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Note 64
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CW Test Manual

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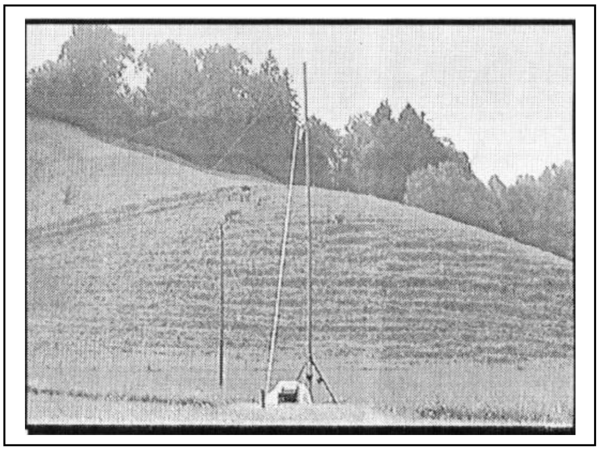
NEMP Laboratory, Spiez



CW Test Manual

December 7, 1994

By F.M. Tesche

Contents

Glossary of Terms

Acceptance test

A test performed at the completion of system construction and prior to system delivery to insure that all system requirements have been met by the contractor.

Advanced Signal Processing Program (ASPP)

A data analysis program running in Windows on the PC for analysis of CW and pulsed test data.

Angle of incidence

The angle of arrival of an incident EM field (usually a plane wave) on a system or observer on the ground.

Angular frequency

The radian frequency ω defined as $\omega = 2\pi f$.

Apertures

Holes or other imperfections in a shield though which EM fields are able to penetrate.

Assessment

An evaluation of the survivability of a system subject to a weapons environment.

Balun

A wide-band matching transformer designed to connect a balanced antenna (like a dipole) to an unbalanced transmission line (like a coaxial line).

Bounding waveform

A hypothetical waveform which is a composite of many realistic waveforms, having the fastest rise-time, the longest fall-time and the longest peak amplitude of all of the realistic waveforms. It is frequently used for system hardening design purposes.

Calibration by the ruler

Refers to the electrical calibration of an E-field or H-field sensor not by measuring the response, but by simply measuring the geometry (length, width, etc.) and inferring the response through equations.

Complex-valued

A function that is described by complex arithmetic, with numbers having a real part and an imaginary part.

Conducting penetration

A wire penetrating into a shielded region.

Continuous wave

Refers to an idealized sinusoidal signal that has no beginning or end.

Coupling path

The pathway or route by which external EM energy incident on a system is able to penetrate and propagate on its way to sensitive internal components.

CW

Continuous wave.

Diffusive penetrations

The penetration of EM fields into a shielded enclosure through wave propagation (diffusion) through imperfectly conducting material.

E1

Refers to the early-time portion (0 to 1 μs) of the transient EM field produced by a high-altitude nuclear detonation.

E2

Refers to the intermediate-time component (1 μs to 1 sec) of the transient EM field produced by a high-altitude nuclear detonation.

E3

Refers to the late-time component (for times > 1 sec) of the transient EM field produced by a high-altitude nuclear detonation.

Earth-reflected field

The component of the total EM field that is due to a reflection of the incident field in the earth.

Electromagnetic fields

The combination of electric and magnetic fields, which propagate together from an electrical source to a distant location and cause a "action at a distance", with no intervening medium other than free space. These fields are described by Maxwell's equations.

Electromagnetic pulse

A transient electromagnetic field radiated from a variety of sources: a lightning discharge, electrostatic spark, a transient antenna, or a nuclear detonation.

EM

Electromagnetic.

EMP

Electromagnetic pulse.

EMTECH antenna

An inverted "V" antenna produced by EMTECH AB in Sweden.

Environment

Refers to the EM fields exciting a facility, vehicle, or other conducting object.

ESD

Refers to electrostatic discharge which is a potentially damaging occurrence of static electricity creating a spark which can adversely affect electrical equipment.

Fiber optics

A means of transmitting information modulated on a light beam transmitted on a bundle of fibers. This offers immunity to electrical disturbances, as the fibers do not conduct electrical signals.

Fresnel reflection coefficients

Complex-valued coefficients which provide the amplitude and phase of the reflected EM plane wave components from a lossy earth in the frequency domain.

Geomagnetic storms

Naturally occurring variations of the geomagnetic field which cause electrical effects in long electrical conductors in a manner similar to MHD-EMP.

Ground loops

Conducting loops formed by electrical conductors with a ground (or earth) return.

Hardened military system

A system used by the military that has been designed to withstand various weapons effects such as blast, shock and EMP.

Hardness

The property of an electrical system to withstand external EM stress.

Hardness surveillance

The act of periodically monitoring a system to verify that the system hardness remain in its desired state.

HEMP

High-altitude EMP.

High-altitude EMP

The electromagnetic pulse arising from the detonation of a nuclear bomb at high altitudes (higher than 30 km in altitude).

Horizontally-polarized

Refers to the state of polarization of a plane wave EM field in which the E-field vector is entirely in the horizontal plane.

HPM

Refers to the subject of high power microwaves which is a potentially dangerous form of EM radiation transmitted through a series of horn-type antennas.

Incident field

The component of an electromagnetic field which comes only from the sources producing the field.

Magnetohydrodynamic EMP (MHD-EMP)

The late-time component of HEMP ($t > 1$ s) due to the interaction of the ionized bomb debris with the geomagnetic field.

Mission critical

Refers to a feature of function of a system or sub-system that is crucial to the successful operation of the system.

NEMP

Nuclear EMP.

Norm

A mathematically-derived scalar number that is used to characterize attime-domain eaveform. Examples are the peak amplitude, maximum rise time, and energy content of a waveform.

Nuclear EMP

An electromagnetic pulse arising from a nuclear detonation.

PARTES

Refers to the concept of testing a large facility for EMP response by performing a number of sub-tests with localized excitation fields, and then analytically combining the partial results to infer the plane wave response of the system.

Polarization

Refers to the spatial characteristics of the EM field. Usually, the E-field vector is the field component used in defining the type of polarization of the field, with the terms vertically polarized and horizontally polarized being commonly used.

Protection devices

Electrical components such as filters, spark-gaps, gas arrestors, etc. that are designed to limit the passage of transient energy into a protected system.

Pulse generator

The source of transient excitation in an EMP simulator. This usually consists of a large capacitor and pulse-forming network which is charged and then discharged into a radiating antenna to launch a simulated EMP to a system under test.

RF

Radio Frequency (10 kHz to 1 GHz).

Sensor

An electrical device for measuring the response of E-fields, H- fields, current or charge.

Shield topology

A description of the electrical configuration of the shield (or EM barrier) surrounding a system which is used for EM protection.

Simulator

An electrical device which produces a NEMP using conventional (non-nuclear) pulse technology.

Stress/response interface

The location within a system where the EM stress (excitation) is to be compared with the EM response of the internal equipment.

Sub-system

A part of a larger electrical system that can be viewed as a single functional unit. For example, in an aircraft system, the communication equipment would be viewed as a sub-system.

Survivability

The ability of a hardened system to withstand the effects of an attack and continue to perform its intended function.

Time-harmonic

Refers to a CW signal.

Total field

The EM field exciting a conductor, comprising of the sum of the incident field and all other reflected or scattered field components from the ground or near-by objects..

Transfer function

A mathematical relationship between the response and an excitation.

Vertically-polarized

Refers to the polarization state of an EM plane wave in which the E-field vector is contained entirely in the vertical plane (i.e., the plane of incidence). In this case, the E-field has both a vertical component and a horizontal component

HEMP Testing Overview

Introduction

Electromagnetic fields, both naturally-occurring and manmade, can have unwanted effects on modern electrical systems. The adverse effects of lightning on electrical power systems has long been a concern in the design and location of power equipment. Similarly, electrostatic discharge (ESD) poses a safety concern in areas where there is a possibility of an explosion or fire due to ignition of hazardous chemicals and other substances. High power microwave (HPM) threats pose hazards to the safe operation of guidance and control systems in vehicles. The possibility of a transient electromagnetic pulse (EMP) is a concern in the event of a nuclear detonation.

In this document, we will discuss a method for testing the response of an electrical system to an external EM fields, either transient in nature or appearing as a continuous wave (CW) signal. The basic test concept is to simulate an incident EM field by a suitably-designed localized antenna system which is excited in a CW mode. By measuring the induced system response, both in magnitude and phase, the time-harmonic (i.e., frequency domain) response of the system can obtained. Transient responses then can be developed by using a numerical evaluation of the Fourier integral.

