Progress In Electromagnetics Research, PIER 62, 127–142, 2006

PERFORMANCE ANALYSIS OF EMI SENSOR IN DIFFERENT TEST SITES WITH DIFFERENT WAVE IMPEDANCES

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Abstract—Electromagnetic Interference (EMI) is becoming a crucial issue in the era of modern electronic systems. For EMI measurement, it is required to place a sensor to receive the radiation from the equipment in a suitable test environment. The performance of the sensor depends on its Antenna Factor, which is the ratio of the incident electric field on the antenna surface to the received voltage at the load end. Here, a Method of Moment-based numerical technique has been used to evaluate the performance of a sensor in different test environments with different wave impedances. The evaluation of the sensor has been performed in terms of the Antenna Factor. The results are presented for free space environment of impedance 377Ω and Gigahertz Transverse Electromagnetic (GTEM) Cell of characteristic impedance 50Ω. The results show well agreement with experimental data.

1. INTRODUCTION

The use of electronic equipment has grown steadily in our day to day life to sophisticated military and spacecraft technologies. To avoid the electromagnetic interference (EMI) and related hazards, stringent electromagnetic compatibility (EMC) testing of the electronic devices is necessary. Suitable test environment (e.g., Open Area Test Site (OATS), anechoic chamber, Gigahertz Transverse Electromagnetic (GTEM) Cell) is required to perform the testing. The compliance of the devices conforming to the standards of interference is tested by measuring the radiated electric field due to any electronic equipment using the sensor. Accurate measurements in any field require accurately calibrated equipment. When measuring radiated signals, the front end of the measurement system is the sensor. The characteristic of the sensor is determined by its Antenna Factor. The ratio of the incident electric field at the surface of the sensor to the received voltage at the antenna terminal when terminated with 50 ohms load is known as the Antenna Factor [1]. The Antenna Factor is mostly evaluated using rigorous, time consuming and expensive measurements [2]. However, the numerical evaluation is preferred by the researchers for accurate and easy evaluation of Antenna Factor [3–5]. The common method to measure the electric field is to put an antenna with known Antenna Factor in the desired field. Generally the Antenna Factor chart supplied by the manufacturer is given for free space with wave impedance 377Ω. However, the wave impedance may vary in different test environment which may cause to vary the Antenna Factor of the same sensor. The authors have not noticed appreciable theoretical work on this area and concentrated on this. Here, a Method of Moment based numerical technique has been used to predict the Antenna Factor of a wire antenna as a function of the wave impedance of the wave propagating in that medium. The GTEM Cell with characteristic impedance of 50Ω is taken as an example. It should be noted that the same theory for the thin wire can be extended for different types of conducting structures (e.g., broadband dipole loaded with circular disc) which can be modeled as a combination of thin wire structures [5].

2. FORMULATION OF ANTENNA FACTOR

A wire antenna is considered to be placed in a linear, isotropic and homogeneous dielectric medium of permittivity ε and permeability μ with wave impedance η_1 (Figure 1). A known incident field of intensity E^i is incident on the wire.

The following assumptions are made to simplify the analysis:

- The wire is perfectly conducting. For wires of good conducting material the assumption of a surface current is approximately true and leads to no complications. The infinite conductivity causes the total tangential electric field to vanish on the surface of the wire.
- The wire radius is taken to be much less than the wavelength, it can be assumed that only z-directed currents are present.

The incident field induces a linear current density J_s which reradiates and produces an electric field that is referred as the scattered electric field E^s. The other field present is the incident field E^i.

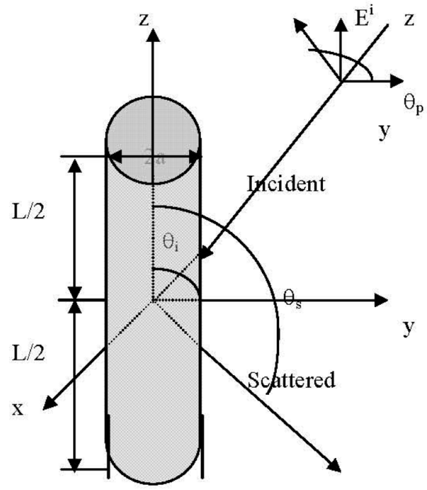

Figure 1. Uniform plane wave incidence on wire antenna.

