RADIATED INTERFERENCE AND SUSCEPTIBILITY CHARACTERISTICS OF UNSHIELDED LINES

R. J. Mohr
Airborne Instruments Laboratory
A Division of Cutler-Hammer, Inc.
Deer Park, Long Island, New York 11729

SUMMARY

Because of relatively large effective radiating area, interface wiring is often a prime source of interference radiation and pickup in electronic systems. This paper presents a technique which allows quantitative prediction of the radiation and susceptibility characteristics of open wires. The technique is particularly well suited to predicting performance in the radiated interference and radiated susceptibility test setups of interference specifications.

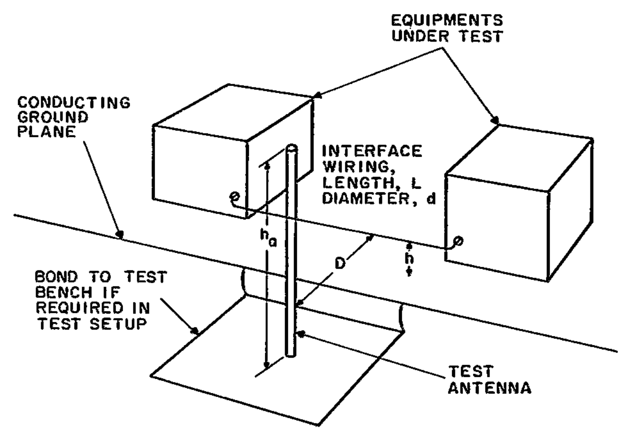
Babcock and Sagasta[1] presented useful data for the prediction of radiated interference in the test setups of MIL-I-6181D and MIL-I-11748B. Their data, however, did not show the effect of the diameter of the radiating wire, or the effect, in depth, of its height. In addition, their results could not be extended to modified test setups, for example, that of MIL-STD-462.

The arrangement of the radiating wire over a ground plane, in typical EMC test setups, suggests the use of an electric dipole model for analysis. Use of this technique in accordance with the approach by Gerry[2] was found to give very conservative results. In order to apply his technique to the problem where the radiating wire and antenna are of dimensions comparable with their separation, several refinements in his approach are required. In particular, it is necessary to represent the wire as an array of dipoles and to average their effect over the length of the receiving antenna.

This paper first presents the results of this analysis and illustrates their use in EMI predictions; next the derivation of the material is shown; finally experimented verification of the theory is given.

TEST SETUP AND PREDICTION GRAPHS

Figure 1 shows the setup considered herein and the dimensions typical of setups in various specifications.* For a given antenna arrangement the important parameters of the wire are its height h, length L, and diameter d. In this paper the rod will always be considered to be located opposite the center of the wire for maximum interference radiation or pickup.



SPECIFICATION	D	h_a
MIL-I-6181D	12 INCHES	41 INCHES
MIL-I-11748B	36 INCHES	108 INCHES
MIL-STD-462	1 METER	41 INCHES

Figure 1. Radiated Interference Test Setup

Figure 2 shows the predicted open circuit antenna induced voltage as a function of wire length. This figure is applicable for h = 2 inches and d = 0.032 inch.

---

* MIL-I-11748B radiated test arrangements, including the antenna separation and the tilt of the antenna away from the vertical, are a function of the equipment under test. The arrangement chosen herein is that used by Babcock and Sagasta[1] (per telephone conversation with Mr. Babcock). Hence the predictions of this paper can be compared with their results.

