Sensor and Simulation Notes

Note 302

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MONOPOLE EMISSIONS IN A TEM CELL AND ITS RELATIONSHIP TO EMISSIONS IN FREE SPACE

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Abstract

Following the procedures developed at the University of Colorado and the National Bureau of Standards, U.S.A., the GTEM-1500 developed at BBC-KLR has been evaluated for its ability to measure the emission characteristics of electrically short monopoles. Given the fact that the design of GTEM-1500 is substantially different from the conventional NBS TEM cells, it was considered useful to do this characterization of the GTEM-1500. The usefulness of this work lies in being able to relate the emissions from an electrically small device in GTEM-1500 to free space emissions, by making use of calibration curves developed in this note.

CONTENTS

I. Introduction

Past work at the National Bureau of Standards (NBS) and the University of Colorado in the U.S. [1, 2 and 3] has established the possibility of making accurate emission measurements in TEM cells under certain specialized conditions. One such situation is when the practical device under test can be modelled by an equivalent dipole of the electric or magnetic type. The consequent restrictions are that the device dimensions as well as the cross sectional dimensions of the cell be small compared to the operating wavelength. A large device in the cell would deviate significantly from the dipole approximation in its emission characteristics, requiring higher multipole analyses.

The work done in this area at NBS consisted of measuring the emissions from an electrically short monopole into the cell and comparing the radiation resistances of the monopole in the cell with its value in free space. The present work follows along the same lines as before, while explicitely measuring and plotting coupled power in to the BBC developed TEM cell (GTEM-1500) and comparing it with calculated emissions in the cell and calculated free space emissions as well. In essence, a set calibration curves are developed for the BBC's GTEM-1500, which can relate the emission measurements in the GTEM-1500 to free space emissions for certain electrically small devices. Since GTEM-1500 differs considerably from the conventional TEM cell, it was considered useful to undertake these experimental measurements resulting in calibration curves for the GTEM-1500, following the procedure developed at NBS, USA.

In Section II, a brief description of the GTEM-1500 is presented, followed by a review of monopole emissions in free space, in Section III. Section IV compares emissions in GTEM-1500 with calculations, resulting in the required calibration curves. The report is concluded with a summarizing Section V followed by a list of references.

II. Brief Description of the TEM Cell (GTEM-1500)

A conventional TEM cell illustrated in figures 1 and 2 consists of a central rectangular metallic box with a symmetrically placed inner septum. It also has two tapering sections on either side which terminate in coaxial connectors at both ends [4]. A modification of this device consists of a vertically offset septum [5], with a view to increase the test volume available for device placement, with an associated loss of some amount of field uniformity. Both of these two-port devices are useful in measuring electromagnetic susceptibilities and, emissions under specialized conditions.

GTEM-1500 differs considerably from the conventional cell design, as may be seen in figure 3. It is essentially a one-port device with:

a) coaxial connector at the input
b) a vertically offset inner conductor
c) no central parallel region
d) no output tapering transmission line
e) an absorbing medium at the end of the input taper followed by lumped element load in specially shaped septum terminating in a back 'plate' made up of a wire mesh.

The overall dimensions are indicated in figure 4.

By examining figures 3 and 4 and comparing them with the conventional designs of figures 1 and 2, the differences become obvious. In the GTEM-1500, one has a spherical TEM mode with $E_r=H_r=0$ where r is the radial coordinate of a spherical coordinate (r,Θ,ϕ) system with its origin at the theoretical apex of the device. The angle Θ_o of the input taper is seen to be ~20°. This implies that at least to a first order approximation, the analyses available for the cell with an offset septum [5], should apply because of the relatively low value of Θ_o.

For the problem of monopole emissions at hand, it is essential that the GTEM-1500 should have acceptably good VSWR characteristics (VSWR<1.2 over the entire frequency band of interest) so that nearly all of the emitted power is coupled to the transmission line. In reality,

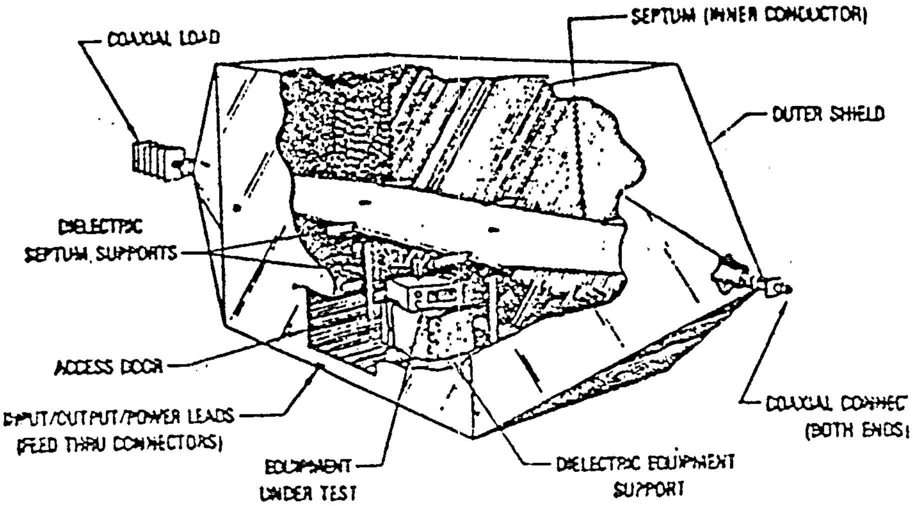


Figure 1. A conventional, symmetric TEM cell developed at the National Bureau of Standards, USA.

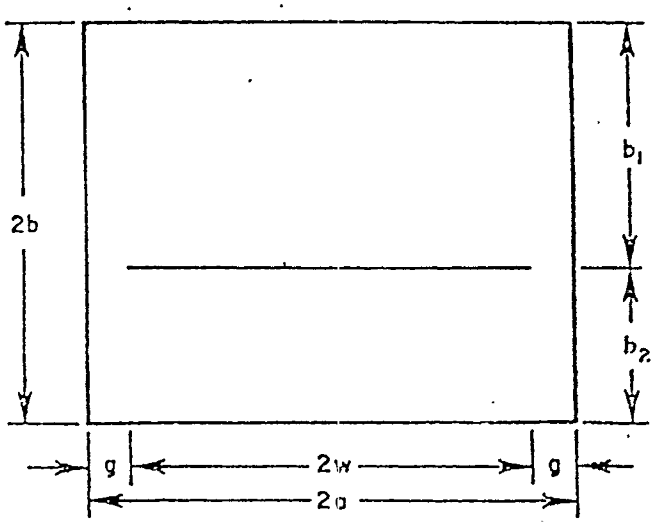


Figure 2. A modification of the above, with a vertically offset inner conductor, shown in cross section.

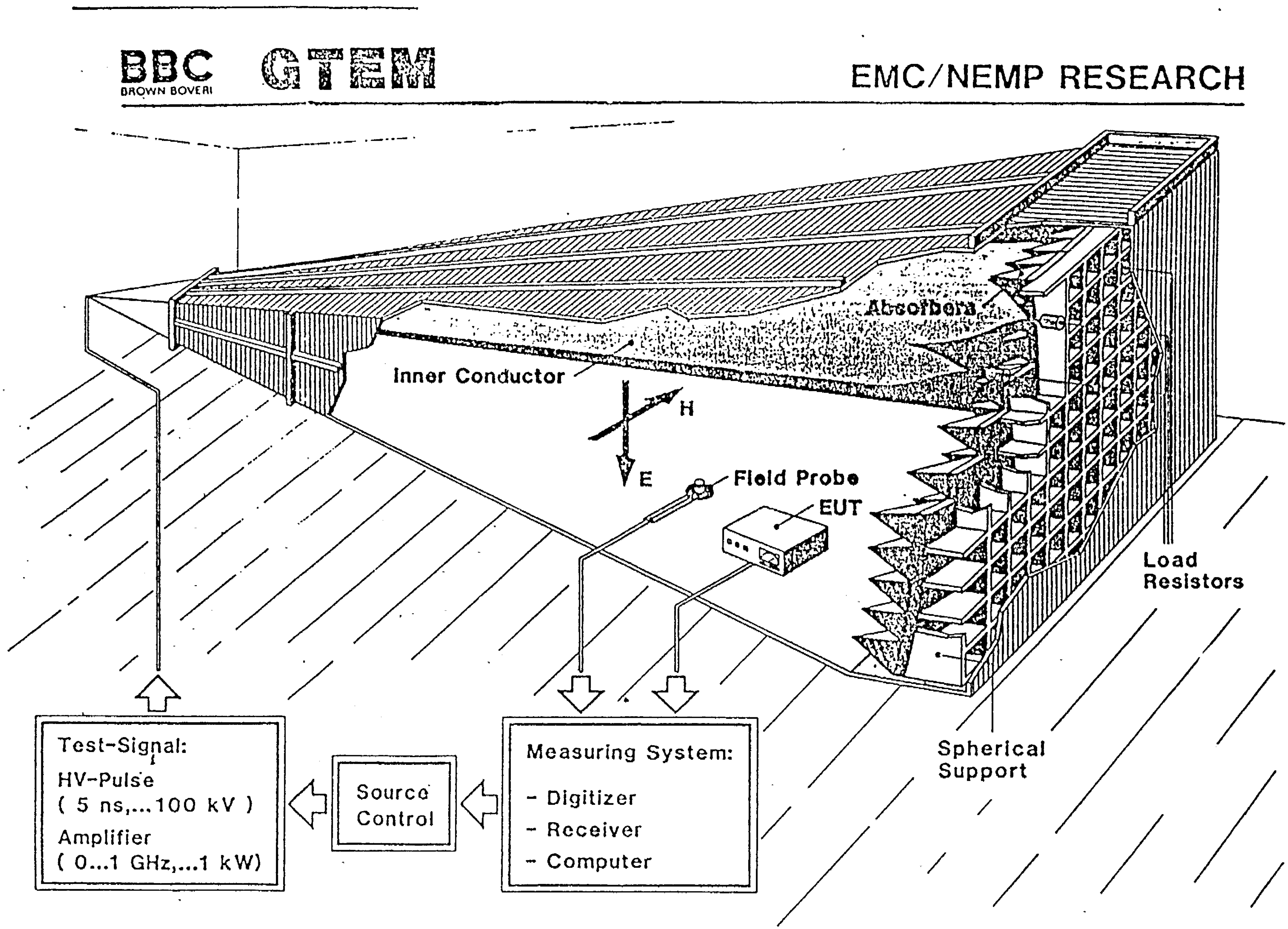


Figure 3. Schematic diagram of GTEM-1500 developed at [illegible] Research Center.

