Sensor and Simulation Notes

Note 340

May 1992

A Simple Model of Small-Angle TEM Horns

Everett G. Farr
Farr Research
Albuquerque, NM 87123

Carl E. Baum
Phillips Laboratory
Albuquerque, NM 87117

Abstract

When designing an antenna system for radiating a transient pulse, it is necessary to have a simple model for each of the competing antennas, in order to make comparisons. Previous work on TEM horns has provided numerical models, however no simple model exists. The purpose of this paper is to provide such a simple model. The model consists of approximating the TEM horn by a continuum of electric and magnetic dipoles, and summing their contributions. High frequency contributions are accounted for approximately by including an additional step-function term. Approximate plots of the fields in both the time and frequency domains are provided. It is demonstrated that at low frequencies a TEM horn acts like an electric dipole. Finally, a number of suggestions are provided for improving the response of the TEM horn.

I. Introduction

There is currently a need for a simple model of the TEM horn. This need arises when one wants to compare a TEM horn to other candidate antennas for radiating a transient pulse, such as the Impulse Radiating Antenna (IRA) [1-3]. Although some published literature exists, i.e. [4,5], they are generally done numerically, so their results are not easily adapted to other configurations for comparison. The analysis in this paper provides the general behavior of small-angle TEM horns, and shows the asymptotes in the frequency domain. Although this technique is less rigorous than the numerical methods of [4-5] (except in the high frequency limit where it is exact), it should be in a more convenient and usable form.

A model similar to that of the present paper (for intermediate and low frequencies) is developed in [6,7]. For the early-time behavior the present paper provides a more accurate description, due to the non-ideal reflection at the end of the horn and the matching to the aperture integral in [2].

A simple analysis of an Impulse Radiating Antenna, which consists of a paraboloidal reflector fed by a conical TEM feed, is provided in [3], which in turn uses results from [2]. The purpose of this note is to provide a comparably simple model of a TEM horn.

A diagram of a TEM horn is shown in Figure 1. It consists of a conical TEM transmission line of constant impedance. The analysis to be presented here will be most valid in the limit of small β.

We begin with a simple transmission line model of a TEM horn. This model then requires a modification for high frequencies, which we provide. Although the theory is at first generated for fields on boresight, this is then expanded to include the off-boresight fields at low frequencies. It is shown that the behavior of a TEM horn at very low frequencies is just the same as a short electric dipole. Finally, we provide suggestions on how to improve the response of the TEM horn.

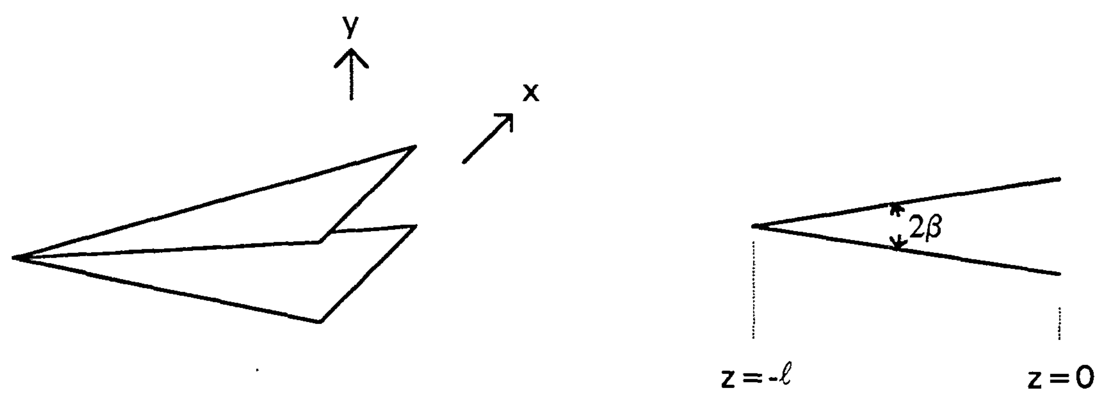

Figure 1 A TEM Horn.

II. Transmission Line Model of the TEM Horn

The first step in the analysis is to provide a low-frequency model of the TEM horn. At low frequencies, the TEM horn looks like an open circuited transmission line. A diagram showing this in Figure 2.

Note that the source is a voltage step of magnitude $2V_o$. After passing through the matched load, half the voltage is lost, and a voltage step of V_o is actually launched onto the antenna. This matched load is important for proper behavior of the antenna, in order to prevent multiple reflections. It does, however, create a loss of half the voltage. There may be ways of eliminating the factor of 2 loss in voltage, i.e., by using a high-frequency bypass capacitor, as discussed in Section VI of this paper. For our purposes, it is simplest to just assume that a voltage step of V_o is launched onto the antenna, with some method of absorbing (at the apex) reflections from the aperture.

A diagram of the open-circuited model of the TEM horn is shown in Figure 2. We may express the current and voltage on the line as a function of time as

$$I(z',t) = \frac{V_o}{Z_c} \left[u(t - z'/c - \ell/c) - u(t + z'/c - \ell/c) \right] \tag{2.1}$$

$$V(z',t) = V_o \left[u(t - z'/c - \ell/c) + u(t + z'/c - \ell/c) \right] \tag{2.2}$$

where $u(t)$ is a unit step function and Z_c is the characteristic impedance of the TEM horn. The value of Z_c for a given geometry may be found from the methods in [8]. It turns out that the charge per unit length is more useful that the voltage, so this is simply expressed as

$$\begin{aligned} Q'(z,t) &= C'V(z,t) \\ &= \frac{V_o}{cZ_c} \left[u(t - z'/c - \ell/c) + u(t + z'/c - \ell/c) \right] \end{aligned} \tag{2.3}$$

where $C' = 1/(cZ_c)$ is the capacitance per unit length of the transmission line, and c is the speed of light.

