

Sensor and Simulation Notes
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Some Considerations Concerning a Simulator with
the Geometry of a Half Toroid Joined to a
Ground or Water Surface

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Abstract

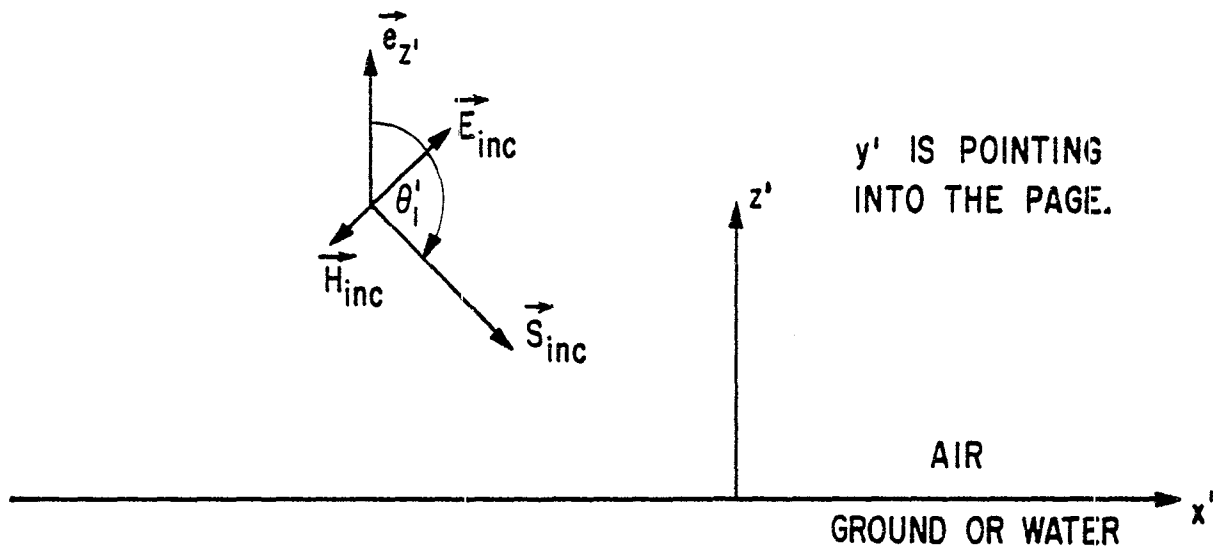
This note considers some of the features of the design of an EMP simulator consisting of a capacitive pulse generator driving a half toroid above and joined to a ground or water surface. This type of simulator can be used to simulate a pulsed plane wave incident on the ground or water surface. By appropriate orientation of the toroid and choice of the generator parameters one can match several characteristics of the desired plane wave, including polarization, direction of incidence, peak incident fields, and complete time integral of the resultant magnetic field at the ground or water surface.



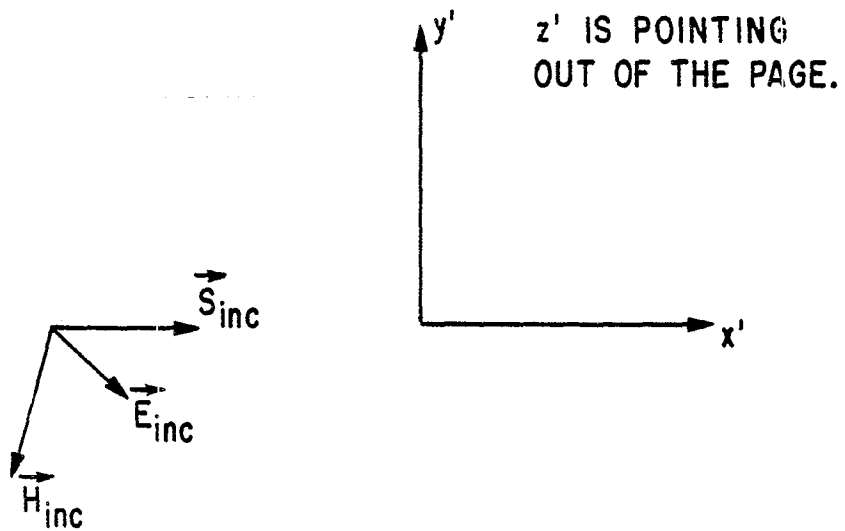
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A. SIDE VIEW



B. TOP VIEW

FIGURE 1. GEOMETRY OF INCIDENT PLANE WAVE

\vec{e}_1 is parallel to \vec{S}_{inc} and we have

$$\vec{e}_1 \times \vec{e}_2 = \vec{e}_3$$

$$\vec{e}_2 \times \vec{e}_3 = \vec{e}_1 \quad (3)$$

$$\vec{e}_3 \times \vec{e}_1 = \vec{e}_2$$

\vec{e}_2 and \vec{e}_3 are orthogonal unit vectors in the plane of \vec{E}_{inc} and \vec{H}_{inc} ; these incident fields can then be represented in terms of \vec{e}_2 and \vec{e}_3 . In fact, we can consider a general angle of polarization of the incident wave as the linear combination of a first incident wave with \vec{E} parallel to \vec{e}_2 and \vec{H} parallel to \vec{e}_3 plus a second incident wave with \vec{E} parallel to \vec{e}_3 and \vec{H} parallel to $-\vec{e}_2$. Figure 1 shows a general polarization.

