ELECTROMAGNETIC COMPUTATIONAL METHODS IN THE TEACHING OF ELECTROMAGNETIC COMPATIBILITY

Reinaldo Perez
Jet Propulsion Laboratory
California Institute of Technology

Abstract

The teaching of Electromagnetic Compatibility (EMC) is gaining acceptance as an important subject that needs to be taught in the Electrical Engineering curriculum at the undergraduate and graduate levels. It has become evident that EMC plays an important part in the design and manufacture of electronic components, subsystems and systems; hence, the need for its teaching. Traditional approaches for the teaching of EMC have focused on analytical methods for the study of diverse types of interference mechanisms. Recently, the use of computational electromagnetic methods in the analysis and solution of EMC problems has been introduced in the teaching of EMC. Students have shown great interest in an EMC course where the use of computer methods helps in their understanding of this, sometimes, difficult subject.

INTRODUCTION

In a regular electrical engineering curriculum at the undergraduate level students are taught the fundamentals which will guide them in the design, analysis, manufacture, and testing of electronic components, devices and systems. At the graduate level a greater "in depth" view is taken of the previously taught subjects. Regardless of the level of instruction (undergraduate vs graduate) most of the teaching in our engineering schools is still done in a sequential manner. For example, a student will not take a course in Antenna Theory until a course(s) in Electromagnetic Theory is part of his/her general knowledge. Not surprisingly most graduate courses have undergraduate courses as pre-requisites. Recently however, an emphasis on "synthesis engineering education" has caught the attention of many educators [1]. In synthesis engineering education, subjects from different fields can be taught simultaneously by making use of commonalities among the subjects themselves; hence, the description of the radiated fields from a radiating dipole (as taught in an antenna course) can be covered as an extension in the treatment of Maxwell's equations.

The subject of Electromagnetic Compatibility (EMC) is slowly gaining acceptance as a topic that could fit the synthesis engineering education approach that is needed for the solution of real-world Electromagnetic Interference (EMI) problems, which are constantly faced by the electronic industry [2]. Too often however, in the design and manufacture of electronic devices very little attention is focused on the possibility that EMI may occur among susceptible devices. For example, though students are taught the fundamentals of how to design and manufacture many types of electronic devices, the fact that such devices may not function together in the common electromagnetic environment of a system is hardly taught at most engineering schools [3]. EMC, as part of the synthesis engineering approach, should be taught at all stages in design/electronic manufacture engineering courses.

Because EMC/EMI is not properly taught to most engineers, many of our engineering schools are graduating professionals who lack this expertise within the field of electronic design. In industry, this situation often translate to the lack of implementation of comprehensive EMC plans in the design stages of electronic products; hence, EMC is only considered after the design is complete and inherent incompatibilities arise. Because EMC is not "built-in" in the design process, EMI problems are fixed using "band-aid" approaches. The final results are delays in product delivery, degraded performance, and increased costs.

There is a need to educate our future engineers in good design practices which incorporate, among other things, good EMC planning. Incorporating EMC in a synthesis engineering education approach is the best method to accomplish this task. In the last few years several universities in the US and Europe have taken steps to incorporate EMC in their undergraduate electrical engineering curriculum [4-6]. This effort has also been extended to graduate education [7]. The use of Electromagnetic (EM) computational methods has been a valuable tool in the teaching of EMC at the graduate level [7]. The first part of the paper reviews some fundamentals of EMC codes that use analytical methods. The second part of the paper discusses the use of computational electromagnetic methods in the teaching of EMC. Some examples where students can learn to apply EM computational methods for solving EMC problems are discussed. It is assumed that the students already have a basic understanding of EMC which is typically gained from an undergraduate course on the subject.

FUNDAMENTALS OF EMC CODES BASED ON ANALYTICAL METHODS.

Before the advent of digital electronics the general concepts of EMC and EMI referred mostly to Radio Frequency Interference (RFI) effects between transmitters and receivers. The root causes of RFI are the inherited non-linearities existing in transmitter and receiver circuits which could downgrade their performance. Tables

1a and 1b show a list of RFI problems (transmitters and receivers) and how they originate. As an introduction, EMC students are exposed to these RFI concepts with several worked examples. Though some computer codes are used for performing RFI analyses [8-9], they are not discussed in this paper.

The introduction of digital electronics has significantly increased EMI problems in electronic devices creating a marked awareness of the importance of EMC. Digital electronics not only has increased the frequency range of the noise environment (KHz to several GHz), but has also increased the susceptibility of electronic components to that noise environment [10]. Presently, EMC has to address interference issues at the inter-system level (e.g between transmitters and receivers) and at the intra-system level (self-compatibility). There is a pressing need to teach engineering students about good EMC design practices in our digital/analog design courses.

The use of software tools based on analytical methods for the solution of EMI problems focuses on the following principles: a) analytical methods are suitable for teaching at the classroom level, b) analytical methods provide physical and mathematical insights into the theory of EMC for ease of understanding by the students, and c) analytical methods can provide results which are reasonably accurate for topologically simple EMC problems, which in many practical situation are a good approximation to the real EMC situation.

EMC codes which use analytical methods can process large amount of input data and perform a large number of computations. Students are taught however, that the "physics" of the codes is based on several variations of well known analytical expressions for the different types of EMI coupling mechanisms. Several coupling models between noise sources and victim circuits are included in such codes: cable-to-cable, field-to-cable, antenna-to-antenna, and field-to-box. Figure 1 shows an example of an EM near-field cable-to-cable coupling model [11]. The induced noise voltages on the susceptible circuit ($V(Z_2)$ and $V(Z_L)$) have been coupled capacitively and inductively (through C_c and L_{12}) from the EMI source circuit (represented by source and load impedances Z_s and Z_l respectively). Similarly, Figure 2 shows an analytical model for solving a far-field field-to-cable EMI problem [12]. In Figure 2 the solution for the induced current I_s can be obtained through the application of Stokes'theorem to integrate the equation $\nabla \times \mathbf{E} = -j\omega\mathbf{B}$ to obtain the expression $\int \mathbf{E} \cdot dl = -j\omega \int \mathbf{B} \cdot \hat{n}dS$. After a series of mathematical manipulations, involving transmission line theory, the expression for I_s in Figure 2 is obtained.

There are several computer codes written through the years which use analytical approximations, of the types discussed above, in the solution of several types of EMC problems [8-9]. Students are briefly introduced to the use of these codes for the analysis of simple problems. Figure 3 shows a simple sketch of the types of problems that students can analyze using the codes in references 8 and 9.

