Sensor and Simulation Notes

Note 297

30 January 1987

A WIDE-BANDWIDTH ELECTRIC-FIELD SENSOR FOR LOSSY MEDIA

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Abstract

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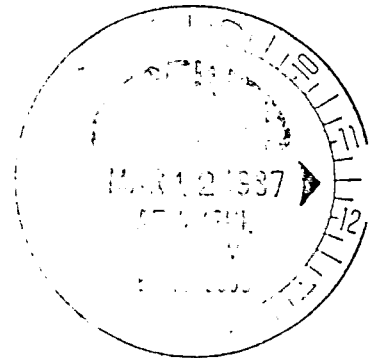:ry is presented.

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Abstract

A wide-band electric-field sensor for use in lossy media, such as soil or water, is described, and its response characteristics are discussed. Such a sensor was built and used to measure the EM fields in soil beneath a string of ten capacitive-discharge pulsers. A sample sensor response time history is presented.

1. INTRODUCTION

The measurement of transient electric fields in a lossy medium requires special care in the design of the E-field sensor (Refs. 1-5). In particular, the response should be wide-band and the presence of the sensor should not unduly disturb the electric fields that would be in the medium in the absence of the sensor. The purpose of this note is to describe the design and operation of such a sensor that was used successfully to measure electric fields in soil beneath an EMP simulator.

2. DISCUSSION OF CONCEPT

Although the sensor that was built and tested measured two orthogonal components of the E field, for simplicity of this discussion only a single-component sensor will be considered for the present. A schematic illustration of this sensor is shown in Figure 1. It consists of three parallel conducting rods, perpendicular to the component of the E field being measured (E_x in Figure 1). The middle rod, which is the local reference for the electric potential, is hollow to allow the signal lines to come out through the interior of the tube. The two outer rods are connected to the center tube by two strings of resistors which form resistive dividers. These resistors, which are isolated from the surrounding medium by placing them inside dielectric tubes, as illustrated in Figure 2, should have as nearly uniform as possible resistances per unit length from the outer rods to the inner tube. If this resistance were perfectly distributed, the voltage drop per unit length along the resistors would be the same value as the local electric field in the medium. As a

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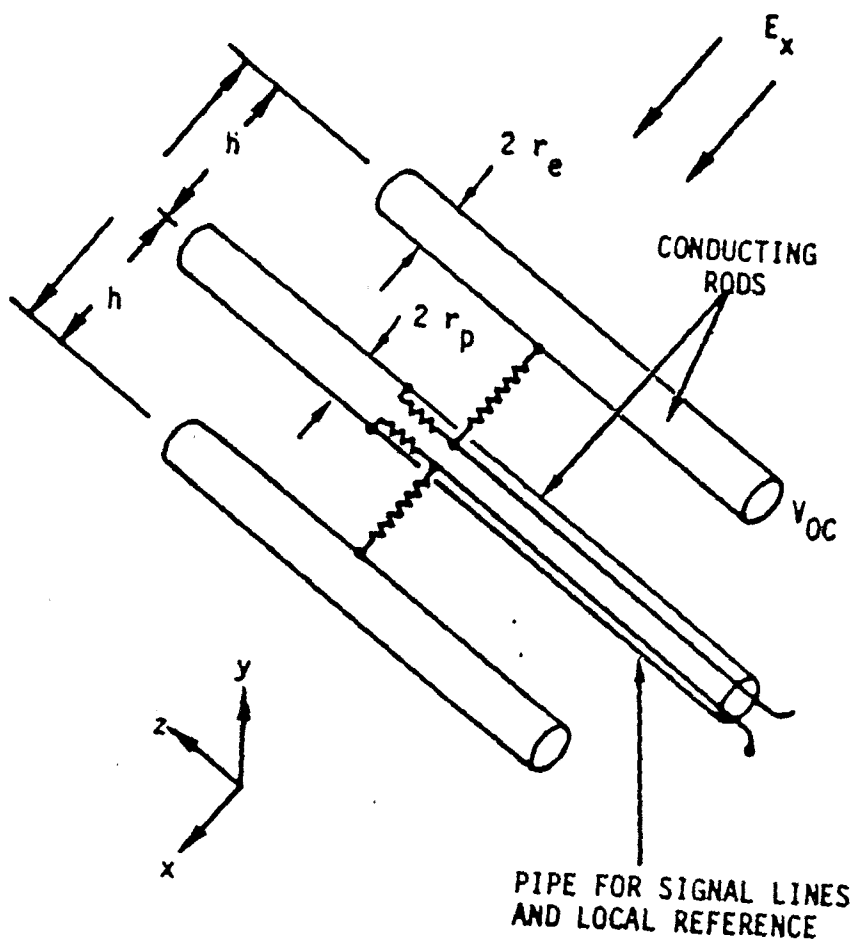
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Figure 1.   Sensor geometry for single E-field measurement

