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TRANSIENTS IN RESISTIVELY LOADED ANTENNAS AND THEIR COMPARISON WITH CONICAL ANTENNAS AND TEM HORNS

Motohisa Kanda

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CONTENTS

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The receiving and transmitting transient responses for a relatively short, linear antenna with continuous resistive loading are investigated theoretically and experimentally. The antenna considered is a nonconducting cylinder with continuously deposited, varying-conductivity, resistive loading.

The current distribution, the corresponding effective length, and the driving point impedance are calculated by use of the method of moments and compared with the Wu-King approximation. The receiving and transmitting transient responses are calculated in the frequency domain using the results of the effective length and driving point impedance. The use of FFT then allows the determination of transient fields for a known input waveform. The receiving and transmitting transient responses for a conical antenna and a TEM horn are also investigated theoretically to compare with the transient response of the resistively loaded antenna.

Time domain measurements were performed using a time domain antenna range with a time domain automatic network analyzer. The agreements between theory and experiments of the receiving and transmitting transient responses for the resistively loaded antenna, the conical antenna, and the TEM horn are very good.

The receiving transient response of the resistively loaded antenna indicates that an impulse shape of 70 ps duration is well preserved. This provides the unique capability of this antenna to measure fast, time-varying, transient fields with minimal pulse-shape distortion due to nonlinear amplitude or phase characteristics.

Key words: Conical antenna; EMP; FFT; loaded antenna; method of moments; TEM horn; time domain measurements; transients in resistivity.

I. INTRODUCTION

Recent study related to electromagnetic pulse (EMP) phenomena has focused strong attention on the subject of transient EM fields. Antenna structures which are able to preserve time-domain waveform of EMP need to be inherently broadband and non-dispersive. One such antenna which has been successfully fabricated is a linear antenna with continuously tapered resistive loading [1, 2, 3, 4].

In the previous papers by the author [3, 4], the current distributions on the resistively loaded linear antenna were calculated by solving the wave equation numerically using the method of moments [5]. Using the current distribution obtained by the method of moments, other quantities of interest, such as the input admittance, the near-field and far-field radiation patterns, and the radiation efficiency, were calculated and compared with the results calculated from the Wu-King current distributions [1]. To verify the theoretical results, several resistively loaded linear antennas were fabricated, and their CW receiving characteristics were examined theoretically and experimentally. The CW receiving characteristics were examined using both a TEM cell [6] and a near-field extrapolation range [7] to cover the frequency range from 5 kHz to 5 GHz.

The purpose of the present paper is to theoretically and experimentally investigate the receiving and transmitting transient responses for a relatively short, linear antenna with continuous resistive loading. The antenna considered is a nonconducting cylinder with continuously deposited, varying-conductivity, resistive loading.

The current distribution, the corresponding effective length, and the driving point impedance of the resistively loaded linear antenna are calculated by use of the method of moments [5] and compared with the Wu-King approximation [1]. The receiving and transmitting transient responses of the resistively loaded linear antenna are calculated in the frequency domain using the results of the effective length and the driving point impedance. The use of the fast Fourier transform (FFT) then allows the determination of transient fields for a known input waveform. As a comparison, the receiving and transmitting transient responses for a conical antenna and a TEM horn are also investigated theoretically.

Finally, the time domain measurements were performed using a time domain antenna range with a time domain automatic network analyzer. The comparison between theoretical and experimental results of the receiving and transmitting transient responses for the resistively loaded linear antenna, a conical antenna, and a TEM horn are also given in this paper.

II. THE RECEIVING AND TRANSMITTING TRANSIENT RESPONSES

The radiated electric field $E_\theta^{rad}(f)$ from a linear antenna at distance r in the far-field region is given by [8]

$$E_\theta^{rad}(f) = j \frac{60\, V_o(f)}{Z_o(f) + Z_g} F(f) \frac{e^{-jkr}}{r} , \qquad (1)$$

where F(f) is the field characteristic of an antenna with an antenna impedance $Z_o(f)$, $V_o(f)$ is the driving voltage of a generator with an impedance Z_g, f is a frequency, and k is a wave number. The transmitting transfer function of the antenna is then defined as

$$S_t(f) \equiv \frac{E^{Rad}(f)}{V_o(f)} = j \frac{60}{Z_o(f) + Z_g} F(f) \frac{e^{-jkr}}{r} . \tag{2}$$

When the same antenna is used for receiving, the received voltage $V_L(f)$ across a load impedance Z_L is given by

$$V_L(f) = \frac{-h_e(f)E^{inc}(f)Z_L}{Z_o(f) + Z_L} , \tag{3}$$

where $E^{inc}(f)$ is a normal incident field to an antenna with an effective length $h_e(f)$. The receiving transfer function of the antenna is then defined as

$$S_R(f) \equiv \frac{V_L(f)}{E^{inc}(f)} = \frac{-h_e(f)\ Z_L}{Z_o(f) + Z_L} . \tag{4}$$

Here a field characteristic F(f) and an effective length $h_e(f)$ are related through the Rayleigh-Carson reciprocity theorem [8],

$$F(f) = kh_e(f). \tag{5}$$

Therefore, for the analysis of general transient phenomena in the far-field region, it should be noted that a transmitting transient response is simply the time derivative of a receiving transient response.

III. THE EFFECTIVE LENGTH AND THE DRIVING-POINT IMPEDANCE OF A RESISTIVELY LOADED LINEAR ANTENNA

For a linear antenna with continuous resistive loading where the internal impedance per unit length $Z^i(z)$ is given by

$$Z^i(z) = \frac{60|\psi|}{h - |z|} , \tag{6}$$

the approximate current distribution is found to be of a traveling wave in nature [1], i.e.,

$$I_z(z) = \frac{V_o}{60\psi(1-j/kh)}\left(1 - \frac{|z|}{h}\right) e^{-jk|z|} . \qquad (7)$$

The symbols have the following meanings: a is a radius of an antenna, h is a half physical length of a dipole antenna, k is a wave number,

$$\Psi \cong 2\left\{\sinh^{-1}\frac{h}{a} - C(2ka,2kh) - jS(2ka,2kh)\right\} + \frac{j}{kh}(1-e^{-j2kh})$$

and C(a,x) and S(a,x) are the generalized cosine and sine integrals.

In the previous papers by the author [3, 4], the current distribution on the resistively loaded linear antenna for different frequencies is calculated by solving the one-dimensional wave equation numerically using the method of moments [5]. The detailed discussion on the subject is given elsewhere by the author [4]. Here, to simplify the integral equation, it is assumed that a wire radius, a, is much smaller than a wavelength, λ, i.e., $a << \lambda$, so that the current can be considered to flow in a filament along the z-axis rather than on the surface of a cylinder.

The numerical solutions using the method of moments and the analysis based on the approximations by Wu and King have been applied to a resistively loaded linear antenna. The resistive antenna elements are made by depositing a linearly tapered thin film alloy on a glass rod. For a dipole configuration, a glass rod, 15 cm long and 0.254 cm in diameter, is used as a substrate for the deposited element. The resistive loading profile and the photograph of the resistively loaded dipole antenna are, respectively, shown in figures 1(a) and 1(b).

The magnitude and the phase of the current distributions on the resistively loaded antenna are calculated using both the method of moments and the Wu-King approximation [1], and are shown in figure 2 at 1 GHz along with experimental result.

The effective length, $h_e(f)$, of the resistively loaded linear antenna is calculated by

$$h_e(f) = \frac{1}{I_z(0)} \int_{-h}^{h} I_z(z)dz . \qquad (8)$$

Using the approximate current distribution given in eq (7), the effective length $h_e(f)$ and the driving-point impedance $Z_o(f)$ of the resistively loaded linear antenna are calculated and given by

$$h_e(f) = \frac{2}{k^2 h} (1 - jkh - e^{-jkh}) \tag{9}$$

and

$$Z_o(f) = 60\psi(1 - \frac{j}{kh}). \tag{10}$$

The effective length and the driving-point impedance are shown in figures 3 and 4, respectively.

The more exact analyses for the effective length and the driving-point impedance of the resistively loaded linear antenna were performed by numerically integrating eq (8) for the current distribution obtained by the method of moments, and are also shown in figures 3 and 4, along with experimental results.

The results of the effective lengths and the driving-poing impedances obtained from both the approximate current distributions and the moment method results are used in eq (1) and (3) to calculate the receiving and transmitting transient responses in the frequency domain. The use of the FFT then allows the determination of transients fields for a known input waveform.

IV. THE EFFECTIVE LENGTH AND THE DRIVING-POINT IMPEDANCE OF A CONICAL ANTENNA

The effective length, $h_e(f)$, of a conical antenna can be derived from its radiation field using the Rayleigh-Carson receiprocity theorem. The driving-point impedance, $Z_o(f)$, of a conical antenna is given by the ratio of the frequency domain representation of the voltage applied at the antenna terminal to the frequency domain representative of the resultant current flowing into the antenna terminal. The detailed analyses of the effective length, $h_e(f)$, and the driving-point impedance, $Z_o(f)$, of a conical antenna were performed by C. W. Harrison, Jr., and C. S. Williams, Jr. [9], and are given below.

$$h_e(f) = \frac{1}{k^2 \ell \left(1 + \frac{\beta}{\alpha}\right)} \left(\frac{\beta}{\alpha} e^{jk\ell} - d^{-jk\ell}\right)$$

$$\cdot \sum_{n=1}^{\infty} P_n(\cos\theta_o) P_n'(o) \left(\frac{2n+1}{n^2+n}\right) \frac{j^{n+1}}{h_{n-1}^{(2)}(k\ell) - \frac{n}{ka} h_n^{(2)}(k\ell)} \tag{11}$$

and

$$Z_o(f) = Z_c \left(\frac{1 - \frac{\beta}{\alpha}}{1 + \frac{\beta}{\alpha}} \right) . \qquad (12)$$

The symbols have the following meanings:

ℓ is the length of the antenna,

$P_n(\cos\theta)$ is the Legendre polynomial of order n,

$h_n^{(2)}(k\ell)$ is the spherical Hankel function of the second kind.

$$Z_c = \frac{\zeta_o}{2\pi} \ln \cot \frac{\theta_o}{2} .$$

$$\frac{\beta}{\alpha} = e^{-j2ka} \left\{ \frac{1 + j \frac{\zeta_o}{2\pi Z_c} \sum_{n=1}^{\infty} \frac{2n+1}{n(n+1)} \left[P_n(\cos\theta_o) \right]^2 \zeta_n(k\ell)}{-1 + j \frac{\zeta_o}{2\pi Z_c} \sum_{n=1}^{\infty} \frac{2n+1}{n(n+1)} \left[P_n(\cos\theta_o) \right]^2 \zeta_n(k\ell)} \right\} ,$$

and

$$\zeta_n(ka) = \frac{h_n^{(2)}(k\ell)}{h_{n-1}^{(2)}(k\ell) - \frac{n}{ka} h_n^{(2)}(k\ell)} .$$

The results of the effective length and the driving-point impedance given respectively by eq (11) and (12) are used in eq (1) and (3) to calculate the receiving and transmitting transient responses in the frequency domain. The use of FFT then allows the determination of transient fields for a known input waveform.