The EMP being simulated is taken as a plane wave infinite in extent. The two independent polarizations where \vec{E} is parallel to \vec{e}_2 or \vec{e}_3 have different reflection characteristics at the ground surface. These two cases have been considered in another note.² Here we need some of the reflection characteristics of the ground-air interface for infinite plane waves at low frequencies for comparison with the simulator performance at low frequencies.

As a first case let the incident \vec{E} be parallel to \vec{e}_2 and thus parallel to the plane of incidence. From reference 1 assuming a uniform ground (or water) medium for $z' < 0$ we have that the net or resulting field components in the low-frequency limit are as follows: E_x' is zero while E_z' and H_y' are both doubled over the values for the incident wave. As a second case let the incident \vec{E} be parallel to \vec{e}_3 and thus perpendicular to the plane of incidence. For this case in the low-frequency limit we have the following results: E_y' is zero, H_z' is zero, and H_x' is doubled over the value for the incident wave.

The low-frequency fields at the ground-air interface can then be summarized as: E_x' , E_y' , and H_z' are all zero while E_z' , H_x' , and H_y' are all doubled with respect to the values for the incident wave. This applies for all polarizations. Another way to state this is that in the low-frequency limit there are only vertical E and horizontal H (with respect to the ground-air interface) and that these fields are double those in the incident wave.

2. Capt Carl E. Baum, EMP Theoretical Note 25, The Reflection of Pulsed Waves from the Surface of a Conducting Dielectric, February 1967.

II. Geometry of Simulator

The simulator of interest, as shown in figure 2, consists of a half toroid connected to the ground or water surface plus a pulse generator configured to initiate the electromagnetic fields from a position on the toroid. The toroid would also have some impedance per unit length Z' distributed around the toroid for wave-shaping purposes. For purposes of the present note the pulse generator is assumed capacitive with a capacitance C_g charged to an initial voltage V_0 . The generator is also assumed configured to radiate a bicone wave at early times by use of a bicone section³ or distributed source⁴ inserted in the toroid. The distributed source is assumed configured to reproduce the bicone electric field distribution tangential to an appropriate surface, perhaps a circular cylinder.

The half toroid could be made several ways. It could be a balloon or wires supported by balloons with provision for resistive or other impedance loading through which the current flowing around the toroid must pass. The toroid can have rather light weight. The generator and switch assembly, however, can have fairly large weight if it is a high energy pulser. The pulser will then need additional support but balloons represent a possible solution. Also non conducting guy ropes would be used to hold the toroid and generator in a particular geometric orientation. Ground rods would be used to electrically connect the ends of the half toroid to soil; for use over water conductors would be similarly located for electrical contact with the water.

As shown in figure 2 the plane of the toroid can be angled with respect to a vertical axis by an angle ξ_1 with $|\xi_1| < \pi/2$. The pulse generator can be placed at some angle ξ_2 with respect to the top position of the half toroid where ξ_2 is defined on the plane of the toroid. If we define some horizontal reference axis for the system under test then the points at which the half toroid meet the ground or water surface are chosen to lie on an axis which is rotated from this horizontal reference axis by some angle ξ_3 . The system under test is taken to lie on an area roughly centered between the two intersection regions of the half torus with the ground or water surface.

Note that the early-time electric field radiated from the pulse generator toward the system is parallel to the toroid

3. Capt Carl E. Baum, Sensor and Simulation Note 69, Design of a Pulse-Radiating Dipole Antenna as Related to High-Frequency and Low-Frequency Limits, January 1969.

