Sensor and Simulation Notes

Note 377

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Low-Frequency-Compensated TEM Horn

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Abstract

The TEM horn is an antenna which can be used for radiating (or receiving) fast electromagnetic transients. However, it presents an open circuit to the transient source (pulser) which can sometimes be a problem. This is relieved by adding a resistive termination connecting the two horn conductors. The placement of the path(s) for the current in this termination is important in that it significantly affects the low-frequency antenna performance. By routing these currents behind the horn, the associated magnetic dipole moment can be oriented to combine with the electric dipole moment to orient the low-frequency radiation in the forward direction, the same direction as the high-frequency radiation.

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1. Introduction

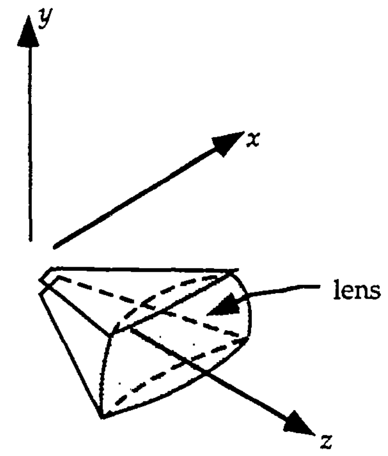
One type of antenna used for radiating an electromagnetic transient is what is commonly referred to as a TEM horn [6, 7, 9, 13], as illustrated in fig. 1.1. This may also include a lens at the horn aperture to convert the spherical TEM wave (in transmission) incident on the lens into a plane wave at the antenna aperture. With a fast-rising step-like incident wave in transmission this radiates an approximate impulse as an important part of the far-field waveform. Such is a lens impulse radiating antenna (lens IRA or LIRA). This lens gives a significant improvement in the high-frequency boresight radiation. However, in this paper, the concentration is on the low-frequency properties.

Such an antenna can taken various forms as illustrated in fig. 1.1. Beginning with a general case of two conical plates in fig. 1.1A, one can go to the common case of two symmetry planes as in fig. 1.1B. For future reference, this horn is taken to be of length ℓ from the apex (near which is the source connection) to the aperture plane where the plate separation is $2b$ and each plate width is $2a$. With the symmetry planes taken as the $x = 0$ plane (R_x symmetry group) and the $y = 0$ plane (R_y symmetry group) we have the symmetry group $C_{2a} = R_x \otimes R_y$ which has a two-fold rotation axis (the z axis) as well as the two symmetry planes. The configuration in fig. 1.1C has the $y = 0$ symmetry plane replaced by a ground plane (ideally perfectly conducting), and is analyzed in the same way as the previous case with appropriate factors of two included. Note in fig. 1.1B the source (pulse generator) is assumed to have a differential output to maintain the symmetry, while in fig. 1.1C the pulser should have a single-ended output and the various associated hardware can be "hidden" behind the ground plane so as not to interfere with the antenna fields.

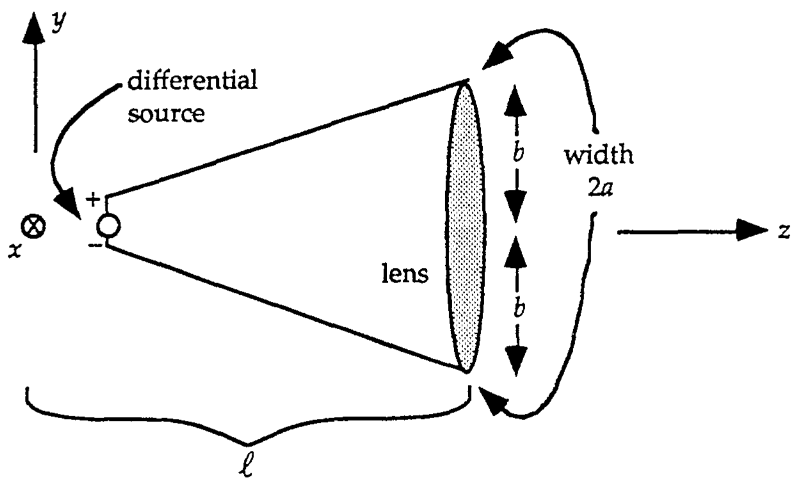
Continuing the discussion of symmetry, fig. 1.2 shows how this extends to the sources, here represented by coaxial cables connected to the horn conductors. Consider first the unbalanced connection as in fig. 1.2A where there are three important antenna currents, two on the horn conductors and one on the coax (or more generally pulser) exterior. With the Kirchhoff current condition at the junction

