Dr. F.M. Tesche
Electromagnetics Consultant
9106 Chapel Valley
Dallas, TX 75220 USA
Tel: (214) 956-9378
Fax: (214) 956-9379
E-Mail: 72461.3170@compuserve.com

July 12, 1996

Dr. Carl Baum
Phillips Laboratory
PL/WSM
2550 Aberdeen Ave. SE
Kirtland AFB, New Mexico
87117-5776

SSN 398

Dear Carl,

Enclosed please find a revised copy of a new SSN Note entitled *Some Considerations for the Design of Pulse-Radiating Antennas* which I have written. This work has not been funded by other sources, and consequently, no additional approval is needed for its publication.

I hereby give my permission for this paper to be published in your note series.

Thank you

Sincerely,

Frederick M. Tesche

Sensor and Simulation Notes

Note 398

July 12, 1996

# Some Considerations for the Design of Pulse-Radiating Antennas

F. M. Tesche
Electromagnetics Consultant
9106 Chapel Valley Rd.
Dallas, TX 75220
72461.3170@compuserve.com

## Abstract

*This note discusses some of the basic concepts involved in designing a pulse radiating antenna system. The system consists of a pulsed source, a transmission line to conduct the pulse to the radiator, and the antenna which radiates the pulse into the far-field. Each of these elements affect the pulse shape of the final radiated field in a manner that can be predicted from simple models. Using a dipole antenna as an example, a hypothetical pulse radiating system is analyzed and typical radiated fields are computed. Key points in the design of these radiating systems are summarized.*

# Contents

## 1. INTRODUCTION

There is a continuing interest in the transmission and detection of pulsed radio-frequency (RF) energy. Applications range from non-destructive testing and remote sensing, to ultra-wideband (UWB) weapons. To develop more sophisticated applications in this area, and to better comprehend the technical limitations in this area, it is important to understand how antennas behave under a transient excitation.

Unfortunately, much of our knowledge and intuition about antennas is based on experience gained in considering the narrow-band, time harmonic (i.e., frequency-domain) behavior of a radiator. Concepts of input impedance, current and charge distribution and the far-field radiation pattern are almost always described in the frequency domain and they are usually applied to narrow-band applications.

Antennas operating in the time domain can behave differently than in the frequency domain. For example, a particular antenna system can be designed to have a null in its radiation pattern in a particular direction when it is operated at its design frequency $f_o$. This is commonly done in AM or FM broadcast systems to shape the coverage area to minimize interference. In the time domain, however, the radiated field from the same antenna at the same observation angle will have a significant response. This is due to the fact that the transient signal may be decomposed into a large number of time harmonic signals, and even if the spectral component at the particular frequency $f_o$ is zero, the total transient response will be non-zero.

This short note is offered as an introduction to the area of pulse-radiating antennas and discusses some of the important aspects of designing such systems. By its nature, this subject can be quite mathematical. In this note, however, the description will be general in nature, with only references to the mathematical treatments being provided Section 6.

## 2. TRANSIENT VERSUS CW SIGNALS

The responses of an antenna, or any other linear system for that matter, can be thought of either in the time domain, or in the frequency domain where the transient waveform is decomposed into a spectrum of sinusoidal waveforms, which when added together, reconstruct the original waveform. This decomposition is the basis of Fourier transform theory[1].

Table 1 illustrates several typical waveforms and their resulting frequency domain spectral magnitudes. In the frequency domain, the spectrum is a complex-valued quantity, and it is characterized by both the magnitude and a phase quantity, which is not illustrated in the table.

Signal 1 is the pure sinusoidal waveform. It is characterized by a single spectral component at the frequency of oscillation, $f_o$. This is the waveform or spectrum that is commonly used for a time-harmonic analysis of circuits or antennas, and it forms the basis for ones intuitive understanding of radiating antennas. Notice that the transient waveform has no discernible starting or stopping time: it exists for all time.

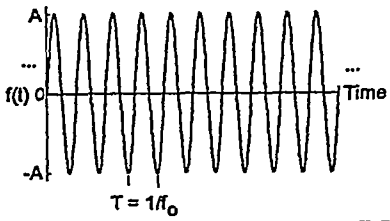
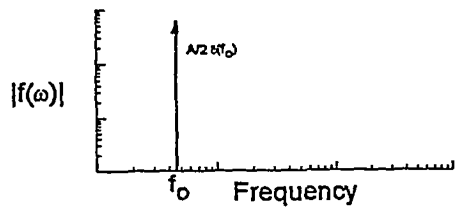
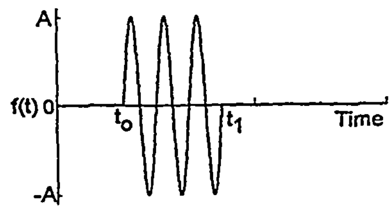
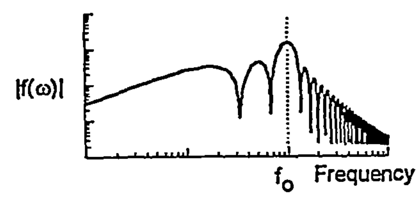
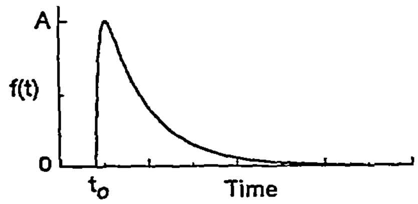
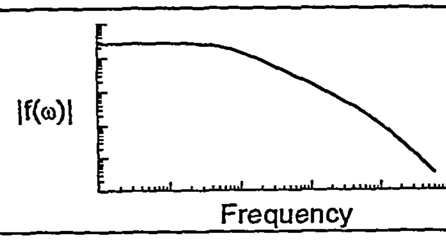
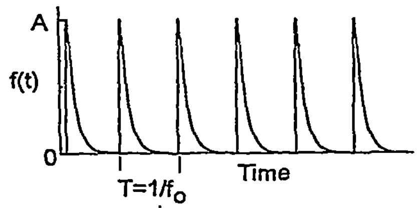
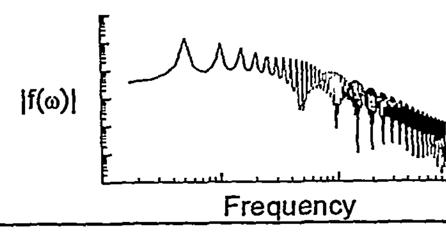
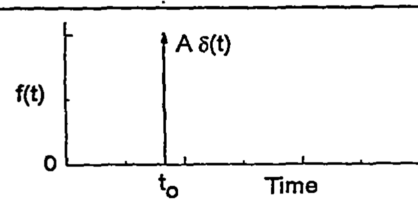
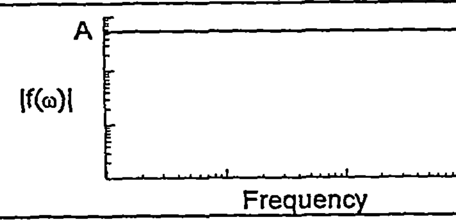
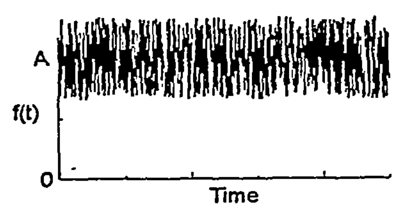
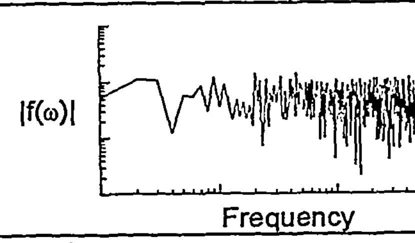
If only a piece of the sinusoidal waveform is taken, as in signal #2, we now have a time-limited signal that can be thought of as a "pulse" in the time domain. The spectrum of this waveform has spread out away form the original frequency $f_o$ . As a result, there are other frequencies that must be considered in the analysis. A simple time-harmonic analysis at frequency $f_o$ will not be adequate in understanding the behavior of a system to this excitation. Other transient signals are also shown in the table, and a general trend is evident: the shorter the waveform is in the time domain, the wider is the spectrum needed to represent it.

