Sensor and Simulation Notes
Note 87
9 July 1969

# A Distributed-Source Conducting-Medium Simulator for Structures Near and Below the Ground Surface

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## Abstract

This note considers various features of the design of a distributed-source conducting-medium simulator which would be used for simulating the nuclear EMP near a surface burst and in the region near and below the ground surface. This simulator is considered from the point of view of showing what the major parts of such a simulator might include and how these might be arranged in space.

# I. Introduction

The problem of simulating the nuclear electromagnetic pulse (EMP) close to a surface nuclear burst and near the ground surface is a complex one indeed. There is a nuclear radiation field which produces a source current density of high energy electrons in both the air and the ground and makes the air a conducting medium. The conductivity and source current density, or Compton current density, are both very time dependent. Associated with the conductivity and Compton current density there are electric and magnetic fields produced. The air conductivity is also significantly affected by the magnitude of the electric field, and the Compton current density can be affected by both the electric and magnetic fields. The electromagnetic fields, current densities, and conductivities together comprise the electromagnetic environment or EMP to be simulated. In as much as the nuclear radiation ($\gamma$ rays, X rays, neutrons) can affect the response of a system to the electromagnetic environment by altering the system characteristics in some way, the nuclear radiation effects are also part of the simulation problem. In this note we consider some of the problems associated with the design of a type of EMP simulator which is intended to simulate the EMP close to a nuclear burst and on a structure near and below the ground surface.

One approach to this simulation problem which we have discussed in previous notes basically consists of a surface transmission line[1] to guide a high-frequency electromagnetic wave over the ground surface and a buried transmission line[2] to give the proper distribution of the low-frequency electromagnetic fields with depth into the ground. This approach is not too difficult to implement and has been used as a simulator. However, there are some deficiencies in this simulation technique in that some features of the EMP environment are not included. The medium above the ground should be conducting; portions of the system which contact this medium and can couple electromagnetic energy into the system can have their source impedance characteristics significantly changed by the presence of the air conductivity. (Note that the air conductivity is a function of time and the electric field magnitude, so that impedance is only a rough concept here.) With a conducting medium above the ground there are also significant conduction currents in the air extending out into the late-time portions of the EMP. The portions of the

1. Capt Carl E. Baum, Sensor and Simulation Note 46, The Single-Conductor, Planar, Uniform Surface Transmission Line, Driven from One End, July 1967.

2. Lt Carl E. Baum, Sensor and Simulation Note 22, A Transmission Line EMP Simulation Technique for Buried Structures, June 1966.

system in contact with the air can then collect these late-time currents and may thereby significantly increase the amount of energy collected. If a surface transmission line with a nonconducting upper medium is used as a simulator then the only currents in the upper medium are displacement currents which are only significant for the early-time or high-frequency portion of the simulated EMP; this could significantly limit the validity of such a simulation technique with respect to certain types of coupling modes to the system. Of course, there is also the limitation in this simulation technique that the nuclear radiation and Compton current density are not present as in the real case.

In this note we discuss some of the features of a simulation technique which more completely simulates the EMP close to a surface nuclear burst. One might call such a simulator a distributed-source conducting-medium simulator, such a title mentioning two of its important features. Two previous notes[3,4] have discussed some aspects of such a simulator. This simulator would also use a buried transmission line.[2] The purpose of this note is to outline what in its major features such a simulator might look like and to discuss some of the design problems that need more attention and may be considered in future notes.

The general idea of a simulator is to reproduce, at least approximately, some feature of the environment produced by a nuclear burst on some system of interest. The simulator which gives the best simulation is of course the one which includes the most features of the environment in the most accurate and complete manner. One would like to assume as little about the system response as possible by duplicating the real case as completely as possible and thereby minimize the chance of overlooking some significant system coupling to the environment. The distributed-source conducting-medium simulator is a step in this direction.

## II. Form of Electromagnetic Wave to be Generated by Simulator

Referring to figure 1 we can now discuss the basic electromagnetic wave around which the whole simulation concept is based. The geometry in figure 1 is two dimensional, all parameters being assumed independent of y. For the present considerations we also

3. Capt Carl E. Baum, Sensor and Simulation Note 48, The Planar, Uniform Surface Transmission Line Driven from a Sheet Source, August 1967.

4. Capt Carl E. Baum, Sensor and Simulation Note 66, A Simplified Two-Dimensional Model for the Fields Above the Distributed-Source Surface Transmission Line, December 1968.

