NOTE 26

THE INFLUENCE OF FINITE SOIL AND WATER CONDUCTIVITY ON CLOSE-IN SURFACE ELECTRIC FIELD MEASUREMENTS

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24 September 1966

Sensor and Simulation Notes

Note XXVI
24 September 1966

The Influence of Finite Soil and Water Conductivity on Close-in Surface Electric Field Measurements

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Abstract

The parallel wire mesh, vertical dipole just above a ground or water surface is appropriate for measuring the close-in vertical electric field from a nuclear surface burst if the air conductivity is much less than the conductivity below the surface. When the conductivity of the lower medium is of the same order as or less than the air conductivity, the azimuthal wire mesh, vertical dipole design is more suitable for measuring the electric field just above the surface interface. For this latter case, there is not only a radial electric field above the interface, but also significant vertical and radial electric field components below the surface interface. The electric field components below the surface may also be distorted by the sensor related equipment in the lower medium.

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ABSTRACT

The parallel wire mesh, vertical dipole just above a ground or water surface is appropriate for measuring the close-in vertical electric field from a nuclear surface burst if the air conductivity is much less than the conductivity below the surface. When the conductivity of the lower medium is of the same order as or less than the air conductivity, the aximuthal wire mesh, vertical dipole design is more suitable for measuring the electric field just above the surface interface. For this latter case, there is not only a radial electric field above the interface, but also significant vertical and radial electric field components below the surface interface. The electric field components below the surface may also be distorted by the sensor-related equipment in the lower medium.

I. Introduction

A previous note discussed some general considerations for dipole electric field probes which are designed to measure the close-in electric fields, at the ground or water surface, from a nuclear surface burst.[1] The time-varying air conductivity leads to operating the dipole unloaded and the electric field dependence of the electron mobility leads to a parallel-plate structure which does not distort the electric field. Minimizing the electrode mass (per unit effective electrical surface area) by using wire mesh parallel plates aids in reducing the noise signal from the Compton current density. The wire mesh structure also allows conduction currents in the air to flow easily around the electrode structure instead of through it. Finally, further considerations lead to choosing materials for the sensor which minimize neutron and X-ray effects.

These previous considerations are based on a ground or water conductivity which is much larger than the air conductivity. In this case the electric field just above the surface is essentially perpendicular to the surface. In this note, these considerations for close-in electric field sensors are generalized to the case in which the air conductivity is comparable to or greater than the conductivity of the lower medium.

II. Effect of Finite Soil and Water Conductivity on Surface Electric Fields

Figure 1 shows the overall geometry for the electric field measurement with the nuclear surface burst at $r = 0$ in the spherical coordinate system. Consider a local Cartesian coordinate system, (x, y, z), centered at the ground or water surface at some radius of interest as illustrated. In general, near the origin of this

1. Lt. Carl E. Baum, Sensor and Simulation Note 15, Radiation and Conductivity Constraints on the Design of a Dipole Electric Field Sensor, February 1965.