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INSULATING
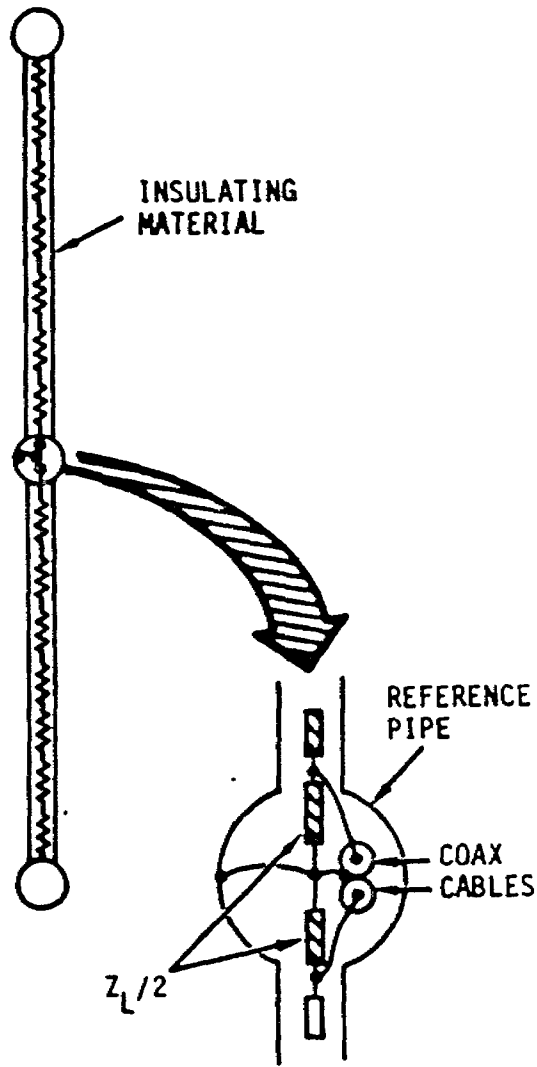MATERIAL

REFERENCE
PIPE

COAX
CABLES

$Z_L/2$

Figure 2. Resistor strings and sensor connections

result, the capacitance between the resistors and the medium would not be charged up. This implies a sensor with a large bandwidth (Refs. 6-7), and the rise time of the sensor response will not be limited by this capacitance.

Using closely packed, uniform resistors also reduces the voltage across individual resistors, which minimizes the possibility of arc breakdown around a resistor.

The connections to the voltage divider are illustrated in more detail in the inset in Figure 2. The signal cables are added to measure the voltages across the two innermost resistors in the resistor strings. These voltages are related to the electric field between the outer rods and the center tube by the resistive-divider ratio and the electrode separation. The connections between the cables and resistors should be as symmetric and as small as possible because the resulting capacitance with respect to the medium can affect the rise time of the sensor.

For a sensor that measures two orthogonal components of the E field, the setup is essentially the same as described above, except that two more conducting rods are added parallel to the three rods in Figure 1, but located at 90 degrees from the first pair of outer rods. Each of these rods has its own resistive string and set of coax signal cables.