4. Capt Carl E. Baum, Sensor and Simulation Note 84, The Distributed Source for Launching Spherical Waves, May 1969.

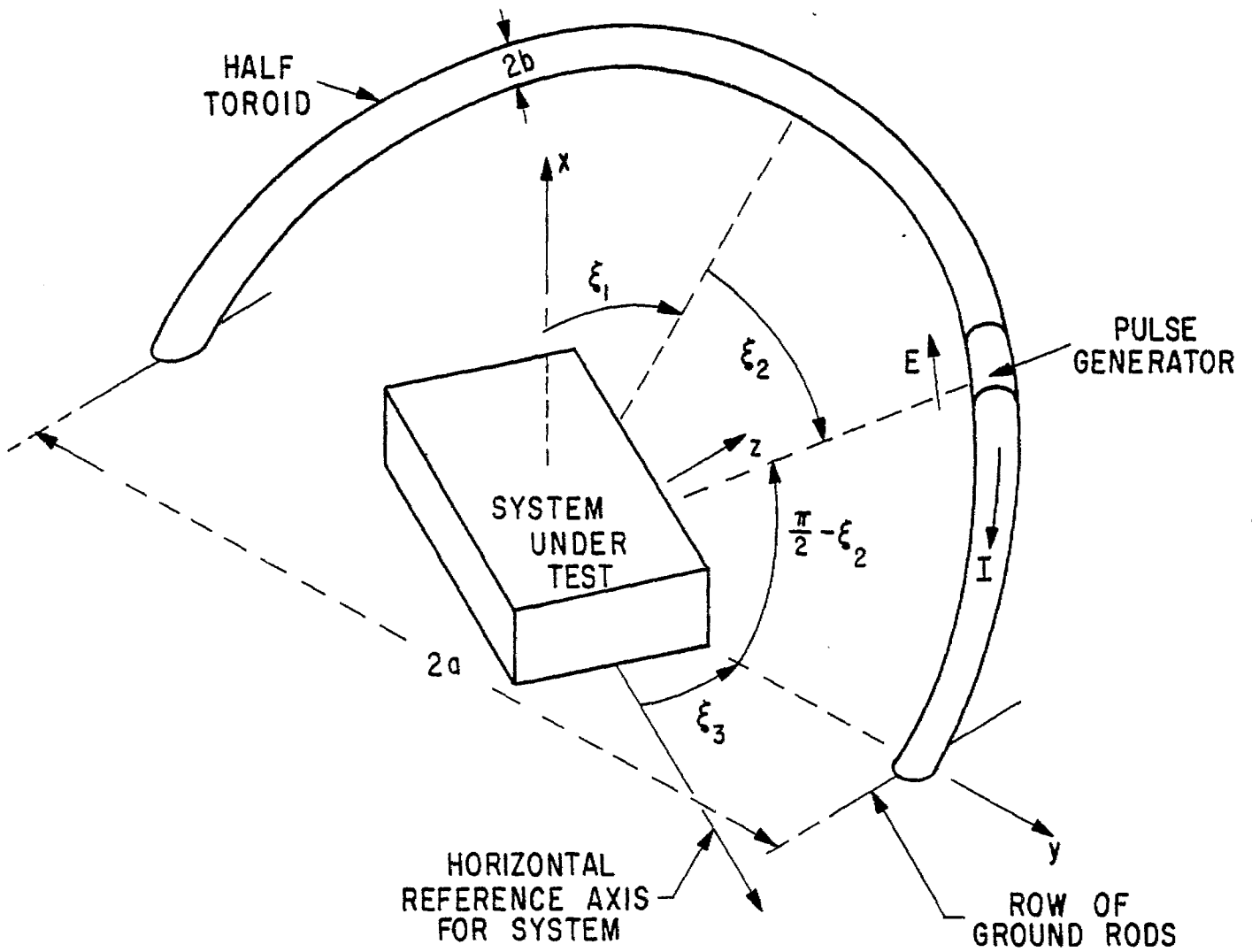


FIGURE 2. GEOMETRY OF SIMULATOR

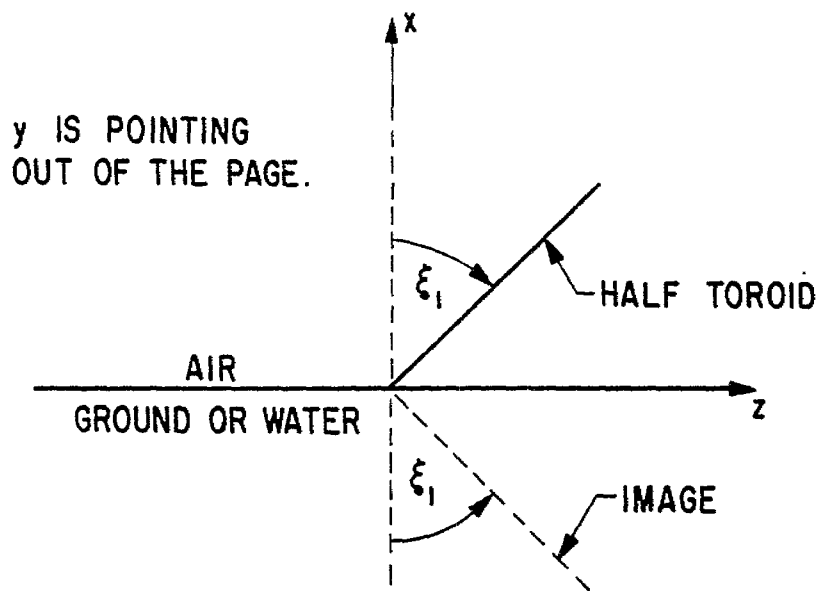
perimeter in the vicinity of the generator; the associated early-time magnetic field radiated from the pulse generator toward the system is perpendicular to the plane of the toroid. By appropriate choice of ξ_1 , ξ_2 , and ξ_3 all combinations of direction of incidence and polarization of the early-time portion of the wave can be achieved; this is a significant feature in the flexibility of such a simulator. To bring the simulator to the ground for repair etc. one can rotate ξ_1 to $\pm\pi/2$ if there are no intervening obstacles. This would allow the simulator configuration to be assembled in its desired shape on the ground and then rotated to the desired ξ_1 in the same shape.