We now break the line up into a continuum of incremental electric and magnetic dipoles. A diagram of this is shown in Figure 3. The incremental dipoles are constructed from each differential length of the transmission line, and its associated current and charge per unit length. Thus we find

$$dm_x(z',t) = I(z',t)\ dA(z') \tag{2.4}$$

$$dp_y(z',t) = Q'(z',t)\ h(z')\ dz' \tag{2.5}$$

where $h(z')$ is the local equivalent height, and $dA(z') = h(z')dz'$ is the incremental loop area. Thus, the incremental magnetic dipole becomes

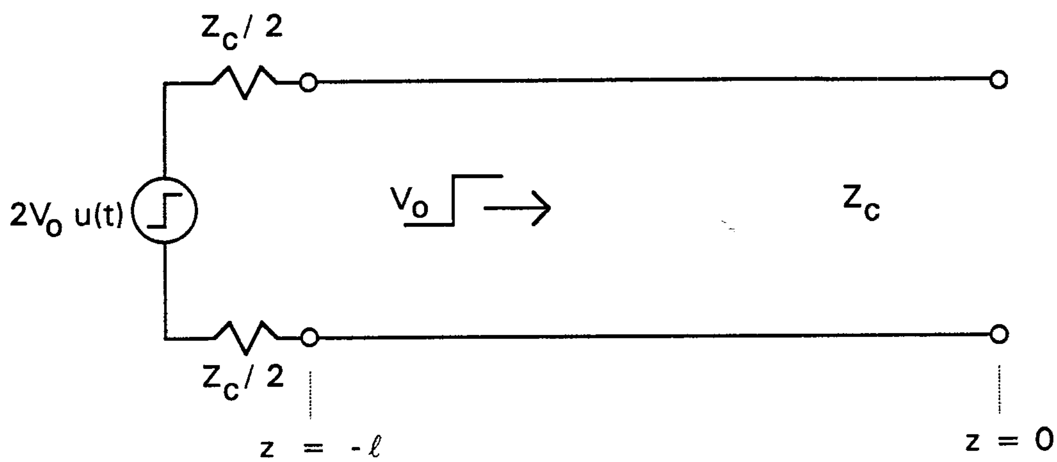

Figure 2. The low-frequency model of a TEM horn

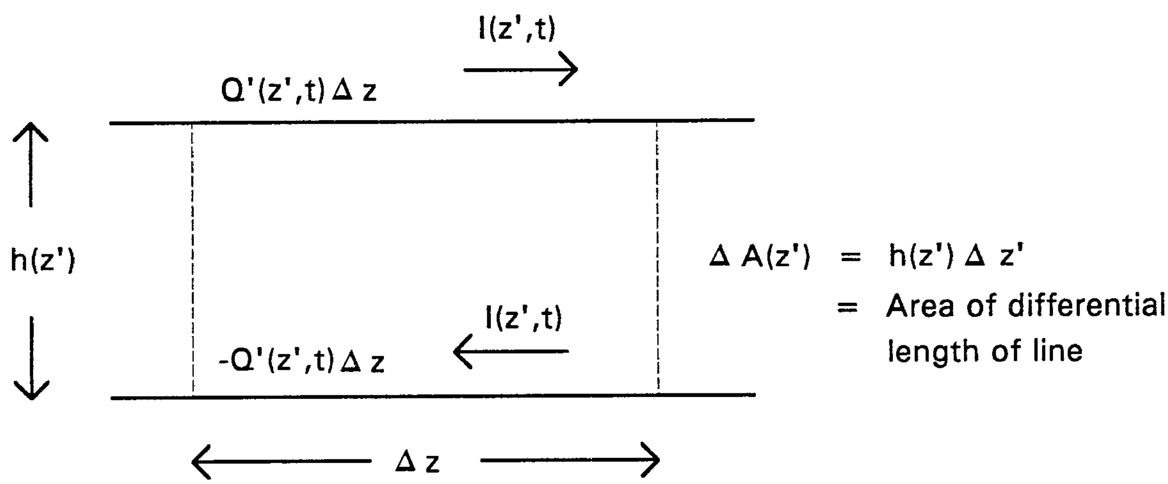

Figure 3. A differential length of transmission line showing the currents and charges that generate the differential electric and magnetic dipoles.

$$dm_x(z',t) = I(z',t)\ h(z')\ dz' \tag{2.6}$$

We note also that

$$h(z') = 2\,(z'+\ell)\ \tan(\beta) \tag{2.7}$$

We now define a constant for convenience

$$I_o = \frac{2V_o \tan(\beta)}{Z_c} = \frac{2V_o}{Z_o}\frac{\tan(\beta)}{f_g} \tag{2.8}$$

where $f_g = Z_c / Z_o$ is the geometrical impedance factor, and Z_o is the impedance of free space. Combining the previous equations we find

$$dm_x(z',t) = I_o\,(z'+\ell)\left[u\left(t-\frac{z'+\ell}{c}\right) - u\left(t+\frac{z'-\ell}{c}\right)\right] dz' \tag{2.9}$$

$$dp_y(z',t) = \frac{I_o}{c}(z'+\ell)\left[u\left(t-\frac{z'+\ell}{c}\right) + u\left(t+\frac{z'-\ell}{c}\right)\right] dz' \tag{2.10}$$

Thus, we have found the differential magnetic and electric dipoles formed by the transmission line.