Signal #3 is a double-exponential, mono-polar pulse, which is often used to represent a transient EM field produced by a nuclear explosion (an electromagnetic pulse - EMP), electrostatic discharge (EDS), or some sort of UWB device. This pulse has a very large bandwidth and because of this, it is capable of exciting the resonant frequencies of a target or system. For an EM weapon design, however, this is not a very clever choice of waveform since much of the energy contained in the spectrum is away from these characteristic target frequencies. Consequently, much of the radiated energy is wasted.

This discussion is somewhat academic, however, because the signal #3 *cannot be radiated by a physical antenna.* This is because the spectrum of the pulse has a DC component, and DC cannot be "radiated" by a finite-sized antenna. Radiated waveforms from a real antenna must have a total area under the curve equal to zero (no DC component), and consequently, they must be bi-polar. Reference [2] discusses these issues in more detail.

Thus, signal #3 will not be realized by an antenna, or for that matter, for any other set of radiating sources. However, it is commonly used in analysis studies of pulse radiating systems, because it can provide a good approximation to the early-time portion of a more complex (and physically realizable waveform).

Table 1. Different Types of Waveforms and Their Corresponding Spectra

| Signal | Time Domain Waveform | Frequency Domain Spectral Magnitude |
|---|---|---|
| 1.<br>Sinusoidal waveform |  |  |
| 2.<br>Sinusoidal pulse |  |  |
| 3.<br>Single-pulse |  |  |
| 4.<br>Pulse train |  |  |
| 5.<br>Impulse (δ-function) |  |  |
| 6.<br>Noise with a DC offset |  |  |

Each of the transient disturbances in Table 1 can be represented symbolically by the function $f(t)$. As noted in the examples, this function need not be continuous, but must be a single-value function of time. Since the squared function $f^2(t)$ is proportional to an instantaneous power quantity, the time integral of this quantity is proportional to the total energy contained in the signal, as

$$W = \int_{-\infty}^{\infty} |f(t)|^2 dt \ . \tag{1}$$

For any real system or process, this expression must be finite. The infinite sinusoidal waveform of Table 1 clearly violates this requirement, unless it is assumed to start and stop at some distant times.

The relationship between the time domain waveform $f(t)$ and its spectrum, $F(\omega)$, is given by the Fourier transform. There are several different forms for this expression [3], one of which is the exponential form:

$$f(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} F(\omega) \exp(j\omega t) d\omega \ . \tag{2a}$$

where $\omega = 2\pi f$ is the angular frequency. The spectral density $F(\omega)$ is a complex-valued function, which represents the amplitude and phase of a sinusoidal waveform component given by the phasor $\exp(j\omega t)$. It may be determined from a knowledge of the time function through the inverse relation,

$$F(\omega) = \int_{-\infty}^{\infty} f(t) \exp(-j\omega t) dt \ . \tag{2b}$$

As a consequence of these expressions, it is possible to reconstruct a transient waveform from its frequency spectrum. The ability to construct a transient response in this manner is very useful, as many analysis techniques for linear systems have been developed using the concept of a time-harmonic analysis [4]. This amounts to determining the response of a system to a single sinusoidal excitation waveform of infinite duration, with no defined turn-on time. Of course, this analysis must be performed for a large number of frequencies, which is usually referred to as a wide-band analysis.

From a practical standpoint, however, the evaluation of the integrals in Eq.(2) can be time consuming, especially if there are several thousand points in the transient waveform or in the frequency spectrum. An efficient numerical method for performing Fourier transforms is the fast Fourier transform (FFT), which was popularized by Cooley and Tukey. This algorithm is a discrete Fourier transform that is based on powers of 2, and has been discussed by several authors, including [5] and [6].

## 3. CONSIDERATIONS FOR A PULSE-RADIATING ANTENNA SYSTEM

Figure 1 illustrates a simple radiating system, containing a source generator, a feed line and an antenna, all of which produce a radiated EM field at a distance form the source. In this section we will describe the pertinent design considerations for radiating broad-band pulses from this structure. Note that although this antenna is very simple - a dipole-type antenna - the same considerations arise in the design of any other type of antenna system. Consequently, this discussion will provide general guidance for designing any pulse radiating structure.

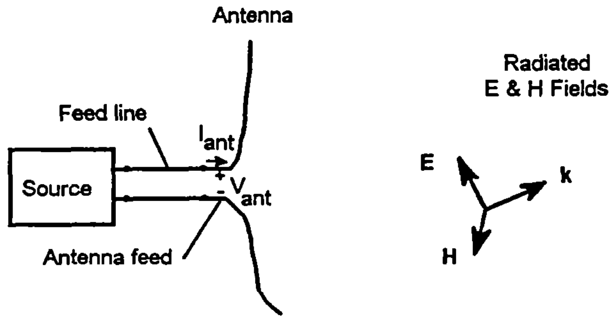



Figure 1. Illustration of a simple radiating system.

### 3.1 DESIGN CONCEPTS

The design of the radiating system of Figure 1 is facilitated by developing a model of the system containing the important electrical features of the source and antenna. As shown in Figure 2, the source can be represented by an equivalent circuit having a source impedance and voltage (a Thevenin circuit). The feed line is usually considered to be a transmission line, which is described by a characteristic impedance and propagation velocity, and the antenna may be represented by a two-port circuit, with the input port being the feed-point on the antenna structure, and the output port being located at the observation location in the far-field where the E and H-fields are determined. In this manner, an antenna is often thought of as a special type of transformer which transforms the traveling voltage and current waves on the transmission feed line into outwardly propagating E and H-fields in free space.