At any point on the surface of the wire, the total tangential field along z-direction will vanish.

$$E_z^t(r = r_s) = E_z^i(r = r_s) + E_z^s(r = r_s) = 0 \tag{1}$$

2.1. Integral Equations for Currents

For the computation of the current distribution on the wire, it is required to evaluate the electric field components on the surface of the wire. The detailed theory is available in the literature [6, 8]. However, for the sake of understanding some portions are presented here.

In general, the incident unit plane wave at the antenna is expressed as follows

$$E^i = u_t e^{-jk_t \cdot r_n} \tag{2}$$

For simplification of the problem, it is considered that the incident wave is coming from $\theta_i = \frac{\pi}{2}$.

The z-component of vector potential A is expressed as follows [6]

$$A_z = \frac{\mu}{4\pi} \iint J_z \left(\frac{e^{-jkR}}{R} \right) ds' \tag{3}$$

where R is the distance between the source point (x', y', z') and observation point (x, y, z) i.e.,

$$R = \sqrt{(x - x')^2 + (y - y')^2 + (z - z')^2}$$

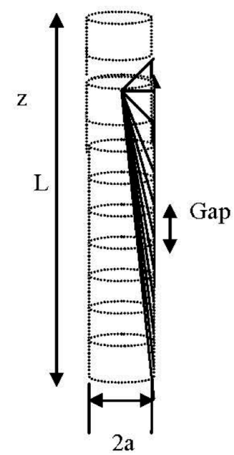

Figure 2. Dipole segmentation and its equivalent current.

$$= \sqrt{\{\rho^2 + a^2 - 2\rho a \cos(\phi - \phi') + (z - z')^2\}}$$

It should be mentioned here, that though the concept of vector potential is mainly used for unbounded medium for solving radiation problems, it is also used in bounded medium e.g., rectangular and circular waveguide structures by other scientists e.g., R. F. Harrington [7]. The magnetic vector potential is used in waveguide-like bounded structure i.e., the GTEM Cell because electric current sources are involved.

Considering the wire as very thin, the current density (independent of the azimuthal angle ϕ) is written in terms of $I_z(z')$ as follows

$$A_z(\rho = a) = \mu \int_{-L/2}^{L/2} I_z(z') G(z, z') dz' \tag{4}$$

where

$$G(z, z') = \frac{1}{2\pi} \int_0^{2\pi} \left(\frac{e^{-jkR}}{4\pi R} \right) d\phi' \text{ and}$$

$$R(\rho = a) = \sqrt{4a^2 \sin^2 \left(\frac{\phi'}{2} \right) + (z - z')^2} \ \ [6].$$

For very thin wire ($a \ll \lambda$)

$$G(z, z') = G(R) = \frac{e^{-jkR}}{4\pi R} \tag{5}$$

Applying Maxwell's equations

$$\vec{H} = \frac{1}{\mu}\vec{\nabla} \times \vec{A} \quad \text{and} \quad \vec{E} = \frac{1}{j\omega\varepsilon}\vec{\nabla} \times \vec{H}$$

and equation (3)–(5), equation (1) is simplified in the following form [6, 8]

$$E_z^s = -\frac{j}{\omega\varepsilon}\int_{-L/2}^{L/2} I_z(z')\left(\frac{e^{-jkR}}{4\pi R^5}\right)[(1+jkR)(2R^2-3a^2)+(kaR)^2]dz' \tag{6}$$

The intrinsic impedance $\eta_1 = \sqrt{\frac{\mu}{\varepsilon}}$ of the medium is identical to the wave impedance [8]. This is true for uniform plane waves and TEM wave.