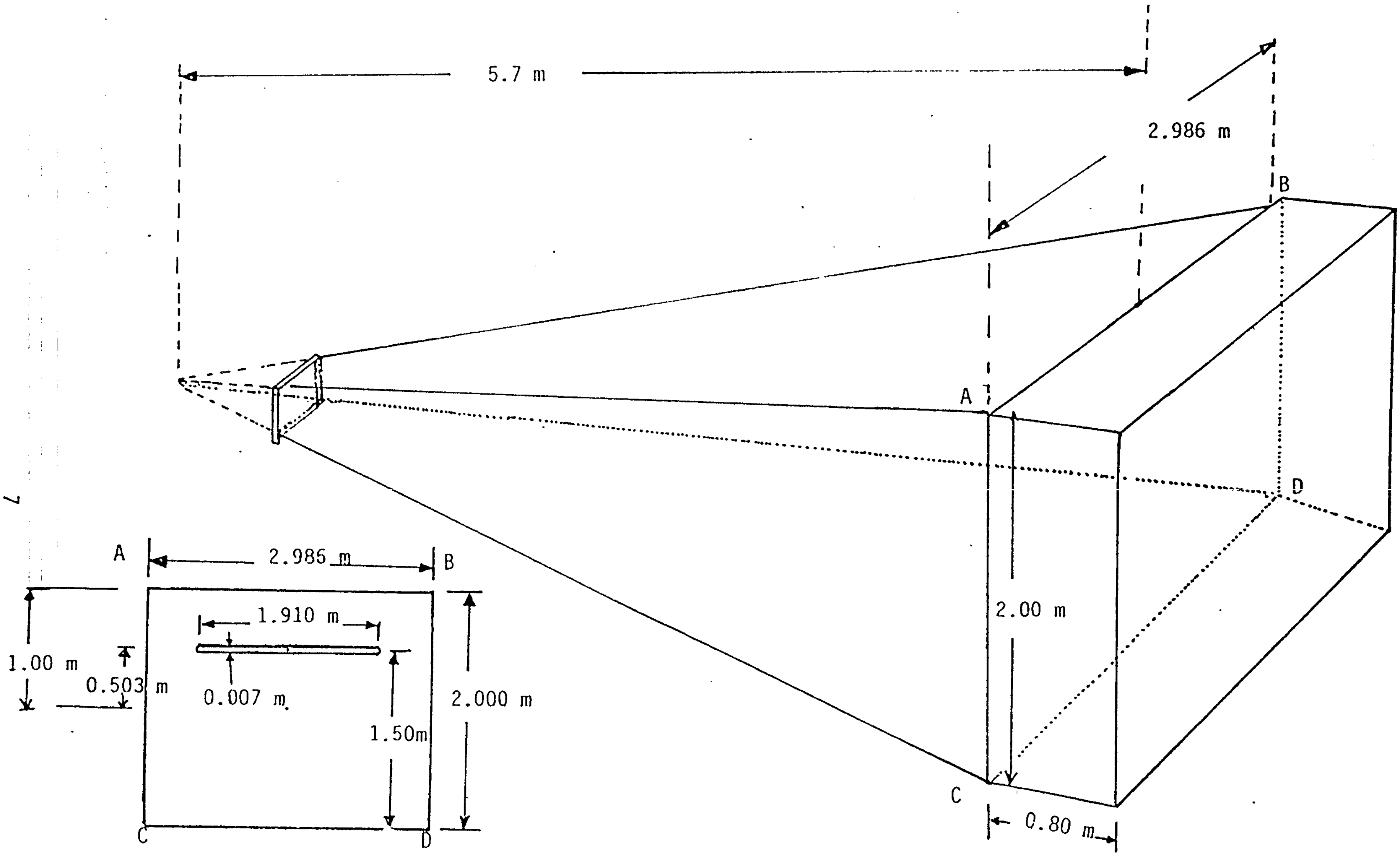


Figure 4. Approximate overall dimensions of GTEM-1500 and cross sectional dimensions at ABCD.

half the emitted power is carried to the measurement port at the input while the other half is absorbed by the terminator. The VSWR or equivalently the return loss in dB measured at the input port of GTEM-1500 prior to the emission measurements are shown in figure 5. The two curves in figure 5 are for the two cases of an empty cell and with a metallic box of about (1/3) the cross sectional dimensions and an axial length of about (1/6)th the overall length. It is observed that even in the presence of the metallic box, the return loss is better than 17 dB (~VSWR of 1.3) over a frequeny range of dc to 1 GHz. In comparison, the short monopole is of length ≅2.5 cm which will have no impact on the VSWR/ return loss of the cell. So, the VSWR of the cell with the monopole is essentially the same as that of an empty cell which is recorded in figure 5 and is acceptable for emission measurements of up to about a GHz. Although, the VSWR is acceptable even at frequencies above 1 GHz, the emission measurements were performed until 1 GHz to ensure electrically short monopole criterion for the 2.5 cm long antenna.

In the following section, a brief review of the monopole emissions in free space is presented before considering the emission measurements in the GTEM-1500.

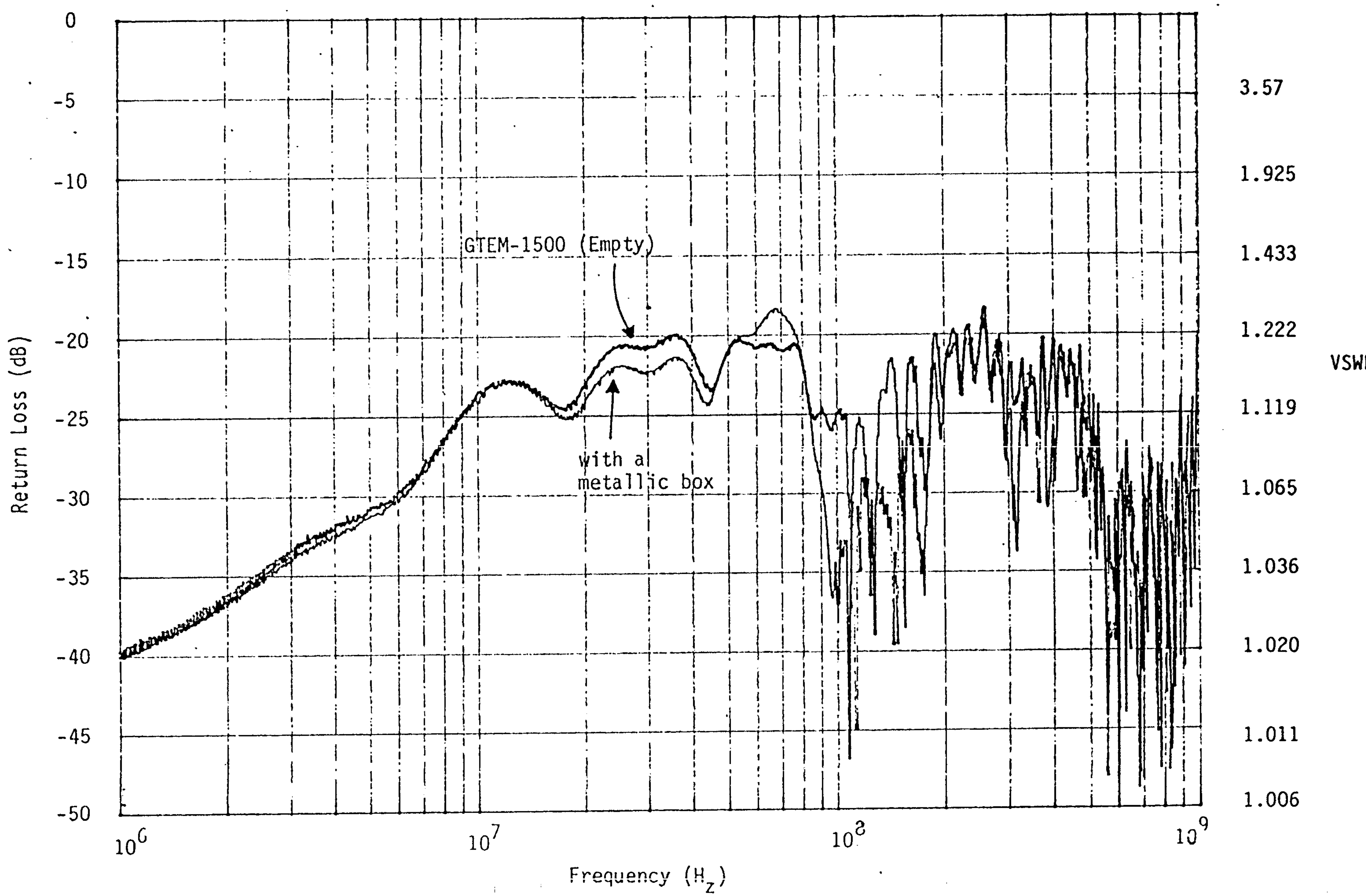


Figure 5. VSWR and Return loss in dB measured at the input port of GTEM-1500 prior to emission experiments.