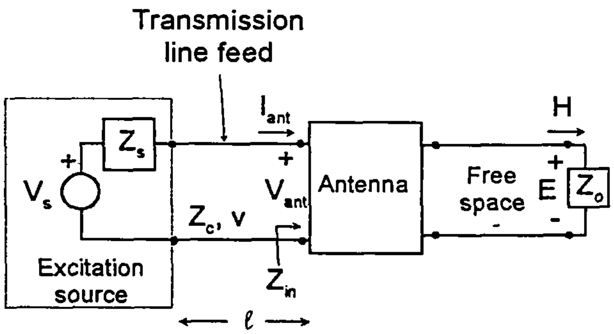



Figure 2. Analysis model for the antenna system.

The design of the antenna system requires an understanding of the following issues:

- how the input impedance of the antenna, $Z_{in}$, will load the voltage excitation source, thereby limiting the amount of available power to the antenna,
- the radiation pattern of the antenna,
- the efficiency of the antenna in radiating at the selected frequency of operation, and
- other practical issues, such as the possibility of high-voltage arcing, lightning protection measures and mechanical considerations for the construction of the antenna.

For a CW antenna operating at a frequency $f_o$, these issues are usually considered under the assumption that $f_o$ is a constant. Typically $f_o$ is viewed as one of the many fixed parameters defining the antenna characteristics. For a pulse-excited antenna, however, the frequency is a variable quantity and the above issues must be taken into account at each of the frequencies contained in the excitation spectrum. In the following subsections, important points in each of these areas are discussed.

### 3.1.1 Antenna loading of the source

The first step in describing the behavior of an antenna is to understand how the antenna affects the energy source connected to it. For the example system shown in Figure 2, it is possible to represent the effects of the antenna at its input terminals by a lumped input impedance, denoted by $Z_{in}$, which is defined as

$$Z_{in}(\omega)=\frac{V_{ant}(\omega)}{I_{ant}(\omega)} \tag{3}$$

where $V_{ant}(\omega)$ and $I_{ant}(\omega)$ are the voltage and current phasors at the terminals of the antenna.

The value of $Z_{in}$ is important is determining the radiation of the antenna. The voltage across the gap of the antenna, $V_{ant}$ , which can be viewed as providing the excitation to the antenna, is not simply the applied source voltage $V_s$, but it depends on the characteristics of the transmission line feed section (the characteristic impedance $Z_c$ and the line propagation velocity $v$), the source impedance $Z_s$, as well as on the antenna input impedance. For the feed line of a length $l$, the voltage $V_{ant}$ can be expressed using transmission line theory as [7]

$$V_{ant}(\omega)=\frac{V_S(\omega)e^{-\gamma\ell}(1-\rho)}{\frac{Z_c}{Z_{in}}(1+\rho e^{-2\gamma\ell})+(1-\rho e^{-2\gamma\ell})} \tag{4}$$

where $\gamma = j\omega/v$, and $\rho$ denotes the voltage reflection coefficient at the source end of the line, which is defined as

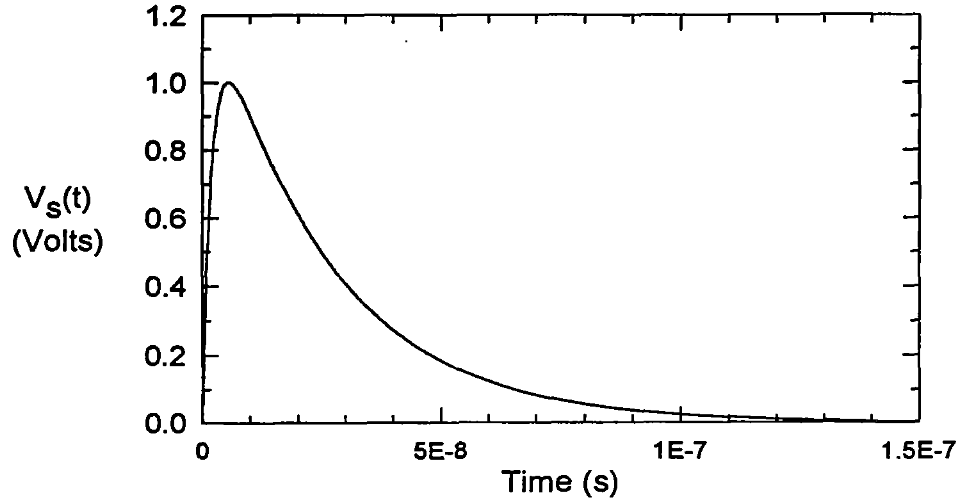
$$\rho=\frac{Z_s-Z_c}{Z_s+Z_c}. \tag{5}$$

Because of the exponential functions in Eq.(4), the voltage response will oscillate as the frequency $\omega$ varies, and this will lead to reflections in the transient response. These oscillations can be eliminated, however, by insuring that the source is *matched* to the transmission line section. As discussed by Baum in [8], this requires that $Z_S = Z_C$, with the result that $\rho = 0$. Under this assumption, the antenna voltage becomes

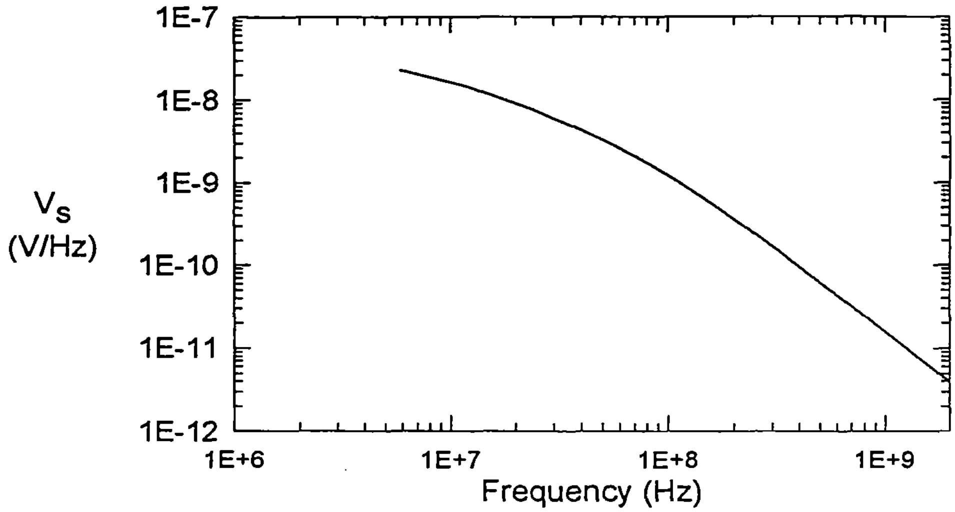
$$V_{ant}(\omega)=\frac{V_s(\omega)e^{-\gamma\ell}Z_{in}}{Z_c+Z_{in}}. \tag{6}$$

Unfortunately, the antenna voltage in Eq.(6) can still vary markedly in frequency due to of the variations of the input impedance of the antenna. The power input into the antenna is defined at $P_{ant} = ½\, \mathrm{Re}[V_{ant} \cdot I_{ant}^*]$ and it is clear that if the antenna impedance is either zero ( due to a short) or infinity (open circuit), there is no input power to the antenna. Consequently, there is no radiated power at these frequencies. Variations in the impedance between these extreme values will cause fluctuations in the power delivered from the source.