Putting $\eta_1 = \frac{k}{\omega\varepsilon}$, equation (6) can be written as follows

$$E_z^s = -\frac{j\eta_1}{k}\int_{-L/2}^{L/2} I_z(z')\left(\frac{e^{-jkR}}{4\pi R^5}\right)\left[(1+jkR)(2R^2-3a^2)+(kaR)^2\right]dz' \tag{7}$$

Putting the simplified expression for z-directed scattered field (equation (7)), equation (1) is expressed in a more convenient form as follows

$$-\frac{j\eta_1}{k}\int_{-L/2}^{L/2} I_z(z')\left(\frac{e^{-jkR}}{4\pi R^5}\right)\left[(1+jkR)(2R^2-3a^2)+(kaR)^2\right]dz' = -E_z^i(\rho=a) \tag{8}$$

where for observations along the center of the wire ($\rho = 0$)

$$R = \sqrt{(a^2 + (z - z')^2)} \tag{9}$$

Equation (9) is acceptable for thin wire.

From equation (8) it has been noticed that the magnitude of the current distribution on the antenna surface is inversely proportional to the η_1 of the medium.

Here, it should be noted that for free space $\eta_1 = 377\Omega$. But for an air-cored co-axial structure with characteristic impedance 50Ω (e.g., GTEM Cell), which supports the propagation of TEM wave only, the TEM mode propagating in the medium has wave impedance of 50Ω.

2.2. Current Distribution Using Method of Moments

A simple solution to equation (8) is obtained by approximating the integral as the sum of integrals over N small segments. Using pulse basis function and point-matching, equation (8) is rewritten as follows [9]

$$[V^t] = [Z][I] \tag{10}$$

where

$$[I] = \begin{bmatrix} I(1) \\ I(1) \\ \cdot \\ \cdot \\ I(N) \end{bmatrix} \quad [V^t] = \begin{bmatrix} E^i(1) \cdot \Delta l_1 \\ E^i(2) \cdot \Delta l_2 \\ \cdot \\ \cdot \\ E^i(N) \cdot \Delta l_N \end{bmatrix} \tag{11}$$

From equation (11), the current distribution on the wire is found by solving simple matrix equation.

The normalized radiation pattern of the antenna inside the GTEM Cell remains same as in the free space.

2.3. Antenna Factor

The ratio of incident electric field on the surface of the sensor to the received voltage at the antenna terminal when terminated by 50 ohm load is known as Antenna Factor.

$$Antenna\ Factor = \frac{Incident\ electric\ field\ (E_i)}{Received\ voltage\,(V)} \tag{12}$$

The Thevenin's equivalent circuit diagram of an EMI sensor is shown in Figure 3. The receiving antenna is replaced by an equivalent open circuit voltage V_{oc} at the two terminals of the antenna and its impedance. Generally the receiver (e.g., spectrum analyzer) impedance is considered as 50 ohm. To avoid any inaccuracy in the evaluation of

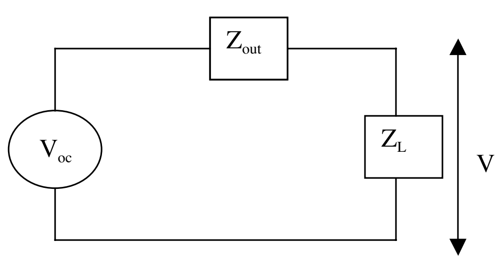

Figure 3. Thevenin's equivalent circuit diagram of a sensor.

the open-circuited voltage, the concept of concentrated load is used here [10]. In this method the load connected with the antenna is considered to be concentrated within the gap of the sensor. For the exact evaluation the load should be considered as distributed, however, the concept of concentrated load gives accurate result for a spectrum analyzer as the receiver. The matrix equation including the unknown current distribution on the antenna surface is modified as follows

$$[V^i] = [Z'][I] \tag{13}$$

Here $[Z'] = [Z] + [Z_L]$ with $[Z]$ as the impedance matrix that depends on the geometry of the structure and $[Z_L]$ as the diagonal matrix with only one non-zero diagonal element of the value of the load impedance. The short-circuited current (I_{SC}) and load current (I_L) are achieved from equation (13) putting the respective values of Z_L (refer Figure 3). The output impedance and hence the open-circuited voltage are achieved in terms of I_{SC}, I_L and Z_L as follows

$$Z_{out} = \frac{Z_L}{Z_L \times I_{sc} - V_L} V_L \tag{14}$$

$$V_{oc} = Z_{out} \times I_{sc} \tag{15}$$

The Antenna Factor of the receiving antenna is then achieved applying equation (9).

