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J. K. Breakall
H. G. Hudson

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Lawrence Livermore National Laboratory

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THE EQUIVALENT CURRENT MEASUREMENT TECHNIQUE AND ITS COMPARISON WITH CURRENT PROBE METHODS *

J. K. Breakall and H. G. Hudson

Lawrence Livermore National Laboratories

P.O. Box 808

Livermore, Ca. 94550

ABSTRACT- **An equivalent current measurement technique is presented which has advantages over conventional probe methods. The technique has been successfully implemented in internal microwave coupling experiments at the Lawrence Livermore National Laboratory time domain range. Currents have been measured for short-circuit terminations at the bases of cables inside cavities with apertures illuminated by incident waves. Results have been obtained at frequencies much higher than the upper limit of the best commercially available current probes. A theoretical development of the technique and a description of its experimental implementation are given. Representative results and their comparison with those taken with a commercially manufactured current probe are also presented.**

I. INTRODUCTION

Scale-model electromagnetic measurements have been traditionally performed using either swept or stepped continuous wave (CW) methods in the frequency domain. These same measurements can be also made using transient techniques in the time domain because of recent advances in subnanosecond pulse and sampling technology. An extremely important parameter in electro-

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magnetic measurements is the current on a wire excited be some incoming incident wave. This has been traditionally measured using some type of current probe which senses the magnetic field in the near vicinity of the wire. While the current induced on a thin wire excited by a transient impulse or generator can be measured directly with a current probe, the frequency response of such probes is usually less than the upper frequency content of the pulser or upper limit of the other measuring equipment. Many types of current probes have to be clamped around the wire resulting in larger probes for thicker wires and therefore even lower frequency response characteristics. The probe itself and its attached cable also disturb the field distribution in the vicinity of the wire and can give erroneous current results.

Measurements are presently being undertaken at the Lawrence Livermore National Laboratory (LLNL) electromagnetic transient range to study the current response of wires excited by incident waves coupled through an aperture in a cavity. The effects of the size and shape of the aperture and the cavity and the position of the wire inside the cavity are being studied. The LLNL transient range consists of an 8.5 x 8.5 m ground plane and a 3 m high monocone antenna having a smooth aluminum surface. The parameter of most interest in these coupling studies is the short circuit current at the base of the wire shorted to the ground plane. Shielding effectiveness can be measured by comparing the response of the wire by itself and then the wire response inside the cavity with an aperture. These measurements are made with transient pulses having frequency content up to about 3 GHz. Highly resonant modal structure in the response is present with Q's as high a 1000 under certain configurations. The best commercially available current probes respond well up to about 1 GHz. Most of the important responses mentioned in the work above are at frequencies higher than this 1 GHz limit. To compute the short circuit current with a maximum frequency response limited only by the pulsers and sampling equipment used and not have a limitation on wire size, a method was invented which has proven very successful. With only measurements of the voltage induced at the feedpoint of the wire from an incident wave and the self-impedance at the feedpoint, the short circuit current can be computed. Furthermore, the current with any arbitrary load connected to the feedpoint can likewise be calculated.

II. METHOD

The straightforward procedure for this technique will now be given. An equivalent antenna circuit model of the receiving object with wire loaded at its terminals by Z_L(f) is shown in Fig. 1. The self or internal impedance of the object is Z_A(f) which can be measured at its terminals using Time-Domain-Reflectometer (TDR) techniques in the absence of any external excitation. The open-circuit voltage V_{oc}(f) induced at the antenna terminals is simply the product of the incident field E_{inc}(f) and the effective antenna height of the object h_{eff}(f). It will be shown that measurements of E_{inc}(f) and h_{eff}(f) will not be required in deriving the current. Using the following voltage divider relationship,

$$V_{oc}(f) = E_{inc}(f)h_{eff}(f) = \frac{Z_A(f) + Z_L(f)}{Z_L(f)} \cdot V_L(f) \tag{1}$$

where V_L(f) is the induced voltage across the load Z_L(f) from the incident field.