3. EQUIVALENT CIRCUIT

The equivalent circuit of a single-component sensor is shown in Figure 3. The open-circuit (driving) voltage of the system is

$$V_{OC} = h_{eq} E_{inc} = (h + \sqrt{h^2 - r_e^2}) E_{inc}$$
$$\cong 2h E_{inc} \quad \text{for } h/r_e \gg 1 \tag{1}$$

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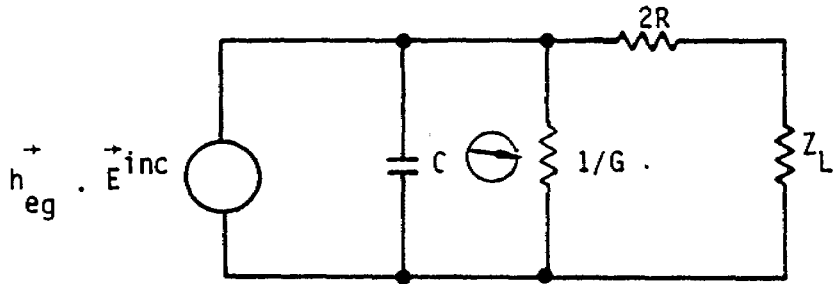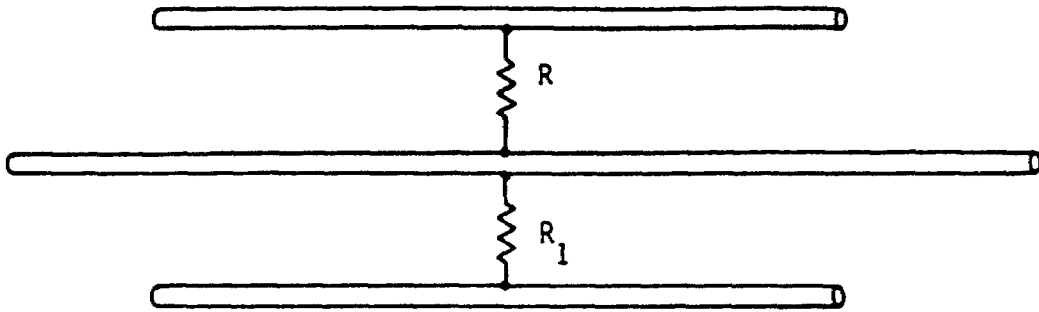
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Figure 3.   Equivalent circuit of sensor

The conductance (G) and capacitance (C) between the two outer rods are given by

$$G = \frac{\ell\sigma}{f_g} \qquad (2)$$

$$C = \frac{\ell\varepsilon}{f_g} \qquad (3)$$

where ℓ is the length of the rods.

$$f_g = \frac{1}{\pi} \cosh^{-1}(h/r_e) . \qquad (4)$$

and σ and ε are, respectively, the conductivity and dielectric constant of the medium.

For 50Ω sensor cables and scopes, Z_L should be $100\ \Omega$.

In order for the sensor to measure the open-circuit voltage properly, the total resistance (R) of each resistor chain must be selected so that the fields in the soil are loaded by a negligible amount. The criterion for doing this, and thus providing a simple, constant transfer function for the sensor, is that the reciprocal of the conductance of the medium between the two outer rods be much less than the total resistance between the two rods via the resistor strings; that is,

$$1/G < < (2R + Z_L) \qquad (5)$$

Physically, this means that the current that flows through the resistor strings is much less than the current that flows through the soil in the vicinity of the two outer rods.

4. SENSOR BANDWIDTH LIMITS

The sensor bandwidth is limited by capacitive effects around the load (Z_L) connectors (Figure 2) and the transit time for an electromagnetic wave between the two outer sensor rods. For a theoretically perfect sensor, this transit time is the ultimate limitation.

5. SAMPLE SENSOR DATA

Figure 4 is a schematic illustration of a sensor configuration for measuring two orthogonal components of the E field. The center (reference) conductor extends beyond the measurement conductors, which are in two perpendicular planes. The resistor strings are located symmetrically on a plane, in insulating tubes.

Figure 5 illustrates the test setup and a typical sensor time history. A sensor with two orthogonal sensor planes was buried in soil with the planes oriented to measure the vertical and horizontal components of the field. The top of the vertical plane was 0.5 m below the soil surface. The parameters of the sensor and soil are included in Figure 5. It will be noted that $1/G$ is much less than $2R + Z_L$, in agreement with the requirement given in Eq. 5.