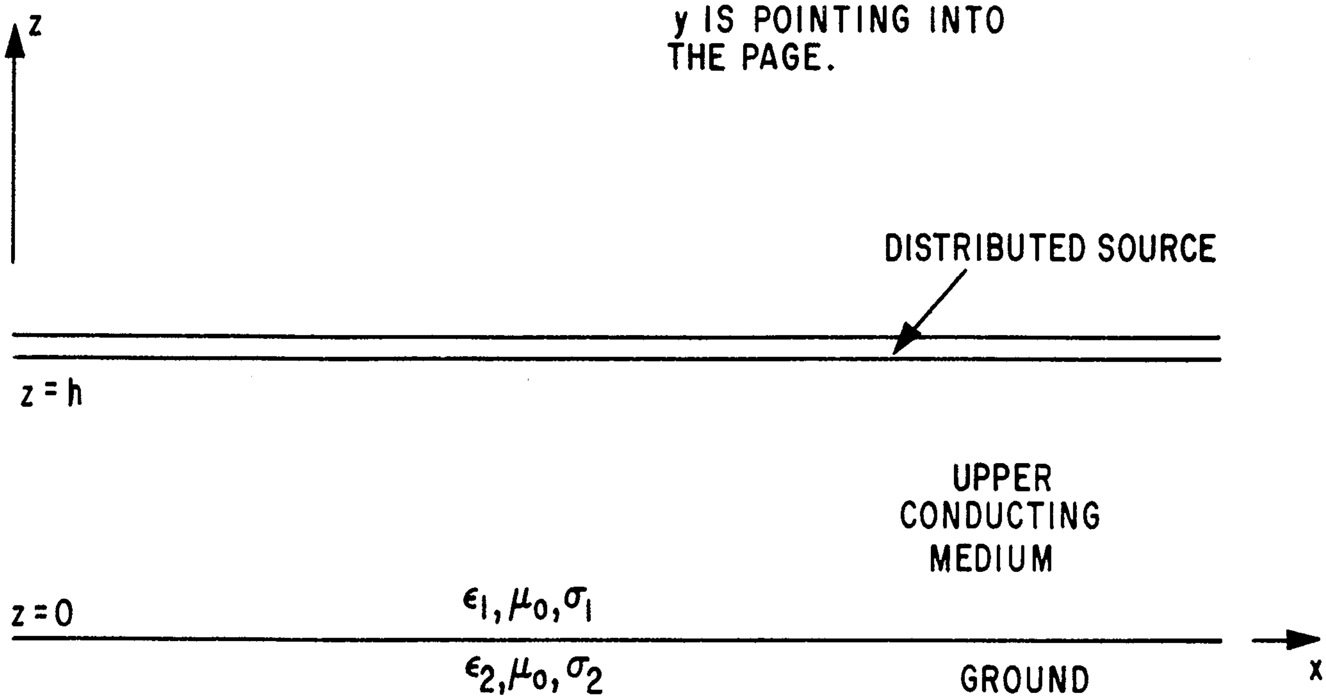


FIGURE 1. DISTRIBUTED SOURCE OVER CONDUCTING MEDIUM

ignore the finite extent of the geometry in the +x and -x directions. The ground surface is taken as $z = 0$. In the ground (soil, rock, or whatever) we have permittivity $\varepsilon_2$, permeability $\mu_o$, and conductivity $\sigma_2$; for $0 < z < h$ these parameters are respectively $\varepsilon_1$, $\mu_o$, $\sigma_1$. This medium for $0 < z < h$ is added above the ground and can be considered as part of the simulator. Note that we could also in general have different permeabilities for the two media of interest but list them both as $\mu_o$, the free-space value, as being the typical case of practical importance. We have the definition[5]

$$z' \equiv z - h \tag{1}$$

so that $z' = 0$ is the position of the source plane. However in some cases where we might choose $\sigma_1 = \sigma_2$ and $\varepsilon_1 = \varepsilon_2$ then it may be convenient to use $z = 0$ as the source position instead of the ground surface.

The distributed source is located on the plane $z' = 0$ (or $z = h$) and has the characteristic that it establishes the tangential electric field on this plane to have only an x component of the form

$$E_s = E_o\left(t - \frac{x}{c}\right) e^{-\frac{x}{\chi}} \tag{2}$$

where

$$c \equiv \frac{1}{\sqrt{\mu_o \varepsilon_o}} \tag{3}$$

is the speed of light in free space. Equation 2 gives the time domain form of the source field with an exponential attenuation with distance with an e-folding distance $\chi$ which might be about 200 meters, and which corresponds to the $\gamma$-ray mean free path in air near sea level. $E_o$ gives the waveshape which is constant in retarded time. The Laplace transform of equation 2 is

$$\tilde{E}_s = \tilde{E}_o e^{-\gamma_s x} \tag{4}$$

where

5. All units are rationalized MKSA.

$$\tilde{\gamma}_s = \frac{s}{c} + \frac{1}{\chi} \tag{5}$$

where s is the Laplace transform variable and a tilde, ~, denotes the two sided Laplace transform (or Fourier transform with $s = i\omega$). Note that the exponential attenuation with x is particularly convenient because of the way it becomes part of $\gamma_s$ in the Laplace transformed source equation (equation 4).

