Calibration of the 41 inch (1.04m) receiving monopole.

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1.04m mono cal.rep.doc  
22-1-2009

1) Introduction

The 41 inch (1.04m) monopole antenna is commonly used to measure radiated emissions from 10kHz to 30MHz at a distance of 1m from the Equipment Under Test (EUT) and its associated cables. The antenna is only used to measure vertically polarized fields from the EUT. Another use for the monopole is to measure high levels of field, either for a safety analysis, or antenna calibration or in radiated susceptibility testing. The antenna is invariably used in the near field where the field wave impedance is often higher than the impedance of free space (337Ω). The near/far field transition at 10kHz is 4777m and at 30MHz it is 1.59m. Therefore, for a high impedance source the wave impedance is only just approaching 377Ω at 30MHz at 1m distance and it is much higher at lower frequencies. Due to the high wave impedance the antenna factor (AF) of the antenna, defined as the ratio between the incident field and the voltage developed at the antenna terminal, is very dependent on the load impedance. Also the input impedance of the monopole at lower than resonant length frequencies is high and capacitive. For these reasons to obtain a low antenna factor for measuring very low level fields the load impedance should be high whereas in measuring high levels of field, where the antenna factor can be high, a 50Ω load impedance can be used.

The typical EMI measurement antenna will have a buffer stage, with or without gain which converts a high input impedance to a 50Ω load, which is the normal cable and input impedance of EMI measurement equipment. At low frequency the load resistance often dominates the sensitivity of the antenna whereas above typically 0.1MHz the ratio of the antenna self capacitance to the buffer input capacitance, which includes device input capacitance and stray capacitance, determines the antenna factor. Another important parameter for the buffer is the output noise. Some of the MIL-STD 461F RE102 limits are shown in plot 5.1. For a number of applications, these limits have a worst case minimum value of 24dBµV/m from 2MHz to 100MHz. The noise level of the buffer, any subsequent amplifier and the measuring instrument, when measured with a 9-10kHz bandwidth, and when added to the 1.04m monopole antenna factor, must be at least 6dB below this limit.

Although capacitive coupling and mutual inductance between two monopole antennas 1m apart does not appear to be of importance when calibrating with a low receiving antenna load impedance, it may be significant when the load impedance is high. The antenna factors of many commercially available 1m monopoles are based on a theoretical calculation and on the measured gain/loss of the buffer/amplifier. This approach ignores the curvature of the incident field in the near field. It also assumes an infinite ground plane whereas the typical ground plane is a 24” x 24” counterpoise which is either bonded to the underlying ground plane (floor of the chamber) by a wide braid or bonded via an extension of the counterpoise to the metal topped table on which the EUT is bonded. One factor may be that different sources of E field can exhibit very different wave impedances, another factor may be the mutual coupling between EUT and antenna. This report shows how these factors can seriously affect the measured antenna factor.
2) **Antenna Factor of monopole when loaded with 50 Ohm**

2.1 **Two identical antenna AF measurement.**

The definition of Antenna Factor (AF) is the ratio of incident E field on the antenna to the voltage developed at the terminal of the antenna: \( \text{AF} = \frac{E}{V} \).

One method of measuring antenna gain is the two identical antenna method described in reference 1 page 51. The measured voltage into a 50 Ohm load is made via two paths. One is the radiated path in which a 50 Ohm attenuator is used at the input of the transmitting 1m monopole and a second attenuator at the input of the receiving 1m monopole. The second is a direct path in which the two cables with the attached attenuators are joined together. The problem with obtaining the Antenna Factor (AF) from the gain is the unknown value of wave impedance, also the ratio of wave to antenna impedance may play a role in the conversion from the incident E field to voltage developed in the 50Ω load. With the two monopoles 1m apart and using

\[
Z_w = 377\Omega \times \frac{\lambda}{2\pi}
\]

the calculated AF from the measured gain is close to the theoretical figure at 10MHz and higher and also the measured, using a calibrated bow tie antenna described in section 3 of this report, is close at 10MHz and above. However at lower frequencies a large difference between theoretical and measured is seen using this calibration technique.