III. Monopole Radiation in Free Space

The monopole geometry and its dimensions are shown in figure 6. The equivalent circuit of the generator system feeding the monopole is shown in figure 7. The monopole is 2.5 cm long and is fed by a generator set at 1 V rms output. The measurement is done over a frequency range of 1 MHz to 1 GHz. At the highest frequency of interest (1 GHz), the monopole is (2.5/30) = (1/12)th the wavelength and hence is electrically short over the entire range of frequencies. Consequently, we can approximate the antenna feed current distribution to be triangular. In other words, the antenna current I_a (amps) at the feed point goes linearly to zero at the free end of the antenna. In addition, the short monopole antenna is capacitive with an antenna capacitance of C_a, shown in figure 7. C_s is the stray capacitance in the experiment measured independently to be = 1.5 pF.

It is also observed that the voltage measured in the experiment is at Node B_1 in figure 7, where as we need voltage at Node B (i.e., across the antenna) in order to estimate the antenna current I_a from a calculated value of C_a and knowing C_s. The value of C_a is determined from the following expression

$$X_a = -\frac{1}{\omega C_a} = \left[-\frac{60\ \ln\left(1.15 \times \frac{h}{2a}\right)}{\tan\left(2\pi h/\lambda\right)}\right] \tag{1}$$

where

$$\begin{aligned}
X_a &\equiv \text{capacitive reactance of the monopole antenna } (\Omega) \\
\omega &\equiv \text{radian frequency} = 2\pi f \ \text{(radians/s)} \\
f &\equiv \text{frequency (Hz)} \\
h &\equiv \text{height of the monopole (m)} = 0.025 \text{ m} \\
a &\equiv \text{radius of the monopole (m)} = 0.0004 \text{ m} \\
\lambda &\equiv \text{operating wavelength (m)}
\end{aligned} \tag{2}$$

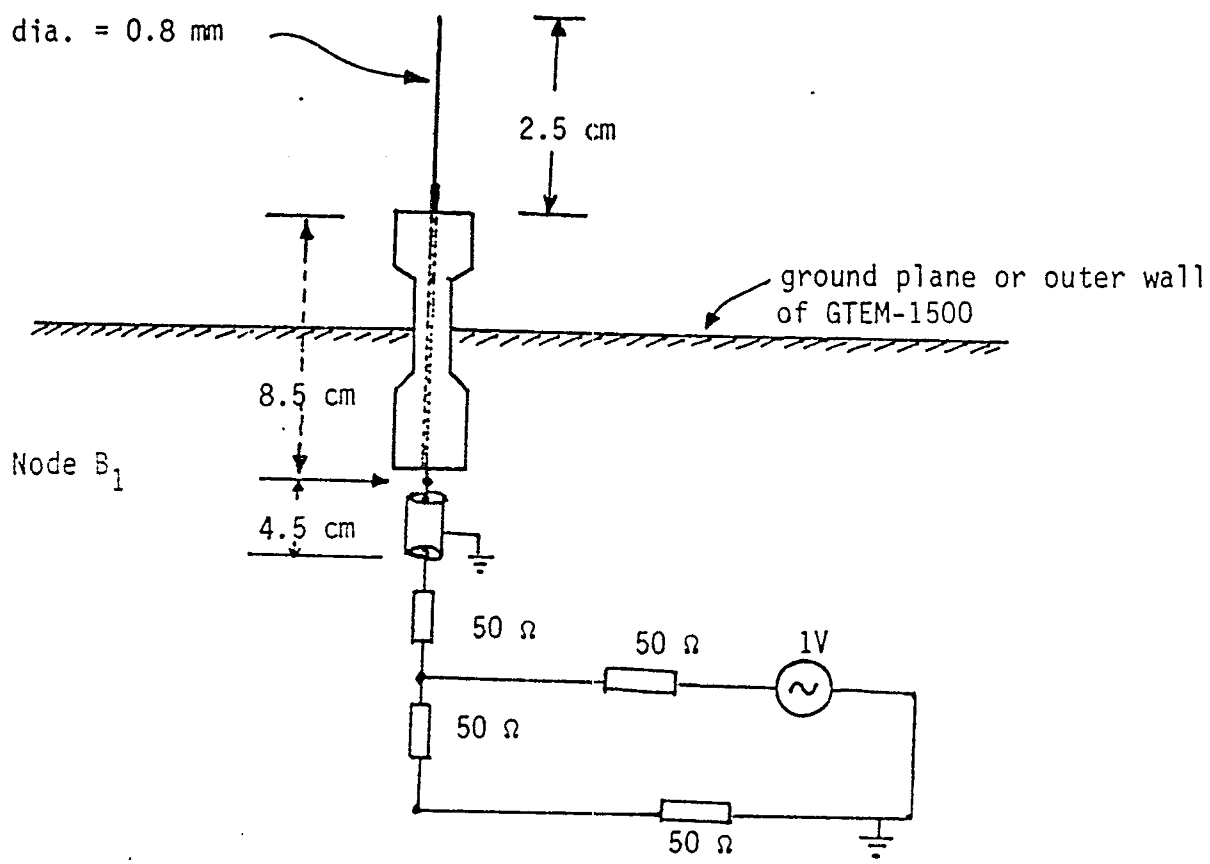


Figure 6. Geometry of the feed arrangement.

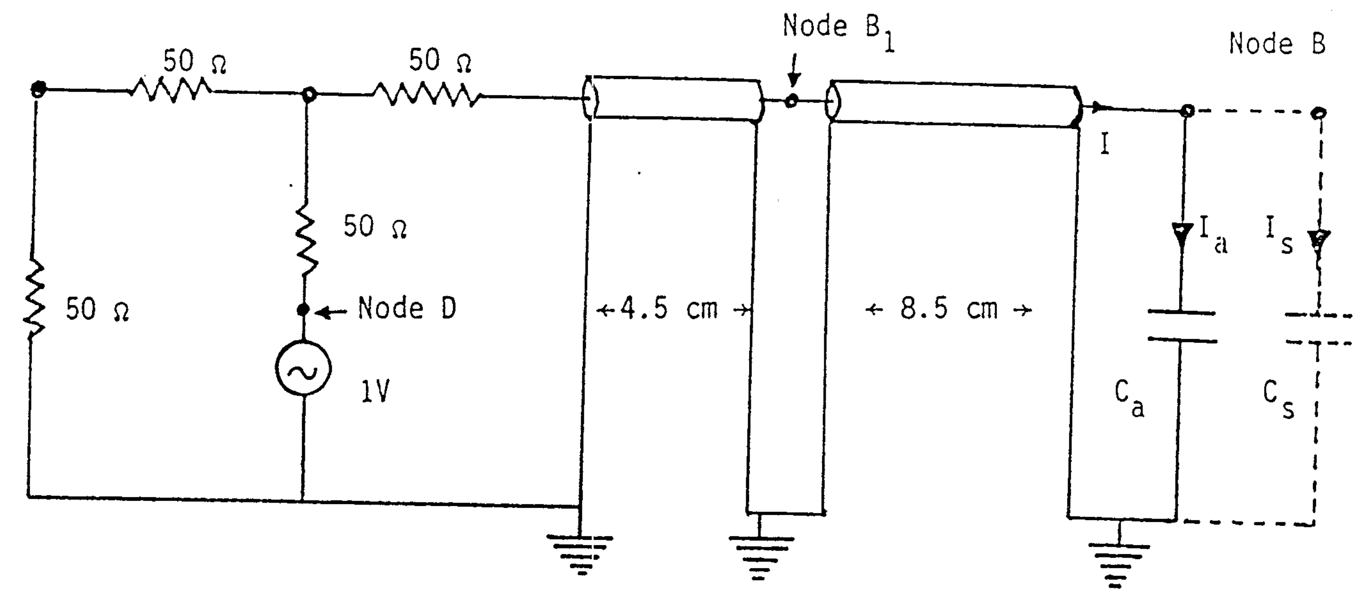


Figure 7. Equivalent circuit of the feed system.

The radiation resistance R_a of the monopole can be evaluated from [6]

$$R_a = 40 \times \pi^2 \times (\frac{h}{\lambda})^2 \tag{3}$$

Over the frequency range of interest i.e., 1 MHz to 1 GHz, the value of antenna capacitance from equation (1) is evaluated to be 0.4 pF. A measured value of antenna capacitance is 0.5 pF, resulting in the following two possibilities

$$\left.\begin{array}{llll} \text{Case 1.} & C_a = 0.4 \text{ pF} \; ; & C_s = 1.5 \text{ pF} \; ; & C_{tot} = 1.9 \text{ pF} \\ \text{Case 2.} & C_a = 0.5 \text{ pF} \; ; & C_s = 1.5 \text{ pF} \; ; & C_{tot} = 2.0 \text{ pF} \end{array}\right\} \tag{4}$$

It is also possible to compute the Node voltage B_1 using hybrid (lumped + distributed elements) circuit analysis code, Electromagnetic Transient Program (EMTP) [7] and compare it with measured voltage at node B_1. Once this comparison is established to be acceptable, then EMTP could be used to compute the antenna voltage V_a at node B. Note that all voltage,current and power quantities are rms values. The total rms current I is then given by,

$$I = V_a \, j\omega(C_a + C_s) = V \text{ (at node B)} \times j\omega(C_a + C_s)$$

$$= I_a \text{ [if the stray cap. } C_s = 0] \tag{5}$$

Once the total current is known from a knowledge of V_a, C_a, C_s and ω, the antenna current is determined from

$$I_a = I \times \left[\frac{C_a}{C_a + C_s}\right] \quad \text{amps} \tag{6}$$

$$I_a = V_a \, j\omega(C_a + C_s) \; \frac{C_a}{C_a + C_s} = V_a \, j\omega C_a \tag{7}$$

In the above expressions, V_a is the antenna voltage and is the same as the voltage at node B evaluated by EMTP. The calculation of power radiated by the monopole in free space has several steps as summarized below.