With the particular form of source field as in equations 2 and 4 the source is similar to the nuclear source in some important respects. It propagates at speed c and its amplitude attenuates with distance in a manner which approximates the attenuation of the real source with distance. In reference 3 the electric fields, magnetic fields, and current densities are calculated and the derivation is not repeated here. However certain features of the fields and current densities which result can be simply stated in qualitative terms. First all the fields and current densities of course have the same dependence on x as the source field. The source current associated with the wave below the source also has the same x dependence as the source field. Note that the source current and source field are in the opposite direction at the source, or the plane $z = h$, at least for early times. This feature of the simulator is also similar to the nuclear EMP where the Compton current density and electric field above the ground are in roughly opposite directions so that the Compton current imparts energy to the fields. In the simulator, however, the source current is localized to a plane instead of being distributed throughout the upper medium. The wave is, however, still being roughly locally generated which is necessary at high frequencies if the wave has to propagate to the position of interest through a conducting medium.

Since the source current attenuates with distance x as in equations 2 or 4, the same as the fields, then at low frequencies or late times there is a significant derivative of the source current with respect to x. Then by the equation of continuity, if one is to avoid piling up an arbitrarily large amount of charge along the source, there must be a significant vertical current density passing between the source surface ($z = h$) and the ground through the upper medium. (Note that typically $h \ll \chi$.) It is the fact that the upper medium is conducting which allows this vertical current density to flow at low frequencies and thus also allows the source current to have a significant derivative with respect to x at low frequencies.

The wave impedances for the two media of interest are

$$Z_1 = \sqrt{\frac{s\mu_o}{\sigma_1 + s\epsilon_1}}, \qquad Z_2 = \sqrt{\frac{s\mu_o}{\sigma_2 + s\epsilon_2}} \tag{6}$$

One of the advantages to be gained with the conducting medium in contact with the sources is the fact that the magnitude of the wave impedance is less than the free space value. This is particularly true at low frequencies or late times because of the form in which the conductivity influences the wave impedance. Note that the magnitude of the wave impedance can also be lowered at high frequencies by using an upper medium with $\varepsilon_1 > \varepsilon_0$ (the permittivity of free space). With the magnitude of the wave impedance decreased, the magnitude of the electric field for a given magnetic field level is also typically decreased. Viewed another way, for a given electric field magnitude the magnetic field magnitude can be increased by the use of $\sigma_1$ plus $\varepsilon_1 > \varepsilon_0$. Since the dielectric strengths of the materials either used in the vicinity of the simulator or normally located there are one of the limiting factors on the field strengths obtainable there is an advantage in minimizing the electric field magnitude associated with a given magnetic field waveform.

One should note, of course, that the $\sigma_1$ and $\varepsilon_1$ one might use are typically constants independent of time. This is different from the nuclear EMP environment. However at least some of the important effects associated with the air conductivity are included in this type of simulation.

## III. High-Frequency Part of Simulator

The desired form of wave for this simulator (discussed in the previous section) applies most directly to the high-frequency part of the simulator, illustrated in figures 2 and 3. The high-frequency part of the simulator has the additional conducting medium above the ground. It would be physically located above that portion of the system under test where parts of the system are near or above the surface of the ground. It is these portions of the system which are most significantly affected by the locally generated high frequencies and by the close proximity of the conducting air associated with a nuclear surface burst. The low frequency energy sources might be configured somewhat differently, as is discussed in the next section.

