Interaction Notes
Note 468
July 4, 1988

Field Excitation of a Two-Wire Transmission Line in a TEM Cell

D. Hansen, H. Schär, D. Königstein and H. Hoitink
Asea Brown Boveri Corporate Research,
EMI Control Center
Baden, Switzerland

and

D.V. Giri
Pro-Tech
125 University Avenue
Berkeley, CA 94710
U.S.A.

Abstract

Uniform plane wave interacting with a perfectly conducting two-wire transmission line has been experimentally investigated, by placing the transmission line in a TEM cell. The resulting voltage or current response in a terminating impedance of the transmission line has been computed using an available theoretical model, and then compared with the experimental data. The relative orientation of the transmission line with respect to the incident electromagnetic field is varied. The motivation for this work lies in our belief that several theoretical models exist for wave-line interaction problem, but information about experimental data and comparison with the computations is somewhat lacking in the open literature.

Contents

Section **page**

1. Introduction

The problem of interaction between an electromagnetic wave and a transmission line made up of two or more conductors, has been studied by several researchers [1-10] in the past. A primary goal of such studies is to evaluate the voltage or current responses in terminating impedances, in time and/or frequency domains. Such studies help in our understanding of how electromagnetic waves couple to more complex cylindrical structures, e.g., overhead power or communication lines above ground, buried cables etc. Such coupling mechanisms contribute significantly to the damaging effects of electronic systems that are vulnerable to severe electromagnetic environments. It is wires and transmission lines that interconnect electronic systems or subsystems, and hence the interaction of waves and conductors continues to be an important area of research. The analytic basis for coupling calculation has been the conventional transmission line theory. One possible approach is to use the Telegraphist's equations [11] for the line voltage and current with a distributed voltage source as the driving function. The distributed voltage source is proportional to the longitudinal (parallel to the transmission line conductors) component of the incident electric field [4,5 and 6]. One can also think of this distributed voltage source as arising from the time rate of change of magnetic flux linking the conductors. In effect, the transmission line response (i.e., terminal voltage or current) may be computed using only, either the electric field components or the magnetic field components. It is also noted that using only the electric field components results in simplifications in the computations, since the magnetic fields approach is more cumbersome owing to spatial derivatives of all three components. Furthermore, only the differential TEM mode of propagation on the line is considered. Non-TEM modes are ignored and the common mode currents in the two wires produce no response in the terminating impedances.

An alternate numerical approach would be to use a method of moments calculation, which solves the Maxwell's equations by zoning the finitely long wires and satisfying the boundary conditions on the conductor surfaces.

While we have outlined two computational approaches above, the primary focus in this paper is on experimental measurements. We are motivated, for two reasons to perform this experimental study of illuminating a two-wire uniform line inside a TEM cell, and comparing the measured results with calculated respones. One reason is that, there appears to be inadequate experimental information in the open literature about wave-line interaction. Secondly, such an experimental study also provides us with an insight into the behaviour of the fields in the TEM cell. Specifically, one can get an idea of the presence of non-TEM modes above a certain frequency. The TEM cell cited above is researched and manufactured by Asea Brown Boveri Ltd. and has been called the GTEM [12]. It is substantially different from the conventional TEM cells [13] and attempts to enlarge the bandwidth and optimize the working volume.

In concluding this introductory section, a few remarks are in order about the organization of this paper. In Section 2, GTEM is briefly reviewed while highlighting the planar TEM field calculations that become the illuminating fields for the transmission line. Section 3 describes the experimental configurations while Section 4 is concerned with analytical models for computing the responses. We compare the experimental results with the calculations in Section 5 and offer some concluding remarks in Section 6.

2. The Incident Field in GTEM

In this section, we briefly review the design details of GTEM (Gigahertz TEM) [12]. Basically this new family of TEM cells consists of a tapered transmission line similar to the input launcher of a conventional offset TEM cell that is terminated in a distributed load. GTEM is schematically shown in figure 1. For a given size of the working volume, the GTEM design can be relatively smaller in size compared to conventional designs as there are no central rectangular coaxial line and the tapered output section. The inner septum is offset for an optimum working volume.

Figure 2 shows the cross sectional dimensions of GTEM-1500 at the end of the tapered section. Its overall dimensions are approximately 3 m wide, 2 m high and 6 m long. The model number 1500 comes from the maximum height of the inner septum (1500 mm) at the end of the waveguide. The performance evaluation of GTEM-1500 at the input terminals include measuring the VSWR (return loss), shown in figure 3a, and the TDR measurements shown in figure 3b. The measured E and H fields, using D-dot and B-dot sensors in the middle of the bottom plate are shown in figure 3c. The return loss objective was 20 dB or more, the VSWR objective was 1.2 or less. These are met over the range of dc to 1 GHz. The TDR impedance at the input is in the range of 45 Ω to 52 Ω and the reflections are within the limits of +2 % and -5 %. The measured electric and magnetic fields as functions of frequency are also flat over the entire range of dc to 1 GHz within 5 dB, corresponding roughly to a variation of ± 40 % . 20 % type of deviation from the flatness are observed around 150 MHz. The field measurement appears to indicate the presence of some non-TEM modes in the 100's of MHz, since the deviation from the flat (TEM mode) response becomes significant. So, one can conclude a very precise planar TEM wave propagation in the GTEM, at least up to a frequency of 150 MHz. The calculations of the transmission line response performed in this paper assume a plane wave incidence and hence, we could expect agreement between theory and experiment, only up to a frequency where the TEM mode dominates.