V. THE ANALYSIS FOR A TEM HORN

Since the concept of an effective length becomes ambiguous for a TEM horn, the transmitting transient response in a TEM horn is calculated from the radiation field of a TEM horn. The receiving transient response is then determined using the Rayleigh-Carson reciprocity theorem given in eq (5) in conjunction with eq (1) and (3).

It is assumed that the horn flare angle and the plate widths are chosen so that the TEM horn guides only the TEM mode by maintaining a constant characteristic impedance. Then, by neglecting the edge diffraction effect and fringe fields, the linearly polarized spherical field at the aperture is assumed to be

$$E_y(x',y',0) = \frac{r_o^2}{\sqrt{r_o^2 + x'^2 + y'^2}} \; \frac{e^{-jk\left(\sqrt{r_o^2+x'^2+y'^2} - r_o\right)}}{\sqrt{r_o^2 + y'^2}} , \tag{13}$$

Here, the orientation of the x'y'z' coordinates is shown in figure 6, in which the source is assumed to be at a distance r_o from the center of the aperture.

The radiated electromagnetic fields, $E^{rad}(x,y,z)$, outside the aperture are then evaluated by use of the plane-wave spectrum analysis technique [10]. That is, since

$$\overline{S}(k_x,k_y) = \frac{1}{2\pi} \iint_{\text{aperture}} \overline{E}(x',y',0)\, e^{j(k_x x'+k_y y')}\, dx'\, dy', \tag{14}$$

then

$$\overline{E}^{rad}(x,y,z) = \frac{1}{2\pi} \iint_{-\infty}^{\infty} \overline{S}(k_x,k_y)\, e^{-j(k_x x+k_y y+k_z z)}\, dk_x\, dk_y \tag{15}$$

with $k_x^2 + k_y^2 + k_z^2 = k^2 = (\frac{2\pi}{\lambda})^2$. These integrations were carried out by use of an FFT algorithm.

The other and perhaps more conventional technique for calculating the radiation field of a TEM horn is as follows. Given the aperture electric field, $\vec{E}$, in eq (13), one can determine an equivalent magnetic current, M, at the aperture by

$$\vec{M} = 2\vec{E} \times \vec{n} \tag{16}$$

By use of an electric vector potential $\vec{F}$, i.e.,

$$\overline{F} = \frac{1}{4\pi} \iint_{\text{aperture}} \vec{M}\, \frac{e^{-ikr}}{r}\, ds \quad , \tag{17}$$

one can determine the electric and magnetic fields through the following relationships:

$$\vec{E} = - \nabla \times \vec{F} \quad (18)$$

and

$$\vec{H} = -j\omega\varepsilon_o \vec{F} + \frac{1}{jw\mu_o} \nabla(\nabla \cdot \vec{F}). \quad (19)$$

As an example, the E_y component becomes

$$E_y^{rad}(x,y,z) = \frac{1}{4\pi} \iint_{aperture} M_x(x',y') \left(jk+\frac{1}{r}\right) \cdot \frac{e^{-jkr}}{r} \cdot \frac{z}{r} dx'dy' \quad (20)$$

These two techniques are used to calculate the radiation field from a TEM horn in the frequency domain. The receiving characteristic of a TEM horn is determined from the transmitting characteristic by use of the Rayleigh-Carson reciprocity theorem given in eq (5) with eq (1) and (3).

VI. FREQUENCY DOMAIN RESULTS

In this section, the receiving and the transmitting characteristics of the resistively loaded dipole, a conical antenna, and a TEM horn are given in the frequency domain. The receiving and the transmitting characteristic are evaluated theoretically and compared with experiments.

The experiments are performed using a time domain antenna range with a time domain automatic network analyzer (TDANA). The transmitting characteristics of antennas are determined experimentally by using the resistively loaded antenna for a standard receiving antenna, since its receiving characteristic is well defined theoretically as given in section VI.1. On the other hand, the receiving characteristics are determined experimentally by using a conical antenna for a standard transmitting antenna, since its transmitting characteristic is well defined theoretically as given in section VI.3. The TDANA measures the time domain waveform of the impulse response.

The time domain waveform is then digitized and stored in the minicomputer memory. By acquiring an ensemble of many waveforms, it is possible to perform signal averaging within the minicomputer to improve the signal to noise ratio in the measurements. The minicomputer then computes the receiving and the transmitting characteristics from the digitized, averaged waveform using the FFT.

VI.1 Resistively Loaded Linear Antenna

The magnitude and the phase of the transfer function of the receiving characteristic for the resistively loaded linear antenna with 100 Ω load are calculated theoretically and are respectively shown in figures 5(a) and 5(b) along with the experimental results. Generally, the agreement between theory and the experimental result is very good.

It is found from figure 5 that the magnitude of the receiving transfer function is relatively flat above 200 MHz, whereas it rolls off 6 dB per octave below 200 MHz. The phase of the receiving transfer function is constant over the frequency range from 100 kHz to 100 MHz. Although the relatively small phase dispersion takes place above 100 MHz, the over-all phase degradation for the entire frequency range from 100 kHz to 10 GHz is only 160 degrees.

VI.2 TEM Horn

The magnitude of the receiving transfer function for a 36 cm long TEM horn with 100 Ω load is calculated theoretically and is shown in figure 6 along with the experimental results. The agreement between theory and the experimental result is good except at frequencies below 50 MHz. The theoretical result for the receiving transfer function of the TEM horn is based on the assumption that, regardless of its operation frequency, the tangential electric field at the TEM horn aperture is assumed to be a linearly polarized spherical wave as given in eq (13). Moreover, the magnitude of the assumed linearly polarized spherical wave at the horn aperture is assumed to be constant with frequency by ignoring all the reflections both at the aperture and at the throat at the TEM horn. It is, however, apparent from the results of reflection coefficient measurements made for the TEM horn that the reflection, particularly at the horn aperture, becomes very severe at 100 MHz (∿0.98).

Therefore, the assumption of the constant spherical field at the horn aperture totally fails in the frequency range below 100 MHz. Moreover, it is also apparent that particularly at the low end of the frequency range below 100 MHz, when the aperture size (21.6 cm in this case) becomes much smaller than a half-wavelength, the assumption of a linearly polarized spherical wave at the horn aperture may also fail. An improved theoretical model, which will take into account the effects due to the aperture and the throat of the TEM horn, will be developed and presented as the subject of a future paper.

VI.3 Conical Antenna

The transfer function of the transmitting characteristics for a conical antenna (2.7 m long, 8 degrees apex angle) is calculated theoretically and is given in figure 7. In this figure, there are two curves, one of which corresponds to summation up to 57 terms and the other corresponds to summation up to 139 terms in eq (11) and (12). Both the curves agree with each other very well, indicating that the convergence is very good for a numerical solution with a 57-term summation. It is found from figure 7 that the transfer function of the transmitting characteristic for the conical antenna is reasonably flat above 10 MHz.

VII. TIME DOMAIN RESULTS

Once frequency domain solutions are determined, use of the FFT then allows the determination of transient fields for a known input waveform. The experiments were performed by use of a time domain antenna range with a time domain automatic network analyzer. The impulse generator generates extremely narrow (70 ps) duration impulses with relatively flat spectrum amplitudes greater than 60 dBμV/MHz up to 5 GHz as shown in figure 8.

This impulse was used both as a driving voltage for the investigation of transmitting transient responses and as an incident impulse field for the investigation of receiving transient responses.

VII.1 Resistively Loaded Linear Antenna

The receiving and the transmitting characteristics of the transient responses for the resistively loaded linear antenna are calculated theoretically using the FFT and shown respectively in figures 9(a) and 9(b) along with the experimental results. Generally, the theoretical results based on the current distributions by the method of moments and by the Wu-King approximation agree very well with the experimental results.

As indicated in figure 9(a), the original 70 ps pulse was broadened due to some dispersion. Figure 9 also indicates clearly that the transmitting characteristic of the transient response is proportional to its receiving characteristic differentiated with respect to time, as expected from the Rayleigh-Carson reciprocity theorem given in eq (5).

VII.2 TEM Horn

The receiving and the transmitting characteristics of the transient responses for the TEM horn are calculated theoretically and are shown in figure 10 along with the experimental results. The agreement between the theory and the experiments is very good, although the theory developed in Sec. V fails at frequencies below 100 MHz. Since the lowest frequency points included in the FFT analysis is 20 MHz, the deficiency in the theory at the frequency range between 20 MHz and 100 MHz, which corresponds to only 5 frequency points in the FFT analysis, does not seem to affect much the time domain waveform.

VII.3 Conical Antenna

The transmitting characteristic of the transient response for the conical antenna is calculated theoretically and given in figure 11 along with the experimental result. The theoretical calculations for the time domain waveform using the 57-term summation agree very well with that using the 139-term summation.

VIII. CONCLUSION

The receiving and transmitting transient responses of the resistively loaded linear antenna, the TEM horn, and the conical antenna are investigated theoretically and experimentally using the FFT technique. The receiving transient response of the resistively loaded linear antenna indicates that the shape of a 70 ps impulse is well preserved.

The results of theoretical and experimental investigations indicate that the receiving and transmitting transient responses of a relatively short linear antenna with continuously tapered resistive loading can be analyzed very well theoretically. Since its receiving transient response is well behaved, the resistively loaded linear antenna should find very wide applications as a standard receiving antenna for the measurements of fast, time-varying, transient electromagnetic fields with minimal pulse-shape distortion due to nonlinear amplitude or phase characteristics.