$$\sum_{n=1}^{N} I_n = 0 \tag{1.1}$$

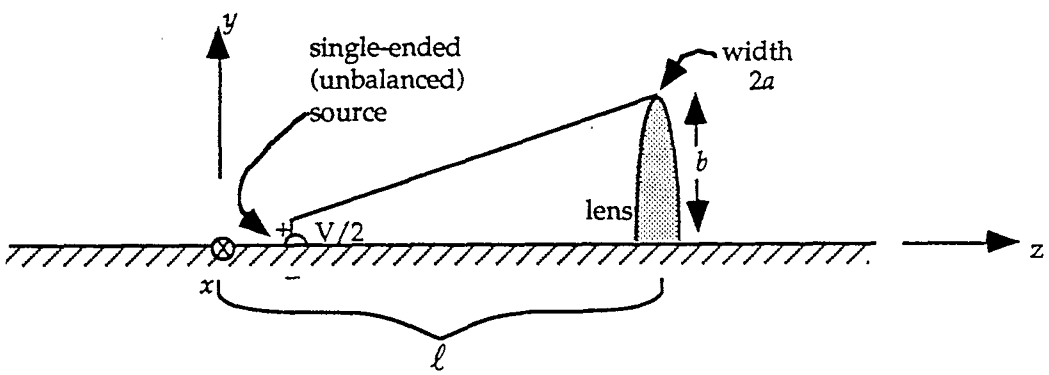
there are two independent currents in the set of three. This corresponds to two TEM-like antenna modes, a differential mode ("between" the two horn conductors) and a common mode ("between" the horn conductors and the coax shield [10, 11]). This situation is remedied as in fig. 1.2B by the addition of a common-mode choke (inductance) which constrains $I_3 \simeq 0$ and hence $I_2 \simeq -I_1$. This is a balun which leaves only the differential TEM antenna mode. Another approach to give only a differential mode is a differential source as in fig. 1.2C, here indicated by two coaxes operated in opposite polarity. This is related by symmetry to the single-ended pulser made part of the ground plane in fig. 1.2D. This last



A. Two flat-plate cones (in general asymmetric).

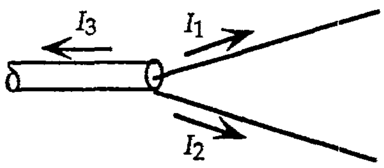


B. Two flat-plate cones with two symmetry planes (C_{2a} symmetry).

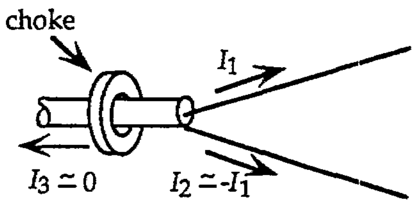


C. Flat-plate cone with ground plane.

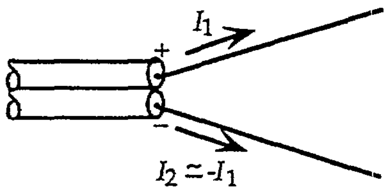
Fig. 1.1. TEM Horn Antenna Which May Include a Lens.



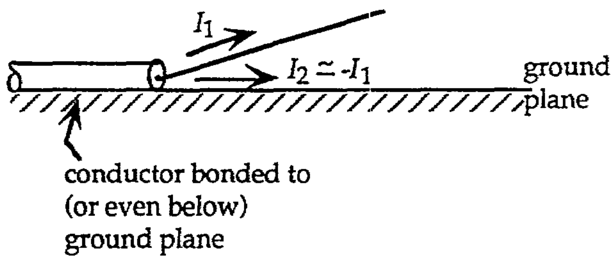
A. Unbalanced connection (two TEM-like modes on exterior).



B. Choke (balun) to suppress external pulser currents.



C. Balanced connection.



D. Symmetry maintained by ground plane.

Fig. 1.2. Feeding TEM Horn Antenna.

example can also be used to model the case of an asymmetrical TEM horn where the ground plane is truncated giving a large "lower" conductor that behaves as a ground plane, at least for times before the scattering from the various truncations reaches the observer.