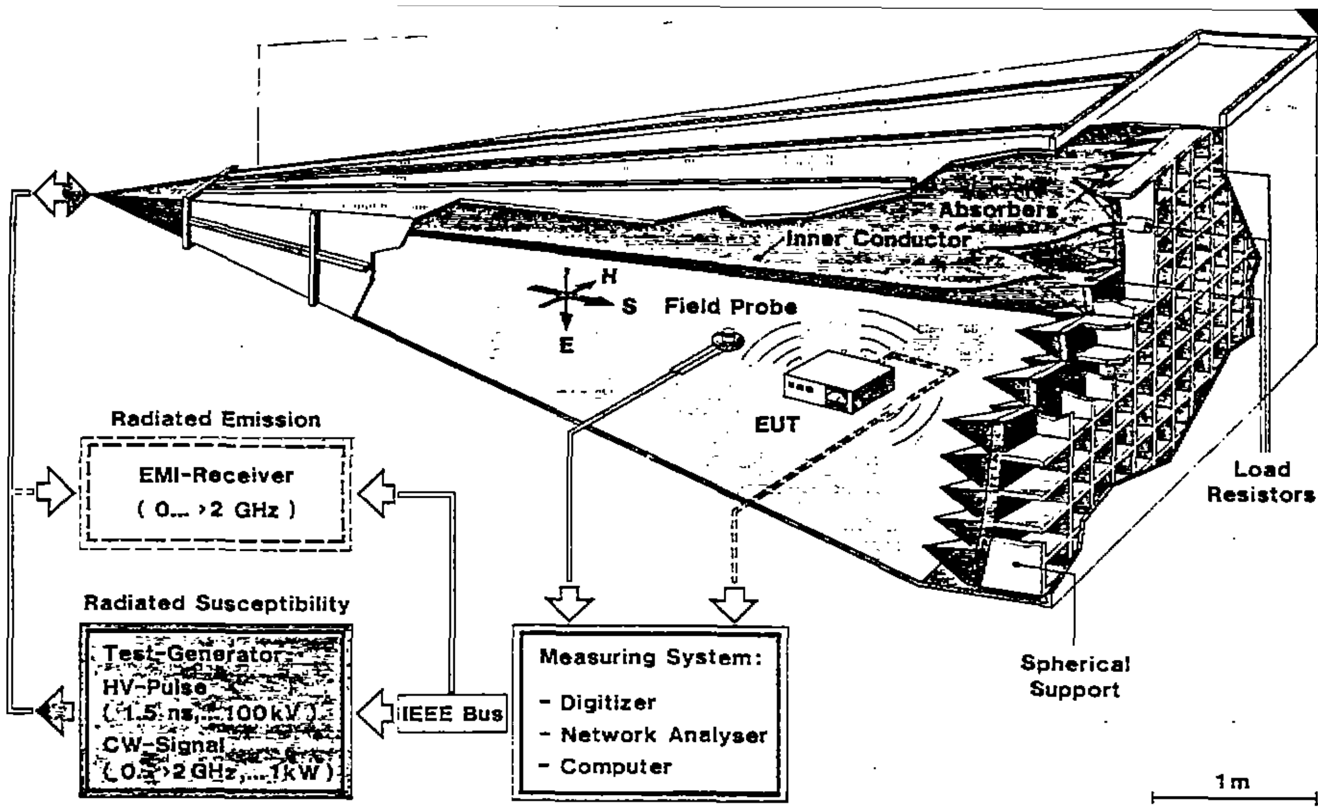


Figure 1. Schematic diagram of GTEM-1500 developed at Asea Brown Boveri (ABB) Research Center

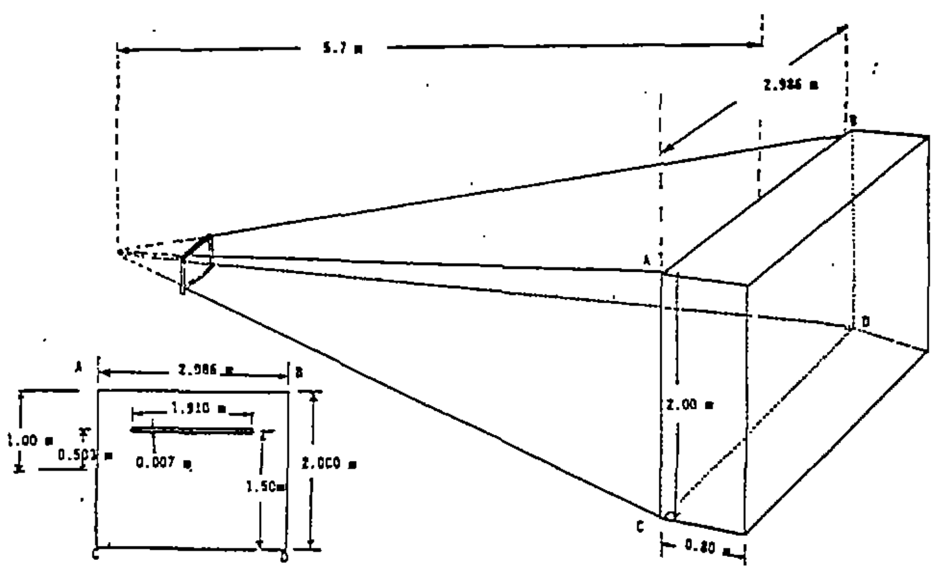
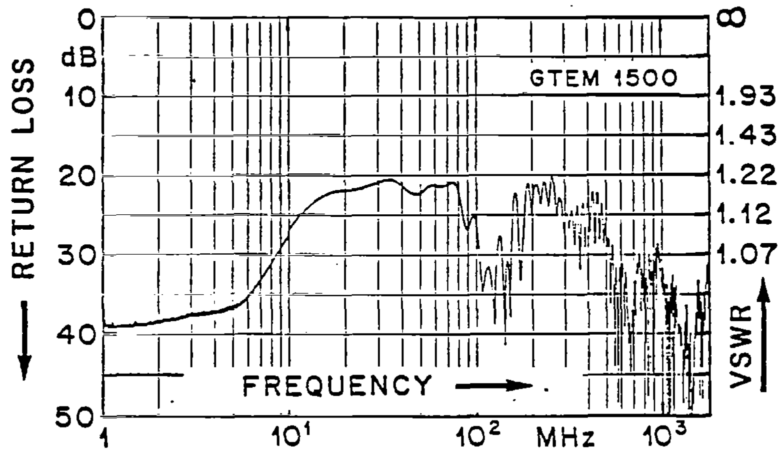
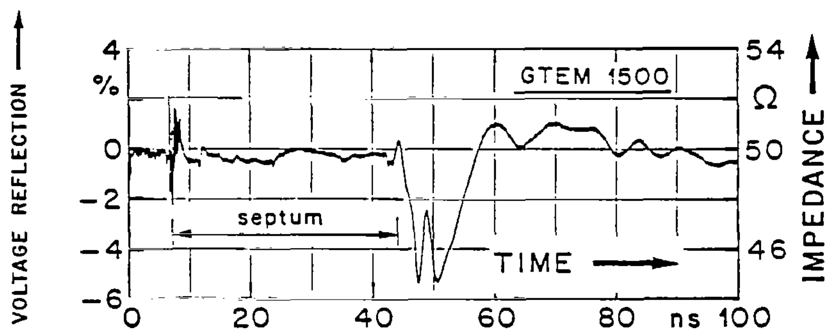


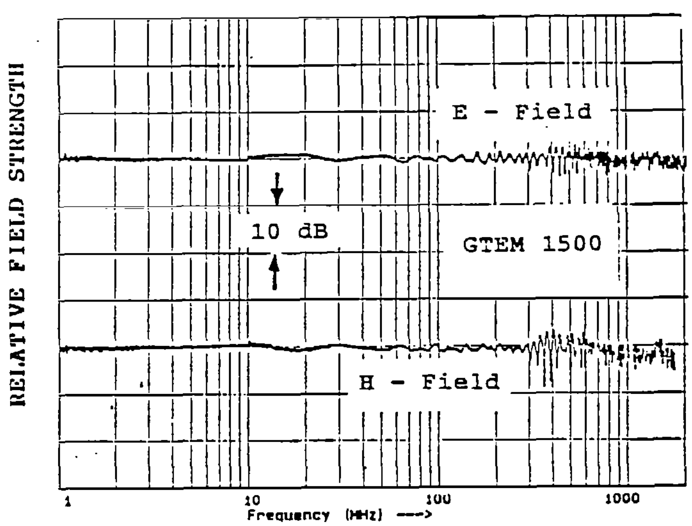
Figure 2. Approximate overall dimensions of GTEM-1500 and cross-sectional dimensions at ABCD