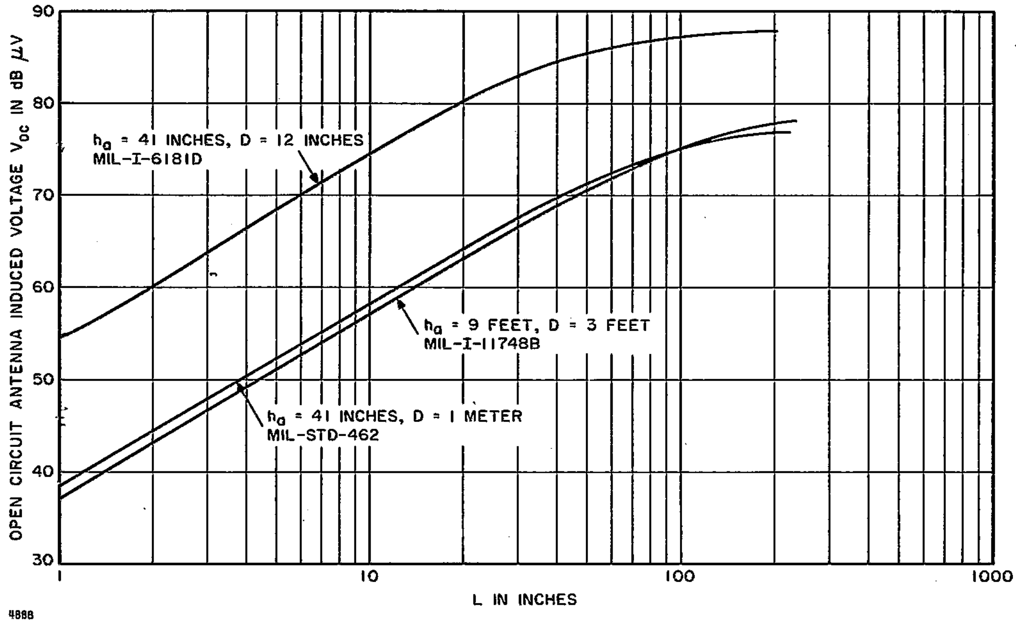


Figure 2. Antenna Induced Voltage vs Length of Radiating Wire for 1-Volt rms on Wire of h = 2 Inches and d = 0.032 Inch

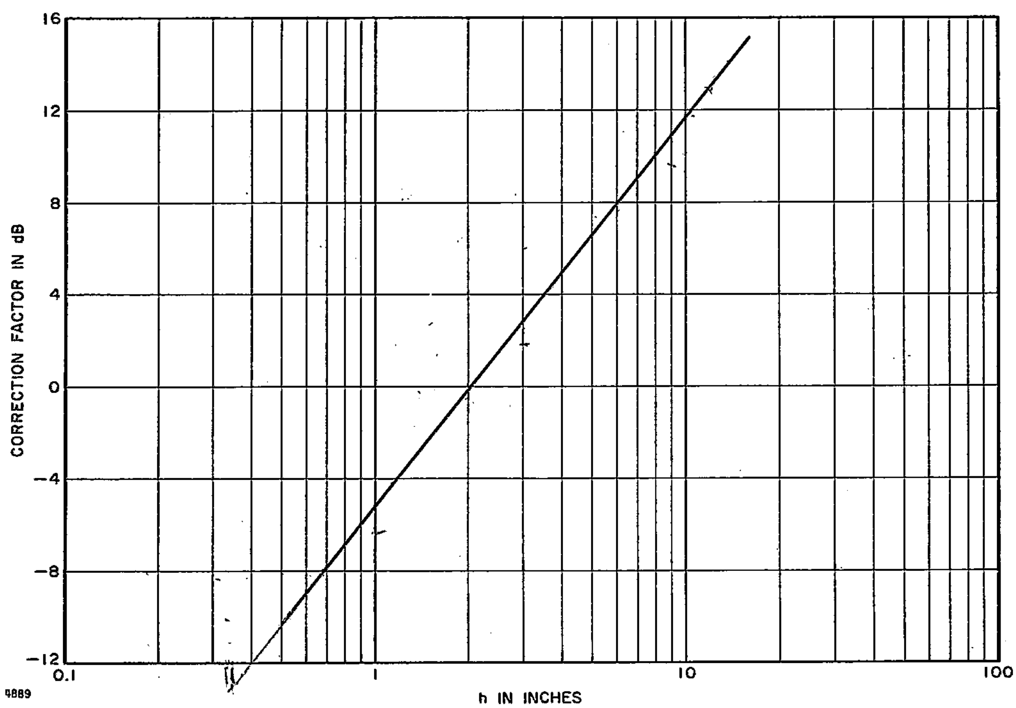


Figure 3. Effect of Height of Radiating Wire on Radiated Interference (Add Correction Factor to Radiated Level from Figure 2)

Figures 3 and 4 show correction factors to be applied to Figure 2 for other wire heights and diameters. MIL-STD-461 radiation limits are expressed in field strength units rather than in terms of antenna induced voltage. To convert the predictions from Figure 2 to field strength, the effective antenna height (in dB) should be added. For the 41-inch rod antenna, this factor is +6 dB.