ELECTROMAGNETIC COMPUTATIONAL APPROACH TO EMC MODELING

As the topology of the EMC problem becomes more complex, the need arises to consider alternate methods of solutions. The complexity in the modeling not only pertains to the different types of coupling modes but also to the complexity in modeling the diverse number of noise sources and susceptible circuits.

Highly evolved Electromagnetic (EM) codes have recently been used in the analysis of EMC problems [13-14]. The codes use highly mathematical techniques which are based on the rigorous physics of electromagnetic phenomena. The objective in introducing the students to these EM computational methods is to prepare them for solving more complex EMI problems. However, it is important that the students learn to recognize the limitations of these modeling tools, since EMC problems can have intricate topologies with many degrees of difficulties.

As a preliminary step, students are prepared in advanced areas of electromagnetic theory such as radiation, reflection, scattering,...etc. Upon this foundation the students are then introduced to several asymptotic and computational techniques which have been very useful in electromagnetics. The material is presented at the introductory level, avoiding an in-depth theoretical exposure of each of these subjects due to time constrains in the teaching. The format followed in the exposure of each of these computational techniques is: 1) introducing the students to a historical and theoretical background concerning the origin, derivation and applicability of a particular EM technique, and 2) teaching the students how such technique can be used to model and solve EMI problems. The students develop a fundamental understanding of the physics used in these codes; hence, becoming "intelligent" users of the codes, rather than merely using the codes for obtaining solutions. Table 2 describes the scope of the theoretical introduction presented to the students concerning several of the EM computational techniques. Table 3 provides a brief description of two widely known EM codes which can have applicability to EMC analysis. These codes are introduced to the students for their use.

TWO EXAMPLES IN THE USE OF "EM" COMPUTATIONAL METHODS FOR THE MODELING OF EMI PROBLEMS.

For the purpose of illustrating the type of problems taught in EMI modeling using EM computational methods, two examples are described which illustrate how useful some of these modeling techniques can be in solving a variety of interference-type problems. In both examples the Method of Moments is used. It must be emphasized that in EMC, sometimes the most difficult task is the proper modeling of the EMI problem; hence, students are taught only simple modeling cases during the course.

Example 1: Prediction of Radiated EMI from a PCB

One of the most effective contributions for EMC analysis in the area of proper design of multilayer Printed Circuit Boards (PCBs). This important subject started receiving considerable attention in the early 1980's when the FCC and European regulatory agencies started imposing radiated and conducted emission limits on all computing devices that use clock pulses above 10 KHz. For the first time there was a real incentive to minimize the amount of EM emissions from PCBs and associated parts which make up a computing device.

Several models have been developed through the years which have attempted to predict the amount of radiated EMI form PCBs. These models go from simple loop antenna models [15] to more complex transmission line models [16-17]. The students learn to appreciate quickly however, that EMI prediction from PCBs is a small portion of the total EMI picture that deserves serious attention when modeling the EMI from a computing device. For example, they're shown that the radiated noise from power and I/O cables due to common mode current is most often the major source of EMI from such devices [18]. Furthermore, the EMI analysis can become even more complex if scattering effects and coupling between elements from several PCBs in a device are considered.

With the objective of introducing the students to some fundamentals in EMI modeling, the task of predicting the levels of radiated electric fields from a portion of a PCB is pursued. The results obtained are compared with measured radiation. The measurements were made at an Open Field Test Site (OFTS). In this example the radiation associated with a clock signal generated on a multilayer PCB is analyzed using the method of moments. The system board of a personal computer was used. To keep the model simple and within the capability of the computer resources, only a small portion of the board was considered.

Board Description: The personal computer board selected for the evaluation was composed of five layers: Three signal planes, one ground plane and one voltage plane. The spacing between each layer was 0.3556 mm and the total thickness of the board was 1.42 mm. A portion of the clock signal was selected. The remaining circuit was separated from the selected circuit by cutting the trace lines. The chips and components were left mounted on the PCB. The resulting circuit comprised four chips: two CMOS and two TTL, as shown in Figure 4. The crystal oscillator was connected to the clock chip, which generated the 12 MHz clock pulse with a 50 % duty cycle; rise time was 10 nS. The output of the clock chip was connected to the remaining four chips in shunt configuration . The board was supplied by a 5 V DC external source.

Measurements: The multilayer PCB and a horizontally polarized tuned dipole antenna were mounted at the fixed height of 1 m above a reflecting ground plane at an OFTS. The horizontal distance from the feed point of the antenna to the nearest point on the board was 3 m. The largest area of the board was oriented parallel to the reflecting surface with the components side up. The radiated signals were measured at all the odd harmonics from 36 MHz to 180 MHz.

Modeling Method: The reflecting ground plane was modeled as a wire mesh using 25 coordinated points interconnected with 40 equal-length straight round wire segments. For the multilayer board, the clock trace which connects the clock generator chip to the other chips utilized several signal planes. The traces were modeled by 19 different lengths of straight round wires. The board ground plane was modeled by using the method of images, i.e imaging the traces with respect to the ground plane. Since the rest of the circuit is nonactive and terminated by the impedance of the remaining chips and components, it was found that the induced currents on these nonactive traces are very small in comparison with the current flow on the active circuit. A 3-dimensional model representing the traces and their images is shown in Figure 5. A total of 74 wire segments were used in the model. The input capacitances of each chip ranging from 3 pF to 10 pF, were obtained from several data books. These component values are nominal in nature and no attempt was made to obtain the complex values of impedances .vs. frequencies which are needed for more accuracy in these models (data books on chips seldom provide this information). The reactances were calculated for the appropriate frequency and were connected to the clock trace at the chip location and the image points. Since the total thickness of the board was 1.42 mm, the board was considered very thin in terms of the wavelength of interest, and hence the dielectric material between layers was also very thin. The dielectric material was found to have a minimal effect on the total field. The squared trace cross-sectional dimensions were translated to the radius of equivalent round wires. The clock signal was modelled as a 12 MHz signal source with an amplitude of 5 V peak-to-peak situated midway between the top signal trace and its image trace as shown in Figure 5. The clock rise time and duty cycle were input to the program to calculate the amplitudes of the harmonics. These values are used to represent a radiating source amplitude at the corresponding frequency. For example, at 36 MHz the radiated source used in the field calculation was 0.8444 V.

Results: The plots of the measured and calculated results, shown in Figure 6, cover the range 30-200 MHz. It can be seen from Figure 6 that high correlation of both data sets was obtained. The best correlation was obtained at 180 MHz, having a field intensity difference of 1 dB and a maximum difference of 8 dB at 36 MHz. The greater difference at the low frequency of 36 MHz is mainly due to near field measurement errors and the antenna factor. One would expect the measuring accuracy to increase the frequency as indicated for frequencies above 132 MHz.

