Sensor and Simulation Notes

Note 107

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The Dipole Pulser As a Tool For Studying the Transient Response of EMP Sensors

by

David E. Merewether
Sandia Laboratories
Albuquerque, New Mexico

Abstract

A Dipole pulser is described that can be used to check out the receiving characteristics of an EMP sensor system set out to measure the transient field produced by a nuclear burst or by an EMP simulator.

II. Characteristics of a Dipole Pulser

The dipole pulser (Fig. 1) or its equivalent monopole version is easily constructed from a conduit, a battery, a resistor, and a switch. Its operating characteristics can be inferred from a simplified antenna model to be developed here.

Consider the charged transmission line shown in Figure 2. Closing the switch on the charged transmission line causes the current to flow through the switch. Note that the level is $\frac{V_o}{Z_o}$ and that the pulse duration is $\frac{2h}{V}$, where V is the volocity of propagation of the wave.

Figure 3 indicates the changes which may be expected when the spacing between the line is increased. Increasing the transmission-line spacing results in radiation from the line, and the amplitude of the disturbance decreases with time. Also note that since this radiation is strongest at the higher frequencies, it is the sharp corners on the pulse train which are most rapidly attenuated.

Since the waveform shown in Figure 3c resembles that shown in Figure 3a, analysis of the fields radiated by an antenna with assumed transmission line currents (Fig. 3a) yields useful results. It is shown in the Appendix that this approximation is equivalent to the normally assumed sinusoidal distribution of antenna current. Using this analysis, the field near a dipole in free space was computed when charged and shorted, yielding the waveforms shown in Figures 4a and 5a. Figures 4b and 5b show data measured in an identical situation using a monopole antenna. These data show the accuracy to which the calculation is valid.