a) VSWR and Return Loss as a function of frequency



b) TDR measurements



c) E and H fields in frequency domain

Figure 3: Operating characteristics of GTEM-1500

3. The Two-Wire Line and Experimental Configurations

The geometry of a plane wave illuminating a two-wire transmission line is indicated in figure 4. In the figure, a general situation of a two-wire line of length ℓ with terminating impedances of Z_1 and Z_2 at the two ends is seen to be illuminated by a plane wave where in $\vec{E}$, $\vec{H}$ and $\vec{S}$ represent the electric field, the magnetic field and the Poynting vector respectively. An arbitrary angle of incidence is shown. If $\vec{E}$ is parallel to the (xoz) plane, we have horizontal polarization and if $\vec{H}$ is parallel to the (xoz) plane, we have vertical polarization. The physical dimensions of the transmission line are shown in figure 5 and the characteristic impedance Z_c of the TEM mode on the line is about 420 Ω. The line may be terminated in Z_c on either side to avoid reflections from the ends. This transmission line is placed inside the GTEM at two different cross sections. If (u,v,w) is a set of rectangular coordinate system with its origin at the apex of GTEM (see figure 6a), the two cross sections are defined by w = 3.49 m and w = 4.82 m. Figure 6b shows the transmission line in GTEM with the two possible orientations. In both these orientations, $\vec{E}$ is parallel to the line whereas the $\vec{H}$ and $\vec{S}$ are interchanged in direction. $\vec{H}$ can be oriented from wire to wire and $\vec{S}$ passing through the line or vice versa. In the orientations of figure 6b, there is only common mode currents in the two wires, which produce no response in the terminating impedances. The common mode response in the wires is calculable but is not measurable at the load impedances. The differential mode response in the load impedance for this orientation (figure 6b) is ideally zero, but the measurements may yield small response due to asymmetries

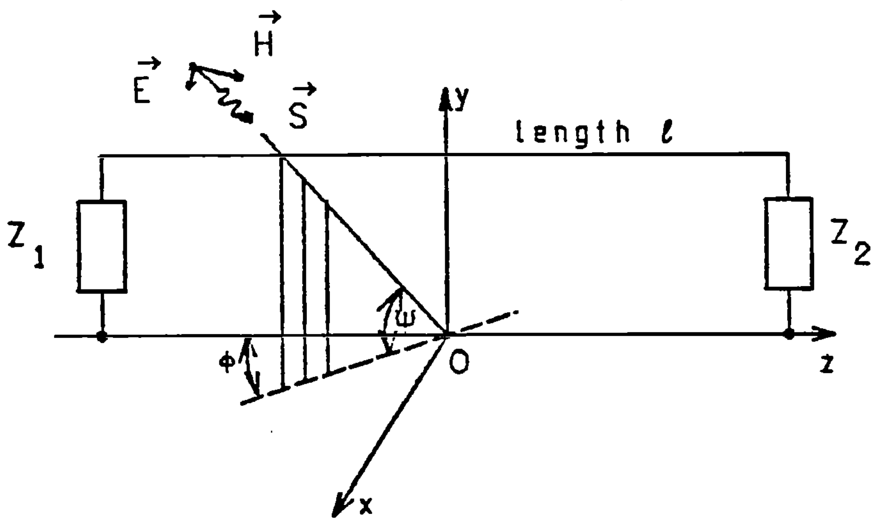


Figure 4. Two-wire transmission illuminated by a uniform plane wave

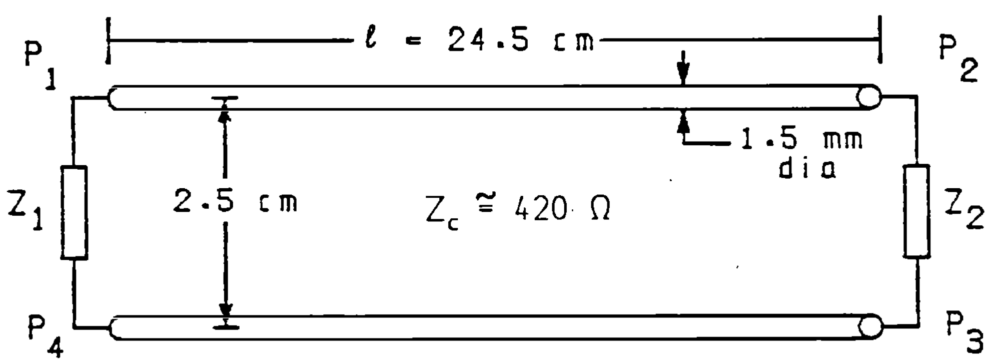


Figure 5. Two-wire line dimensions

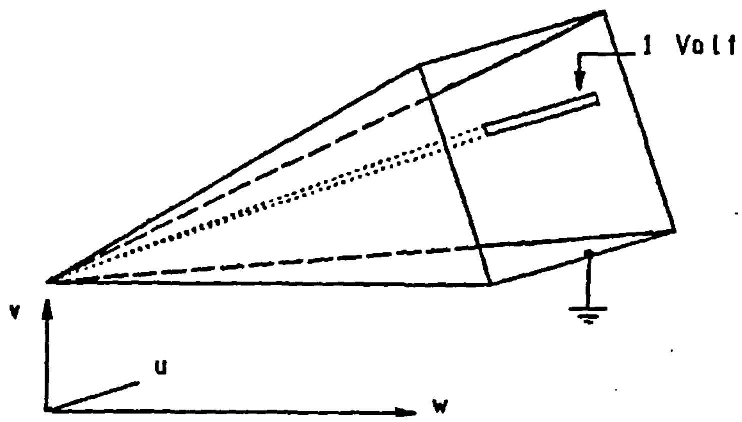
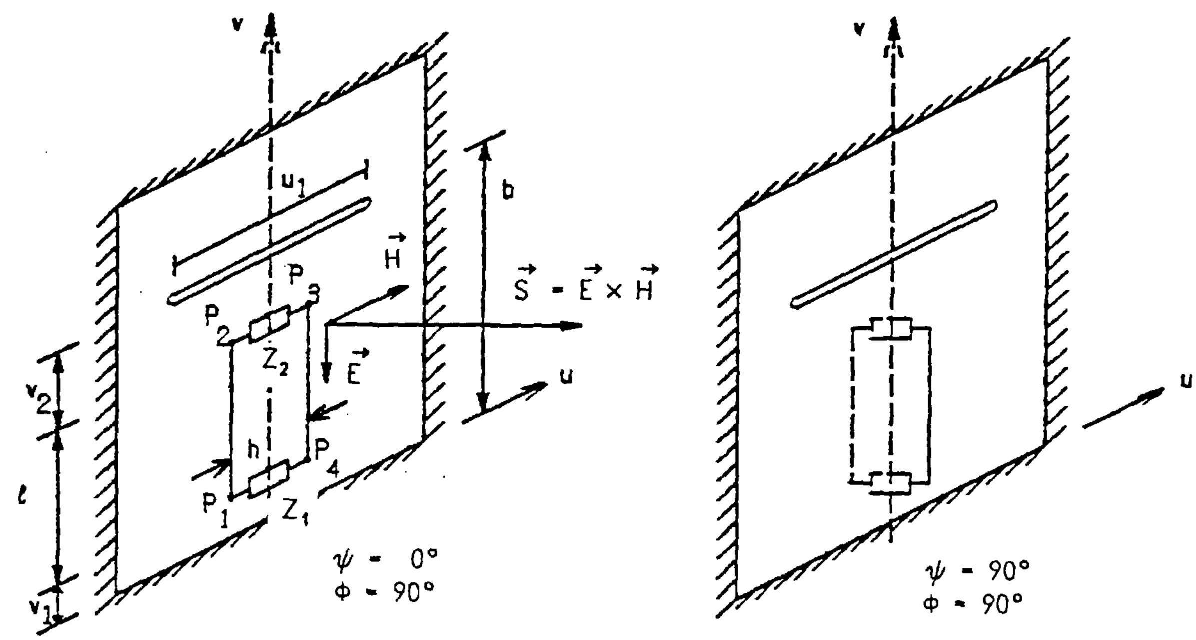