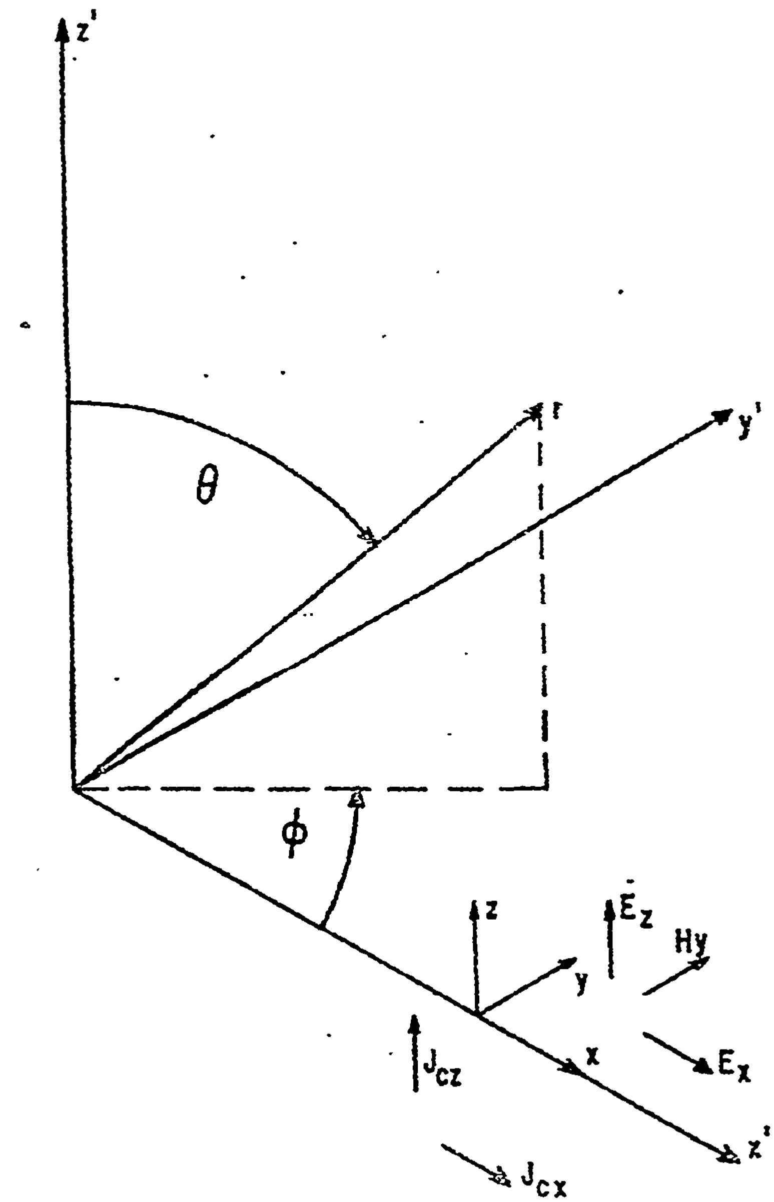

FIGURE I. COORDINATE SYSTEMS

Cartesian coordinate system, there are two Compton current density components, J_{c_x} and J_{c_z}, two electric field components, E_x and E_z, and one magnetic field component, H_y. Note that azimuthal (φ) symetry is assumed.

Figure 2 illustrates the parallel wire mesh type of vertical dipole located near the origin of the local Cartesian coordinates. For this type of structure we have assumed that there is no significant E_x near the ground or water surface. This applies under certain conditions. The electromagnetic parameters of the two media are ϵ, μ, and σ; the subscript, o, applies to the air while the subscript, 1, applies to the soil or water. Then, for $\sigma_1 >> \sigma_o$ and for times longer than the relaxation times (ϵ/σ) in the media, E_x is comparatively insignificant at $z = 0$.

The horizontal electric field remains small up to a vertical height which is determined by the distance that the disturbance in the electric field can propagate from the ground or water surface. This distance (a diffusion depth, or skin depth for high σ_o) limits the allowable vertical extent of the sensor so that the wire mesh does not distort the electric field.

The parallel wire mesh structure does not significantly distort the vertical electric field in the air. The major conductors of the wire mesh are perpendicular to the electric field which is assumed to be essentially vertical. Vertical conductors transmit the signals from the mesh electrodes to a high input impedance electronics package. These vertical conductors can significantly distort the nearby electric field. If the mesh electrodes are sufficiently large, however, the effect of the electric field distortion due to the signal leads becomes small. "Sufficiently large" also means that the effective height of the dipole is very nearly the spacing between the mesh electrodes and that the contributions to the dipole capacitance and conductance are predominantly due to the meshes. The vertical conductors must be designed so that large electric fields near the conductors do not produce breakdown in the ionized air. An insulating dielectric material might be used near these conductors to minimize such problems.

With $\sigma_1 >> \sigma_o$, the electric field components in the lower medium are also much less than E_z in the air (but near the interface). Thus, even though the conductors (cable shields, instrument cases, etc.)