In the frequency domain, the above equations have a simple form. Thus,

$$d\tilde{m}_x(z',s) = I_o\,(z'+\ell)\ \frac{1}{s}\left[e^{-s(z'/c+\ell/c)} - e^{s(z'/c-\ell/c)}\right] dz' \tag{2.11}$$

$$d\tilde{p}_y(z',s) = \frac{I_o}{c}\ (z'+\ell)\ \frac{1}{s}\left[e^{-s(z'/c+\ell/c)} + e^{s(z'/c-\ell/c)}\right] dz' \tag{2.12}$$

Later, we show that the total radiation on boresight from a single differential element is equal to the difference of its electric and magnetic dipoles. We identify the following result for future reference

$$d\tilde{m}_x(z',s) - c\,d\tilde{p}_y(z',s) = -2I_o\,(z'+\ell)\ \frac{1}{s}\ e^{s(z'/c-\ell/c)}\ dz' \tag{2.13}$$

Note that the contribution due to the forward-going wave cancels out, while that of the wave returning from the open circuit adds. This is analogous to the behavior of the Balanced Transmission-line Wave (BTW) sensor [9].

Let us now identify the radiation due to the differential electric and magnetic dipoles. We adapt here some formulas from [10,11] to the case of a short magnetic dipole located at $z = z'$ and an observation point on boresight at (0,0,z). Thus, we find that the radiated field from one of the differential magnetic dipoles is

$$d\tilde{E}_y^m(z,z',s) \;=\; \frac{e^{-s(z-z')/c}}{4\pi z}\;\frac{\mu_o}{c} s^2 \;\; d\tilde{m}_x(z',s) \qquad (2.14)$$

This result is valid for $z >> \ell$ and $|s|$ bounded. To be strictly rigorous, one would have to multiply the above equation by $[1 + O(z'/z)]$. Furthermore, the field on boresight due to a differential electric dipole is

$$d\tilde{E}_y^p(z,z',s) \;=\; -\frac{e^{-s(z-z')/c}}{4\pi z}\;\mu_o s^2 \;\; d\tilde{p}_y(z',s) \qquad (2.15)$$

with restrictions similar to those for the magnetic dipole. If we sum the last two equations, we get the total field on boresight at (0,0,z) due to both the electric and magnetic dipoles for a differential section of the transmission line. Thus,

$$d\tilde{E}_y^{TOT}(z,z',s) \;=\; \frac{e^{-s(z-z')/c}}{4\pi z}\;\frac{\mu_o}{c} s^2 \;\left[\, dm_x(z',s) \;-\; c\, dp_y(z',s)\,\right] \qquad (2.16)$$

Now we see why we generated the difference of electric and magnetic dipoles in (2.13). If we combine (2.13) and (2.16), and integrate over the length of the TEM horn (with respect to z'), we find

$$\tilde{E}_y^{TOT}(z,z',s) \;=\; -\frac{\mu_o I_o}{2\pi z c}\; e^{-s(z+\ell)/c}\; s \int_{-\ell}^{0} (z'+\ell)\, e^{(2s/c)z'}\, dz' \qquad (2.17)$$

After a little math, the integral is evaluated, and we find

$$\tilde{E}_y^{TOT}(z,s) \;=\; -\;\frac{\mu_o I_o \ell}{4\pi z}\; e^{-s(z+\ell)/c}\left[1 - \frac{c}{2\ell}\frac{1}{s}\left(1 - e^{-s2\ell/c}\right)\right] \qquad (2.18)$$

If we recall the definition of I_o in (2.8), we note that $\mu_o I_o \ell = V_o h/(c f_g)$. Substituting this into the above equation, and replacing z with r on boresight, we find

$$\tilde{E}_y^{TOT}(r,s) \;=\; -\;\frac{V_o}{r}\,\frac{h}{4\pi c f_g}\; e^{-s(z+\ell)/c}\left[1 - \frac{c}{2\ell}\frac{1}{s}\left(1 - e^{-s2\ell/c}\right)\right] \qquad (2.19)$$

This is the final answer we have been looking for in the frequency domain.

It is now necessary to convert the above result to the time domain. In order to do so, we specify a retarded time t_r such that

$$t_r \;=\; t \;-\; \frac{z+\ell}{c} \qquad (2.20)$$

The inverse transform is easily given by

$$E_y^{TOT}(r,t_r) = -\frac{V_o}{r}\frac{h}{4\pi c f_g}\left[\delta(t_r) + \frac{c}{2\ell}\left[-u(t_r) + u(t_r - 2\ell / c)\right]\right] \tag{2.21}$$

This is the simple model we have been looking for. It suggests that the step response of a TEM horn has a component due to a δ function, and another component due to a pulse function. A sketch of this function is shown in Figure 4.

We can check the validity of the above result (2.21) in two ways. First, we note that the total area under the curve is zero, a necessary condition for any radiated field. Second, we can check the magnitude of the δ-function against results given in [2]. In [2], it was shown that the field radiated from the aperture formed by two cylindrical conductors is given by

$$E(r,t) = \frac{V_o}{r}\frac{h}{4\pi c f_g}\delta_a(t) \tag{2.22}$$

In this equation, $\delta_a(t)$ is a specialized form of the Dirac delta function whose area is constant but whose pulse width decreases as $1/r$. At large distances from the antenna, it is essentially equivalent to the usual δ-function. The result of (2.22) assumes an aperture where the voltage between the two conductors is $V_o u(t)$. It also assumes a characteristic dimension of the aperture is $h_a = h_e/2$. Since the magnitude of the δ-functions in both (2.21) and (2.22) agree, we have some confidence that our result is correct.