Figure 5 shows the mutual capacitance between vertical rod antenna and open wires. This figure is applicable for h = 2 inches and d = 0.032 inch.

The capacitance is used in the calculation of pickup on the wire due to signals radiated by the rod. As for radiated interference calculations, Figures 3 and 4 give correction factors for wire height and diameter. Examples of the use of these graphs follow.

EXAMPLE 1. RADIATED INTERFERENCE PREDICTION

Interface wire length	L = 48 inches
Height over ground plane	h = 6 inches
Wire size no. 12 AWG	d = 0.080 inch

Determine maximum permissible conducted signal level on wire at 1 MHz that will not cause narrowband radiation to exceed limits of MIL-STD-461.

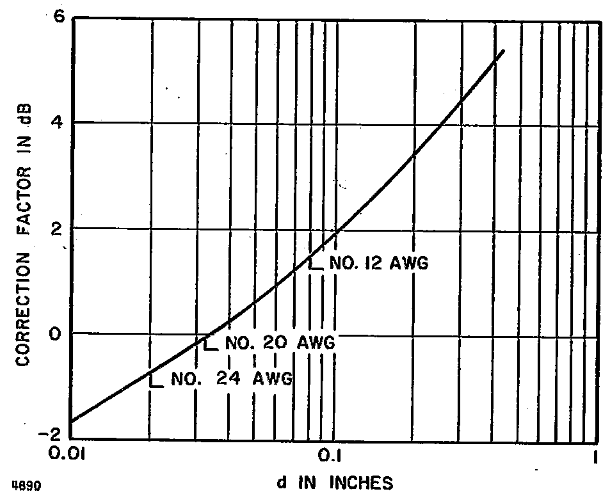


Figure 4. Effect of Diameter of Radiating Wire on Radiated Interference (Add to Radiated Level from Figure 2)