Now, suppose that the load impedance is changed from Z_L(f) to Z'_L(f). The current corresponding to Z'_L(f) is then

$$I_L(f) = \frac{V_{oc}(f)}{Z_A(f) + Z'_L(f)} = \frac{Z_A(f) + Z_L(f)}{Z_A(f) + Z'_L(f)} \cdot \frac{V_L(f)}{Z_L(f)} \tag{2}$$

where the expression for V_{oc}(f) Eq. 1 has been substituted into Eq. 2. In our case the short-circuit current is of particular interest, therefore in Eq. 2 setting $Z'_L(f) = 0\Omega$ and $Z_L(f) = 50\Omega$, which is the impedance of our instrumentation

$$I_{SC}(f) = \frac{Z_A(f) + 50}{Z_A(f)50} \cdot V_L(f) \tag{3}$$

for $Z_L = 50\Omega$.

The frequency spectrum of V_L(f) is measured using the instrumentation system shown in Fig. 2 and of Z_A(f) is measured using the TDR instrumentation shown in Fig. 3. V_L(f) is the Fast Fourier Transform (FFT) of the measured time domain voltage which feeds the transmission line having characteristic impedance of 50Ω and terminated by the scope with 50Ω. In the TDR system two measurements are required to compute the internal impedance Z_A(f). First, V_{load}(t), the pulse reflected from the test object is recorded by the digital sampling oscilloscope. If the time delay

for reflections from the load is sufficiently long, the reflected signal can be measured in a time window far removed from the initial outgoing pulse from the pulser. The spectrum of the reflected voltage V_{load}(f) is likewise computed by an FFT of the time domain waveform. The second TDR measurement requires connecting either an open or short circuit as a reference load in place of the test object. The reflection coefficient $\Gamma_L(f)$ of the test object can then be calculated defined at the reference plane where the open or short circuit is placed.

$$\Gamma_L(f) = \frac{V_{load}(f)}{V_{open}(f)} = \frac{-V_{load}(f)}{V_{short}(f)} \tag{4}$$

Normally, $V_{open}(f) = -V_{short}(f)$ so $\Gamma_L(f)$ is independent of the type of reference load used. Some slight differences have been noted in our experiments, however. These are probably due to the practical ways of using connectors with terminations and the small amount of radiation leakage in the open circuit case.

Finally, the desired object internal impedance Z_A(f) is found

$$Z_A(f) = \frac{1 + \Gamma_L(f)}{1 - \Gamma_L(f)} \cdot Z_0 \tag{5}$$

where Z_0 is the characteristic impedance of the transmission line, in our case $Z_0 = 50\Omega$. This fully characterizes the internal impedance of the test object. The desired short-circuit current at the feedpoint can be found using the result for Z_A(f) Eq. 5 and the measured response of the test object V_L(f) both in Eq. 3.

III. RESULTS

Some representative results from our experiments are shown for short-circuit currents for a 30 cm long monopole and a 22.5 cm long wire inside a cylindrical cavity with an aperture are shown in Figs. 4 and 5. The cavity configuration "PLUTO" (Preliminary LLNL Universal Test Object) is shown in Fig. 6. In Figs. 4 and 5, part (a) shows the magnitude of the test object's internal impedance Z_A(f) as calculated using the TDR technique and Eq. 5. Part (b) shows the time domain short-circuit current at the feedpoint as calculated using the inverse FFT of Eq. 3 (solid) and as measured using a high quality Tektronix CT-1 current probe (dashed), part (c) shows the

spectrum of the short-circuit current computed using Eq. 3 (solid) and by taking the FFT of the CT-1 measurements (dashed).

The calculated and measured time responses are generally in good agreement, the main difference being at the peaks. This probably is due because the upper frequency response of the CT-1 probe is only about 1 GHz, whereas the calculated response is greater than 2.5 GHz. Calibration of the CT-1 probe as provided by the manufacturer may also be inaccurate.

The time response as calculated using the inverse FFT of Eq. 3 is noncausal as seen in Figs. 4b and 5b. This is caused by truncation effects when the waveforms have not decayed to zero in the time window of analysis. This effect is apparently of little consequence in the rest of the waveform or in the spectrum, however. Notice also in Figs. 4b and 5b that the spectrul responses compare very well up to about 1 GHz. Above this frequency the response of the CT-1 probe begins to fall off noticeably.