Step 1) estimate antenna capacitance C_a; use of equation (1) gave 0.4 pF while measured value is 0.5 pF

Step 2) measure stray capacitance C_s; this was found to be 1.5 pF from measurement

Step 3) measure the voltage at node B_1 since node B is inaccessible and compare with calculated voltage at node B_1 using EMTP code

Step 4) step 3 should validate the values of C_a and C_s

Step 5) using EMTP, compute the node voltage at B, which is the same as V_a

Step 6) estimate the rms antenna current using

$$I_a = \left[\frac{V_a}{j X_a} \right] = V_a \, (j\omega C_a) \tag{8}$$

Step 7) Power radiated P_a by the monopole in free space is then given by

$$P_a = |I_a|^2 \; R_a = \left| \frac{V_a}{X_a} \right|^2 R_a$$

$$= (\omega C_a |V_a|)^2 \; R_a \quad \text{watts} \tag{9}$$

$$P_a \text{ (in dBm)} = 10 \, \ell og_{10}(P_a \times 10^3) \tag{10}$$

Let us carry out the above outlined steps for our cases.

Step 1) $C_a = 0.4$ pF from equation (1)

$C_a = 0.5$ pF from measurement

Step 2) $C_s = 1.5$ pF from measurement

$\rightarrow C_t = C_a + C_s = 1.9$ pF or 2 pF

Step 3) $(C_a + C_s)$ is varied, taking values of 1 pF, 2 pF and 3 pF; the measured voltage at node B_1 is compared in phase and magnitude with calculated voltage at node B_1 in figure 8, 9 and 10; it is observed that a total capacitance of 2 pF yields the best fit, of the three values considered. The results of figure 9 with C_a=0.5 pF and C_s=1.5 pF led us to obtain good agreement between measured and calculated powers, as is seen later in this report.

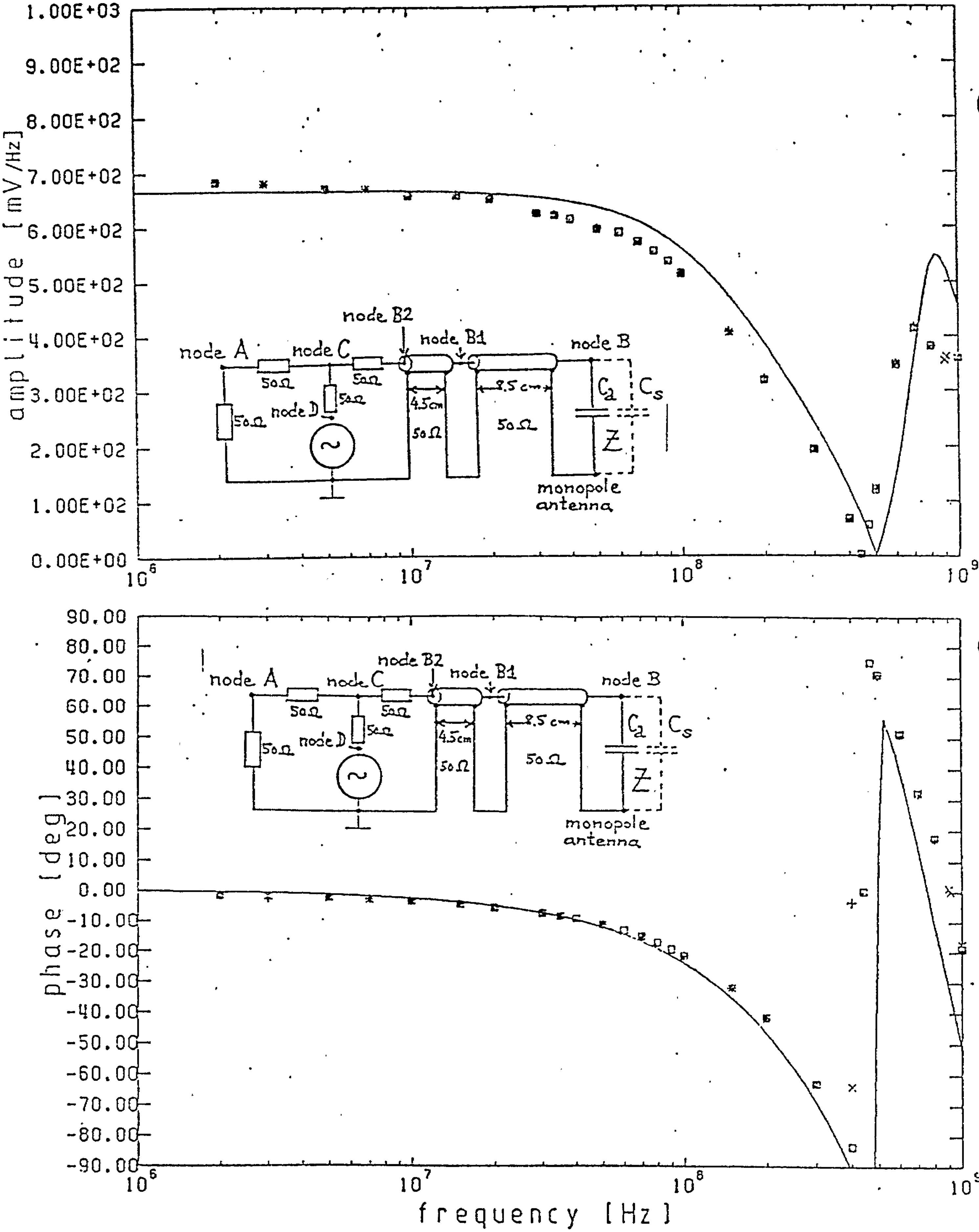


Figure 8. Amplitude and phase of voltage at Node B_1.

———————— calculated; ▫ ▫ ▫ measured; $(C_a + C_s) = 1$ pF

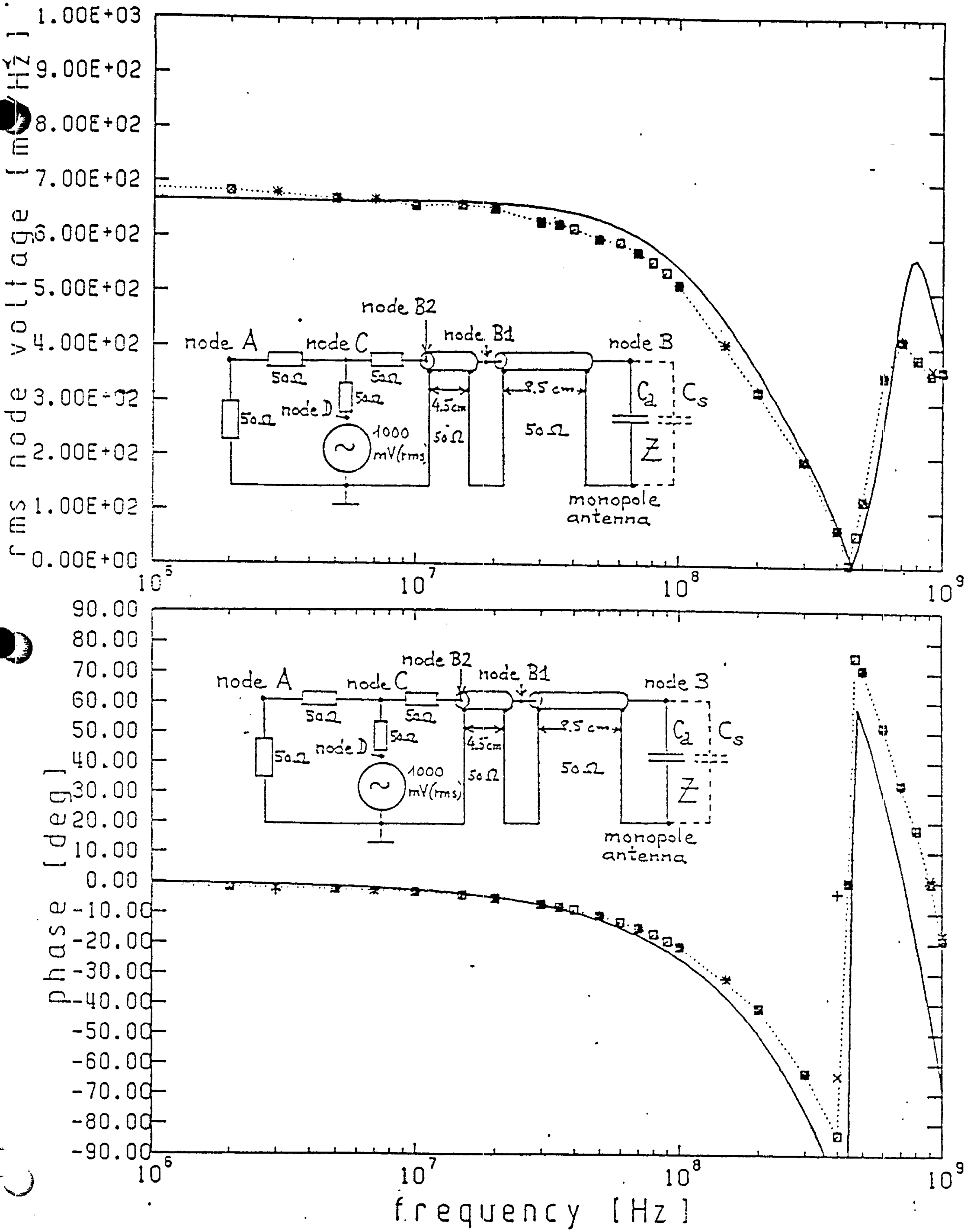


Figure 9. Magnitude and phase of rms voltage at node B1.
———— calculated; □ ■ × + measured; C_a=0.5pF, C_s=1.5pF(best fit)

