On the Nature and Use of the 1.04 m Electric Field Probe

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Repeatability problems have been noted with 1.04 m rod antenna measurements in the past (Jensen [1], Turnbull [2]). The problems noted center on resonances caused by the test set-up that result in erroneous measurements of field intensity with actual detected levels varying among test facilities. A complete history of the use of the 1.04 m rod antenna from the 1950s forward and test data showing the effects of different rod antenna use may be found in Javor [3].

Various vehicle-related standards utilize the 1.04 m rod antenna below 30 MHz. Military (MIL-STD-461 basic and all revisions), aerospace (RTCA/DO-160 basic through the E revision), and automotive EMI standards (CISPR 25-2002, among others) all make use of the rod antenna. To date, only MIL-STD-461F (2007) incorporates fixes to the resonance problem. And none of the other standards address the accuracy of the fundamental measurement, at frequencies where resonances are not a problem. Recently, Weston [4] criticized the MIL-STD-461F change. His main points are discussed herein.

Analytical modeling supported by experimental investigation shows that a floated counterpoise with transformer coupling between the rod antenna matching network and the test chamber ground provides the best performance at all frequencies. Experimental data shows the unacceptable perturbation caused by a grounded counterpoise. In addition to these particular issues, and as a means of making specific points, the general nature of the rod as an electric field probe, and the transfer function between field source and measured field intensity are explained.

INTRODUCTION

The 1.04 m rod "antenna" is electrically short at all test frequencies and does not function as a true antenna, which is a transducer that effectively radiates or receives "power" associated with electromagnetic fields. The rod is better understood as an electric field probe or sensor. The output impedance associated with the induced voltage in the rod is the reactance of 10 pF. Networks used with rod antennas are impedance matching devices which convert the rod's high impedance to a 50 Ohm output.

Use of the 1.04 m rod antenna has changed dramatically since its introduction in 1953 (MIL-I-6181B). Original use is shown in Figure 1, with the rod element connected directly to a battery-powered EMI receiver; the only ground connection being a very short bond strap to the tabletop ground plane. The first change allowed remote use of the EMI receiver from the antenna, which made EMI testing more practical, but introduced both a potential ground loop and also a difference in rf potential between the rod counterpoise and the EMI receiver. Another change increased the upper frequency at which the rod antenna was used from 25 to 30 MHz. This, coupled with a later change that increased separation between antenna and test sample from the original 12 inches to the present one meter

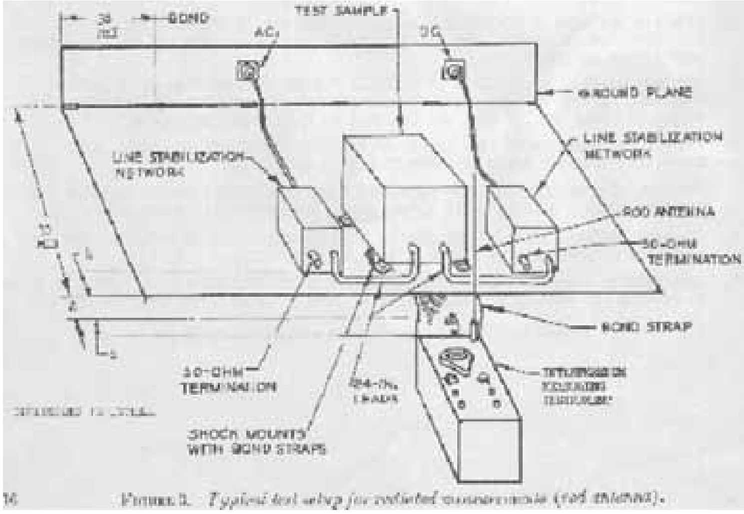


Figure 1a. *MIL-I-6181B use of 1.04 m rod antenna (ca. 1953).*

Figure 1b. *Recreation of Figure 1a.*

made the measurement more susceptible to test chamber resonances. There was good rationale for the changes, but measurement accuracy suffered. The counterpoise isolation proposed herein restores the integrity of the measurement set-up as originally configured.

The field sensing mechanism of the rod antenna is the effective potential difference between the rod base (counterpoise) and the rod tip. Since the rod's potential is measured relative to the counterpoise's potential, anything that affects the counterpoise's potential affects the measurement. This is the key point ignored by all present standards. Weston's critique [5] does not ignore the effect of the counterpoise, but that effort promotes the use of the grounded counterpoise, which references [1] – [3] as well as this effort show to be quite detrimental. Of all present standards, only MIL-STD-461F (2007) attempts to provide some control of the counterpoise potential. In so doing, MIL-STD-461F provides dampening of resonances occurring above 20 MHz.

Theoretical 1.04 m rod performance, actual performance of the traditional and the MIL-STD-461F implementation, and the proposed counterpoise isolation technique are compared herein. It is important to realize that "traditional" does not imply correct. In [3], evolution of the use of the 1.04 m rod antenna from the earliest days is explained and it is shown that what is now considered "traditional," due to common use since 1970, is in fact an aberration.