3. RESULTS

3.1. Theoretical Results

To generate the theoretical Antenna Factor data, software written in FORTRAN 77 is run on a Pentium 350 MHz processor based personal

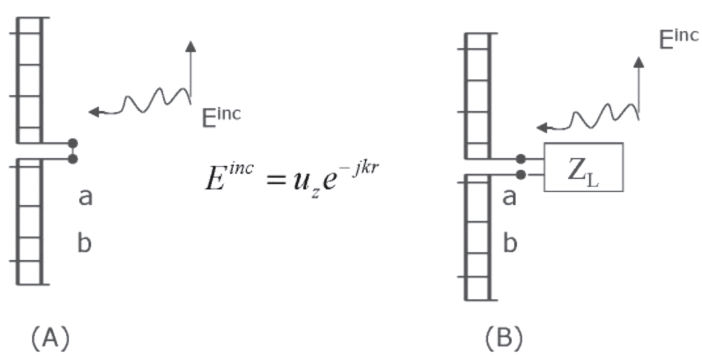

Figure 4. Wire antenna with concentrated load.

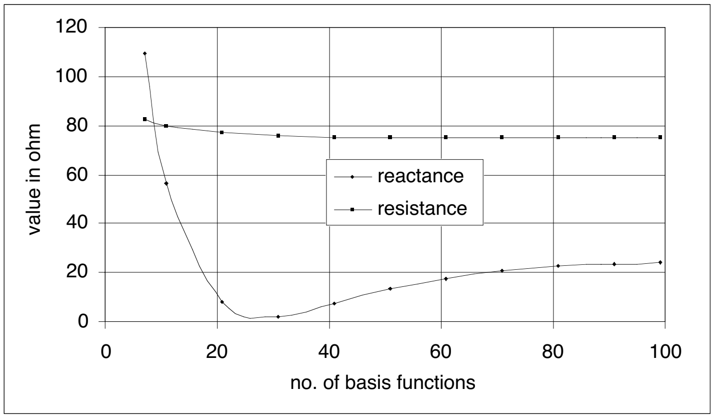

Figure 5. Convergence of antenna impedance with the increase in no. of basis functions with $l = 0.47\lambda,\ a = 0.005\lambda$.

computer supported by LINUX operating system. To achieve the convergence the antenna impedance versus total number of subsections is plotted in Figure 5 for a wire antenna with dimension $l = 0.47\lambda$ and $a = 0.005\lambda$. The free space Antenna Factor value for an Anritsu dipole MP 651A has been evaluated theoretically and compared with the values from the chart supplied by the manufacturer. The length and diameter of the arms of the Anritsu dipole were measured for different frequencies and those values were incorporated for numerical evaluation of Antenna Factor.

The theoretical results for the current distribution (magnitude) and Antenna Factor of an antenna placed inside the GTEM Cell and also in free space are plotted in Figures 7–8. The theoretical method explained in this paper can be extended for the evaluation of Antenna Factor in any other air-cored cell with different wave impedance (η_1). The Antenna Factor in other hypothetical mediums is presented in Table 1.

3.2. Experimental Results

For the beginning, it is necessary to have a brief idea of GTEM Cell, which has also been designed and developed [11]. The GTEM Cell is considered as a suitable test environment for EMI measurements [12, 13]. Very few works were performed by other researchers on the determination of the Antenna Factor inside a GTEM Cell [14]. The GTEM Cell is basically a section of gradually flared rectangular coaxial transmission line terminated with a matched load. The inner conductor

