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Some Characteristics of Planar Distributed Sources for Radiating Transient Pulses

Capt Carl E. Baum
Air Force Weapons Laboratory

Abstract

This note considers some of the characteristics of a planar distributed source for radiating a pulse in a narrow beam to large distances. Two cases are considered. In the first case (toward which most of the discussion is aimed) the distributed source is used to radiate a pulse which has a single polarity after the initial rise out to as large a time as possible; as a radiated pulse from a finite size source with finite energy the waveform must eventually change polarity (for a given field component). Considering the case of a spherically expanding wave, a lower bound for the unipolar pulse width is established based on the radius of curvature of the wavefront and the size of the source array. Then the height of the array above the ground is considered for its effect in limiting the unipolar pulse width. In the second case the distributed source is discussed from the viewpoint of radiating a pulsed CW waveform because of the gains associated with focusing the fields at desired positions in space. In this note most of the discussion is qualitative, pointing out many of the potential features of such arrays. Detailed quantitative investigations are left to future notes.

I. Introduction with Basic Source Layout and Impedances

A general class of approaches to simulation of the nuclear electromagnetic pulse consists of radiating an electromagnetic pulse from some kind of antenna to a position where some system is being tested. This position may be at various distances from the antenna, from distances of the order of the antenna dimensions or less out to distances which are large compared to all the antenna dimensions. Depending on the frequencies (or times) and distances from the antenna of interest and depending on the antenna design one may be able to use far field types of field calculations to simplify the analysis. Many previous notes in this series have considered types of radiating antennas which behave as electric dipoles (for far fields) at least at low frequencies. While the far field radiation from antennas (of finite size) exhibits a significant limitation of antennas as radiators at low frequencies, they still have use in many applications because of other advantages gained. Perhaps some future notes can consider other types of antennas which at low frequencies are basically magnetic dipoles or combined electric and magnetic dipoles, or perhaps even higher order multipoles for special applications.

In the present note we consider a special type of antenna for radiating a transient pulse, specifically a planar distributed source. One might also call this a timed planar array. Basically this is a distributed source which generates a tangential electric field on a planar surface. This might be accomplished in various ways such as with capacitors, interconnecting conductors, and timed switches. The sources might not be on the effective source plane but the electrical signals might be transmitted via transmission lines to the source plane. Using various types of transmission-line combinations one might route energy from one pulser (energy source) to more than one position on the effective source plane. A previous note discusses a type of distributed source for launching a TEM wave on a cylindrical transmission line using multiple conical transmission lines each driven by an individual source or many driven from one common source via transmission lines.[1] In that note it was pointed out that one had to be careful in connecting such transmission lines to the cylindrical transmission line being driven if the source voltage or voltages were to have the same coupling to the cylindrical transmission line at both high and low frequencies. For the present application as a planar radiating array there are significant low-frequency limitations to its radiation characteristics, while for high frequencies efficiency will be obtained

1. Capt Carl E. Baum, Sensor and Simulation Note 31, The Conical Transmission Line as a Wave Launcher and Terminator for a Cylindrical Transmission Line, January 1967.

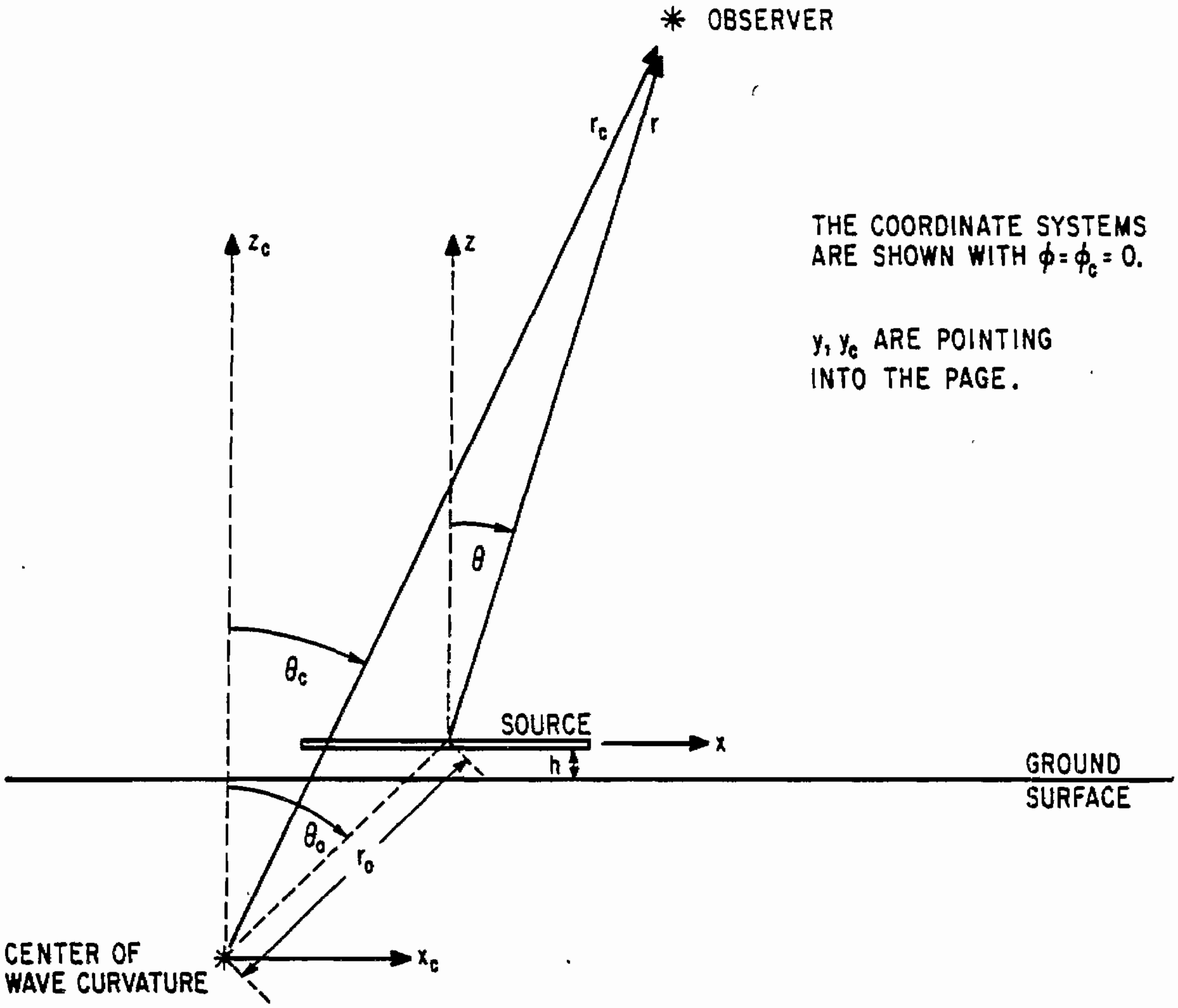
by giving a highly directional characteristic to the radiated energy. There may be cases in which one is not very concerned about some additional low-frequency loss and is only looking at the simulator for its early-time or high-frequency characteristics. In such cases one might consider the use of more general transmission-line networks to transmit signals from pulsers to the effective source plane. One might even use some impedance mismatching to optimize the magnitude of the radiated fields depending on the significant limitations of the sources used. Again non-uniform transmission lines might be used to act as pulse transformers. The interconnection of the transmission lines themselves can also be used to achieve various types of transformer action. These types of transformers have certain frequency dependent characteristics which must be included in the design of a simulator using such techniques. Of course various combinations of individual sources with transmission-line networks could also be used.

This planar distributed source will in general have the source field turned on at different times across the source plane to shape the wave as desired. This is similar to the technique discussed in another note where sources are turned on at different times to produce an outward propagating spherical wave.[2] In yet another note a special form of planar distributed source is discussed; it is placed above a ground surface and the individual sources are triggered at different times to produce a special field distribution in space and time near the ground surface.[3] In the simulator discussed in the present note the sources are switched in a sequence which can be varied so as to give a transient pulse which is radiated in some beam with a small angle of divergence so as to increase the magnitude of the electromagnetic fields produced at some large distance from the distributed source. By changing the switching sequence the beam direction is changed. One should note that changing the beam direction changes the field components near the source plane and can in general change the impedance the individual source elements "see" so that the source impedance can be important, whether this be capacitor and switch impedance, transmission-line impedance, etc.