Figure 6a Rectangular (u,v,w) coordinates for the GTEM cell



(b) $\vec{S}$ through the line

(c) $\vec{S}$ in the plane of the line

Figure 6. Two possible orientations of the transmission line in GTEM cell

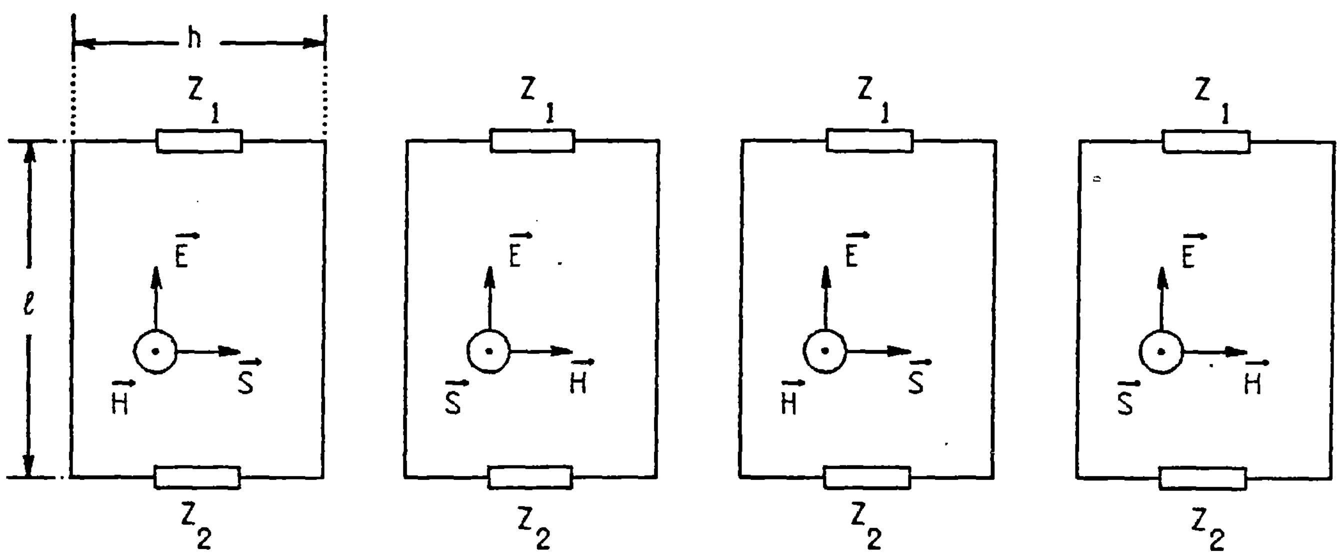
or non-uniformities in the geometry. On the other hand, the orientation of figure 6c leads to a differential mode response in the load impedances which can be measured and computed for comparison.

The measurement of the differential mode current through one of the terminating impedances is performed at two different cross sections of the GTEM cell for both orientations, resulting in four sets of experimental data. The experimental parameters for these four cases are listed in Table 1. It is observed that the transmission line terminating impedances are not equidistant from the bottom plate and the septum, i.e., v_1 is not equal to v_2 in all four cases. In fact, v_1 is much less than v_2, to ensure that the spurious responses due to transmission lines leading away from the current clamp are minimized. An optical link with a bandwidth of 100 MHz was tried but the physical dimensions of the metallic box of the optical link appear to perturb the measurements perhaps by elevating the electric field excitation. Finally, the measurements were made by connecting the current clamp, measuring the current through the impedance at the bottom end of the transmission line directly to a connector in the bottom plate of GTEM. This is the reason why $v_1 = 11$ cm and significantly smaller than v_2.

In addition, the vertical illuminating field varies to some extent over the length of the transmission line. The variation is not significant and an average value of the field is used for purposes of calculation.

Table 1 Experimental Parameters

Parameters	Units	Case 1	Case 2	Case 3	Case 4
<u>Fixed</u>					
ℓ	cm	24.5	24.5	24.5	24.5
h	cm	2.5	2.5	2.5	2.5
v_1	cm	11.0	11.0	11.0	11.0
Z_1	Ω	420	420	420	420
Z_2	Ω	420	420	420	420
ϕ	degrees	90	90	90	90
<u>Variable</u>					
w	m	3.49	3.49	4.82	4.82
b	cm	90.00	90.00	128.00	128.00
v_2	cm	54.50	54.50	92.50	92.50
$E(v_1)$	V/m	0.85	0.85	0.82	0.82
$E(v_1+\ell)$	V/m	1.03	1.03	0.91	0.91
$E_{average}$	V/m	0.94	0.94	0.86	0.86
ψ	degrees	90	nominal 0 calcul. 2	90	nominal 0 calcul. 2



Case 1   Case 2   Case 3   Case 4

Finally, it is also seen for cases 2 and 4 that the differential mode response should be ideally zero. A relatively small response was still measurable owing to geometrical non-uniformities. For this reason, in the computational approach a value of $\psi = 2$ degrees was used for purposes of comparison with the measurement. The results presented are on the basis of (10 V/m/Hz) field excitation on the two-wire transmission line in free space and GTEM while actual measurements were performed with about 20 V signal applied at the input port of the GTEM cell for improved signal to noise ratios in the experiment.