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FIGURE CAPTIONS

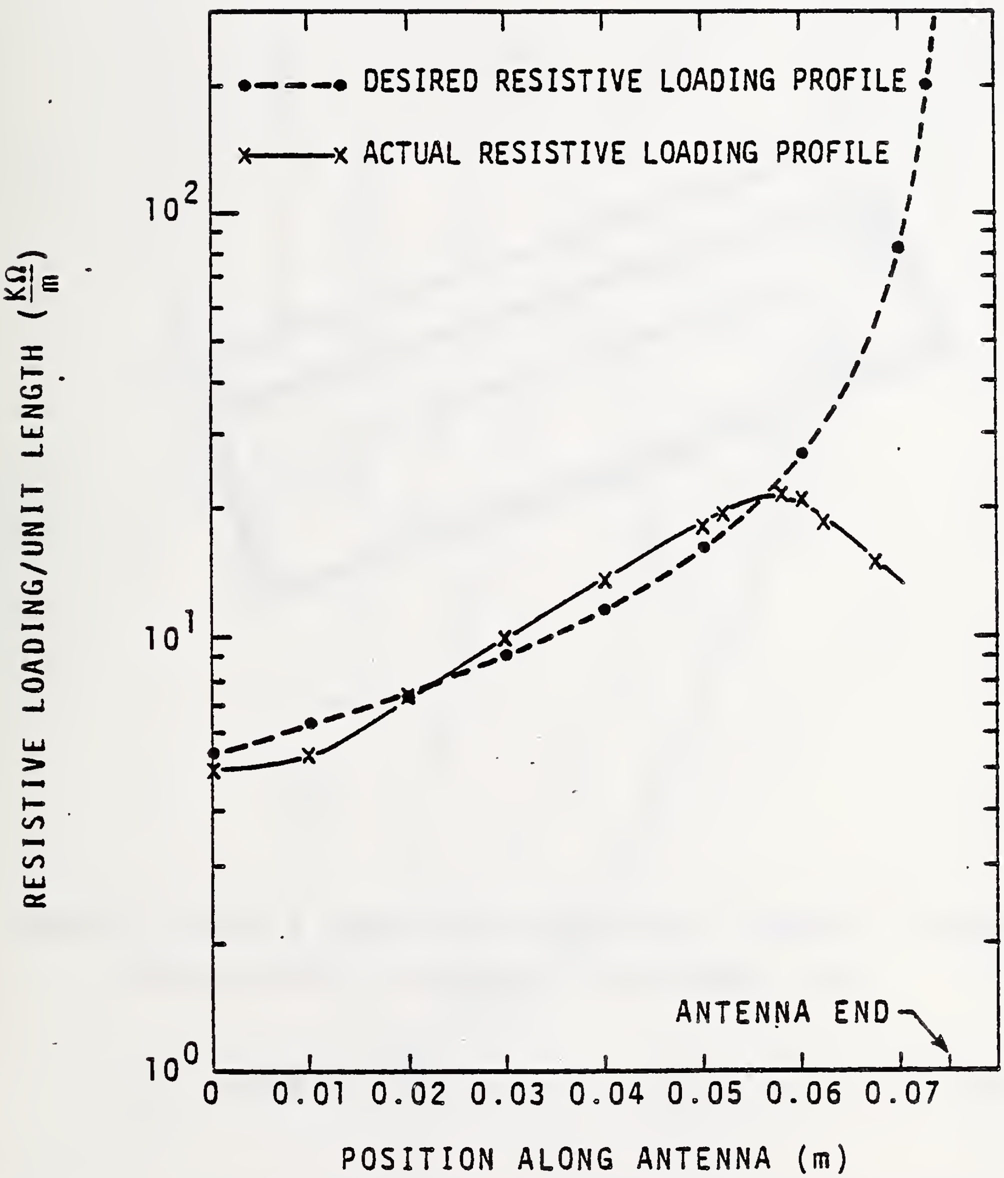

Figure 1. Dipole with continuously tapered resistive loading.

a) Resistive loading profile.

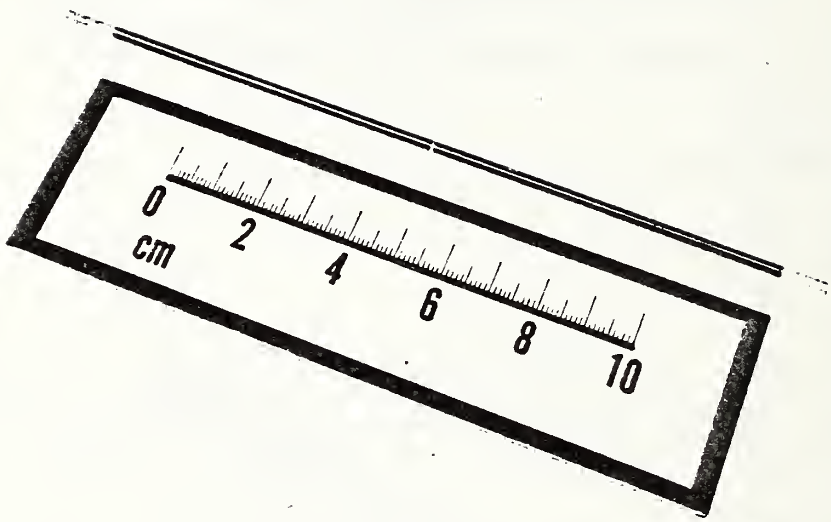

Figure 1. Dipole with continuously tapered resistive loading.
b) Photographs of resistively loaded dipole.

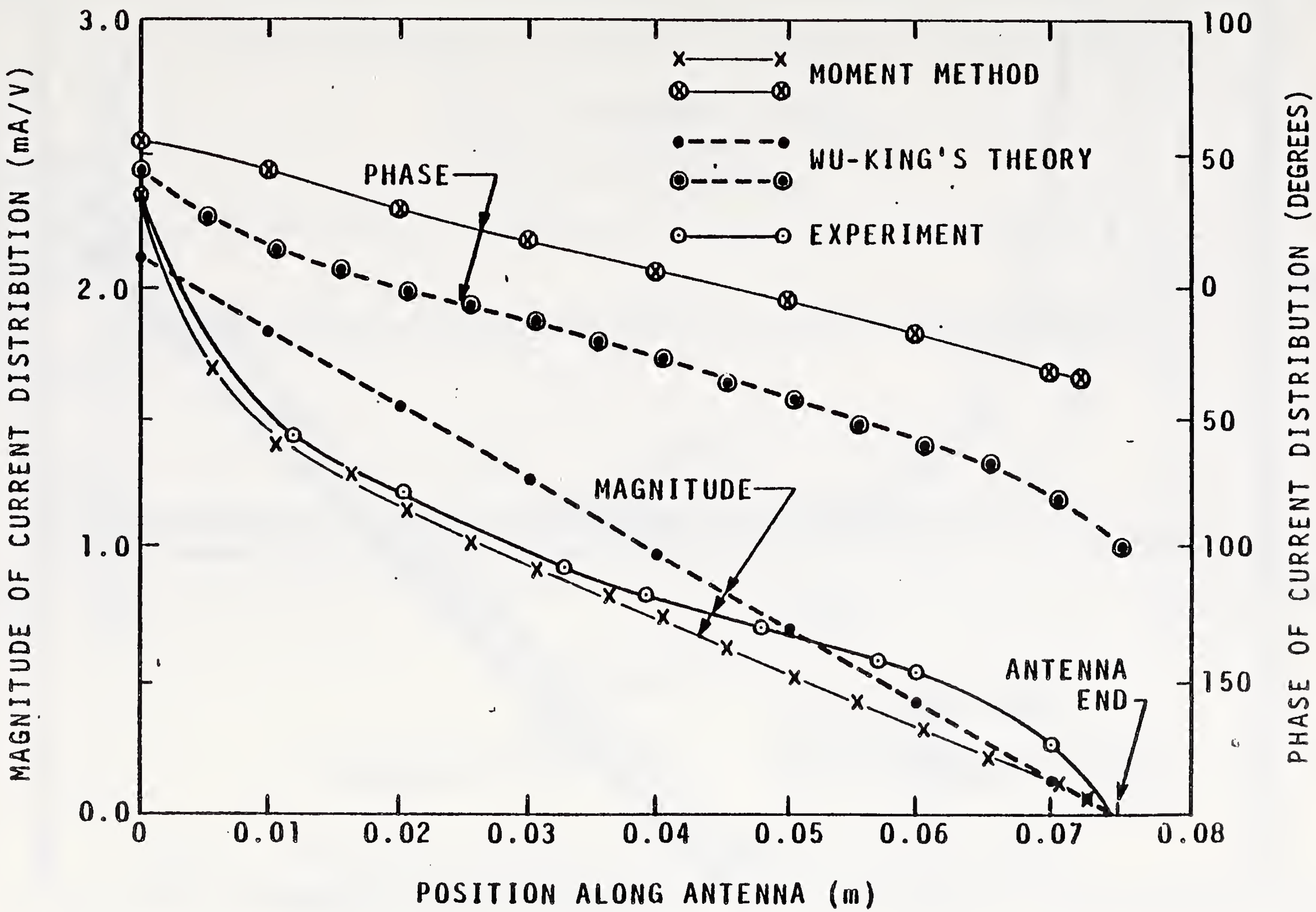

Figure 2. Current distribution of resistively loaded dipole at 1 GHz.