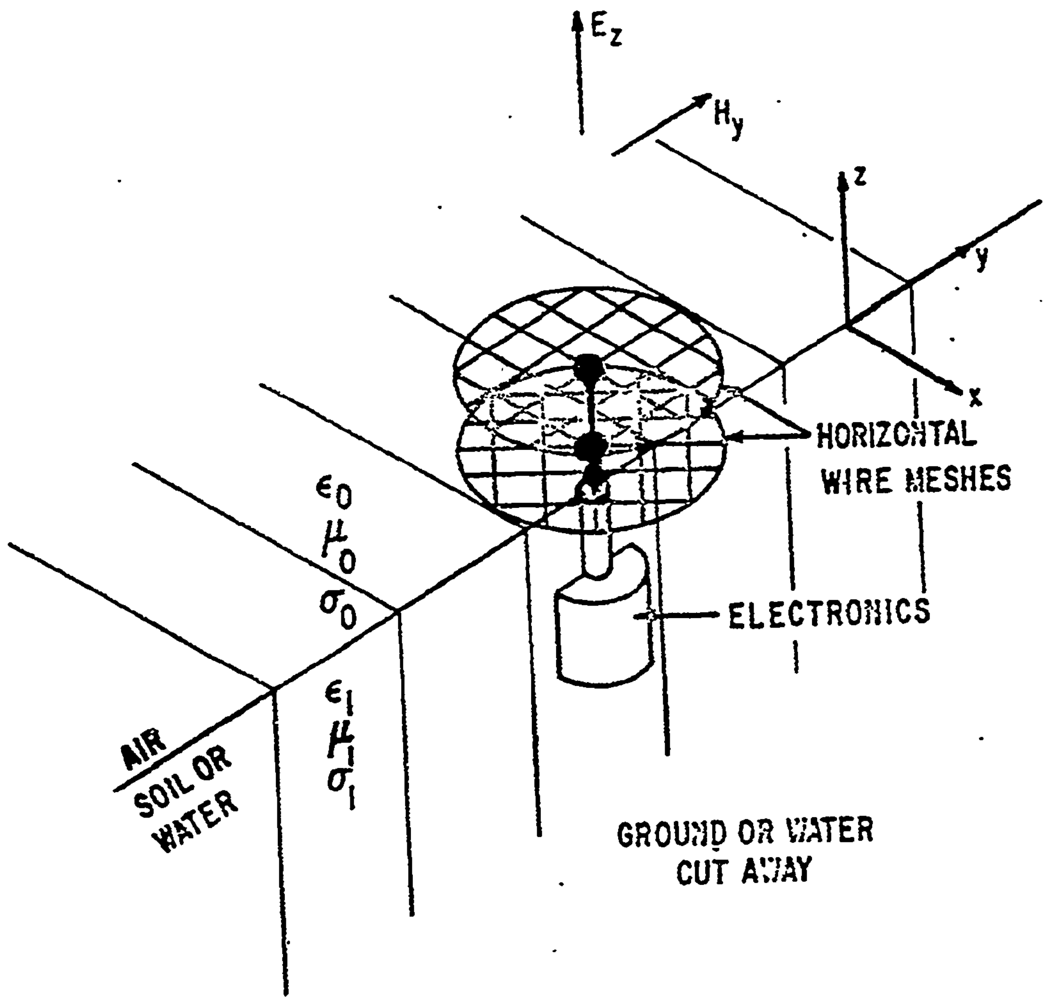

FIGURE 2. PARALLEL WIRE MESH, VERTICAL DIPOLE

in the ground or water distort these fields, the electric fields in the air are not significantly affected. The ground or water surface may be locally considered as a perfectly conducting ground plane and as such may be used as a reference for the vertical electric field measurement.