4. Analytical Models Used for Comparison

As was indicated earlier in Section 1, two independent approaches for computing the transmission line responses have been used, as briefly described below.

a. Transmission Line Theory

With reference to figure 4, showing an electromagnetic wave incident on a two-wire transmission line, Vance [5] has formulated the problem using the electric field component along the transmission line. This is equivalent to considering the distributed voltage sources due to magnetic flux linking through the line. Recall that for all the four cases under consideration, there is no electric field parallel to the terminating impedances. Vance's [5] formulation can be specialized to the present cases at hand i.e. horitontal polarization, $\psi = 90°$ or $0°$ (see figure 4), yielding

$$\tilde{I}_1(\omega) = \tilde{I}_2(\omega) \tag{1a}$$

$$\tilde{I}_1(\omega) = \frac{\tilde{E}_{average}(\omega)}{Z_c}\, \ell\, [1 - e^{-jkh\sin(\psi)}]\, e^{-\frac{jk\ell}{2}} \left[\frac{\sin\left(\frac{k\ell}{2}\right)}{\left(\frac{k\ell}{2}\right)}\right] \tag{1b}$$

where $\tilde{I}_1$ and $\tilde{I}_2$ are frequency spectrum of the current flowing through the terminal impedances ($Z_1 = Z_2 = Z_c$ for the present), and

$\tilde{E}_{average}(\omega)$	$\equiv$ longitudinal illuminating field = constant
ℓ	$\equiv$ length of the line = 24.5 cm
Z_c	$\equiv$ characteristic impedance $\simeq$ 420 Ω
k	$\equiv$ propagation constant = $(2\pi/\lambda) = (\omega/c)$
ω	$\equiv$ radian frequency
c	$\equiv$ speed of light $\simeq 3 \times 10^8$ m/s
λ	$\equiv$ incident wave length
h	$\equiv$ line separation $\simeq$ 2.5 cm
ϕ	$\equiv$ azimuthal angle of incidence = 90° for all cases
ψ	$\equiv$ elevational angle of incidence = 90° for cases 1 and 3 = 0° for cases 2 and 4

Equations (1a) and (1b) also indicate that if $\psi = 0$, these differential mode responses ideally vanish, for cases 2 and 4. However, for calculational purposes, we have used $\psi = 2^\circ$ for these two cases to account for experimental inaccuracies.

If we are only concerned with magnitude of the spectrum, we get from equation (1b)

$$|\tilde{I}_1(\omega)| = |\tilde{I}_2(\omega)| = \left| \frac{\tilde{E}_{average}(\omega)}{Z_c} \, \ell \, 2 \sin\left(\frac{h\, k \sin(\psi)}{2}\right) \frac{\sin\left(\frac{k\,\ell}{2}\right)}{\left(\frac{k\,\ell}{2}\right)} \right| \qquad (2)$$

The above expression starts from zero at dc frequency and monotonically increases, peaking at $\omega_p = (c\pi/\ell)$ and has a null at $\omega_n = (2c\pi/\ell)$. This corresponds to a $f_p = [c/(2\ell)]$ and $f_n = (c/\ell)$, where ℓ is the length of the transmission line, equal to 24.5 cm in our case resulting in $f_p \simeq 612$ MHz and $f_n = 1.22$ GHz. Equation (2) is a simple expression for computation. Observe that we have approximated $\tilde{E}_{average}(\omega)$ to be a constant ($\tilde{E}_{average}$ of Table 1) independent of both frequency and position along the transmission line, meaning the time domain excitation is a delta function whose strength is equal to this constant.

A second computational approach is to use a method of moments to solve the problem of two-wire line in free space illuminated by a plane wave. This approach consists of zoning the transmission line and solving the boundary value problem by satisfying the Maxwell's equations everywhere and the boundary conditions on the conductor surfaces.

The two approaches outlined above have been used for a test case of a two wire line (see figure 5) excited by an uniform plane wave with an average electric field of 10 V/m/Hz at varying incident angles ($\psi = 90^\circ$, 45° and 15°). The computations of the current $\tilde{I}1$ (A/Hz) flowing through the termination are shown in figure 7. The agreement between the two calculational approaches is excellent, for this simple problem, for all three incidences considered. We have chosen to use the Vance's [5] transmission line theoretical model for comparison with the measurements in the following section.

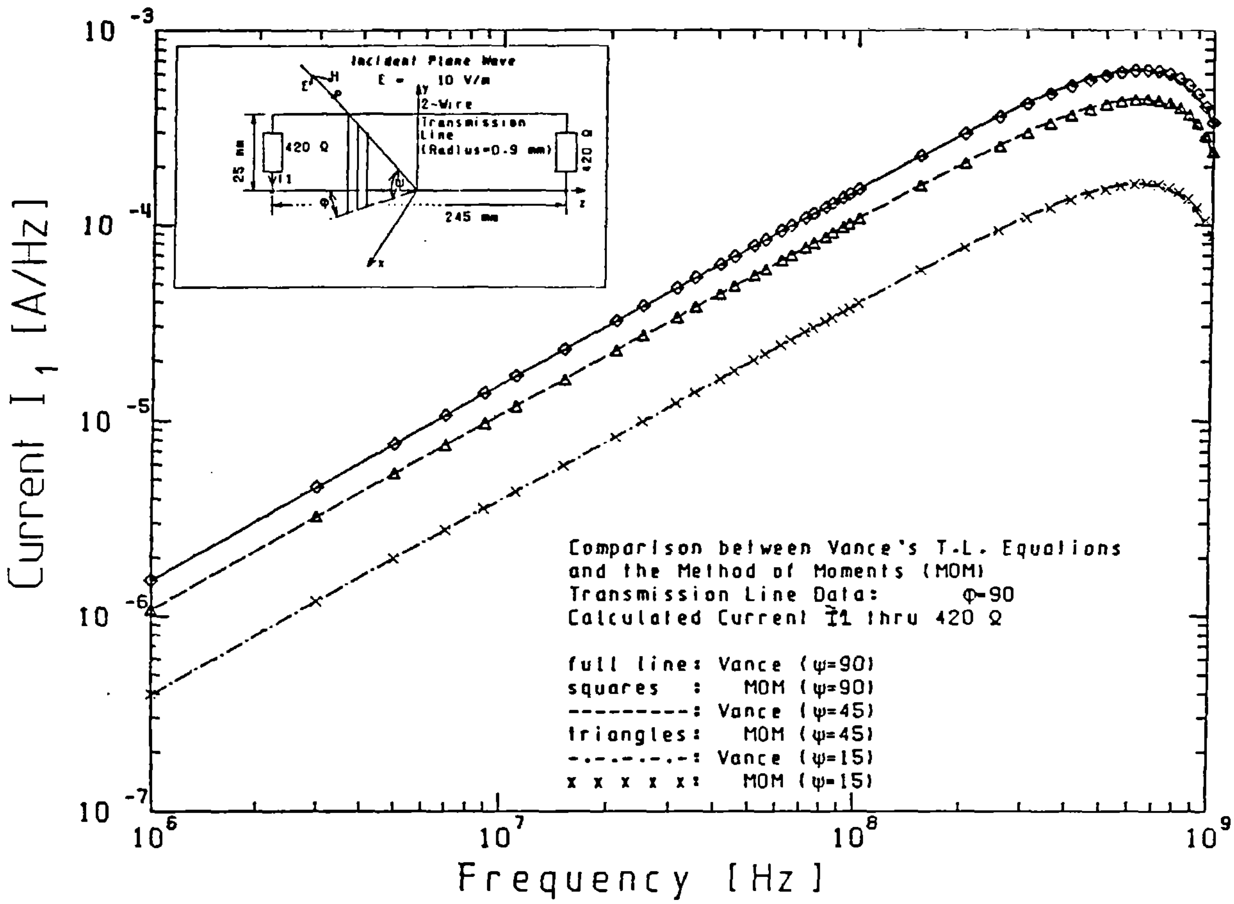
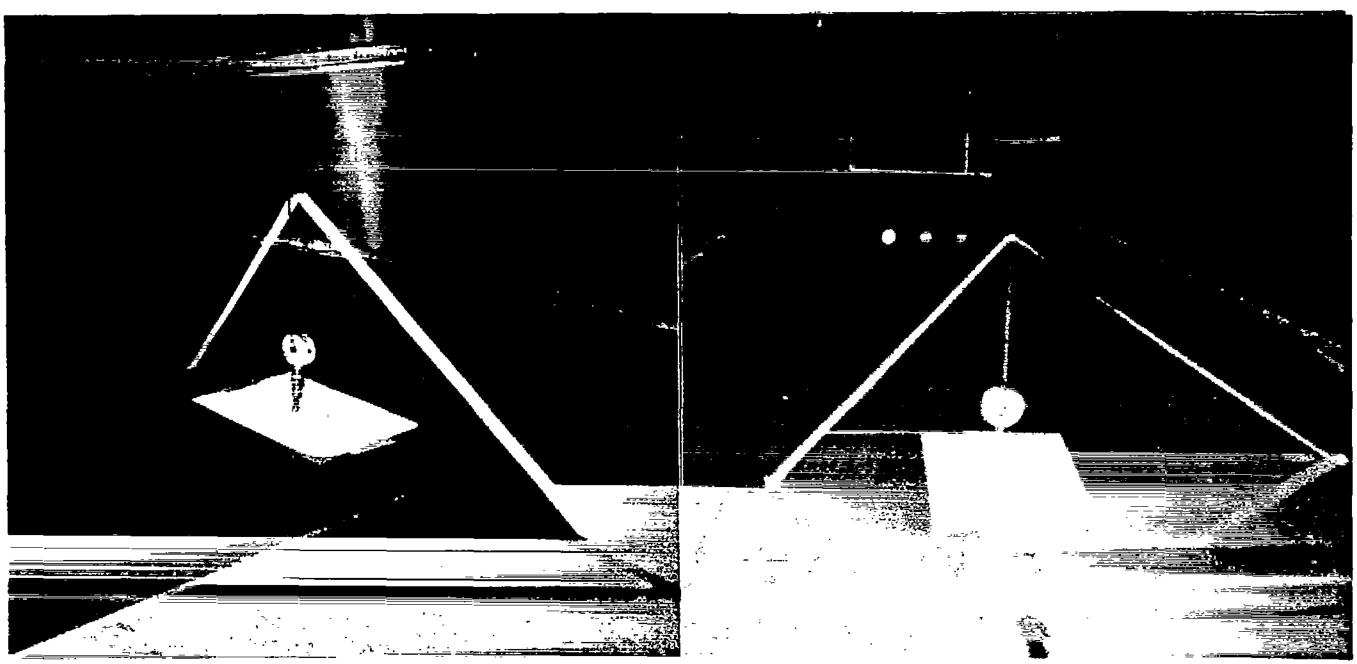