The half toroid has a mean major diameter of $2a$ and a minor diameter of $2b$ as illustrated in figure 2. We will often assume that $a \gg b$ in order to simplify the calculations. Note that since the system under test lies roughly in the center of the toroid then the distance of the system from the pulse generator is just a , the major radius of the toroid, independent of the orientation of the toroid and pulse generator as specified by ξ_1 , ξ_2 , and ξ_3 .

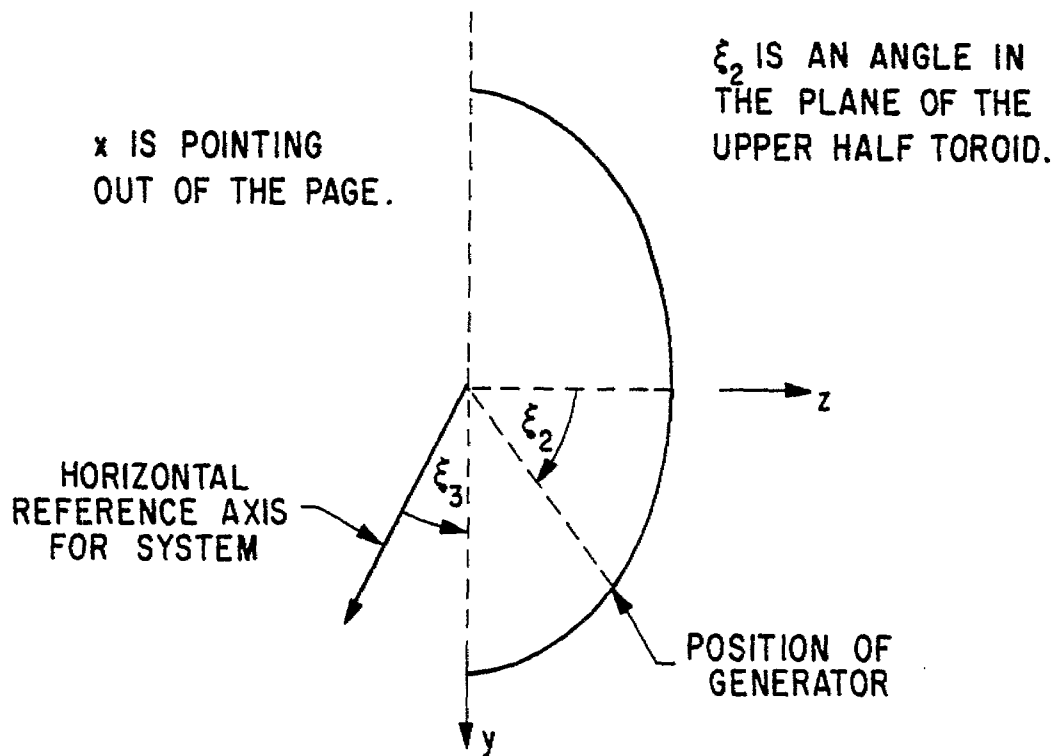
In section I and figure 1 we defined a cartesian coordinate system (x', y', z') based on both the incident plane wave of fixed polarization and the ground or water surface. For convenience in analyzing the performance of this kind of simulator we define a new set of cartesian coordinates (x, y, z) based on the half toroid and the ground or water surface. These new coordinates are shown in figures 2 and 3. In this new choice of coordinates the x axis is perpendicular to the ground or water surface and the y and z axes lie on the ground or water surface. The y axis is chosen such that it passes through the centers of both positions where the half toroid meets the ground or water surface. The coordinate origin is taken on the ground or water surface at the geometric center of the toroid. Note that for the case that the ground or water medium is considered as a perfect conductor the electromagnetic fields in the simulator can be calculated as an image problem where an image half toroid with pulse generator is included below the $x = 0$ plane as shown in figure 3.

For the special case that $\xi_1 = 0$ the plane of the half toroid and its image is the x, y plane and the half toroid and its image form a full toroid. This case is interesting in that it simplifies the geometry for purposes of calculating the fields. One can define cylindrical coordinates (ψ, ϕ, z) with the relations

$$\begin{aligned} x &= \psi \cos(\phi) \\ y &= \psi \sin(\phi) \end{aligned} \tag{4}$$



A. SIDE VIEW



B. TOP VIEW

FIGURE 3. COORDINATES FOR SIMULATOR

The full toroid is then placed enclosing the circle $\Psi = a$ and is described by the equation

$$(\Psi - a)^2 + z^2 = b^2 \quad (5)$$

Perhaps detailed solutions for the fields for frequencies with wavelengths of the order of a (as well as high and low frequency limits) can be worked out in future notes for this special case. However one should note that in some cases the ground or water may not be sufficiently highly conducting for the high-conductivity results to be applied accurately.