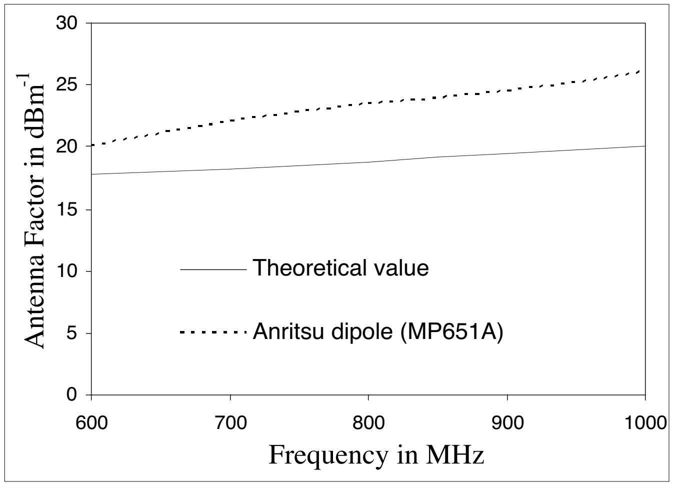

Figure 6. Plot of Antenna Factor versus frequency of an Anritsu MP651A antenna.

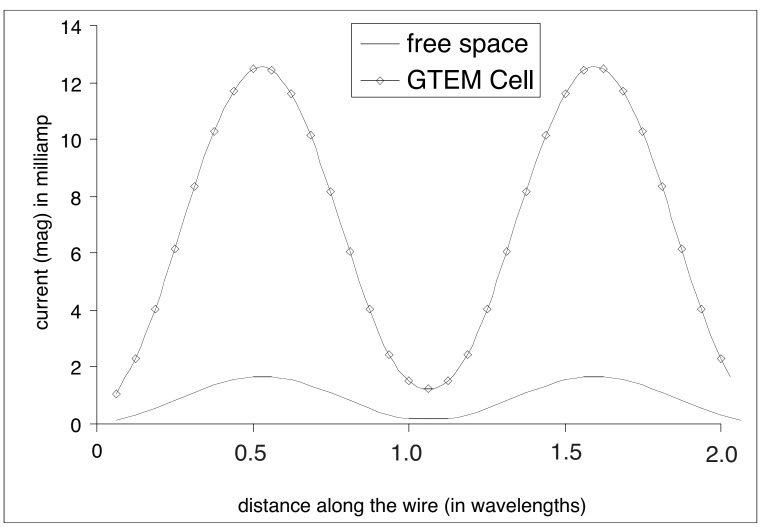

Figure 7. Comparison of current distribution on a wire antenna with $L = 2\lambda$; $L/2a = 74.2$ and gap at the center for $\eta = 50\Omega$ (inside GTEM Cell) and $\eta = 377\Omega$ (free space).

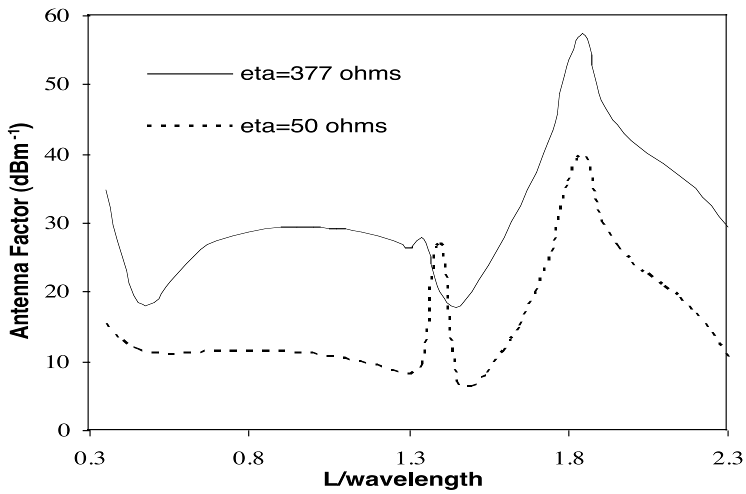

Figure 8. Plot of Antenna Factor vs. L/λ for $\eta = 50\Omega$ (inside GTEM Cell) and $\eta = 377\Omega$ (free space) of a dipole sensor with $L/2a = 74.2$ and gap at the center.

Table 1. Variation of Antenna Factor of an antenna placed in medium with different η_1.