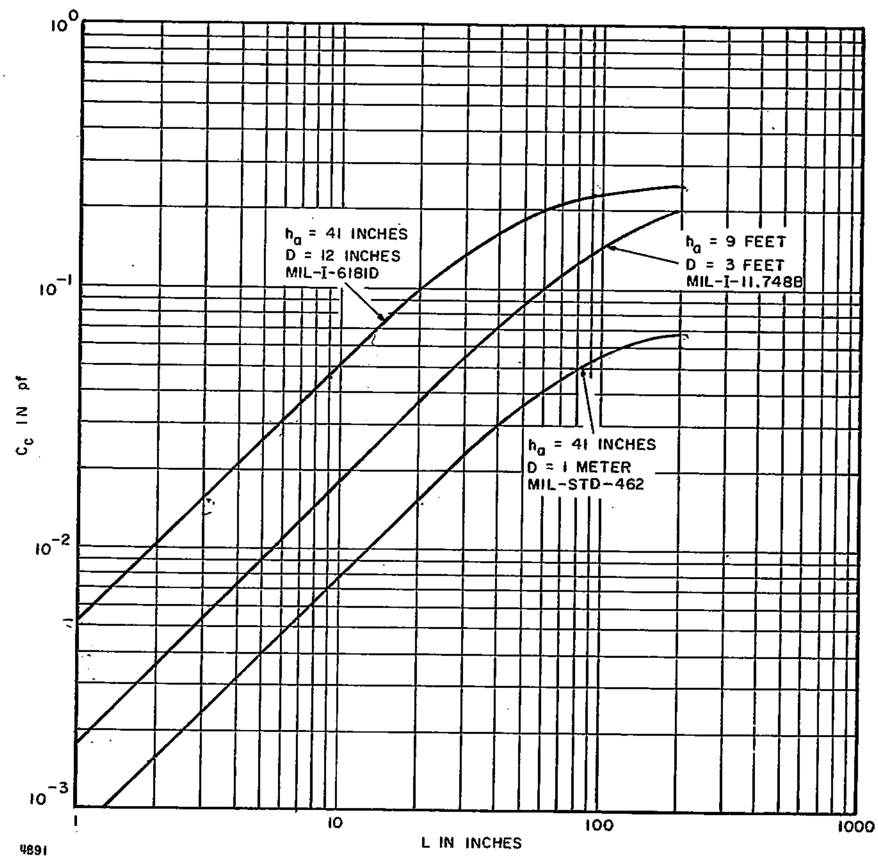


Figure 5. Mutual Capacitance Between Vertical Rod Antenna and Open Wire oh h = 2 Inches and d = 0.032 Inch)

From Figure 2, a 1-volt signal on a 48-inch long wire will induce 71 dBμV in the MIL-STD-462 radiated interference setup. From Figure 3, the height factor for h = 6 inches is +8 dB. From Figure 4, the diameter factor for d = 0.080 inch is +1.5 dB. The conversion factor to field intensity for the 41-inch rod antenna is 6 dB. The predicted measured field intensity for 1 volt on the the wire, in this example, is

$$E = 71 + 8 + 1.5 + 6 = 86.5 \text{ dB}\mu\text{V/m}$$

The MIL-STD-461 limit at 1 MHz is 26.5 dBμV/m. Since a 1-volt signal will cause the radiated interference to exceed the limit by 60 dB, the maximum permissible signal level on the open wire is 60 dB below 1 volt, or 60 dBμV.

EXAMPLE 2. RADIATED SUSCEPTIBILITY PREDICTION

Interface wire length	L = 24 inches
Height over ground plane	h = 2 inches
Wire size no. 24 AWG	d = 0.020 inch

Determine pickup on wire in radiated susceptibility tests of MIL-I-6181D; assume impedance of 100 ohms on each end of wire.

The induced interference will be calculated first for a wire diameter of 0.032 inch and a height of 2 inches, and then corrected for the actual diameter and height.

Figure 6 shows the equivalent circuit. In this figure, e_a is the voltage applied to the antenna base (0.1 V rms for MIL-I-6181D), and the terminating resistors are $R_1 = R_2 = 100$ ohms. The coupling capacitance from Figure 5 is C_c = 0.115 pF. The reactance of this coupling capacitance at frequencies below 25 MHz is much greater than the impedance of the pickup circuit. The current ccupled to the pickup circuit via this capacitance is, therefore, independent of the pickup circuit impedance and is,

$$i_c = 2\pi f C_c e_a$$

Therefore at 1 MHz

$$e_c = 50\, i_c = 3.6\mu V = 11.2 \text{ dB}\mu V$$

From Figure 3, the height correction factor is 0 dB. From Figure 4, the diameter correction factor is -0.7 dB. The net coupled voltage is then 10.5 dBμV.

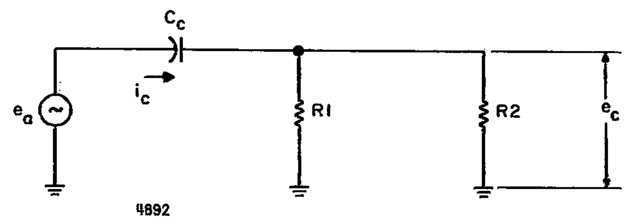


Figure 6. Equivalent Circuit for Radiated Susceptibility Analysis

DERIVATION

DIPOLE MODEL

To use a dipole model, the radiating wire and ground plane is replaced by the wire and its image as shown in Figure 7a. The separation between wires is shown as 2h, where h is the height of the wire over the ground plane. The field at any point P in space can be considered as due to a summation of fields at that point due to each differential length of line. The pair of wires can then be considered as made up of differential sections dl, as shown in Figure 7a. Figure 7b shows the equivalent differential dipole model where dQ = Qdl/L.