Figure. 7 Comparing the transmission line response by two different approaches (Vance [5] and MOM). The incident plane wave is horizontally polarized.

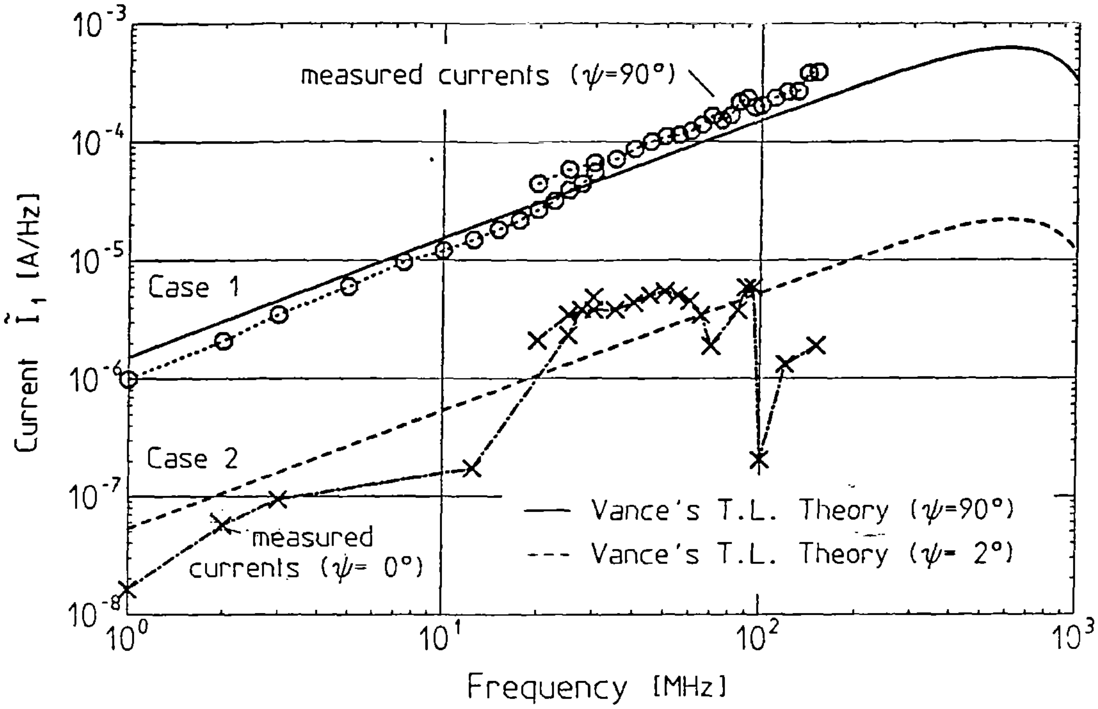
5. Comparison of Theoretical and Experimental Results

The four cases that we have experimented with are listed in Table 1 and the experimental parameters in Table 1 are illustrated in earlier figures. The transmission line and the current clamp, in its two orientations in GTEM may be seen in Fig. 8. Observe that the current clamp (ESH2-Z1 for the 1 - 30 MHZ and ESV-Z1 for 20 - 1000 MHz) is directly connected to a connector in the bottom plate of GTEM, to avoid spurious couplings to cables, optical links etc. The frequency range of the observed data was limited by us to 1 to 150 MHz, where we are reasonably well assured of the appearance of a fairly precise TEM mode propagating in GTEM cell. Figure 9 shows the comparison of calculations and experimental data. The comparisons are made on the basis of 10 V/m/Hz incident electric field. Cases 1 and 3 give maximum signals and cases 2 and 4 result in minimum signal. It is recalled that $\psi = 2^\circ$ is used in computing cases 2 and 4, which may be termed 'experimental noise floor'. Observe also that cases 1 and 2 are in better agreement than cases 3 and 4, owing to the fact that cases 3 and 4 are closer to the termination and the excitation fields are much 'cleaner' under cases 1 and 2.