The gain calibration may be made on an Open Area Test Site (OATS) with antenna counterpoises either coupled uncoupled. One calibration set up which approximates the measurement test set ups for the RE02/RE102/D0-160 section 21 tests is with the counterpoise of one antenna bonded to the conductive table top in the anechoic chamber/damped room and with the second antenna coupled to the first as illustrated in figure 2.1. In this configuration some differences in AF are seen versus the measurement made on the OATS. Some of this difference may be due to the anechoic chamber/damped room. This despite a very close correlation to the open area test site, see reference 1 pages 582 and 583, does differ over the frequencies of interest. Another reason for the differences may be due to extending the counterpoise of one antenna to the conductive table top.

Plot 2.1 compares the approximate antenna factors using the two antenna calibration method with the two antennas either coupled or uncoupled. In the uncoupled case the counterpoise of one antenna is connected to the conductive table top and the second antenna counterpoise is bonded to the shielded room floor using a wide copper plate. These tests were made on the OATS with antennas 1m apart.
Figure 2.1 Test set up with one counterpoise bonded to the conductive table top and Coupled to the second counterpoise

Plot 2.1 AF using the measured gain and an approximation for the wave impedance, with the antennas either coupled or uncoupled.

Plot 2.1 illustrates the importance of the extension of the counterpoise and also if the antenna is to be used either coupled or uncoupled the importance of a separate calibration for each configuration.
2.2 Theoretical monopole AF with a 50Ω load

The antenna factor of a receiving monopole above a perfect ground plane, connected to a 50Ω load is given by:

\[
AF = (1 + (Z_{ant}/50)) \times \frac{1}{Heff}.
\]

Where

\(Z_{ant}\) is the antenna impedance

\(Heff\) is the antenna effective height.

\(Z_{ant}\) for a monopole is given on page 57 of reference 1

The effective height describes the current distribution on the antenna. For a physical length of the rod which equals \(\frac{1}{4} \lambda\) the current distribution is nearly sinusoidal with an average value of 0.64 for \(Heff\). For an electrically short monopole \(Heff\) is close to 0.5.

\(Heff\) for the monopole may be found from:

\[
Heff = (\frac{\lambda}{\pi \tan(H/2)})/2
\]

Where \(H = \beta \times h = \frac{2\pi h}{\lambda}\)

Where \(h\) = physical height of the monopole rod.

The reactance and AF in dB for the 1.04m monopole loaded with 50Ω is shown in table 2.1 and the AF is plotted in plot 4.1.

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Antenna Reactance (Ω)</th>
<th>AF (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>.01</td>
<td>-1,256,259</td>
<td>94</td>
</tr>
<tr>
<td>.02</td>
<td>-628.129</td>
<td>88</td>
</tr>
<tr>
<td>.05</td>
<td>-251,251</td>
<td>80</td>
</tr>
<tr>
<td>.1</td>
<td>-125,625</td>
<td>74</td>
</tr>
<tr>
<td>.5</td>
<td>-25,125</td>
<td>60</td>
</tr>
<tr>
<td>1</td>
<td>-12562</td>
<td>54</td>
</tr>
<tr>
<td>5</td>
<td>-2,512</td>
<td>40</td>
</tr>
<tr>
<td>10</td>
<td>-1256</td>
<td>34</td>
</tr>
<tr>
<td>15</td>
<td>-837</td>
<td>31</td>
</tr>
<tr>
<td>20</td>
<td>-628</td>
<td>28.5</td>
</tr>
<tr>
<td>25</td>
<td>-502</td>
<td>26.7</td>
</tr>
<tr>
<td>30</td>
<td>-418</td>
<td>25</td>
</tr>
</tbody>
</table>
This data is presented in reference 3. The transmitting monopole was 2.5m high and the receiving antenna also 2.5m high and loaded with 50Ω. The OATS site had a ¼ inch wire mesh stretched on a 30m x 60m concrete slab. A second measurement was made with a 1m monopole connected to a matching preamplifier as well as to a commercial monopole antenna with buffer.

Using the equations in reference 1 to obtain the Zant and Heff of the 2.5m antenna loaded with 50Ω and comparing the Zant and AF to the data in reference 3 shows a close correlation between the two.

3) 10cm bow tie antenna used to measure the E field during calibration.