Another interesting comparison one can make is to compare (2.21) to the response of an IRA (with a reflector). In [3] it is shown that a good approximation for the IRA radiation is

$$E_y^{TOT}(r,t_r) = \frac{V_o}{r}\frac{D}{4\pi c f_g}\left[\frac{c}{2F}\left[-u(t_r) + u(t_r - 2F/c)\right] + \delta(t_r - 2F/c)\right] \tag{2.23}$$

where D is the diameter of the reflector, f_g is the ratio of the feed impedance to the impedance of free space, and F is the focal length of the reflector. It might be expected that these antennas have the similar forms for their radiated fields, although when we add the correction for high frequencies the similarities will be reduced.

While the result in (2.21) is certainly simple, it is actually a bit too simple. The δ-function part of the above response is a derivative of the input voltage. This model is correct for frequencies with $h << \lambda / (2\pi)$ (where $\lambda = c/f$) due to the transmission-line approximation. The δ-function is incorrect except for the area that it represents. In fact, the very early-time part of the radiated waveform should be proportional to the driving function itself (due to a non-zero β) which in our case is a step function. In the section that follows, we make corrections for the early-time high-frequency behavior.

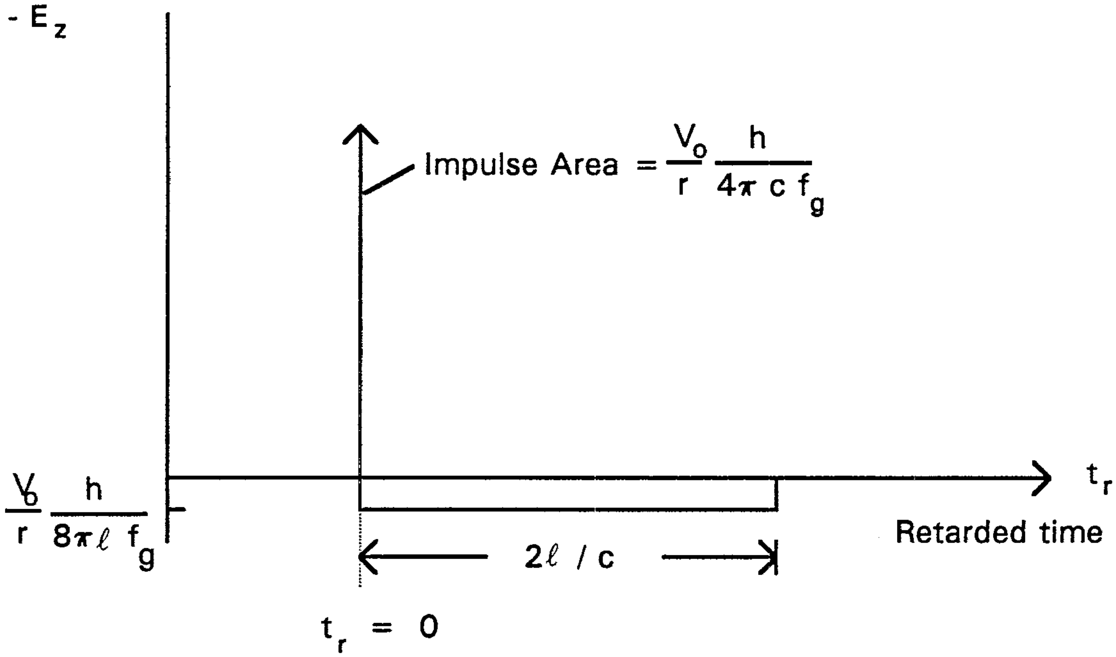

Figure 4. Step response of a narrow angle TEM horn using the simplified low-frequency model.

III. Correction for High Frequencies

There is a time span during which the field radiated from the TEM horn has the same shape as the input voltage waveform. Since we are using a step function to drive the antenna, at early times the our radiated waveform must be a step. Apparently, our model requires a modification.

In [2] it is shown that the area under the delta function in (2.21) is correct, but the peak magnitude needs to be that of a step function. An illustration of this is shown in Figure 5. For a certain clear time, an observer on boresight cannot see effects due to the end of the TEM horn. For small angles, this clear time is

$$t_c \cong \frac{h^2}{8\ell c} \;, \qquad \frac{h}{\ell} \to 0 \tag{3.1}$$

In order to be rigorous, the above equation should be multiplied by $\left[1+O(h/\ell)^2\right]$. Thus, if the TEM horn is driven with a step function, for a time t_C one should see a step function in the radiated field on boresight. The magnitude of the step is just proportional to the field in the center of the horn. The field in the center of the horn is approximately V_0/h. Thus, until the clear time, the field is

$$E(r,t) = \frac{V_o}{r}\,\frac{\ell}{h}\,u(t)\;E_y^{norm} \;, \qquad t<t_C \tag{3.2}$$

where E_y^{norm} is the field in the center of the aperture of the TEM horn, normalized to V_o/h. For many configurations (low impedances), $E_y^{norm} \cong 1$, so it can be ignored. This is demonstrated in greater detail in [12]. For the remainder of this paper, we will adopt that approximation as well.