As an example of typical responses for the antenna driving voltage as provided by these expressions, consider a hypothetical case of a thin, center-fed dipole antenna with an overall length $L = 1$ meter, connected to a transmission line feed of length $l = 3$ meters with a 50 Ω characteristic cable impedance. We will assume for illustrative purposes that the excitation voltage is a simple double exponential function shown in Figure 3a, which has a frequency-domain spectrum illustrated in part b of the figure.




a. Transient response




b. Frequency domain spectral magnitude

Figure 3. A double exponential excitation function $V_s$ for the antenna.

The voltage at the antenna terminals can be calculated from Eq.(4) with a specification of the excitation spectrum $V_s(\omega)$ and the input impedance of the antenna, $Z_{in}$. This latter quantity can be determined using numerical methods, or it may be approximated by simple analytical functions [7,9]. For the 1 meter dipole antenna, Figure 4 illustrates the magnitude of the input impedance of the antenna as a function of frequency. Note that for a dipole antenna, a common input impedance is considered to be about 73 Ω. This is the value of the impedance when the antenna's length is equal to $\lambda/2$, where $\lambda = c/f$ is the wavelength. For the 1 meter antenna, this corresponds to a frequency $f$ = 150 MHz.

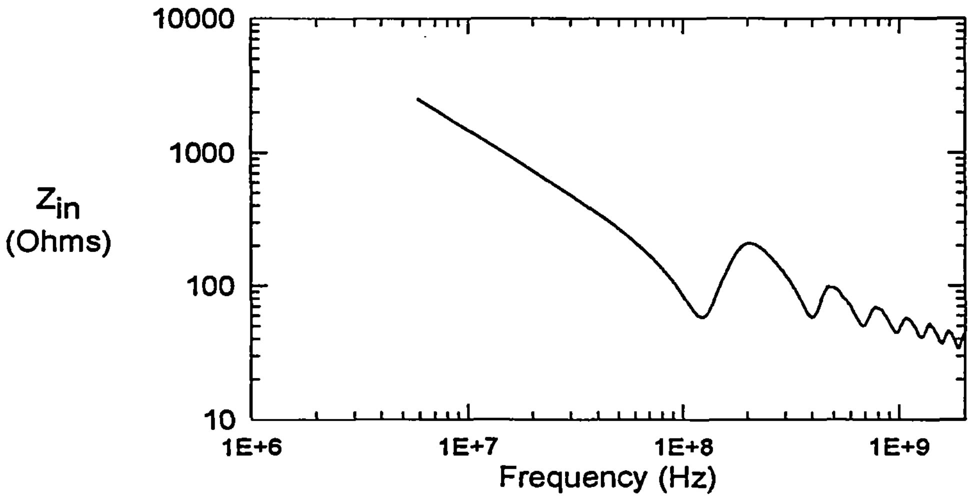
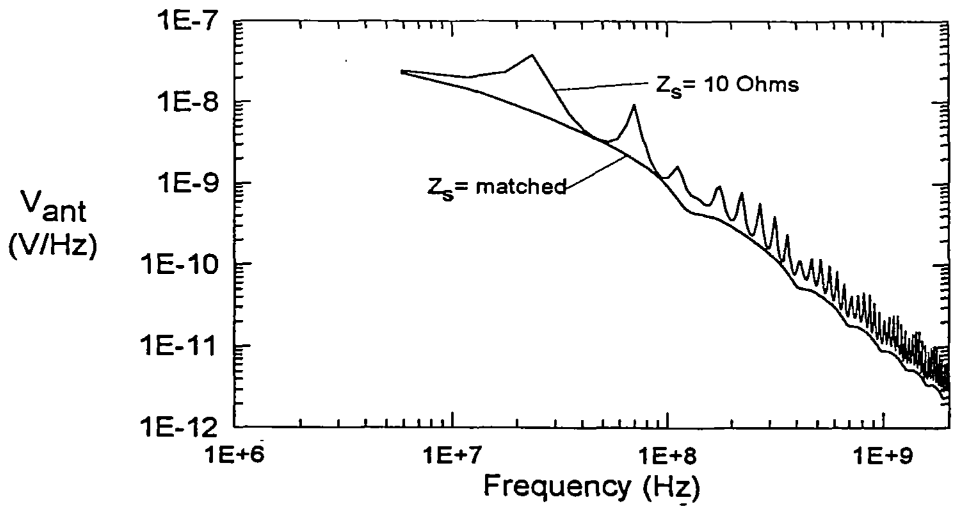


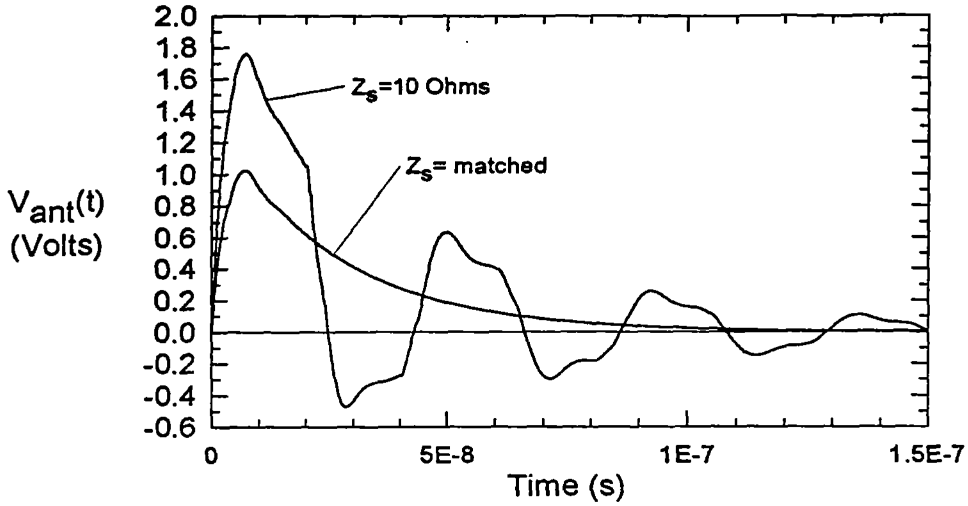

Figure 4. The input impedance magnitude of a 1-meter dipole antenna

Using the this antenna impedance, Eq(4) can be evaluated, yielding the curves for the antenna voltage shown in Figure 5. Plotted in this figure are the antenna voltages for two assumed values of source impedance: $Z_S$ = 10 $\Omega$ and a matched load of 50 $\Omega$. From part a of this figure, it is seen that a non-matched line has significant peaks, or resonances, in the spectrum, arising from multiple oscillations on the transmission line feeding section.