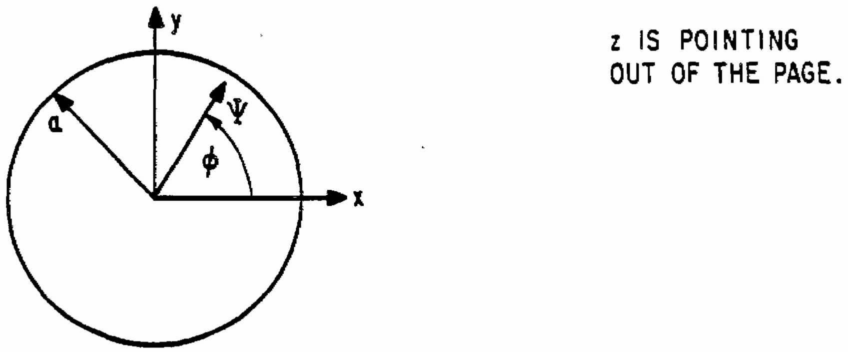
Figure 1 shows the overall geometry for such a pulse-radiating distributed source. This is shown for a circular planar array of radius a at a height h above the ground. The

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

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



A. SIDE VIEW WITH TWO SETS OF COORDINATE SYSTEMS



B. TOP VIEW WITH ASSUMED CIRCULAR SOURCE BOUNDARY

Figure 1. GEOMETRY OF PLANAR RADIATING DISTRIBUTED SOURCE

array could have other shapes than circular and might even be on surfaces with some curvature instead of on a plane. However, the circular planar geometry parallel to a flat ground surface is chosen for the present discussion. The center of the array is taken as a reference point for cartesian (x, y, z), cylindrical (Ψ, ϕ, z), and spherical (r, θ, ϕ) coordinates related by[4]

$$x = \Psi \cos(\phi) \ , \qquad y = \Psi \sin(\phi)$$
$$z = r \cos(\theta) \ , \qquad \Psi = r \sin(\theta) \tag{1}$$

The array is taken to lie on the x, y plane (i.e. z = 0) and has an outer boundary for the present discussion given by $\Psi = a$. There is a second set of coordinate systems as shown in figure 1A based on what is termed a center of wave curvature which is at a distance of r_o from the array center at an angle θ_o with respect to the negative z axis (i.e. at $\theta = \pi - \theta_o$). Based on this center of curvature we have cartesian (x_c, y_c, z_c), cylindrical (Ψ_c, ϕ_c, z_c), and spherical (r_c, θ_c, ϕ_c) coordinates related by

$$x_c = \Psi_c \cos(\phi_c) \ , \qquad y_c = \Psi_c \sin(\phi_c)$$
$$z_c = r_c \cos(\theta_c) \ , \qquad \Psi_c = r_c \sin(\theta_c) \tag{2}$$

We have unit vectors $\vec{e}_x, \vec{e}_y, \vec{e}_z$ for the x, y, z coordinates and the directions of the x_c, y_c, z_c coordinates are chosen such that they have the same unit vectors, i.e. $\vec{e}_x = \vec{e}_{x_c}$ etc. Other unit vectors for the two cartesian and two spherical systems are similarly defined but are not as simply related as are the unit vectors for the two cartesian systems. For convenience the center of wave curvature is chosen to lie on the x, z plane and is shown in figure 1A at $\phi = \pi$. The center of wave curvature is defined for later use when considering spherical waves radiated from the source array. Generally coordinate positions will refer to an observation position far from the source where one is interested in the fields.

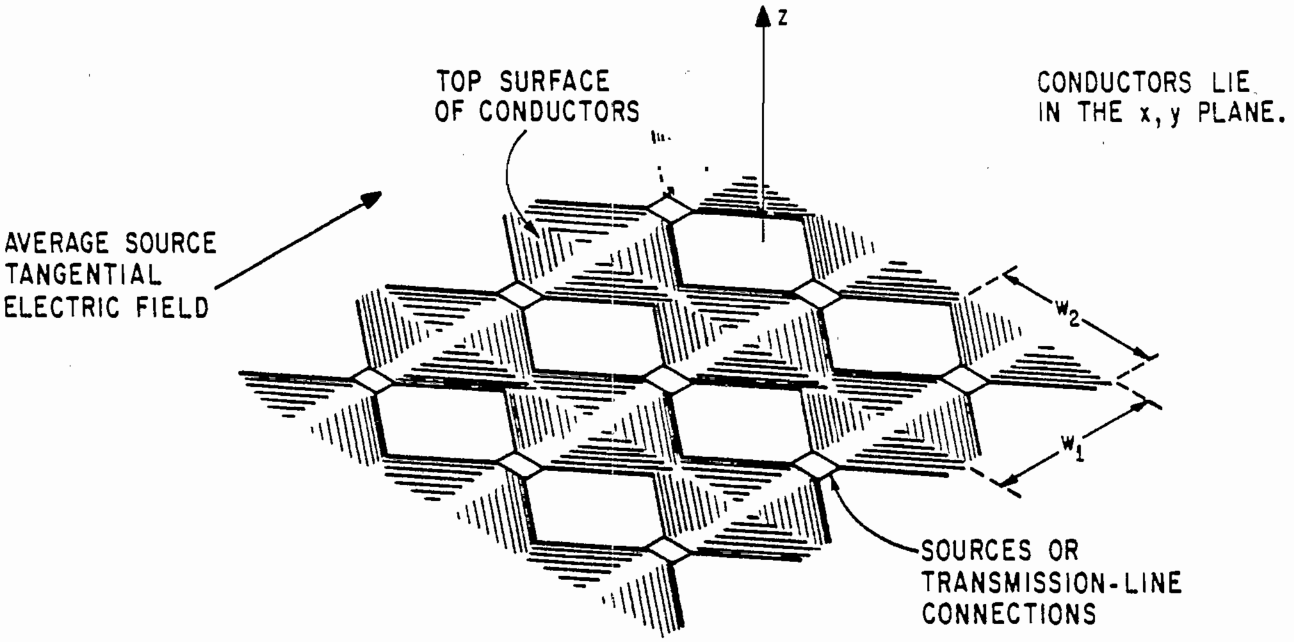
A large planar distributed source might be made by the interconnection of many small sources, each source typically a capacitor and switch close to the source plane. Alternatively the signals might be transported via transmission lines to the source

4. All units are rationalized MKSA.

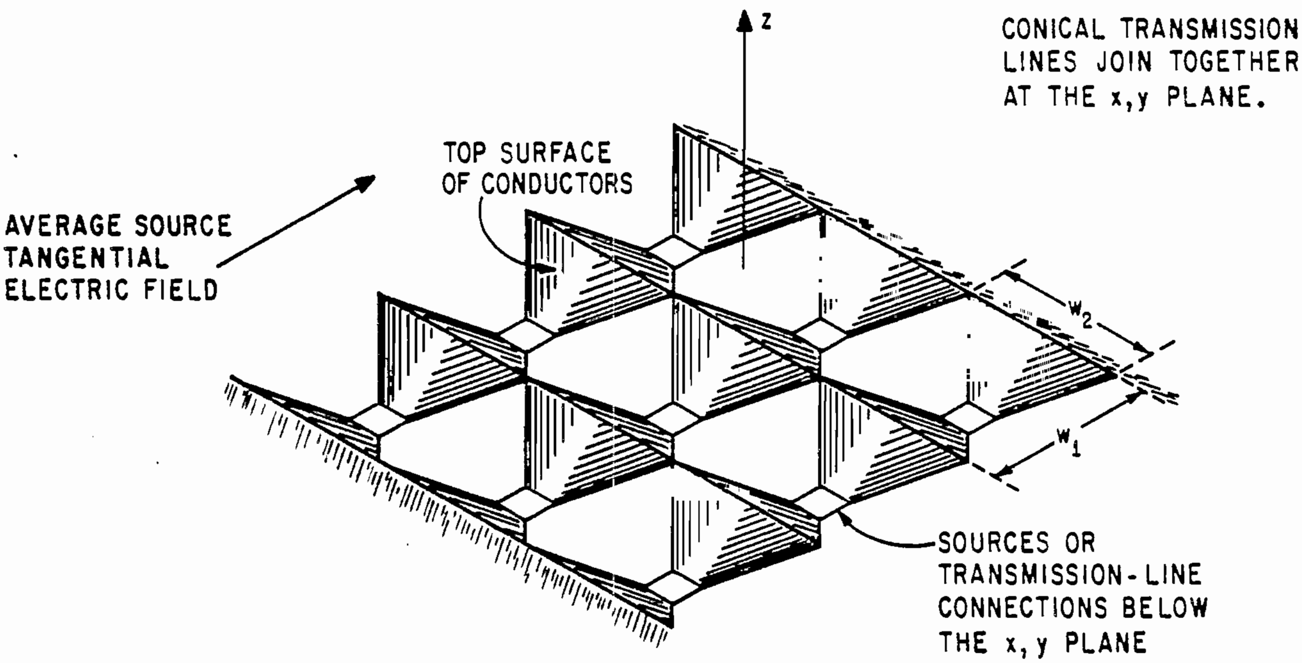
plane. At the source plane the sources or transmission lines need to be connected together as one array so that currents can flow in the array with a non zero average tangential electric field established along the array for efficiently radiating at wavelengths large compared to the basic cell size. There are various types of geometries of conductors for connecting the sources or transmission lines on the source plane. Figure 2A shows the individual sources connected by planar biconical conductors; figure 2B shows them connected by biconical conductors shaped like tapered strip lines. These are just different forms of conical transmission lines hooked together to form an array as discussed in reference 1. The sources or transmission lines connect to the apexes of the conical transmission lines. The conical transmission lines have well-defined pulse impedances applying to early times. A planar bicone has a pulse impedance discussed in another note in which it is considered in a sensor application.[5] The transformations used in this reference can also be used to obtain the distribution of the early-time fields radiated. For the more general angles of conical transmission lines the technique discussed in reference 1 can be used to find the early-time pulse impedance and fields by transforming a conical transmission line to an equivalent cylindrical one. One should note that these considerations only apply for times before the fields from one conical transmission line interact with another line, at least as far as influencing the fields which reach the observer. These conical-transmission-line techniques (or other suitable methods for interconnecting the sources) can be used to try to optimize the early-time performance of a distributed source. However there are many considerations of the boundary-value-problem variety which govern the transition from very early times to times large compared to characteristic times associated with conical transmission lines. Such problems are not considered in this note but will hopefully be treated in future notes. Perhaps types of interconnecting conductors other than conical transmission lines can even be considered.