In this development, we will mainly be interested in the nuclear EMP as the threat environment. This is described in more detail in the next section. It should be kept in mind, however, that this test method can be applied to a variety of other EM fields, like lightning, HPM, etc., since what is determined is a system transfer function. With a knowledge of the transfer function, the system's impulse response can be determined and the response due to an arbitrary excitation can be found by convolution.

The Nuclear Electromagnetic Pulse Threat

A nuclear detonation in or above the earth's atmosphere produces an intense electromagnetic pulse (EMP) [1,2]. This pulse also is referred to as a nuclear EMP (NEMP). A detonation at an altitude above about 40 km produces an EMP that is called a high-altitude EMP (HEMP). This environment lacks the blast and shock waves that are typically associated with nuclear detonations within the

1. W. J. Karzas and R. Latter, "Electromagnetic Radiation from a Nuclear Explosion in Space," *Phy. Rev.*, 126 (6), pp. 1919-1926, June 15, 1962.
2. C. L. Longmire, "On the Electromagnetic Pulse Produced by Nuclear Explosions," *IEEE Transactions on Antennas and Propagation*, Vol. AP-26, No. 1, January 1978.

atmosphere. It consists entirely of electromagnetic (EM) field disturbances. A large portion of the radiated EM energy is contained in the radio frequency (rf) portion of the spectrum. Consequently, these pulsed fields can induce large transient currents in power lines, communications cables and antennas. This can lead to upset or misoperation of electrical equipment, and possibly, permanent damage to sensitive electrical components.

Early-Time, Intermediate-Time and Late-Time EMP

For convenience in describing the HEMP environment, the electromagnetic disturbance is divided into three components: E_1, E_2, and E_3. This division is based on the different production mechanisms and on the time scales of the disturbance. The transient electromagnetic fields radiated from such a detonation can vary significantly with the weapon design characteristics, the device yield and the detonation height. Furthermore, the position of the observer relative to the detonation is important.

The early-time E_1 component of HEMP is a steep-front, short-duration pulse with a rise-time of a few nanoseconds. This waveform rapidly decays to zero in times of about one microsecond or less. A single high-altitude nuclear burst can subject much of Europe to a peak E_1 HEMP electric field (E-field) of several tens of kV/m.

Following this early-time HEMP environment, a more slowly varying and less-intense EM field is observed. This is the intermediate-time E_2 environment. It is characterized by an E-field strength of several hundreds of V/m, with a typical time scale on the order of hundreds of μs.

The E_2 wave component is followed by a low amplitude, late-time signal, having an amplitude of a few tens of V/km. This response, denoted as E_3, results from geomagnetic perturbations caused by a high-altitude nuclear detonation and has a response time up to several hundreds of seconds. This later component of the HEMP signal is also referred to as magnetohydrodynamic EMP (MHD-EMP). This can effect power systems in a manner similar to geomagnetic storms [3].

For a comparison of these three environments, Figure 1 presents a qualitative view of the E-field components found in HEMP, with the various production mechanisms indicated. As noted above, the various parts of this environment have different properties; consequently, it is difficult to compare them in a single plot on a quantitative basis. For example, the E_1 field is an incident field that does not take into account the presence of the earth. The E_3 environment, however, is a total field which is the sum of the incident and earth-reflected field. Furthermore, the polarization of these components of HEMP are different.

3. J. R. Legro, N. C. Abi-Samra and F. M. Tesche, *Study to Assess the Effects of Magnetohydrodynamic Electromagnetic Pulse on Electric Power Systems*, ORNL/Sub-83/43374/1/V3, Martin Marietta Energy Systems, Inc., Oak Ridge National Laboratory, Oak Ridge, TN 37831, May 1985.

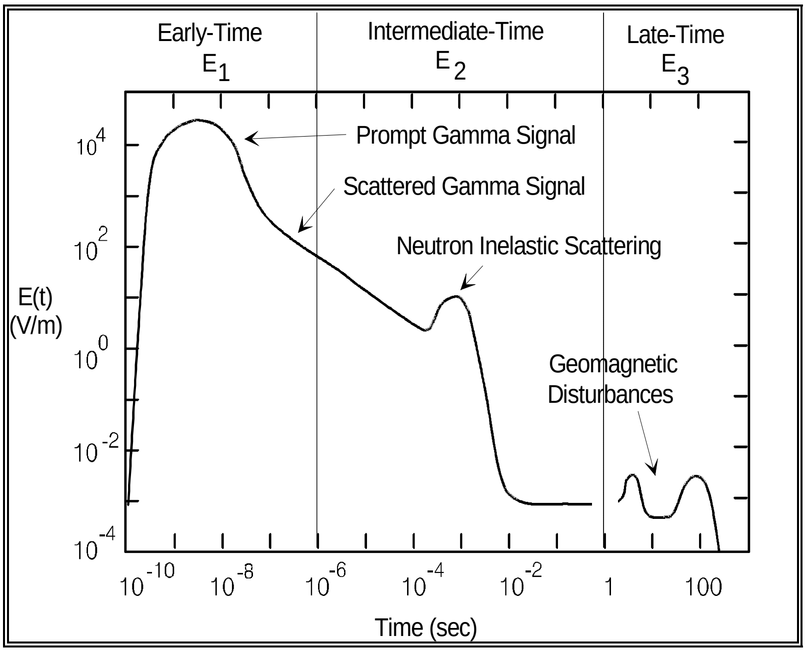


Figure 1. Qualitative example of the transient HEMP E-field environments.

HEMP Environments for System Assessment vs. System Design

To assess the effects of EMP on electrical systems, appropriate specifications of the E_1, E_2, and E_3 field components are required. These excitation fields, together with a specification of the initial condition, or state, of the electrical system, are used to determine the probable response of the system to this environment. For localized systems, such as a vehicle or small protected facility, the dominating response mechanism is the early-time E_1 field. The later time E_2, and E_3 field components become important for systems such as electrical power systems, in which conductors several hundreds of kilometers exist and can effectively couple to these low-frequency fields. In this manual, we will deal exclusively with the early-time HEMP environment.

Since it might be possible to infer information about a weapon design from actual EMP environments, such detailed information cannot be provided in an unclassified document. As a result, different unclassified EMP waveforms have been developed and utilized in the literature [4, 5, 6].

It is important to recognize that these generalized waveforms do *not* represent an actual EMP, but attempt to incorporate the potentially damaging features of EMP, such as a large peak amplitude, a fast rise-time, and a long fall-time. Such an EMP waveform is referred to as a "bounding waveform", and is used most effectively in *designing* a hardened military system where survivability is of prime importance. Typically, this worst-case HEMP environment is applied with

4. K.W. Klein, P. R. Barnes and H. W. Zaininger, "Electromagnetic Pulse and the Electric Power Network," *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-104, No. 6, June 1985.
5. P. R. Barnes, E. F. Vance and H. W. Askins, Jr., *Nuclear Electromagnetic Pulse (EMP) and Electric Power Systems*, ORNL-6033, Martin Marietta Energy Systems, Inc., Oak Ridge National Laboratory, Oak Ridge, TN 37831, April 1984.
6. *EMP Engineering and Design Principles*, Bell Laboratories Publication, Whippany, NJ, 1975.

the angle of incidence and polarization chosen so that the induced system response is maximized. The design of a HEMP-hardened system then proceeds with this worst-case response as a design criterion for the expected system excitations.

In performing a realistic assessment of the effects of HEMP, a worst-case definition of the environment is inappropriate. The actual HEMP environment can vary considerably in pulse shape, amplitude, polarization and angle of incidence at different observation locations on the ground. This variation of these parameters away from the set of values providing the worst-case response gives to system responses to HEMP that are typically much smaller than those for the bounding waveform. If a bounding EMP waveform were to be used in the assessment of an extended electrical system, such as the electric power network, unrealistically large estimates of the system responses would be obtained and the resulting assessment of a system response would be too pessimistic. Consequently, for a realistic assessment of the effects of HEMP on a system, the definition of the excitation environment is of key importance.

A Simple Definition of the Early-Time HEMP Waveform

Keeping the above-mentioned limitation of specifying a bounding waveform in mind, a commonly-used bounding HEMP environment for the E_1 field is the Bell Laboratory waveform which is defined as a simple double exponential function as

$$E(t) = E_o \, \Gamma \left(e^{-\alpha t} - e^{-\beta t} \right)$$

with E_o = 50,000 V/m, $\alpha = 4 \times 10^6$ sec, $\beta = 4.76 \times 10^8$ sec and Γ is a normalization constant so that the peak value of the E-field is actually E_o.