So the TEM horn ideally has only two radiating conductors supporting a single TEM mode. Note that the use of many independent conductors (wires or strips) to form the conical plates is to be avoided since these support *additional* and *undesirable* TEM modes. These can act like slots which are highly resonant (when an integer number of half or quarter wavelengths in length, depending on terminations). The conical plates can be made of mesh provided the resulting loops have perimeters which are all small compared to a wavelength at the highest frequencies of interest in the pulse. There are also higher order (non-TEM) modes present [3, 4], but these are ideally introduced only after reflection of the pulse from the end (truncation) of the horn. If desired, they can be partially suppressed, but this ought not to be done by techniques which interfere with the desired TEM mode or which produced additional unwanted TEM modes.

Due to the truncation of the cone, there is a large low-frequency reflection (positive due to open circuit) back to the pulser. This also makes the antenna look like an electric dipole at low frequencies [9]. In the present paper, the proper termination of such an antenna, both to give a resistive low-frequency antenna impedance and to maximize the forward radiation (+z direction) at low frequencies, is discussed.

2. Resistive Termination and Matched Electric and Magnetic Dipole Moments for Low Frequencies

One of the potential problems of TEM horn is its capacitive impedance at low frequencies, becoming an open circuit as the frequency tends to zero. When connected to a pulser, such an impedance may present problems, depending on the specifics of the pulser design. If the pulser is connected to the antenna via a transmission line (e.g., a coax) of characteristic impedance Z_1, then one may wish to terminate the pulse at the antenna by a resistance of value R with

$$R = Z_1 \tag{2.1}$$

so that there is no reflection at low frequencies back into the transmission line and toward the pulser. Antennas do not radiate (to the far field) at low frequencies ($\lambda >>$ antenna dimensions) [65]. There can be a large stored energy, however, in the near field. A terminating resistor can be used to dissipate this energy and prepare the pulser/antenna system for the next pulse.

Where should one place this terminating resistance? Figure 2.1 indicates three possibilities. Note that while a differential pulser and antenna are indicated, the use of a ground plane in place of the $y = 0$ symmetry plane is also allowed as discussed in the previous section. In fig. 2.1A, the termination is near the horn apex where the source connects to the antenna. At low frequencies the current on the horn conductors is then negligible (due to open circuit) but the charge ($\pm Q$) on these conductors is significant and gives the dominant electric dipole moment

$$\begin{aligned}
\vec{p} = p\,\vec{1}_y = Q\,\vec{h}_{eq} \quad &\equiv \text{ low-frequency electric dipole moment} \\
Q = C_a V \quad &\equiv \text{ low-frequency charge on antenna} \\
C_a \quad &\equiv \text{ antenna capacitance} \\
\vec{h}_{eq} = h_{eq}\,\vec{1}_y \quad &\equiv \text{ antenna equivalent height}
\end{aligned} \tag{2.2}$$

For a small-angle tem horn we have [9]

$$\begin{aligned}
&h_{eq} \simeq b \quad , \quad C_a \simeq \frac{\varepsilon_o \ell}{f_g} \\
&p = C_a\, h_{eq} \simeq \frac{\varepsilon_o \ell\, b}{f_g} V \\
&f_g \equiv \frac{Z_c}{Z_o} \equiv \quad \equiv \text{ antenna equivalent height} \\
&Z_c \equiv \text{ impedance of TEM mode on horn} \\
&Z_o = \left[\frac{\mu_o}{\varepsilon_o}\right]^{\frac{1}{2}} \equiv \text{ wave impedance of free space}
\end{aligned} \tag{2.3}$$