Part b illustrates the antenna driving voltage in the time domain, with the effects of the transmission line oscillations clearly evident. These are undesirable in the design of a "clean" pulse radiating system. Such oscillations on the line can be eliminated by insuring that matched terminations (loads) are provided on the feeding line wherever possible.




a. The spectral magnitude




b. The transient response

Figure 5. The response of the antenna voltage for two different values of source impedance.

### 3.1.2 Radiation patterns for the antenna

A second important issue in understanding pulse radiation is to determine the direction in which the radiation leaves the antenna. For an antenna operating at a single frequency, the radiation is determined by a simple spatial pattern, as shown in Figure 6. Many narrow band antennas are designed with special requirements to tailor the radiation patterns for a specific area of coverage. The locations of the nulls in the radiation pattern can be located so as to minimize interference and the peaks in the patterns are usually adjusted to enhance the desired transmitted signal levels.

For the response of a transient antenna, however, the problem is more complicated, as a wide band of frequencies must be considered. As a consequence, if there is a null in the CW radiation pattern in a particular direction at a fixed frequency, a small change in the frequency will shift the null's direction, as is evident from Figure 6. This implies that for such a transient antenna, energy leaves the antenna in all directions (with the possible exception of symmetry planes), and the waveform of the field changes as the observation angle varies.

This effect is illustrated in Figure 7, which presents the radiated E-field from a step-function excited linear antenna for various angles of observation. Note that this transient response is highly oscillatory, due to the reflections of current at the ends of the antenna.

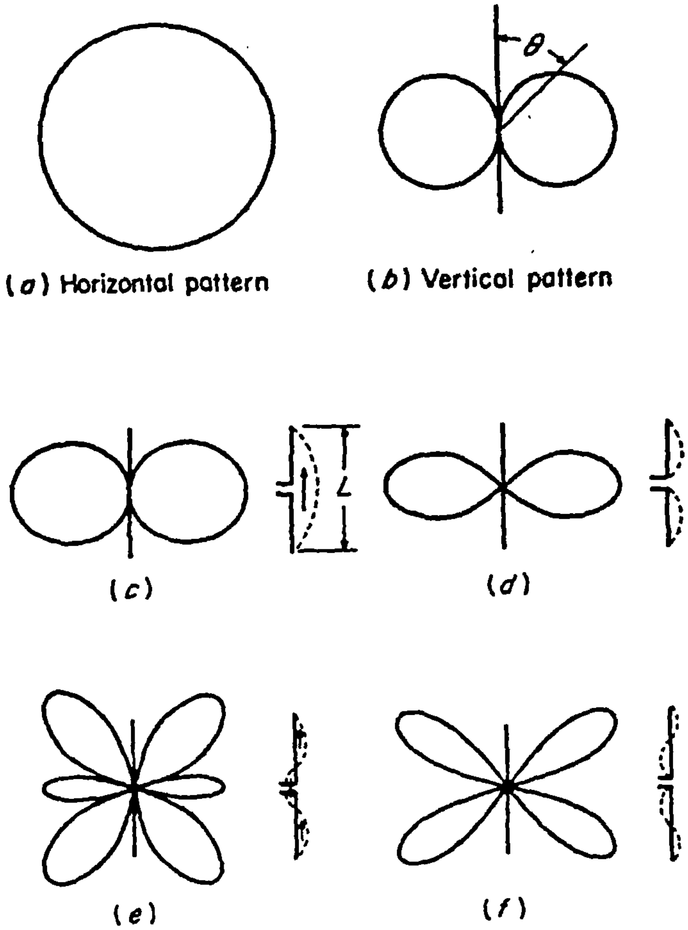



Figure 6. Radiation patterns for a center-fed dipole antenna operating at a single frequency. (a) horizontal pattern; (b) vertical pattern for $L \ll 1$; (c) pattern for $L = \lambda/2$, (d) pattern for $L = 1\ \lambda$; (e) pattern for $L = 1.5\ \lambda$; (f) pattern for $L = 2\ \lambda$. (from ref.[10]).

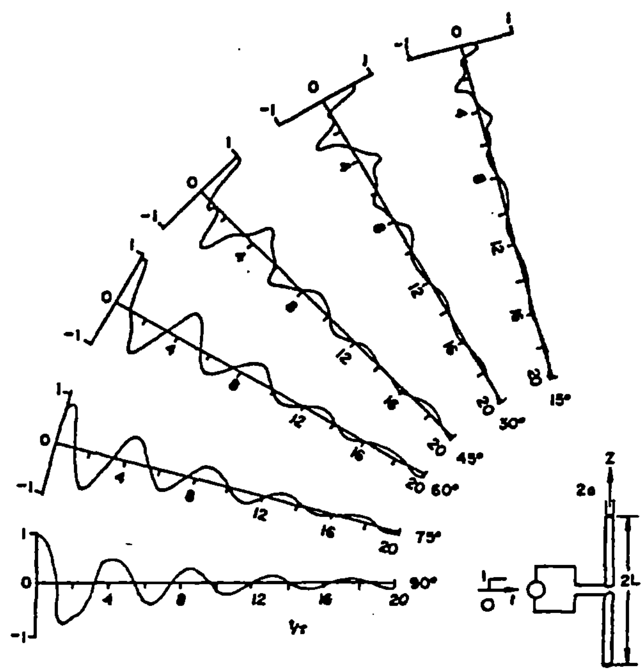


Figure 7. The radiated E-field from a linear antenna excited by a unit amplitude step-voltage source (from ref.[11]).

### 3.1.3 Efficiency of radiation

Given a *unit amplitude* voltage excitation of the antenna. Figure 8 presents the normalized radiated E-field ($rE_\theta$) as a function of frequency for the observation angle $\theta = 45^o$, which is illustrated in part (b) of Figure 6. Such calculations can be made using the antenna analysis procedures discussed in [7,9]. This function is basically a *radiation transfer function* relating the radiated E-field to the antenna voltage, which may be expressed as

$$rE_\theta = T_r(\omega)V_{ant}\,. \tag{7}$$

There are several interesting features of the radiated field shown in Figure 8. Notice that there is a general increase in the response as frequency increases. This function is roughly proportional to $\omega$, and a detailed analysis indicates that this behavior arises from the fundamental radiation characteristics of a point dipole source. In the time domain, this spectral behavior provides a response that is related to the *derivative* of the driving waveform. In addition, there are several resonances noted in the radiated field spectrum at high frequencies. These arise from the oscillations on the dipole structure, and like the transmission line resonances, these are expected to cause complications in the generation of a clean radiated pulse from the antenna.