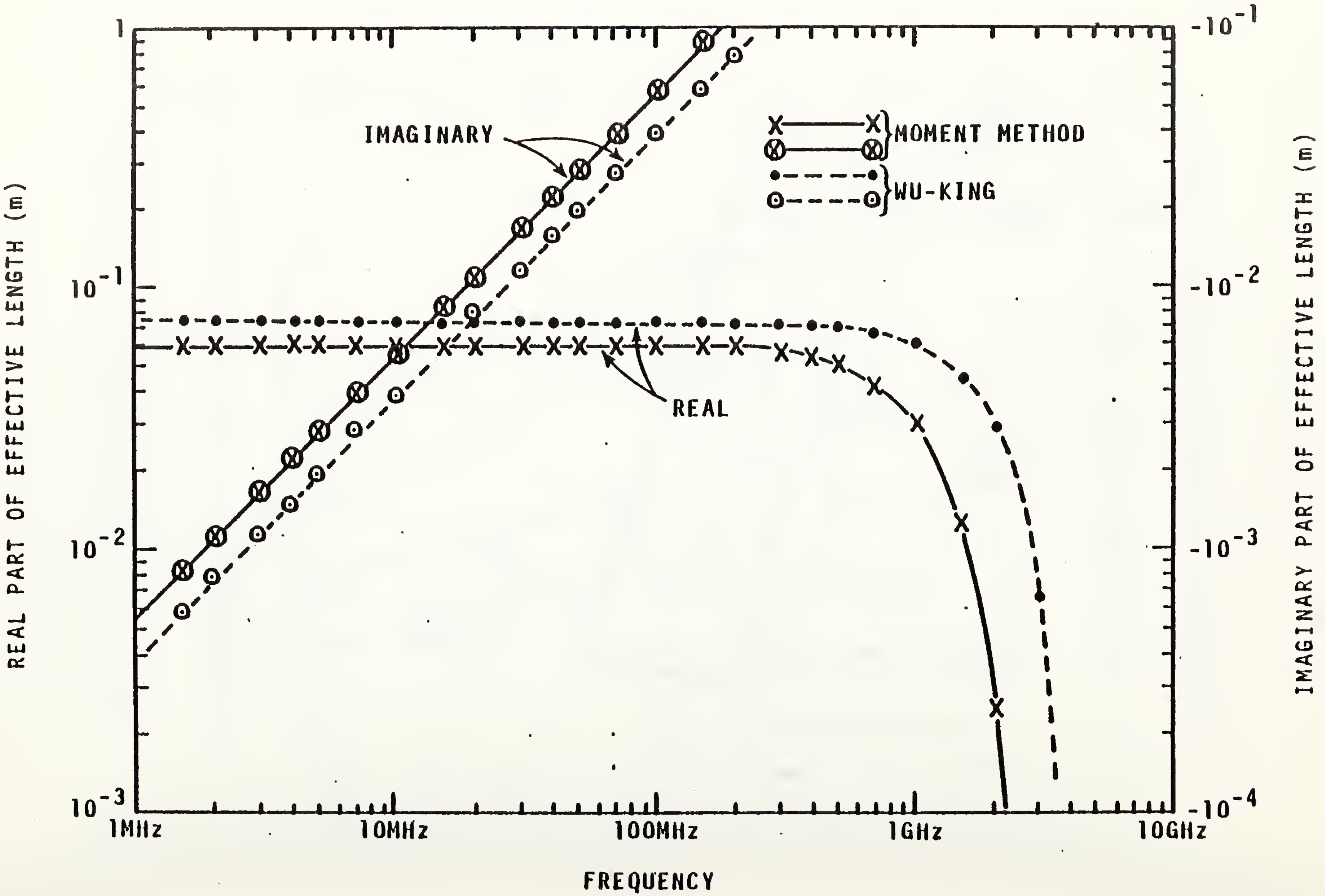

Figure 3. Effective length of resistively loaded dipole.

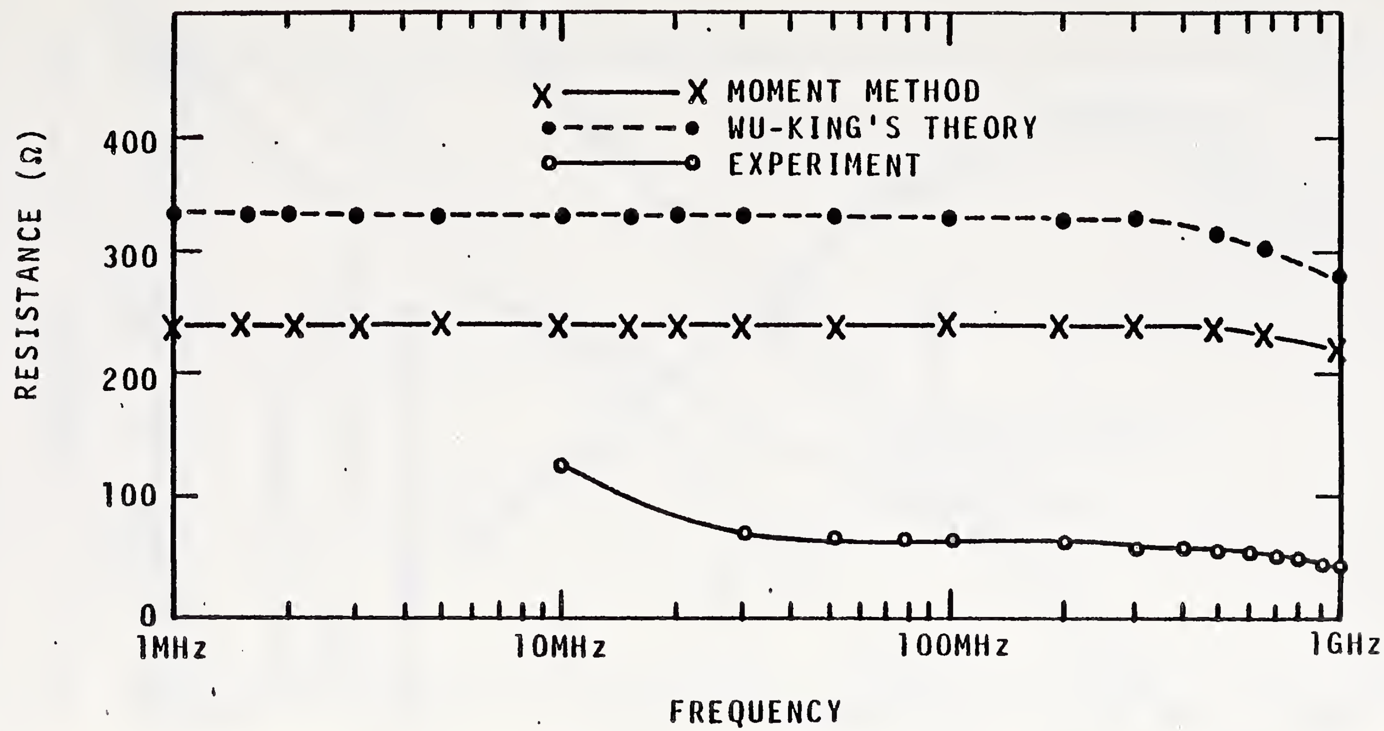

Figure 4. Driving-point impedance of resistively loaded dipole.

a) Real part (resistance).

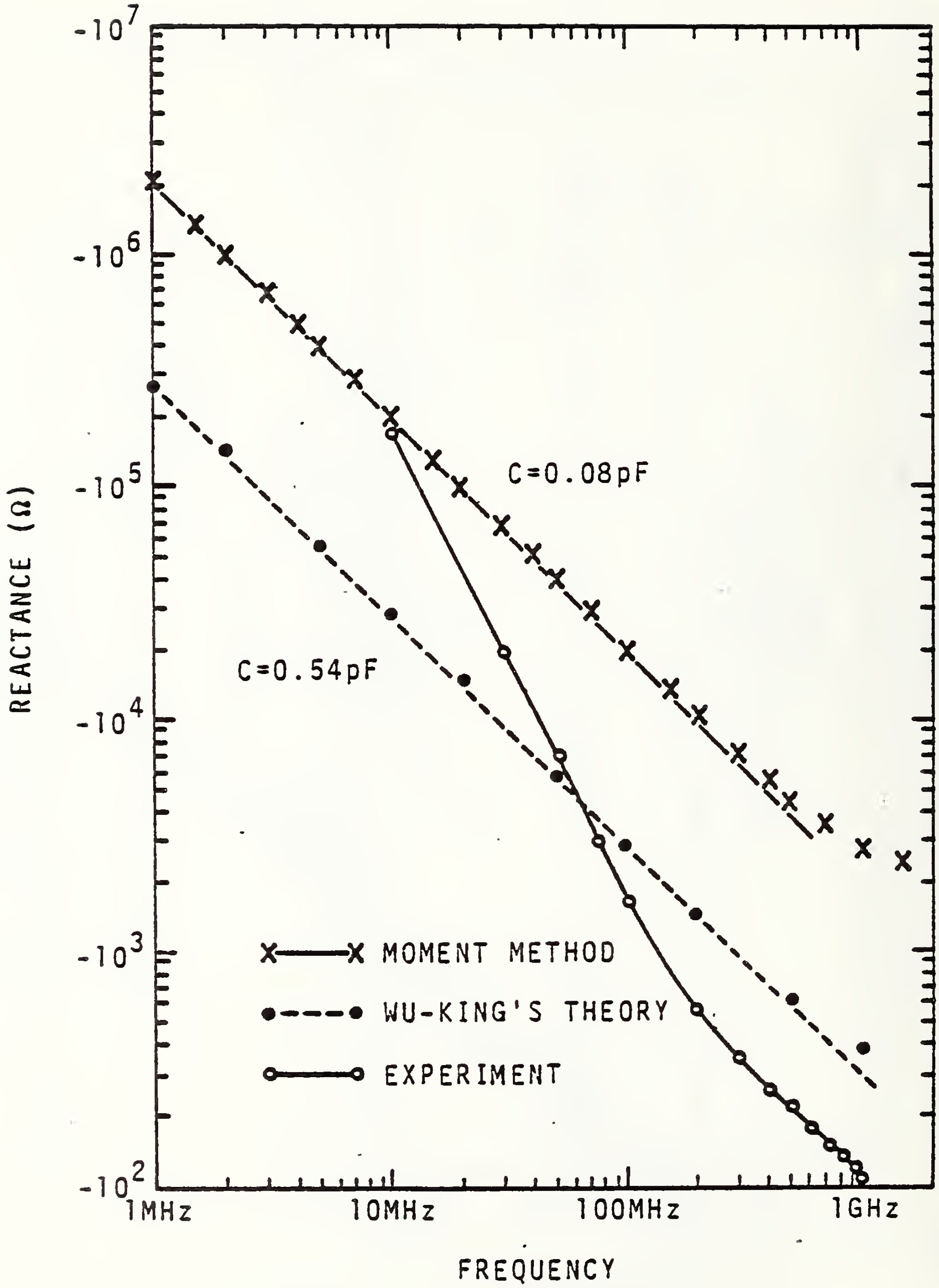

Figure 4. Driving-point impedance of resistively loaded dipole.
b) Imaginary part (reactance).