Value to the students: When students learn the use of the method of moments technique for predicting the radiated emissions from a small portion of a PCB, the practical applications for the design and layout of more complex circuits becomes self-evident to them. Several questions related to the design of PCBs were raised by the students in this exercise: 1) what are the computational limitations as the analysis of a PCB becomes more complex ?, 2) how can the technique be applied for obtaining a PCB layout that would radiated the least ?, b) how can this methodology be implemented within a PCB layout CAD system for designing an optimun board (i.e in terms of least emissions) to comply with regulations.

Example 2. Calculation of a 3-m Site Attenuation.

The FCC and European regulatory agencies require that all equipment capable of producing radiated and conducted RF noise be tested in order to quantify the amount of noise they emit. The radiated measurements are usually made at an Open Field Test Site (OFTS). The OFTS is an open area which contains a metal ground plane, above which locations are designated for an Equipment under Test (EUT) and a measuring dipole antenna. The distance between the EUT and antenna is usually 3.0 meters, and the measurements are made for both horizontal and vertical polarization while the EUT is being exercised electronically. Because errors can occur in the measured values due to imperfections at the site (e.g the presence of obstructing features), it is important to "characterize" the site and measure its suitability for performing these emission measurements by calculating or measuring its site attenuation.

Site Attenuation Description: The Site Attenuation Measurements (SAM) were designed to "qualify" an OFTS for radiated emissions measurements. The qualification test is conducted by comparing theoretical and experimental values of a signal which is transmitted between two tuned-dipole antennas separated by 3.0 meters. One antenna is selected as the receiving antenna, the other one as the transmitter. The receiving antenna is scanned vertically between 1-4 meters while the transmitting antenna height is fixed at 2.0 m. Figure 7 shows an illustration of the measurement set-up for SAM. A detailed procedure for calculation of SAM can be found in reference [19]. Published data however, reveals considerable discrepancy between experimental and theoretical values below 150 MHz. The reason for these discrepancies is that theoretical values were calculated: a) using far field theory, b) neglecting the coupling between the dipole antennas, c) neglecting the coupling of the dipole antennas and the ground plane, specially for vertical polarization.

Modeling Description: To evaluate SAM more effectively and to avoid the aforementioned discrepancies, the method of moments can be used. Accordingly, both dipole antennas over the ground plane are modeled as a number of segments. The number of segments is dependent on the physical sizes of the commercial tuned-dipoles used and the frequency range of interest (30 MHz-1000 MHz). In this example the maximum size of each dipole antenna used was about 2.5 meters. Theoretically, in order to provide good accuracy up to 1000 MHz using the method of moments code supplied to the students, each dipole antenna and its image should have been divided in 33 segments ($\lambda/4$), each segment with a length of about 7.5 cm each. However, because of the extensive amount of computations (computing time is proportional N^3, N being the number of segments) only 10 segments per dipole were used. Three different wire radi were used in the modeling (3.2 mm, 2.4 mm, 1.6 mm). Each wire radius corresponded to a frequency range used by the dipole (30-60 MHz, 60-340 MHz, and 340-1000 MHz). These frequency ranges correspond to the three different types of elements (rods) used in the dipoles. The galerking method with sinusoidal basis fuctions was used in the method of moments. Figure 8 shows the method of moments representation of the transmitting and receiving dipoles over the ground plane. In the figure V_t is the driving source voltage at the transmitting antenna. The method of moments calculates the mutual impedance between segments and self-impedances of each segment. The output current of each segment is determined by solving simultaneous equations which state that the boundary conditions on each segments are satisfied. The output voltage of the receiving antenna (V_r) is determined by the product of the output current at its center segment (calculated by the method of moments) and the input impedance of the receiver at the antenna end of the coaxial cable. The site attenuation (S_{atn}) is then calculated by $S_{atn} = V_t/V_r$.

Measurements and Calculations: Figure 9 shows the results of comparing the calculated values, using the method of moments, with measured values for vertical polarization. Figure 10 shows the results of comparing the calculated values, using the method of moments, with the FCC theoretical specifications (FCC does not consider vertical polarization for SAM). Notice that the discrepancies between measurements and calculations in Figures 9 and 10 do not exceed 3-4 dB. The allowed deviation between the FCC theoretical specification and measured results is 3 dB.

Value to the students: When students make use of the method of moments for calculating the site attenuation, they learn the usefulness of a computational technique which allow the easy modeling of a complex engineering problem based on the correct physics (e.g the need to account for mutual coupling between atennas and with the ground plane). If the modeling of the physics is correct, the measured results will corroborate with the calculated data.

CONCLUSION

In the fast developing field of electronics as IC chips become faster and the packaging of electronic devices decreases in size, electromagnetic compatibility problems are bound to increase. The teaching of EMC is important in a synthesis engineering education approach, since it teaches future engineers to consider good EMC practices in the design and manufacture of electronic devices. Though traditional EMC codes have emphasized limited analytical methods in their analysis of EMI problems, the use of electromagnetic computational methods has been shown useful in giving engineering students a broader spectrum for their analytical skills. These tools no only enhance the students' capabilities, but can serve as viable instruments for teaching some of the basic and important principles in EMC.

REFERENCES

[1] IEEE Spectrum Magazine, "Refreshing Curricula", March 1992.

[2] Divenkar, D. et al. "Simulate transmission line effects in high speed PCB and MCM systems", Electronic Design, April 11, 1991.

[3] Ott, Henry, "EMC Education: The missing Link", IEEE International Symposium in Electromagnetic Compatibility, Washington, DC, 1981.

[4] Clayton R. Paul, "Establishment of a University Course in Electromagnetic Compatibility", IEEE Trans. on Education, February 1990, pp. 111-118.

[5] Marvin, A.C. "The undergraduate course in EMC at the University of York, England," IEEE Trans. on Electromagnetic Compatibility, pp. 169-172, August 1983.

[6] Shihab. S, "Undergraduate EMC Course at the Royal Melbourne Institute of Technology", IEEE International Symposium in Electromagnetic Compatibility, Cherry Hill, August 1991.

[7] Perez. R, "Teaching Electromagnetic Compatibility at the Graduate Level," IEEE International Symposium in Electromagnetic Compatibility, Cherry Hill, New Jersey, August 1991.

[8] TRW Systems Group, "Specifications and Electromagnetic Compatibility Program (SEMCAP)" Ver. 7.4, One Space Park, Redondo Beach, CA 90278, October 1975.