We are now in a position to modify the ideal low frequency waveform. Although the δ function of (2.21) is incorrect, its area is correct. Thus, we have a waveform that, until the clear time, looks like a step function, and afterward drops off to zero in some unknown manner. However, the area under the total initial portion of the waveform is the same as the area under the δ-function of (2.21). This is followed by the pulse function as earlier shown in (2.21). A diagram of this is shown in Figure 6.

Since we know the peak magnitude of the radiated field from (3.2), and we also know the area under the "broadened" delta function (the same as the area under the delta function in (2.21)), we can define an equivalent pulse width. This pulse width is just

$$t_a \equiv \frac{\Psi_a}{c} \equiv \frac{\text{Pulse Area}}{\text{Max height}} = \frac{\dfrac{h}{4\pi c f_g}}{\dfrac{\ell}{h} E_y^{norm}} = \frac{h^2}{4\pi c \ell f_g E_y^{norm}} \tag{3.3}$$

The problem of the effective width of an impulse is described in more detail in [2], and our symbols are consistent with [2]. Note that t_a is much smaller than the overall duration of the signal, $2\ell/c$. This is especially true when β is small.

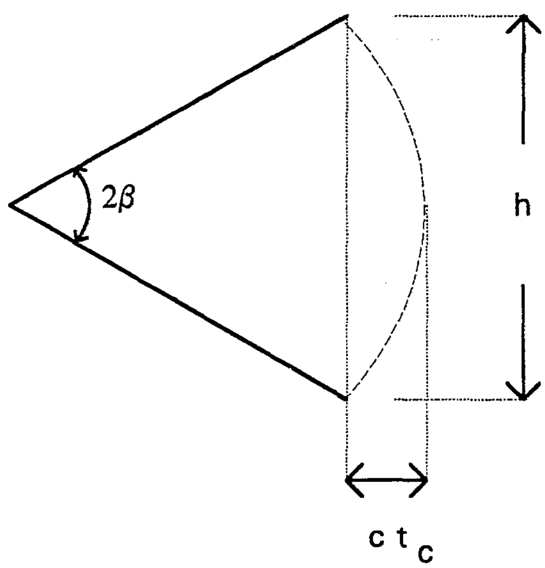

Figure 5. Clear Time associated with the initial phase of the TEM horn radiation.

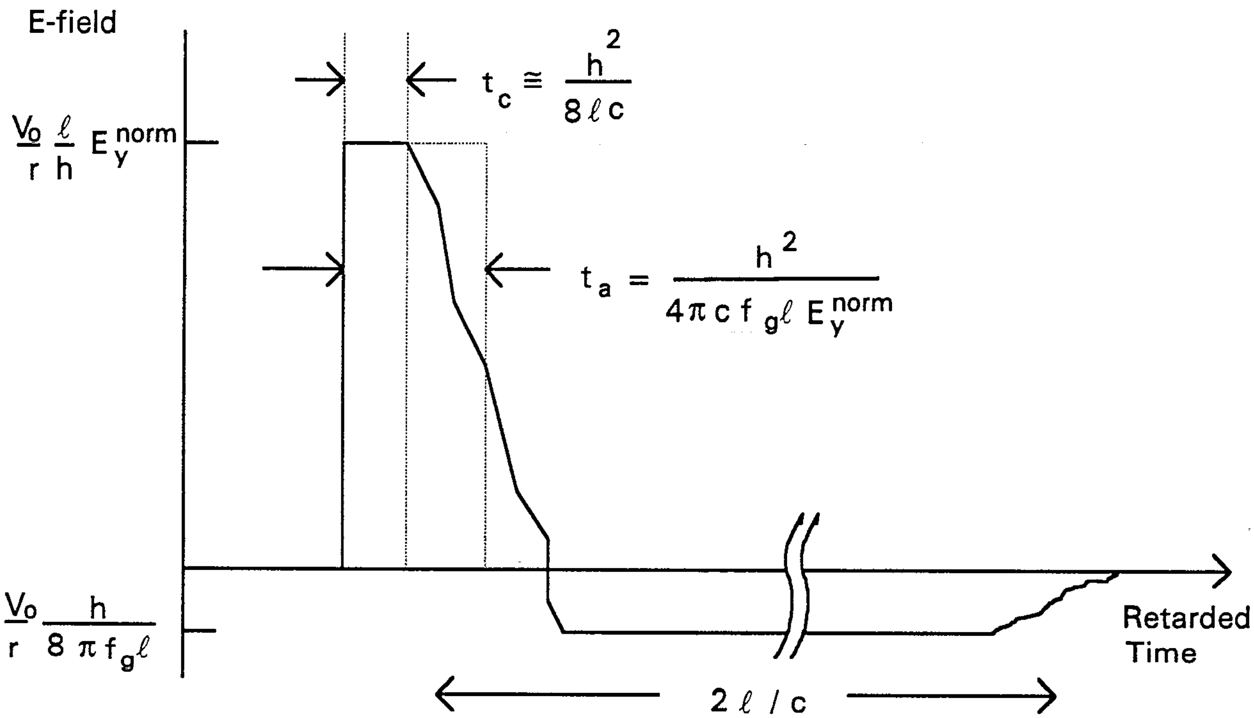

Figure 6. Broadening of the δ-function in the step response of the TEM horn.