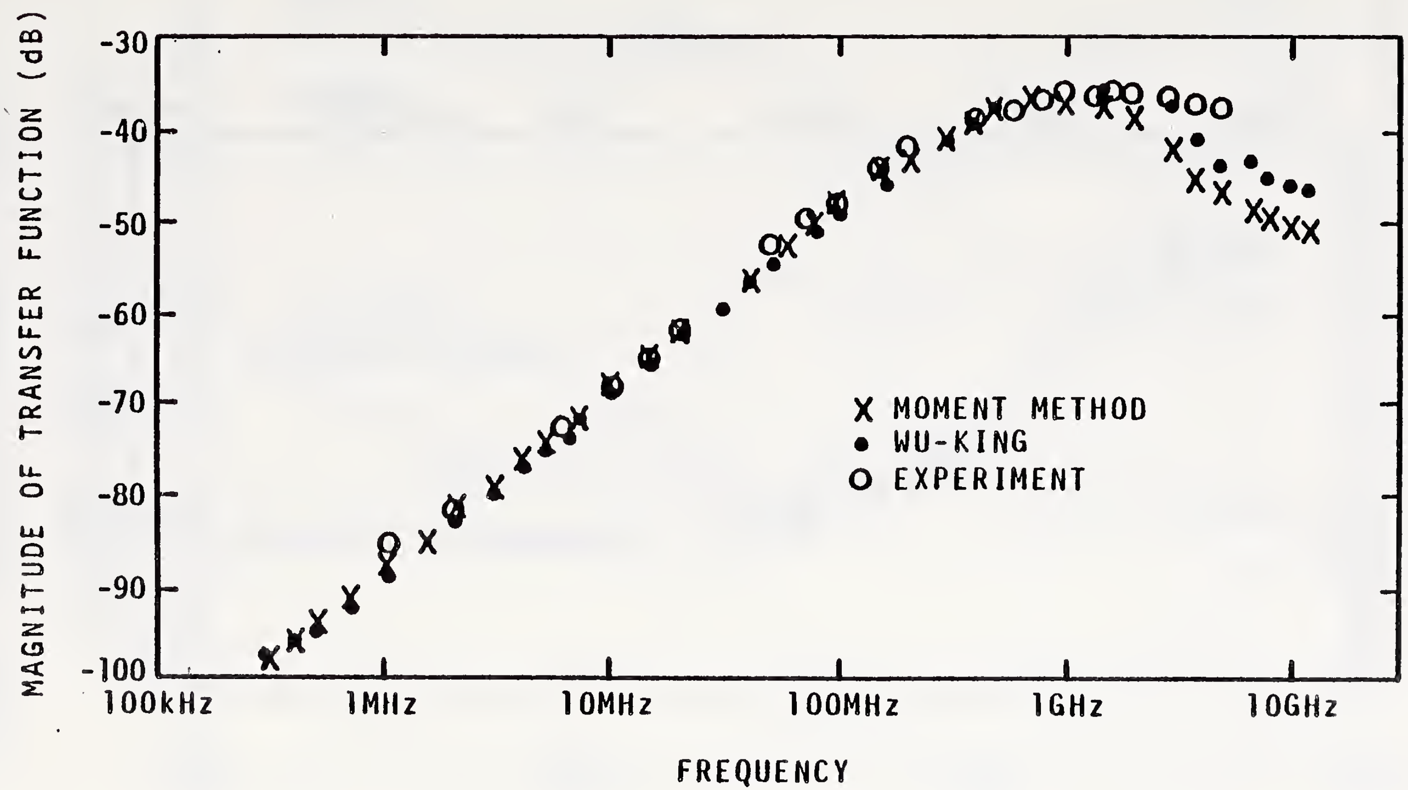

Figure 5. Receiving transfer function of resistively loaded dipole.

a) Magnitude.

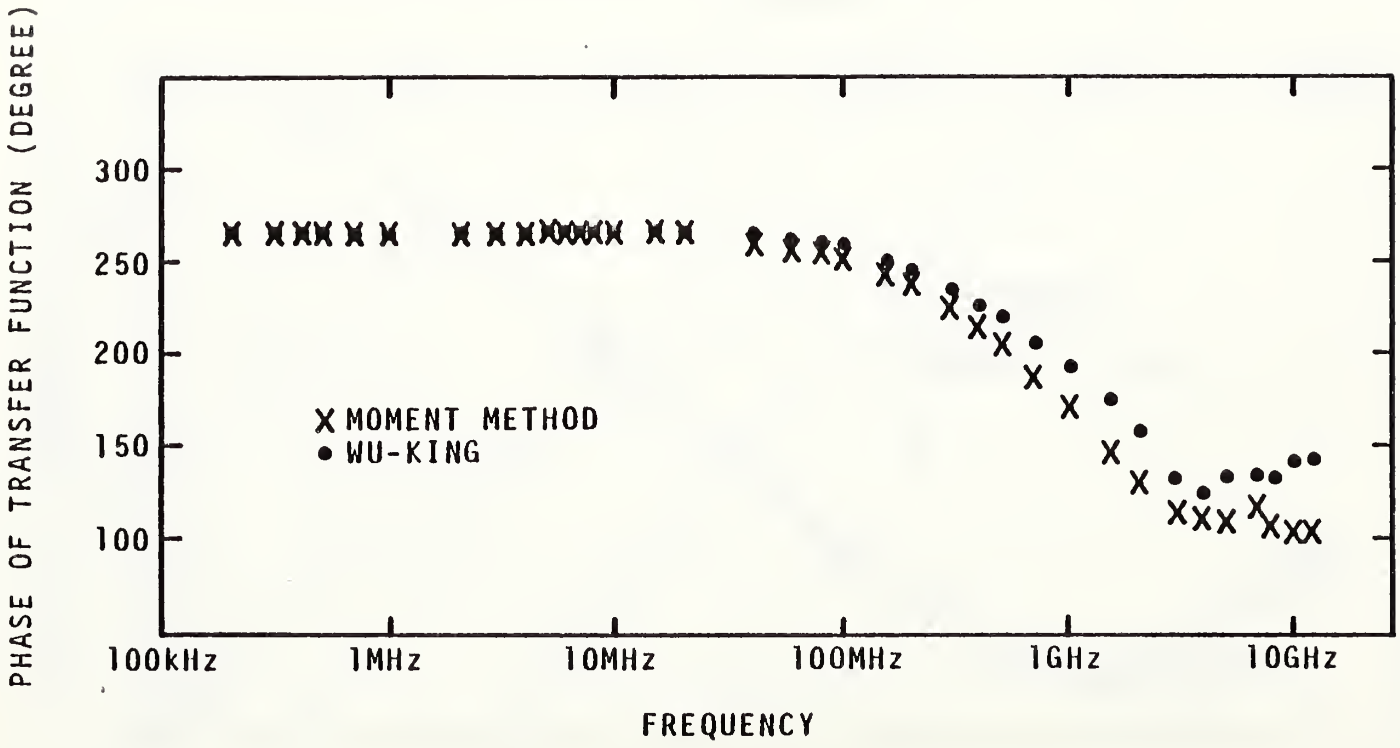

Figure 5. Receiving transfer function of resistively loaded dipole.

b) Phase.

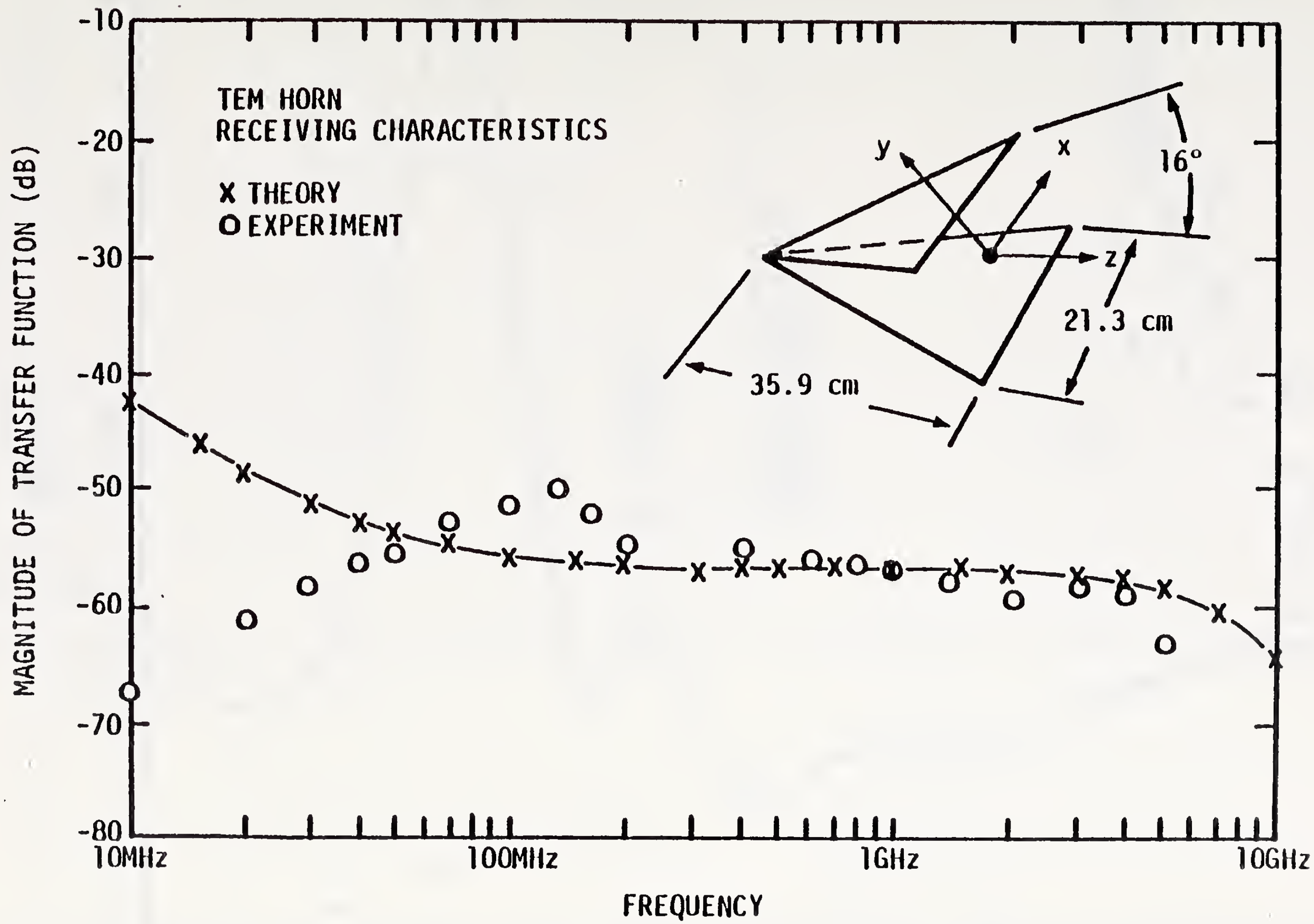

Figure 6. Receiving transfer function of TEM Horn.