Wave Impedance (η_1) in Ω	Antenna Factor (dBm^{-1})
50 (GTEM Cell)	11.17
200	15.07
377 (free space)	18.07
500	19.91

or septum is vertically offset to create a larger usable test volume. The end termination consists of a combination of low- frequency circuit element 50Ωs load and a high-frequency absorber wall for absorbing the incident propagating wave, as in anechoic chamber. The basic idea of wave propagation in a GTEM Cell is to propagate a slightly spherical wave from a source into a 50Ω rectangular coaxial transmission line and its distributed hybrid transmission without any geometrical distortions to the TEM wave. The advantages of GTEM Cell over other test facilities are less amount of required RF drive power in susceptibility tests and the compact size compared to anechoic chambers with same performance in field homogeneity. The GTEM Cell does not suffer from ambients like an Open Area Test Site (OATS), nor do we have to adjust the antennas.

For the validation of the theoretical results achieved using the present method, the following steps has been followed:

i) The electric field produced for a known applied power to the GTEM Cell is found out from the spectrum analyzer reading connected to the dipole antenna, considering the Antenna Factor as a known quantity.
ii) The electric field is theoretically evaluated using the theoretical value of Antenna Factor of the dipole antenna.
iii) The experimental and theoretical values of electric field are compared.

The apparatus necessary for performing the experiment are a R. F. signal generator, a spectrum analyzer, an Anritsu Dipole (MP651A/B) and the GTEM Cell. The desired amount of R. F. power is fed to the GTEM Cell by means of a R. F. signal generator (Figure 10). The dipole is placed inside the Cell and is connected to the spectrum analyzer. The dipole picks up the field and the resultant voltage or power is shown in the spectrum analyzer. Now to find out the electric

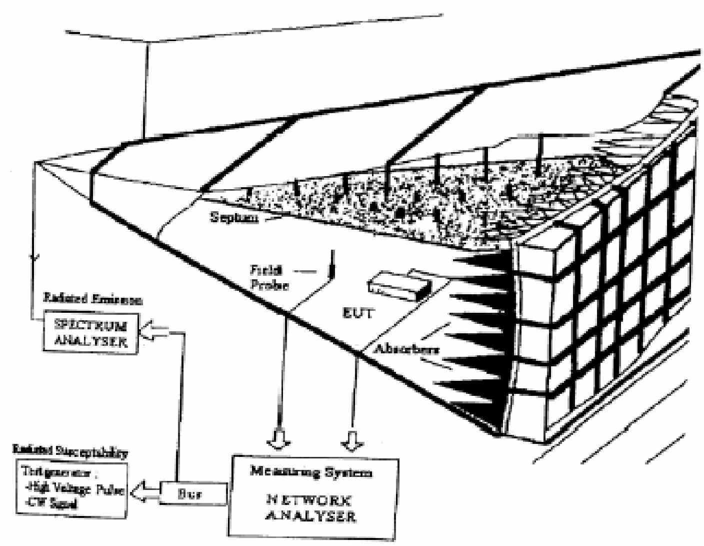

Figure 9. Isometric view of complete GTEM cell based test facility.

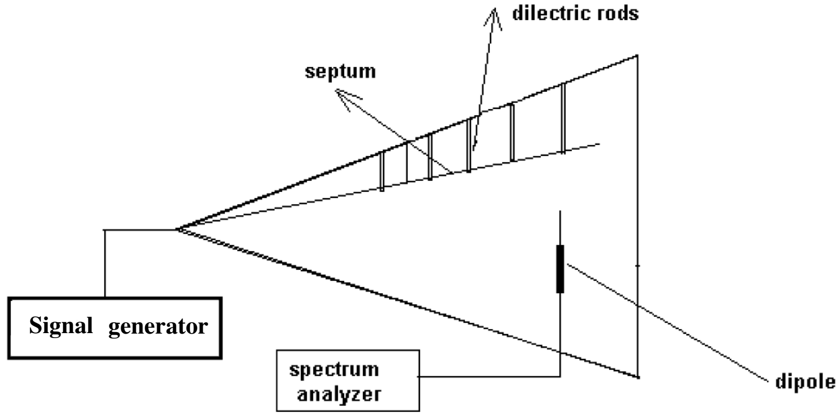

Figure 10. Experimental set-up for validating the results obtained by theoretical analysis.

field it is required to know the resultant voltage at the spectrum analyzer and also the Antenna Factor of the dipole at that particular frequency. From equation (8) and also from the theoretically evaluated Antenna Factor values presented in Table 1, it has been noticed that the Antenna Factor in different mediums with different impedances can be expressed in terms of the free space Antenna Factor as follows

$$E(dB\mu V/m) = V(dB\mu V) + A.F. + 20 * \log_{10}(\eta_1/377) \tag{16}$$

Here $V(dB\mu V)$ is the voltage measured using the spectrum analyzer and A. F. is the free space Antenna Factor for the frequency under consideration.