The 10cm long bow tie is connected to a low noise differential input with an input resistance of 2 Megohms and an input capacitance of approximately 3pF. The wiring from bow tie to differential input adds approximately a further 2.2pF of capacitance. The differential input is converted to a single sided signal and applied to a detector with a logarithmic response. The detector allows a very high (dB) dynamic range. The output of the detector is connected to an A/D converter the output of which is translated to a digital data stream which is the input of a fiber optic driver. The electronics and battery are contained in a 6cm x 6cm x 2.5cm shielded box and the only connection to the box is the non conductive fiber optic cable. The bow tie is connected to the box using 13cm long thin wires. Thus the perturbation in the measured E field by the measuring antenna cable and equipment is kept to a minimum.

Reference 2 describes the bow tie and provides a formula for its calibration but the exact input capacitance of the differential input and stray capacitances must be known. Instead the bow tie was placed in the center of a 0.6m stripline antenna. The E field under the antenna was calculated from the height of the antenna and the input level.

The bow tie antenna is calibrated from the calculated E field under the strip line and the digital output of the bow tie and digitizer. At 10kHz and 20kHz the calibration curve shows a very slight difference compared to the AF above 20kHz. However the calibration curves for 0.05, 0.1, 0.5, 1, 5, 10, 15, 20, 25 and 25MHz are identical.

Photo 2.1 shows the bow tie under the 0.6m stripline antenna.
4) **Theoretical AF and measured using the bow tie or the bow tie with 50 Ω load.**

One monopole was used as the transmitting antenna and the second as the receiving antenna with the antennas 1m apart. The voltage across the terminal of the receiving antenna $V_t$ was measured from 10kHz to 30MHz. The rod of the receiving antenna was then replaced by the 10cm calibrated bow tie. As the incident field changes with height above the counterpoise the measurement of the E field was made with the center of the bow tie at heights of 10cm, 27.8cm, 45.6cm, 63.4cm, 81.2cm and 99cm. The average value of field E was then used in the AF calculation.

The AF in dB is $20 \log (E/V_t)$

Plot 4.1 compares the theoretical AF with the measured for both coupled and uncoupled configurations. Again we see that having the counterpoises coupled or uncoupled affects the AF above 10MHz.
Plot 4.1 Comparison between theoretical and measured AF coupled and uncoupled.

5) Calibration of the Antenna Factor of the 1.04 monopole with buffer.

In a practical MIL-STD or DO-160 test set ups the emission source may be from the EUT bonded to the conductive table top. Apart from emissions from apertures this would also occur if a voltage difference exists between the equipment case and the underlying ground plane. This emission source can, very approximately, be considered a second monopole antenna. One of the reasons for the voltage difference between the equipment case and the ground plane is common mode current flowing on the attached cables. This common mode current results in a voltage drop down the length of the cable which will appear on the equipment enclosure if the cable is shielded and attached to the enclosure. Even if a ground braid is used to bond the EUT to the table top, as required, current flow in the ground braid can result in the voltage drop.

For floor standing equipment a typical cable configuration is for the cables to be connected to the top or sides of the enclosure and brought down the sides at a height of 5cm and then laid out on the ground plane on the floor of the room again at a height of 5cm. This cable then forms a transmission line with a characteristic impedance determined by the height and diameter of the cable.

The two identical antenna calibration method was used on the OATS with the antennas 1m apart at 10MHz and above. Again an approximate wave impedance was used to obtain the AF from the gain. The calibration was first made with the receiving antenna loaded with 50Ω. A second set of data was obtained with the receiving antenna connected to a buffer. This buffer was different (resulted in a higher AF) than the buffer used for the data in plot 5.1. The difference between the two measurement was subtracted from the AF with 50Ω load to obtain the high frequency AF of the monopole with buffer.
The results of these calibrations are shown in plot 5.2 and again the coupled AF is lower than the uncoupled and shows peaks and troughs.

The three following additional test set ups were used to calibrate the monopole. The monopole to monopole set up in the anechoic chamber, and the TX line to monopole set up, also in the chamber, approximate the two practical MIL-STD measurement set ups discussed, whereas the plate antenna calibration, made outside of the chamber, may more closely approximate a far field measurement with the exception that the wave impedance will be higher. These measurements were all made with an improved buffer (lower AF than used for the data in plot 5.2.

5.1) Plate antenna

The counterpoise was connected to the return of a signal source and the antenna placed under a second brass plate with the 24” x 24” dimensions. This second plate was located at a height of 1.34m above the antenna counterpoise. The test set up is shown in figure 5.1.