One of the design problems associated with the portion of the simulator including the high-frequency sources is the uniformity of the fields and current densities produced in the upper conducting medium and the ground. Real sources (like capacitors and switches) are somewhat discrete. The distributed source might then be typically realized as an array or matrix of discrete modules distributed over the source surface and appropriately interconnected, charged, and triggered in a manner which approximates the desired sheet source. One would expect variations in the fields and current densities near the sources over distances comparable to the source spacing. One would also typically expect

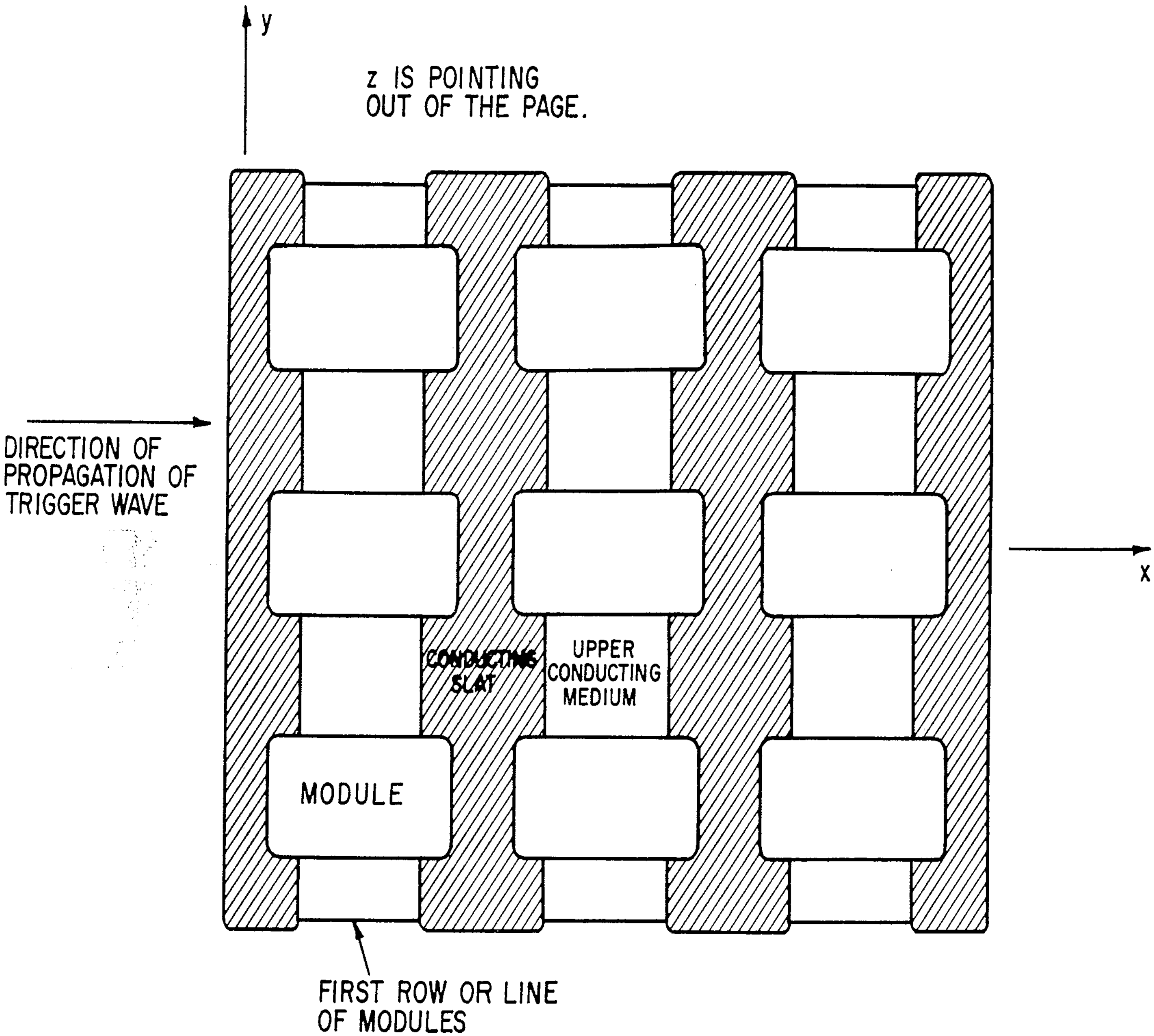


FIGURE 2. TOP VIEW OF HIGH-FREQUENCY PART OF SIMULATOR

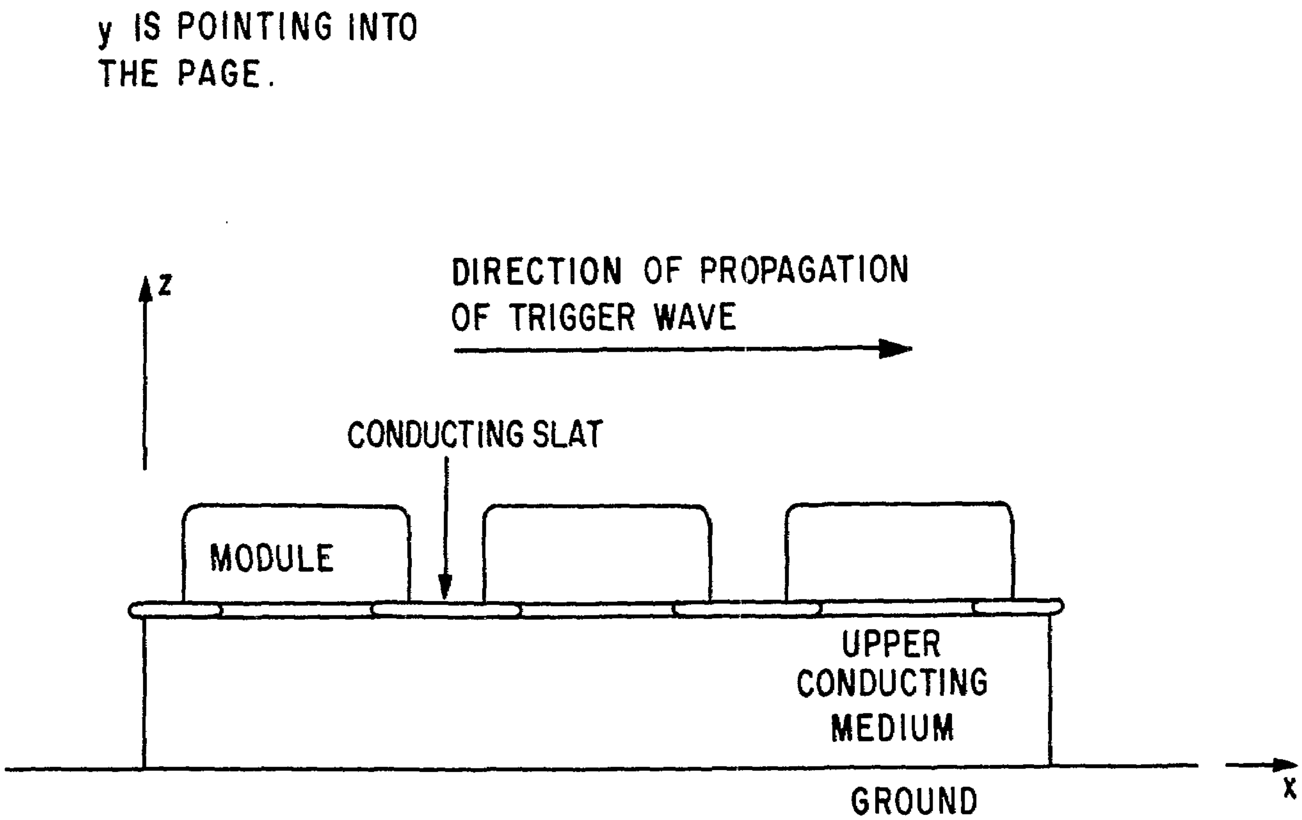


FIGURE 3. SIDE VIEW OF HIGH-FREQUENCY PART OF SIMULATOR

variations in the early-time behavior of the pulse associated with the source spacing.

For purposes of illustration in figures 2 and 3 we show this high-frequency distributed source with 9 modules arranged 3 by 3 and covering approximately a square area over the upper conducting medium. Typically a much larger number of modules might be desired to obtain better uniformity and better rise characteristics for the electromagnetic wave. The general layout of the high-frequency distributed source consists of first conducting slats run in a direction perpendicular to the electric field; these slats tie the array together and provide the electrical contact between the source modules and the upper conducting medium. Connected between two adjacent slats is a row or line of source modules; all modules in a row are triggered simultaneously, establishing a voltage between adjacent slats. Each row of modules can be approximately considered as an electromagnetic line source (of finite length). All the rows of sources can be collectively considered as a source matrix or array. The source rows are triggered sequentially in order of increasing x at times such that the wave propagates in the +x direction at speed c. Within each row the trigger signal might be distributed to each module by electrical cables. The trigger signal can be distributed to each row by an electromagnetic wave (pulsed light beam, pulsed microwave, pulsed laser, etc.) which propagates over the source array in the +x direction at speed c and is picked off at each row. Alternatively, each module might pick off the electromagnetic trigger wave individually.

