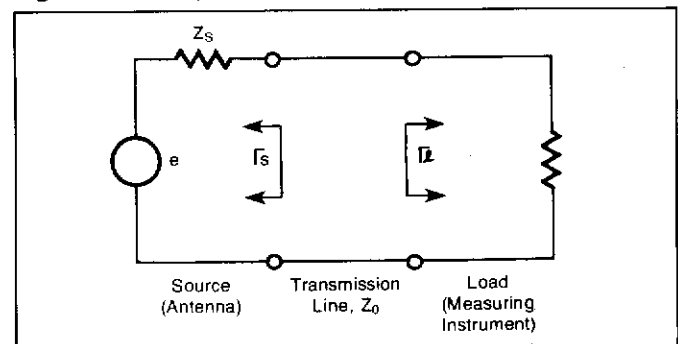


Figure 9—Equivalent Circuit for Receiving Antenna and Receiver.

To complete the model for site attenuation measurements, draw a similar circuit for the transmitting side.

$$.28 \leq \frac{V}{V_m} \leq 2.4, \text{ or } -11, +7.6 \text{ dB} \quad (5)$$

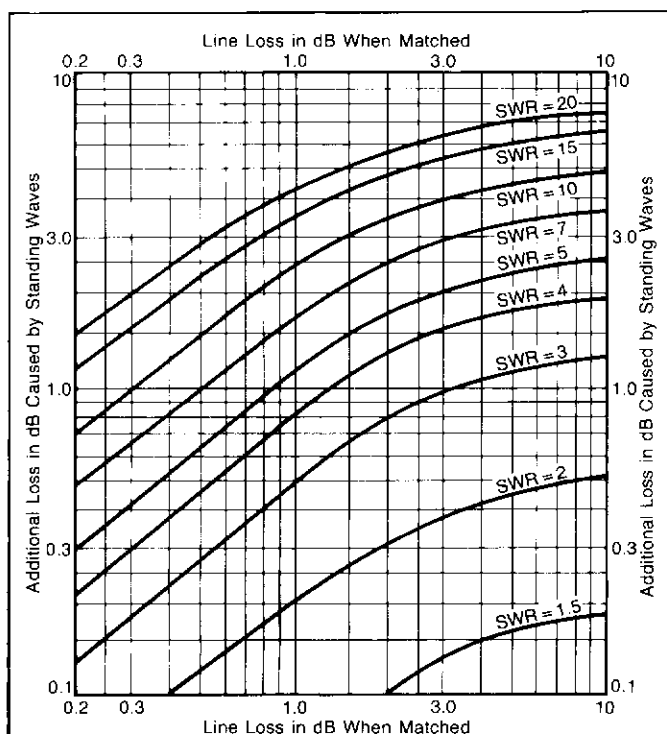
These maxima are not ordinarily achieved. However, it is important to realize that unpredictable errors of several dB will be more the norm than the exception when high VSWR's are present.

Another matter to consider is the effect of line VSWR on cable loss. The loss of coaxial cable is normally specified per unit length under matched conditions. When the VSWR is higher than 1, the cable loss increases as shown in the chart in Fig. 10. When cable loss is already high, the effect can be quite noticeable. For example, a line exhibiting a 5 dB loss under matched conditions would exhibit a 7.5 dB loss under a VSWR of 3:1. For high standing wave ratios—such as 10:1—the effects become very dramatic, even for small matched line losses. For example, a matched line loss of 2 dB would become a line loss of 5.5 dB! It has been claimed that the often used biconical antenna exhibits VSWR's of 10:1 or more in the range of 30-50 MHz.⁷

EMC Consumer Comments

If a person is acquiring antennas or concerned with the performance of those already owned, the following information is needed:

- Balun Tests: loss in a 50 ohm system and VSWR. This is all the information needed for tuned dipoles. The antennas used by the FCC have balun loss (measured as described above) of under 1 dB and corresponding VSWR's of less than 1.5:1.



Increase in line loss because of standing waves (SWR measured at the load). To determine the total loss in decibels in a line having an SWR greater than 1, first determine the loss for the particular type of line, length and frequency, on the assumption that the line is perfectly matched.

Locate this point on the horizontal axis and move up to the curve corresponding to the actual SWR. The corresponding value on the vertical axis gives the additional loss in decibels caused by the standing waves.

Figure 10—Cable Loss as a Function of VSWR and Matched Line Loss.

(Chart from ARRL Antenna Handbook.) Extra loss is due to higher currents and voltages on line relative to those under matched conditions.

The following is the end of the Dash article that appeared in Oct. 1983.

- Experimentally derived antenna factors at a proven site:⁸ This is much more important for the more exotic broadband antennas than for the tuned dipoles. For the broadband antennas, the impedance of the antenna proper is varying with frequency, forcing the balun to match to a *moving target*. VSWR is also important for broadband antennas, but it can only be measured when the antenna is assembled and on the mast.

Remember that a balun composed of transmission line elements will have a limited range over which it can perform its matching function. The FCC found it necessary to use four antennas to cover the 20-1000 MHz range. Yet even today, most commercially available tunable dipole sets cover this range with three baluns. The low frequency balun is commonly specified to cover the range of 25-200 MHz—a range of 8 to 1! This range is too wide to expect matching with uniformly low VSWR. The situation is not much different than it was 25 years ago. Many baluns are built on the old pattern, especially in the low frequency range. Beware of *specifications* listing the average antenna VSWR—this is not enough information. It is the extreme values which create measurement uncertainty. *Test before you buy!*

A moment's reflection will show that even experimentally derived antenna factors can be guaranteed to retain full validity only when the antennas are used in an environment similar to the calibration environment. The antenna factor measured by the standard site method treats each antenna and connecting cable as a unit. For example, under conditions of perfect match between generator, cables, antennas and receiver, an accurate antenna factor will be obtained, and the effects of cable length can be easily accounted for. Field use with another receiver matched to a coaxial line of different length will give the calculated results. Consider, however, a different case. Suppose the later field use occurs with a mismatched receiver. Then the voltage measured by this receiver is subject to the two variations discussed above, viz., uncertainty due to VSWR, and increased cable attenuation. Clearly, if the antenna factor is measured under less than ideal conditions, where neither antenna nor receiver are matched to the connecting line, the situation will be much worse because the variations in the apparent antenna factor under differing field usage conditions will be larger.

Summary

Experience has shown that much of the expense and worry over the quality of a *site* results because certain important factors are overlooked. One must be sensitive to the fact that site attenuation measurements are strongly influenced by high VSWR and that commercial baluns often exhibit high VSWR. These effects will be aggravated by long cable lengths. Also keep in mind that the performance of any antenna owned or contemplated owning can be easily checked.

References

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7. White et al., op. cit.
8. Smith, op. cit.