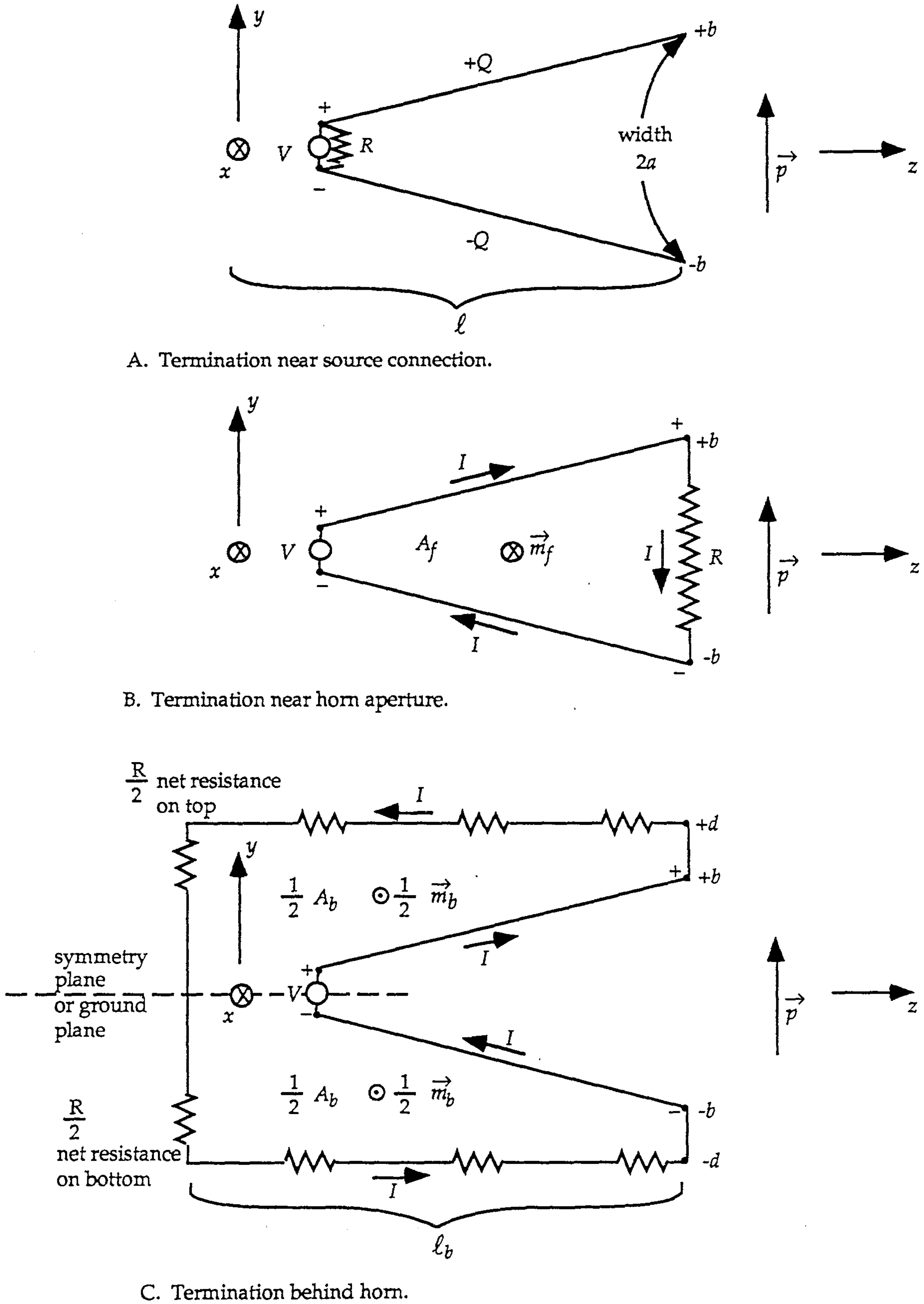


Fig. 2.1 Termination Locations for TEM Horn

(Note that the addition of a lens at the horn aperture increases the capacitance a little.) This dipole moment gives a low-frequency radiated field which has nulls on the y axis in the $\pm y$ directions, and which radiates equally well in the forward (+z) and backward (-z) directions. At high frequencies the termination R at the horn apex appears in parallel with Z_c; if this is matched to Z_1 to avoid high-frequency reflections back into the source there will not be a low frequency match (as in (2.1)). Besides it would be better that the high-frequency portions of the wave from the pulser radiate without being partially absorbed by the termination. So the horn apex may not be a good place for the termination resistance.

One may consider placing the termination resistance near the horn aperture as in fig. 2.1B. This has the advantage of letting the high frequencies go past the resistor strings (say two for symmetry near the plate edges). This can be viewed from an optical viewpoint (the small area intercepted on the aperture plane by the resistors) or as due to the inductance associated with the resistor paths. One may even push these paths outward ($\pm x$ directions) to move them farther away from the $x = 0$ plane (but still connecting to the plate edges). This type of termination is similar to that used in some guided-wave EMP simulators [12]. There is, however, a disadvantage associated with the orientation of the resulting low-frequency magnetic dipole moment $\vec{m}_f$ ("f" for front termination). Note that the termination gives a loop of area

$$A_f = \ell b \tag{2.4}$$

which gives a magnetic dipole moment of

$$\begin{aligned} \vec{m}_f &= m_f \vec{1}_x \quad , \ m_f = I A_f \\ I &= \frac{V}{R} \end{aligned} \tag{2.5}$$