BACKGROUND

Analytical modeling and chamber testing described herein are based on a one meter long cable suspended 5 cm above a ground plane 10 cm back from the edge of the plane as shown in Figures 2 and 3. A level of -10 dBm was applied from 2 – 32 MHz driving a 50 Ohm termination. The -10 dBm level converts to 70.7 mV in a 50 ohm system. All data plots are 2-32 MHz. The test chamber size was 8' x 8' x 8', unlined. The lowest chamber resonance can be calculated from a commonly used equation to be 87 MHz, which is almost three times the highest measurement frequency of interest (30 MHz). Thus the fact that the measurements were made in a hybrid shield/screen room with no absorber lining does not affect measurement integrity. The rod antenna used was the Ailtech 95010-1, with a constant antenna factor of 8 dB/m from 10 kHz to 40 MHz. Data plots included herein are uncorrected raw antenna-induced potentials. The correlation of this data with analytical predictions is not obscured by any hidden factors. The rod antenna network was also used to measure counterpoise potentials with respect to the chamber floor. For this measurement, the network has 0 dB voltage gain and no correction factor is necessary for the actual voltage.

Figure 2. *Radiating structure, following common usage.*

EFFECTIVE FIELD STRENGTH MEASURED BY AN IDEAL 1.04 M ROD ANTENNA

An analytical derivation is presented of the voltage developed on the 1.04 meter rod antenna due to radiation from a one meter long cable suspended 5 cm above a ground plane, spaced one meter away, as in Figures 2 and 3a. A separate but similar derivation is provided for the configuration of Figure 3b. The computed values will serve as targets

Figure 3a. *MIL-STD-462 Notice 2 through MIL-STD-461E, RTCA/DO-160 through -160E, CISPR 25-2002 rod antenna set-up.*

Figure 3b. *MIL-STD-461F rod antenna set-up.*

for the experimental measurements which follow. For those who wish to skip the derivation, here is an outline of what is involved. First the electric field from a line of charge and its image as described above is derived using Gauss' Law. Then the component of each field along the length of the rod antenna is developed, and then each of those fields is integrated along the length of the rod to get the induced potential. The end-to-end potentials due to the line and its image are summed and compared to the actual measurements and the results are captured in Table 1.

The derivation starts with the static (dc) equation for the electric field from a line of charge. The method of images is used to get the net electric field at any distance from a pair of positive and negative lines of charge. The vertical component of the net electric field is integrated over the line representing the 1.04 m rod antenna. The integration is the potential collected by the rod antenna. The static analysis is valid because the rod antenna measurement at one meter, below 30 MHz is a quasi-static measurement: both the radiating element and the receiving elements are electrically short (one-tenth wavelength or less), and the separation between radiator and pick-up is less than $\lambda/2\pi$, the accepted near field - far field boundary for a near isotropic radiator (λ being wavelength).

Drawing 1. *Radially directed electric field line from center of line of charge of length L.*

The radially symmetric electric field from the center of a line of charge of finite length L (drawing 1) is (Gauss' Law)

$$E = \frac{1}{2\pi\varepsilon_0}\frac{\rho_L}{r}\frac{1}{\sqrt{1+(2r/L)^2}} \qquad \textbf{Eqn. 1a}$$

where,
E is the radially directed electric field in Volts per meter,
ε_0 is the permittivity of free space (8.85 pF/m)
ρ_L is the linear charge density, Coulombs per meter
r is the radial separation from the line of charge, meters,
L is the length of the line of charge, 1 meter in our case.

In order to keep the math tractable, the first two terms of a binomial expansion of the radical term are retained.

$$\frac{1}{\sqrt{1+(2r/L)^2}} \quad \frac{L}{2r}\left[1-\frac{1}{2}\left(\frac{L}{2r}\right)^2\right]$$

This is accurate to within 4%. Equation 1a then reduces to

$$E \approx \frac{\rho_L L}{4\pi\varepsilon_0}\left[\frac{1}{r^2}-\frac{1}{8}\left(\frac{L^2}{r^4}\right)\right] \qquad \textbf{Eqn. 1b}$$

The only value not immediately available in equation 1b is the linear charge density. We can use the definition of capacitance to express the linear charge density in terms of the capacitance of the wire and the potential on it:

$\rho_L = q/L = CV/L$ **Eqn. 2**

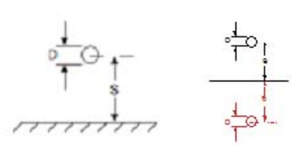
where,
q is charge, Coulombs,
C is capacitance in Farads, and
V is the potential on the line, in Volts

In the above, we have everything but the capacitance of the wire. In order to evaluate that, we have to evaluate the expression for the capacitance of a two wire line.

From Barnes [5], we have

$$C(pF/m) = \frac{\pi\varepsilon_0}{\ln\left[S/D+\sqrt{(S/D)^2-1}\right]} \qquad \textbf{Eqn. 3}$$

where S and D are as in drawing 2a.



Drawing 2a. *Geometry for wire above ground on left, geometry for capacitance calculation on right. Because separation between wire & image is twice that in actual set-up, the value plugged into equation 3 for S is 10, not 5 cm.*

For values of S = 5 cm, and D = 1mm (AWG 18), we get C = 5.25 pF/m. Actual cable length was 1.1 m.

Using equation 2, we compute the linear charge density, knowing that the line potential is -10 dBm, or 97 dBuV, or 70.7 mV.