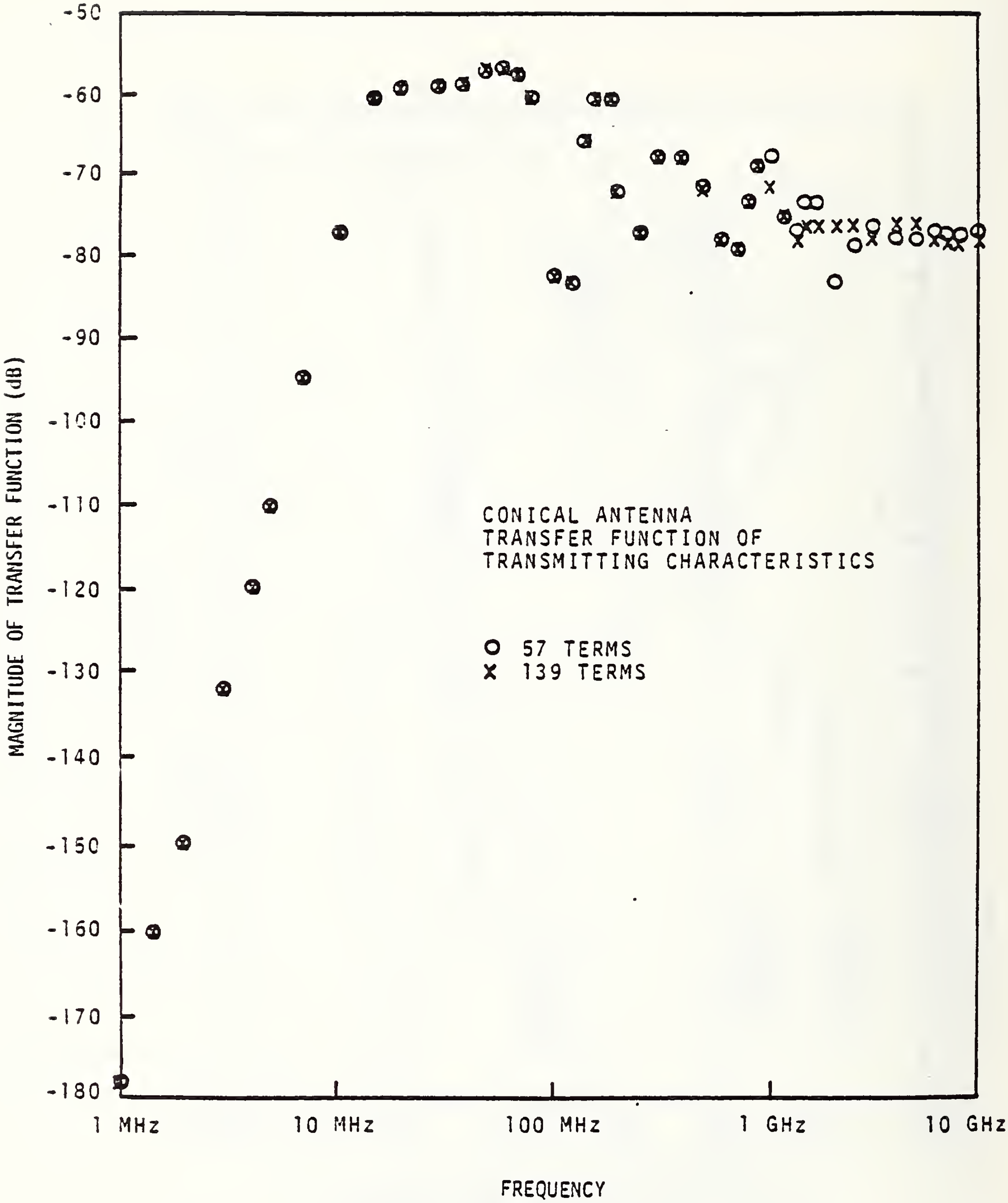

Figure 7. Transmitting transfer function of conical antenna.

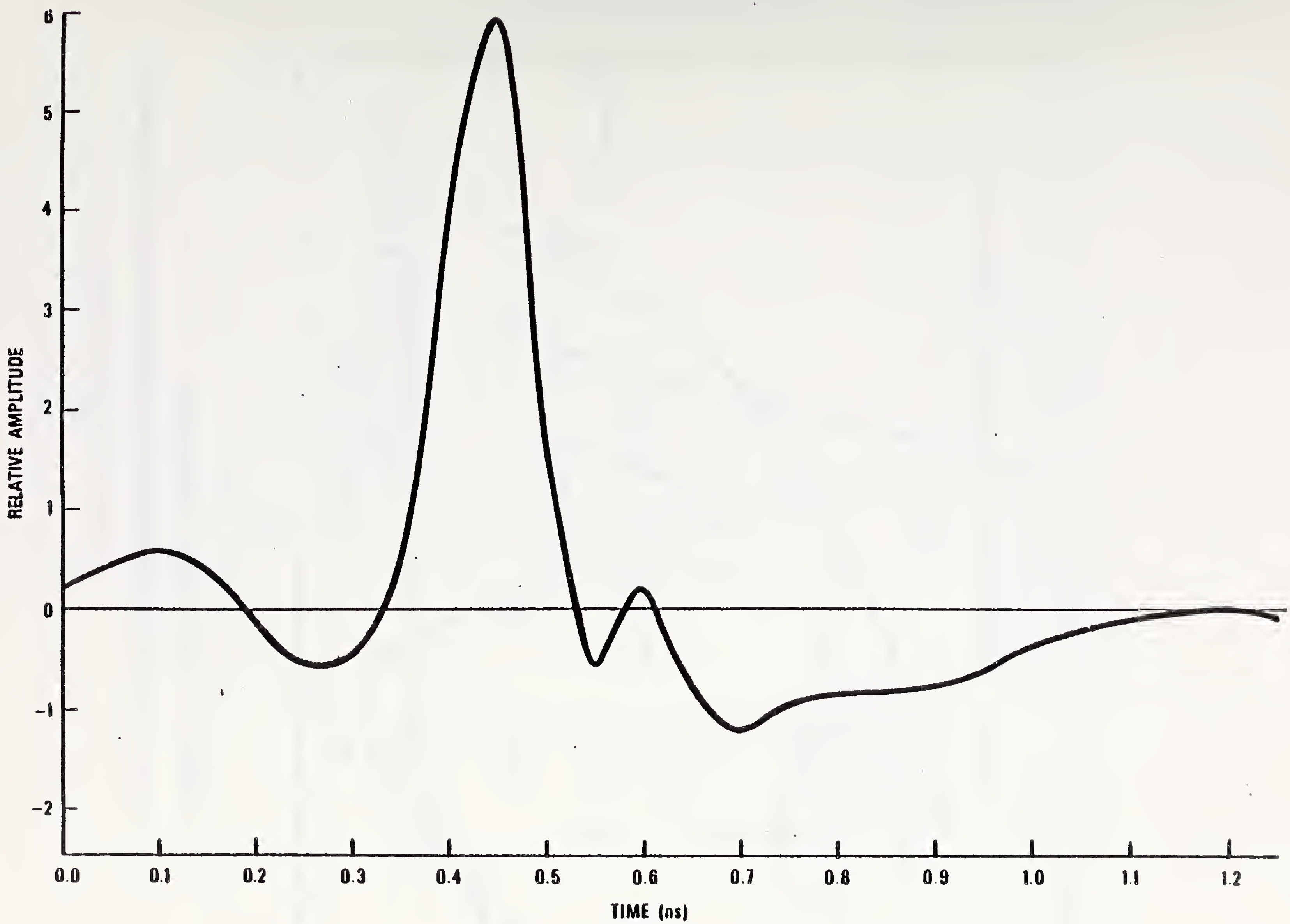

Figure 8. Time domain measurement.

a) Time domain picosecond impulse.

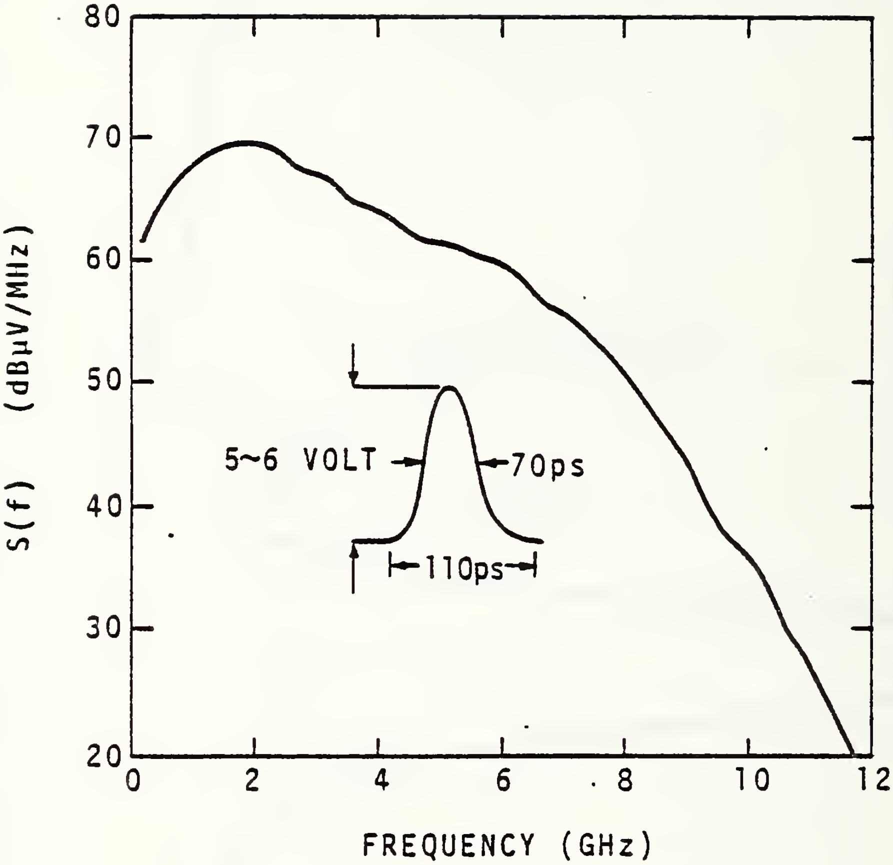

Figure 8. Time domain measurement.

b) Spectrum amplitude of picosecond impulse.