IV. CONCLUSIONS

A method for measuring current responses on wires has been developed based on antenna theory methods. It allows current response measurements to be made that are far superior to those made with conventional current probes. This method has proven very successful in coupling and shielding effectiveness work at Lawrence Livermore National Laboratory. For the cases studied this method is seen to be more sensitive and accurate over a much wider frequency range than measurements using a Tektronix CT-1 probe. A wide range of applications exist for this method especially at higher frequencies where fast pulsers are or will be available.

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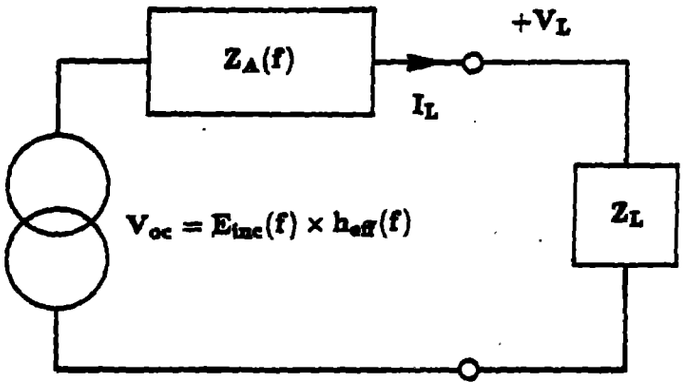

Figure 1. The equivalent circuit of the receiving object loaded at its terminals by Z_L. The internal of self-impedance as measured using TDR techniques is Z_A and V_{oc} is conveniently represented as the incident plane wave field times an effective length.