IV. Frequency Response

Having identified an idealized response and a corrected response with a broadened δ-function, it is now necessary to show the frequency domain response. In addition, we will show that the step response in the frequency domain is flat in the middle, and rolls off at 20 dB/decade at break frequencies at both the low and high ends.

Taking the transform of (2.21), we find the ideal response on boresight is

$$\tilde{E}(r,s) = -\frac{V_o}{r}\frac{h}{4\pi c f_g}\left[1 - \frac{c}{2\ell}\left[\frac{1}{s} - \frac{e^{-s2\ell/c}}{s}\right]\right] \tag{4.1}$$

Next, we identify the low-frequency 3 dB point for the cutoff. By expanding the above equation for small ω, we find the low frequency response is just

$$\tilde{E}(r,s) = -\frac{V_o}{r}\frac{h}{4\pi c f_g}\frac{\ell}{c}s \quad , \qquad \omega << c/\ell \tag{4.2}$$

where $s = j\omega$. At mid frequencies in the simplified model, the response is just a constant,

$$\tilde{E}(r,s) = -\frac{V_o}{r}\frac{h}{4\pi c f_g} \tag{4.3}$$

The intersection occurs at f_1, where

$$f_1 = \frac{c}{2\pi\ell} \tag{4.4}$$

Thus, we see that in order to decrease the low-end 3 dB frequency, we can only increase the length of the TEM horn (at the expense of space).

Finally, we identify a high-end 3 dB frequency. We note that at early times, the field is the step response of (3.2). Therefore at very early times and very high frequencies, the response is

$$\tilde{E}(r,s) = -\frac{V_o}{r}\frac{\ell}{h}\frac{1}{s}E_y^{norm} \tag{4.5}$$

where we recall $E_y^{norm} \cong 1$, as discussed in the previous section. This generates a high frequency rolloff. The intersection of this equation with the "ideal" high frequency result of (4.3) occurs at

$$f_2 = \frac{2\ell c f_g E_y^{norm}}{h^2} \tag{4.6}$$

We may now sketch the asymptotes of the frequency domain step response of the TEM horn. These are shown in Figure 7. We show here both the "ideal" response, which does not account for the broadening of the δ-function, and the actual response, which does take this into account.

If we wish, we may correct our frequency domain transfer function for the broadening of the δ-function. Although this must be considered approximate, it does provides the correct high-frequency asymptotes. Thus, we simply multiply the ideal frequency domain result of (2.19) by an extra pole to account for the high frequency rolloff. This gives

$$\tilde{E}_y^{TOT}(r,s) = -\frac{V_o}{r}\frac{h}{4\pi c f_g}e^{-s(z+\ell)/c}\left[1-\frac{c}{2\ell}\frac{1}{s}\left(1-e^{-s2\ell/c}\right)\right]\frac{1}{1+s/\omega_2} \tag{4.7}$$

where $\omega_2 = 2\pi f_2$, and f_2 is defined in (4.6).

Based on these results, one can clearly see a problem with using a TEM horn as a radiator of transient signals. In order to keep f_2 high, it is necessary to use a small h. However, a small h has the additional unwanted effect of reducing the mid-frequency response, as shown in (4.1). One can help this problem a great deal by using a lens in the aperture, as described in [1]. In fact, by using the right lens, one should be able to get close to the ideal response of Figure 7. However, then one faces the problem of the additional weight of the lens.

Since there is a tradeoff in h, one might ask how to pick the optimal h for a given situation. Let us assume that we are required to radiate a signal with a frequency content that goes up to some important maximum frequency, f_{max}. Under these circumstances, the best performance is achieved when f_{max} is equal to the high-frequency break point f_2. Assuming a constant ℓ and f_g, the optimal height is simply determined from (4.6) with $f_2 = f_{max}$ as

$$h_{opt} = \sqrt{\frac{2\ell c f_g E_y^{norm}}{f_{max}}} \tag{4.8}$$

Thus, we see that in order to keep our signal within the mid-band portions of Figure 7 (i.e. operating as an ideal differentiator), there is a maximum limit on h.

Another way of saying this is as follows. If one needs twice the output (while keeping f_g constant), one may double the height, h. But if one does so, then it is necessary to also quadruple the length ℓ of the TEM horn, in order to maintain the same high frequency cutoff f_2. Thus, it is possible for TEM horn antennas to get very long, very fast. Note that at least one competitor to the TEM horn, the reflector IRA, does not suffer from this problem, since it has no high-frequency rolloff problem.