[9] RADC-TR-342, "Intrasystem Electromagnetic Compatibility Program (IEMCAP)," Rome Air Development Center, Air Force Systems Command, December 1981.

[10] Paul, Clayton, Introduction to Electromagnetic Compatibility, John Wiley & Sons, 1992.

[11] Paul, Clayton, "Solution of the Transmission Line equations for three-conductor lines in homogeneous media," IEEE Trans. on Electromagnetic Compatibility, EMC-20, No. 1, February 1978.

[12] Smith Albert, A. "A More Convenient Form of the Equations for the Response of a Transmission Line Excited by Nonuniform Fields," IEEE Trans. on Electromagnetic Compatibility, August 1973.

[13] Perez. R, "Analysis of Electromagnetic Interference Effects in Spacecraft Generated by Electrostatic Discharges using the Method of Moments" 6th Annual Review of Progress in Applied Computational Electromagnetics, Monterey, CA, March 1990.

[14] Lee, C.F, et al. "Electromagnetic Radiation from a VLSI Package and heatsink Configuration", IEEE International Symposium in Electromagnetic Compatibility, Cherry Hill, New Jersey, August 1991.

[15] Raut, R. "On the Computation of Electromagnetic Field Components from a practical Printed Circuit Board", IEEE International Symposium on Electromagnetic Compatibility, September, 1986.

[16] Bush, D.R. "Radiated Emissions of Printed Circuit Board Clock," IEEE International Symposium on Electromagnetic Compatibility, 1985.

[17] S. Daijavad, et al. "A Fast Method for Computing Radiation from Printed Circuit Boards," IEEE International Symposium on EMC, August 1990,

[18] Paul, Clayton and Bush, D.R, "Radiated emissions from common-mode currents," IEEE International Symposium on Electromagnetic Compatibility, Atlanta GA, August 1987.

[19] Calibration of a Radiation Measurement Site--Site Attenuation, Federal Communications Commission, Bulletin OCE 44, Docket 21371, Appendix A, Sept 9, 1977.

RFI PROBLEMS IN TRANSMITTERS	**BRIEF DESCRIPTION OF RFI PROBLEM**	**METHODS OF SUPPRESSION**
Sideband Splatter(1)	Deviations from the required response law in the transmitter modulator causing spectrum broadening. AM/FM, SSB, DSB systems.	- Filtering
Internal Harmonic Generation(2)	Deviations from the linearity of a transmitter final amplifier	-Balanced circuits -Filtering -Wave trap
Intermodulation and Cross modulation(3)	Mixing of two or more signals in a non linear element. Resulting multiplicative mixture of both signals	-Filtering
Oscillator Noise	Similar to sideband splatter except at a lower level	-Filtering -Design of very good oscillators

In Table 1a the following applies:

(1) Output of nonlinear element plus narrowband filter centered at carrier ω_c. Input function is X_1.

$$\sum_{n=1}^{N} \sum_{k=1}^{n} a_n \binom{n}{k} X_1^{n-k} \frac{k!}{\left(\frac{k-1}{2}\right)! \left(\frac{k+1}{2}\right)!} Cos(\omega_c+\phi_c)$$

(2) output of nonlinear device is

$$y = a_0 + a_1 x + a_2 x^2 + \dots + a_k x^k$$
$$where \quad x = x_1(t) + Cos\, w_c t$$

(3) Let Signal 1

$$X_1(t) = m_1(t)\ Cos\,(\omega_1 t + \phi_1(t))$$

Let Signal 2

$$X_2(t) = m_2(t)\ Cos\,(\omega_2 t + \phi_2(t))$$

$X(t) = X_1(t) + X_2(t)$ go through a nonlinear device to obtain the result

$$y(t) = a_0 + a_1 x + a_2 x^2 + a_3 x^3$$

For intermodulation:

$$y(t) = m_1^2(t)\ Cos[(2\omega_1 - \omega_2) + 2\phi_1(t) - \phi_2(t)] + higher\ order\ modes$$

For crossmodulation:

$$y(t) = m_1^2(t)\ m_2(t)[Cos\ \omega_2 t + \phi_2(t)]$$

Table 1a. RFI PROBLEMS IN TRANSMITTERS.

RFI PROBLEM IN RECEIVERS	**BRIEF DESCRIPTION OF PROBLEM**	**METHOD OF SUPPRESSION**
Broadband Noise	Noise from natural sources (thermal, shot, solar, atmospheric) or man-made (discharges, switching of electronic devices, antenna behavior)	-Limiting & blanketing before broadband noise is filtered in the IF amplifier
Co-Channel Interference	Signals from communication sources are assigned a frequency near the center frequency of receiver	-Good care in frequency assignment
IF Channel Interference	Penetration of unwanted signals centered at one of the IF channels of the receiver	-Selectivity of the input RF circuit and/or stray paths must be controlled
Spurious Response(4)	Nonlinearities in early stage gives rise to harmonics of incoming signals; nonlinearities in the mixer and frequency multiplication in local oscillator	-Filtering prior to mixer
Intermodulation & Crossmodulation (see Table 1a)	Intermodulation: when two or more unwanted signals are present at the input. crossmodulation:transfer of information from an undesired carrier onto the desired one	-Filtering
Desensitization	Reduction of receiver gain when a large unwanted signal enters the receiver	-Filtering prior to receiver

In Table 1b the following applies:

(4) Mixing operation:

if oscillator is $y_1 = A \cos \omega_1 t$

and signal is $y_2 = x_s(t) \cos(\omega_s t + \Phi_s)$

For non linearity

$$y = \sum_{n=0}^{N} b_n y^n$$

and the result of $y = y_1 + y_2$ *is*

$$\sum_{n=0}^{N} b_n \sum_{k=0}^{n} \binom{n}{k} x_s^k(t) \cos^k(\omega_s t + \phi_s)\, A^{(n-k)} \cos^{(n-k)} \omega_1 t$$

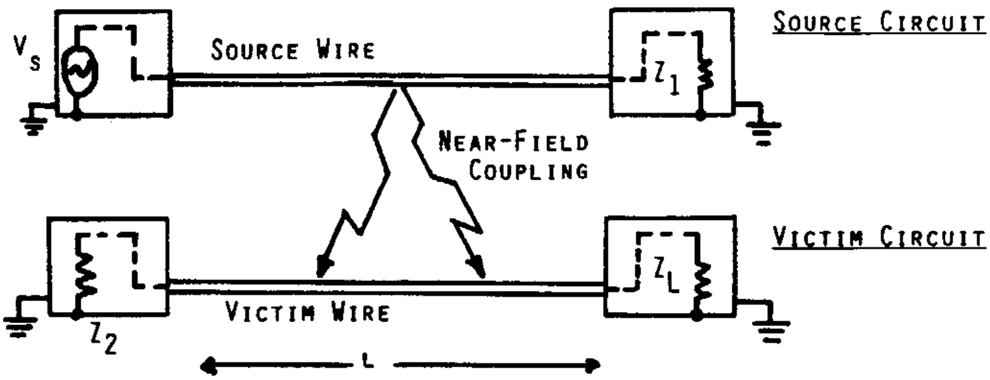
Table 1b. RFI PROBLEMS IN RECEIVERS.