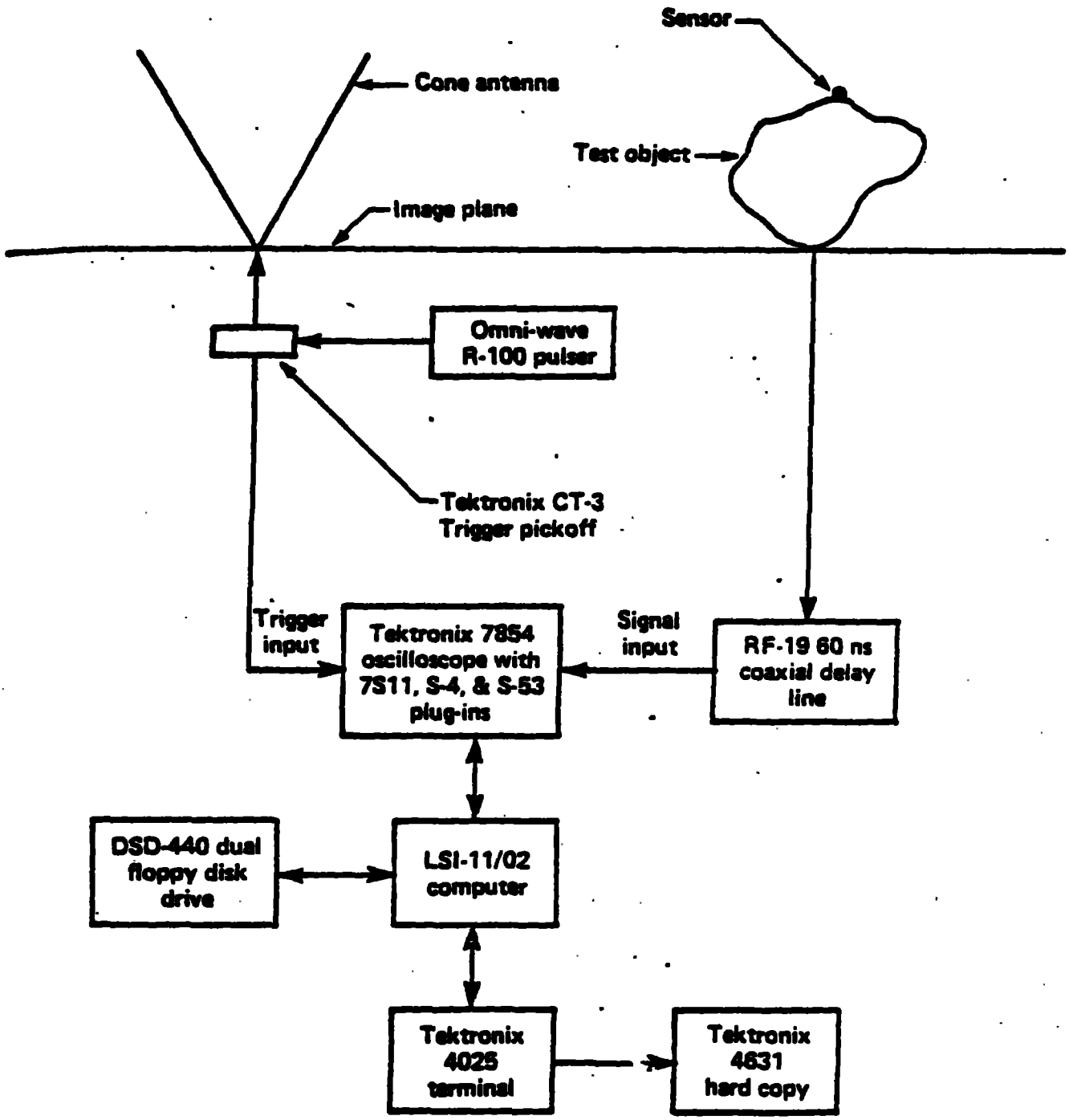

Figure 2. Instrumentation system block diagram for the Electromagnetic Transient Measurement Facility.

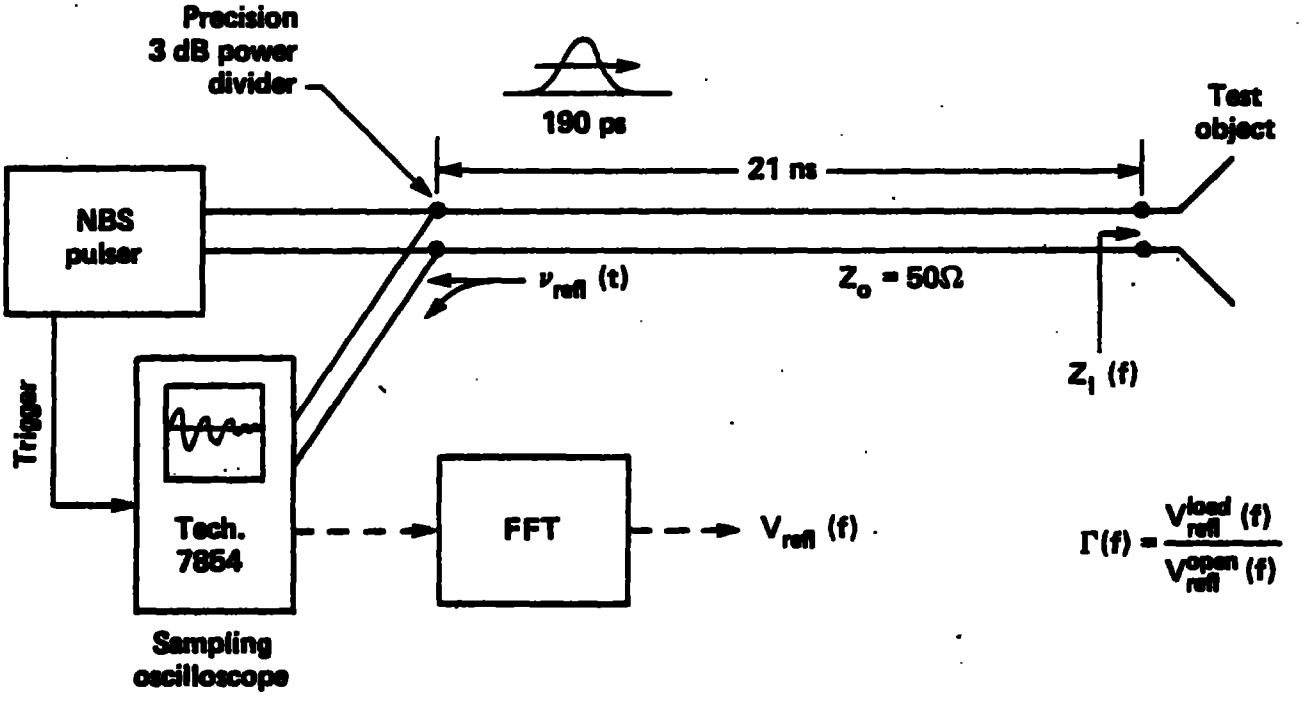

Figure 3. Time Domain Reflectometer (TDR) instrumentation system used to measure the internal impedance, Z_A, of a test object.