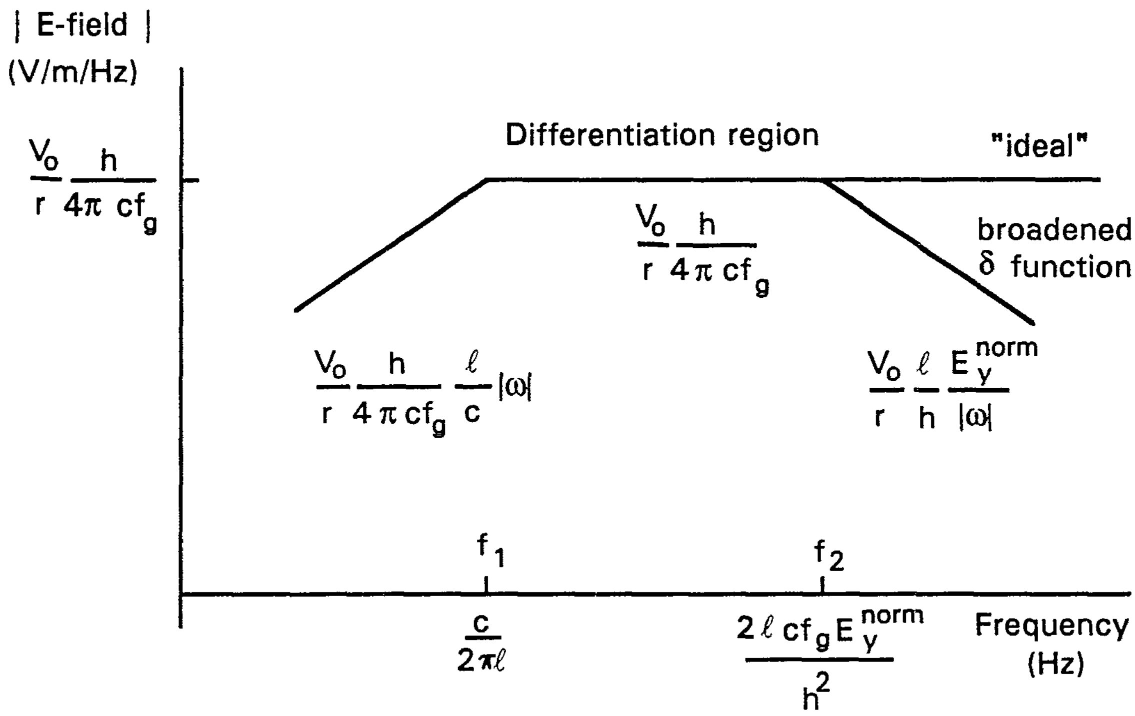

Figure 7. Frequency response asymptotes of the TEM horn with step excitation.

V. Low-Frequency Response Off Boresight

It is of some interest to identify the low-frequency response of a TEM horn for all directions, instead of just on boresight. In doing so, we will show that at low frequencies, the response is just that of a short electric dipole. This can be used to show that a TEM horn does not have any directivity at low frequencies, unlike some competing antennas such as an IRA.

We begin with the expressions we found earlier for the frequency domain electric and magnetic dipoles (2.11 - 2.12). For convenience, we repeat them here

$$d\tilde{m}(z',s) = I_o\,(z'+\ell)\frac{1}{s}\left[\,e^{-s(z'/c+\ell/c)} - e^{-s(z'/c-\ell/c)}\,\right]dz' \tag{5.1}$$

$$d\tilde{p}(z',s) = \frac{I_o}{c}(z'+\ell)\frac{1}{s}\left[\,e^{-s(z'/c+\ell/c)} + e^{-s(z'/c-\ell/c)}\,\right]dz' \tag{5.2}$$

In the limit of low frequencies, we may expand the exponentials. Thus, we find

$$\begin{aligned} d\tilde{m}_x(z',s) &= -\frac{2\,I_o}{c}\,\ell\,(z'+\ell)\;dz' \\ d\tilde{p}_y(z',s) &= \frac{2I_o}{c}\frac{1}{s}\,(z'+\ell)\,dz' \end{aligned} \tag{5.3}$$

Clearly, at low frequencies, the magnetic dipole is less significant than the electric dipole, so we may ignore it. The total electric dipole moment may be found by integrating over dz', and we find

$$\tilde{p}_y(s) = \frac{I_o\ell^2}{c}\,\frac{1}{s} \tag{5.4}$$

or substituting from (2.8) for I_o,

$$\tilde{p}_y(s) = \frac{V_o\varepsilon_o h\ell}{f_g}\;\frac{1}{s} \tag{5.5}$$

Finally, in the time domain, we find

$$p_y(t) = \frac{V_o\varepsilon_o h\ell}{f_g}\;u(t) \tag{5.6}$$

Thus, our final result is that a TEM horn looks like a short electric dipole at late times, with a known magnitude. One could easily use the above two equations in the standard formulas for radiation from electrically small dipoles [10], but the result is already well known. One gets a doughnut-shaped cosine pattern, with nulls above and below the TEM horn (±y-direction). The output is proportional to the second derivative of the input waveform.

There may be times when one wants an antenna for radiating a transient that has some directivity at low frequencies. This may be useful in reducing interference with one's own equipment. This characteristic is available with antennas of the IRA class as described in

[1-3]. We have just demonstrated that a TEM horn does not provide such low-frequency directivity.

VI. Modifications for Better High-Frequency Performance

One can think of two ways that the response of the TEM horn could be improved. We would like to suggest these now.

The most obvious improvement one could add would be to add a lens. The resulting antenna would then have characteristics more similar to the IRA of [1-3] than to the TEM horn. In fact, this idea was suggested in [1]. The characteristics of the resulting antenna would approach the "ideal" model of the TEM horn in Figure 7. A diagram of a possible configuration is shown in Figure 8. If a perfect lens were available, then the "ideal" response would be accurate. Since perfect lenses are difficult to build (since they require a continuously varying μ and ε [13]), reflections will be present at the aperture. This is primarily due to reflections at the lens boundaries, say for a dielectric lens. These reflections result in a radiated field somewhat below the horizontal line of the ideal response of Figure 7 at high frequencies.