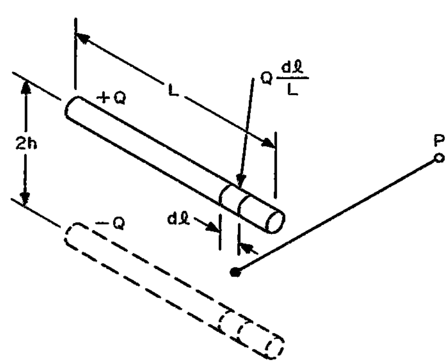
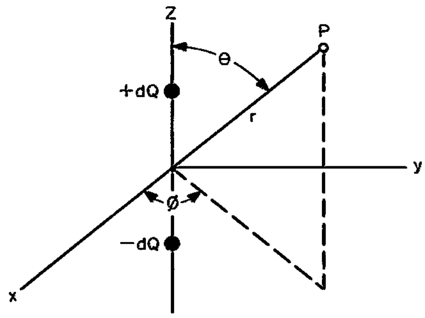


Figure 7a. Radiating Wire and Its Image



B. DIPOLE MODEL OF DIFFERENTIAL SECTION OF LINE

4893

Figure 7b. Dipole Model of Differential Section of Line

The radial and tangential electric field components are[3]

$$dE_r = dQ \frac{h}{\pi \epsilon r^3} (1 + j\beta r) \cos\theta \, \epsilon^{-j\beta r} \quad (1)$$

$$dE_\theta = dQ \frac{h}{2\pi \epsilon r^3} (1 - \beta^2 r^2 + j\beta r) \sin\theta \, \epsilon^{-j\beta r} \quad (2)$$

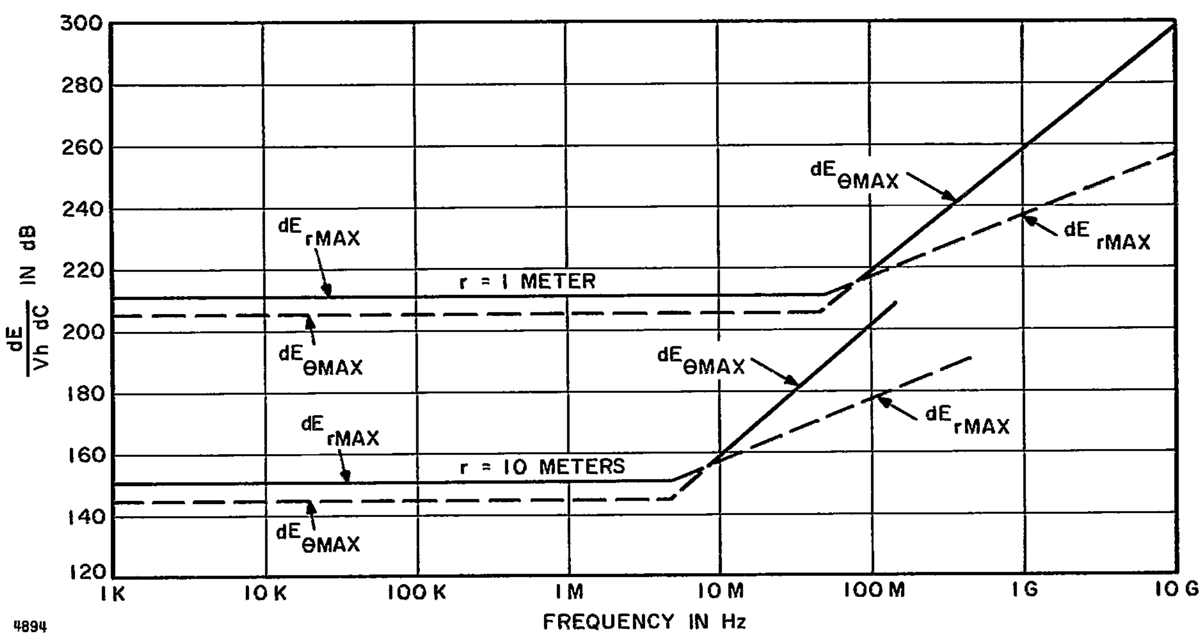
where ϵ and β are the permitivity and plane wave propagation constant of the medium in which the dipole is immersed. For free space

$$\epsilon = 8.85 \times 10^{-12}$$

$$\beta = \frac{2\pi}{\lambda} = \frac{2\pi f}{3 \times 10^8}$$

where f is the frequency in Hz.