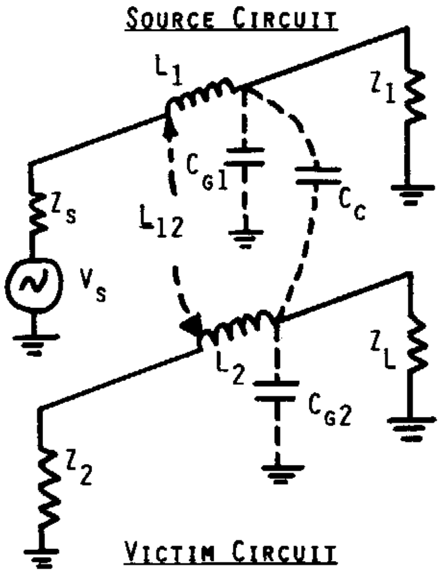
COMPUTATIONAL "EM" METHODS	**BACKGROUND FROM MAXWELL EQUATIONS**	**APPLICABILITY**	**EXAMPLES OF USEFULNESS TO EMC**
Finite Element Methods	Helmholtz equation. Dirichlet boundary condition. Ritz-Galerkin Method	Waveguide structure in microwave, millimeter wave and optical wavelength region	Electric and Magnetic fields in cavity-type structures
Method of Moments (MOM)	Electric and Magnetic field integral equations solved via expansion of basis functions	Antennas or any radiating structure that can be modeled correctly	Electric and Magnetic fields from physical antennas, and from cables, PCB traces..etc.
Spatial Network Theory	Differential form of Maxwell equations solved in time domain	Waveguide problems, wave penetration, reflection,diffraction, radiation	EMP, coupling problems (field-to-cable) in near and far fields
Geometric Theory of Diffraction (GTD)	Expansion of geometrical optics. Results from asymptotic expansion of Maxwell's equations	Diffraction from conducting scatterers of almost any shape	Field-to-cable coupling where effects of the scattered incident filed is needed
Physical Optics & Physical Theory of Diffraction (PO/PTD)	similar to GTD, but induced surface current is separated: uniform and diffracted. Elementary edge waves are considered	Diffractions from large objects for which for which PO/PTD can be constructed	Field-to-cable coupling analyses between complex radiators and cables near large structures

Table 2. "EM" METHODS TAUGHT TO STUDENTS WITH APPLICABILITY TO EMC

NUMERICAL ELECTROMAGNETIC CODE (NEC)	**GENERAL ELECTROMAGNETIC CODE FOR THE ANALYSIS OF COMPLEX SYSTEMS (GEMACS)**
Capabilities: EM radiation, antenna performance, radar cross section,EMC. Emphasis is on accurate modeling of field emissions, field sources	Capabilities: EMC, EMP, ECM, ECCM, jamming susceptibility. EM radiation and scattering. Radar cross section. Emphasis is on modeling fields and field sources. Includes reflectivity, scattering conducting surfaces.
Outputs: Current distribution on wires and surfaces. Coupling between antennas. Near and far field strengths.	Outputs: Current distribution on wires, surfaces. Coupling between antennas. Scattering of conductive surfaces. Behavior of cavities
Physical Modeling: Electric Field Integral Equation (EFIE) via Method of Moments (MOM).	Physical Modeling: Electric Field Integral Equation (EFIE) via Method of Moments (MOM), Geometric Theory of Diffraction (GTD), Finite Element Method (FEM), Hybrid Models (MOM/GTD/FEM).

Table 3. DESCRIPTION OF TWO "EM" CODES TAUGHT TO THE STUDENTS.





L=LENGTH OF WIRES

L_1 = WIRE INDUCTANCE OF SOURCE CIRCUIT

Z_S = IMPEDANCE OF SOURCE CIRCUIT

C_{G1}= CAPACITANCE TO GROUND IN SOURCE CIRCUIT

V_S = VOLTAGE OF SOURCE CIRCUIT

Z_1 = LOAD IMPEDANCE OF SOURCE CIRCUIT

C_C = COUPLING CAPACITANCE

Z_2 = SOUCE IMPEDANCE OF VICTIM CIRCUIT

Z_L = LOAD IMPEDANCE OF VICTIM CIRCUIT

C_{G2} = CAPACITANCE TO GROUND IN VICTIM CIRCUIT

L_{12}= MUTUAL INDUCTANCE

$$V(Z_L) = \frac{j2\pi f l \frac{Sin(\beta L)}{\beta L} Z_L[C_c Z_1 Z_2 - L_{12}] V_s}{[---]}$$

$$V(Z_2) = j2\pi f l \frac{Sin(\beta L)}{\beta L\,[---]} Z_2\Big[[Cos(\beta L)\,[Z_L Z_1 C_c + L_{12}]] + j2\pi f l \frac{Sin(\beta L)}{\beta L}[Z_L C_c L_1 + Z_1 L_{12}(C_{g1}$$