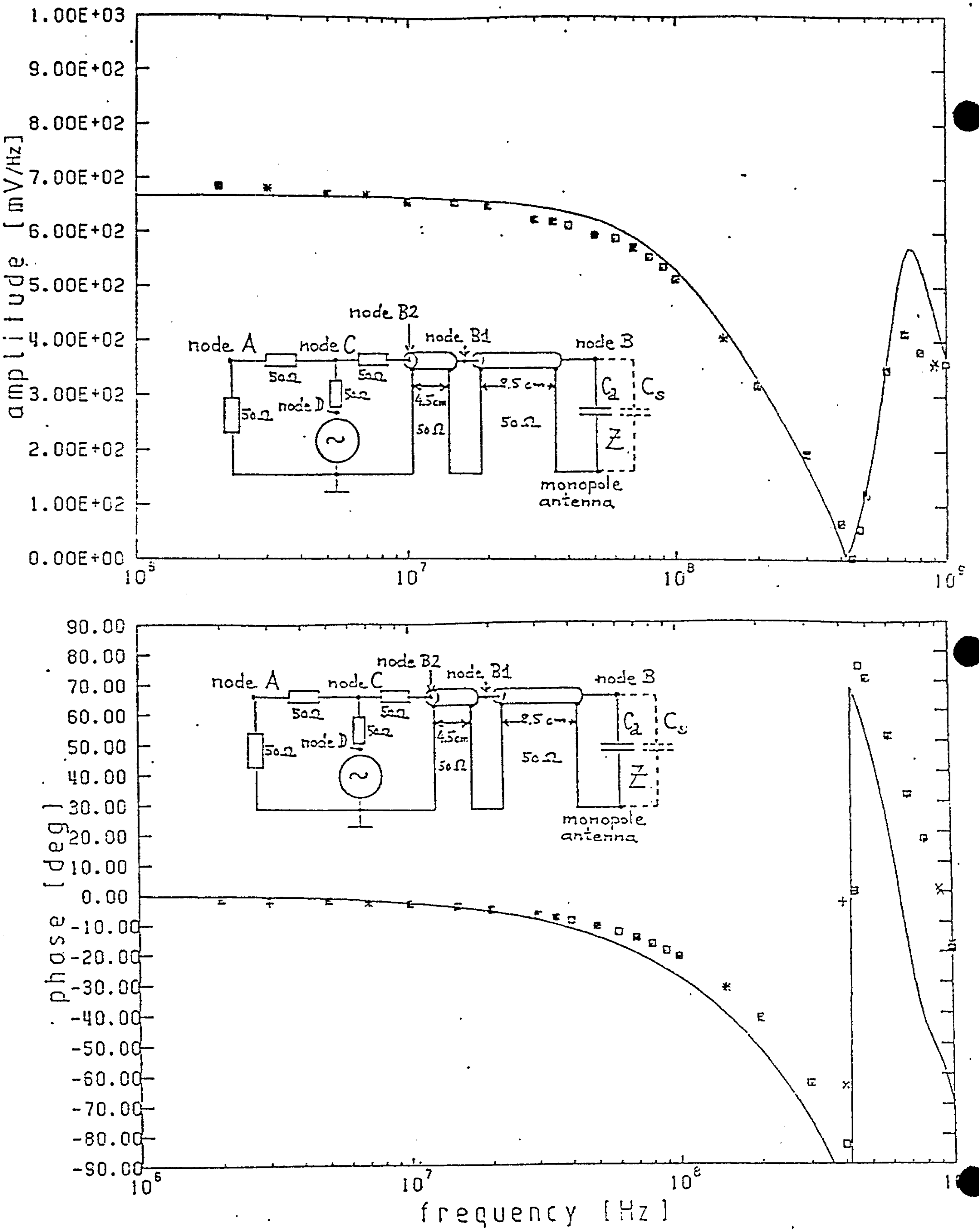
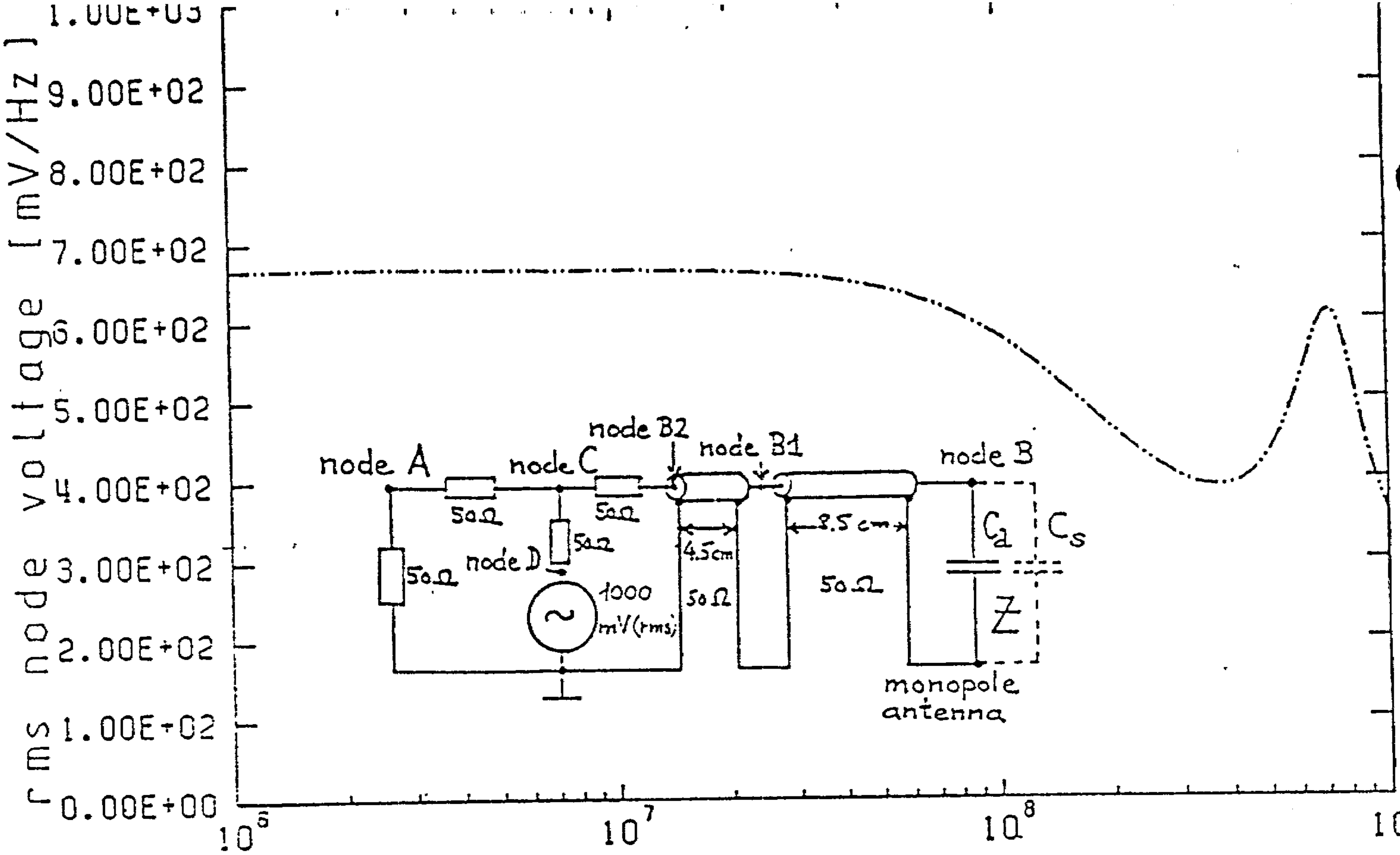


Figure 10, Amplitude and phase of voltage at Node B_1. ________ calculated; ▫ ▫ ▫ measured; $(C_a + C_s) = 3$ pF

Step 4) using EMTP, the antenna voltage is computed and shown in figure 11, for the case of C_t = 2 pF

Step 5,6 and 7) the power radiated by the monopole in free sapce is evaluated using equations (8), (9) and (10), and shown plotted in figure 12.

In concluding this section, it is observed that we now have the power radiated by the monopole antenna in free space, which may later be compared with coupled power into the cell, if the monopole was located at selected positions in the cell. This forms the subject for the next section.