ρ_L = 5.25 pF/m*1.1 m * 0.07 Volts = 0.4 pC/m

Substituting into equation 1b (and noting that L = 1.1 meter, we have the equation for the electric field from the wire of our test set-up, but ignoring the effect of the ground plane.

$$E^{+}(x) = 3.6\ mV\left[\frac{1}{r^2} - \frac{1.21}{8r^4}\right] \qquad \textbf{Eqn. 4}$$

Using the method of images (drawing 2b), we calculate the electric field from an identical line of opposite charge 5 cm below the ground plane. The symmetry of the situation is such that between –d/2 and d/2, the horizontal components of the two field lines cancel precisely, but the vertical components add, and they add in a negative sense. Above d/2 the contribution from the two wires are in opposite phase and tend to cancel.

Given the geometry of drawing 2b, the expression for the electric field from the above ground wire is

$$E^{+}(x) = 3.6\,mV\left[\frac{1}{x^2+D^2} - \frac{1}{8}\frac{1.21}{(x^2+D^2)^2}\right] \qquad \textbf{Eqn. 5a}$$

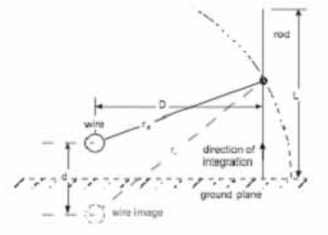
where x is vertical displacement from the point on the rod opposite the wire closest to the region of integration.

Equation 5a is the magnitude of the radially directed electric field; we desire the vertical component parallel to the rod. From the geometry of drawing 2b, the expression for the vertical component of the field is

$$E^{+}_{\perp}(x) = 3.6\ mV\left|\frac{1}{x^2+D^2} - \frac{1}{8}\frac{1.21}{(x^2+D^2)^2}\right| * \frac{x}{\sqrt{x^2+D^2}}$$

or

$$E^{+}_{\perp}(x) = 3.6\ mV\left[\frac{x}{\sqrt{x^2+D^2}^{\,3}} - \frac{1}{8}\frac{1.21x}{\sqrt{(x^2+D^2)}^{\,5}}\right] \qquad \textbf{Eqn. 5b}$$



Drawing 2b. *Method of images geometry.*

We can similarly calculate the electric field from the line of charge below the ground plane, which is removed vertically by a separation of d.

$$E^{-}(x) = -3.6\ mV\left[\frac{1}{(x+d)^2+D^2} - \frac{1}{8}\frac{1.21}{\{(x+d)^2+D^2\}^2}\right]$$

when x≥ d/2, and **Eqn.5c**

$$E^{-}(x) = -3.6\ mV\left[\frac{1}{(x+d/2)^2+D^2} - \frac{1}{8}\frac{1.21}{\{(x+d/2)^2+D^2\}^2}\right]$$

when 0 < x < d/2 **Eqn.5d**

Just as above, this is the magnitude of the radially directed field; we desire the vertical component, which is ($x \geq d/2$)

or

$$E^{-}_{w}(x) = -3.6\,mV\left[\frac{1}{(x+d)^2+D^2} - \frac{1}{8}\frac{1.21}{\{(x+d)^2+D^2\}^2}\right] * \frac{x+d}{\sqrt{(x+d)^2+D^2}}$$

$$E^{-}_{w}(x) = -3.6\,mV\left[\frac{x+d}{\sqrt{(x+d)^2+D^2}^{\,3}} - \frac{1}{8}\frac{1.21(x+d)}{\sqrt{(x+d)^2+D^2}^{\,5}}\right] \qquad \textbf{Eqn. 5e}$$

and (when $0 < x < d/2$)

$$E^{-}_{w}(x) = -3.6\,mV\left[\frac{x+d/2}{\sqrt{(x+d/2)^2+D^2}^{\,3}} - \frac{1}{8}\frac{1.21(x+d/2)}{\sqrt{(x+d/2)^2+D^2}^{\,5}}\right] \qquad \textbf{Eqn. 5f}$$

The potential induced along any curve due to an electric field impinging upon it is given in general by

$$\mathrm{V} = \int_{\text{rod base}}^{\text{rod tip}} \underline{\mathbf{E}} \cdot \mathrm{d}\underline{\mathbf{l}} \qquad \textbf{Eqn. 6a}$$

where the integral is understood to be a line integral, with electric field in the direction of the curve at every point being summed over the length of the curve.

In the case of the rod antenna, we are integrating over its length, starting at the base and ending at the tip 1.04 meters above it. We can calculate the potential from the above ground wire, and then separately calculate the potential due to the image wire, and then, carefully taking into consideration the signs, combine the different contributions to arrive at the net potential induced in the rod. In order to perform the integration, the various expressions for the electric field from the above ground wire (equation 5b) and the image wire (equations 5e when $x \geq d/2$ and equation 5f when $0 < x < d/2$) are substituted for $\underline{\mathbf{E}}$ in equation 6a, and dx substitutes for d$\underline{\mathbf{l}}$. Because the vertical components of the electric field are parallel to the rod, the dot product of equation 6a becomes a simple scalar multiplication.

In addition to separate expressions for the electric field from the image wire according to whether x is either less than or greater than d/2, the signs of the fields must be properly treated. From 0 to d/2, the contributions from the wire and its image add because the vertical component of each field is downwards. Above d/2, the vertical components are oppositely directed, and they subtract from each other. In the case of the MIL-STD-461F set up, with part of the rod below the ground plane, there is a short region below the ground plane where the field contributions from wire and image again subtract, but the signs of each contribution are opposite what they are when $x > d/2$ above the ground plane. It is also important to note that the range of integration is not based on the rod antenna as an absolute, but in relationship to where the radiating wire is. The radiating wire closest to the zone of integration is the zero point for integrating. Thus in some cases we integrate up from some point along the rod, and down the other direction from that point.