(a) (b)

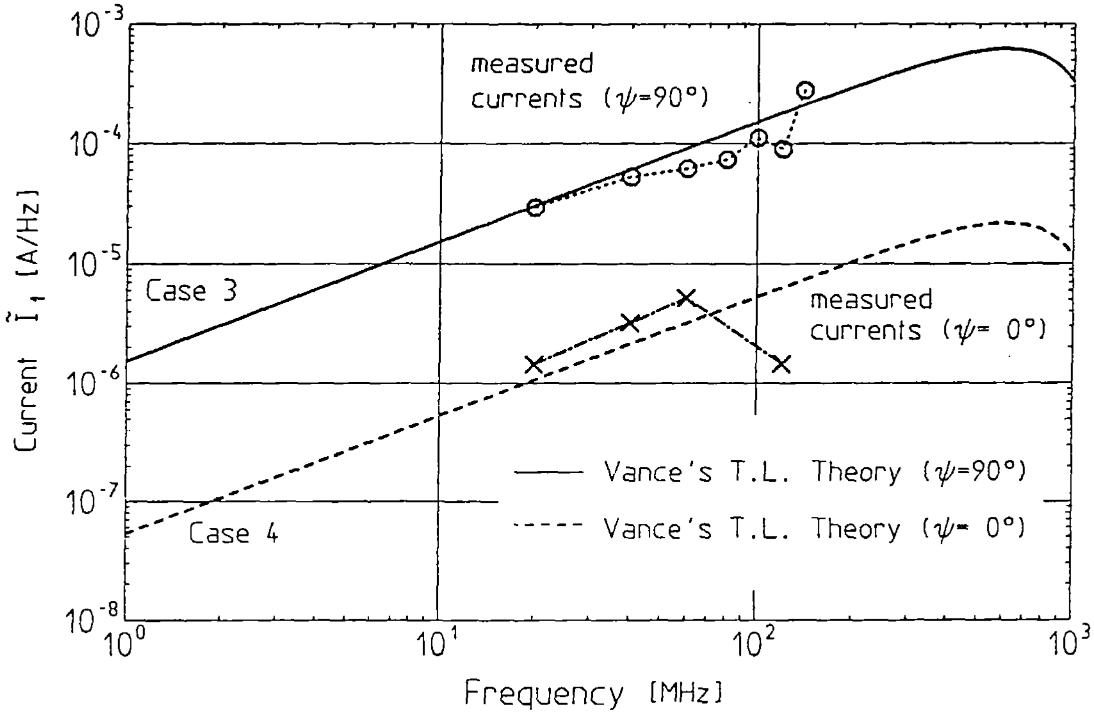
Figure 8. Transmission line experiment in GTEM
(a) Angle of incidence $\psi = 0^\circ$ (no signal)
(b) Angle of incidence $\psi = 90^\circ$ (max. signal)



Measured and calculated currents thru Z_1 at location
w = 3490 mm,
b = 900 mm.

Transmission line data:

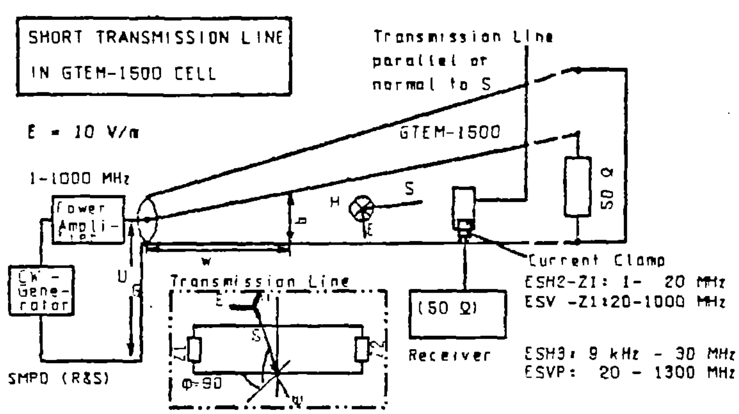
$Z_1 = Z_0$,
$Z_2 = Z_0$,
$\Phi = 90°$.



Measured and calculated currents thru Z_1 at location
w = 4820 mm,
b = 1280 mm.

Transmission line data:

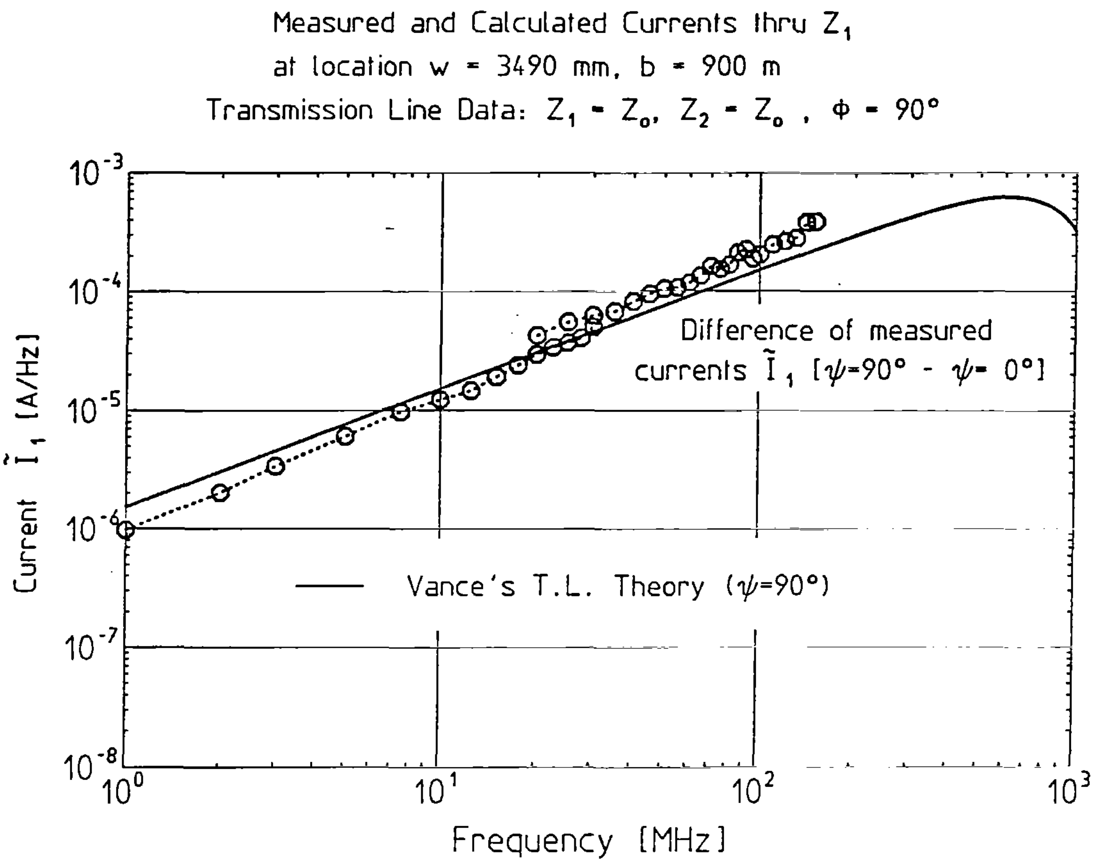
$Z_1 = Z_0$,
$Z_2 = Z_0$,
$\Phi = 90°$.



Experimental set up.