Figure 2 shows two horizontal wire meshes positioned just above the ground or water surface. In some cases, it may be suitable for the lower mesh to be coincident with the interface between the two media. Or, the lower mesh may be removed entirely so that the probe is operated single-ended. In such a case, however, it would become necessary to study the plasma sheath problem at the ground plane which may now influence the signal. Also, in such a case the probe would no longer be differential, a differential probe being desirable for rejecting Compton current noise. A truly differential sensor requires that the spacing between the two meshes be much smaller than the height of the lower mesh from the ground or water surface. The differential sensor, however, may introduce other kinds of problems such as large common mode signals.

We must also consider the case in which the ground or water conductivity is comparable to or even less than the air conductivity. The vertical electric field just above the interface, then, is not the only important electric field component. All the other electric field components above and below the interface become of the same order. We can use some rough numbers from another note to estimate at what point these other field components become important.[2]

If we consider the conductivities to be time independent, then the characteristic relaxation times for the two media are:

$$t_{r_0} = \frac{\epsilon_0}{\sigma_0} \qquad (1)$$

and

$$t_{r_1} = \frac{\epsilon_1}{\sigma_1} . \qquad (2)$$

2. Lt. Carl E. Baum, EMP Theoretical Note 19, A Technique for the Approximate Solution of EMP Fields from a Surface Burst in the Vicinity of an Air-Ground or an Air-Water Interface, September 1966.

The characteristic diffusion times are

$$t_{z_0} = \frac{\mu_0 \sigma_0 z^2}{4} \tag{3}$$

and

$$t_{z_1} = \frac{\mu_1 \sigma_1 z^2}{4} \tag{4}$$

for the two media. The air conductivity is about

$$\sigma_0 \approx 10^{-12} \gamma \tag{5}$$

with γ in roentgens/second.[3] For simplicity, only a γ-ray pulse which is changing slowly with respect to the attachment time of electrons to neutral oxygen molecules is considered. The time constants for the air are then

$$t_{r_0} \approx 8.9 \gamma^{-1} \tag{6}$$

and

$$t_{z_0} \approx 3.1 \times 10^{-19} z^2 \gamma . \tag{7}$$

The approximate parameters for the lower medium are listed in the following table.

Parameter	NTS Soil (Frenchman Flats)	Sea Water
$\frac{\epsilon_1}{\epsilon_0}$	16	80
σ_1	0.03	4

3. All units are rationalized MKS unless otherwise specified.

Parameter	NTS Soil (Frenchman Flats)	Sea Water
$\frac{\sigma_o}{\sigma_1}$	$0.5 \times 10^{-10} \gamma$	$2.5 \times 10^{-13} \gamma$
t_{r_1}	7.1 ns	0.18 ns
t_{z_1}	$0.63 \times 10^{-8} z^2$	$1.3 \times 10^{-6} z^2$

Table I. Parameters for lower medium.

The permeability is taken equal to μ_o in each case. The above expressions are derived and discussed in the previously referenced note.

For changes in γ long compared to the relaxation time, the tangential electric field at the ground or water surface is approximately

$$E_x \approx -E_o \left[1 + \sqrt{\frac{\sigma_1}{\sigma_o}}\right]^{-1} , \tag{8}$$

where $-E_o$ is the radial electric field for positive z for times much less than the diffusion time in the air (Equation 7). This characteristic electric field is

$$E_o \approx 2 \times 10^4 \text{ volts/meter} . \tag{9}$$

For $\sigma_o << \sigma_1$ the radical electric field at the interface becomes insignificant. In some practical cases, however, σ_o/σ_1 may be comparable to unity, or even larger. In this latter instance E_x becomes comparable to E_z and may therefore have an influence on electric field sensor design. The diffusion depth for the fields in air decreases with increasing γ. Thus, the diffusion depth for the fields in air may even become comparable to, or smaller than, the maximum height of the sensor from the ground or water surface. This reduces the vertical electric field and increases the horizontal electric field near the top of the sensor.