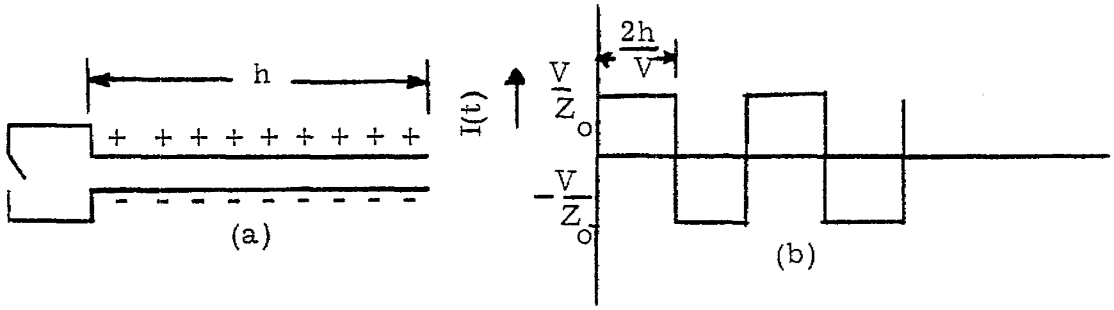

Figure 2. Short Circuit Current of Charged Transmission Line

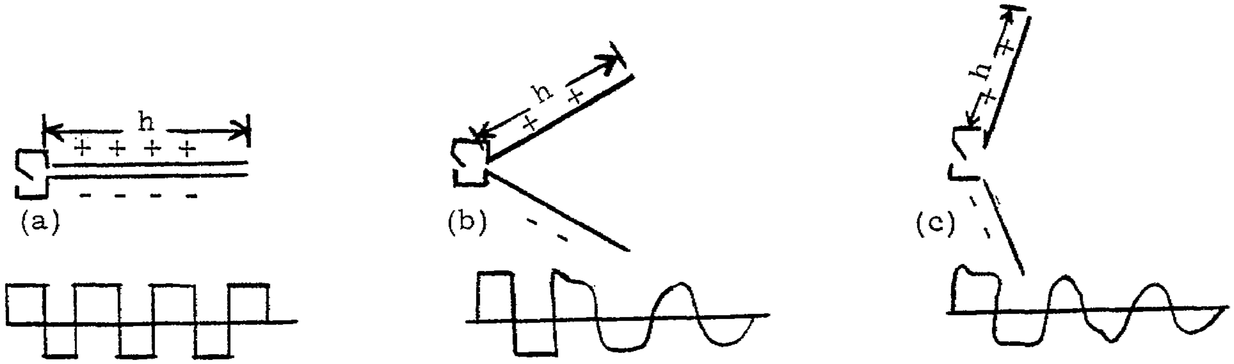

Figure 3. Effect of Spreading a Transmission Line on its Short Circuit Current

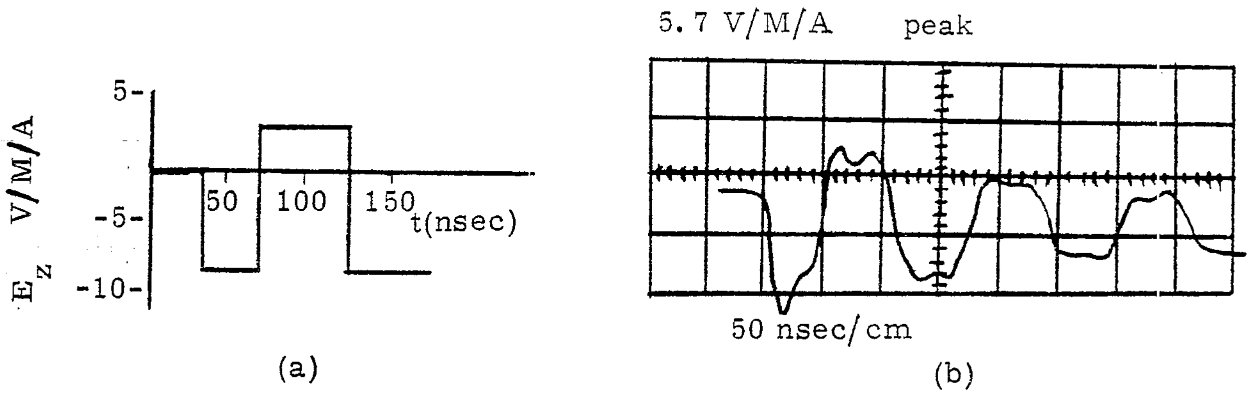

Figure 4. Calculated and measured fields from vertical monopole

R_o = 30' h = 28'

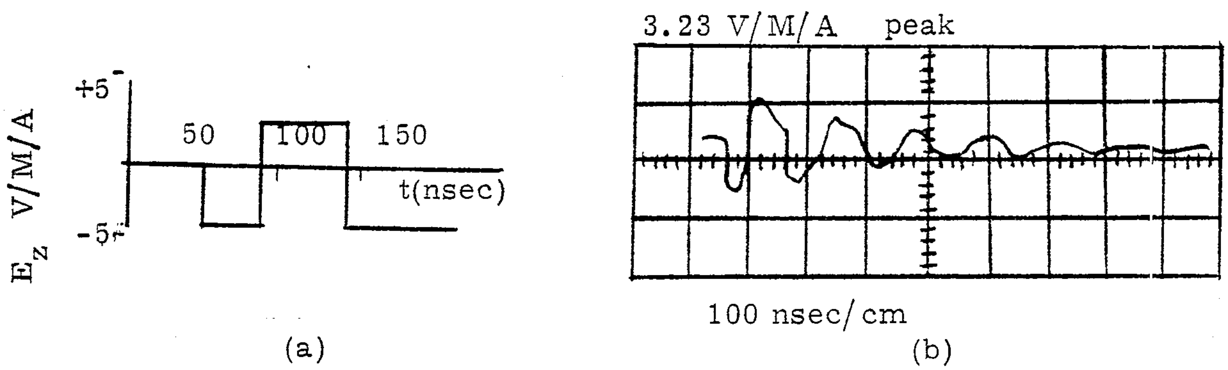

Figure 5. Calculated and measured fields from vertical monopole

R_o = 50' h = 28'

III. The Terminated Dipole Pulser

A transmission line can be terminated in its characteristic impedance, eliminating the reflection from the switched end. A mono-polarity current pulse results. Although an antenna does not truly have a characteristic impedance, the same principle can be applied approximately, and a single current pulse results as shown in Figure 6.