Call the portion of the x, y plane associated with one source (or cable connection) and its interconnecting conductors a cell. For characteristic times large compared to the transit times associated with both the cell dimensions and the extension of the interconnecting conductors in the z direction the individual sources combine to form a distributed source. The interconnection of the individual sources makes the voltages put on each cell give an average tangential electric field on the x, y plane equal to the voltage across the cell divided by the cell dimension in the direction of the average tangential electric

5. Capt Carl E. Baum, Sensor and Simulation Note 42, A Conical-Transmission-Line Gap for a Cylindrical Loop, May 1967.



A. PLANAR CONICAL TRANSMISSION LINES



B. NON-PLANAR CONICAL TRANSMISSION LINES

Figure 2. CONNECTION OF INDIVIDUAL SOURCES TO FORM ARRAY

field. Knowing an average tangential electric field over each cell (or perhaps even more details of the electric field distribution) one can integrate over this source field to obtain the fields away from the source plane.[6]

An important point for characteristic times large compared to the cell transit times (including extension in the -z direction) is that the impedance each source (or transmission line from one or more sources) drives is governed by the overall array characteristics and not by small things such as interconnecting conical transmission lines in each cell. The wave impedance of free space is just

$$Z_o = \sqrt{\frac{\mu_o}{\varepsilon_o}} \simeq 376.7 \ \Omega \tag{3}$$

where μ_o and ε_o are respectively the permeability and permittivity of free space. If the cell voltages are all initiated simultaneously so that a plane wave is radiated in the +z direction then for times before the array boundary can influence a particular cell this cell drives a surface impedance Z_o associated with the upward propagating wave. There is also a wave propagated in the -z direction which has a surface impedance Z_o associated with it provided the conductors below the source are arranged to negligibly interfere with this wave; this applies for times before reflections (such as from the ground surface) come back to the distributed source. The distributed source then must drive a surface impedance of $Z_o/2$, the parallel combination of the upward and downward surface impedances associated with the two waves. Let w_1 be the cell dimension in the direction of the source electric field and w_2 be the dimension in the perpendicular direction (still parallel to the x, y plane). Then the impedance driven by each cell is just $(w_1/w_2)(Z_o/2)$. If capacitive sources are used at the apex of the conical transmission lines one may or may not match their early-time pulse impedances to $(w_1/w_2)(Z_o/2)$; one might make the impedance different or even non-uniform with distance from the source in an attempt to peak up the rise time of the radiated wave. If long transmission lines are used to transport the energy from the sources to the conical transmission lines, and if one does not want to have energy reflected back down the transmission lines then ideally both the conical transmission lines and the transmission lines leading to the sources would be both chosen to

6. 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.

have pulse impedances $(w_1/w_2)(Z_o/2)$. Of course one does not expect impedance matching to necessarily give a perfect match at very early times between the conical transmission lines and space because the field pattern on a conical transmission line does not match a uniform plane wave thereby introducing some discontinuity.

In using such a radiating distributed source one might like to vary the polarization and propagation direction of the upward launched wave. Consider characteristic times long compared to cell transit times but before reflections from the ground or the edge of the array can reach a particular cell of interest. While the array may be used to radiate other than planar waves (say spherical waves) at times before the source edge is significant, let us consider the case that the wavefront curvature near the array is small so that we can consider the wave as planar for impedance purposes. Let θ_o be the direction of propagation of the upward launched wave with respect to the positive z axis. Furthermore let the direction of propagation be parallel to the x, z plane as shown in figure 1.

This still leaves the polarization to choose. Consider two cases. First let the source electric field be in the x direction. The wave launched has a magnetic field with only a y component and an electric field with x and z components. The electric field is at an angle θ_o with respect to a plane of constant z. The source electric field (tangential to the x, y plane) is the x component of the total electric field and is thus reduced by a factor of $\cos(\theta_o)$ from the magnitude of the total electric field. The magnetic field at the source is the same as the total magnetic field in the wave. Since the electric and magnetic fields in the wave are related by Z_o, the surface impedance which the source drives associated with the upward wave is just $Z_o \cos(\theta_o)$, the ratio of tangential electric and magnetic fields parallel to the x, y plane. Similarly, if there is nothing to perturb the fields below the source then there will be a surface impedance $Z_o \cos(\theta_o)$ for the source to drive associated with the fields below the source. This gives a net impedance for each cell for this case as

$$Z_{x_1} = \frac{w_1}{w_2} \frac{Z_o \cos(\theta_o)}{2} \tag{4}$$

This applies for times before the ground reflection reaches the position of interest on the source.

If there are objects which perturb the field below the source then, in general, the result of equation 4 must be modified. In particular suppose that there are vertical conductors of small cross section leading from the source plane to the ground surface which short out E_z for wavelengths large compared to w_1 and w_2. Then for such wavelengths the fields below the source are guided to propagate in the -z direction even though the source field is turned on at different times across the source plane. Provided that these conductors associated with an individual cell have total x and y dimensions which are negligible compared to w_1 and w_2, then the surface impedance which the distributed source drives (associated with the fields below the source) is just Z_o. Note that for wavelengths large compared to w_1 and w_2 the fields in this downward wave look like a uniform plane wave (except possibly near the vertical conductors) because the fields associated with one cell approximately match to the fields on the adjacent identical cells on all sides. The small differences in wave launching times from one cell to the next can be allowed for by short (or high frequency) pulses in the net currents on the vertical conductors. Combining in parallel the impedances associated with the fields above and below the source plane gives an impedance for each cell as

$$Z_{x_2} = \frac{w_1}{w_2} Z_o \left[\frac{1}{\cos(\theta_o)} + 1\right]^{-1}$$

$$= \frac{w_1}{w_2} Z_o \frac{\cos(\theta_o)}{1 + \cos(\theta_o)} \tag{5}$$

Note that since the impedance driven by the source associated with the downward wave can be increased for $0 < \theta_o < \pi/2$ by the use of vertical conductors below the source, and since the downward wave does not add to the desired radiation, then such vertical conductors may be desirable to reduce unnecessary loading of the source plane. These vertical conductors might be transmission lines transporting energy to the source plane, or might be trigger cables to initiate sources at the source plane. They might also be wires expressly added to minimize the source loading. Since the main electric field (or average source field) is in the x direction one could let the conductors have large extents (even connecting across cells) in the y direction. However if one desires to be able to easily change polarization by changing source connections one would then restrict both x and y extent of the vertical conductors below the source plane. Note that such conductors below the source plane are assumed to be connected to the sources, conductors, and other electrical items in each cell in the same manner from cell to cell such that they fit into a uniform electric field and periodic geometrical arrangement from cell to cell considered in the direction of the desired average source electric field for the present results to hold. In particular one wishes to avoid shorting out some of the cells with the conductor arrangement, or making a type of wave guiding structure which lowers the effective surface impedance seen by the source for the volume below the source.