Between 0 and d/2 along the rod antenna, the electric field from the wire above the ground plane contributes a potential given by

$$V^{+} = -3.6\,mV\int\left[\frac{x}{\sqrt{x^2+D^2}^{\,3}} - \frac{1}{8}\frac{1.21x}{\sqrt{(x^2+D^2)}^{\,5}}\right]dx \qquad \textbf{Eqn.6b}$$

Between d/2 (5 cm) and 1.04 meter along the rod antenna, the electric field from the wire above the ground plane contributes a potential given by

$$V^{+} = 3.6\,mV\int\left[\frac{x}{\sqrt{x^2+D^2}^{\,3}} - \frac{1}{8}\frac{1.21x}{\sqrt{(x^2+D^2)}^{\,5}}\right]dx \qquad \textbf{Eqn. 6c}$$

Between 0 and d/2 along the rod antenna, the electric field from the image wire contributes a potential given by

$$V^{-} = -3.6\,mV\int\left[\frac{x+d/2}{\sqrt{(x+d/2)^2+D^2}^{\,3}} - \frac{1}{8}\frac{1.21(x+d/2)}{\sqrt{(x+d/2)^2+D^2}^{\,5}}\right]dx \qquad \textbf{Eqn. 6d}$$

Between d/2 (5 cm) and 1.04 meter along the rod antenna, the electric field from the image wire contributes a potential given by

$$V^{-} = -3.6\,mV\int\left[\frac{x+d}{\sqrt{(x+d)^2+D^2}^{\,3}} - \frac{1}{8}\frac{1.21(x+d)}{\sqrt{(x+d)^2+D^2}^{\,5}}\right]dx \qquad \textbf{Eqn. 6e}$$

Integrals of the form

$$\int\left[\frac{x+a}{\sqrt{(x+a)^2+D^2}^{\,3}}\right]dx = \frac{-1}{\sqrt{(x+a)^2+D^2}} \text{ and } \int\left[\frac{x+a}{\sqrt{(x+a)^2+D^2}^{\,5}}\right]dx = -\frac{1}{3}\frac{1}{\sqrt{(x+a)^2+D^2}^{\,3}}$$

Equation 6b simplifies to

$$V^{+} = 3.6\,mV\left[\frac{1}{\sqrt{x^2+D^2}} - \frac{1}{24}\frac{1.21}{\sqrt{x^2+D^2}^{\,3}}\right]$$

with x running from 0 to d/2.

Eqn. 6f

Equation 6c simplifies to equation 6f with a change of sign out front.

$$V^{+} = -3.6\,mV\left[\frac{1}{\sqrt{x^2+D^2}} - \frac{1}{24}\frac{1.21}{\sqrt{x^2+D^2}^{\,3}}\right]$$

with x running from d/2 to 1.04 meters.

Eqn. 6g

Equation 6d simplifies to

$$V^{-} = 3.6\,mV\left[\frac{1}{\sqrt{(x+d/2)^2+D^2}} + \frac{1}{24}\frac{1.21}{\sqrt{(x+d/2)^2+D^2}^{\,3}}\right]$$

with x running from 0 to d/2.

Eqn. 6h

Equation 6e simplifies to

$$V^{-} = 3.6\,mV\left[\frac{1}{\sqrt{(x+d)^2+D^2}} + \frac{1}{24}\frac{1.21}{\sqrt{(x+d)^2+D^2}^{\,3}}\right]$$

with x running from d/2 to 1.04 meters.

Eqn. 6i

Three problems of interest are the "traditional" or MIL-STD-461E set-up, MIL-STD-461F, and a variation on the traditional approach where the antenna electronics box at the base of the rod sits on top of the counterpoise instead of below it. We use equations 6f – i to calculate all the various potentials from the wire above ground and its image. Then we sum all the contributions. This represents the open circuit potential between the rod base and tip and also the effective field intensity. Half this calculated potential is the open circuit potential on the rod, loaded and then amplified by the rod antenna base and presented into 50 Ohms.

"Traditional" or MIL-STD-461E calculation - Solve for the potential on the rod antenna from the radiating wire when the base of the rod antenna is the same height as the ground plane, and one meter away (Figure 3a).

Between 0 and d/2 along the rod antenna, the electric field from the wire above ground contributes an induced potential on the rod between 0 and d/2 of -3.6 uV (equation 6f).

Between 0 and d/2 along the rod antenna, the electric field from the image wire contributes a potential given by equation 6h of -15.4 uV (equation 6h).

Thus the total potential induced from 0 to 5 cm is -19 uV.

Equation 6g yields a potential of 938 uV induced between 5 cm and 1.04 meters due to the field from the wire above ground.

Equation 6i yields a potential of -1283 uV induced between 5 cm and 1.04 meters due to the field from the image wire.

The sum of the potentials over the whole rod is -364 uV, or 51.2 dBuV. Per above discussion, this means the effective field intensity is 51.2 dBuV/m and the unloaded potential appearing at the base of the rod to be amplified is 45.2 dBuV. Because the Ailtech 95010-1 rod antenna used in this effort loads the open-circuit potential by 2 dB, then provides 0 dB voltage gain, the output to an EMI receiver would be 43.2 dBuV, or -63.8 dBm.