Figure 9. Comparison of theory and experiment

One could subtract the measurement of case 2 from case 1 and case 4 from 3 to arrive at an improved experimental data for cases 1 and 3. This has been done and the results shown in figure 10. As may be expected, once again this results at cross section w = 3.49 m (closer to the source and farther away from the terminator) compare better than at w = 4.28 m (closer to the terminator).



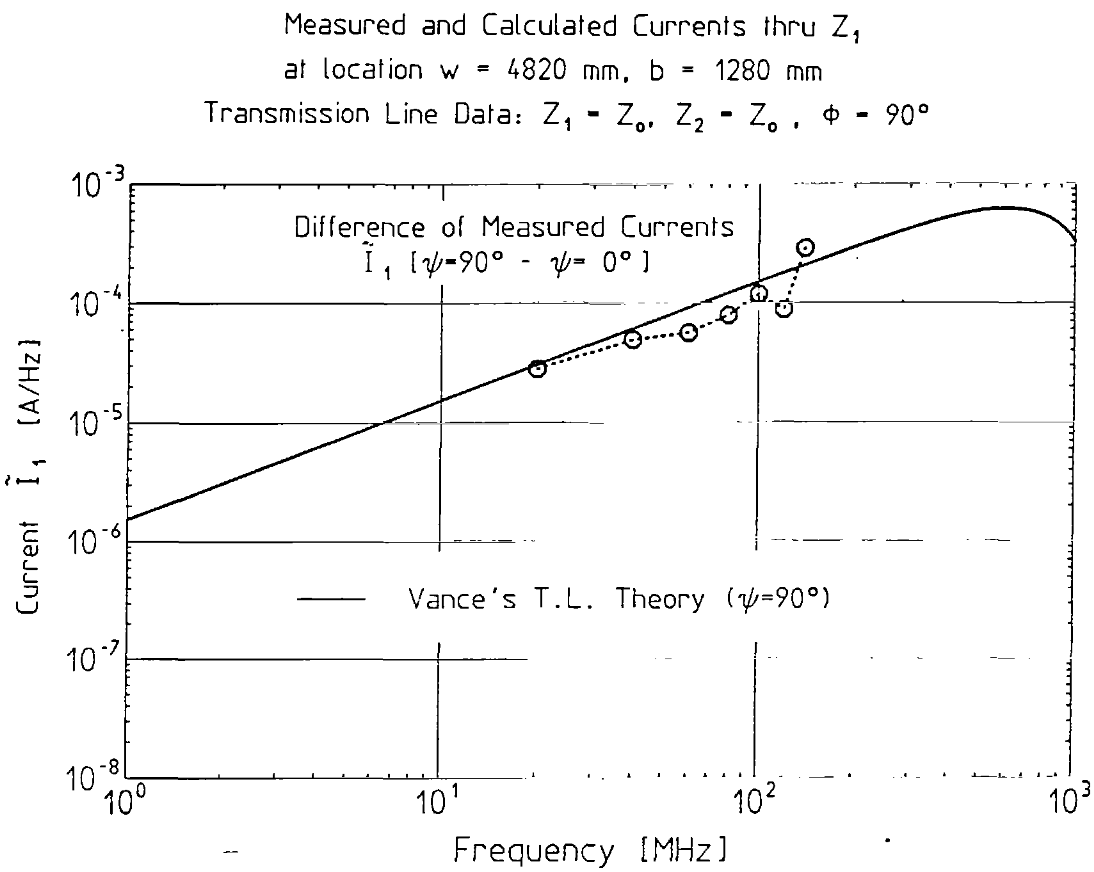


Figure 10. Transmission line response at two cross sections obtained from subtracting (magnitude sense only) the "null" signal from the maximum signal measurements.

6. Concluding Remarks

We have addressed the problem of field excitation of uniform two-wire transmission line while focussing attention on the experimental measurements. Theoretical approaches are available in the literature for computing the transmission line response. The plane wave source used in the experiment is the propagating TEM mode in a GTEM cell. This cell differs from the conventional TEM cells and has been reviewed briefly in this paper. The electric and magnetic fields as functions of frequency are constant within ± 1.5 dB up to about 150 MHz and consequently, the experimental data is recorded in the range of 1 to 150 MHz. Two different computational approaches are also compared giving us the required reliability in the computations before comparing with measurements. The comparisons are in good agreement in the frequency range considered. We were partly motivated to perform this study, since experimental data about wave-line interaction seems to be lacking in the literature. Work is under way to achieve even further improvements with respect to precise field uniformity and to use small transmission lines as a measurement tool to detect existing higher order modes, especially in the frequency range up to 1 GHz throughout the test volume.

References

[1] C.D. Taylor, R.S. Sutterwhite and C.W. Harrison, Jr., "The Response of a Terminated Two-Wire Transmission Line Excited by a Non-Uniform Electromagnetic Field", IEEE Transactions on Antennas and Propagation, Vol. AP-13, November 1965, pp 987-989

[2] C.R. Paul, "Frequency Response of Multiconductor Transmission Lines Illuminated by an Electromagnetic Field", IEEE Transactions on Electromagnetic Compatibility, Vol. EMC-18, No. 4, November 1976, pp 183-190

[3] S. Frankel, Multiconductor Transmission Line Analysis, ArTech House, Inc., 1977

[4] A.A. Smith, Jr., Coupling of External Electromagnetic Fields to Transmission Lines, John Wiley and Sons, New York 1977

[5] E.F. Vance, Coupling to Shielded Cables, John Wiley and Sons, New York, 1978

[6] K.S.H. Lee, "Two Parallel Terminated Conductors in External Fields", IEEE Transaction on Electromagnetic Compatibility, Vol. EMC-20, No. 2, May 1978, pp 288-295

[7] F.M. Tesche, T.K. Liu, S.K. Chang and D.V. Giri, "Field Excitation of Multiconductor Transmission Lines", Interaction Note 351, September 1978

[8] C.E. Baum, T.K. Liu and F.M. Tesche, "On the Analysis of General Multiconductor Transmission-Line Networks", Interaction Note 350, November 1978

[9] M. Aguet, M. Ianovici and C.C. Lin, "Transient Electromagnetic Field Coupling to Long Shielded Cables", IEEE Transaction on Electromagnetic Compatibility, Vol. EMC-22, No. 4, November 1980, pp 276-282

[10] W. Blumer and N. Ari, "The Response of a Terminated Uniform Two-Wire Transmission Line Excited by a Plane Electromagnetic Field", Submitted to ELECTROMAGNETICS, 1987

[11] S. Ramo, J.R. Whinnery and T. Van Duzer, Fields and Waves in Communication Electronics, John Wiley and Sons, 1984 Edition, Chapter V, pp 210-225

[12] D. Königstein und D. Hansen, "A New Family of TEM Cells with Enlarged Bandwidth and Optimized Working Volume", 7th International Zurich Symposium and Technical Exhibition on Electromagnetic Compatibility, 3-5 March, 1987

[13] M.L. Crawford, "Generation of Standard EM Fields Using TEM Transmission Cells", IEEE Transaction on Electromagnetic Compatibility, Vol. EMC-16, pp 189-195, November 1974