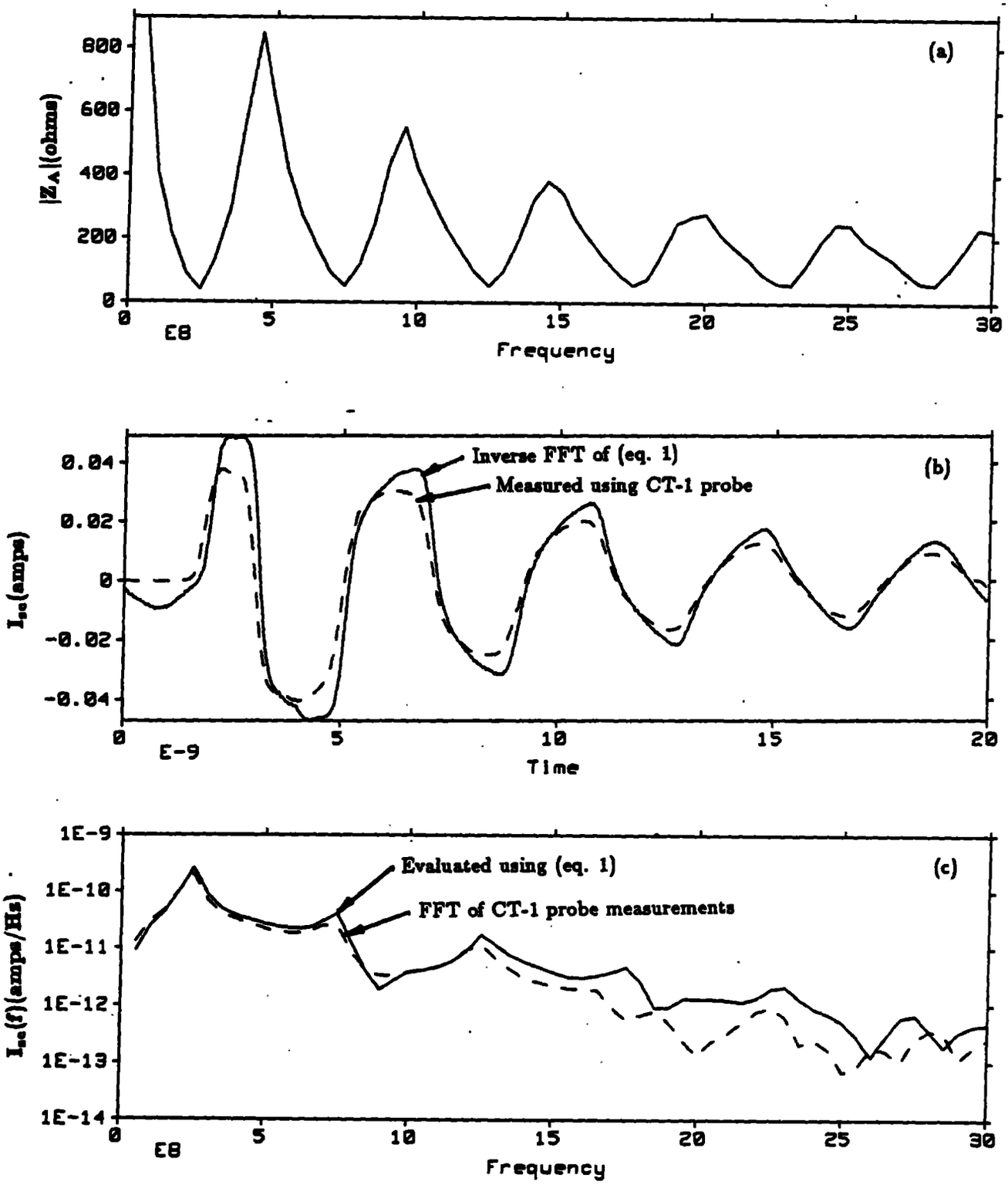

Figure 4. Responses of a 30 cm monopole; (a) Magnitude of the self-impedance using TDR, (b) Short circuit curent time response, (c) Short circuit current frequency response.