For future reference we define the generator position as

$$(x, y, z) \equiv (x_0, y_0, z_0) \quad (6)$$

The coordinates of the generator are

$$\begin{aligned} x_0 &= a \cos(\xi_2) \cos(\xi_1) \\ y_0 &= a \sin(\xi_2) \\ z_0 &= a \cos(\xi_2) \sin(\xi_1) \end{aligned} \quad (7)$$

Now we go on to consider some of the high-frequency and low-frequency performance characteristics for such a simulator assuming the ground or water is highly conducting. These are followed by a brief consideration of some of the problems associated with shaping the simulator response at intermediate frequencies.

III. Early-Time or High-Frequency Performance

For the early-time portion of the waveform as seen at the system under test, only the portion of the toroid near the pulse generator has any influence. We assume the generator to be capacitive with capacitance C_g and we assume that the generator feeds a bicone (ref. 3) or is arranged as a distributed source (ref. 4) designed to give a bicone type wave. Provided the rise time of the wave (zero to peak) is less than the clear time from the ends of the bicone or equivalent distributed source then the peak of the radiated fields can be readily calculated. Let the peak electric and magnetic fields in the incident wave arriving

at $(x, y, z) = (0, 0, 0)$ be \vec{E}_1 and \vec{H}_1 . Also let the generator be charged to a voltage V_0 and let C_g be large enough that any decay of the generator voltage in times of the order of the rise time is negligible. Define

$$E_1 \equiv |\vec{E}_1|, \quad H_1 \equiv |\vec{H}_1| \quad (8)$$

and let

$$\vec{E}_1 \equiv E_1 \vec{e}_e, \quad \vec{H}_1 \equiv H_1 \vec{e}_h \quad (9)$$

where \vec{e}_1 , \vec{e}_e , and \vec{e}_h are related to the unit vectors used in section I to describe the incident plane wave. For the simulator we appropriately use them to describe the incident wave in the center of the simulator at early times when the wave can be locally considered an approximate incident plane wave.

Using the results of references 3 and 4 we have

$$E_1 = \frac{V_1}{a}, \quad H_1 = \frac{1}{Z_0} \frac{V_1}{a} \quad (10)$$

where V_1 is a convenient constant (with units of volts) which is related to the generator charge voltage as

$$V_1 = V_0 \left\{ 2 \left[\ln \left[\cot \left(\frac{\theta_0}{2} \right) \right] \right] \right\}^{-1} \quad (11)$$

and where Z_0 is the impedance of free space given by

$$Z_0 = \sqrt{\frac{\mu_0}{\epsilon_0}} = \frac{E_1}{H_1} \quad (12)$$

The angle θ_0 is a parameter of the bicone or distributed source. For typical choices of θ_0 then V_1 may grossly be about half of V_0 ; this would correspond to a bicone impedance of the order of 120 Ω . Note that if a line is drawn from the position of the generator to the observer $(0, 0, 0)$ this line is perpendicular to the toroid circumference at the generator. Thus the observer at $(0, 0, 0)$ is on the equator of the bicone or distributed source. This fact is used in obtaining equation 11. For some other type

of early-time wave launcher there might be some other relation (instead of equation 11) to obtain V_1 and thereby E_1 .

The direction of the incident wave at $(0, 0, 0)$ is given by the unit vectors where \vec{e}_1 is the direction of propagation, \vec{e}_e is the direction of the incident electric field, and \vec{e}_h is the direction of the incident magnetic field. Relating these unit vectors to the unit vectors for the cartesian coordinate system we have

$$\begin{aligned}\vec{e}_1 &= -\cos(\xi_2)\cos(\xi_1)\vec{e}_x - \sin(\xi_2)\vec{e}_y - \cos(\xi_2)\sin(\xi_1)\vec{e}_z \\ \vec{e}_e &= \sin(\xi_2)\cos(\xi_1)\vec{e}_x - \cos(\xi_2)\vec{e}_y + \sin(\xi_2)\sin(\xi_1)\vec{e}_z \\ \vec{e}_h &= -\sin(\xi_1)\vec{e}_x + \cos(\xi_1)\vec{e}_z\end{aligned}\quad (13)$$

The unit vectors for the incident wave are related as

$$\begin{aligned}\vec{e}_1 \times \vec{e}_e &= \vec{e}_h \\ \vec{e}_e \times \vec{e}_h &= \vec{e}_1 \\ \vec{e}_h \times \vec{e}_1 &= \vec{e}_e\end{aligned}\quad (14)$$

Note that \vec{e}_1 and \vec{e}_e are both parallel to the plane of the half toroid while \vec{e}_h is perpendicular to this plane.