A second improvement involves the loss of voltage at the apex of the TEM horn due to the presence of the matched load. One way around this might be to bypass the matched load with a capacitor. This would in theory allow all the early-time voltage through, but still provide an approximately matched load in order to eliminate reflections from the aperture. A diagram of this is shown in Figure 9. Times of order $Z_c C$ ought to be large enough to get the early part of the pulse through with negligible attenuation, but small enough compared to ℓ/c to still terminate the resonances of an otherwise lossless transmission line. The result of this is that in order to launch a wave of magnitude V_o onto the feed, it would now only be necessary to use a voltage source of magnitude V_o, rather than the $2V_o$ used in Figure 2. This brings the response of the TEM horn more in line with that of the reflector IRA, except for the low-frequency pattern. The analysis of the resulting configuration (with capacitive bypass) is a bit more complicated than the present case, and is probably best left for a later paper. Nevertheless, it is worthwhile to point out that such a possibility exists.

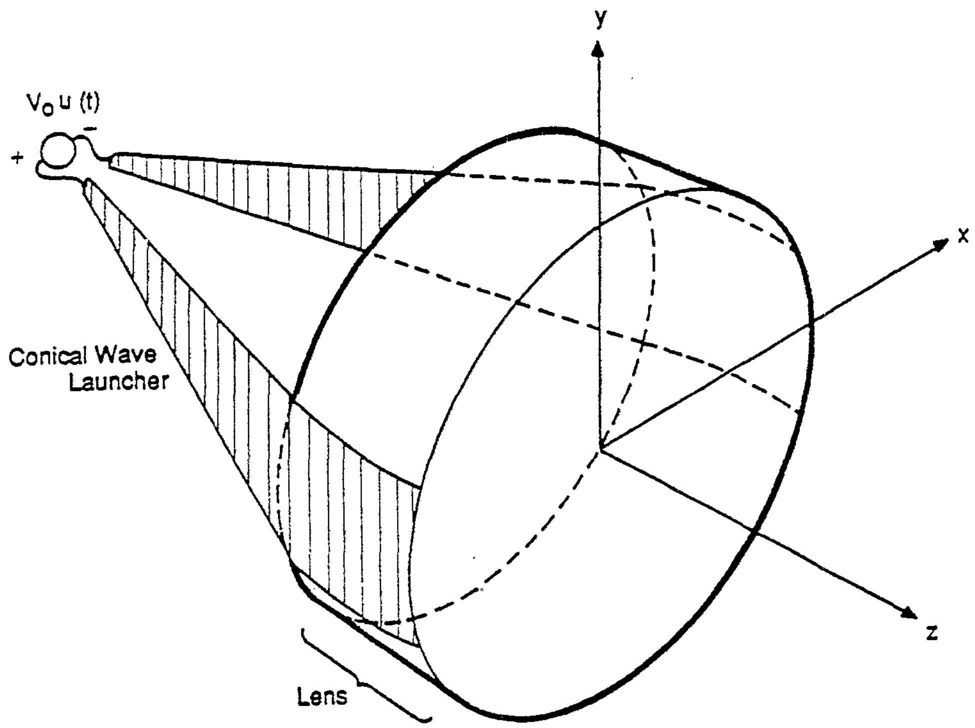

Figure 8. Lens IRA: Addition of a lens to a TEM horn for improving high-frequency response, from [1].

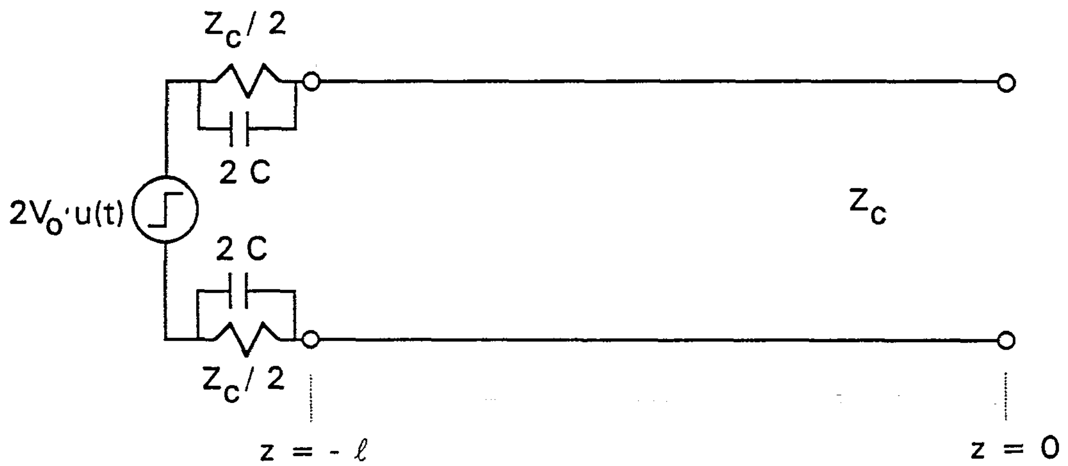

Figure 9. Shunt capacitor for TEM horn for reducing loss at the source.

VII. Conclusions and Recommendations

A simple model has been generated that provides the approximate behavior of a narrow-angle TEM horn. This model should be useful to system designers who are considering using TEM horns for radiating a transient pulse. It identifies the magnitude of the mid-band response, and 3 dB frequencies for upper and lower frequency rolloffs. In addition, recommendations are made for improving the response of the TEM horn.

Since the tools are now in place, it is straightforward to carry out a direct comparison between an IRA (reflector or lens) and a TEM horn (no lens). Such a comparison will appear in another paper soon.

A TEM horn will probably not be competitive if a loss of half the signal is a requirement (as was dictated by the matching circuit in this paper). Therefore, further work will be necessary to further develop the capacitive shunt idea that was mentioned briefly in Section VI of this paper.

VIII. References

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