The electric field in the soil was provided by a series of ten capacitive-discharge field drivers located vertically above the E sensor. These drivers produced an approximately 100 kV/m horizontal E field at the ground surface. The reduction in the horizontal field at the sensor (peak $E \simeq 70$ kV/m) is due to diffusion through the conductive soil. The observed 10-to-90% rise time of the signal was about 7 ns.
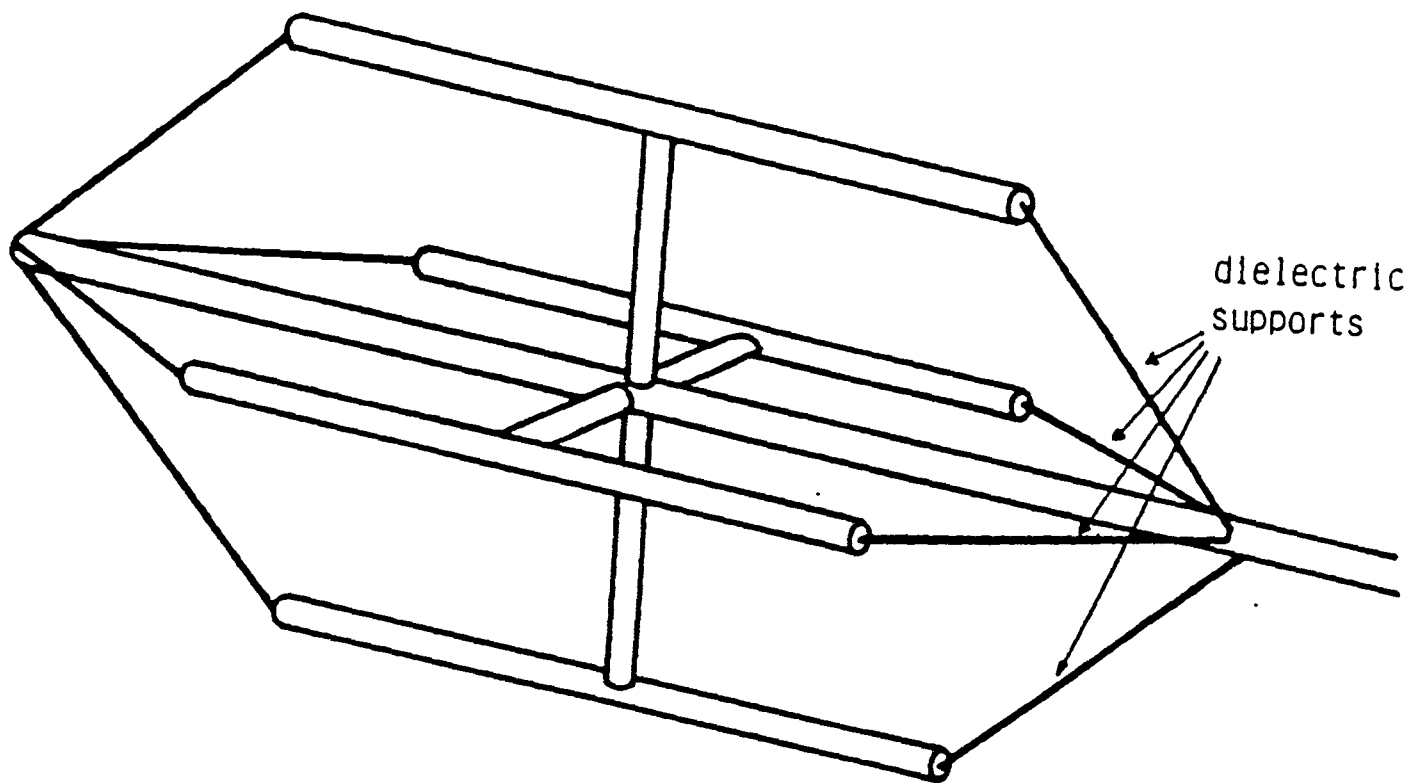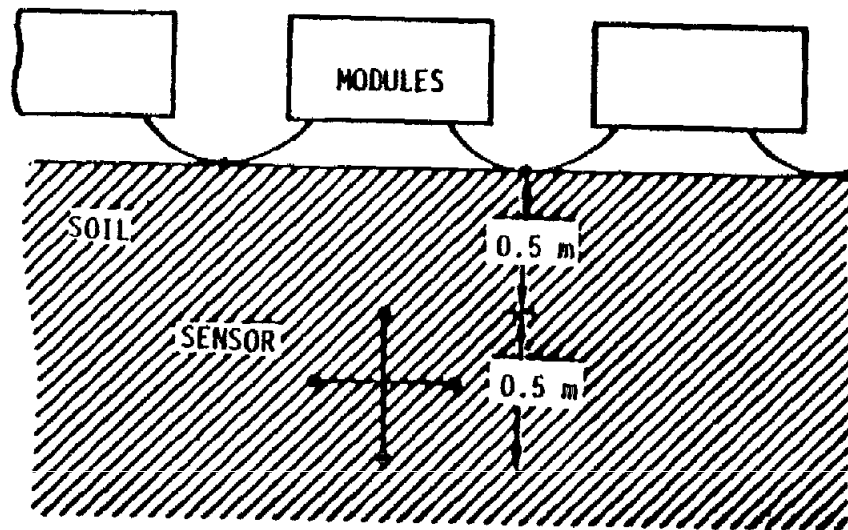
dielectric
supports