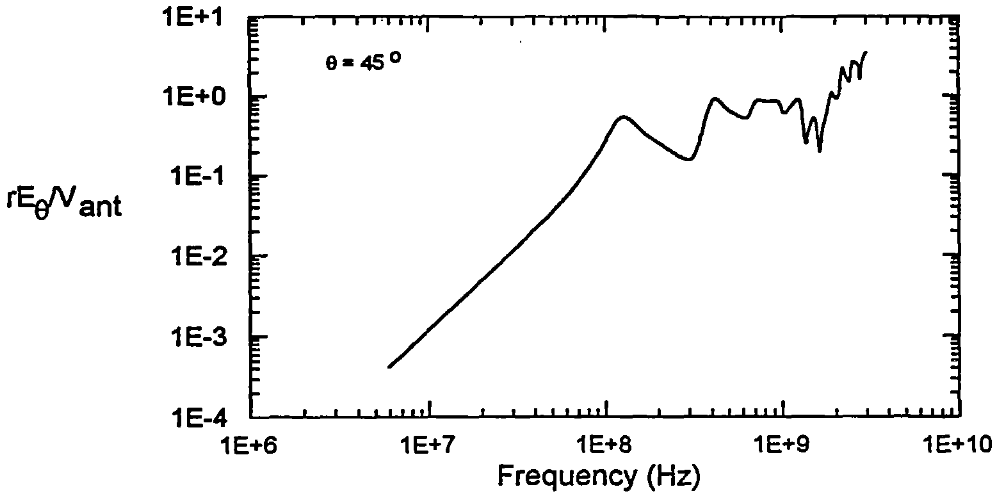
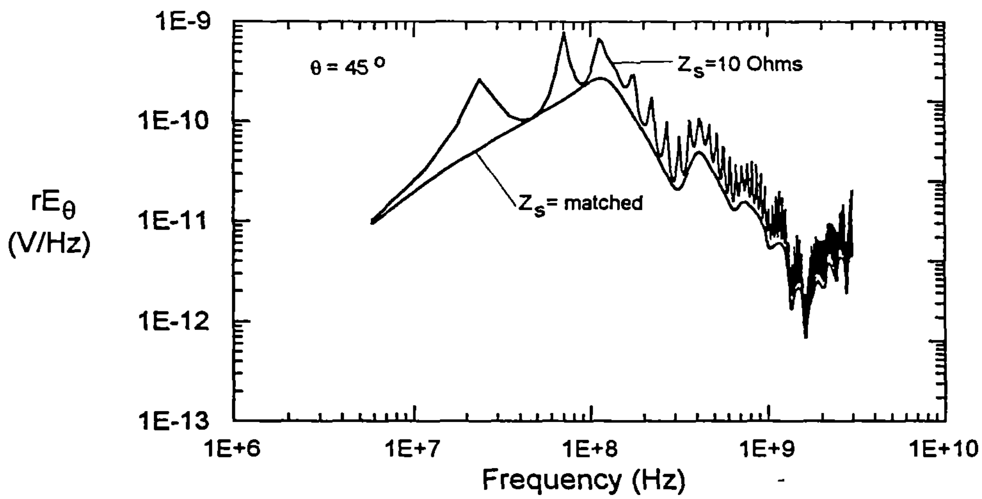
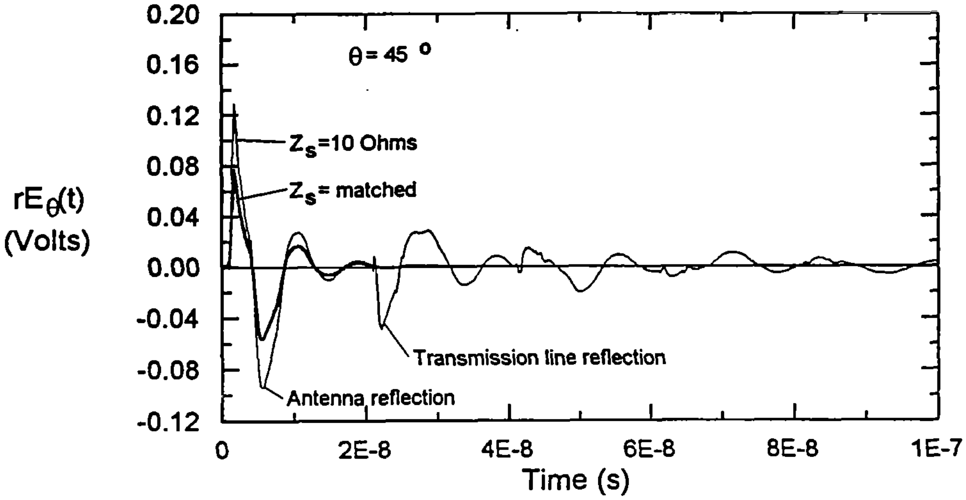



Figure 8. Plot of the radiated E-field transfer function $T(\omega) = rE_\theta/V_{ant}$ for the 1-meter linear antenna.

The spectrum of the antenna voltage source $V_{ant}$ shown in Figure 5a can be multiplied by the radiated field transfer function of Figure 8 to provide the spectrum for the antenna having the specified excitation waveform of Figure 3. This results in the radiated field $rE_\theta$ spectrum illustrated in Figure 9a. As noted in this figure, the composite response contains resonances of both the transmission line feed and the antenna. By matching the transmission line feed at the source end, these former resonances can be eliminated. Figure 9b illustrates the transient radiated field for the two different source impedances, and it is clear that the late-time transmission line oscillations have been removed when the line is matched.




a. The spectral magnitude




b, Transient response

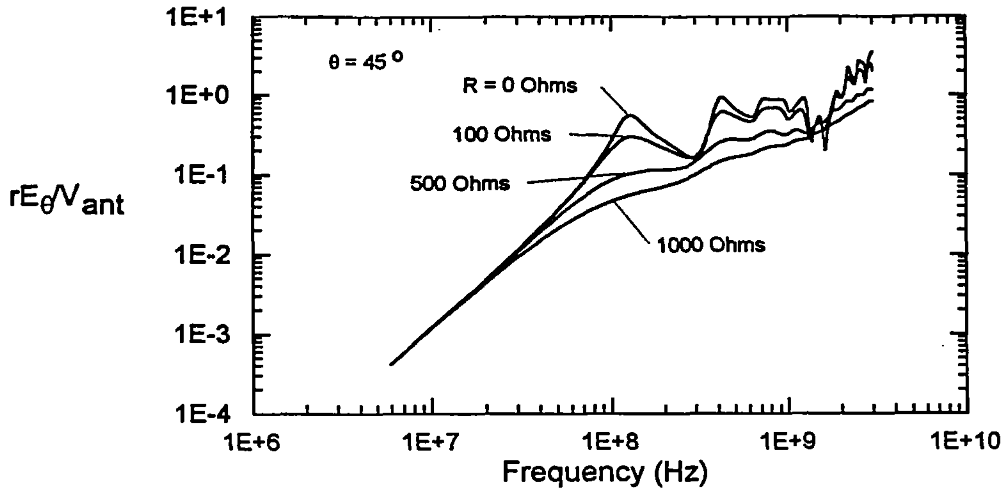
Figure 9. Plots of the radiated E-field from the transmission line fed dipole antenna with the pulse excitation of Figure 2.