This transient waveform can be thought of as arising from a superposition of many sinusoidal waveforms of different amplitudes and phases (i.e., the frequency-domain spectrum). The Fourier transform of the double exponential waveform above can be obtained analytically, yielding the following expression for the spectrum of the incident HEMP:

$$E(j\omega) = E_o \, \Gamma \left(\frac{1}{\alpha + j\omega} - \frac{1}{\beta + j\omega} \right) .$$

Figure 2 illustrates the transient E-field waveform for this HEMP environment and the corresponding frequency-domain spectrum is shown in Figure 3.

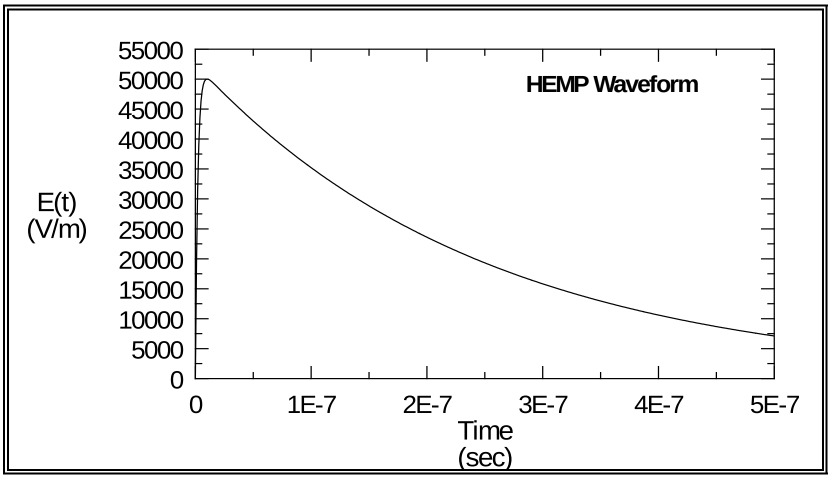


Figure 2. Transient HEMP waveform.

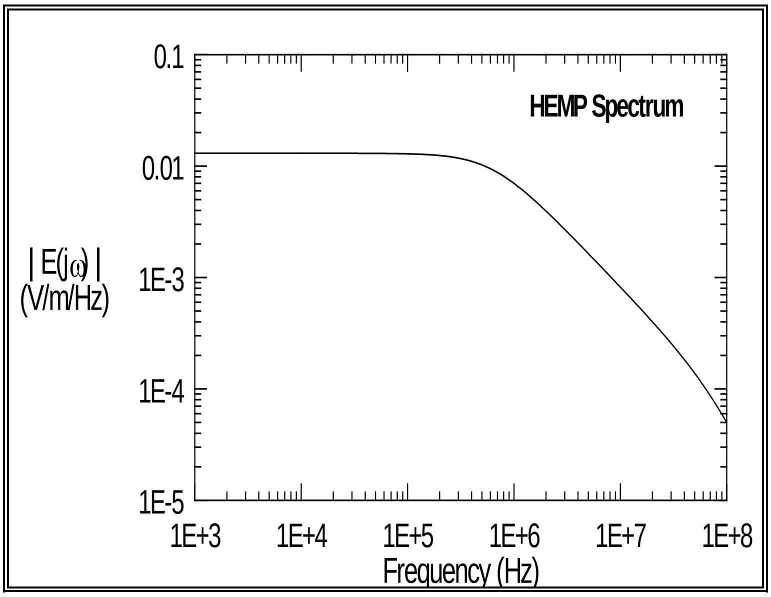


Figure 3. Frequency response of HEMP waveform.

Polarization Components of the HEMP

On the ground, the early time E_1 pulse appears as a transient plane wave arriving from the direction of the burst point. This is illustrated in Figure 4. Either a vertically-polarized field, a horizontally-polarized field, or a combination of the two, are possible, depending on the relative location of the observer to the burst point. Studies have shown, however, that the majority of observation locations on the earth surface will experience an incident field that is primarily horizontally-polarized. Consequently, simulations of HEMP effects on systems frequently use an antenna or simulator producing a horizontally-polarized E-field.

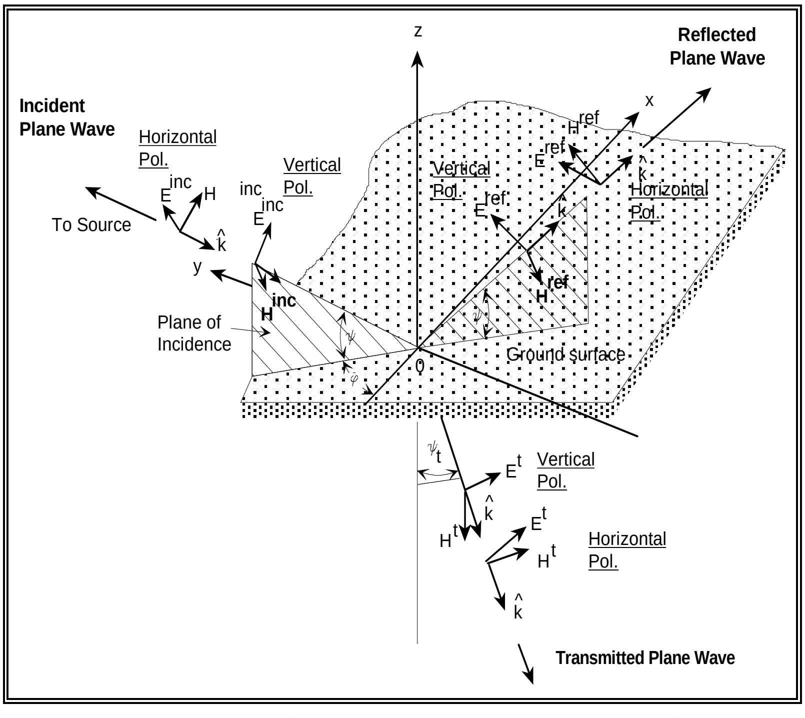


Figure 4. Incident, reflected and transmitted plane waves for E_1.

Effects of the Earth on the HEMP Fields

The incident HEMP field is reflected from the earth, and it is the sum of the incident and ground-reflected fields that excites the system. Thus, the specification of the incident HEMP field alone is not sufficient for evaluating a system response. The ground reflection is also important.

The reflected fields are described in the frequency domain by the Fresnel reflection coefficients which depend on the earth parameters and the angle of incidence of the EMP. Appendix A summarizes the important equations describing the reflected and transmitted fields in the earth, and illustrates the results of waveforms and spectra for different parameters.

Need for System Testing

HEMP testing of an electrical system is necessary because mathematical and numerical models of the system cannot provide sufficiently accurate results to give a high confidence level in the assessment of a system's survivability. This is discussed in Appendix C of this manual. Many different factors enter into the decision to perform an EMP test:

- relative importance of the system and its survivability requirements
- type of system, its physical configuration and the location
- available funds, time and personnel for testing, and
- desired accuracy of the results

Prior to determining the test requirements for a system, the above factors must be carefully weighed to see if a test is really needed.

Types of HEMP Tests

There are several different types of tests that can be performed on systems to determine the response to a HEMP excitation. Some tests are rather simple and straightforward, while others require large facilities and significant data processing capabilities. This section will briefly describe the major types of HEMP tests

System-Level Transient Tests

Perhaps the most through test of a system (aside from using an actual nuclear environment) is to perform a threat-level test on the entire system.

Description

This type of test involves locating a threat-level, pulsed EMP simulator near the facility being investigated, and conducting a series of measurements by changing parameters such as the angles of incidence, the system's electrical configuration (i.e., doors open or doors shut, etc.)

Figure 5 illustrates an EMP simulator similar to the Swiss MEMPS facility, together with some equipment under test for such a full-scale transient test. The biconical pulse generator located at the top of the simulator antenna structure launches a horizontally-polarized, transient EM wave with an electric field amplitude approaching 50 kV/m down to the equipment. An external electric (or magnetic) field sensor provides a measurement of the excitation field, and various measurements of the system response (involving internal current or field probes, for example) are made.