For comparison to the low frequency performance in the next section we have the vertical component of the incident electric field (in the x direction) as

$$\vec{E}'_1 \equiv (\vec{E}_1 \cdot \vec{e}_x)\vec{e}_x = \sin(\xi_2)\cos(\xi_1)E_1\vec{e}_x\quad (15)$$

Similarly the horizontal component of the magnetic field has only a z component as

$$\vec{H}'_1 \equiv (\vec{H}_1 \cdot \vec{e}_y)\vec{e}_y + (\vec{H}_1 \cdot \vec{e}_z)\vec{e}_z = \cos(\xi_1)H_1\vec{e}_z\quad (16)$$

Another high-frequency characteristic of the simulator is the rise time (or, more generally, the shape of the rise) of the incident wave at $(0, 0, 0)$. This is a property of the details of the pulse generator and the wave launcher (bicone, distributed source, etc.) in the immediate vicinity of the generator. One may wish to also make this rise match that of the desired incident plane wave but this problem is not considered here. Also the wave incident on $(0, 0, 0)$ is spherical (i.e. not perfectly plane) with radius of curvature a . As ξ_1 and ξ_2 are changed some of the reflection characteristics at $x = 0$ will change. This may be particularly significant if the generator is placed close to the ground compared to a .

IV. Low-Frequency Performance

Now we consider the performance of the simulator in the low-frequency limit. With a generator capacitance C_g and initial voltage V_0 we have a charge stored in the generator given by

$$Q_0 = V_0 C_g \quad (17)$$

When the generator is switched into the toroid the charge on the generator flows as a current I around the toroid and through the ground as shown in figure 2. This current (I) will have different time histories at different positions around the toroid, but the complete time integral of I is independent of position around the toroid and is given by

$$Q_0 = \int_{t_0}^{\infty} I dt \quad (18)$$

where t_0 is the time that the pulse generator is switched into the toroid. This result depends on there being no significant shunting of current around the generator by additional loads in parallel with the capacitive generator. Also the total impedance around the toroid and ground (or water) path must be finite in the low-frequency limit. Of course taking the integral out to $t = \infty$ in practical terms means considering the integral out to times much larger than times of interest for a single pulse.

Now suppose that we wish to simulate an incident plane wave of the form

$$\vec{E}_{inc} = E_2 \left(t - \frac{\vec{r} \cdot \vec{e}_1}{c} \right) \vec{e}_e, \quad \vec{H}_{inc} = \frac{1}{Z_0} E_2 \left(t - \frac{\vec{r} \cdot \vec{e}_1}{c} \right) \vec{e}_h \quad (19)$$

where we assume E_2 has a positive peak and where \vec{r} is the position vector given by

$$\vec{r} \equiv x\vec{e}_x + y\vec{e}_y + z\vec{e}_z \quad (20)$$

In the previous section we defined the peak incident electric field to reach $\vec{r} = \vec{0}$ in the simulator as E_1 so that if we set

$$E_1 = \max_{0 < t < \infty} E_2(t) \quad (21)$$

then the simulator gives the required peak incident electric and magnetic fields. Further suppose that $E_2(t)$ is basically a one-sided pulse with not only an initial peak E_1 , but also a finite non-zero time integral out to times large compared to times of interest. Let this integral be defined as

$$\Phi \equiv \int_0^{\infty} E_2(t) dt \neq 0 \quad (22)$$

where we have assumed $E_1(t) = 0$ for $t < 0$ which further implies $t_0 > -a/c$ as used in equation 18 for the time of firing the pulser. The velocity of light is

$$c = \frac{1}{\sqrt{\mu_0 \epsilon_0}} \quad (23)$$

As discussed in section I the low-frequency fields at the ground or water surface due to an incident plane wave have only vertical electric and horizontal magnetic fields. These resultant fields are just twice the vertical component of the incident electric field and horizontal component of the incident magnetic field respectively in the low-frequency limit. The relations between the incident fields and the vertical component of \vec{E} and the horizontal component of \vec{H} , both in magnitude and direction, are given in equations 15 and 16. Since the complete time integral of a quantity is equal to the Fourier or two-sided Laplace transform of the quantity with the frequency set to zero we have at $\vec{r} = \vec{0}$

$$\int_0^{\infty} \vec{E} dt = 2\vec{e}_x \left[\vec{e}_x \cdot \int_0^{\infty} \vec{E}_{inc} dt \right] = -2 \frac{\sin(\xi_2)}{\cos(\xi_2)} \cos(\xi_1) \phi \vec{e}_x \quad (24)$$

$$\begin{aligned} \int_0^{\infty} \vec{H} dt &= 2\vec{e}_y \left[\vec{e}_y \cdot \int_0^{\infty} \vec{H}_{inc} dt \right] + 2\vec{e}_z \left[\vec{e}_z \cdot \int_0^{\infty} \vec{H}_{inc} dt \right] \\ &= 2 \cos(\xi_1) \frac{\phi}{Z_0} \vec{e}_z \end{aligned}$$

These complete time integrals are the low-frequency fields which we wish to simulate, preferably in both magnitude and direction. Note then that E_1 and ϕ are two useful numbers for specifying some features of the environment to be simulated. E_1 relates to the peak and tells something about the high-frequency content of the pulse; ϕ gives the time integral of the resulting field components as well as the low-frequency content.