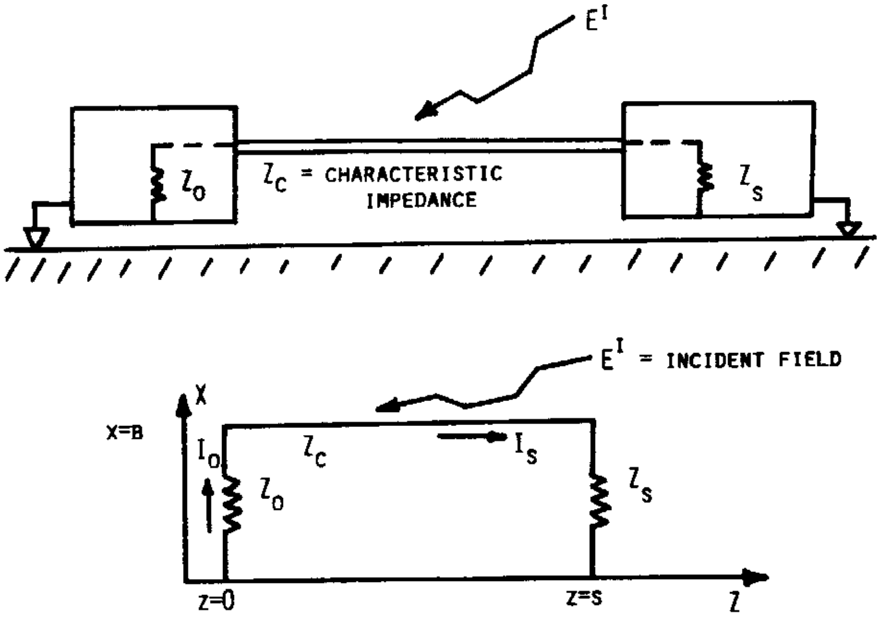
where

$$[---] = (Z_s + Z_1)(Z_2 + Z_L) Cos^2(\beta L) -$$

$$j4\pi^2 f^2 l^2 \frac{Sin^2(\beta L)}{(\beta L)^2} [[Z_1 Z_s (C_{g1} + C_c) + L_1][Z_2 Z_L (C_{g2} + C_c) + L_2] - [L_{12} - C_c Z_s Z_1][L_{12} - C_c C_1 Z_2]] +$$

$$j2\pi f \frac{Sin(\beta L)}{\beta L} Cos(\beta L) [(Z_2 + Z_L) [Z_1 Z_s (C_{g1} + C_c) + L_1] + (Z_s + Z_1) [Z_2 Z_L (C_{g2} + C_c) + L_2]]$$

Figure 1. CAPACITIVE & INDUCTIVE NEAR FIELD COUPLING



$$I_o = \frac{1}{[---]} \int_0^s P(z)\left[Z_c \mathit{Cosh}\gamma(z-s) - Z_s \mathit{Sinh}\gamma(z-s)\right]dz -$$

$$\frac{Z_c}{[---]} \int_0^b E_x^i(x, s)\,dx + \frac{Z_c \mathit{Cosh}\gamma s + Z_s \mathit{Sinh}\gamma s}{[---]} \int_0^b E_x^i(x, 0)\,dx$$

$$I_s = \frac{1}{[---]} \int_0^s P(z)\left[Z_c \mathit{Cosh}\gamma(z) - Z_o \mathit{Sinh}\gamma(z)\right]dz -$$

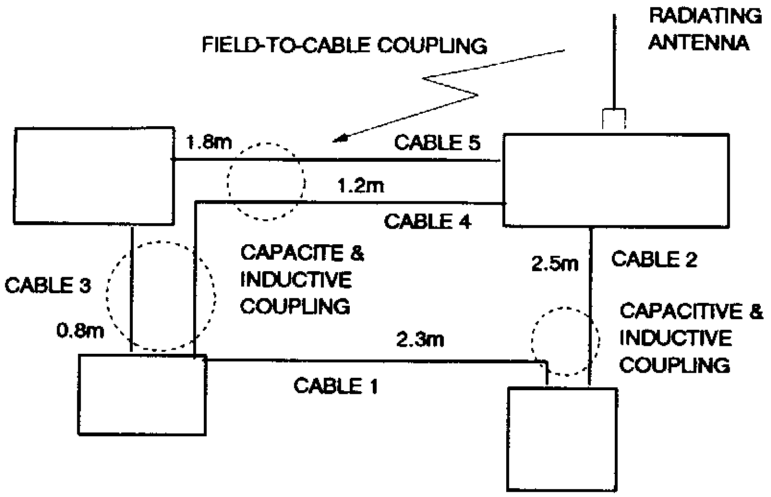
$$\frac{Z_c}{[---]} \int_0^b E_x^i(x, 0)\,dx + \frac{Z_c \mathit{Cosh}\gamma s + Z_o \mathit{Sinh}\gamma s}{[---]} \int_0^b E_x^i(x, s)\,dx$$

where

$$P(z) = \left[E_z^i(b, z) - E_z^i(0, z)\right]$$

$$[---] = [Z_c Z_o + Z_s Z_c]\mathit{Cosh}\gamma s + \left[Z_c^2 + Z_s Z_o\right]\mathit{Sinh}\gamma s$$

Figure 2. FIELD TO WIRE COUPLING



Example:

cables 1&2 are shielded, 3,4 & 5 unshielded
cables 1&2 are AWG 20, cables 3, 4 & 5 AWG 22
shield thickness of cables: 1.2 mm
dielectric constant of insulators for all cables: 3.2
Source & Load impedances are given for each circuit
Height above ground plane: 8.0 cm
capacitances to ground:cables 1&2=15pF;cables 3,4&5:20pF
coupling capacitances between cables are given

FIGURE 3. TYPICAL EMC PROBLEM ANALYZED USING ANALYTICAL METHODS

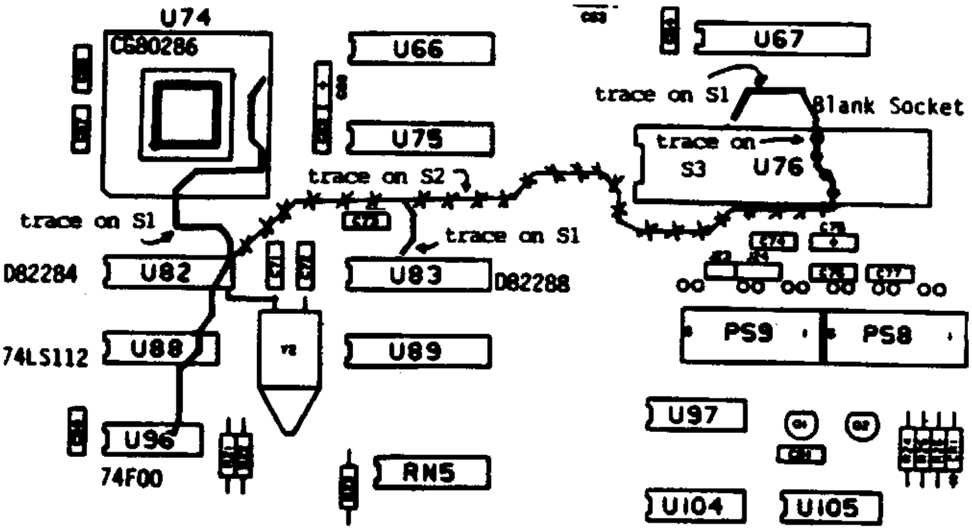


FIGURE 4. PORTION OF A CLOCK CIRCUIT ON THE MULTILAYER BOARD.