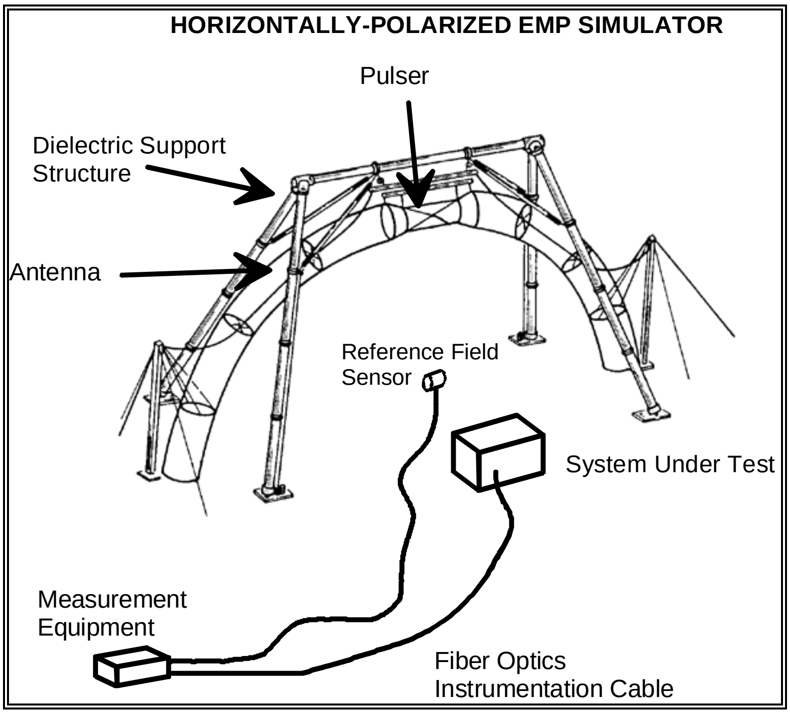


Figure 5. System-level testing using a threat-level EMP simulator.

Connections between the reference sensor, the sensors within the system under test and the instrumentation equipment are usually made using fiber optics transmission equipment so as to eliminate any adverse effects of electrical conductors on the system measurements.

Typically, large amounts of transient data are recorded and saved in this type of test for analysis after the test is completed. The results of the post-test analysis are usually expressed as a probability of survival of the system in the event of an HEMP event, and involve the concept of waveform norms. Details of how the determination of the system survivability is estimated are discussed in Appendix C, and norms are discussed in Appendix D.

Advantages

The principal advantage of this type of test is that the entire system is subjected to the desired threat-level environment. As a result, any nonlinear protection devices will be stressed and the resulting system response will include the effects of these elements. Furthermore, the effects of other unintended nonlinearities, such as flashovers in cables which are very difficult to predict analytically, will be included.

Disadvantages

The equipment involved in such tests is bulky, expensive and not easily transportable. Consequently, a fixed-site simulator is usually used for this type of testing. If the system to be tested cannot be easily moved, this test is difficult to conduct. Furthermore, there is usually a large amount of data generated by this type of test, and the post-test analysis effort can be considerable.

CW Field Illumination Tests

An alternative to the full-scale, threat level pulse testing it to use the CW field illumination test concept. This type of testing is the subject of this manual.

Description

The CW test concept is similar to that of the system-level pulse testing concept in that a radiating structure (i.e., antenna) is located near the system under test, as illustrated in Figure 6. Unlike the pulse test, however, the excitation of the antenna is time harmonic and is swept through a range of frequencies, starting at a low frequency of 10 to 100 kHz and stopping at a high frequency of 100 to 200 MHz. Some newer CW testing systems will operate up to the GHz frequency range.

The basic goal of the CW test is to measure a transfer function from a suitable reference EM field quantity outside the facility to a response inside the facility. As this measurement is conducted in the frequency domain, the transfer function is a complex-valued function, characterized by its magnitude and phase, or conversely, by a real and imaginary part.

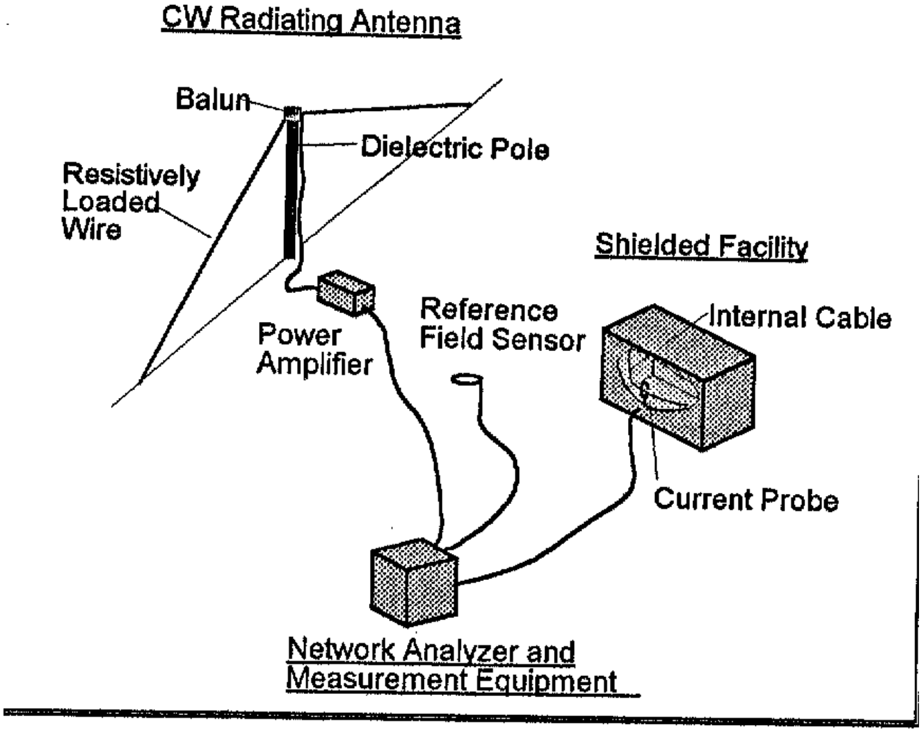


Figure 6. Configuration for CW testing.

Suitable external reference quantities include a components of the incident or total E or H-fields, a current induced on a long external cable, or perhaps the input current in the CW antenna itself. In cases when the measured response is to be extrapolated to a HEMP response, the choice of the external reference must be made so that it can be related to an incident HEMP field.

Internal response quantities can include E and H-fields inside the facility, currents on internal cables, and voltages at equipment terminals.

Additional details on the antenna, field sensors, network analyzer and other equipment needed for this type of test are provided later in this document.

Advantages

This form of testing has several advantages over the full-scale pulse testing described earlier. The equipment used is readily available and significantly less costly than for pulse testing. Furthermore, the entire system can be easily transported to remote sites and quickly erected.

Because of the narrow-band characteristics of the excitation and measurement process, the effects of noise can be reduced. Typically, it is easier to get a "clean" cw spectrum than to get a clean transient waveform.

The peak input power into the antenna is low - usually on the order of 50 to 100 W. This power, moreover, is swept across the frequency band in a relatively short period of time (on the order of minutes) and any interference to communications services is minimal. For special cases where it is necessary to prevent transmission at specific frequencies, the operation of the CW system can be modified to eliminate transmission at the selected frequencies.

Disadvantages

The major disadvantage of CW testing is that because of the low power level and non-transient mode of operation, nonlinear protective devices within the system are not triggered. In addition, other unpredictable nonlinearities, such as cable insulation flashover, will not be noted. Consequently, this test method only provides the linear (or low-level) response and systems tested in this manner may appear to be more vulnerable than they really are, since the nonlinear effects can add extra protection - if they operate.

This deficiency may not be bad in some circumstances, as many systems used both nonlinear devices together with electrical filters. CW testing on these systems provides a reasonable worst-case estimation of the response - namely the response that would be obtained if the nonlinear device were not to function properly. Moreover, there is a way to analytically combine the low-level CW measurements of a system with the nonlinear device characteristics to permit a calculation of the pulsed, nonlinear behavior of the system. This approach is developed in [7] and is summarized in Appendix B.

A second disadvantage of this test approach is that the final measured result is usually not the final desired result. To obtain the extrapolated transient HEMP response, some additional data processing must be undertaken, and this can give rise to errors in the resulting transient response.

Current Injection Testing

The two previous tests are applied to the entire system. An alternate test concept is to excite only parts of the system. One way of doing this is to identify important electrical conductors entering a facility and inject pulse or CW currents onto the cables, as illustrated in Figure 7. The injected currents will then re-distribute themselves within the facility, and provide an indication of the system response under external field excitation conditions.

7. Liu, T.K. and F.M. Tesche, "Analysis of Antennas and Scatterers with Nonlinear Loads," *IEEE Trans. AP*, Vol. AP-24, No. 2, March 1976.