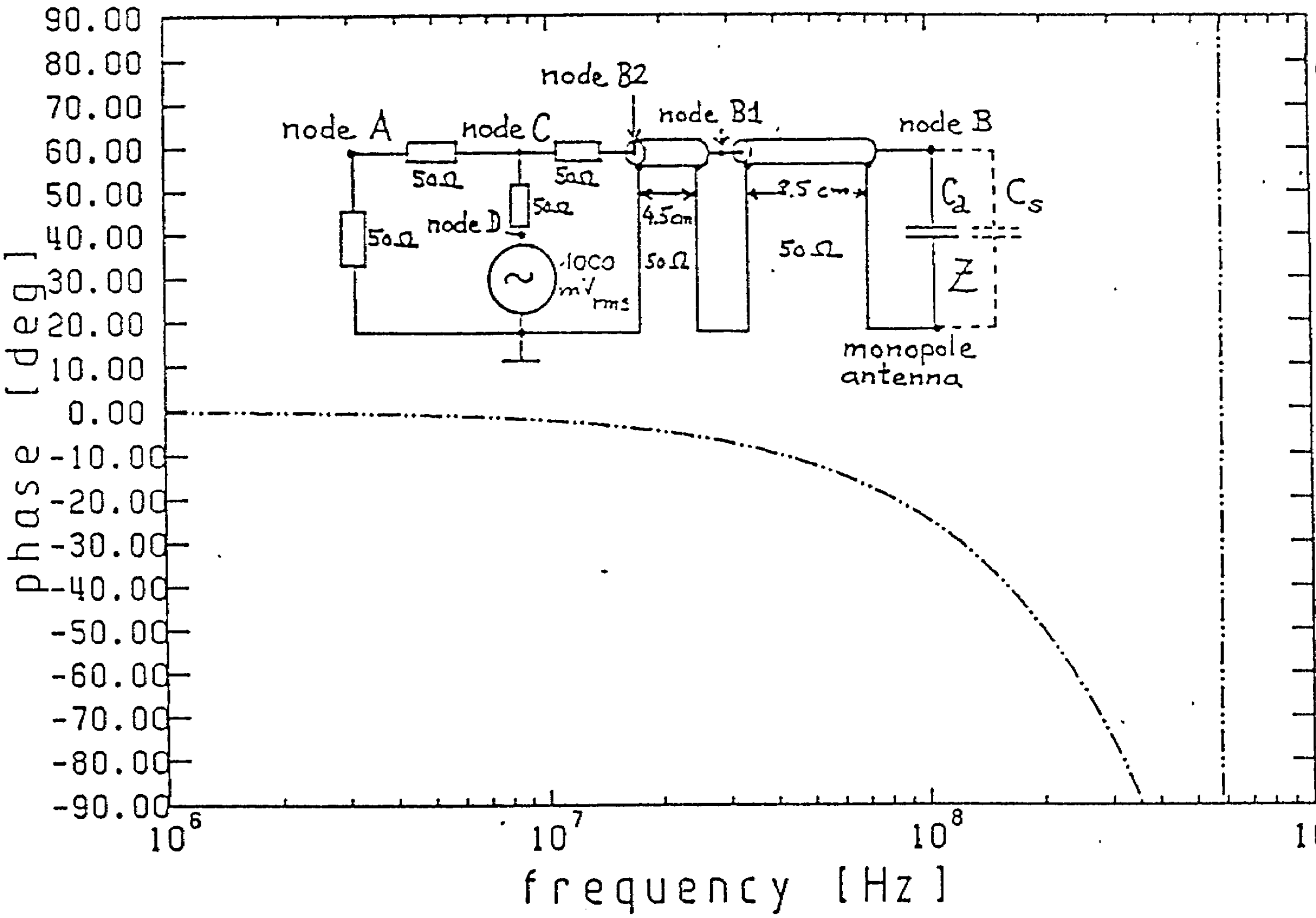


Figure 11. Calculated rms voltage (magnitude and phase) at node B, which is the same as rms antenna voltage V_a, with C_a=0.5pF; C_s= 1.5pF

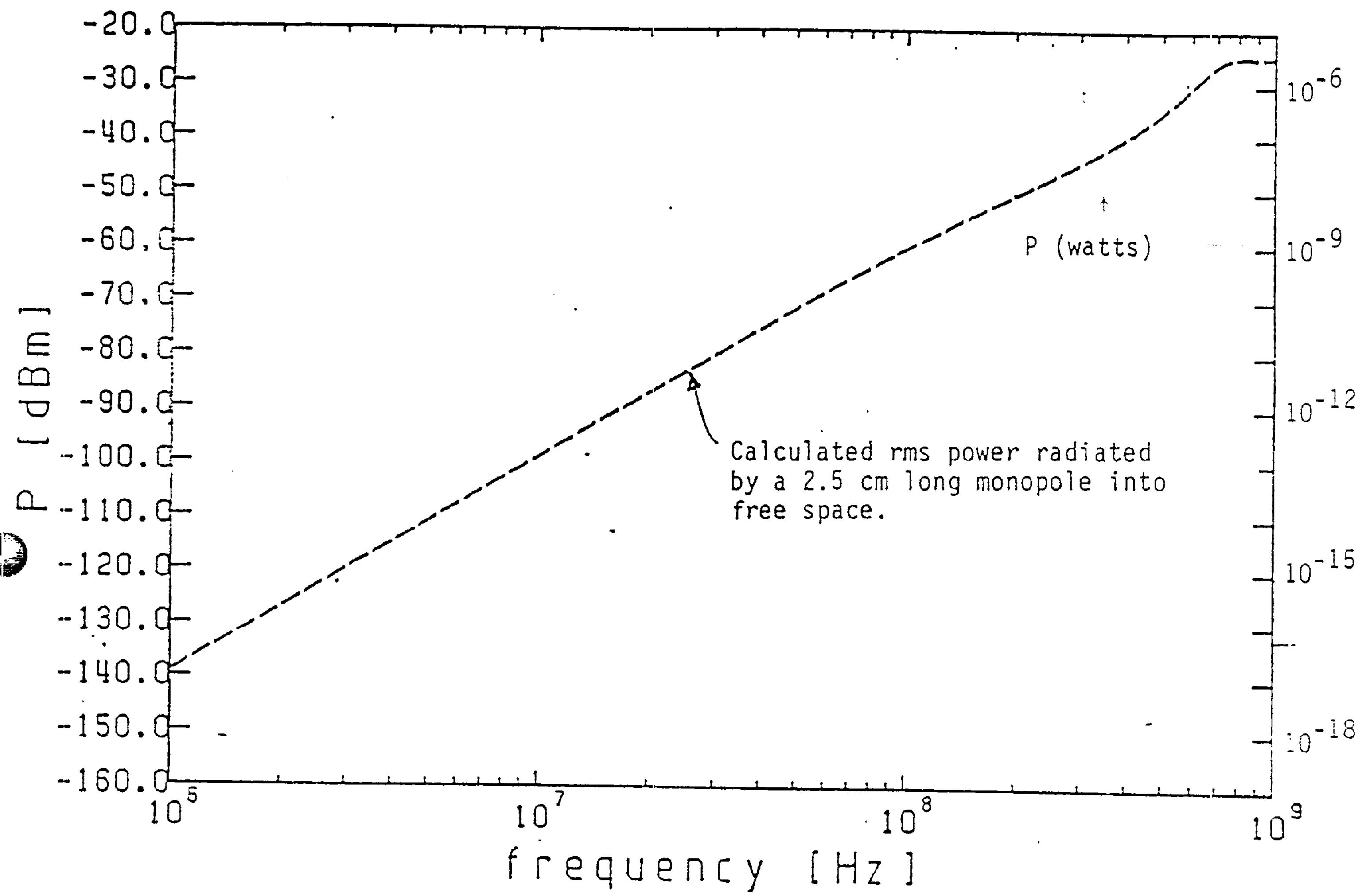


Figure 12. Rms power radiated by a 2.5 cm long monopole antenna in free space, while driven by a generator shown in figure 7.

Note: $C_a = 0.5$ pF ; $C_s = 1.5$ pF

IV. Monopole Radiation in the TEM Cell (GTEM-1500) in Comparison with Free Space Radiation

When the monopole is inserted in the TEM cell as indicated by the photograph in figure 13, it couples power into the cell which is assumed to flow equally towards the input port and load. This coupled power measured at the input port is then given by

$$P_{ci}(f) = (1/2) \left| I_a(f) \right|^2 R_i \qquad (11)$$

The factor of (1/2) accounts for half the coupled power flowing toward the load and absorbed by it. The antenna current $I_a(f)$ is determined as discussed in the preceding section. The radiation resistance of the monopole in the cell depends on the location of the monopole in the cell and how well the power is coupled to the TEM mode of propagation. Three locations, nearly the same as in [2, 3] are considered. These locations are indicated in the cross sectional diagram of figure 14. The radiation resistance R_i at various positions is given by [2, 3]

$$R_i = \frac{Z_o}{4} \left[\frac{h}{b_1} \left\{ \frac{E_o}{(V/b_1)} \right\}_i \cos(\Theta_i) \right]^2 \qquad (12)$$

where

Z_o ≡ characteristic impedance of the TEM modein the cell = 50 Ω

h ≡ height of the monopole = 0.025 m

b_1 ≡ height of the inner septum from the outer conductor, on the side where monopoles are located (see figure 14)

i ≡ index to denote the location of monopole called positions A, B and C

Θ_i ≡ angle between the monopole axis and the local electric field of the TEM mode, which could vary over the length of the monopole; however, for the case of 2.5 cm monopole, Θ_i is ≅ 0 at all three positions over the length of the monopole.

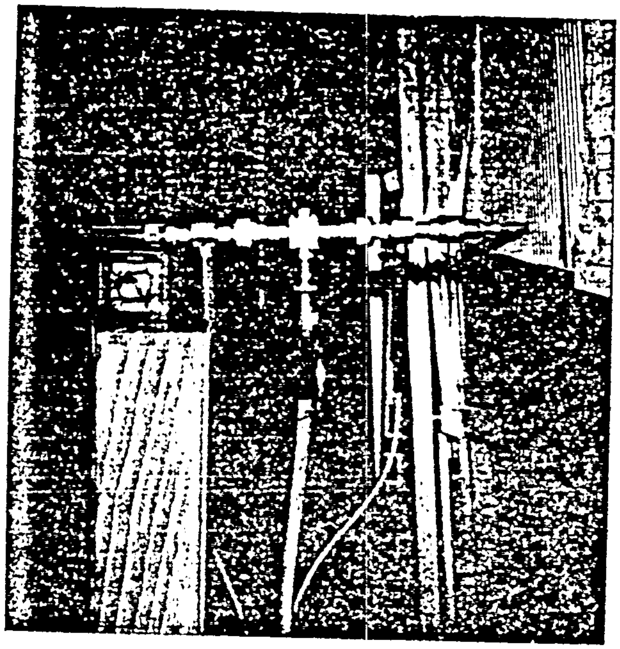


Figure 13. Monopole antenna (2.5 cm long) inserted into GTEM-1500 at position C.

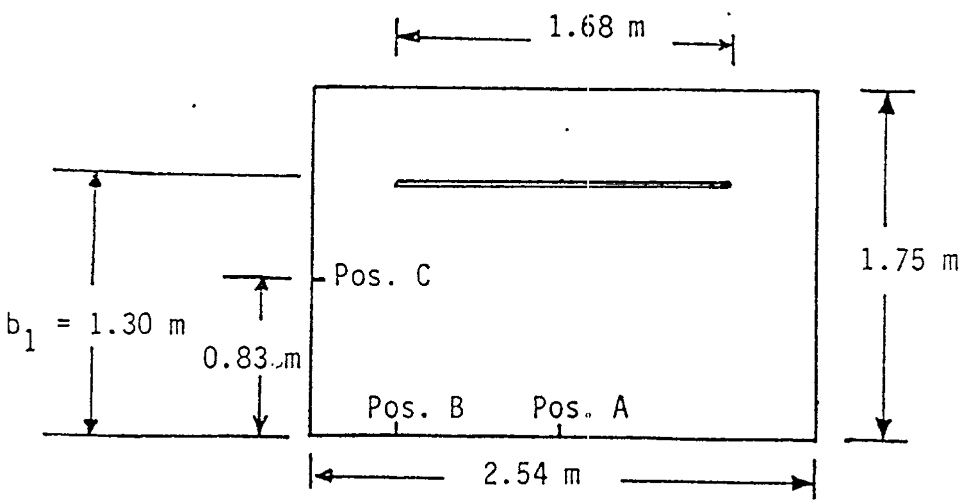


Figure 14. The three positions of the monopole antenna in GTEM-1500.