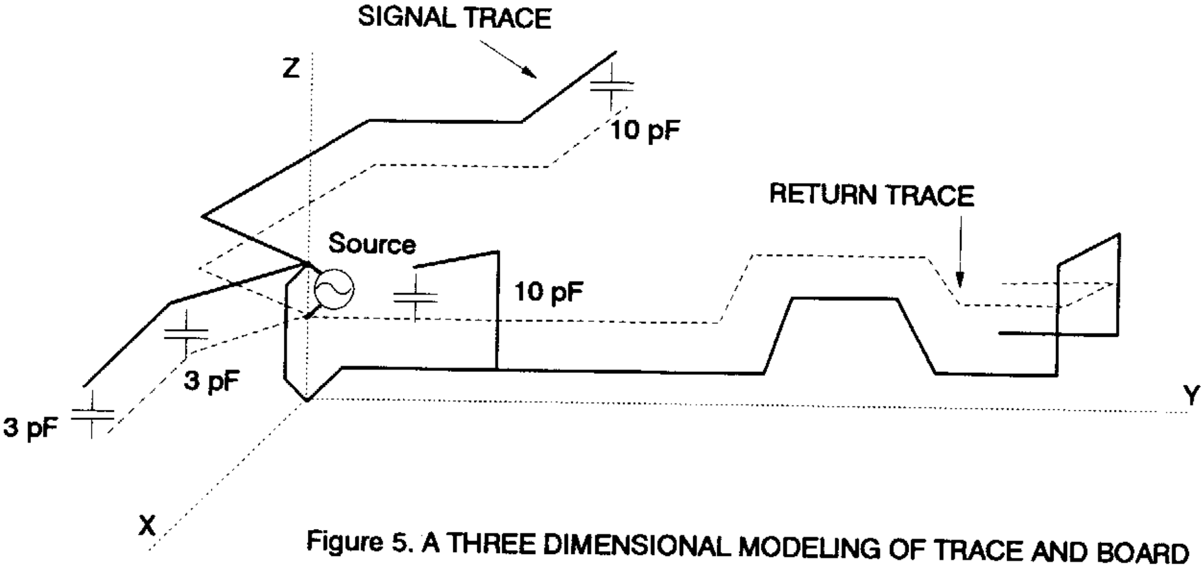


Figure 5. A THREE DIMENSIONAL MODELING OF TRACE AND BOARD

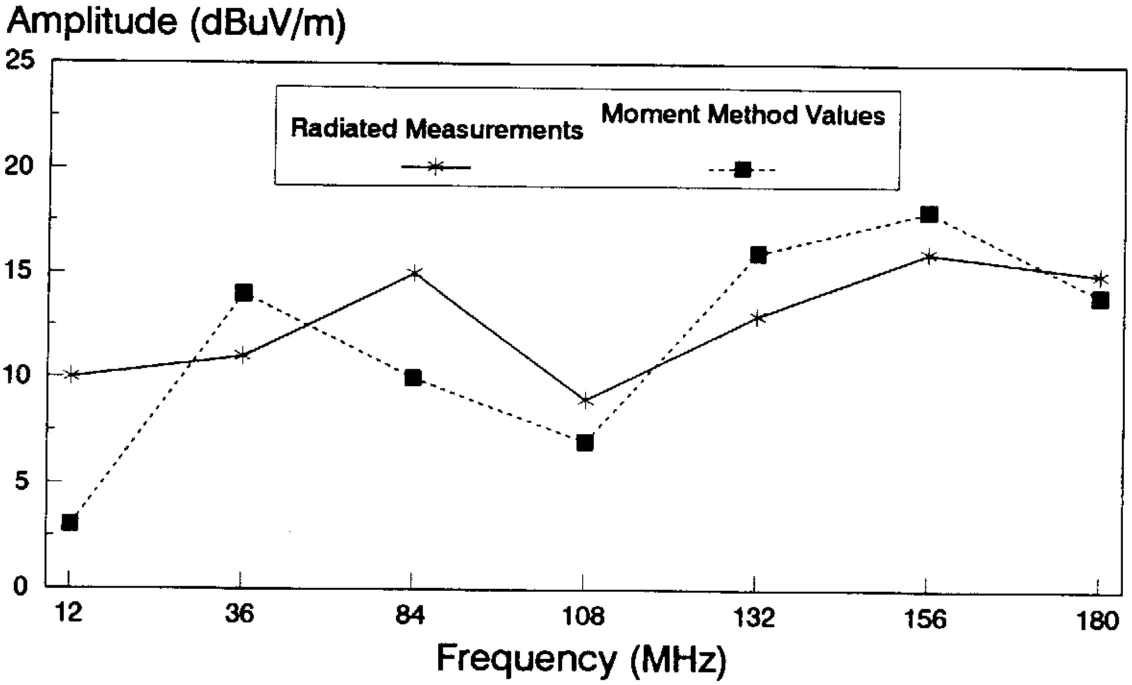


FIGURE 6. AN ELECTRIC FIELD COMPARISON BETWEEN MEASURED DATA AND MOMENT METHOD DATA.