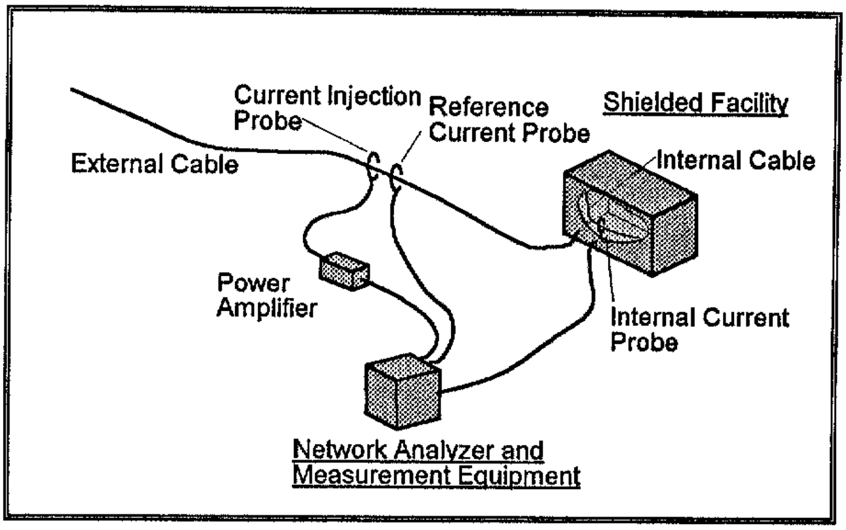


Figure 7. Current injection testing of a facility.

Description

Typically for this type of test, a pre-test analysis must be performed to identify the important conductive current paths into the facility or system being considered. These might include power lines, communication cables or mechanical conductors. For each of these conductors, an analysis of the external EM field coupling must be performed to estimate the amplitude and waveshape of the HEMP response. Then, a current injection source having the proper transient (or spectral characteristics) is applied to each of the selected conductors and the internal responses are measured.

Advantages

The advantage of this type of test is that pulse injection equipment is typically smaller and less expensive than the full-scale simulator and associated equipment. Furthermore, threat-level currents are easier to induce by pulse injection methods than by an EM field illumination. When operated in a pulsed mode, this type of testing also provides the possibility of exciting nonlinear devices located along the conducting paths being excited. Thus, a pulsed current injection test and a CW field illumination test can complement each other.

Disadvantages

This type of test is fundamentally incomplete, as the possible synergistic effects of simultaneous excitation of the whole system are not taken into account. Thus, there is always some unknown error in this simulation technique. Furthermore, a crucial part of this test is the linking of the injected current levels on the external conductors to the incident HEMP field is often done by analysis, and consequently, it will have uncertainties associated with it.

Partial Illumination Testing

Partial illumination testing is the counterpart to pulse injection testing, except that the system excitation is viewed as arising from a partial EM field excitation of the system instead of a current injection on one of the system's conductors. This testing approach is sometimes denoted as the PARTES concept [8].

Description

This test is accomplished by using small electric or magnetic dipole antennas referred to as "drivers" at various locations on the exterior surface of the system being tested. Locally, these drivers produce an EM field excitation of the system and a suitable internal response can be measured. Either CW or pulse testing is possible using this concept.

By considering a suitably large number of driver locations and by analytically combining the measured responses for each, the response of a plane wave excitation of the system can be inferred.

Advantages

The main advantage of this approach is that electrically large systems can be tested. Although such systems might require many measurements as the driver location is changed, the method can allow for such testing.

Disadvantages

The principal disadvantage of this testing is that considerable analytical work must be done to correctly combine the measured data files to obtain the final desired result. In addition, there is always the open question of deciding upon the best locations of the driver sources. Finally, the question of nonlinear device operation is not addressed completely in this type of test.

Sub-System and Component Testing

Moving away from full-scale system testing, there is testing at the sub-system (i.e., "black-box") level and at the component level.

Description

In this test, a piece of electronic equipment or perhaps even a discrete component within the equipment is tested for its response. In doing this the HEMP stress at the component must be determined, wither from a test or by analysis.

Advantages

Component testing is relatively inexpensive and is rapidly conducted. Furthermore, if the component or equipment fails, hardening procedures can be determined by analyzing the mode of failure of the device.

Disadvantages

The major disadvantage of this type of testing is that it is difficult to insure that the component is tested with the same electrical stress that would be found under HEMP excitation conditions. The HEMP stress deep within a system is difficult to know exactly without performing a system level test. (If such a test were to be performed, there then would be no need to perform a component test!)

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8. Baum, C.E., "The PARTES Concept in EMP Simulation", AFWL EMP Sensor and Simulation Note 260, December 9, 1979.

Typically, the HEMP stress at a component is usually determined by analysis and this is then used to design the proper pulse or CW excitation of the component.

The Smoke Test

The smoke test, also called the "General's Test", is the simplest HEMP test to perform. It is a threat-level, transient system test designed to see what happens to a system when exited by HEMP.

Description

In this test concept, the system is located in the working volume of a threat-level simulator and the simulator is pulsed one or more times. Aside from the field reference sensor and associated recording equipment, no other data acquisition is needed. It is basically a pass-no pass test, and is sometimes referred to as a “go-no go” test.

Advantages

This test is rapid to conduct, needs minimal personnel and planning, and aside from the fixed costs of the system being tested and the simulator facility, it is inexpensive.

Disadvantages

There are several disadvantages with this type of test which need to be considered in view of the test’s simplicity. First, there is a risk that the system will be permanently damaged by the testing and that costly repairs to the system will be needed. Second, there is usually only one “example” of the system tested. If it survives the test, there is no guarantee that another system of the same type will have the same behavior. And finally, with this type of test, there is no information as to a possible safety margin. (See Appendix C).

Definition of the Stress/Response Interface

In each of the above tests, it is clear that there is a stress/response interface defined. This interface is the point at which the electrical stress or excitation provided by the external HEMP environment is defined and the process of determining the final system response is begun.

For system-level tests, such as the full-scale transient test or the CW test, this interface is at the external system surface and the HEMP stress is just the incident plus ground-reflected EM field. The internal response in this case is usually very complex, as it depends on the many coupling and propagation paths within the system.

At the other extreme, there is the component test, where the stress-response is at the terminals of a component. Here, the electrical response of the component is simple to determine, but the HEMP stress on the component is complicated and difficult to know exactly.

Every HEMP test, therefore, contains the following key aspects:

- definition of the location of the stress/response interface within the system,
- estimation (by analysis or by test) of the HEMP stress at the interface,

- determination (by test or by analysis) of the system's ability to withstand the HEMP-induced stress at the interface (i.e., the system strength), and
- a comparison of the stress/strength relationships to determine the probable system behavior.

Use of Test Data

Data acquired under test programs can have several different uses, depending on the nature of the test and on whether the data are transient or CW.

Acceptance of New Systems

A new system which is designed to be hardened against the effects of HEMP will have one or more hardness specifications for the design. At the end of the construction of the system and just before formal delivery by the manufacturer, it is common to require an acceptance test to demonstrate that the system meets the required HEMP specifications.

The data acquired in test programs can be used for acceptance purposes. Such tests can be simple "proof" tests where the survivability of the system is validated, or they can amount to detailed measurements of stress levels at the defined interfaces and a verification of safety margins by determining the strength of critical components or critical inputs to subsystems.

System Assessments

For a system that is not subject to HEMP survivability requirements, or which has not been previously tested, a test program can provide data useful for assessing the current state of HEMP hardness. This amounts to making detailed measurements of HEMP-induced stress at the defined interface points and then comparing these stresses with the known (or estimated) susceptibility of the components. This comparison of the stress/response characteristics permits an estimation of the system behavior.

Hardness Surveillance Monitoring

Once a system is determined to be hardened against HEMP, periodic measurements of the system can be made to insure that the state of hardness remains intact. Frequently, such measurements consist of CW transfer functions from an observable outside the system to one inside. Changes of this transfer function over a period of time indicates a degradation in the hardness of the system or a reduction of the safety margin.

System Design

A final use of test data is in the area of new system design. Experience in system testing can lead to an understanding of how to better harden equipment and how to design, from the ground up, a HEMP-hardened system.

Uncertainties

In each of the testing concepts described above, there are uncertainties which add errors to the final test results. Generally, these errors are difficult to know quantitatively, but a list of the uncertainties will at least help the test personnel to be aware of potential difficulties with the testing. Significant uncertainties can result from the following:

- a poor knowledge of the incident HEMP environment and how it relates to a specification of the simulation excitation function,
- an imprecise knowledge of the electrical properties of the ground,
- spatial variations of the simulated HEMP field,
- errors in the calculations for extrapolating a low-level response to HEMP levels,
- measurement errors,
- lack of precise information of the failure levels of components, and
- unknown degradation of the system hardness over time.