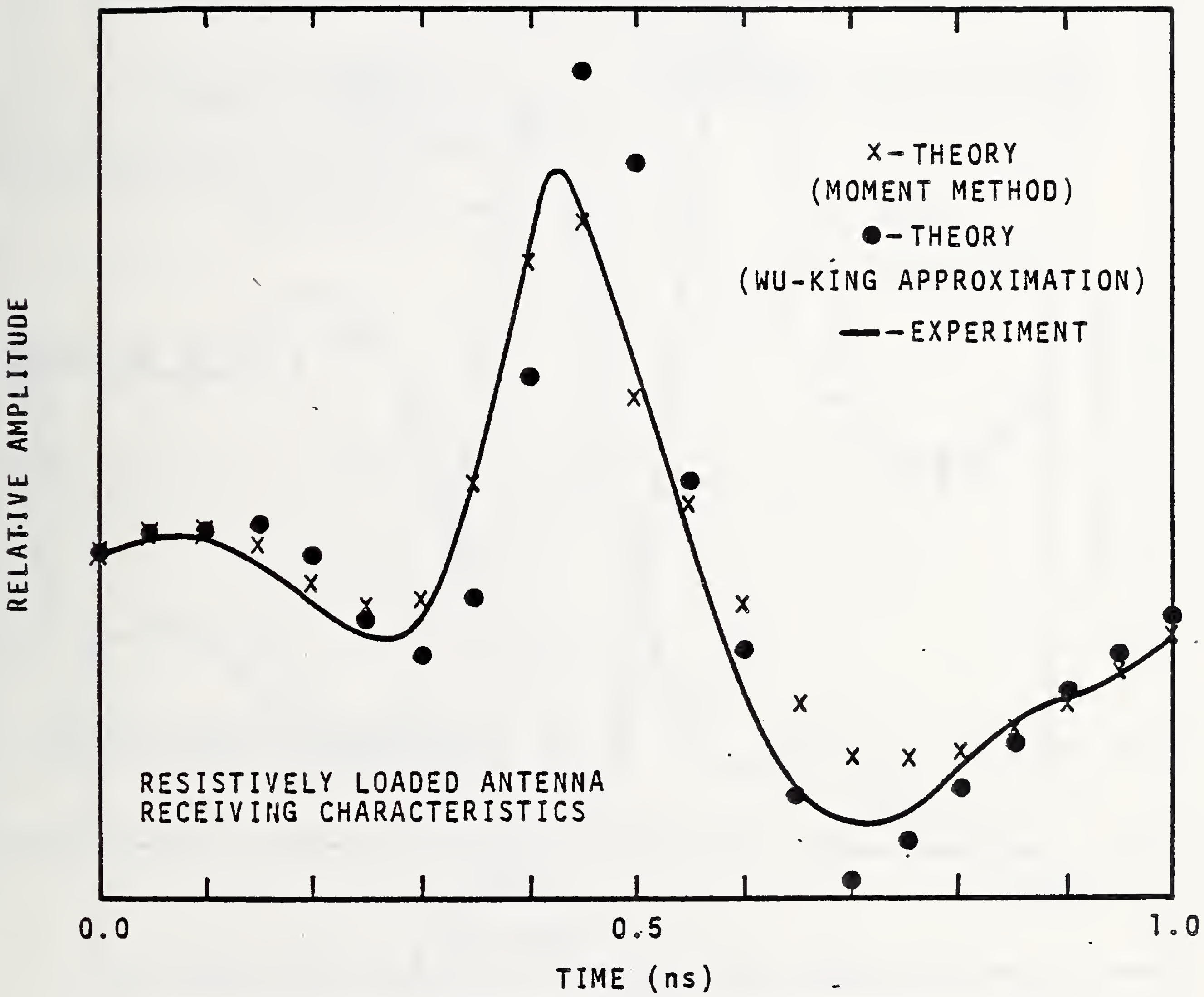

Figure 9. Transient response of resistively loaded antenna.

a) Receiving characteristic.

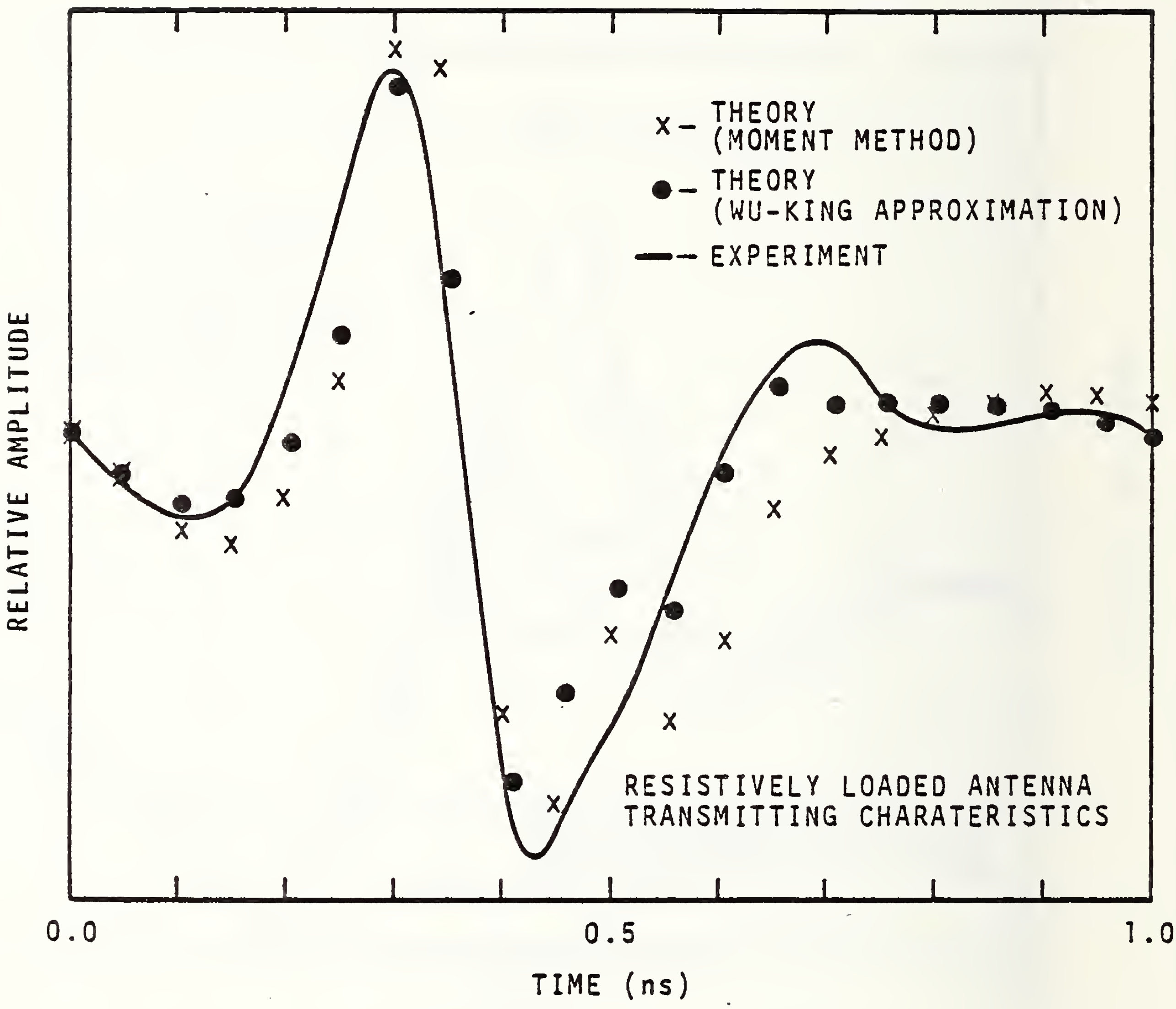

Figure 9. Transient response of resistively loaded antenna.
b) Transmitting characteristic.

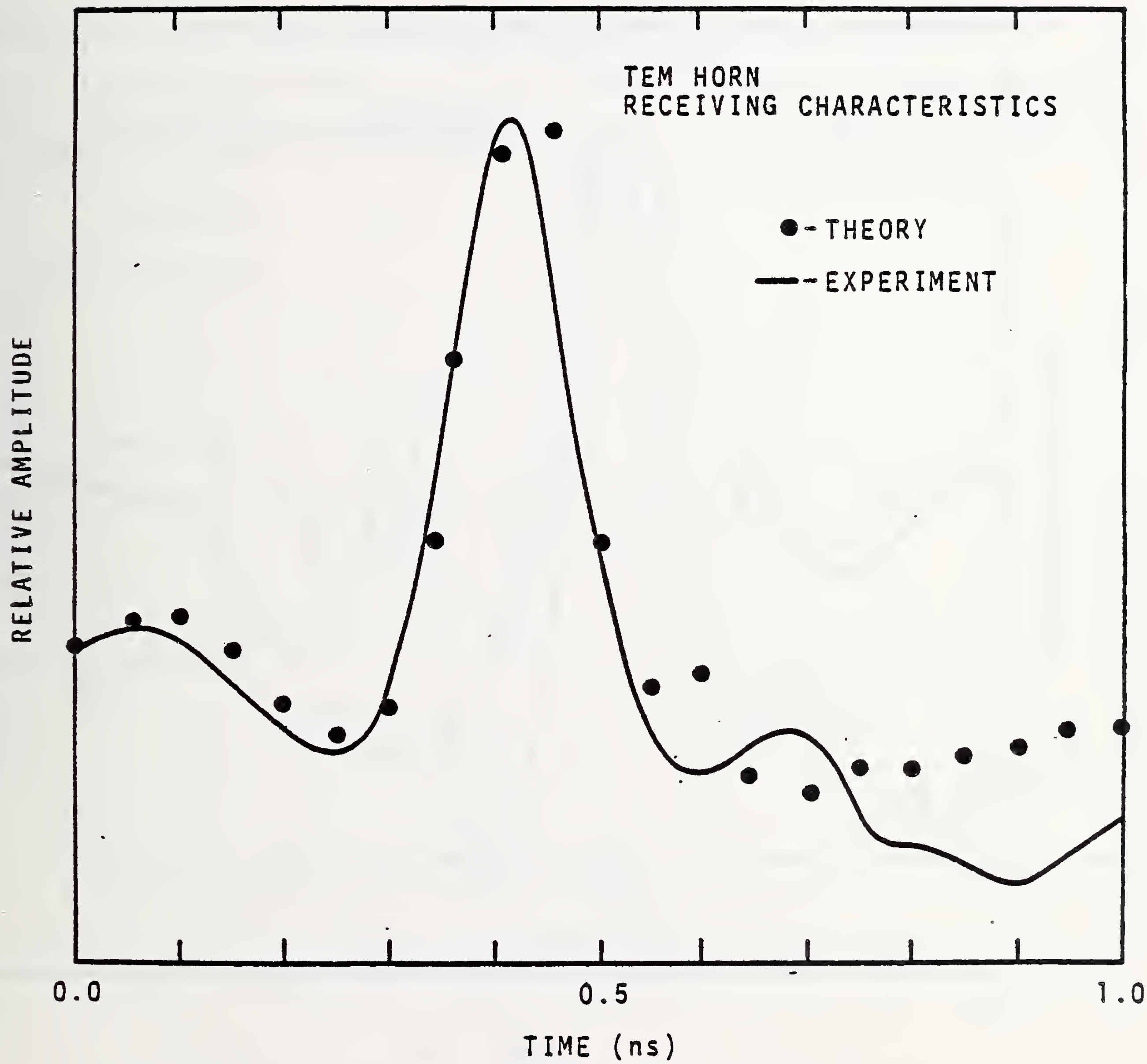

Figure 10. Transient response of TEM horn.

a) Receiving characteristic.