Since the chart for Antenna Factor supplied by the manufacturer is given for free space, equation (16) is used to convert this value for the GTEM Cell based test environment.

To compare the experimental results with the theoretical one, the Antenna Factor evaluated using the theory as mentioned in Section 2.3, is used in the following equation

$$E(dB\mu V/m) = V(dB\mu V) + A.F.(GTEM\ Cell) \tag{17}$$

For the experiment, the frequency of operation is set at 1 GHz. The voltage developed at the antenna terminal when connected to the spectrum analyzer is measured. The Antenna Factor of the Anritsu dipole (MP651A/B) in free space at a frequency 1 GHz is found as 26 dBm^{-1} according to the chart supplied by the manufacturer [15].

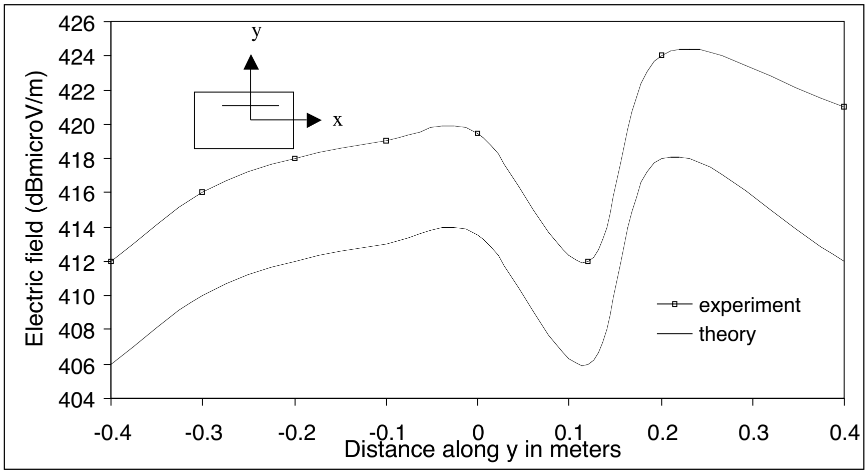

Figure 11. Comparison of theoretical and experimental values of electric field (Ey) vs. distance along y-axis in meters for $x = 0.2\,\mathrm{m}$, power $= 0.1\,\mathrm{mw}$.

Putting this value of Antenna Factor in equation (16), the experimental values of electric field are obtained. These experimental data are compared with the theoretically evaluated electric field in Figure 11.

4. DISCUSSION

In this paper extensive analysis has been made on the performance of a wire antenna as EMI sensor as a function of the wave impedance of the medium. Here, the Antenna Factor of a wire antenna is evaluated in free space and compared with the data supplied by the manufacturer [15]. The plot shows that the trend of both the plots is same, though slight deviation between the results is noticed. This is expected because the exact structure of the shielded balun circuitry and the insulating covering material connected to a practical MP651A/B dipole cannot be estimated and hence cannot be possible to incorporate in the theory.

Next the free space value of Antenna Factor has been compared with the theoretical values when placed inside the GTEM Cell. The following observations have been made from the results:

- The current distribution plots (Figure 7) show that for the same incident electric field the magnitude of the induced current is more for the antenna placed inside the GTEM Cell.
- The Antenna Factor of the same sensor becomes less when placed

inside the GTEM Cell (Figure 8) compared to its free space value. The Antenna Factor is the ratio of the incident electric field on the surface of the antenna to the received voltage at the antenna terminal. An antenna with lesser Antenna Factor produces a higher voltage at the antenna terminals for a given amount of incident field and is considered as a better receiver. Figure 8 shows that the same antenna behaves as a better receiver for $\eta = 50\Omega$ i.e., inside GTEM Cell.