We now have the desired low-frequency form of the resultant fields as functions of the time integral of the desired incident fields as well as the angles of incidence and polarization of the incident wave. Next we need the low-frequency fields in the simulator. Consider the low-frequency form of the resulting magnetic field under the assumption of a highly conducting ground or water medium so that we can use image theory as illustrated in figure 3 where we have two half toroids. First note that, at low frequencies, the current in the half toroid and its image is uniform around the entire toroid plus image. Also for low frequencies the magnetic field can be easily calculated from the current for the case of $b \ll a$ so that the current can be considered as localized at a distance a from $\vec{r} = \vec{0}$ in the plane of the half toroid or the image. Again we write the low-frequency quantities as complete time integrals of the time domain quantities.

Consider the low-frequency magnetic field at $\vec{r} = \vec{0}$ as composed of two parts, one associated with the currents in the upper half toroid and one with the currents in the image as

$$\int_0^{\infty} \vec{H} dt = \int_0^{\infty} \vec{H}_{upper} dt + \int_0^{\infty} \vec{H}_{image} dt \quad (25)$$

The field at $\vec{r} = \vec{0}$ associated with the upper half toroid is perpendicular to the plane of this toroid and equal in magnitude to one half of the field associated with a full toroid of major radius a (centered on $\vec{r} = \vec{0}$) in this plane giving

$$\int_0^{\infty} \vec{H}_{\text{upper}} dt = \frac{1}{2} \frac{1}{2a} \vec{e}_h \int_{t_0}^{\infty} I dt = \frac{Q_0}{4a} \vec{e}_h$$

$$= \frac{Q_0}{4a} [-\sin(\xi_1) \vec{e}_x + \cos(\xi_1) \vec{e}_z] \quad (26)$$

By symmetry the field associated with the image has the same z component, but opposite x component, giving

$$\int_0^{\infty} \vec{H}_{\text{image}} dt = \frac{Q_0}{4a} [\sin(\xi_1) \vec{e}_x + \cos(\xi_1) \vec{e}_z] \quad (27)$$

Combining these results for the low-frequency magnetic field at $\vec{r} = \vec{0}$ gives

$$\int_0^{\infty} \vec{H} dt = \frac{Q_0}{2a} \cos(\xi_1) \vec{e}_z \quad (28)$$

Comparing the low-frequency magnetic field produced by the simulator (equation 28) with that desired to simulate the field associated with the incident plane wave (equations 24) gives

$$Q_0 = \frac{4a\phi}{Z_0} \quad (29)$$

Note that both low-frequency magnetic fields (equations 24 and 28) have exactly the same direction and are both proportional to $\cos(\xi_1)$. Thus by appropriate choice of Q_0 this type of simulator is capable of matching (at $\vec{r} = \vec{0}$) not only the early-time or high-frequency characteristics of the desired incident plane wave of constant polarization (including peak, direction of incidence, and direction of polarization) but also the low-frequency resulting magnetic field (at $\vec{r} = \vec{0}$).

From section III we have the generator voltage V_0 related to the characteristics of the early-time wave launcher and the desired peak electric field E_1 in the incident wave at $\vec{r} = \vec{0}$. From this section we have the generator charge Q_0 related to the desired low-frequency magnetic field at $\vec{r} = \vec{0}$, which in turn is

related to the time integral of the electric field for the desired plane wave, i.e. ϕ . Combining the high and low frequency results gives the generator capacitance as

$$C_g = \frac{Q_o}{V_o} = \frac{Q_o}{V_1} \frac{V_1}{V_o}$$

$$= \frac{4\phi}{Z_o E_1} \left(\frac{V_1}{V_o} \right) \quad (30)$$

where V_1/V_o is given by equation 11 for a bicone wave launcher or equivalent distributed source. Since ϕ is the time integral of the incident electric field and E_1 is its peak one could define some effective pulse width as

$$t_{\text{eff}} \equiv \frac{\phi}{E_1} \quad (31)$$

giving

$$C_g = \frac{4}{Z_o} t_{\text{eff}} \left(\frac{V_1}{V_o} \right) \quad (32)$$

Thus the generator capacitance depends on only the effective pulse width desired (related to an incident plane wave) and V_1/V_o which is just a characteristic of the design of the early-time wave launcher. Specifically C_g does not explicitly depend on ξ_1 and ξ_2 ; only if one desires to change t_{eff} as the polarization and direction of incidence are changed need one change C_g . There may, of course, be other ways of changing t_{eff} such as by adding impedances in parallel with the generator, if desired. Note also that changing ξ_1 and ξ_2 with a fixed also leaves E_1 and ϕ both unchanged.