From equations 1 and 2, dE_r is a maximum at $\theta = 0$; dE_θ is a maximum at $\theta = \pi/2$. These maxima, $dE_{r\,max}$ and $dE_{\theta\,max}$, are plotted in Figure 8 for r = 1m and r = 10m. For convenience, the fields are shown normalized to VdC rather than to dQ, where V is the voltage on the wire and C is the capacitance per unit length of the wire, both, as measured to ground. The solid lines show the maximum field level at any point, distance r from the dipole. These are equivalent to the envelopes shown by Gerry[2]. It is seen that for r less than 1 meter, $dE_{r\,max}$ and $dE_{\theta\,max}$ are independent of frequency to over 40 MHz.



4894

Figure 8. Field Intensity vs Frequency at Fixed Distance from Dipole

Because of the orientation in most test setups, the base of the antenna, which is the closest part of the antenna to the dipole, is located in the vicinity of $\theta = \pi/2$, that is, where E_θ is a maximum. Assuming P to be at $\theta = \pi/2$, and opposite the midpoint of the line at distance S, the field at P is

$$E = \int_{-L/2}^{L/2} \frac{CVhdl}{2\pi\epsilon L\left(S^2 + l^2\right)^{3/2}} \tag{3}$$

$$= \left(\frac{CVh}{2\pi\epsilon}\right)\left\{\frac{1}{S^2\left[S^2 + \left(\frac{L}{2}\right)^2\right]^{1/2}}\right\}$$

The capacitance per unit length of a wire over a ground plane is

$$C_w = \frac{24.2}{\log_{10}\frac{4h}{d}} \times 10^{-12} \text{ farads/meter} \tag{4}$$

Substituting equation 4 into equation 3

$$\frac{E}{V} = \left\{\frac{0.435Lh}{S^2\left[S^2 + \left(\frac{L}{4}\right)^2\right]^{1/2}}\right\}\left(\frac{1}{\log_{10}\frac{4h}{d}}\right) \tag{5}$$

All dimensions in the above are MKS units.

Equation 5 expresses the field intensity at a single point. Since each point on the rod is at a different distance from the wire, the field intensity will vary over its length, being stronger near its base and weaker near its top. Using the distance to the midpoint of the rod as the mean distance, * the average field intensity along the rod is

$$\frac{E_{av}}{V} = \left\{\frac{0.435Lh}{\left[D^2 + h_e^2\right]\left[D^2 + h_e^2\left(\frac{L}{4}\right)^2\right]^{1/2}}\right\}\left(\frac{1}{\log_{10}\frac{4h}{d}}\right) \tag{6}$$

where h_e is the electrical length (one-half the physical length) of the rod antenna. The open circuit induced voltage of the antenna is

$$V_{oc} = h_e E_{av} \tag{7}$$

Using E_{av} from equation 6 in equation 7, the radiated field pickup may be determined.

Because of the interdependence of the various parameters in equation 6, it is not possible to show concisely the dependence of radiation on a single parameter. That is, the variation of E_{av} with L is influenced by the particular value of h, and the variation with d is dependent on h, and so forth. However, useful information can be obtained by varying one parameter at a time while the others are fixed at some convenient median values. The convenient median values used are

$h = 2$ inches

$l = 1$ foot

$d = 0.032$ inch

The results are plotted in Figures 2, 3, and 4.

DETERMINATION OF MUTUAL CAPACITANCE

The mutual capacitance between the rod and the open wire may be determined from the known capacitance of the rod to ground, and the open circuit antenna induced voltage, by considering the arrangement as a capacitance voltage divider. The capacitance of a vertical rod to ground may be expressed as[4]

$$C_a = \frac{4\pi\epsilon h_e}{\ln\frac{4h_e}{d_a}} \tag{8}$$

where d_a is the mean diameter of the antenna.

* Here the slight difference in elevation of the base of the rod antenna relative to the ground plane beneath the wire is ignored. This difference in height is typically 4 to 6 inches in the setups treated.