Comparing this to the electric dipole moment we have

$$\begin{aligned} \frac{m_f}{p} &= \frac{A_f I}{C_a h_{eq} V} \simeq \frac{\ell b f_g}{\epsilon_0 \ell b} \frac{1}{R} \\ &= \frac{Z_c}{R} c \ = \ c \ \text{ for } R = Z_c \\ c &= [\mu_0 \varepsilon_0]^{-\frac{1}{2}} \equiv \text{speed of light} \end{aligned} \tag{2.6}$$

This is precisely the condition for matched electric and magnetic dipole moments to radiate in the $\vec{p} \times \vec{m}_f$ direction, i.e., the direction $-\vec{1}_z$ [2, 5]. This, however, is undesirable in that this is opposite to the direction of high-frequency radiation.

To cure this problem we need to reverse the direction of the magnetic dipole moment as indicated in f.g .2.1C. Here the termination resistance is distributed along one or more parallel paths behind the horn. This gives a low-frequency magnetic dipole moment $\vec{m}_b$ ("b" for back termination) given by

$$\vec{m}_b = m_b \vec{1}_x \ , \ m_b = -IA_b \qquad (2.7)$$
$$A_b \simeq \ell_b \ d - \ell b$$

where $2d$ is the extent in the $\pm y$ direction with $d \geq b$, and $2 \ \ell_b$ is the extent in the $\pm z$ direction with $\ell_b \geq \ell$. Note the closing of the current path *behind* the horn apex. In this case, as well as the previous, the $y = 0$ symmetry plane can be replaced by a ground plane, in which case, the resistive load (now $R/2$) is connected to the ground plane behind the horn apex.

Note that the $\vec{p} \times \vec{m}_b$ direction for the low-frequency radiation is now in the direction $+ \vec{1}_z$. Comparing these dipole moments we have

$$-\frac{m_b}{p} = \frac{A_b \ I}{C_a \ h_{eq} \ V} = \frac{A_b}{C_a \ h_{eq}} R \qquad (2.8)$$

As in (2.6), one would like this ratio to be approximately c. This would give a null in the low-frequency back radiation while maximizing the low-frequency forward radiation (a cardiod pattern [8]).

To achieve this balance we have various parameters under our control. For the magnetic dipole we have A_b controlled by ℓ_b and d (with ℓ and b presumably chosen on other criteria). The electric dipole moment is, however, not as simple as that given in (2.3) due to the charge distributed on the termination. Suppose, first, that the termination resistance is concentrated on the left end in fig. 2.1C, leaving the portions of the termination path on $y = \pm d$ as conductors. This increases both h_{eq} and C_a above the case in (2.3). As $b \to 0$ with $\ell_b >> d$, this case has the termination conductors as an approximate transmission line of characteristic impedance Z_b. If this is terminated at the left end with $R = Z_b$ then the matched $\vec{p} \times \vec{m}_b$ condition is achieved. Note that this is not necessarily merely a two-wire transmission line as two or more pairs of conductors (and associated parallel termination resistors at the left) can also be used for this purpose. If the (now with small b) TEM horn has $Z_c = Z_b$, then the horn is also terminated at low frequencies.

As the above discussion indicates, the electric dipole moment can be increased by the termination conductors. Suppose, second, that the termination resistors are at the right end of the termination where they connect to the horn ($z = \ell$). With the remainder of the path for the termination currents as conductors, then at low frequencies these have zero potential (with respect to the $y = 0$ symmetry plane). The potential V on the horn induces negative charges on the top termination conductors ($y = + d$) and positive charges on the bottom ones, the net result being that the termination conductors are a low-frequency shield for the TEM horn and reduce the electric dipole moment *below* that in (2.3). The magnetic dipole moment remains as in (2.7) which still sllows for adjustment of A_h by the conductor positions to achieve the desired match.

The termination resistance may also be distributed along the termination path in a variety of ways. This gives a third case intermediate between the previous two. The distributed resistance may also help to dampen resonances on the horn structure. With R chosen to match Z_c and/or Z_1 (which can also be interpreted as a source impedance), then choice of d, ℓ_b, the number and spacing of the parallel termination paths, and the form of the distribution of R on these paths, can be used to obtain the desired ratio of c in (2.8) for matching the dipole moments. Detailed calculations and/or measurements are required for this purpose.