### 3.1.4 Removal of antenna resonance effects

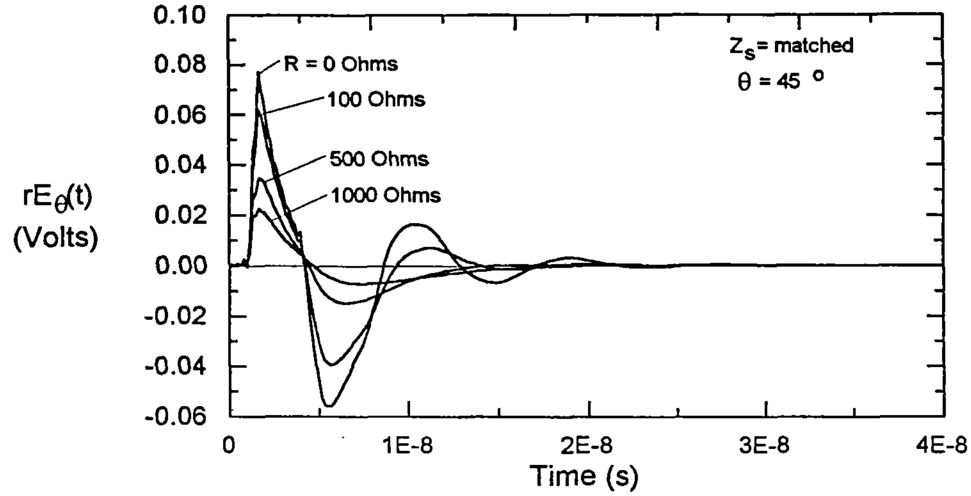
Even with the transmission line section matched, the radiated pulse in Figure 9b has unwanted characteristics due to the antenna resonances. One way of eliminating these resonances is by adding a resistive load along the length of the antenna. This will attenuate the traveling waves on the dipole and reduce the unwanted reflections from the end of the antenna - all done at the expense of reducing the amplitude of the radiated fields.

Such antenna loading has been described by several authors [11,12], and standard numerical techniques can be used to calculate the radiated fields in this case [7,9]. Figure 10b shows an example of the normalized radiated field spectrum for the 1-meter dipole with various levels of resistive loading, uniformly distributed along the length of the antenna. Notice that the effect of the loading is to dramatically reduce the antenna resonances, while still maintaining the fundamental increase of the field with $\omega$.

The transient radiated field for the double exponential excitation function of Figure 2 is shown in Figure 10b. Notice that for a total resistance of between 500 to 1000 $\Omega$, the radiated field is virtually free of any late-time reflections, and thus can be considered to be the optimal pulse radiated from this antenna.




a. The spectral magnitude




b. Transient response

Figure 10. The normalized radiated field spectrum (a) and the transient response for the double exponential excitation (b) for a 1-meter, resistively loaded antenna.

### 3.1.5 Synthesis of a specified radiated pulse

Using the expression for the antenna voltage in Eq.(6), together with the computed radiation transfer function $T_r(\omega)$ as defined in Eq.(7) and antenna input impedance $Z_{in}$, the radiated field can be expressed in terms of the excitation source $V_s$ as

$$rE_\theta(\omega) = \frac{Z_{in}(\omega)}{Z_c + Z_{in}(\omega)} T_r(\omega) V_s(\omega) . \qquad (8)$$

In this expression, the exponential term in Eq.(6) has been eliminated, as it contributes only a time-shift to the total response.

The expression in Eq.(8) can be used in the synthesis of a the excitation function needed to radiate a particular pulse shape. Suppose that a particular E-field waveform, and consequently, its spectrum, is specified. Then the needed spectrum of the voltage excitation is given from Eq.(8) directly as

$$V_s(\omega)=\frac{1}{T_r(\omega)}\frac{Z_c+Z_{in}(\omega)}{Z_{in}(\omega)}rE_\theta(\omega), \tag{8}$$

and the time history of the driving source may be determined by Fourier transformation.

While this procedure appears to be simple, there are several issues that must be remembered. If the transfer function $T$ is zero or close to zero for a particular frequency, the term `1/T can become singular. The only way that this can occur and have the excitation voltage spectrum have a finite value is to require that the specified radiated field spectrum $rE_\theta$ also have a zero at this frequency. The implication of this requirement is that only a limited range of radiated fields can be synthesized, and for a particular transfer function $T$. Furthermore, any spectrum for $V_S$ that is calculated in this manner must be physically realizable. This implies that the spectrum must be causal, with its real and imaginary parts related by the Hilbert transform relations [13].

### 3.2 PRACTICAL CONSIDERATIONS

There are many practical aspects of the design of pulse radiating systems. These include the following:

- source voltage or power requirements
- repetition rate requirements
- pulse shape quality (reproducibility)
- E-field breakdown considerations
- illumination volume
- transportability
- maintainability

Each of these elements will have an important role in the design of the antenna. Some, such as the pulse radiation pattern may be difficult to control, while others like transportability or maintainability can be solved by a clever engineering design.

## 4. EXAMPLES OF PULSE-RADIATING STRUCTURES

Several types of radiating structures can be envisioned and have been constructed. Some of these are briefly described in this section.

### 4.1 EMP SIMULATORS

A significant amount of work has been spent in designing pulse systems for EMP testing. Although not designed to be an efficient free-field radiating antenna, the parallel-plate EMP simulator provides a good example of a guided-wave structure. Note that although most of the EM energy produced by this simulator is located in the "working volume" between the parallel plates, this simulator does in fact radiate energy. Such radiated fields have been measured and calculated at distances on the order of several km, as described in [14].

As shown in Figure 11, this simulator consists of a transient source, a resistive load and a transmission line structure connecting the two. The load is designed to eliminate the transmission line resonances, a requirement that has been discussed earlier. The main difference between this bounded wave simulator and a radiating antenna is that the object being illuminated is located within the transmission line structure. Thus, the illuminating fields are not radiated, but rather, are the transmission line fields which are typically a transverse EM wave.

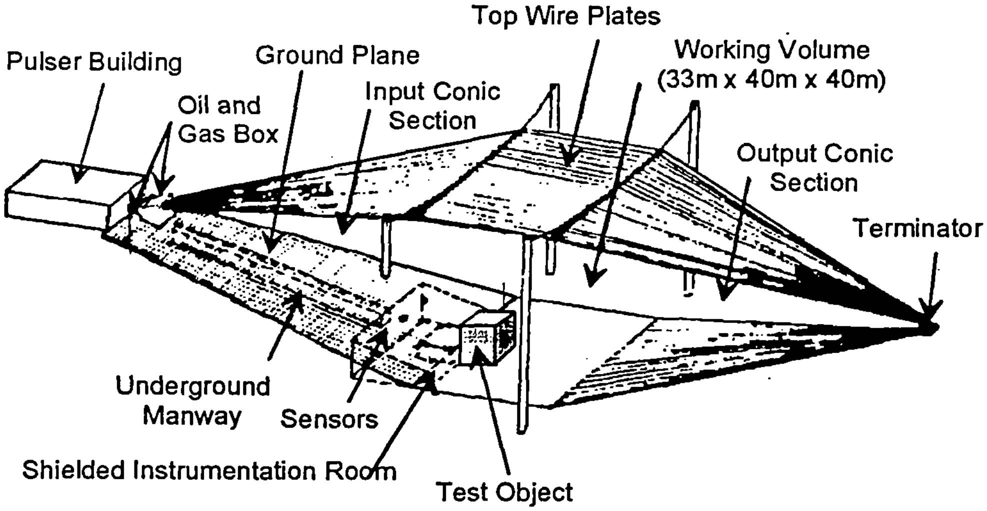



Figure 10. Example of a parallel-plate EMP simulator.