The second case to consider is the case of the source electric field having only a y component with the same propagation direction of the upward wave as before. The upward propagating wave then has an electric field with only a y component and a magnetic field with only x and z components. The surface current density (or current through each cell divided by w_2) associated with the upward wave is equal in magnitude to the x component of the magnetic field or $\cos(\theta_o)$ times the magnitude of the magnetic field. The surface impedance driven by the source plane and associated with the upward wave is then just $Z_o/\cos(\theta_o)$. Similarly if nothing significantly perturbs the downward wave there is another equal surface impedance driven by the source plane. This gives a net impedance for each cell for this case as

$$Z_y = \frac{w_1}{w_2} \frac{Z_o}{2 \cos(\theta_o)} \tag{6}$$

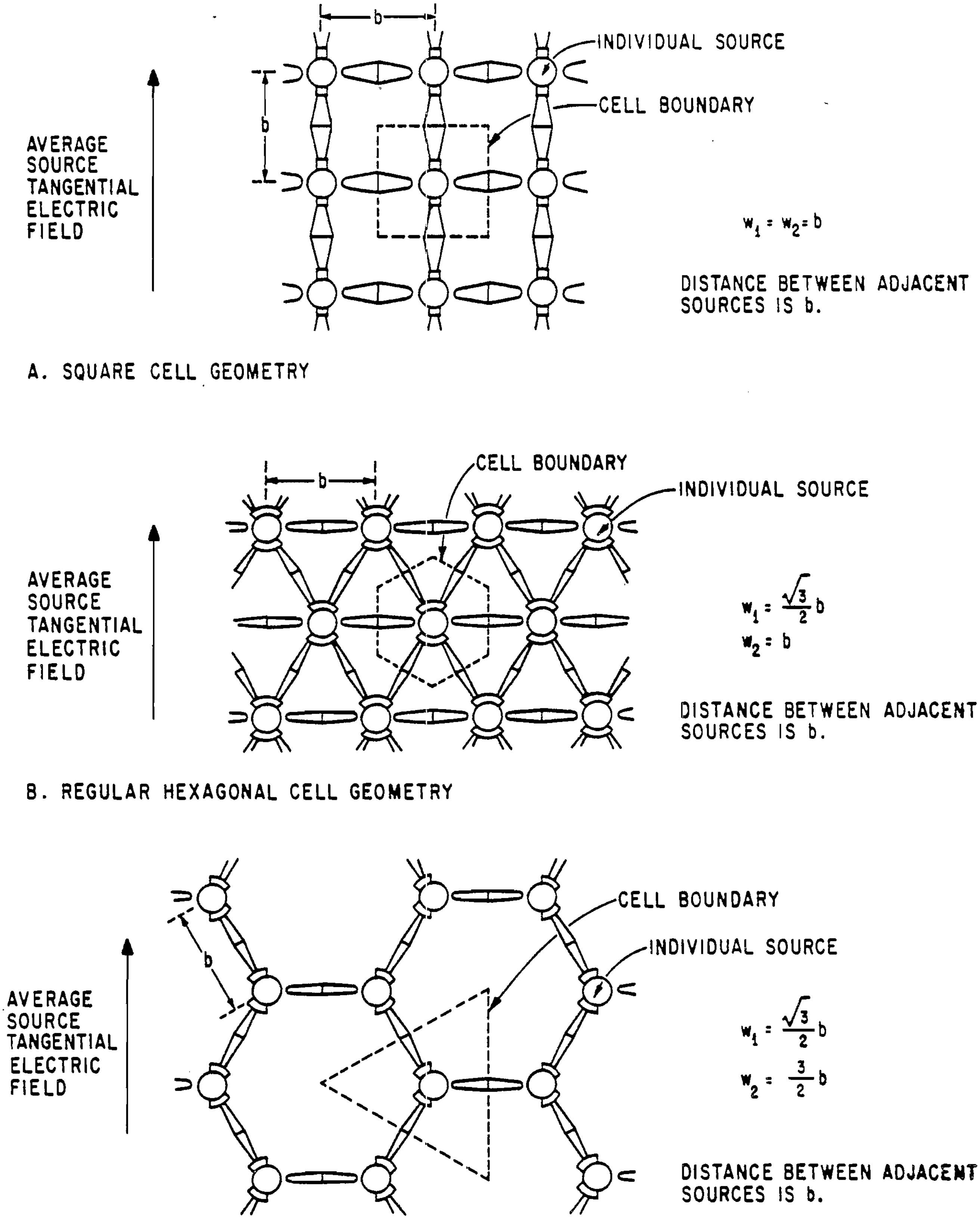
Note that since the downward propagating wave has only a y component of the electric field then vertical conductors with negligible extent in the y direction (small total dimensions in each cell in the y direction compared to w_1) do not significantly change the characteristics of the wave provided they are appropriately electrically connected in each cell. Note that w_1 and w_2 are defined with respect to the direction of the source electric and magnetic fields respectively, not the x and y coordinates.

Thus the impedance driven by the source cells varies with both polarization and direction of propagation of the radiated wave. This implies that one does not have a single impedance to "match" in some sense if one wishes to vary both polarization and propagation direction. If transmission lines are used to transport the energy to the source plane then one might choose a compromise impedance for the transmission lines to optimize the performance over some range of θ_o for one or more polarizations. If the sources are at the source plane then this particular problem is not the same, but similar considerations apply to the optimization of the very early time performance of the conical transmission lines for various θ_o. Note the increase in the impedance loading the sources associated with the downward wave when appropriate vertical conductors are used below the source.

This keeps the minimum downward surface impedance to approximately Z_0. The reader should note that these impedance calculations only apply for characteristic times large compared to transit times associated with the conical transmission lines interconnecting the cells; the times must also be before ground reflections and the presence of the array edge can be detected at the cell of interest. One could try to further increase the downward impedance by increasing the wave impedance below the source, but this would require magnetic materials so as to increase the permeability of the medium while hopefully not significantly increasing the permittivity or conductivity.

Figure 2 shows some possible configurations at the source plane for establishing the average source electric field in a particular direction parallel to the source plane. However one may wish to use other configurations if changes in polarization are desired with the same distributed source. Even for a single polarization the individual sources need not be arranged like the rectangular layout in figure 2. Various staggered arrangements are possible. Figure 3 shows some general schemes for interconnecting the individual sources or transmission lines from the sources. Basically there would be an array of conductors for each desired polarization and a switch arrangement associated with each cell (perhaps remotely operated for quick changes and perhaps involving rotation of the individual sources or appropriate terminals) would switch the source or transmission-line terminals to the appropriate set of interconnecting conductors. Figure 3A shows what might be called an array with a square cell structure; this type of array has 2 source polarizations each of which has two polarities for a total of 4 source electric field directions. Figure 3B shows an array with a regular hexagonal cell structure where the source plane can be divided up into regular hexagons with a source or transmission-line connection at the center of each; this type of array has 3 source polarizations for a total of 6 source electric field directions. Figure 3C shows an array with an equilateral triangular cell structure; including reversal of source polarity this array can also get 6 source electric field directions.

Note that the interconnecting conductors may or may not be bicones and they may or may not lie on a plane (as shown in figure 2 for a case of a single polarization). When operated with some particular polarization not all the interconnecting conductors are needed to join the sources. However the unused conductors are still there and have some influence on the characteristics of the distributed source at very early times. If desired, additional switch electrodes could be provided to short the remaining unused interconnecting conductors together in figures 3A and 3B, or perhaps even to connect these conductors to a zero potential point on differentially charged sources, or even to cable shields of differential transmission lines bringing the



C. EQUILATERAL TRIANGULAR CELL GEOMETRY

Figure 3. INTERCONNECTION ARRAYS FOR CHANGING POLARIZATION: TOP VIEWS

energy to the source plane from remote sources in any of the 3 cases. The array geometries shown in figure 3 (plus some variations on these geometries) can be used to give regular polygons (squares, regular hexagons, equilateral triangles) for the basic cell structure of the array with one interconnecting conductor crossing each side of the regular polygon. As shown in figure 3 the polarization switch could rotate about a vertical axis (perhaps rotating the source or transmission-line connection with it) and achieve the various types of interconnections. Of course one might also use something other than a regular polygon for a basic cell geometry and use other interconnection schemes. Note for equations 3 through 5 that for non rectangular cell geometries w_1 and w_2 refer to effective dimensions for electrically dividing up the source plane; w_1 relates an individual source voltage to the average source electric field parallel to the x, y plane; w_2 relates the current through an individual source to the average surface current density associated with the source array, considered as localized to the x, y plane.

Having considered some features of the basic array design we go on in the next sections to consider some of the fundamental array limitations. These include the finite array size (for the case of a spherically expanding wave) and the ground reflection; both of these effects limit pulse width. Then we go on to give a few remarks about some of the features of such an array used to radiate a pulsed sinusoid instead of trying to obtain a large pulse width of one polarity before the radiated pulse reverses polarity. A pulsed sinusoid might be used if one wished to maximize energy in some frequency band at some observation point; focusing concepts borrowed from optics have some usefulness for such a case.