For the 41-inch and 9-foot rod antennas, and using a mean rod diameter of 1/4 inch, the capacitance is 10 pF and 25 pF, respectively. The mutual capacitance is then approximately

$$C_m = C_a \frac{V_{oc}}{V} \qquad (9)$$

Equation 9 is plotted in Figure 5 for the arrangements of Figure 1. The variation of mutual capacitance with wire diameter and wire height can be obtained from Figures 3 and 4. The use of these curves in correcting for wire diameter and height are shown in example 2.

EXPERIMENTAL VERIFICATION

FREQUENCY DEPENDENCE

Figure 8 predicts no variation in radiated field intensity with frequency to over 40 MHz for distances under 1 m from the dipole. Figure 9 shows experimental verification of this frequency independence to 25 MHz. Also shown for comparison are the predicted radiated levels from Figure 2.

WIRE LENGTH

Tables 1, 2, and 3 compare the predicted dependence of radiation on wire length with measured data. The predicted and measured levels are based on a 1-volt signal on the wire, with h = 2 inches and d = 0.032 inch. The data shown in the Reference 1 column was obtained from data reported by Babcock and Sagasta[1]; their wire diameter was not reported. The comparison of theory with experiment is, in general, good. The Babcock and Sagasta data for the MIL-I-6181D setup appears conservative. This is very probably due to their use of the conservative limit of their measured values, as they reported.

WIRE HEIGHT

Table 4 compares the predicted dependence of radiation on wire height with measured data. In all measured data shown, the wire diameter was 0.032 inch. For values of h in the vicinity of 2 inches, the comparison with theory is good. For values of h either much greater or smaller than 2 inches the correlation is only fair. A limited amount of data with No. 12 AWG wire (diameter 0.080 inch) showed a similar trend. Babcock and Sagasta noted a 6 dB increase of radiation when wire height was changed from 2 to 6 inches. Figure 5 predicts an 8 dB increase for that height change.