3. Concluding Remarks

This paper has explored some improvements to the design of TEM-horn antennas for radiating pulses. A low-frequency terminating resistance can reduce reflections back to the source (pulser and connecting transmission line). By careful placement of the paths for the termination currents and distribution of the termination resistance along these paths one can make the antenna have balanced electric and magnetic dipole moments which concentrate the low frequency radiation in the forward direction.

Other features of such an antenna can include a lens at the horn aperture to make a lens IRA, and a ground plane to suppress the creation of an undesirable common mode at the connection to the horn (the horn apex), effectively making the pulser exterior conductors part of the ground plane. Figure 3.1 gives an example of such an antenna with the various features discussed here. As an added feature, one need not have the ground plane flat as one goes behind the horn apex. How far one should extend the ground plane before truncation or other (downward) bends in the conductor is a complex question. One can truncate the ground plane at the horn aperture if desired, with recognition of the fact that the antenna aperture radiates down as well as up (i.e., the image of the aperture below the ground plane is missing in that case).

Many of the considerations here are only approximate. More detailed calculations and/or measurements can more accurately establish the details, especially for matching the low-frequency dipole moments and for establishing the intermediate frequency response for which the wavelength is of the order of the antenna dimensions. The present paper has considered only the basic features of the antenna design. While the discussion here has been in terms of the performance as a radiator, the considerations also apply to reception by reciprocity.

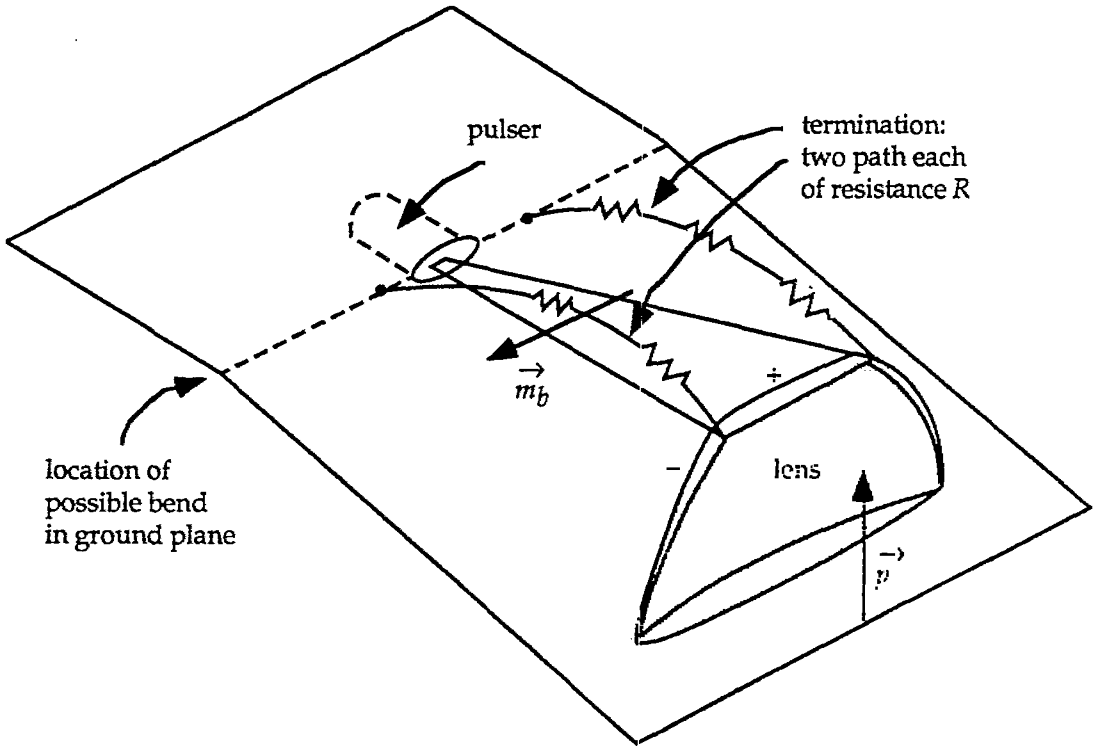


Fig. 3.1 TEM Horn and Lens (Lens IRA) With One Flat-Plate Cone, Ground Plane, and Termination to Location Behind Horn.

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