II. Effect of Source Size in Limiting Unipolar Pulse Width

Since the distributed planar source has finite dimensions and finite capacitive sources (or more generally finite energy) the late-time electric and magnetic dipole moments are bounded in magnitude. This requires that the far field or radiated waveform have a net zero complete time integral; it cannot be a unipolar pulse; the waveform must change sign after the initial peak amplitude. One feature of the simulator is then the width of the pulse from the initial rise to first zero crossing for some significant field component in the radiated pulse. In this section we consider a lower bound for this pulse width for a particular type of radiated wave. This bound is based on the source size.

Consider a spherical wave, for the moment, with an electric field of the form

$$\vec{E} = \vec{E}_1(\theta_c, \phi_c) \frac{r_o}{r_c} u\left(t - \frac{r_c - r_o}{c}\right) \tag{7}$$

where u is the unit step function. Furthermore let $\vec{E}_1$ have no component in the r_c direction so that this type of electric field is a spherical TEM wave in the (r_c, θ_c, ϕ_c) spherical coordinate system. We only consider the region inside a cone of small cone angle with its axis centered on (θ_c, ϕ_c) = (θ_o, 0) so that we will not be concerned with those regions of space where such a wave has singularities; our simulator will only approximately reproduce such a wave over this limited solid angle and for a limited retarded time. Not just any $\vec{E}(\theta_c, \phi_c)$ that one might choose can be used because $\vec{E}$ must satisfy a vector wave equation. This implies that $\vec{E}_1(\theta_c, \phi_c)r_o/r_c$ must satisfy the Laplace equation. Note that the wave radiated from the simulator for early times does not need to be an exact spherical TEM wave; this type of wave is just convenient for illustration. The fact that the wave we are considering is a spherically expanding one, centered on $r_c = 0$, is important in estimating the pulse width. For completeness the speed of propagation of the wave is the speed of light given by

$$c = \frac{1}{\sqrt{\mu_o \varepsilon_o}} \tag{8}$$

Now assume that $r_o >> a$ so that the fractional variation of r_c over the source array is small. Further assume that the variation of $\vec{E}_1(\theta_c, \phi_c)$ over the source array is small and can be neglected. Note that having $r_o >> a$ makes the maximum angular extent of the source small as seen at $r_c = 0$. Then we have at the source array

$$\vec{E}_1(\theta_c, \phi_c) \simeq \vec{E}_2 \tag{9}$$

where $\vec{E}_2$ is some constant vector independent of θ_c and ϕ_c which we might define from

$$\vec{E}_2 \equiv \vec{E}_1(\theta_o, 0) \equiv E_2\vec{e}_p \tag{10}$$

where

$$E_2 \equiv |\vec{E}_2| \tag{11}$$

and $\vec{e}_p$ is a unit vector with constant direction specifying the polarization of the wave.

Let the tangential field specified on the source (averaged over the individual cells) be of the form

$$\vec{E}_s \equiv E_o \vec{e}_s u\left(t - \frac{r_c - r_o}{c}\right) \tag{12}$$

where r_c is taken on the x, y plane and where $\vec{e}_s$ is a unit vector of constant direction parallel to the x, y plane. Now match $\vec{E}_s$ to the components of $\vec{E}$ parallel to the x, y plane using the approximations mentioned above. This specifies

$$\begin{aligned} E_o \vec{e}_s &= -E_2 (\vec{e}_p \times \vec{e}_z) \times \vec{e}_z \\ &= E_2 [(\vec{e}_p \cdot \vec{e}_x)\vec{e}_x + (\vec{e}_p \cdot \vec{e}_y)\vec{e}_y] \end{aligned} \tag{13}$$

where $\vec{e}$ with a coordinate subscript indicates a unit vector in that direction. Now $\vec{E}_s$ is chosen to have the same x and y components as $\vec{E}_2$, but no z component; $\vec{e}_s$ has the same direction as the projection of $\vec{e}_p$ onto the x, y plane. There are two special cases of interest. Case 1 has

$$\begin{aligned} \vec{e}_s &\equiv \vec{e}_{s_1} = \vec{e}_x \\ \vec{e}_p &\equiv \vec{e}_{p_1} = \cos(\theta_o)\vec{e}_x - \sin(\theta_o)\vec{e}_z \\ E_2 &= \frac{E_o}{\cos(\theta_o)} \end{aligned} \tag{14}$$

so that the source electric field is in the x direction and the wave is launched with a total electric field larger by $1/\cos(\theta_o)$. Case 2 has

$$\vec{e}_s \equiv \vec{e}_{s_2} = \vec{e}_y$$

$$\vec{e}_p \equiv \vec{e}_{p_2} = \vec{e}_y \tag{15}$$

$$E_2 = E_o$$

so that the source electric field is in the y direction and the total electric field has the same magnitude.

In equation 12 we have a source tangential electric field of constant magnitude and direction and turned on as a step function at a time that varies over the array so as to produce a spherically expanding wave with radius of curvature r_o and propagating in a direction centered on $(\theta_c, \phi_c) = (\theta_o, 0)$. Of course the source array does not put a step function field with zero rise time on the x, y plane in exactly the form of equation 12. The individual sources have non zero rise times and the cell dimensions prevent the turn-on time of the field over the cell from being precisely the sequence required by equation 12. These effects simply limit the rise time of the radiated wave, but this is not our present concern; we wish to look at the radiated pulse width. Assuming the individual sources are basically capacitive let the capacitance be large enough so that there is negligible decay in the individual source voltages (and thus in $\vec{E}_s$) during times of interest before other limiting effects become important. Note that $\vec{E}_s$ is specified to have a single direction over the source array. This can be achieved using various source interconnections as in the examples in figures 2 and 3. In order to avoid the generation of any tangential electric field perpendicular to the desired $\vec{E}_s$ one can provide continuous conducting paths to short out any average tangential electric field perpendicular to the desired average $\vec{E}_s$. However such shorting paths may not be essential to the performance of the array.

A very significant limitation of the source field as in equation 12 is that it only applies over the finite extent of the source, not the entire x, y plane. However for an observer above the x, y plane near the line $(\theta_c, \phi_c) = (\theta_o, 0)$ the effect of the source edge is only noticed after some delay time after the arrival of the first signal at $t = (r_c - r_o)/c$. (Note that $t = 0$ is defined as the time the center of the array turns on so that part of the array turns on before $t = 0$ if $\theta_o \neq 0$.) Consider the cone (not necessarily circular) with apex at $r_c = 0$ and with its intersection with the x, y plane being the edge of the source array $(\Psi, z) = (a, 0)$. For $z > 0$ inside this cone (i.e. near $(\theta_c, \phi_c) = (\theta_o, 0)$) there is a delay for the effect of the source edge to reach the observer. To check if the observer is in such a position inside this cone note that a straight line from $r_c = 0$ to the observer must pass through the source array, not around it. Note that one reason for considering such a spherically expanding wave is just so such a delay time to seeing the source edge can be established for observers at large r_c (i.e. for $r_c >> r_o$), thereby establishing a minimum pulse width.

Now consider the observer on the line $(\theta_c, \phi_c) = (\theta_o, 0)$ which also corresponds to $(\theta, \phi) = (\theta_o, 0)$. This is because we expect the maximum time delay to seeing the source edge to occur near this line, particularly if we have $r_o >> a$ and $r = r_c - r_o >> a$. Consider the direct path from the effective center of the wave (the center of wave curvature) of length $r_c = r_o + r$. Compare to this a path consisting of a straight line of length r_1 from the center of wave curvature to the source edge plus a straight line of length r_2 from there to the observer. Let r_e be the total path via the point on the edge ($\Psi = a$) so that

$$r_e = r_1 + r_2 \tag{16}$$

Let ϕ_e be the value of ϕ corresponding to the position on the edge of the source ($\Psi = a$) involved in this distance calculation. Consider a plane containing the y axis and at an angle θ_o with respect to the x axis such that it is perpendicular to the line from the center of curvature to the center of the array. Consider a line from the center of the array to the array edge (specified by ϕ_e). This line and plane make an angle θ' with respect to each other where

$$\sin(\theta') = \sin(\theta_o)\cos(\phi_e) \tag{17}$$

Note then that $\theta' + \pi/2$ is the angle between the line from the center of wave curvature to the array center and the line from array center to array edge. Using the law of cosines we then have

$$\begin{aligned} r_1^2 &= r_o^2 + a^2 - 2r_o a\cos(\theta' + \pi/2) \\ r_2^2 &= r^2 + a^2 - 2ra\cos(\pi/2 - \theta') \end{aligned} \tag{18}$$

which can be reduced to

$$r_1^2 = r_o^2 + a^2 + 2r_o a \sin(\theta_o) \cos(\phi_e)$$

$$r_2^2 = r^2 + a^2 - 2ra \sin(\theta_o) \cos(\phi_e) \tag{19}$$

Now define the increase in r_e over r_c as

$$\Delta r \equiv r_e - r_c = r_e - r_o - r \tag{20}$$

so that we have

$$\Delta r = \left[r_o^2 + a^2 + 2r_o a \sin(\theta_o) \cos(\phi_e)\right]^{1/2} - r_o$$

$$+ \left[r^2 + a^2 - 2ra \sin(\theta_o) \cos(\phi_e)\right]^{1/2} - r \tag{21}$$