Note that the peak current and peak field are all controlled by the characteristic impedance Z_o.

For an antenna the approximate characteristic impedance is:*

$$Z_o = 60\,(\Omega - 2)$$

$$\Omega = 2\,\ln \frac{2h}{a}$$

$$a = \text{wire radius}$$

This formula produces the correct result for wires of small diameter, but when large diameter wire is employed the formula is invalid. Figure 7 shows the results of an experimental study.

In this study, several antennas were formed from available pipe and conduit. Charging and shorting these antennas (Fig. 1) produced the normalized peak current recorded on Figure 7. For large cylinders some variation in the data was obtained that depended upon the inductance of the wiring at the antenna feedpoint. The two curves shown bracket the observed data.

For a 2-inch diameter pipe, 1.8 ma/volt is the expected peak current, or Z_o = 550 ohms compared to 970 ohms for the No. 16 wire.

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*Hans J. Schmitt, "Transients in Cylindrical Antennae," IEE Proceedings, April 1960

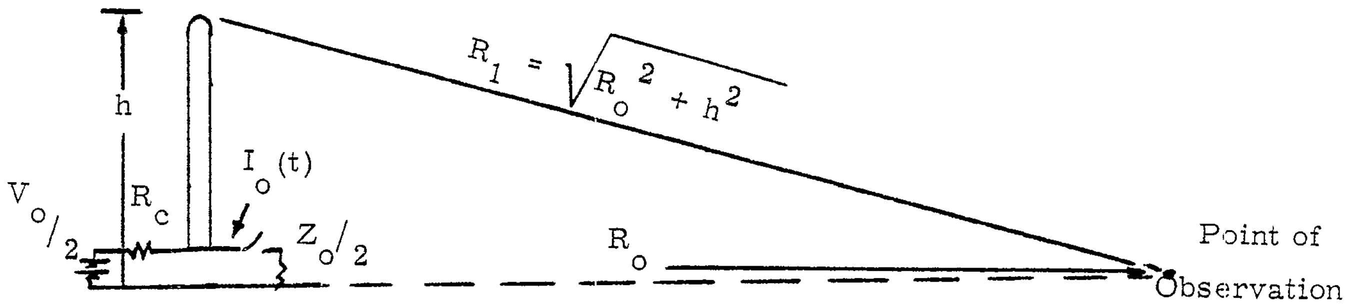


Figure 6a - Terminated Monopole Pulser

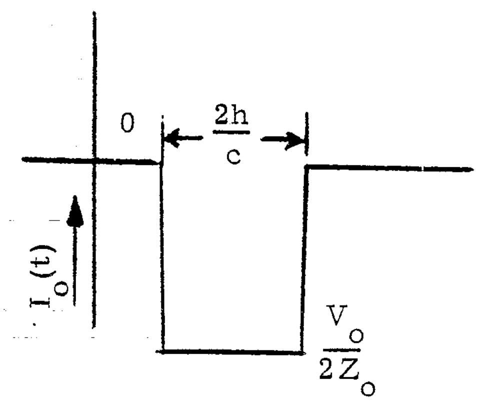


Figure 6b - Predicted Antenna Current at Switch

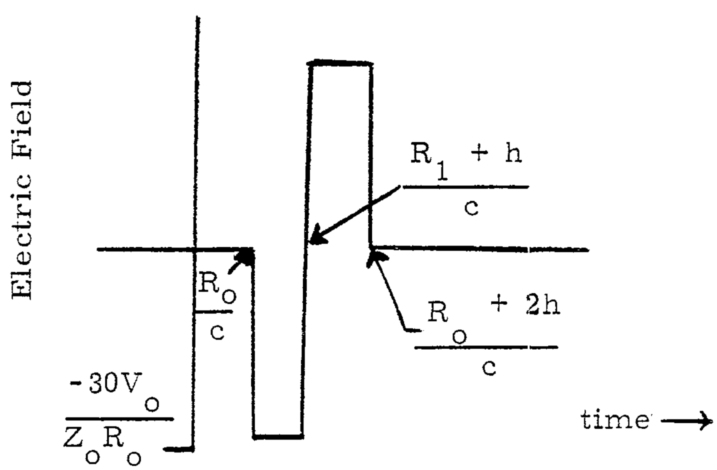


Figure 6c - Predicted Radiated Field for Ro>>h

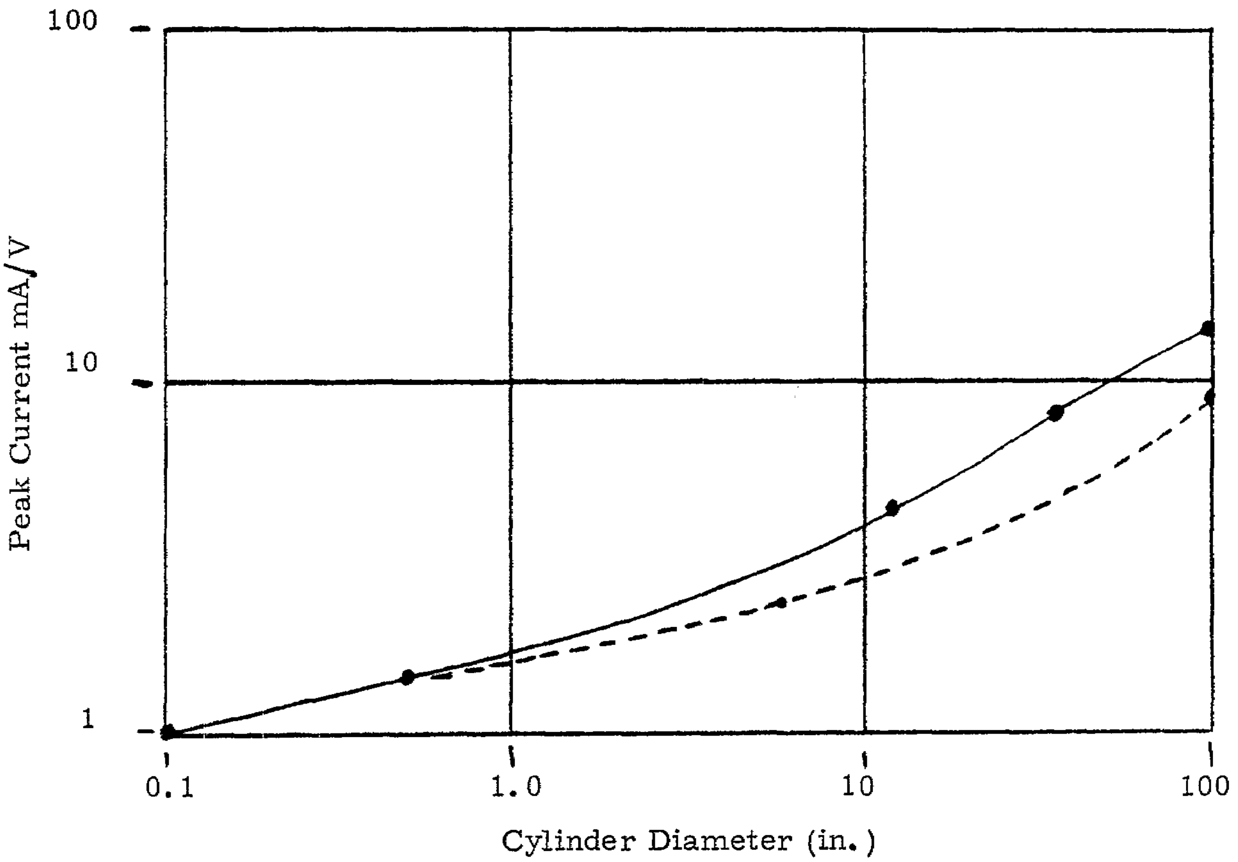


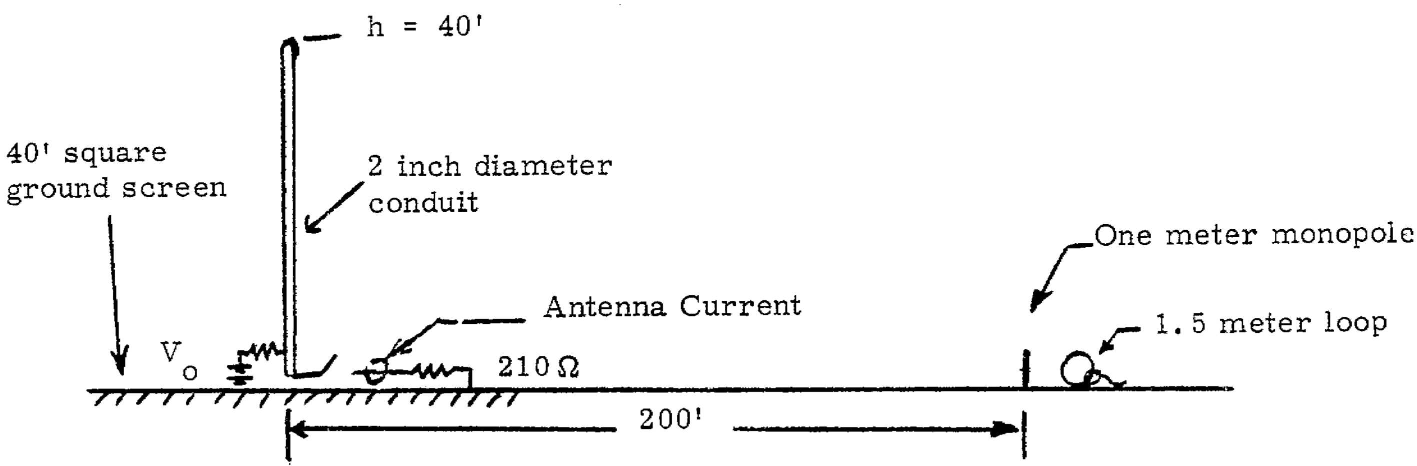
Figure 7. The relation of peak dipole antenna current to cylinder diameter

A terminated monopole pulser was built following the theory given here; this pulser has been extensively used in pretest checkout of EMP sensor systems involving measurements of both E and B fields. Because a trailer containing oscilloscopes and several very long cables are involved in the measurement, a pretest check of the response characteristics is essential. Measurements made at the pulser site using the normal E and B measuring equipment are shown for comparison to the predicted quantities (Figure 8).

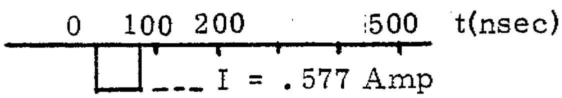
In making the antenna current calculation, it was assumed that the monopole pulser was terminated; this did not really occur. (See measured antenna current.) A somewhat larger value of terminating resistor is suggested by Figure 7, and a larger selection would have removed the current overshoot and the resulting late time E_z and B_ϕ signals.

Note that both the measured E_z and B_ϕ fields are smaller than the predicted quantities; this suggests that the predicted current wave may be too high in amplitude, or possibly that ground propagation resulted in some loss. We also note that since the bandpass of the measuring equipment is only 30 Mhz, the predicted sharp corners on the waveform (12.5 MHz fundamental) are badly rounded.