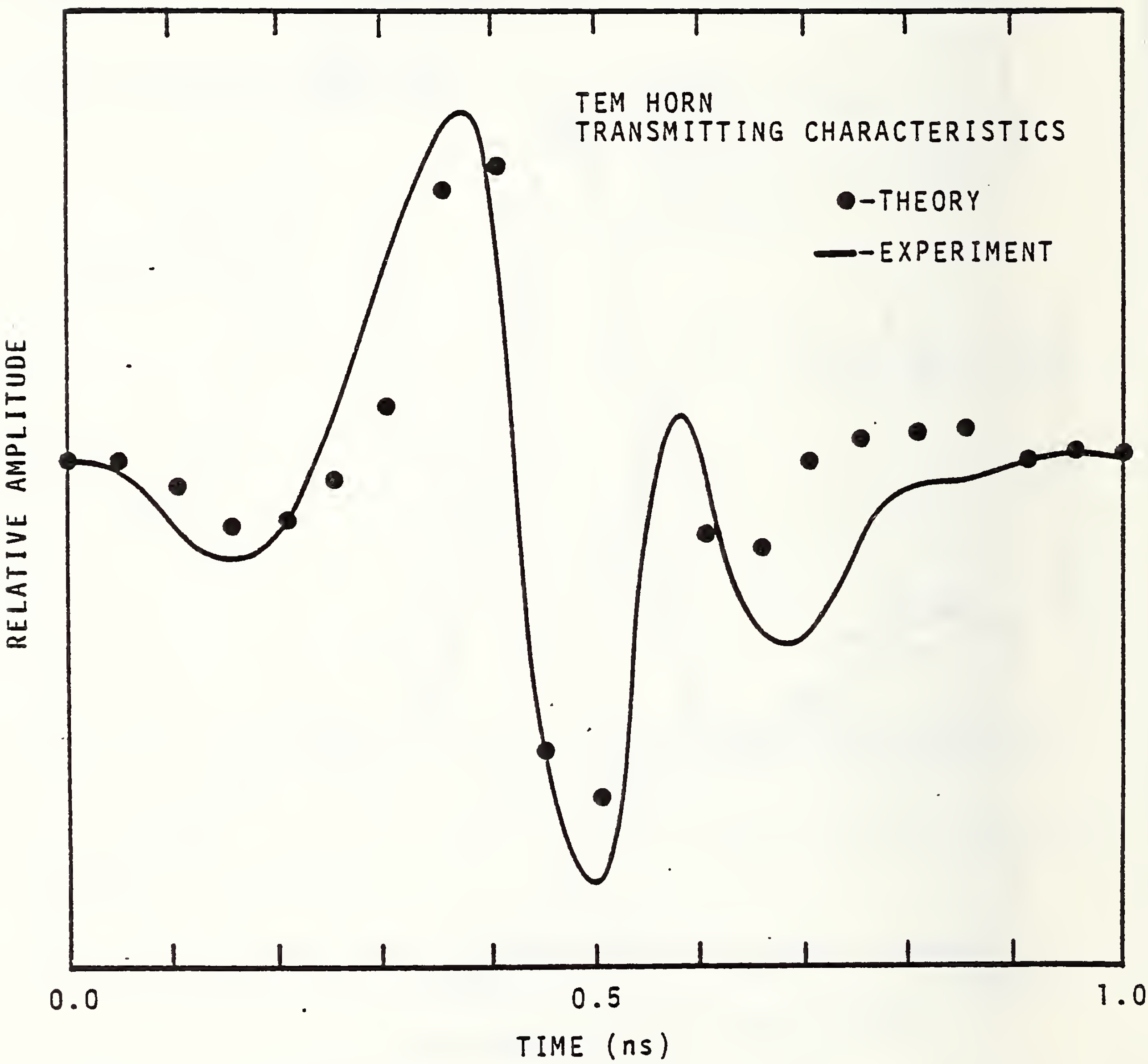

Figure 10. Transient response of TEM horn.

b) Transmitting characteristic.

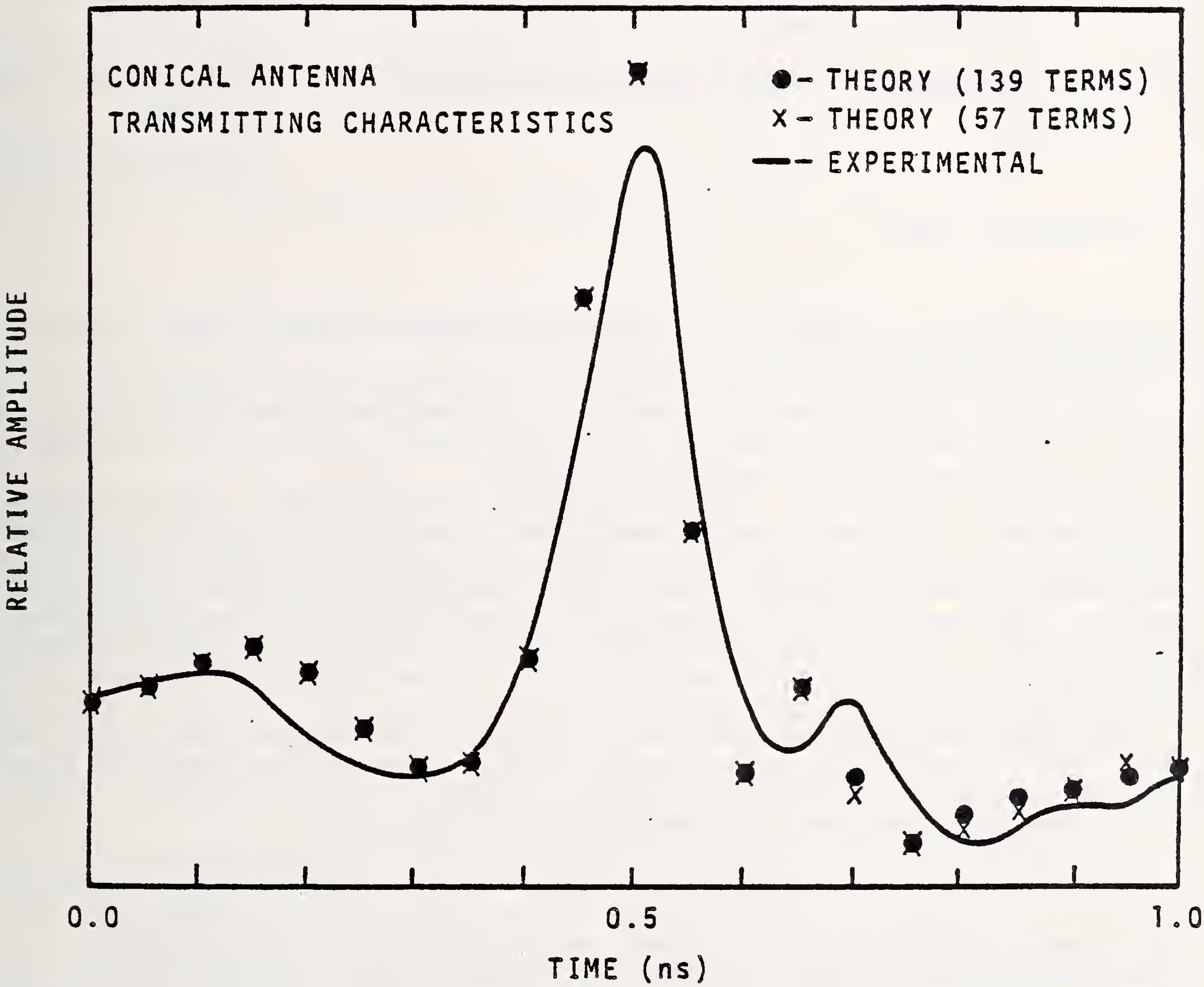

Figure 11. Transmitting transient response of conical antenna.

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15. SUPPLEMENTARY NOTES

16. ABSTRACT (*A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.*)

The receiving and transmitting transient responses for a relatively short, linear antenna with continuous resistive loading are investigated theoretically and experimentally. The antenna considered is a nonconducting cylinder with continuously deposited, varying-conductivity, resistive loading.

The current distribution, the corresponding effective length, and the driving point impedance are calculated by use of the method of moments and compared with the Wu-King approximation. The receiving and transmitting transient responses are calculated in the frequency domain using the results of the effective length and driving point impedance. The use of FFT then allows the determination of transient fields for a known input waveform. The receiving and transmitting responses for a conical antenna and a TEM horn are also investigated theoretically to compare with the transient response of the resistively loaded antenna.

Time domain measurements were performed using a time domain antenna range with a time domain automatic network analyzer. The agreements between theory and experiments of the receiving and transmitting transient responses for the resistively loaded antenna, the conical antenna, and the TEM horn are very good.

The receiving transient response of the resistively loaded antenna indicates that an impulse shape of 70 ps duration is well preserved. This provides the unique capability of this antenna to measure fast, time-varying, transient fields with minimal pulse-shape distortion due to nonlinear amplitude or phase characteristics.

17. KEY WORDS (*six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons*) Conical antenna; EMP; FFT; loaded antenna; method of moments; TEM horn; time domain measurements; transients in resistivity.

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