This is what we expect to measure when configured as in Figure 3a. We also have independent verification that this value is in the right ballpark. The rationale appendix of MIL-STD-461D/E/F cites a relationship between rf potential on a 2.5 meter wire below 30 MHz and the radiated quasi-static electric field intensity. The transfer function is stated to be that the electric field intensity is 40 dB down from the rf potential. In the set-up used in this investigation, the wire is only 1.1 meter long, therefore we expect the transfer function to be 4.25 dB less efficient based on the wire length dependence of equation 1a, or 44.25 dB down. Starting with a wire potential of 97 dBuV, we expect a field intensity of 52.75 dBuV/m. The 51.2 dBuV/m calculation agrees within 1.55 dB.

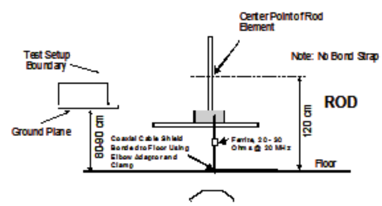
A similar calculation is performed when analyzing rod antenna performance for the Figure 3b MIL-STD-461F set-up. Only the limits of integration differ because of the relative position of the rod antenna and the radiating wire, per drawings 2c and d.

Referring to drawing 2d, the region 1 analysis is the same as that previously for x greater than d/2. Vertical components of the electric field from the wire and its image are opposite in sense and therefore subtract. In region 2, vertical components of the electric field from both wires are equal in magnitude and reinforce downwards. In region 3, the situation is as in region 1, but the sense of the vectors is reversed. Integration limits given with the rod base as zero, but to integrate properly, the closest radiating wire position is the zero point, as previously discussed.

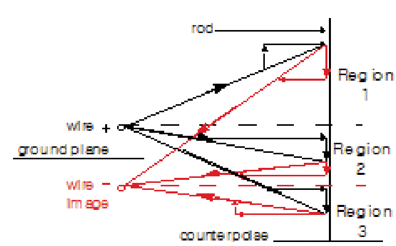
In region 1, limits of integration are d/2 to the rod tip (0.27 m to 1.04 m referenced to the base of the rod as ground). The contribution from the above ground wire evaluates equation 6g with these limits of integration to yield 657 uV. The contribution from the image wire evaluates equation 6i with these limits of integration to yield -966 uV. So the net potential induced in the rod from 5 cm above tabletop to the tip of the rod is -309 uV.

In region 2, the limits of integration are –d/2 to d/2, and there is symmetry making the problem easier to handle. The contribution from both the above ground wire and its image are equal and in the same sense, which is negative. So our computation is twice the result of the above ground wire equation 6f with limits of integration 17 to 27 cm and a change in sign. This comes to -30 uV.

In region 3, the limits of integration are x running from the rod base (68 cm above the floor) to -d/2 (85 cm above the floor), with the bench-top ground plane at 90 cm above ground. The sense of the contributions is opposite from region 1: the vertical electric field component from the above ground wire points downwards (negative), and the vertical electric field component from the image wire points up, positive. Further, equation 6g which was derived for the above ground wire now applies to the image wire, and equation 6i, which was derived for the image wire now applies to the above ground wire. The contribution from the above ground wire evaluates equation 6i with these limits of integration to yield -122 uV. The contribution from the image wire evaluates equation 6g with these limits of integration to yield 43 uV. These sum to yield -79 uV.



Drawing 2c. *MIL-STD-461F rod antenna set-up.*



Drawing 2d. *Geometry for limits of integration of drawing 2c.*

The sum of the potentials induced in regions 1 – 3 is -418 uV, or 52.4 dBuV, so the effective field intensity is 52.4 dBuV/m. That translates to -62.5 dBm at the EMI receiver. This is about 1 dB higher than that predicted for the MIL-STD-461E case where the rod antenna base is level with the ground plane, and is within 0.5 dB of the 40 dB relationship cited in the MIL-STD-461F RE102 appendix.

There is one final wrinkle to be analyzed. MIL-STD-461F precisely controls the height of the rod by stating its center point is 120 cm above the floor. But the earlier technique doesn't control the rod height, because some rod bases are designed to fit under the counterpoise, which is generally level with the tabletop ground plane, and some rod antenna bases, such as that used in this investigation, are designed to mount on top of the counterpoise, thus boosting the rod height by the height of the road antenna base. The rod antenna base used in this investigation was 12 cm tall, and in the author's experience, is about as tall as they come. The effect of using this base on top of the counterpoise is now

Figure 4a. *Rf potential on radiating wire loaded by 50 Ohms. Span is 2-32 MHz, reference is 10 dBm, 10 dB per division (-10 dBm = 97 dBuV).*