Due to the small size of the plates of the antenna and the distance between plates the E field between the plates is not uniform. Therefore the E field with the rod of the monopole removed was measured with the center of the 10cm bow tie at heights of 10cm, 27.8cm, 45.6cm, 63.4cm, 81.2cm and 99cm. The average field strength was then used for the antenna calibration.

The signal source was changed in frequency over the 10kHz to 5MHz frequency range. Results above 5MHz were not believable due to the difficulty of feeding the two plates from the source above 5MHz. The AF using this test method is shown in plot 5.2.

As well as the EMC Consulting buffer a commercial (1) 1.04m rod antenna and buffer was tested under the plate antenna and the results are also shown in plot 5.1. The commercial (1) published “typical” AF is also shown. To reduce the noise floor the input resistance of the EMC Consulting buffer is 220kΩ and this is the reason the AF is higher from 10kHz to 50kHz than the commercial. Typical MIL-STD-462 RE102 limit curves are reproduced in plot 5.1, from which it can be seen that the limit is high at 10kHz and in the worst case reduces log linearly to 2MHz. Despite the higher AF of the buffer at 10kHz the noise floor of the EMC Consulting buffer, preamplifier and spectrum analyzer, measured with a 1kHz bandwidth from 10kHz to 150kHz, is well below the RE102. Likewise from 150kHz to 30MHz the noise floor is well below the limit when measured with a 9kHz bandwidth.
5.2) **1.04m monopole as source**

The calibration test set up was the same as used for the monopole with 50 Ohm load described in section 2. Again the E field was measured at the same six locations above the counterpoise.

The AF of the monopole with buffer was again obtained from the output of the buffer and the average measured E field and is shown in plot 5.2.

5.2) **Vertical transmission line**

The vertical transmission line shown in photo 5.1 was constructed and driven by a generator and power amplifier. The line was terminated in the calculated characteristic impedance of the transmission line at the far end.

The receiving monopole was only bonded to the ground plane on the floor of the room in this test. The average E field measured by the bow tie antenna and the voltage from the output of the buffer was used to calculate the AF of the monopole and buffer.

Again the AF is shown in plot 5.1
Photo 5.1 Transmission line and 10cm bow tie antenna used to calibrate the E field.

Plot 5.1 Comparison of test set ups and monopoles with buffers.
Plot 5.2 Two antenna cal method on OATS at high frequency, coupled and Uncoupled  N.B. buffer with higher AF than used for all other tests.

5.3) Measurement of 1m monopoles with buffer/preamplifier and buffer on a 10m OATS, from reference 3, compared to 1m monopoles 1m apart.

Reference 3 provides AF data on a 1m monopole with buffer/preamplifier and a second (2) commercial monopole with buffer measured on a OATS site with a 2.5m transmitting antenna at a distance of 10m from the 1m monopoles.

No information on the buffers used in reference 3 are forthcoming from the authors, however the buffer/preamp has a 10dB higher AF than the commercial (2) which means that the commercial antenna may include some gain?

The AF of the commercial monopole with buffer (2), tested in reference 3, compared to reference 2’s own antenna and the EMC Consulting monopole, measured under the plate antenna which is the closest match, is provided in plot 5.3.
Comparison of 1m Monopole with buffer

Plot 5.3 The reference #3 antennas AF measured at 10m and the EMC Consulting under the plate antenna

6.1 Typical MIL-STD-641 RE102 limits

Plot 6.1 shows the typical RE102 limits which are highest at 10kHz

Plot 6.1 Typical MIL-STD-461 RE102 limits
7. Conclusions
This report shows how coupling the counterpoise of one monopole to the counterpoise of a second monopole or to the conductive table to simulate a MIL-STD RE test set up can significantly change the AF, especially at high frequency. Also the AF of the monopole is affected by the proximity and type of E field source as shown in the measurements with a second monopole or a vertical transmission line. These effects may be due to mutual coupling when the receiving antenna is terminated in a high impedance (buffer).

The monopole to monopole and transmission line measured AF may be more representative of the actual MIL-STD test set up for RE, whereas the plate antenna test set up has a closer correlation to measurements made in reference 3 at a distance of 10m. Another important factor is the buffer used with the monopole. The differences in AF between the buffers can not be explained only by the ratio between input capacitance and antenna capacitance and so buffer gain or loss must also play a role.

References


3) Development of Standard Monopole Antenna for Antenna Factor Measurement