For small a/r_o and small a/r we have

$$\Delta r = \frac{r_o}{2}\left\{\left(\frac{a}{r_o}\right)^2 + 2\frac{a}{r_o}\sin(\theta_o)\cos(\phi_e) - \frac{1}{4}\left[\left(\frac{a}{r_o}\right)^2 + 2\frac{a}{r_o}\sin(\theta_o)\cos(\phi_e)\right]^2\right.$$

$$\left. + O\left(\left(\frac{a}{r_o}\right)^3\right)\right\} + \frac{r}{2}\left\{\left(\frac{a}{r}\right)^2 - 2\frac{a}{r}\sin(\theta_o)\cos(\phi_e)\right.$$

$$\left. - \frac{1}{4}\left[\left(\frac{a}{r}\right)^2 - 2\frac{a}{r}\sin(\theta_o)\cos(\phi_e)\right]^2 + O\left(\left(\frac{a}{r}\right)^3\right)\right\}$$

$$= \frac{a^2}{2}\left[\frac{1}{r_o} + \frac{1}{r}\right]\left[1 - \sin^2(\theta_o)\cos^2(\phi_e)\right] + aO\left(\left(\frac{a}{r_o}\right)^2\right) + aO\left(\left(\frac{a}{r}\right)^2\right) \tag{22}$$

where r_o and r are considered fixed. The time delay from the first signal till the source edge influences the signal is given from the minimum Δr as

$$\Delta t = \frac{1}{c}(\Delta r)_{min} \tag{23}$$

Now Δt and minimum Δr occur (for small a/r_o and a/r) at $\phi_e = 0$ and $\phi_e = \pi$ where we have the asymptotic result

$$c\Delta t = (\Delta r)_{min} = \Delta_1 + \Delta_2 + aO\left(\left(\frac{a}{r_o}\right)^2\right) + aO\left(\left(\frac{a}{r}\right)^2\right) \tag{24}$$

where we have defined

$$\Delta_1 \equiv \frac{a^2}{2r_o}\cos^2(\theta_o)$$
$$\Delta_2 \equiv \frac{a^2}{2r}\cos^2(\theta_o) \tag{25}$$

Each of these terms in $c\Delta t$ is associated with r_o and r respectively so that the two distances can be conveniently separated in their influence on Δt. Note that if $r >> r_o$ then only Δ_1 is significant and can be regarded as a lower limit for $c\Delta t$ as r becomes large. Also note that Δt is proportional to $\cos^2(\theta_o)$, so as the beam is directed away from vertical (the z axis) Δt decreases.

As a sample calculation to show some possible magnitudes of the various quantities involved suppose we choose a = 1 km, r_o = 20 km, and $E_o = 10^5$ V/m and let the observer be at r = 180 km with $\theta_o = 0$. Then $\Delta_1 \simeq 25$ m and $\Delta_2 \simeq 2.8$ m giving $\Delta t \simeq 93$ ns. From equations 7 through 15 we have (at the observer) an electric field magnitude reduced by r_o/r_c from the source electric field giving about 10^4 V/m. Of course any ionospheric effects are not included here.

Again it is to be emphasized that Δt represents an approximate lower bound on pulse width. It does not consider any of the details of the electromagnetic fields reaching the observer once the presence of the edge of the distributed source can be detected by the observer. Clearly what happens at the observer after the edge is detected depends on what is done at the source edge. The array might just stop leaving only free space (air) beyond it, or various conductor distributions might extend beyond the array edge. Thus various detailed calculations of the boundary-value-problem variety need to be considered. Perhaps some increase in pulse width (before reversal of the radiated waveform) can be achieved without additional sources. Note also that one has some choice in whether or not to short out the component of the average tangential electric field on the source plane perpendicular to the direction of the average tangential electric field being purposely impressed on the array from the multiple sources or transmission lines.

An interesting aspect for a distributed source of this type for launching a spherically expanding wave is that the fields at an observer in the center of the radiated beam can be associated with only a limited portion of the source plane at each time after the first signal arrival. We have used this aspect to find Δt, a lower bound for the radiated pulse width. However, consider times after first signal arrival less than Δt and substitute it for Δt in equations 24 and 25 and substitute an effective source radius a' giving for small a'

$$ct^* = \frac{a'^2}{2}\cos^2(\theta_o)\left[\frac{1}{r_o} + \frac{1}{r}\right] + aO\left(\left(\frac{a'}{r_o}\right)^2\right) + aO\left(\left(\frac{a'}{r}\right)^2\right) \tag{26}$$

where we have defined a retarded time

$$t^* \equiv t - \frac{r_c - r_o}{c} \tag{27}$$

Note then that a' is proportional to $\sqrt{t^*}$ for small t*. For any given t* it is only an area of the source plane proportional to a'^2 and thus to t* which is significant in contributing to the waveform seen at the observer. In designing a source array for a small rise time for the radiated wave one only need have a small portion in the center of the array be fast sources with small cell dimensions and high quality interconnections because only this portion of the array contributes to the rise of the radiated fields. As one goes farther out on the array for larger Ψ the sources can be slower, the cells larger, and the time jitter of the triggering can be larger. For large arrays this could be significant. Again detailed calculations could better quantitatively define the effects of compromises in the quality of the array away from the center. More generally E_o

may be allowed to vary over the array. Furthermore the source capacitances (if capacitive generators are used) influence the waveform and can also be varied over the array.

In considering the radiation of a spherically expanding wave from such an array the calculations have treated a wave in free space. Such an assumption does not apply to all cases; it is useful, however, for illustration. A case where such an assumption may not apply is the ionosphere. For upward propagation to large distances the ionosphere may significantly distort the pulse waveform, but as a simulator that may be desirable since the ionosphere normally distorts a pulsed wave and one may wish to measure this distortion and/or use this distortion to simulate a case of interest. However, due to the geometry of the radiated wave (a narrow beam from the array) there will be some differences in the pulse propagation as compared to a wavefront of larger extent. This merely points out the need for detailed calculations in this area as well.

III. Reflection from Ground Surface

In the previous section we have considered the array limitation for pulse radiation (unipolar) associated with the finite array size. There is another effect associated with reflection from the ground surface which tends to limit the pulse width. Figure 4 shows a portion of the distributed source above the ground surface. For the moment let there be no conductors below the source to guide the wave in that region of space. Let the radius of curvature r_o of the spherical wave launched above the source be large compared to h, the height of the source above the ground. Then approximate the upward launched wave as a plane wave. Since the distributed source is a plane of constant z (i.e. z = 0) then locally there is a plane wave launched below the source at an angle θ_o with respect to $-\vec{e}_z$. This wave reflects off the ground surface, the reflected wave propagating at an angle θ_o with respect to $+\vec{e}_z$. This reflected wave interacts with the distributed source affecting the average tangential electric field at the source plane, and thereby affecting the radiated fields.

A first simple thing to note is the time delay involved in the reflection reaching the source plane. This is a kind of clear time and for times before this the ground reflection has no significance to the upward radiated wave. Referring to figure 4 the source plane is turned on at a time t_o (from equation 12) as