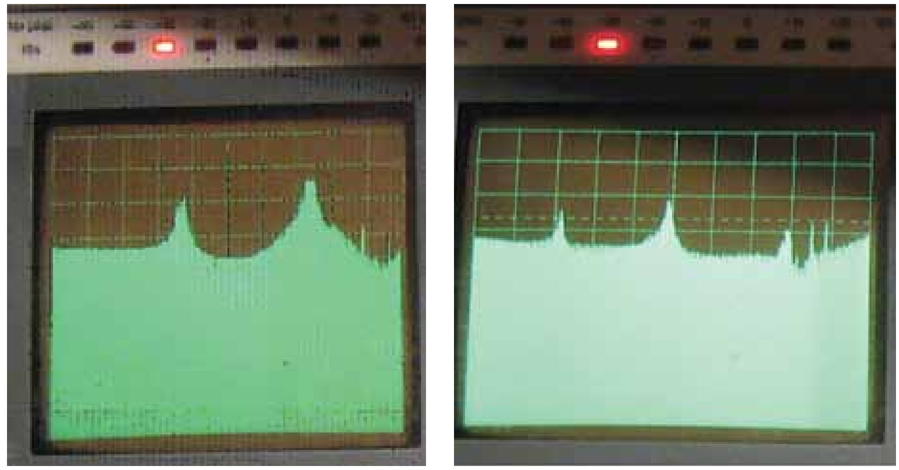
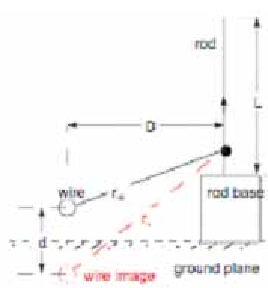


Figure 4b. *Radiated signature using Figure 3a antenna configuration, scanning 2-32 MHz, reference level is – 30 dBm. For picture on left, coax connection to chamber was 12 feet, on the right it was 24 feet. Uncorrected data; field intensity would be 8 dB higher than levels shown.*

analyzed. The analysis follows that for the traditional set-up, except that the limits of integration are from the base of the rod 12 cm above ground to 1.04 meter above that – there is no need to break the integral into different parts, because the vectors now all have the same sense with respect to each other over the entire rod length.

Per drawing 2e we integrate directly from the base at 12 cm above ground to the top of the rod at 1.04 meters plus 12 cm. Note that this makes the limits of integration 7 cm to 1.04 meters plus 7 cm, because our zero point is the wire above ground height of 5 cm.



Drawing 2e. *More exact simulation of Figure 3a.*

Equation 6g evaluates the contribution from the above ground wire as 938 uV. Equation 6i evaluates the contribution from the image wire as -1282 uV. The net result is -344 uV, or 50.7 dBuV. This means an effective field intensity of 50.7 dBuV/m, and the EMI receiver will read -64.3 dBm.

Analytical results for the three measurements of the same radiating wire are compared to measurements presented in section IV. Analytical and measured results for all methods agree well, except for resonances, which is why the MIL-STD-461F approach came about.

Method	Predicted E-field. dBuV/m	Predicted EMI Rcvr rd'g dBm	Meas'd dBm**	Agreement within (dB)
-461E:	51.2	-63.8	-63***	0.8
-461F	52.4	-62.5	-63	0.5
461E*	50.7	-64.3	-64.5	0.2

*antenna base on top of ground plane
**from section IV measurements section
*** absent resonances

Table 1. *Comparison of analytical and measured results.*

The analytical results make the following issues clear: the calculation of rod-coupled potential does not depend on counterpoise configuration. It was not discussed previously, but the only purpose of the counterpoise is to achieve the 10 pF source impedance of the 1.04 meter rod. Absent a counterpoise, that value decreases markedly. A counterpoise is a reference against which the rod antenna induced potential

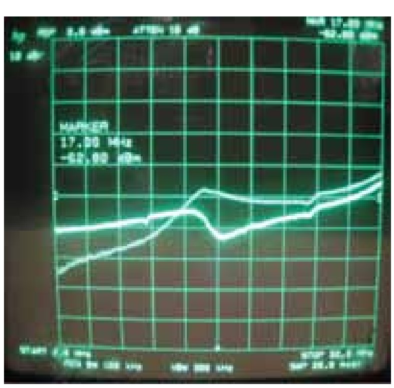


Figure 4c. *Counterpoise potential and rod antenna output super-imposed. Ground plane potential is the curve that is lower at the low end and higher after 14 MHz (2-32 MHz sweep, 17 MHz at center).*

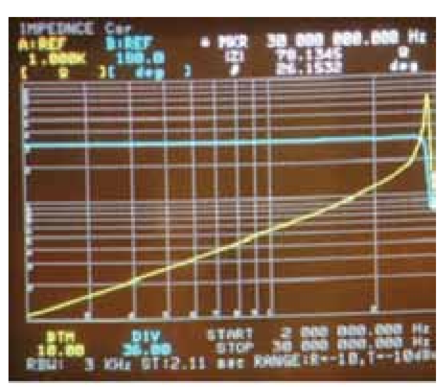


Figure 4d. *Impedance between floor and counterpoise of MIL-STD-461F configuration w/o rf sleeve.*

is measured. *Since the potential at the base of the rod is taken with respect to the counterpoise, if the counterpoise potential is disturbed, the measurement will be off.* This is key in designing the proper set-up. The proper counterpoise configuration is the main subject of the following section.

EXPERIMENTAL VERIFICATION

First, the problem. The traditional Figure 3a set-up yields the cable length (and chamber size) dependent resonances of Figure 4b. Figure 4a is the rf potential on the radiating wire for comparison (stimulus vs. response).

Since the source potential is constant with frequency, we expect the measured radiated field to be likewise, based on the analytical section. Therefore we recognize that the Figure 4b performance is indicative of a problem with the test set-up. This observation and the description of the traditional set-up point out two problems with [4]. [4] doesn't show the radiating source potential, only the radiated fields. Departures from a flat response are observed over the entire 2-30 MHz band. It is not clear in [4] how much of the peaks are due to problems in the rod antenna set-up vs. problems in the radiating element. Secondly, Weston in [4] uses ferrite sleeve lining over the coax connection in both the -461E and -461F set-ups. None of the other the other standards besides MIL-STD-461F require such treatment. Weston displays a knowledge of the problems with MIL-STD-461E in so doing, but for the purposes of comparing and contrasting MIL-STD-461E and MIL-STD-461F methods, one cannot use ferrite sleeve lining in the MIL-STD-461E set-up because there is no requirement to do so.