A final source of uncertainty in the test process is often introduced by the desire to know too much from a single limited test. Only a finite number of excitations can be considered in a test, and consequently, any statistical information about the probability of system survival against HEMP will be incomplete. Furthermore, even of one system is thoroughly tested and characterized, it is difficult to extrapolate the results to an ensemble of similar systems. Each system can be (and usually is) electrically distinct from the others, and consequently, the details of the HEMP responses can vary considerably from system to system. This is why the use of a safety margin in hardening is useful.

Equipment for CW Testing

Overall Measurement Configuration

Figure 6 illustrated a view of a CW test site, including the facility being tested, the CW antenna, the measurement equipment enclosure and associated connections. Figure 8 below provides more information on the details of the configuration of the measurement equipment connections.

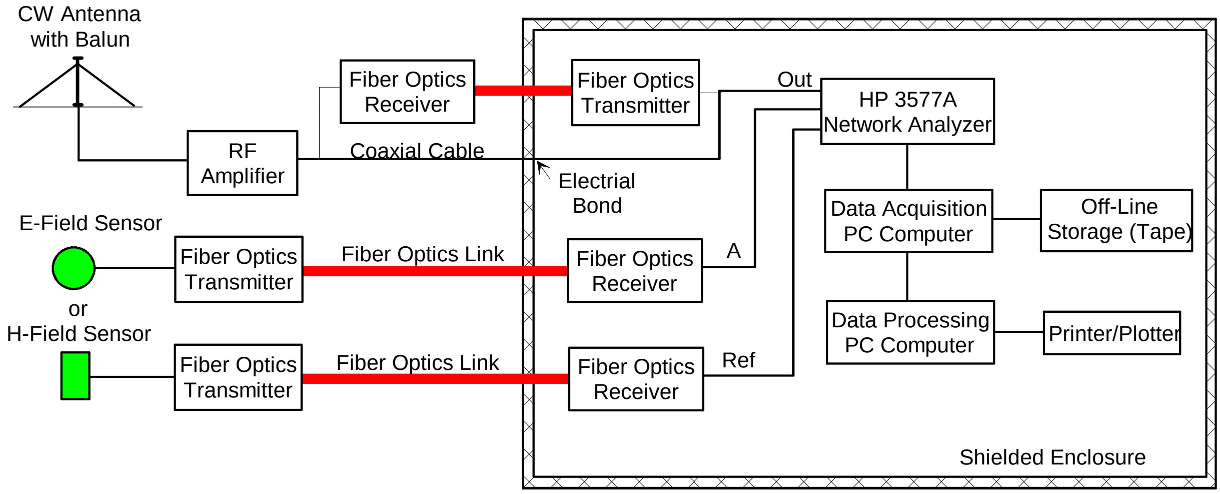


Figure 8. The CW measurement setup.

The heart of the system is a network analyzer, which has the capability of measuring two responses simultaneously: a reference channel and channel A, which is the desired system response. The network analyzer is controlled by a personal computer (PC) by way of the standard IEEE interface bus. Both pieces of equipment should be located in a shielded region, well away from the radiated field produced by the incident field of the CW antenna.

Associated with the measurement computer is a data analysis computer. This analysis function could be contained within the measurement computer itself, or it could be by way of a separate computer, linked directly to the measurement computer by an RS-232 or IEEE bus, or linked indirectly by passing acquired data manually on diskette.

The external field/current sensors for the reference and the measurement channels should not violate the shield topology surrounding the measurement equipment. A common way of insuring that the shielding is maintained is to use fiber optic links for both of these channels. This requires a conversion of the electrical signals at the sensors to optical signals by means of a fiber optics transmitter, the transmission of the optical signals via an optical cable, and the re-constitution of the electrical signal within the equipment enclosure by a fiber optics receiver.

The network analyzer provides an output RF signal which is swept over the frequency range of interest. This signal is transmitted via a 50 Ω coaxial cable to an RF power amplifier, which boosts the signal level and then feeds it to a specially designed antenna to radiate the signal.

The coaxial cable shield should be electrically bonded to the shielded equipment enclosure at the penetration point to isolate the external and internal regions, as indicated in the figure. In addition, ferrite bead attenuators can be located at about 30 cm intervals along the cable to help minimize the unwanted external field coupling and propagation along the cable. An alternative to the use of a hard-wired connection between the network analyzer and the amplifier is to use a fiber optics link, as illustrated in the figure.

The following sections describe in more detail each of the elements in this CW measurement set-up.

The Antenna System

Several different types of radiating antennas are possible, depending on the desired polarizations and the frequency range of operation. For frequencies between about 1 to 100 MHz, the antenna designed by EMTECH shown in Figure 9a radiates an E-field in the direction broadside to the antenna that is mainly horizontally polarized. At lower frequencies, the radiation efficiency drops and at the high frequency end, the radiation field contains side lobes due to the large electrical size of the antenna.

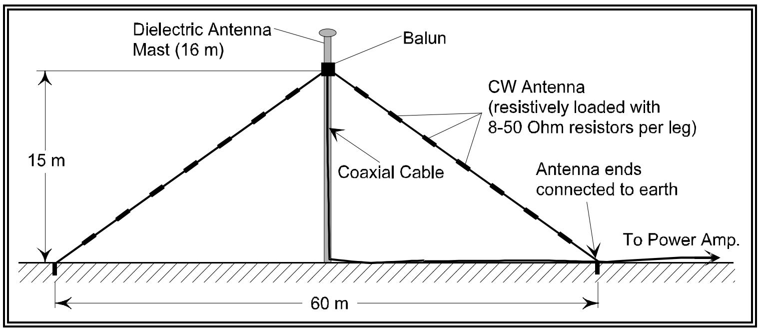
The antenna is connected to the earth at both ends, through a resistance on the order of 400 to 500 Ω. This electrical connection serves to enhance the low-frequency radiation of the antenna.

The antenna is fed at its apex by a power amplifier which is connected via a coaxial cable. This unbalanced line must be matched to the balanced antenna input at the top of the dielectric support tower by a balancing transformer, referred to as a balun. Care must be exercised to insure that during the testing the power level of the amplifier does not exceed the rated operational power level of the balun.

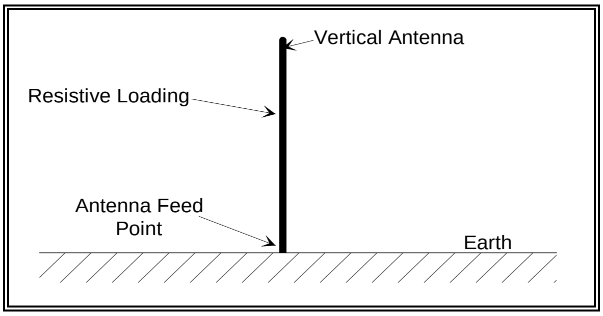
If a vertical incident E-field is desired, a vertical antenna can be employed. This is illustrated in Figure 9b. A vertical conductor is fed by a voltage source between the antenna base and the ground, producing a vertically polarized E-field. At low frequencies (i.e., frequencies such that $\lambda >$ the antenna length), the radiation from this type of antenna is very poor.

Figure 9c illustrates another type of radiating antenna, known as the $P \times M$ antenna. It appears as a simple end-fed transmission line having a load at the end equal to the characteristic impedance of the line. This line has the beneficial property of radiating an EM field having a characteristic impedance of exactly 377 Ω - even at very low frequencies. This radiation occurs in the "backward" direction, that is to say, to the right of the source in Figure 9c. This antenna is effective in this manner only for low frequencies, however. As the frequency begins to increase so that $\lambda >$ the line length, the beam of the radiation begins to move to the forward direction and the antenna becomes the well-known Beverage antenna.

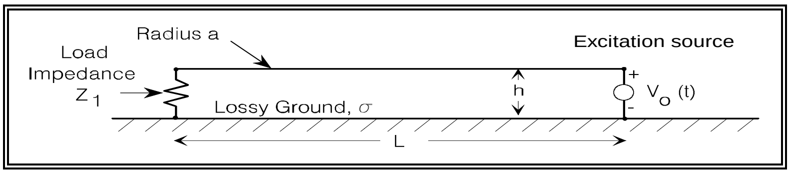
For both the horizontal and vertical antennas, it is important to add resistive loading along the wires. This resistance serves to damp-out the natural antenna resonances, thereby creating a smoother spectrum. In addition, by properly choosing the level of impedance loading on the antenna, the E/H ratio of the fields near the antenna can be made more like that of a plane wave in free-space, namely 377 Ω.



a. Horizontally polarized antenna (EMTECH)



b. Vertically polarized antenna



c. The P x M antenna

Figure 9. Various antennas for CW testing.