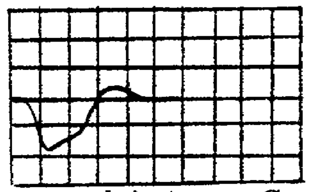
However, we should also note that the use of the pulser here satisfied the objective, no spurious reflections are apparent in the waveforms. The absolute calibration of the sensors is handled as a separate problem.



a) MEASUREMENT PARAMETERS

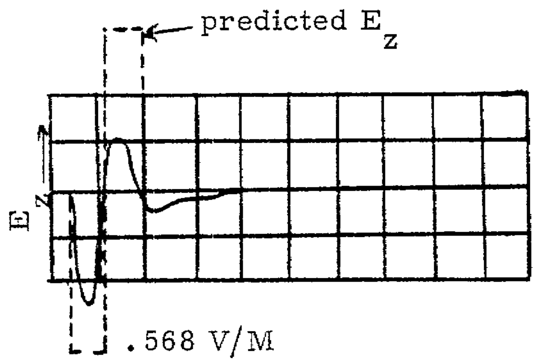


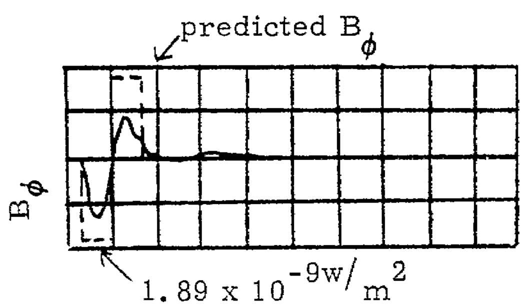
Predicted Antenna Current



Measured Antenna Currents
current = .385 amp/div
time = 50 nsec/div

b) ANTENNA CURRENTS





c) PREDICTED AND MEASURED FIELDS

f_{max} = 30MHz, time = 50 nsec/div

E_z = 1.67 V/M/div, B = 10^{-9} W/M^2/div

Figure 8. Experimental Monopole Pulser Data

APPENDIX

Transient Fields Near Thin Dipoles

The CW field produced by a thin dipole antenna is commonly treated in most texts on antenna theory. At points close to the antenna, the field is highly dependent upon the distribution of current on the antenna. Although this distribution is not accurately known, at most frequencies the sinusoidal distribution is quite accurate.

$$\frac{I(z')}{I(0)} = \frac{\sin k_o(h - |z'|)}{\sin k_o h} \tag{A1}$$

$k_o = \frac{2\pi}{\lambda} = \frac{\omega}{c}$

h = length of antenna

z' = distance from the center of the antenna to a point on the wire.

By utilizing transform methods, the field under transient excitation can be determined.

The z component of the electric field produced by the current distribution is:*

$$E_z = -j \frac{\zeta_o I(0)}{4\pi \sin k_o h} \left[\frac{e^{-jk_o R_1}}{R_1} + \frac{e^{-jk_o R_2}}{R_2} - 2 \cos k_o h \frac{e^{-jk_o R_o}}{R_o} \right] \tag{A2}$$

ζ_o = impedance of free space = 120π.

The geometrical distances are shown on Figure A1.

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*R. W. P. King, Theory of Linear Antennas, p. 528

Dividing through by I(0), this equation can be converted to a transfer function between the electric field and the current entering the input terminals of the antenna.

$$\frac{E_z(s)}{I(s,0)} = \frac{\zeta_o}{4\pi \sinh \frac{sh}{c}} \left[\frac{e^{-\frac{sR_1}{c}}}{R_1} + \frac{e^{-\frac{sR_2}{c}}}{R_2} - \frac{2}{R_o} \cosh \frac{sh}{c}\, e^{-\frac{sR_o}{c}} \right] \qquad \text{(A3)}$$

In the above equation the substitution $s = j\omega$ has been made, converting the transfer function to Laplace rather than Fourier transform notation.

The solution of $e_z(t)$ may be found by multiplying the transfer function by the known I(s, o) and taking the inverse Laplace transform.

The current I(s, 0) with which we desire to use this transfer function is the Laplace transform of the transmission line short-circuit current at the switch. Note that frequency components of this current must be sinusoidally distributed on the line, if this equation is to yield the correct waveform of electric field, since this is one of the assumptions put into the derivation of the transfer function. We must assure ourselves that the current pulse moving up and down the line under transient excitation is equivalent to sinusoidal distribution of current under CW excitation.

The current at any point z' on an open-circuited line of length h, when the line is charged and shorted (or when a battery is abruptly connected to the terminals) is shown in Figure A2.