The source of the resonance problem is the reactive impedance between counterpoise and chamber ground. This consists of the capacitance between the counterpoise and the chamber surfaces, as well as the parallel inductance of the coaxial transmission line shield acting as a ground strap between counterpoise and chamber. Both the capacitance and inductance will be chamber specific. The counterpoise is one plate of a capacitor working mainly against the floor; the effective plate size is the arithmetic average of the counterpoise area and the floor area. Since the size of chambers is uncontrolled (above some minimum), the capacitance will be larger than some minimum value, but otherwise unconstrained. Note that the capacitance depends mainly on the floor size; even if the counterpoise area approaches zero, the floor size sets the effective plate size. The length of coax cable interconnect is clearly dependent on room size and layout, and is even less controlled than the capacitance. Measurements made in the EMC Compliance chamber showed capacitance of 50 pF and inductance close to 0.5 uH. And that was using the MIL-STD-461F configuration less the rf sleeve; the inductance would have been much higher with a long length of coax. For the values measured, the

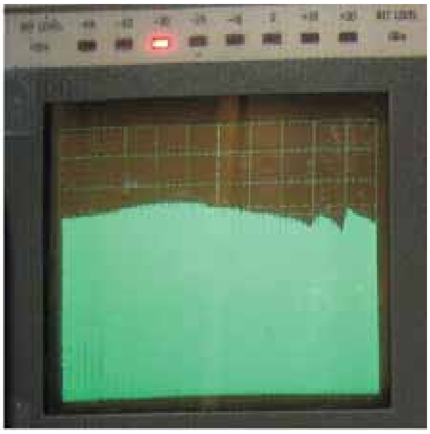


Figure 5a. *MIL-STD-461F-type rf sleeve resonance detuning. Analyzer settings same as for Figure 4b.*

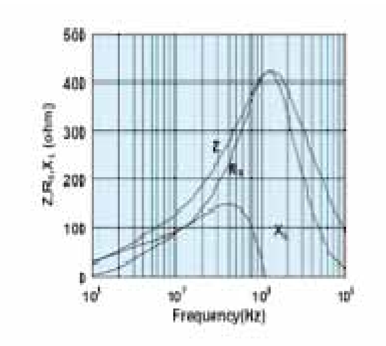


Figure 5b. *Impedance plots of Fair-Rite part 0431176451.*

parallel resonance (open-circuit) is at 31.8 MHz. This is just above the range of resonances seen at most facilities; a longer cable and larger floor area would have dropped the resonance below 30 MHz, where it is normally found. Figure 4c shows the actual potential on the MIL-STD-461F counterpoise with an rf sleeve to dampen the resonance. The potential measured out of the rod antenna base is also superimposed. Regardless of what the rod output is, it is measured with respect to the counterpoise, and the effect is very clear in Figure 4c. Figure 4d is a network analyzer measurement of the impedance between floor and counterpoise in a full-sized MIL-STD-461 test chamber. The inductive nature of the coax ground connection (less rf sleeve) and the resonance with capacitance is quite clear. Again, a longer coax connection to ground ("traditional") configuration, would have moved the resonance to a lower frequency.

In Figure 5a, the plot is for the MIL-STD-461F configuration, Figure 3b, using an rf sleeve solution that meets or exceeds MIL-STD-461F requirements. That solution, shown lying on the floor in Figure 6a, consists of four Fair-Rite 0431176451 sleeves, with a wire running through them that connects to a 270 Ohm resistor. The inductive reactance of these four sleeves (Figure 5b) in series is much greater than 270 Ohms, and the sleeves act as a transformer, with the 270 Ohm resistance being the impedance of the coaxial ground connection at and above 20 MHz. The total assembly is shown in Figure 6a.

Finally, the optimal solution, which is a totally floated counterpoise. A Mini-Circuits FTB1-6 balun was used as an isolation transformer to isolate the counterpoise from chamber ground, as shown in Figure 6a. Figure 6b shows the rod antenna set-up. Figure 6c shows the resultant plot.

At this point it is reasonable to ask how Figure 6c results stack up against "reality." "Reality" defined as the set-up of Figure 7a, with all elements working against the floor of the chamber. Figure 7b shows the results which are about 2 dB lower than the Figure 6c results, for the reason that the rod starts off 12 cm above the floor, as detailed in the theory section. Agreement with theory is within 0.2 dB at the mid-point frequency.