There are various other features of this portion of the simulator which must be included in the design. These include special sources at the front end (smallest x) of the high-frequency part and special terminations at the other end to match the required boundary conditions for the desired high-frequency portions of the wave like that discussed in section II. In order to optimize the waveform the source modules may have other elements besides capacitors and switches. One may also ask whether all the energy needed for the entire waveform for this particular portion of the simulator need be stored in the modules in the source array above the upper conducting medium. Perhaps the energy for the low-frequency or late-time portions of the waveform would better be stored in front of or in back of the high-frequency array and feed the current into the array at late times through special elements connected between the slats in addition to the high-frequency source modules. The source modules will also need some charging circuitry; the whole array might be charged with resistor strings in a manner similar to a Marx generator. The modules could be charged in a manner so as to achieve the desired source attenuation with x. Alternatively elements could be included with the modules to achieve the same effect. There are also dielectric strength problems associated with the array and special choices of materials and geometries in the vicinity of the array can be used to increase the allowable source strengths.

## IV. Low-Frequency Part of Simulator

Figures 4 and 5 give an overall view of some of the major features of the total simulator in what might be a typical configuration. Starting in the center we have the high-frequency source array as discussed in the previous section. This is integrated with several low-frequency sources distributed over the site. These sources are connected to the ground via the two rows of deep rods which form the buried transmission line (reference 2) and some very shallow rods between the sources which allow for currents to flow out of the ground at appropriate positions between the low-frequency sources. The low-frequency sources would also be sequentially triggered at speed c in the +x direction by a trigger wave propagating over the site.

Referring to figure 4 we have divided the site into approximately 9 regions as an example, each region having its own set of low-frequency sources. Note that the regions are laid out to roughly match the field distribution associated with the TEM mode on the buried transmission line which is the principal mode of propagation for the low-frequency fields in the ground. The curved rows of shallow rods in the ground between sources lie along equipotential contours for the TEM mode. At late times during the simulated EMP these shallow rods allow current to flow vertically in the ground provided the low-frequency sources have strengths which attenuate in the +x direction, much the same as the high-frequency sources over a portion of the site. The late-time flow pattern for that portion of the current which passes through the ground surface is illustrated in figure 5 on a plane of constant y through the middle of the simulator. Note the smooth vertical current distribution under the high-frequency sources versus the much less uniform vertical current density associated with the fewer low-frequency sources. The principal current density (the mean horizontal current density) is not included in this sketch.

There are various approaches one might pursue for the low-frequency sources which must store a large amount of energy. One might use resistively damped capacitive generators.[6] In order to improve the generator efficiency at the cost of greater complexity one might have each generator consist of two or more capacitor banks at different charge levels and switched into the

6. Capt Carl E. Baum, Sensor and Simulation Note 44, The Capacitor Driven, Open Circuited, Buried-Transmission-Line Simulator, June 1967.