So far we have matched both \vec{E} and \vec{H} at high frequencies and \vec{H} at low frequencies to the desired plane wave. This leaves \vec{E} at low frequencies which we do not consider in any detail in this note. Qualitatively, however, let the impedance per unit length Z' in the half toroid be resistive with finite non-zero resistance around the half toroid in the low-frequency limit. The current in the toroid at low frequencies will then set up a low-frequency potential distribution around the toroid. This in turn will give a low-frequency electric field at $r = 0$ except for special choices

of resistance distribution together with corresponding choices for ξ_1 and ξ_2 . Thus we can in general make the complete time integral of \vec{E} at $\vec{r} = \vec{0}$ be non-zero by our choice of the low-frequency resistance distribution around the half toroid. For our assumed case of a highly conducting ground or water medium the low-frequency electric field and thus the complete time integral of the electric field at the ground or water surface has only a vertical component; this does match the case of the incident plane wave. Perhaps the calculation of this low-frequency electric field can be considered in future notes.

V. Some Intermediate-Frequency Considerations

In the previous sections we have considered the simulator performance at early-times (and thus high frequencies) and at low frequencies. We have seen how the generator parameters, including initial voltage and capacitance, are chosen by the simulator geometry and the corresponding high and low frequency characteristics of the desired incident plane wave which is being simulated. This leaves the intermediate frequencies to be considered. From another viewpoint shaping the intermediate-frequency performance is related to shaping the pulse seen by the observer (say at $\vec{r} = \vec{0}$) within the already chosen constraints of peak amplitude and complete time integral (at least for the magnetic field in the case of the integral).

One thing one might do to shape the pulse is to choose some special form for Z' , the impedance per unit length added into the toroid. Z' could be made to vary with frequency and/or position around the toroid. As mentioned in the last section Z' should go to a pure resistance per unit length at low frequencies in order to give the electric field (vertical) at $\vec{r} = \vec{0}$ a non-zero complete time integral. The use of resistance should also be useful in shaping the waveform by damping resonances on the simulator structure. Note that at low frequencies the half toroid connected to a highly conducting lower medium is basically an inductance. Tie this to a capacitive generator and the result is a ringing waveform. However, the addition of an appropriate series resistance in the toroid should damp such oscillations. There are also energy losses associated with the finite ground conductivity and radiation into the upper half space above the ground or water surface which should also tend to damp oscillations, or reflections in the simulator structure as seen from another viewpoint.

There are various forms of Z' realizable by passive elements such as resistors, inductors, and capacitors that one might consider. By appropriate choice of Z' one can try to optimize the simulator waveform. However, how close one can achieve some particular waveshape requires detailed calculations of the boundary-

value-problem variety, or perhaps some approximate transmission-line model. There may also be conflicts in the choice of Z' between different desired results such as low-frequency electric field and "best" smooth waveform. As this discussion indicates there is much detailed calculation to be done.

VI. Summary

In this note we have considered some of the design features of an EMP simulator with the geometry of a half toroid joined to a ground or water surface and with a pulse generator driving a bicone or related distributed source. This type of simulator can be used to simulate a plane wave incident on a ground or water surface. The simulator parameters can be chosen to match both high and low frequency parameters of the desired incident waveform, assuming a constant polarization for the incident plane wave. For early times (or high frequencies) the simulator parameters can be chosen to give the desired polarization, direction of incidence and peak field. For low frequencies the polarization and direction of incidence (as it enters into the resultant field directions) is still maintained consistent with the early-time polarization and direction of incidence. Furthermore the generator charge can be chosen to give the desired low-frequency magnetic field. The low-frequency electric field is a more complicated question.

There are many detailed calculations yet to be done, and hopefully some of these may be included in future notes. Such things might include low-frequency electric and magnetic field distributions, arrangement of connections to the ground or water to optimize the current distribution in the lower medium at low frequencies, transmission-line models of the toroid, resistive loading, etc. For an infinitely conducting lower medium and a vertically oriented half toroid ($\xi_1 = 0$) one may be able to do an accurate field solution for all frequencies with corresponding wavelengths large compared to b and for $b \ll a$. One of the attractive features of this type of simulator is its convenient geometry which makes some of the calculations easier than many other structures with the same general topology. In the case of low-conductivity lower media, however, some of the advantages of convenient calculation are lost.

There are also some alternate types of design one might consider which still maintain a toroidal geometry. These could include different configurations of the pulse generator such as placing the switch up in the air but the rest of the pulse generator on the ground or water surface.

A good name for this general type of simulator would be TORUS which is the Latin word from which toroid is derived. It can also be considered an acronym as the Transient Omnidirectional Radiating Unidistant and Static simulator. This acronym mentions several of the features of this type of simulator design.