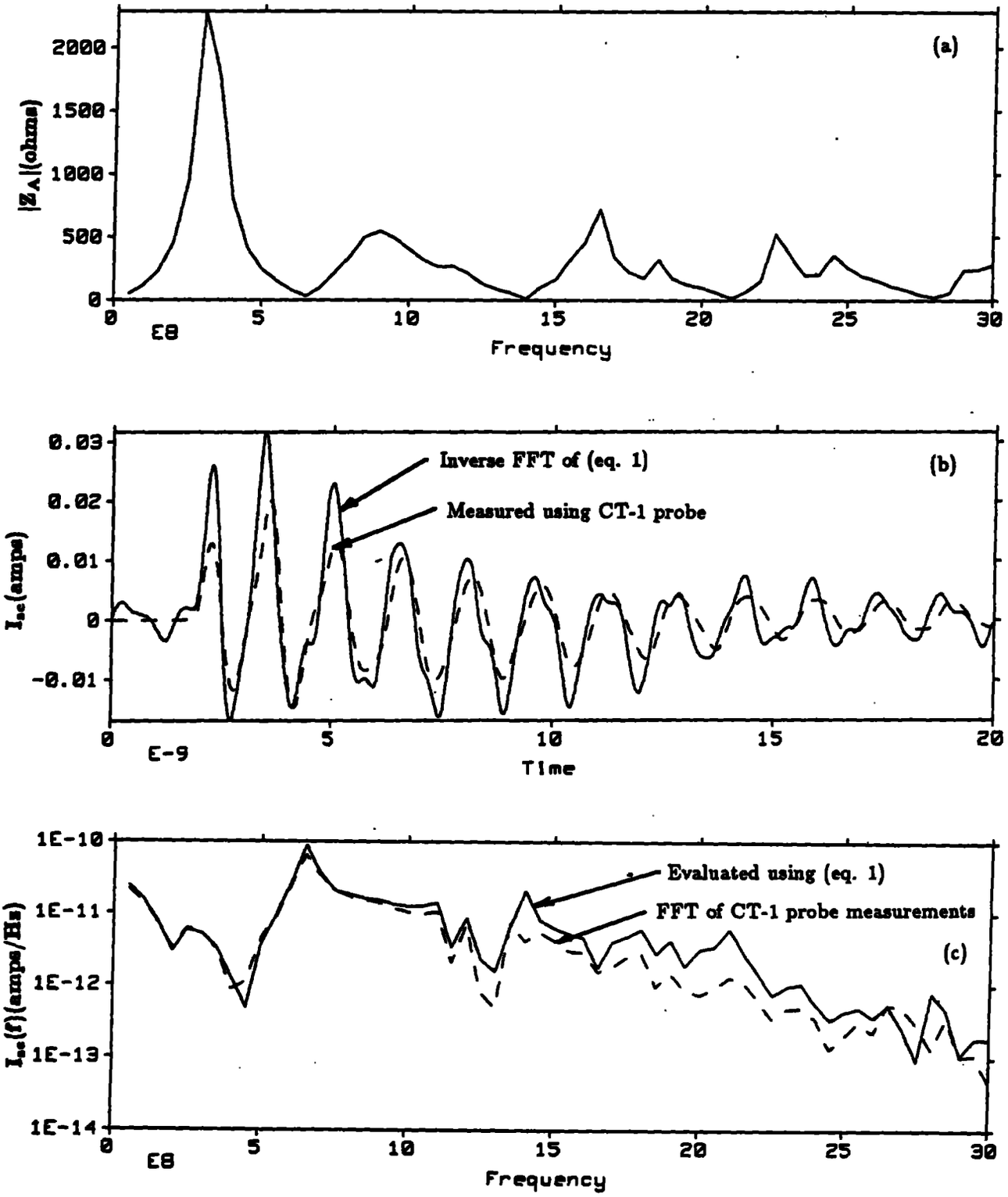

Figure 5. Response of a 22.5 cm wire inside a cavity (PLUTO) with a 15 x 7.5 cm aperture; (a) Magnitude of the self-impedance using TDR, (b) Short circuit curent time response, (c) Short circuit current frequency response.