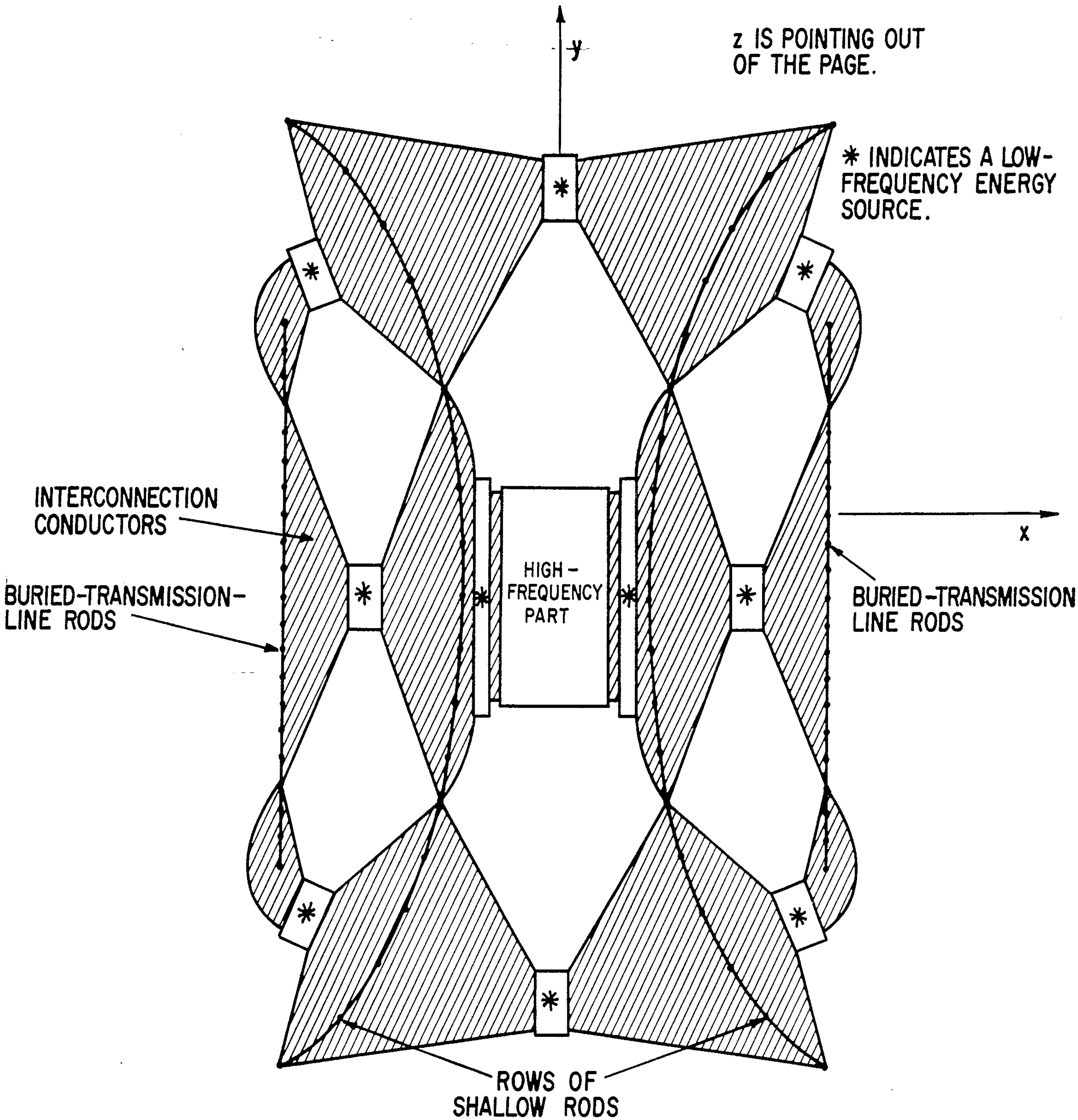


FIGURE 4: EXAMPLE OF SOURCE LAYOUT FOR SIMULATOR : TOP VIEW

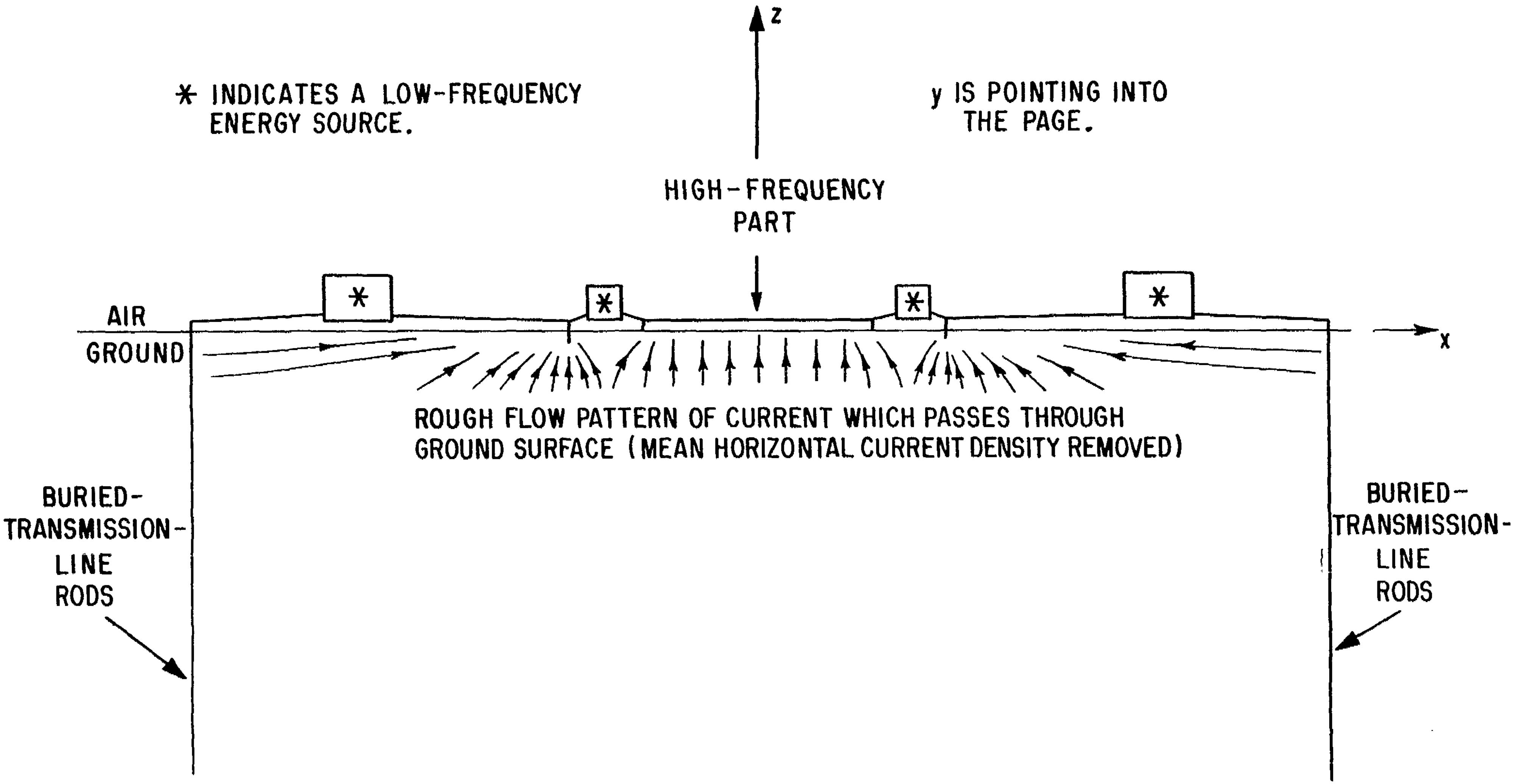


FIGURE 5. EXAMPLE OF SOURCE LAYOUT FOR SIMULATOR: SIDE VIEW IN CENTER

load at different times.[7] Another approach might involve inductive energy storage.[8] Or, some hybrid generator might use both capacitors and inductors.[9] Thus there are many possible design approaches to the low-frequency main energy storage systems.

Again, as mentioned in the last section one of the design problems is the interconnection of the low-frequency main energy sources with the high-frequency sources distributed over the upper conducting medium. The high-frequency sources, perhaps localized to some portion of the total site (as in figure 4), should be made to have approximately the same low-frequency characteristics as the neighboring large low-frequency sources so that they will match together as one simulator array at low frequencies. This matching might be accomplished in the design of the high-frequency source modules, the inclusion of other elements besides the source modules connecting the slats in the high-frequency array, and the inclusion of special energy sources and impedances at the ends of the high-frequency array.

## V. Other Problems in Design of the Simulator

There are, of course, various problems in the detailed design of this kind of simulator which we have not discussed in this note. One such problem concerns the electromagnetic energy which is transiently radiated above the simulator when the energy sources are discharged. This effect puts an additional high-frequency load on the distributed energy sources and should be accounted for in the simulator design. A previous note (reference 4) has discussed a simplified model for this effect.

Some other problems concern what might be termed long appendages to the system under test such as power lines and communication cables. Such items represent conductors extended from a region over which the EMP is being simulated to a region where the fields are not being produced (at least not significantly); this perturbs the simulation of the EMP. Some means should be provided for special connection of these appendages to the simulator with appropriate energy sources, impedances, etc. to