THE EFFECT OF GROUNDING THE COUNTERPOISE

Imagine that instead of the typical EMI test set-up with a test sample and cables on a copper-top bench and a 1.04 meter rod antenna spaced a meter away, that the rod antenna is between the plates of a parallel plate transmission line or TEM cell that has enough separation between the plates to mount the rod antenna with room left over above the top of the rod. For specificity, imagine the plate to be 2.5 meters tall, with the base of the rod antenna resting on (ohmically attached to) the bottom (ground) plate. Such a plate should be well behaved at frequencies up to the 2.5 meter height representing a tenth wavelength, or 12 MHz. If an rf potential, V, is applied to the top plate relative to the bottom plate, then the

Figure 6a. *Rf sleeves and resistor that place 270 Ohms between counterpoise and floor above 20 MHz, and isolation transformer that floats counterpoise.*

Figure 6b. *MIL-STD-461F configuration using isolation XFMR visible near floor ground point. Assembly to the right is the rf sleeve network that gave the plot of Figure 5a.*

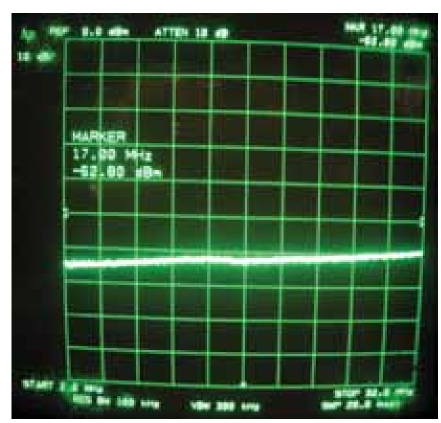


Figure 6c. *Resultant plot from set-up of Figure 6b. Note close agreement with theory (-62.5 dBm).*

electric field near the middle of the plate (ignoring fringing) will be [V/2.5] Volts per meter straight up and down perpendicular to the area of the plates. The rod antenna output, corrected for antenna factor, should yield this same electric field. Now imagine that the rod

Figure 7a. *"Reality" check configuration. Separation of radiating line from back wall the same as when on table-top ground plane.*

antenna base is raised off the bottom plate about 60 cm, the approximate height as required by MIL-STD-461F. What will the rod antenna indicate the field to be in this new position? We know the field is constant, so we should get the same answer. The integration along the rod will yield the same result, because the field is constant. If the rod antenna base and attached counterpoise is floated, then indeed we will ge t the same answer, because the rod potential is measured against its base, and all that has happened is that the rod top and base are at different potentials with respect to the ground plate, but the potential difference between top and base has not changed. But if we connect the antenna base/counterpoise to the ground plate, we are now creating a new ground 60 cm higher than previously, and that means the electric field is now the potential on the top plate divided by 2.5 meters less 60 cm, or [V/1.9] V/m. Clearly the electric field intensity has increased, and we will read this new value. Figure 3 of [4] includes supporting data. Measurements made above a floated counterpoise using a balanced antenna in lieu of a rod where the rod would normally be are much flatter and lower than with the counterpoise grounded.

It seems reasonable based on this model, that floating the counterpoise perturbs the field less than grounding it, and on this basis a floated counterpoise appears the best solution.

CONCLUSION

The 1.04 meter rod is an electric field probe, not an antenna. The analytical section demonstrates this by performing a static computation of the output of such a rod when exposed to a well-defined source field. Close correlation with experimental results establishes the probe-like nature of the rod "antenna." A key point is made that the measured potential induced in the rod is compared to the potential of the counterpoise. If the counterpoise potential is different than the ground of the measurement facility, errors ensue. Further, if the counterpoise ground connection disturbs the field being measured, the act of measuring then disturbs what is being measured. Three typical set-ups for measuring electric field intensity with a 1.04 meter rod antenna have been described. Of the three techniques discussed, a floated counterpoise is the best overall solution. The MIL-STD-461F solution comes in second, and indeed is very close if the rf sleeve makes the coaxial ground connection resistive rather than inductive. The "traditional" technique connecting the counterpoise to the table-top ground plane and using a ground connection of indeterminate length (coax connection) between the antenna base and chamber ground causes unacceptable resonances.

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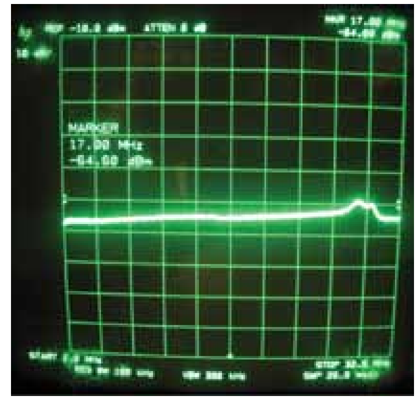

Figure 7b. *"Reality" check data plot. Level within 2 dB of the MIL-STD-461F configuration (Figure 6c).*

suggestions relating to the presentation of the analysis. Robert Scully, lead over EMC at NASA's Johnson Space Center, made suggestions pertaining to the calculation of wire capacitance. These suggestions resulted in closer agreement between analytical and experimental results. Any errors are the sole responsibility of the author.

REFERENCES

- [1] Jensen, Steve, "Measurement Anomalies Associated with the 41 Inch Rod Antenna when Used in Shielded Enclosures," July 17, 2000, <http://www.stevejensenconsultants.com/rod_ant.pdf>.
- [2] Turnbull, Luke, "The Groundplane Resonance: Problems with Radiated Emissions Measurements below 30 MHz." Automotive EMC Conference 2007.
- [3] Javor, Ken, "History of 41 Inch Rod Antenna Use in EMI Testing," <http://www.emccompliance.com/history.php>.
- [4] Weston, David, "1.04 m Rod, Antenna Factor and Received Level in MIL-STD-462/461E Compared to MIL-STD-461F Test Set Up," Interference Technology EMC Test and Design Guide, November 2010: 8-13.
- [5] Barnes, John, "Electronic Systems Design Interference and Noise Control Techniques," Prentice-Hall, 1987: 175-178. Print.

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