## 4.2 A LINEAR ANTENNA

An example of a pulse radiating linear antenna used as an EMP simulator is the RES-1 antenna, which is a resistively loaded dipole antenna, similar to the one discussed earlier in this section. This simulator is illustrated in Figure 11.

This simulator is designed to be carried by an aircraft to the vicinity of a system to be tested. As a consequence, transportability and the power requirements are important in the design of this antenna.

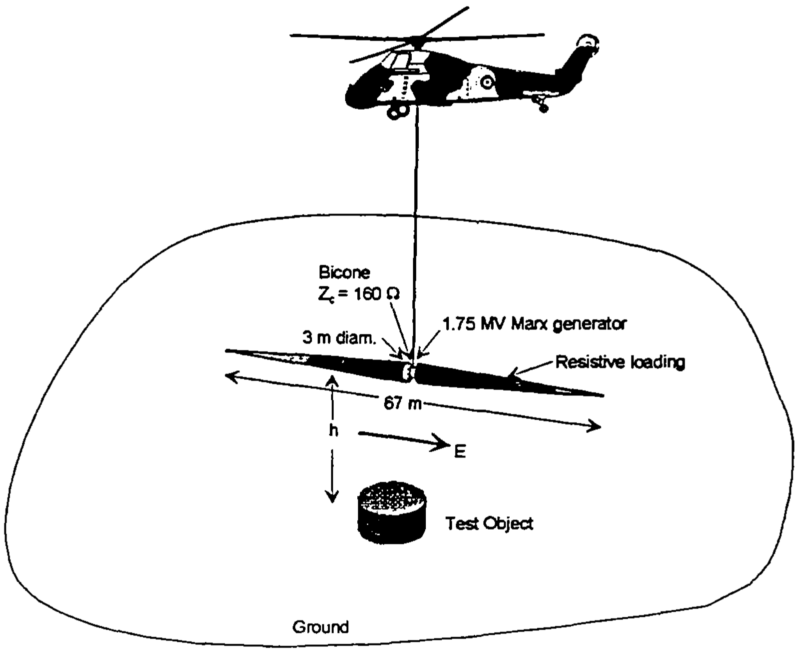



Figure 11 The Radiating EMP Simulator (RES-1) ) at Kirtland AFB, NM. (Airborne, radiating, horizontally-polarized).

## 4.3 HORN-TYPE RADIATORS

Another type of pulsed antenna is the TEM horn antenna [15], as illustrated in Figure 11. Just as in the example discussion of the radiating antenna system earlier, this system has a power source, transmission section and an antenna structure. In fact, the antenna is very similar to a dipole antenna, with the dipole conductors being tilted forward and having a width, both of which enhance the directivity of the antenna. Thus, we expect that there is more energy directed towards the front of the antenna than to the back side.

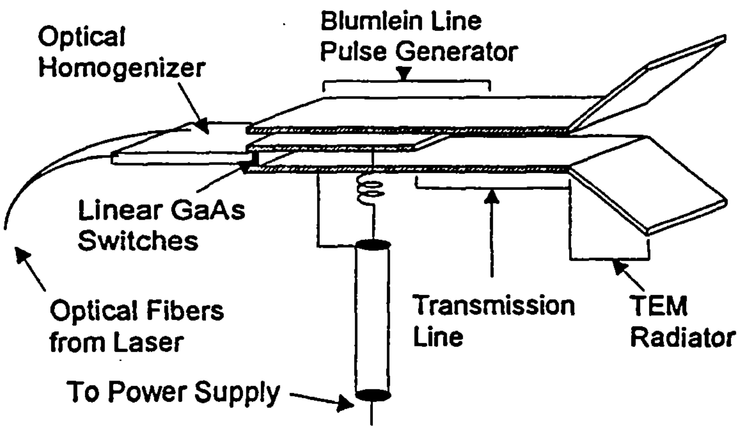



Figure 11. A pulsed horn radiator.

### 4.4 A HYBRID ANTENNA

Another type of pulse radiating structure is a hybrid transmission line fed reflector antenna, as portrayed in Figure 12. This is a class of impulse-radiating antennas (IRA) which have been under development for UWB applications [16, 17]. This antenna consists of a pulse source feeding into a conical transmission line structure which maintains a constant TEM wave impedance of about 400 Ω along its length. The transmission line connects to a parabolic dish reflector through matching load impedances, designed to minimize reflections back to the source.

From an electrical point of view, the transmission line section behaves like a P×M antenna at low frequencies [18], radiating an EM field in the backward direction with an impedance of exactly 377 Ω. At higher frequencies, the TEM wave from the feed line is reflected in the parabolic dish, and re-radiated in the form of a focused beam.

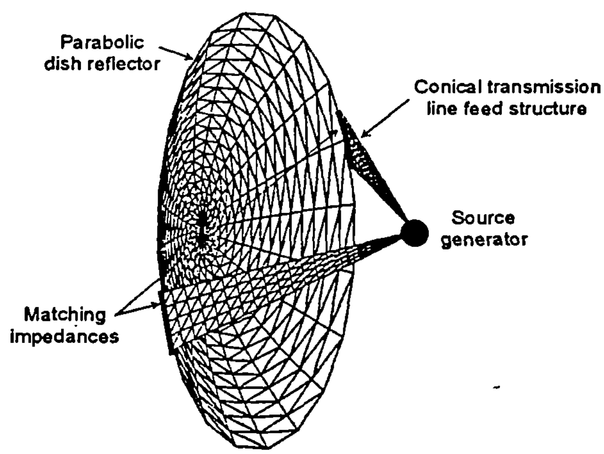



Figure 12. A hybrid impulse radiating antenna.

## 5. DIRECTION OF FUTURE WORK

Much of the basic work in understanding how pulsed radiating structures work has been done, and calculational models are readily available for predicting the responses for specified antenna configurations. The real problem, therefore, is one of *synthesis* and *design* for the development of a specific geometry to radiate a specified pulse with given engineering constraints. To do this, one must have a clear cut goal in mind for the use of the antenna and well defined specifications for the operation of the antenna system.

In performing this design work, it is useful to keep in mind the following principles for the antenna system design:

- try to minimize reflections within the antenna feed structure,
- attempt to eliminate antenna resonance,
- endeavor to match impedances throughout the system, and
- realize that there are basic limitations to the radiation of pulses.

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