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7. Capt Carl E. Baum, Sensor and Simulation Note 49, The Buried-Transmission-Line Simulator Driven by Multiple Capacitive Sources, August 1967.

8. R. W. Latham and K. S. H. Lee, Sensor and Simulation Note 50, The Buried Transmission Line Simulator With an Inductive Energy Source, April 1968.

9. Dale W. Milligan, Sensor and Simulation Note 76, The Buried-Transmission-Line Simulator Driven by Multiple Capacitive Sources and an Inductive Source, March 1969.

minimize any interference with the simulation and to place the proper currents and voltages on various parts of these appendages so as to make the simulation of the nuclear EMP more complete.

## VI. Summary

In this note we have discussed a distributed-source conducting-medium simulator for use in simulating the nuclear EMP close to a surface burst on structures near and below the ground surface. Such a simulator has the desirable features of simulating the air conductivity and conduction current density associated with the EMP. We have considered such a simulator from the point of view of the various features it might include and the possible arrangement and interconnection of the component parts. Hopefully this has given the reader some appreciation of what such a simulator might entail in its major features and the general complexity of the problem.

There are still many detailed design calculations to be performed. These include the field uniformity associated with the high-frequency array of discrete sources, field distortion introduced at the ends of the distributed sources, field distortion associated with the integration of the high-frequency array with large-energy low-frequency sources, field uniformity associated with the discrete low-frequency energy sources and interconnecting conductors, and numerous other detailed problems. Perhaps some of these problems can be considered in future notes.