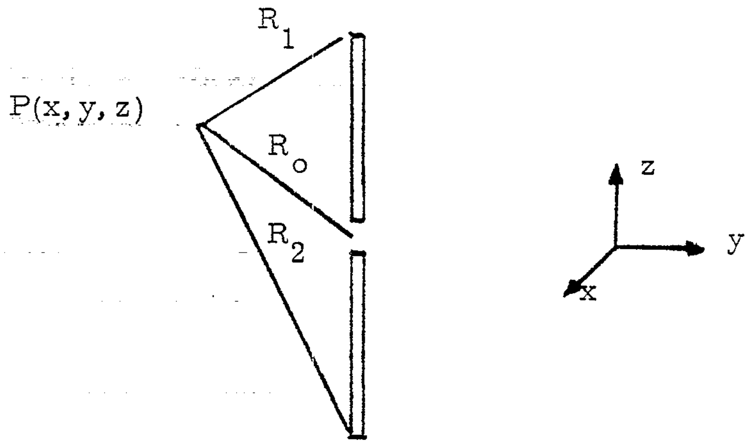

Figure A1. Dipole antenna

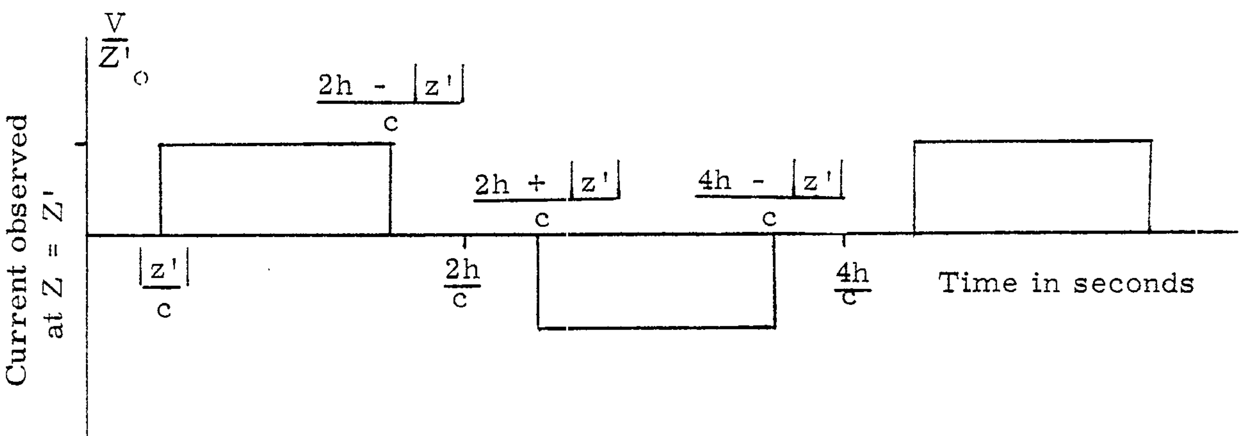

Figure A2. Transient current observed on the antenna

Write

$$I(z', t) = \frac{V}{z_o}\left[U\left(t - \frac{|z'|}{c}\right) - U\left(t - \frac{2h - |z'|}{c}\right) - U\left(t - \frac{2h + |z'|}{c}\right) + U\left(t - \frac{4h - |z'|}{c}\right) + \ldots\right]$$

periodic in $T = \frac{4h}{c}$

where $U(t) = 0$ for $t < 0$, and $U(t) = 1$ for ≥ 0. (The unit step function)