The Antenna Factor of the same antenna in other hypothetical mediums is also presented in Table 1. From Table 1, it can be concluded that the Antenna Factor becomes less for a medium with lesser wave impedance value i.e., the antenna will behave as a better sensor when placed in a medium with lower value of wave impedance.

The experimental values of electric field measured using an Anritsu dipole (MP651A/B) is compared with the theoretically determined electric field using the theoretical Antenna Factor (Figure 11). Figure shows that the trend of the plots is same, though slight deviation (1.5%) between the results is noticed due to the exclusion of the balun circuitry for the theoretical calculation. Also the deviation from the experimental value may be partially due to the approximation of the concentrated load instead of the distributed load. However, from the plot of Figure 11, it has been noticed that the error (1.5%) due to this approximation is acceptable.

5. CONCLUSIONS

For a given sensitivity of spectrum analyzer it is always desired to have the lowest possible value of Antenna Factor to enable the sensor to receive the least value of electric field. It is noticed that for $\eta = 50\Omega$ i.e., inside the GTEM Cell, the sensitivity of the same wire antenna has been increased i.e., small amount of electric field can be detected. The theoretical prediction of Antenna Factor of wire antenna in different surrounding medium is an attractive alternative if one considers the expenditure and time required for calibrating this type of sensors experimentally.

ACKNOWLEDGMENT

The authors would like to acknowledge the financial support given by ISRO-IIT Space Technology Cell, IIT Kharagpur.

REFERENCES

1. Paul, C. R., *Introduction to Electromagnetic Compatibility*, 1–236, John Wiley & Sons Inc., New York, 1992.
2. Smith Jr., A. A., "Standard site method for determining antenna factors," *IEEE Transactions on Electromagnetic Compatibility*, Vol. EMC-24, No. 3, 316–322, August 1982.
3. Wang, K. and R. Nelson, "Numerical simulation of the antenna factor of broad-band dipole antenna," *2001 IEEE, International Symposium on EMC*, Vol. 1, 616–619, 2001.
4. Ghosh, S., A. Chakraborty, and S. Sanyal, "Estimation of antenna factor of wire antenna as EMI sensor," *Journal of Electromagnetic Waves and Applications*, Vol. 16, No. 1, 79–91, 2002.
5. Ghosh, S., A. Chakrabarty, and S. Sanyal, "Loaded wire antenna as EMI sensor," *Progress in Electromagnetics Research*, PIER 54, 19–36, 2005.
6. Balanis, C. A., *Antenna Theory*, 387–396, John Wiley & Sons, Inc., 1997.
7. Harrington, R. F., *Time Harmonic Electromagnetic Fields*, 148–188, McGraw-Hill Book Company, New York, 1961.
8. Balanis, C. A., *Advanced Engineering Electromagnetics*, 282–284, John Wiley & Sons, Inc., 1989.
9. Harrington, R. F., *Field Computation by Moment Methods*, 62–80, R. E. Krieger Publishing Company, Malabar, Florida, 1985.
10. Kolundzija, B. M., J. S. Ognjanovic, and T. K. Sarkar, *WIPL-D: Electromagnetic Modeling of Composite Metallic and Dielectric Structures — Software and User's Manual*, 1–332, Artech House, 2000.
11. Single, M. R., "Analysis, design and development of GTEM cell," M.Tech. Dissertation, 1–150, E & ECE Department, IIT Kharagpur, December 1997.
12. Osburn, J., *New Test Cell Offers Both Susceptibility and Radiated Emission Capabilities*, 39–47, R. F. Design, August 1990.
13. Bronaugh, E. L. and J. D. M. Osburn, "Radiated emissions test performance of the GHz TEM cell," *IEEE International Symposium on Electromagnetic Compatibility*, 1–7, Aug. 12–16, 1991.
14. Bronaugh, E. L. and J. D. M. Osburn, "Measuring EMC antenna factors in the GHz transverse electromagnetic cell," *IEEE 1992 International Symposium on Electromagnetic Compatibility*, 229–231, August 17–21, 1992.

15. Instruction Manual, Dipole Antenna MP651A/B, 1–5, Anritsu Corporation.