The parallel wire mesh, vertical dipole of Figure 2 has the undesirable feature of shorting out the significant radial electric field at high air conductivities. The corresponding changes in the local electric field magnitude and the local air conductivity alter the effective height of the probe. The seriousness of this problem is difficult to determine because of the complexity of the processes involved. With this in mind, it is desirable to avoid this electric field shorting if at all possible.

III. Implications for Surface Electric Field Measurements

Then for the case of high air conductivity (comparable to or greater than the ground or water conductivity) the probe structure needs to be changed from the parallel wire mesh configuration. Consider then the sensor elements in the upper medium. To avoid distorting the electric fields there must be no significant vertical or radial conductors. This leaves the azimuthal or y direction for the probe electrodes. Figure 3 illustrates the resulting azimuthal wire mesh, vertical dipole.

Considering first the probe structure in the air, we have a transmission line type of structure which is composed of two parallel circular cylinders (instead of plates). Each cylinder consists of several wires to form a mesh type structure which has distinct advantages over a continous structure. Using the dimensions illustrated in Figure 3B, we can approximate some parameters of the sensor. (The electrodes are approximated by conducting cylinders.) The sensor is then a transmission line with a characteristic impedance, Z_L, related to the wave impedance, Z, of the medium (ignoring nonlinearities) as

$$Z_L = f_g Z \quad , \tag{10}$$

where f_g is a dimensionless geometric factor. This factor is given by

$$f_g \approx \frac{1}{\pi} \operatorname{arccosh}\left(\frac{b}{c}\right) = \frac{1}{\pi} \ln \left\{ \frac{b}{c} + \left[\left(\frac{b}{c}\right)^2 - 1\right]^{1/2} \right\} \quad . \tag{11}$$

We neglect the fringing fields at the signal removal leads and at the ends of the wire meshes. Neglecting nonlinearities in the air conductivity yields a sensor capacitance