As the presence of the antenna feed cable can perturb the radiated fields, care should be used in locating the cable near the antenna. For optimal performance, the cable should run directly down the support mast and then out from the antenna in a perpendicular direction to the antenna broadside. Periodically-placed ferrite beads on the exterior of the coax can help to eliminate unwanted coupling effects to this cable.

Power Amplifier

The power amplifier takes a low-level CW signal from the network analyzer as an input, amplifies it to a power level on the order of 50 W to 100 W, and then feeds the signal to the CW antenna through a 50 Ω coaxial cable. One possible amplifier is the Amplifier Research AR 100L, as shown in Figure 10, which operates from a low frequency of 10 kHz to a high frequency of 250 MHz.

The frequency of the signal provided to the amplifier is swept over a range of frequencies by the network analyzer. The amplifier should not be overdriven at its input by the analyzer, and the output power does must not overdrive the antenna balun, which would result in possible damage to the balun coils.

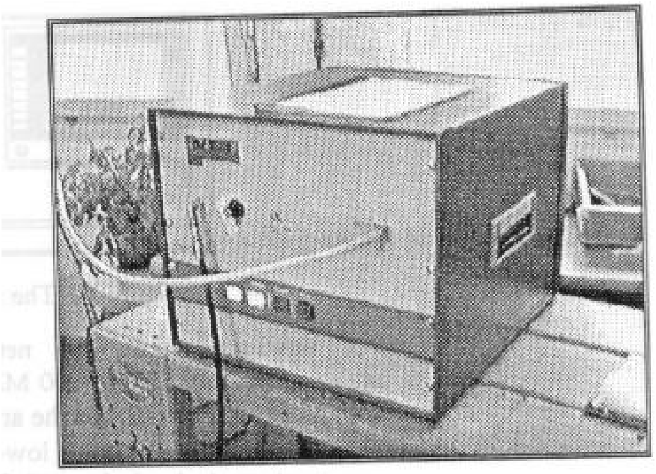


Figure 10. The power amplifier.

The power amplifier is located near the base of the antenna so that the feed cable from the amplifier to the antenna balun is as short as possible. This is illustrated in Figure 11.

Also located near the amplifier is a motor generator unit which provides the necessary power to the equipment. Ideally, the power cable cord should be as short as possible and should be located to lie in a direction perpendicular to the antenna.

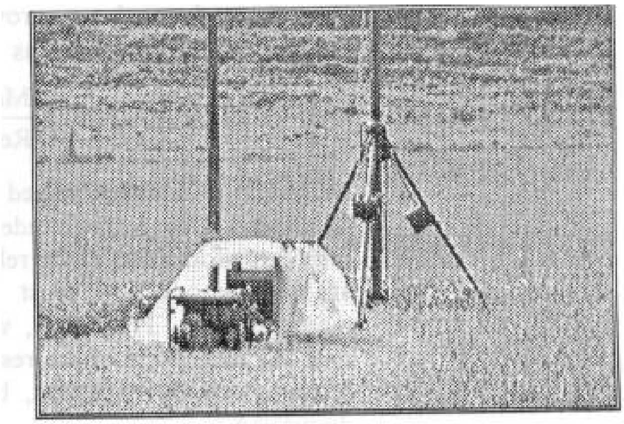


Figure 11. Placement of the power amplifier at the base of the antenna.

The Receiver (Network Analyzer)

The receiver for this system is the network analyzer. One such unit is the Hewlett Packard HP 3577A as shown in Figure 12.

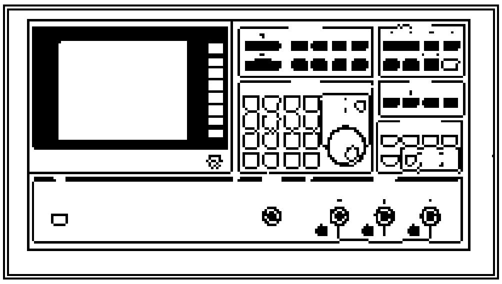


Figure 12. The network analyzer.

For this application, the network analyzer is swept from approximately 10 kHz to 200 MHz in a mode that is controlled by the computer connected to the analyzer through the IEEE bus. The network analyzer provides a low-level, 50 Ω sinusoidal output as it sweeps through the designated frequencies which serves to control the aforementioned power amplifier.

Two input channels to the network analyzer are used: one is the reference channel from the reference sensor located on the exterior of the facility and the other is the measurement channel which is connected to a suitable measurement sensor or probe, which is normally located inside the facility. As noted in Figure 8, these sensor connections should be made with fiber optics transducers, so as to eliminate electrical coupling to the measurement equipment.

The network analyzer provides a transfer function for the measurement $T(\omega)$ defined as

$$T(\omega) = \frac{\text{Measured Response}}{\text{Reference Response}}$$

which is a complex-valued quantity defined at each angular frequency ω by a magnitude and a phase. The phase quantity provides information of the relative times of arrival of the responses at the sensors and must be retained for high-quality CW measurements. Frequently, when CW test results are presented, only the magnitude of the response is plotted and discussed. The phase is equally important, but frequently it is neglected in the discussion.

Reference and Response Sensors

Several different types of sensors are available for CW test purposes. Many of the sensors are the same as those used for transient testing, although some types of antennas which are not useful for transient testing can be used. These include the log-periodic class of antenna which has a poor phase response for radiating or receiving pulsed signals. This section will describe some of the sensors used for CW measurements.

B- and H-field Sensors

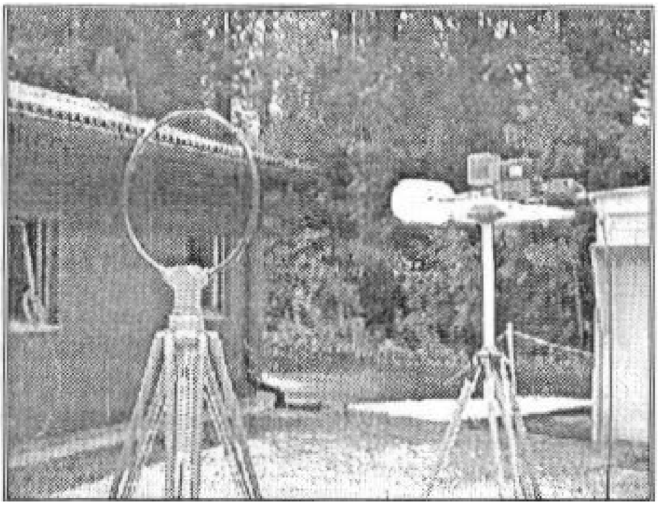
Sensors for measuring the magnetic field are essentially small loops which sometimes may be wound in such a way as to minimize any additional response that the E-field may have on the sensor. All of these sensors create a voltage across the loops that is proportional to the time-rate of change of the magnetic flux passing though the loops. Thus, they are often referred to as B-dot sensors, as they actually respond to the derivative of the B-field.

The basic limiting factor of these types of sensors is their size, since the sensor must be electrically small in order for it to function properly. Figure 13 illustrates several different types of magnetic field sensors that can be employed in CW tests. In Figure 13a, the loop antenna on the left is a low-frequency active antenna made by Rhode & Schwarz. It is designed for measuring the B-field in a range of 10 kHz to 30 MHz, and it is sensitive to the component of the B-field passing perpendicularly through the loop.

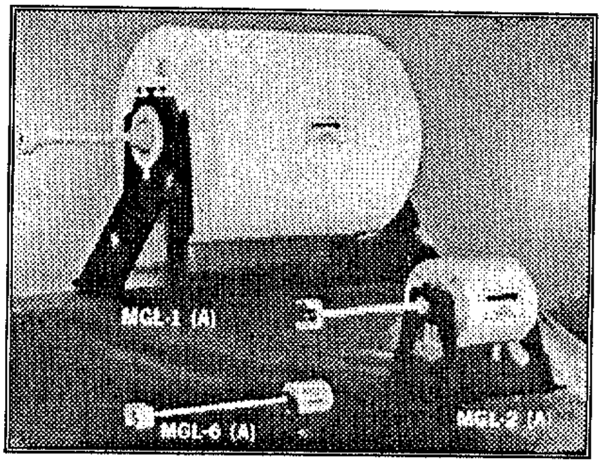
The sensor on the right is a Thomson-CSF H32 active (integrating) H-field sensor. It measures the H-field perpendicular to the cylindrical surface and operates in a range of 9 kHz to 150 MHz.