$\left\{\frac{E_o}{(V/b)}\right\}_i$ ≡ position dependent field factor indicating the variation of the field relative to the average field

For the three positions A, B, C indicated in figure 13, the radiation resistances are computed. The intermediate results are shown in Table 1. The radiation resistances are plotted in figure 15 in comparison with the monopole's radiation resistance in free space.

Knowing the current in the monopole I_a and the radiation resistance R_i at various positions, equation (11) can be used to determine the coupled power. Expressed in dBm, the coupled power is given by

$$P_{ci} \text{ (in dBm)} = 10 \log_{10}(P_{ci} \times 10^3)$$
$$= 10 \log_{10}\left[\frac{10^3}{2}|I_a(f)|^2 R_i\right] \qquad (13)$$

This power has been measured experimentally and compared with calculations. Recalling that, in the determination of I_a, we had a choice of C_a = 0.4 pF (calculated) or C_a = 0.5 pF (measured), both values were used. It was determined that using C_a = 0.5 pF resulted in better agreement with the measurements. The comparison of calculated and measured coupled power into GTEM at positions A, B and C are shown in figures 16, 17 and 18 respectively.

It is observed that the difference between the theory and experiment is typically between 0.5-2.5 dBm in coupled power at the input. The usefulness of figures 16, 17 and 18 lie in being able to relate the measured power in the cell to the free space emission of monopoles (dipoles by equivalence). In other words, when the device has dimensions small compared to wavelength and the cross sectional dimensions (typically 3 times the device dimensions) are also small compared to wavelength, the device radiation (at low frequencies) can be modeled by dipoles of electric and magnetic type and quantified.

TABLE 1 Radiation resistance of the monopole in GTEM-1500

i	$\left\{\frac{E}{(V/b_1)}\right\}_i$	Θ_i	h	b_1	R_i
Position A	0.766	0	0.025 m	1.30 m	0.003 Ω
Position B	0.437	0	0.025 m	1.30 m	0.001 Ω
Postiion C	1.064	0	0.025 m	1.30 m	0.005 Ω

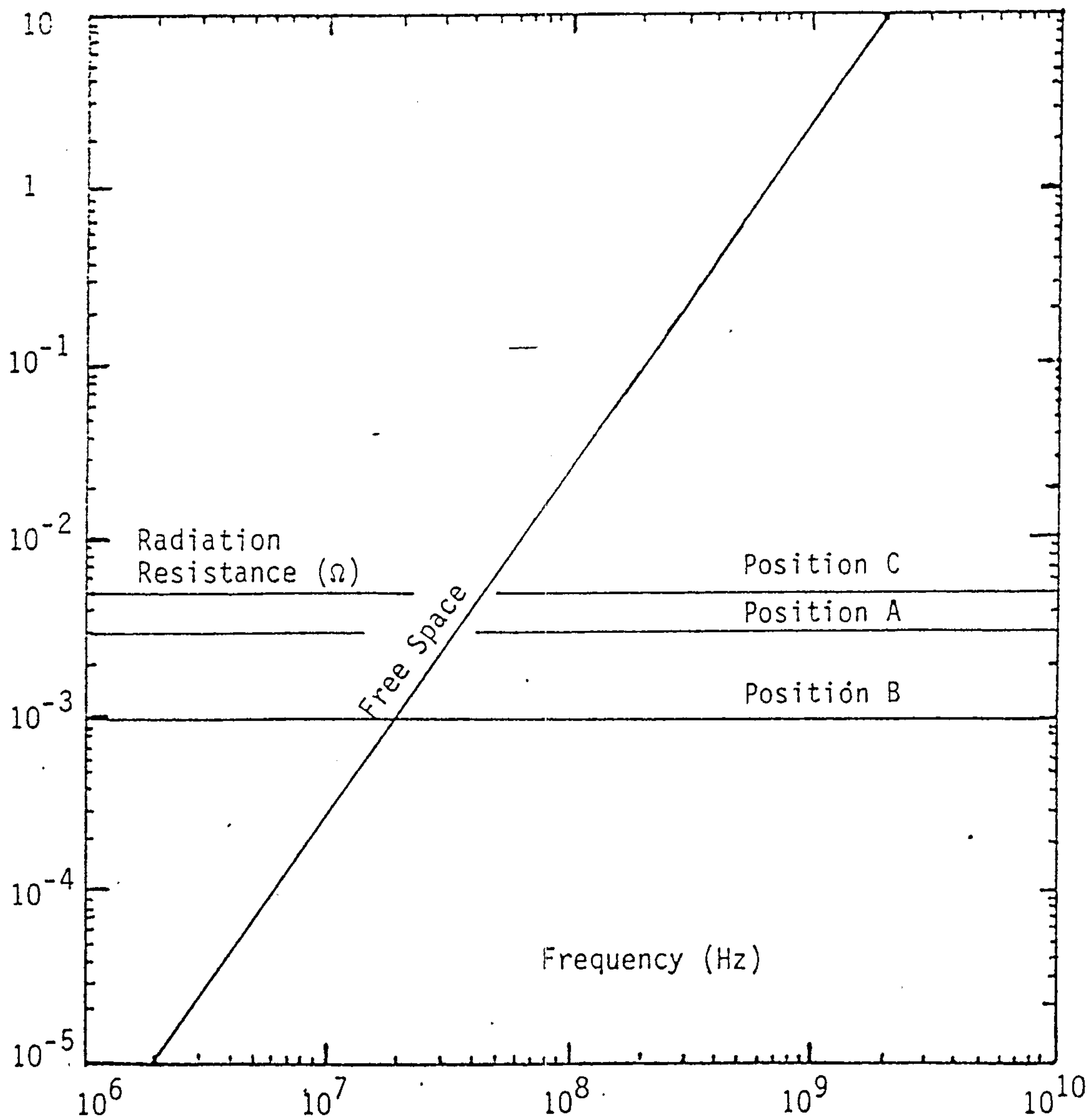


Figure 15. Radiation resistance of the 2.5 cm long monopole in free space and three positions in GTEM-1500.

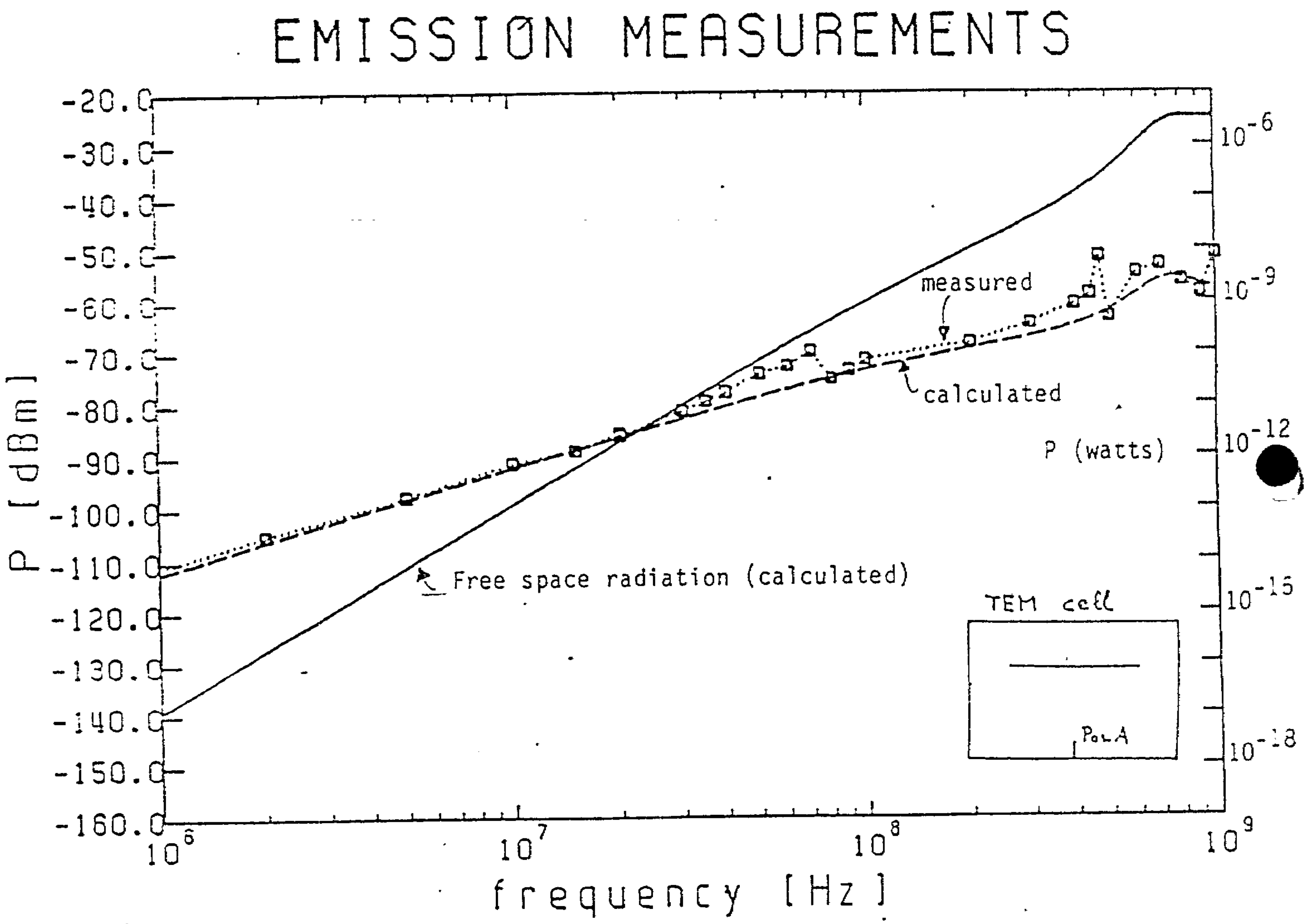


Figure 16. Coupled power at the input terminal of GTEM-1500 with a 2.5 cm monopole radiating at position A.