For a function periodic in $T = \frac{4h}{c}$ $(t \geq 0)$*

$$I_{(z', s)} = \frac{F_1(s, z')}{1 - e^{-\frac{4h}{c} s}}$$

where $F_1(s, z')$ is the Laplace transform of the function $i_1(t, z')$ defined by

$$i_1(t, z') = i(t, z') \quad 0 < t < \frac{4h}{c}$$

$$= 0 \text{ otherwise}$$

Hence we may write

$$I(s, z') = \frac{V}{z_o s}\left[\frac{e^{-\frac{|z'|}{c}s} - e^{-\left(\frac{2h - |z'|}{c}\right)s} - e^{-\left(\frac{2h + |z'|}{c}\right)s} + e^{-\left(\frac{4h - |z'|}{c}\right)s}}{1 - e^{-\frac{4h}{c}s}}\right]$$

which may be reduced to

$$I(s, z) = \frac{V \sinh\left(\frac{h}{c} - \frac{|z'|}{c}\right)s}{z_o s \cosh \frac{h}{c} s} \qquad \text{(A4)}$$

*J. A. Aseltine, "Transform Method in Linear Systems Analysis," p.110

and

$$\frac{I(s,z)}{I(s,0)} = \frac{\sinh\left(\frac{h}{c} - \frac{|z'|}{c}\right)s}{\sinh\left(\frac{h}{c}\right)s}$$

for input in form $e^{j\omega t}$

$$\frac{I(j\omega, z)}{I(j\omega, 0)} = \frac{\sin k_o (h - |z'|)}{\sin k_o h} \qquad \text{(A5)}$$

Equation A5 is the normally assumed form of the sinusoidal distributed current on the antenna.

We may then use Equation A4 with $z' = 0$ for the current at the driving terminals of the antenna resulting from shorting a charged antenna.

$$I(s, 0) = \frac{V}{z_o} \left(\frac{1}{s}\right)\left(\frac{\sinh \frac{h}{c} s}{\cosh \frac{h}{c} s}\right) \qquad \text{(A6)}$$

Since a driving source is a step function, the input admittance to the antenna is just

$$Y_{in} = \frac{I(s, 0)}{V_{in}(s)} = \frac{1}{z_o} \tanh \frac{h}{c} s.$$

Multiplying the transfer function (Equation A3) by the current (Equation A6) produces the Laplace transform of the field at the point P (Figure A1) when the antenna is charged and shorted.

$$E_z(s) = \frac{\zeta_o}{4\pi \sinh \frac{sh}{c}} \left(\frac{V}{z_o}\right)\left(\frac{1}{s}\right)\left(\frac{\sinh \frac{sh}{c}}{\cosh \frac{sh}{c}}\right)\left(\frac{e^{-\frac{sR_1}{c}}}{R_1} + \frac{e^{-\frac{sR_2}{c}}}{R_2} - \frac{2}{R_o}\cosh \frac{sh}{c}\, e^{-\frac{sR_o}{c}}\right)$$

which can be written

$$E_z(s) = \frac{2\zeta_o V}{4\pi z_o}\left[\frac{1}{s}\right]\left[\frac{-e^{-\frac{sR_o}{c}}}{R_o} + \left(\frac{1}{1 - e^{-\frac{4hs}{c}}}\right)\left(\frac{e^{-s\left(\frac{R_1+h}{c}\right)} - e^{-s\left(\frac{R_1+3h}{c}\right)}}{R_1}\right)\right.$$

$$\left. + \left(\frac{1}{1 - e^{-\frac{4hs}{c}}}\right)\left(\frac{e^{-s\left(\frac{R_2+h}{c}\right)} - e^{-s\left(\frac{R_1+3h}{c}\right)}}{R_1}\right)\right]$$

Taking the case where $R_1 = \sqrt{R_o^2 + h^2} = R_2$ we have

$$e_z(t) = \frac{60V}{z_o}\left[- \frac{U\left(t - \frac{R_o}{c}\right)}{R_o} + 2\left(\frac{U\left[t - \left(\frac{R_1 + h}{c}\right)\right] - U\left[t - \left(\frac{R_1 + 3h}{c}\right)\right]}{R_1}\right)\right]$$

for $t \leq \frac{4h}{c}$; the second term is periodic in $\frac{4h}{c}$ thereafter, where U(x) is a unit step function.

This is the desired result, a simple description of the radiated field observed at a point on the plane of symmetry when the antenna is driven by a voltage step (or charged and shorted). The transmitting characteristics of the terminated pulser can also be inferred from these results.