Figure 4. Sensor configuration for two dimensional field

RE-09093

- PROTOTYPE SENSOR

  $r_e = 0.65$ cm $\ell = 50$ cm

  $h = 25$ cm $f_g = 1.38$

  $R = 9.8$ kΩ $\sigma = 10^{-1}$ S/m

  $Z_L/2 = 50$ Ω

  $1/G = 275$ Ω

- OBSERVED RISETIME OF ~7 nsec
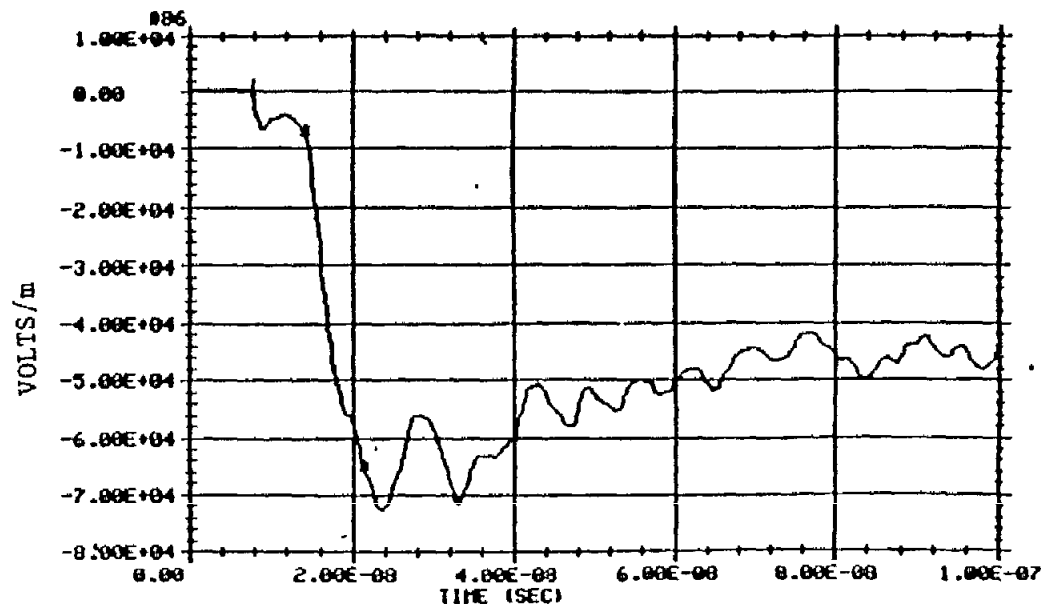
MODULES

SOIL

SENSOR

0.5 m

0.5 m

Figure 5.   Sample of sensor data

References

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7. C. E. Baum, Sensor and Simulation Note #86