$$ct_o = r_c - r_o \tag{28}$$

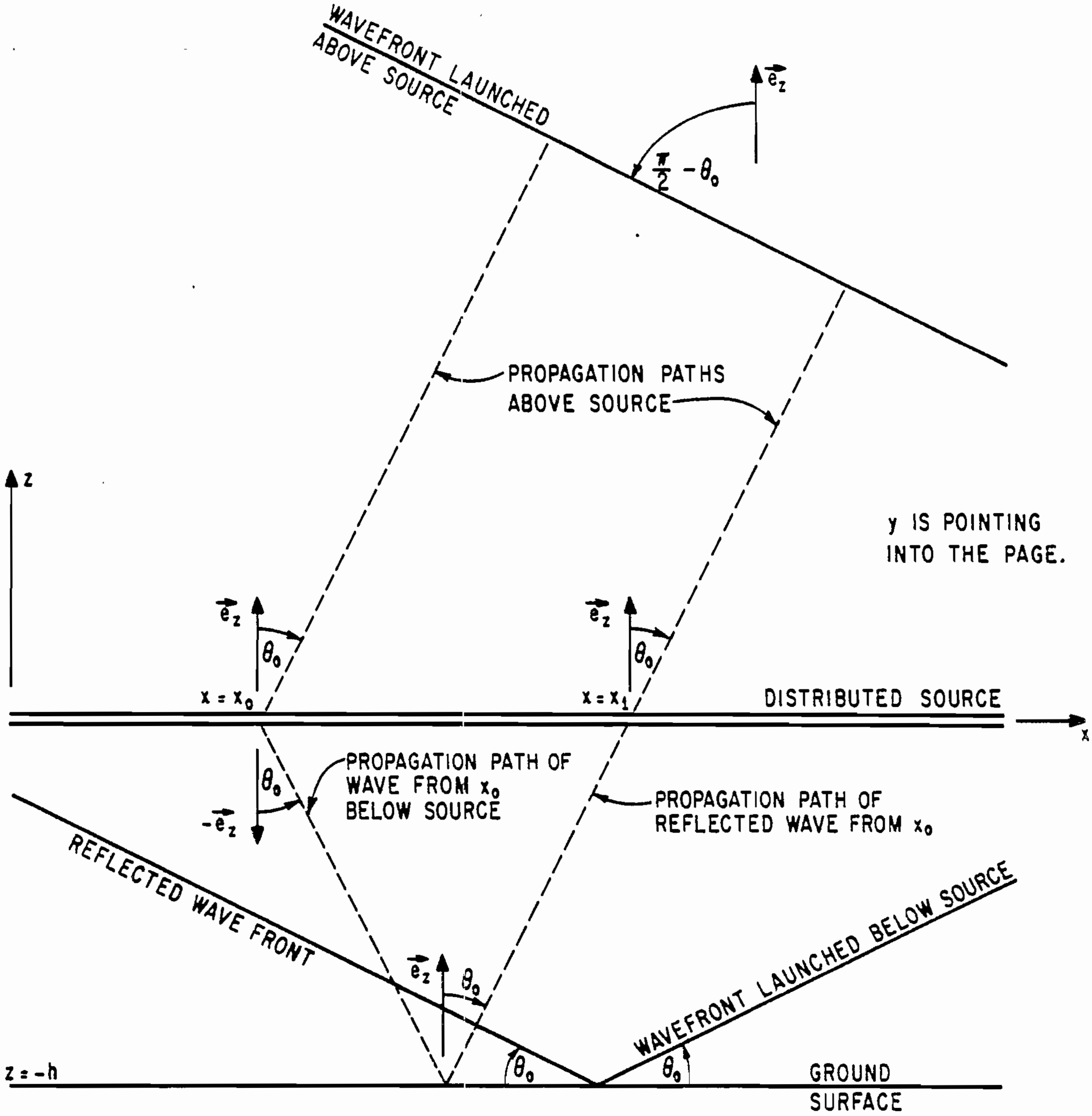


Figure 4. GEOMETRY OF WAVES ABOVE AND BELOW SOURCE PLANE

where for small a/r_o we have at the source $(z = 0)$ for small Ψ/r_o

$$r_c = \left[r_o^2 \cos^2(\theta_o) + (r_o \sin(\theta_o) + x)^2 + y^2\right]^{1/2}$$

$$= \left[r_o^2 + 2xr_o \sin(\theta_o) + \Psi^2\right]^{1/2}$$

$$= r_o\left[1 + \frac{x}{r_o} \sin(\theta_o) + O\left(\left(\frac{\Psi}{r_o}\right)^2\right)\right] \tag{29}$$

so that as $\Psi/r_o \to 0$ with r_o fixed we have

$$ct_o = x \sin(\theta_o) + \Psi O\left(\frac{\Psi}{r_o}\right) \tag{30}$$

Thus we use the approximation

$$t_o(x) \simeq \frac{x}{c} \sin(\theta_o) \tag{31}$$

for the turn on time of the array for reflection calculations. Note that the complete definition of the timing in equation 12 is needed to make the upward launched wave spherical instead of plane.

Now the downward launched wave originating from $x = x_o$ propagates a distance $h/\cos(\theta_o)$ as an approximate plane wave at an angle θ_o with respect to $-\vec{e}_z$ before reaching the ground at $x = x_o + h \tan(\theta_o)$. It reflects from the ground at an angle θ_o with respect to $+\vec{e}_z$ and propagates again a distance $h/\cos(\theta_o)$ reaching the source plane at $x = x_1$ where

$$x_1 = x_o + 2h \tan(\theta_o) \tag{32}$$

The reflected wave arrives at $x = x_1$ at a time

$$t_1(x_1) = t_o(x_o) + 2\,\frac{h}{c}\,\frac{1}{\cos(\theta_o)} \tag{33}$$

The time delay $\Delta' t$ between the source turning on at a particular x_1 and a reflected wave reaching that point is then

$$\begin{aligned}
\Delta' t &= t_1(x_1) - t_o(x_1) \\
&= t_o(x_o) - t_o(x_1) + 2\,\frac{h}{c}\,\frac{1}{\cos(\theta_o)} \\
&\simeq \frac{x_o - x_1}{c}\,\sin(\theta_o) + 2\,\frac{h}{c}\,\frac{1}{\cos(\theta_o)} \\
&= -2\,\frac{h}{c}\,\frac{\sin^2(\theta_o)}{\cos(\theta_o)} + 2\,\frac{h}{c}\,\frac{1}{\cos(\theta_o)} \\
&= 2\,\frac{h}{c}\,\cos(\theta_o)
\end{aligned} \tag{34}$$

From this result we can define

$$\Delta_3 \equiv 2h\,\cos(\theta_o) \tag{35}$$

so that

$$c\Delta' t \simeq \Delta_3 \tag{36}$$

This result for $c\Delta' t$ can be compared to that for $c\Delta t$ in the previous section. One might typically make the two comparable, or perhaps let $c\Delta' t$ be smaller depending on the actual characteristics of the reflection from the ground surface and the source impedances at the source plane.

If conductors are present in the space between the source plane and the ground surface then the characteristics of the reflected wave may be significantly different depending on the details of the conductor arrangement below the source. As discussed in section I conductors below the source might take the form of vertical conductors (wires, transmission lines, etc.) associated with each cell of the distributed source. These vertical conductors can be arranged to not significantly interfere with a wave associated with an average source electric field polarized in the y direction. However an average source electric field polarized in the x direction has the effective surface impedance associated with the fields below the source significantly altered if $\theta_o \neq 0$. Similarly there is a change in the time delay of the wave reflected from the ground surface for such a case. Since E_z below the source is shorted out below the source for wavelengths large compared to the cell dimensions (such as w_1 and w_2) then for an x polarized source electric field the wave below the source propagates basically parallel to the z axis. For this case Δ_3 (as in equation 35) should be taken as 2h since the time delay $\Delta' t$ for the wave to propagate to the ground and return to the source is 2h/c. The presence of the vertical conductors prevents (for this polarization) a wave from propagating from some x_o and being the significant reflection to first reach an x_1 some distance from x_o. However some very high frequencies can reach x_1 (as in equation 32) by such a reflection path.

Now $\Delta' t$ can be used to give the first time that a reflection can return to the source plane. However after the reflection arrives the source plane does not immediately cease to function as such. If the capacitance of the individual sources is sufficiently large then the reflected wave will in turn reflect from the distributed source with initially only a small change resulting in the average tangential electric field at the source plane. The larger the source capacitance the longer it can maintain the average tangential electric field at the source plane as its initial magnitude E_o.

The magnitude of the reflection from the ground surface is time dependent and its characteristics depend on the conductivity, permittivity, and permeability of the ground as well as the direction of incidence and polarization of the wave.[7] With permeability typically μ_o then the tangential electric field in the reflected wave at the source plane is opposite in direction to the source field, at least at low frequencies or late times if the ground conductivity is sufficiently greater than zero.

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

Thus, at least at sufficiently late times, the reflected wave (including subsequent reflections) loads the source array, effectively lowering the magnitude of the impedance seen by the source array and thereby draining the source capacitance more rapidly and collapsing the source field. Note then that the quantitative characteristics of the ground reflection are important and that the ground reflection effects can generally be minimized by minimizing the permittivity and conductivity of the ground, at least in the limit of small θ_o. There are certain high-frequency effects associated with the Brewster angle that pertain to the case of an average source electric field in the x direction; we do not consider this effect here. In any event minimum ground conductivity decreases the low-frequency ground loading of the array.

Conductors distributed over the ground surface can increase the magnitude of the ground reflection by making the ground surface look like a conducting plane. This depends of course on the direction of the conductors (if they are wires, cables, or other elongated conductors) relative to the wave polarization. Such conductors on the ground surface might be trigger cables or other transmission lines (such as for pulses from sources or charging power) leading eventually up to the source plane. Since we wish to minimize adverse ground reflections then we would like to minimize the effects of such conductors by eliminating them or by changing their effects on external high-frequency transient waves. One way to minimize the reflection from such conductors would be to put them through inductive cores with perhaps several turns thereby breaking up these conductors at high frequencies with inductors with impedances of sufficiently large magnitude. Note that transmission lines such as coax cables can be put through or wound on such cores without significantly affecting the signal mode of propagation in the cable. Another phenomenon to be noted with such conductors on the ground under the array is that the large currents induced on them can adversely affect the equipment (trigger generators, etc.) connected to them. Inductive isolators and other protection devices may be useful in this regard.