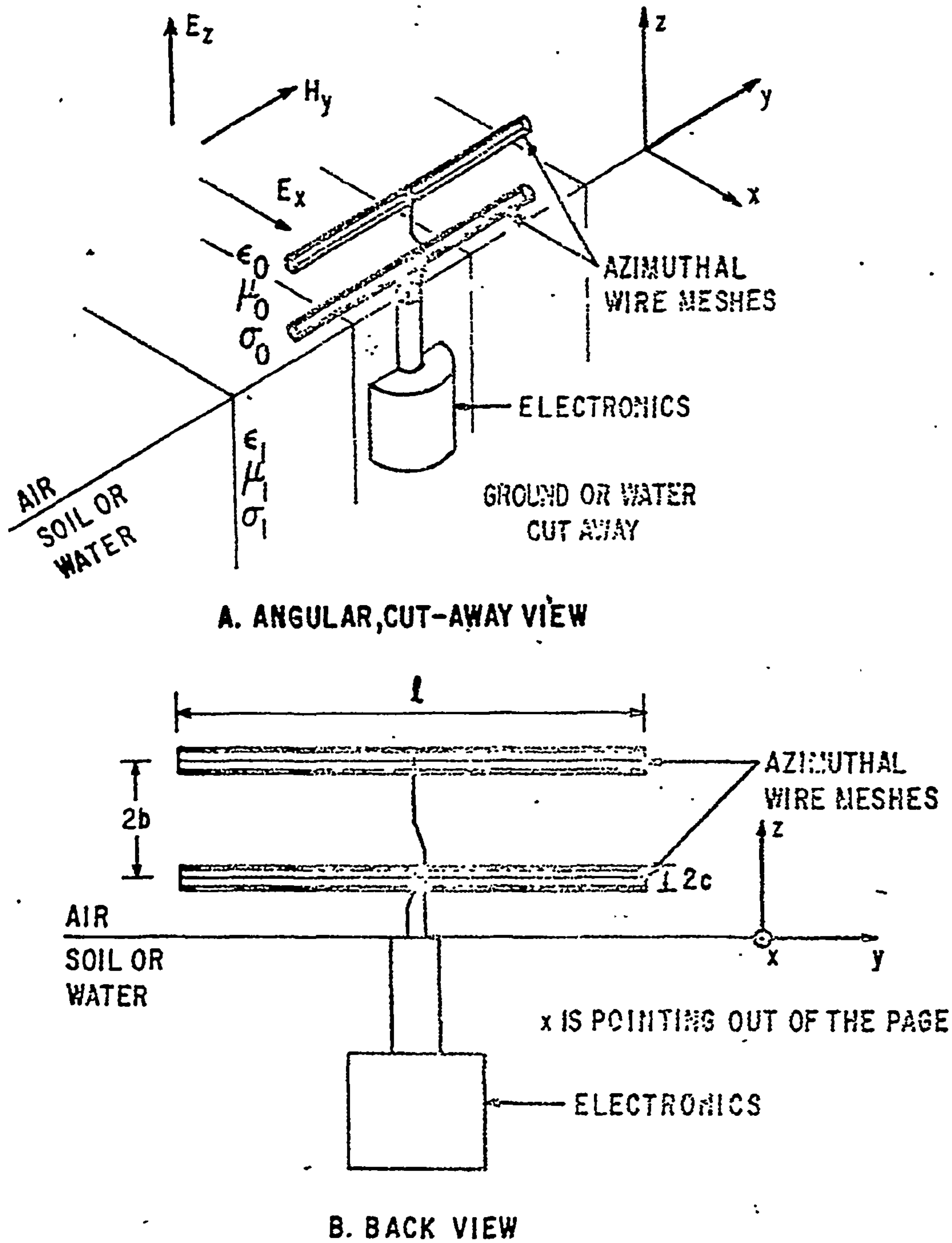

FIGURE 3. AZIMUTHAL WIRE MESH, VERTICAL DIPOLE

$$C_s \approx \frac{\epsilon_o \ell}{f_g} \qquad (12)$$

and a sensor conductance

$$G_s \approx \frac{\sigma_o \ell}{f_g} \quad . \qquad (13)$$

For ℓ equal to the diameter of the parallel wire meshes of Figure 2, this azimuthal mesh structure unfortunately has less capacitance than the parallel plate wire mesh structure for the same electrode spacing. This may be compensated for by lengthening the azimuthal meshes so that their capacitance is much greater than the input capacitance associated with the lead-in wires and the input circuitry. The ratio, b/c, can be decreased to increase the sensor capacitance. There is a limitation in how small we make b/c since the electric field is distorted in the vicinity of the electrodes due to their finite extent in the x and z directions. This distortion should extend over distances comparable to the electrode radius, c. We are, therefore, limited to $b \gg c$.

Since we are now considering the case where σ_1 is comparable to σ_o the ground or water surface can no longer be considered an equipotential. We cannot use the lower medium, therefore, as one of the electrodes for this case. The lower electrode, however, may be placed at or close to the interface, again being careful with regard to plasma sheath problems at the interface. This structure may also be used to measure E_x if it is rotated so that the electrodes are at the same z but at different x. Since E_x is continous across the interface between the two media, the electrodes may be placed at slightly negative z for this purpose.

The probe structure below the interface can no longer be ignored when the conductivities of the two media are comparable. The electric fields are comparable on both sides of the interface. Distortion of the electric field below the interface is then accompanied by similar distortion above the interface. The radial and vertical electric fields in the lower medium may be distorted both by significant radial and vertical conductors which short the field components and by insulators which block the radial and vertical components of the conduction current density. It is necessary for the currents to flow around or through the buried structure in a manner which gives negligible electric field perturbation above the interface.