Note : C_a = 0.5 pF and C_s = 1.5 pF

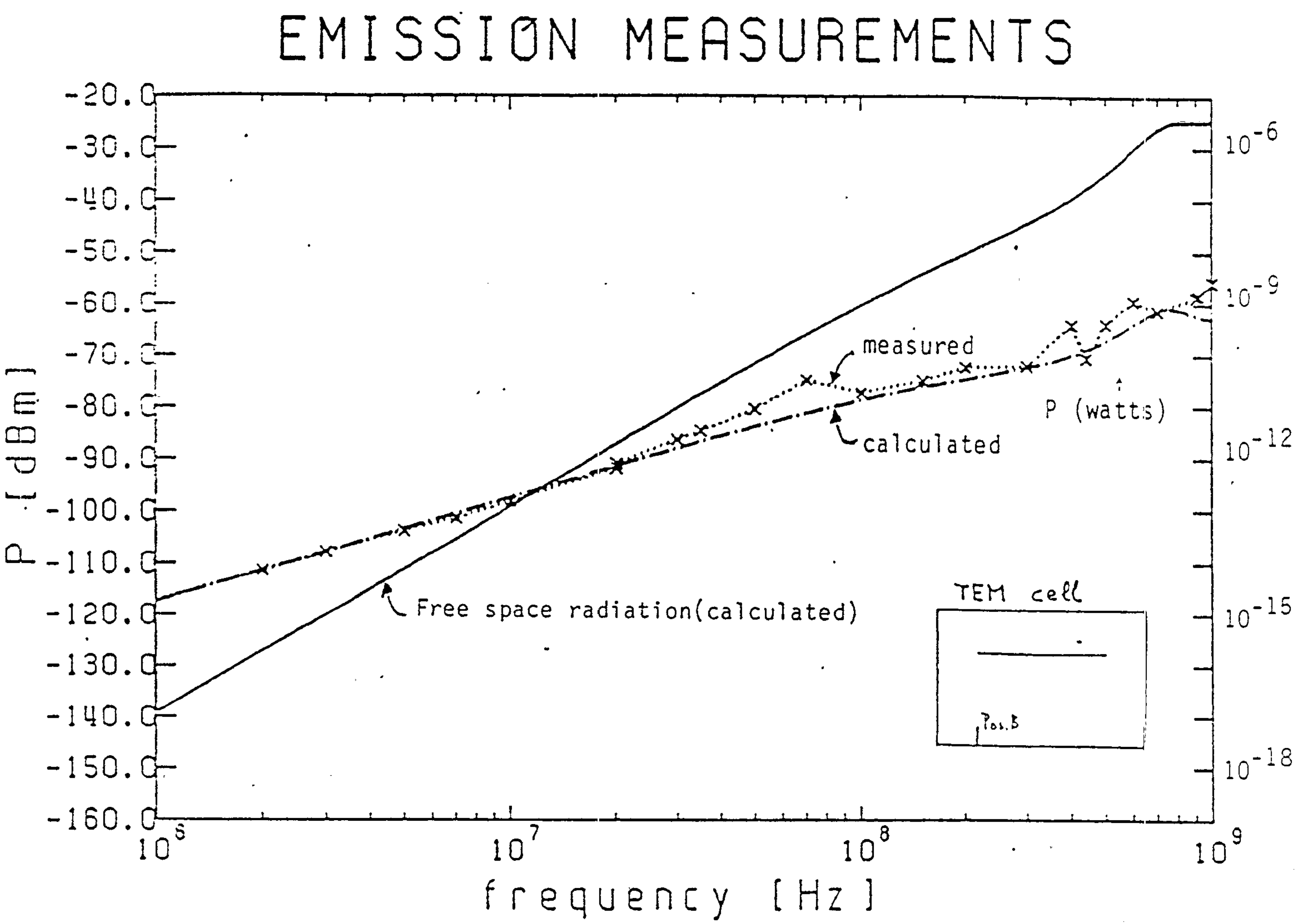


Figure 17. Coupled power at the input terminal of GTEM-1500 with a 2.5 cm monopole radiating at position B.

Note : C_a = 0.5 pF and C_s = 1.5 pF.

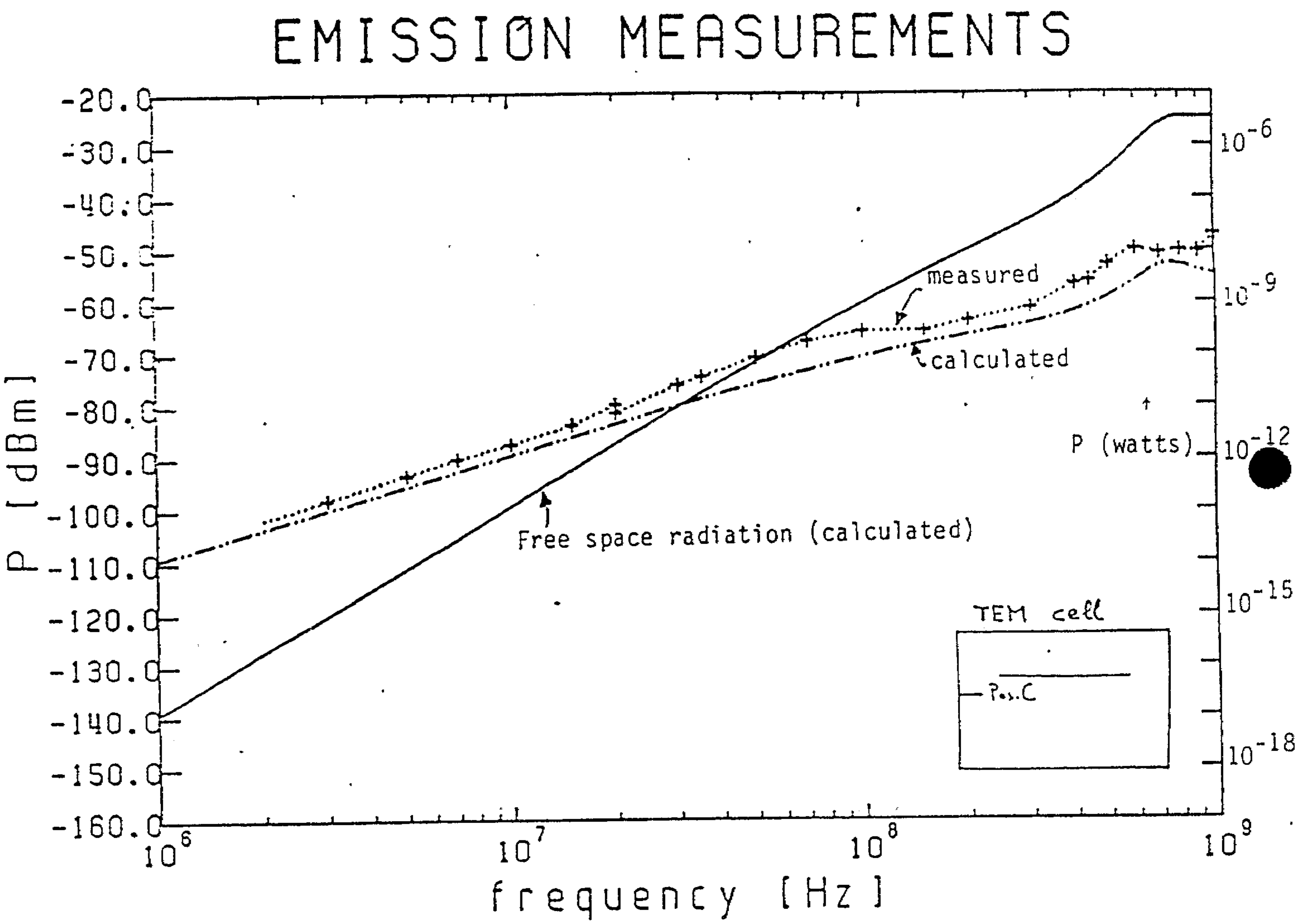


Figure 18. Coupled power at the input terminal of GTEM-1500 with a 2.5 cm monopole radiating at position C.

Note: C_a = 0.5 pF and C_s = 1.5 pF

References

1. J.C. Tippet and D.C. Chang, "Radiation Characteristics of Electrically Small Devices in a TEM Transmission Cell", IEEE Transactions on Electromagnetic Compatibility, Vol. EMC-18, No. 4, pp 134-140, November 1976

2. J.C.Tippet, " Modal Characteristics of Rectangular Coaxial Transmission Line", Ph.D. Dissertation, University of Colorado, Boulder 1978.

3. M.L. Crawford, "Experimental Evaluations of the Radiation Chracteristics of Dipole Sources Enclosed in a TEM Transmission Cell", NBS Report (obtainable from the author)

4. M.L. Crawford, J.L. Workman and C.L. Thomas, "Expanding the Bandwidth of TEM Cells for EMC Measurements", IEEE Transactions on Electromagnetic Compatibility, Vol. EMC-20, No. 3, pp 368-375, August 1978

5. J.C. Tippet and D.C. Chang, "Characteristics Impedance of a Rectangular Coaxial Line with Offset Inner Conductor", IEEE Transactions on Microwave Theory and Techniques, Vol. MTT-26, pp 876-883, November 1978

6. S. Ramo, J.R. Whinnery and T. van Duzer, "Fields and Waves in Communication Electronics, second edition, John Wiley & Sons, 1984

7. EMTP (Electromagnetic Transients Program), Rule Book (version 43), Methods Development Branch, Division of System Engineering, Bonneville Power Administration, P.O. Box 3621, Portland, Oregon 97208