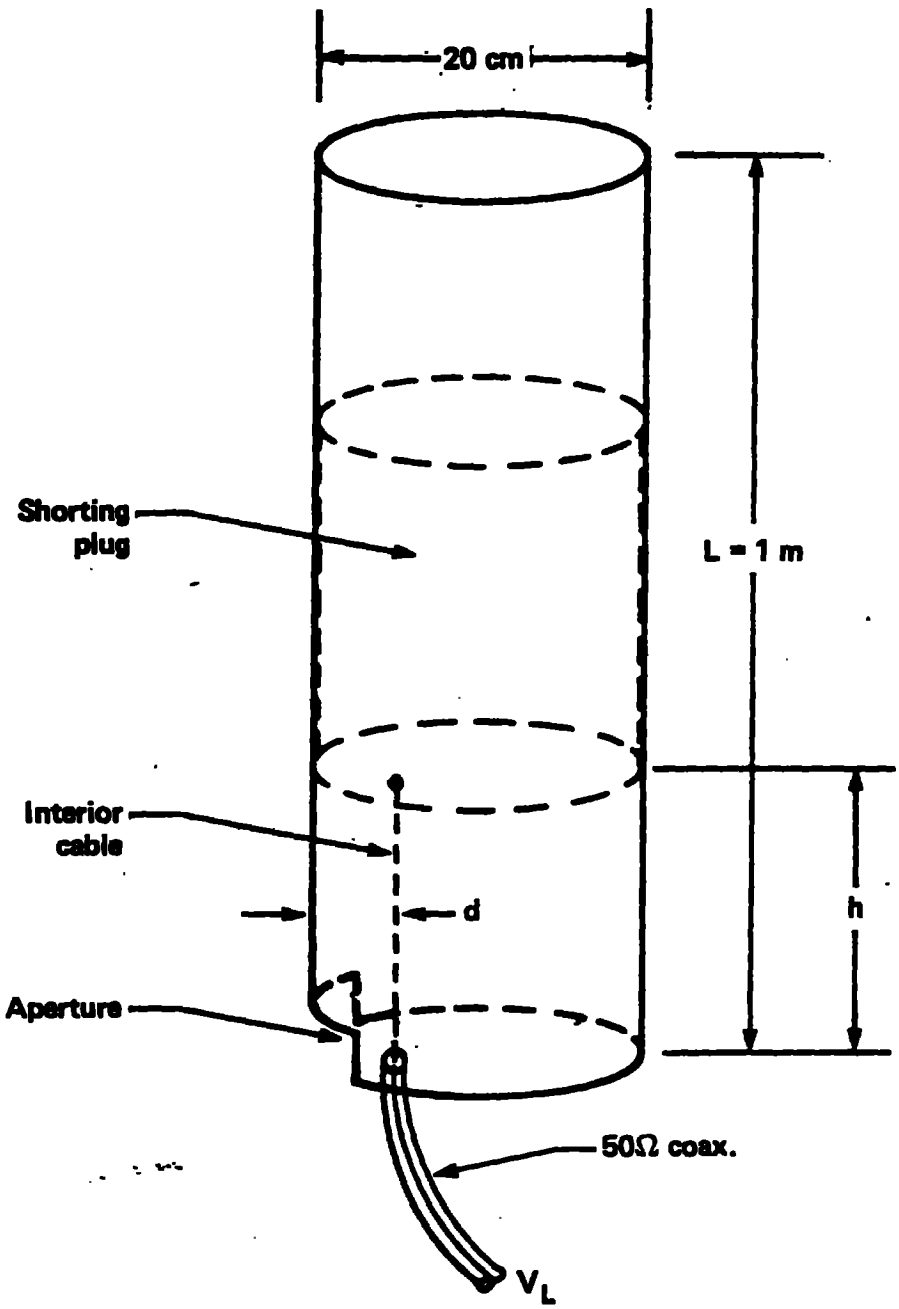

Figure 6. "PLUTO" (Preliminary Livermore Universal Test Object).