There are several techniques which one might possibly use to minimize the effects of the electric field distortion due to the structure below the interface. The sensor electrodes can be constructed large enough to extend far outside the region of electric field distortion. The subsurface conductors can possibly be mainly of azimuthal orientation. For example, the data cable transporting the signal to the recording instruments may leave the electronics package in the azimuthal direction, gradually gaining depth with increasing distance from the probe. Insulating dielectrics can be used to insulate parts of the below ground structure from the soil or water. This may minimize the shorting of the vertical electric field by the electronics package and the cable transporting the signal from the probe electrodes to the electronics package. The electric field shorting problem may also be reduced by using chokes and pulse isolation transformers to break up the electrical continuity of the subsurface structures, data and power cables, etc.

For transient field pulses, the diffusion depth in the ground or water limits the vertical extent of the field penetration. When σ_o decays to much less than σ_1 the subsurface field distortion becomes unimportant. The time for this to happen may be less than some diffusion times or times for which pulse isolation techniques are operative. These field distortion problems can be difficult but perhaps not impossible.

IV. Summary.

With the ground or water conductivity much larger than the air conductivity, we can measure the close-in vertical electric field above the interface using a wire mesh, parallel plate, vertical dipole. If the air conductivity becomes comparable to or greater than the conductivity of the lower medium, there are more stringent requirements on the sensor design. Since there is also a significant radial electric field near the interface, there should be no significant vertical or radial conductors in the air. This leads to the azimuthal wire mesh, vertical dipole. Since there are also significant vertical and radial electric fields below the interface, we should design the subsurface sensor equipment to minimize the electric field distortion so as to avoid significant electric field distortion above the interface.

UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)
General Electric Comapny, TEMPO
816 State Street
Santa Barbara, California 93102

2a. REPORT SECURITY CLASSIFICATION
UNCLASSIFIED

2b. GROUP

3. REPORT TITLE
ELECTROMAGNETIC PULSE SENSOR AND SIMULATION NOTES, VOLUME 1, NOTES 1 through 26

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

5. AUTHOR(S) (First name, middle initial, last name)

6. REPORT DATE
July 1971

7a. TOTAL NO. OF PAGES
406

7b. NO. OF REFS

8a. CONTRACT OR GRANT NO.
F29601-70-C-0010

b. PROJECT NO.

c.

d.

9a. ORIGINATOR'S REPORT NUMBER(S)
AFWL EMP 1-1

9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

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Air Force Weapons Laboratory (WLRE)
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13. ABSTRACT
A series of 26 notes on electromagnetic pulse sensor and simulation techniques. Subjects covered in this volume are: EMP Testing Facility; "Invisible" Absolute E-Field Probe; Combined E and $\dot{B}$ Sensor; On the Properties of Loop Antennas; Underground Testing of Close-In EM Sensors; Minimizing Transit Time Effects in Sensor Cables; Characteristics of the Moebius Strip Loop; Maximizing Frequency Response of a $\dot{B}$ Loop; A Compton Diode for Measuring Both the Gamma Flux and One Component of the Gamma Current; Description of Gamma Anisotropy Sensor (Beatle); Capacitive Probe E-Field Sensors; A Space Charge Limited Radiation Detector; Electric Field and Current Density Measurements in Media of Constant Conductivity; Design Considerations for Twinaxial Cable; Radiation and Conductivity Constraints on the Design of a Dipole Electric Field Sensor; Some Limitations on Microwave Air-Conductivity; A Detector Geometry for Measuring Both the Gamma Flux and One Component of the Gamma Current; Electric Field Sensor for EMP Simulators; Combining Voltage or Current Dividers with Sensor Cables; A Detector Geometry for Measuring the Vertical Gamma Current; Impedances and Field Distributions for Parallel Plate Transmission Line Simulators; A Transmission Line EMP Simulation Technique for Buried Structures; A Technique for the Distribution of Signal Inputs to Loops; A Technique for Measuring Electric Fields Associated with Internal EMP; The Multiple Moebius Strip Loop; The Influence of Finite Soil and Water Conductivity on Close-In Surface Electric Field Measurements. Additional notes in this series are published in subsequent volumes.

DD FORM 1 NOV 65 1473 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

☆ U.S. GOVERNMENT PRINTING OFFICE: 1971 - 432-810/3010

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Security Classification