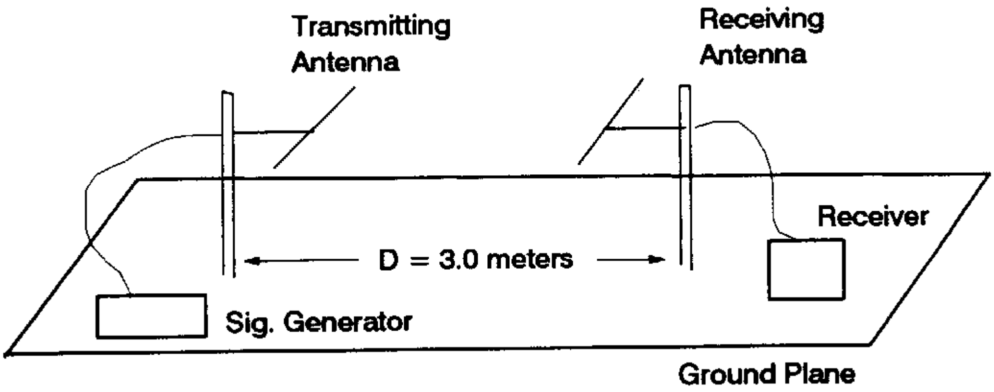


FIGURE 7. MEASUREMENT SET-UP FOR OBTAINING SITE ATTENUATION

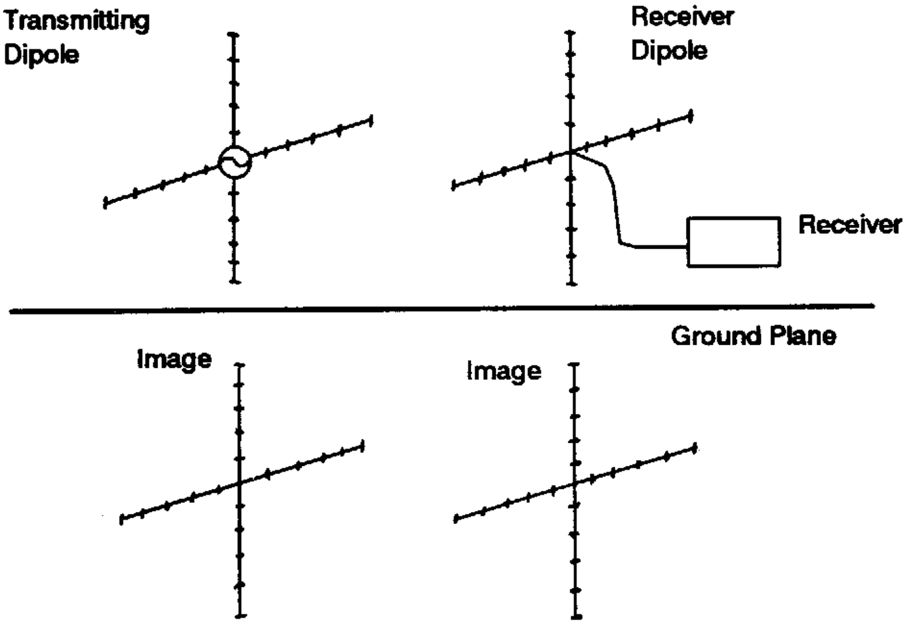


FIGURE 8. MOMENT METHOD MODELING FOR VERTICAL AND HORIZONTAL POLARIZATIONS FOR SITE ATTENUATION CALCULATIONS

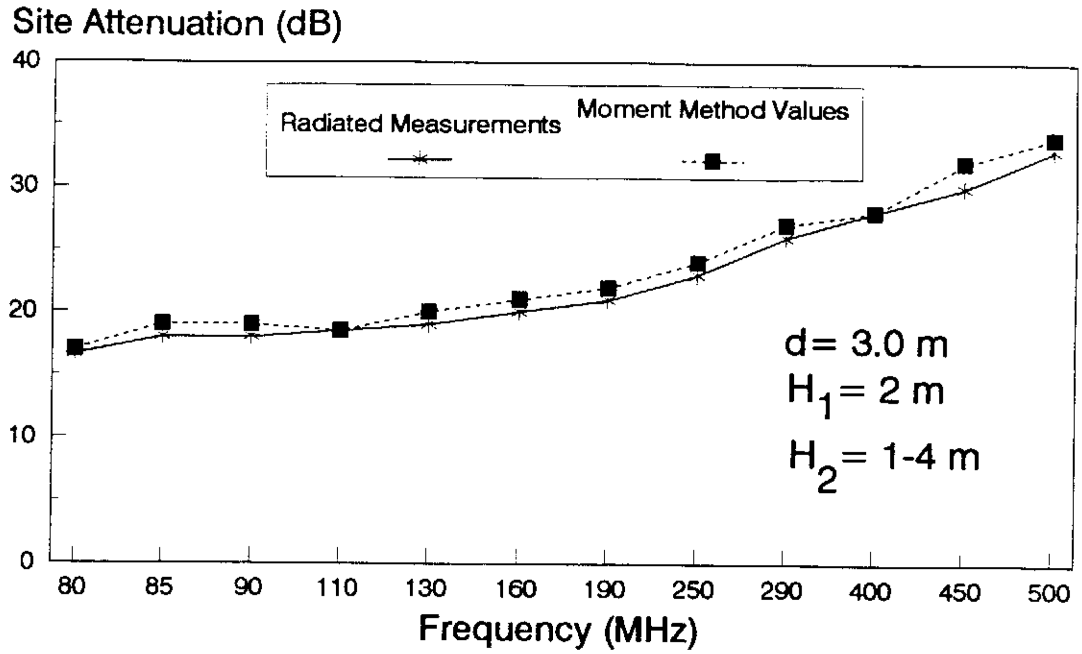


FIGURE 9. COMPARING MEASURED AND CALCULATED RESULTS FOR VERTICAL POLARIZATION USING THE METHOD OF MOMENTS

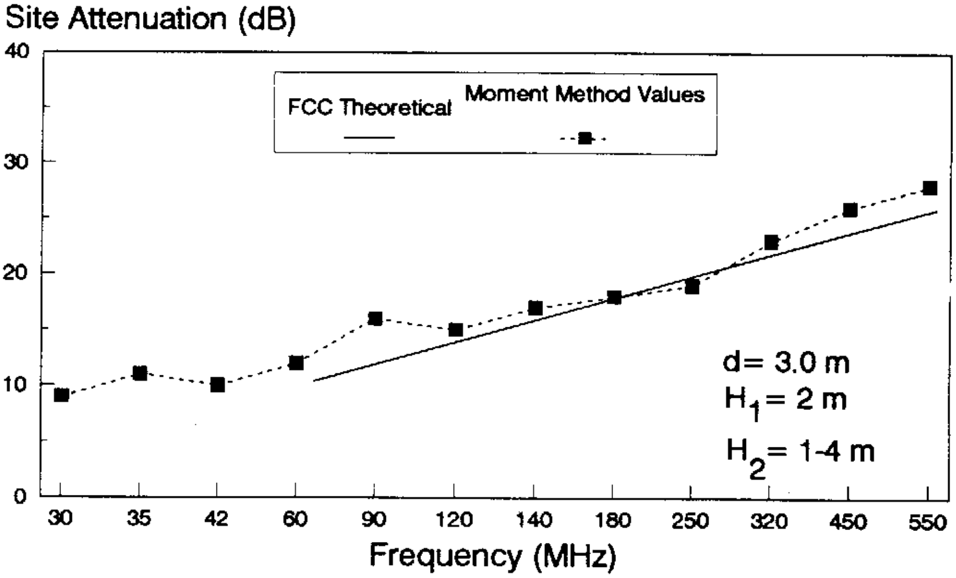


FIGURE 10. COMPARING THE FCC THEORETICAL SITE ATTENUATION FOR HORIZONTAL POLARIZATION WITH METHOD OF MOMENTS