In the previous section (section II) it was pointed out that for a source of this type to launch a spherically expanding wave the portion of the array near $\Psi = 0$ is the most important for the rise time as it is the first to be seen by the observer in the center of the radiated beam. The edges of the array are seen last, determining the clear time Δt. The sources in the center of the array supplying current for longer times need more capacitance (for a fixed voltage and cell geometry) if we are only interested in retarded times out to $t^* = \Delta t$. Similar statements can be made regarding the height h of the array above the ground as it enters into $\Delta' t$ used in this section. Assuming $h << a$ then we might make $\Delta' t$ approximately Δt near $\Psi = 0$ but near $\Psi = a$ we might make $\Delta't$ (and thus h) much smaller with an appropriate variation of h over the range $0 \leq \Psi \leq a$ so as to match $\Delta't$ locally to Δt minus the time delay after $t^* = 0$ that the local sources are seen at the observer. Of course if θ_o, e_s, and the orientation of the x axis are varied between pulses then a single choice of $\Delta't$ as a function of Ψ (and perhaps even ϕ) would be some compromise for optimum operation over the desired range of parameters. Also note that the array need not be flat (nor the ground) and h can be considered locally as long as the radii of curvature of source and ground surfaces are large compared to h. The array timing as in equation 12 can also be adjusted for a curved array to give the same spherical wave above the source.

As mentioned in the previous section there are various things one might do by adding conductors etc. beyond the array edge at $\Psi = a$ in order to optimize the radiated fields even somewhat beyond $t^* = \Delta t$. The effect of the ground reflection will be different at the source edge because of the absence of the distributed source to intercept the reflected wave over part of the x, y plane. What is done in the way of conductors beyond the source edge then has some influence on the reflected wave there and can perhaps be used to try to minimize the adverse effects of the reflected wave.

IV. Source Array Driven with a Pulsed Damped Sinusoid

In the previous sections we have discussed some of the design considerations for a distributed source for radiating a transient pulse in the form of a spherically expanding wave confined to a narrow beam. The radiated waveform has been considered from the viewpoint of determining some of the array and ground effects in limiting the time before the waveform reverses polarity. The discussion has been pointed at maximizing what we have termed the unipolar pulse width. The discussion of this section is pointed at a different but related problem.

Suppose we make the average tangential electric field at the source plane behave as a pulsed damped sinusoid, i.e. let it ring at some radian frequency ω_o with some damping constant α so that the waveform at the source looks of the form $e^{-\alpha t}$ multiplied by some linear combination of $\cos(\omega_o t)$ and $\sin(\omega_o t)$ and zero before some time t_o which will vary over the source as we choose. One might vary the amplitude, phasing of the sine wave, and turn on time of the source over the whole array while keeping ω_o nearly the same over the whole array; α might also be varied somewhat over the array.

Basically this would be a pulsed CW source array having some things in common with a phased array radar. However one might use capacitive sources spread around the array to get a large energy in the radiated pulse and add inductors in some series-parallel combination with the capacitors and switches to give a ringing source waveform. The waveform would be damped by the resistive loading associated with the energy radiated from the array such as the impedance discussed in section I associated with the upward launched wave. Since the downward propagated wave reflects back up to the source we can use it as part of the resonant system and gain efficiency by preventing energy from being dissipated in the ground by purposely covering the ground with conductors. This space below the array can be used for placing inductors and/or resonant transmission lines which can be tuned to vary ω_o, α, and the magnitude of the source field. Even the interconnection conductors going from cell to cell could be inductors. We do not consider here any detailed designs for such resonant systems; the number of such designs is large and falls beyond the scope of this note.

Since we have a pulsed CW source we can use some single-frequency concepts to get at least a rough idea of what might be gained by using such a pulsed CW source. Basically what can be gained is focusing the energy in the array sources through some minimum size cross section area in space centered on the observer of interest. This is basically an optical technique applied at much larger wavelengths but with a correspondingly large source array. For this type of radiating array one is not trying to maximize a unipolar pulse width by launching a spherically expanding wave. In this case one is trying to maximize power density with center frequency ω_o, or total energy with center frequency ω_o, or perhaps power or energy in some narrow bandwidth, or in general some quasi-CW parameter. With this in mind one has many variables to choose to optimize the waveform at the observer in some sense, including at least ω_o, α, and the distribution of the source timing and initial field magnitude over the source. What is done at the edges of the source array to optimize the waveform at the observer may be different for this pulsed CW case from what might be used for the unipolar pulse case. In general we expect the optimum results attainable at the observer to be strongly dependent on ω_o and the position of the observer because of their direct bearing on focal spot size. However we do expect α to have some effect as well. There are obviously many detailed calculations needed to optimize such an array. In this note we merely indicate many of the problems to be considered and advantages to be gained. Hopefully detailed calculations can be presented in future notes.

From the viewpoint of the system under test by such a simulator one would use the test to obtain approximate CW response functions using the feature that the waveform has some dominant radian frequency ω_o. By adjusting the source array to vary ω_o then the approximate response of the system over some range of frequencies is obtained. Of course one could also use much lower power CW arrays for obtaining transfer functions. However, due to the high powers and field strengths obtainable even at large distances by the pulsed CW array under consideration one might be able to overcome some types of noise problems as well as driving some resonances in the system to high level including some nonlinear effects in such coupling modes providing ω_o can be chosen to match the resonance. One application for such a simulator might be for sending pulses through the ionosphere; for α appropriately chosen the effects of ionospheric dispersion might be minimized allowing maximum peak amplitude of the signal to reach an observer in or above the ionosphere.

The question of source quality is somewhat different for the two types of pulsed arrays. The array for a unipolar pulse might be designed for a fast rise time requiring certain features to be included in the cell design and perhaps limiting cell size. On the other hand a pulsed CW array operating at one ω_o or capable of varying ω_o over some limited frequency band might not include such features for high-frequency performance. Alternately the pulsed CW array might not require the amplitude of the radiated fields to be frequency independent at the highest frequencies of interest, but only known to some desired accuracy.

There are various applications for such a pulsed CW array such as for measuring propagation through and reflection from the ionosphere. In some cases one may wish to maximize the power density for some given peak field strength. In such cases one might consider using circularly polarized pulsed CW fields; these could be obtained by firing two or more sets of sources in the array, each source set being aligned to give different source field directions (e.g., two source sets firing at right angles to each other) and triggered in a sequence so as to be appropriately out of phase with each other to give the rotating polarization. Note that phase is only approximate for a pulsed CW source array. Also one might have more than two sets of sources (say 3 as in a 3 phase power system) to produce the circular polarization.

Thus there are many possibilities to consider for this kind of pulsed CW array. By borrowing focusing techniques from optics and techniques for obtaining highly directional CW antennas one can try to optimize the array performance. Of course since we are concerned here with pulsed CW fields then CW results do not necessarily accurately apply to this case. Thus detailed calculations are needed to accurately quantify the performance of such an array and thereby to optimize its performance.

V. Summary

In this note we have considered some of the features of planar distributed source arrays above the ground surface for radiating pulses in narrow beams to some position in space. Most of the discussion has centered on some of the design parameters associated with an array on which an average tangential electric field is established in a triggering sequence to give a spherically expanding transient wave with a single polarity for as large a time as possible. This time from initial rise to first polarity reversal, which we term unipolar pulse width, is affected by several parameters including radius of curvature of the spherical wave at the source, source dimensions, and height of the distributed source above the ground.

A second type of array briefly considered is one to radiate a pulsed CW waveform. The basic advantage to be gained here lies in using focusing techniques to try to maximize the signal around some center frequency at the position in space of interest. Such a simulator might be used for obtaining approximate CW transfer functions. Possibly one distributed source could be used for both types of waveforms if there were sufficient flexibility in varying the triggering sequence and switching in and out the additional elements needed for the case of an appropriately controlled ringing waveform.

Clearly there are many detailed calculations of the boundary-value-problem variety needed to quantify and optimize the performance of distributed sources for giving both types of waveforms. There are questions of what is the best triggering sequence and source field distribution, what should be done at the edge of the distributed source, and how the height above the ground should vary with position. Even the geometry of the individual cells which combine to make up the source array can be optimized. In some cases one may wish to propagate pulses from such arraysinto or through the ionosphere or observe the reflection back toward the surface of the earth; the propagation of these kinds of pulses in the ionosphere then needs to be studied. This note has only discussed some of the design problems for such distributed sources and indicated some of the things which can be done to improve their performance. In general much remains to be done.