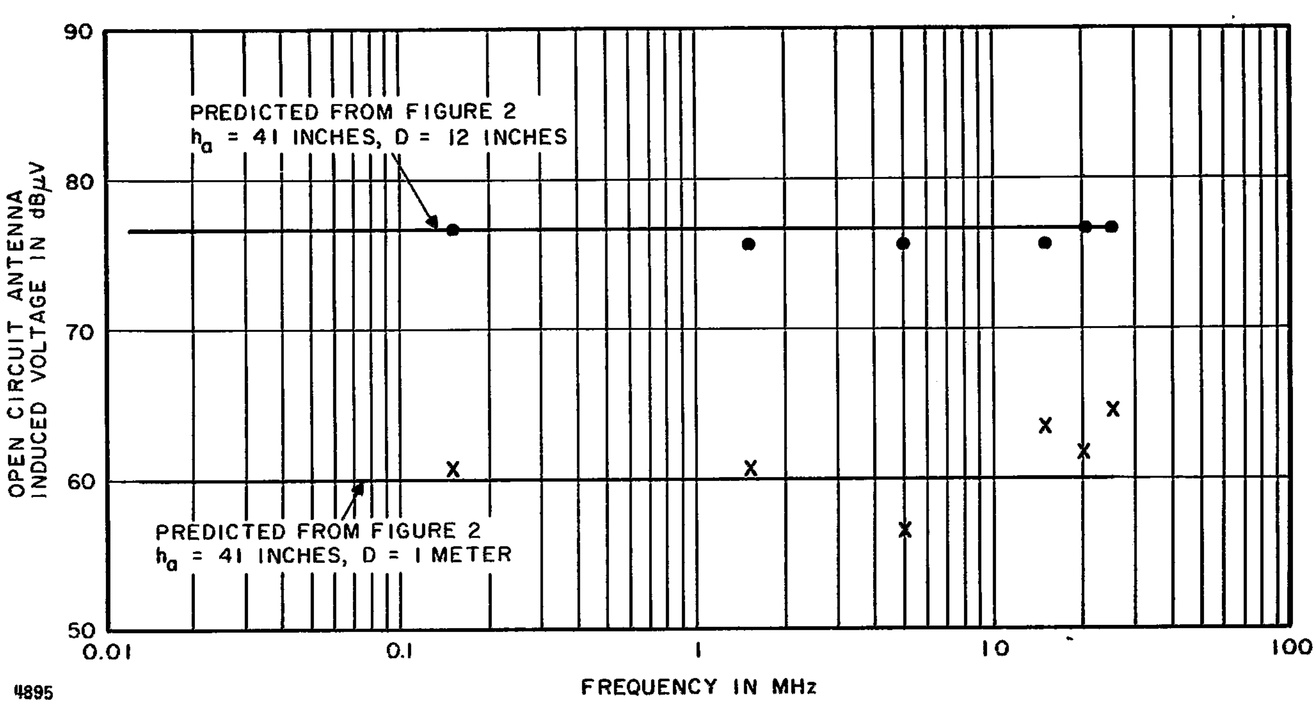


Figure 9. Radiated Interference vs Frequency - Experimental Data for 1-Volt on No. 20 AWG Wire of L = 1 Foot and h = 2 Inches

WIRE DIAMETER

Table 5 compares the predicted dependence of radiation on wire diameter with measured data. The predicted and measured dependence on wire diameter is not strong. The difference between predicted and measured values were within the limits of experimental repeatability.

CONCLUSION

The technique presented herein allows accurate quantitative prediction of radiation and susceptibility characteristics of unshielded wires in the near field of a vertical rod antenna. The technique accurately predicts the influence of the wire length, height, and diameter, and the influence of the distance to the antenna and of its height.

ACKNOWLEDGEMENT

The author wishes to express his appreciation to Mr. D. Depoian of AIL for his performance of the laboratory measurement and Mr. E. W. Karpen of AIL for his helpful comments during the preparation of this paper.

REFERENCES

1. L. F. Babcock and P. J. Sagasta, "Simplified Prediction of Conducted and Radiated Interference Levels for Pulses and Step Functions," IEEE Transactions on Electromagnetic Compatibility, Vol. EMC-8, No. 2, p. 97-101, June 1966.

2. J. R. Gerry, "A New Approach to the Prediction of Component Generated Noise," 1967 IEEE Electromagnetic Compatibility Symposium Record, p. 295-302, 1967.

3. "Electromagnetic Shielding Principles," Rensselaer Polytechnic Institute, Troy, N. Y., under Air Force Contract AF 30(602)-401, March 1, 1956.

4. Edward C. Jordan, "Electromagnetic Waves and Radiating Systems," New York, Prentice-Hall, Inc., 1950, p. 459.

Table 1. Antenna Induced Voltage vs Length of Radiating Wire--MIL-I-6181D Test Setup

Length (feet)	Predicted dBμV	Measured dBμV	Reference 1 dBμV
1	76.5	76.5	80
2	81.5	--	86
3	84.0	--	88
7-1/2	87.0	--	90
8	87.0	89.5	--

Table 2. Antenna Induced Voltage vs Length of Radiating Wire--MIL-I-11748B Test Setup

Length (feet)	Predicted dBμV	Reference 1 dBμV
1	59.0	60
2	64.5	64
3	68.0	68
7-1/2	74.5	72

Table 3. Antenna Induced Voltage vs Length of Radiating Wire--MIL-STD-462 Test Setup

Length (feet)	Predicted dBμV	Measured dBμV
1	60	56
8	75	76

Table 4. Effect of Wire Height on Radiated Interference

Wire Height (inches)	Predicted (dB)	Measured			
		MIL-I-6181D		MIL-STD-462	
		L=1 Foot (dB)	L=8 Feet (dB)	L=1 Foot (dB)	L=8 Feet (dB)
0.5	-10.5	-6	-11	-8	-10
1.0	-5.2	-4	-5	-4	-5
2.0	0	0	0	0	0
4.0	+5.0	+5	+3	+6	+3
8.0	+10.0	+9	+7	+10	+8
12.0	+13.0	+12	+9	+14	+10

Table 5. Effect of Wire Diameter on Radiated Interference. Increased Radiation Level Using No. 12 AWG Wire Instead of No. 20 AWG

Condition	dB
Predicted	1.5
Measured	
MIL-I-6181D Setup	
h = 2 inches	2.0
h = 8 inches	2.0
MIL-STD-462 Setup	
h = 2 inches	2.0
h = 8 inches	1.0