Figure 13b illustrates another type of B-dot sensor sold by EG&G in the U.S. The large MGL-1 sensor has a maximum frequency of 120 MHz and a rise time capability of about 3 ns. The smaller MGL-6 sensor has a maximum frequency of about 1.8 GHx and a rise time capability of about 0.5 ns.

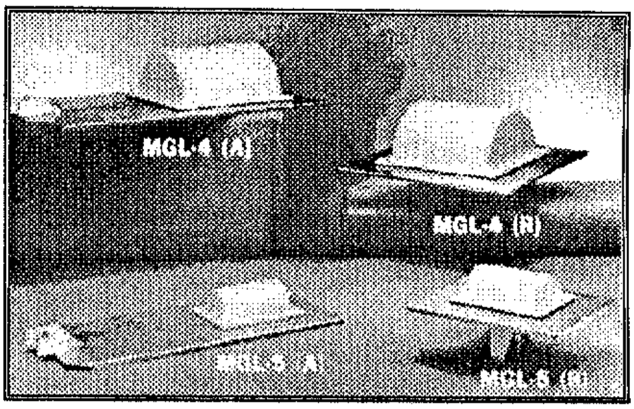
Figure 13c shows a half-loop B-dot sensor sold by EG&G for use in measuring the surface B-field on a ground-plane. (Note that this is equivalent to measuring the surface current.)



a. Free-field B-dot sensors from Rohde & Schwarz and Thomson-CSF



b. Free-field EG&G B-dot sensors



c. Surface-mount EG&G B-dot sensors

Figure 13. Magnetic field sensors.

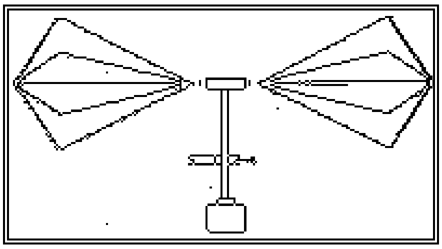
D- and E-field Sensors

Figure 14 shows several possible sensors for measuring the E-field. The antenna in Figure 14a is relatively large (about 1.3 m in overall length), and this limits the upper response of the antenna to about 30 MHz. This sensor responds to the E-field which is parallel to the long dimension of the bicone, and it provided with a calibration factor relating the measured voltage at its terminals to the incident E-field at a specified frequency.

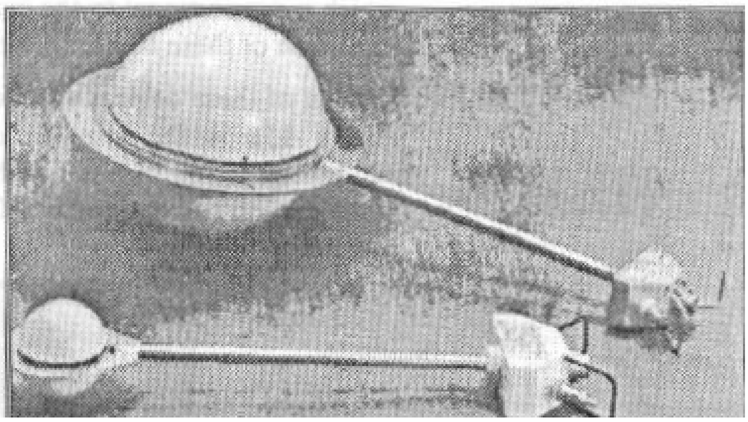
Other types of E-field sensors are possible. Figure 14b illustrates several hollow spherical dipole (HSD) sensors sold by EG&G, which are used to measure the E-field in free space. This sensor provides a response that is proportional to the time-rate of change of the E-field (actually it is the displacement field $D = \varepsilon E$ that is measured). The larger of the two sensors has a maximum frequency of about 45 MHz with a rise time measurement capability of about 7.4 ns. The smaller unit (the HSD-4) has a maximum frequency of 150 MHz and a rise time of 2.3 ns.

For measuring the D-dot field on a groundplane, the sensors in Figure 14c can be used. These are basically one-half of the previous sensors, with the image in the ground serving as the other half.

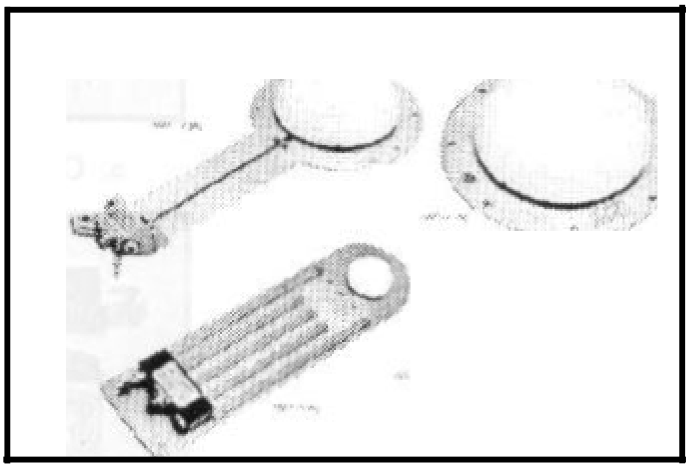
Other types of E-field sensors have rather odd cross-sectional shapes, as shown in Figure 14d. This is the asymptotic conical dipole (ACD) sensor which is designed to provide a known response by simply measuring some geometrical factor. This is known as "calibration by the ruler" and is only possible for a limited number of antenna shapes.



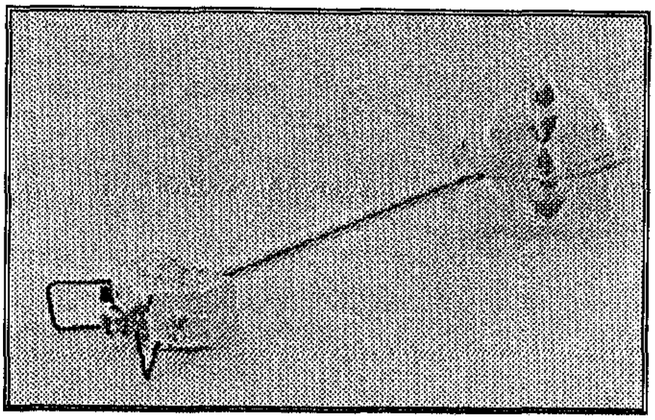
a. The biconical E-field sensor



b. Free-field D-dot sensors



c. Ground-plane mounted D-dot sensors



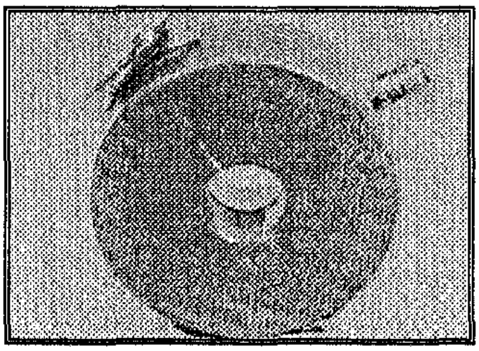
d. The ACT D-dot sensor

Figure 14. Various E-field sensors.

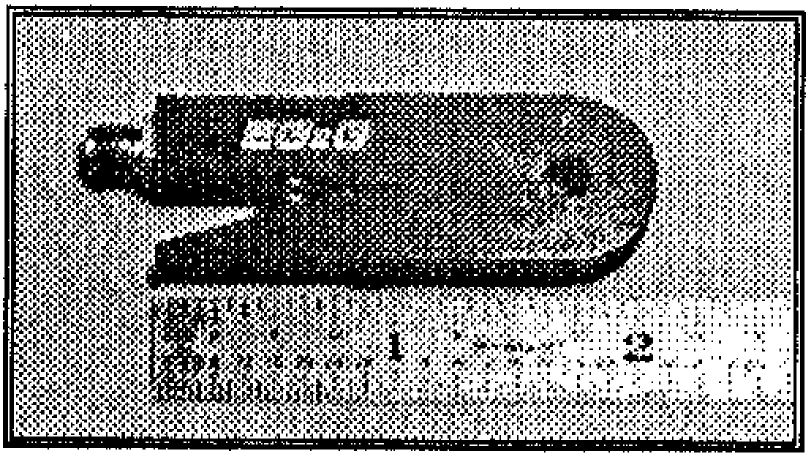
Current Sensors

Current sensors (or probes) are essentially small transformers which are clamped over a cable carrying a current and provide a voltage which is proportional to the current flowing through the cable. The operation of these devices is similar to that of a transformer.

Typical of these devices are the EG&G probes shown in Figure 15. Figure 15a is the snap-on current probe (SCP) which has a bandwidth of 100 kHz to 100 MHz. The smaller unit in Figure 15b is the clip-on current probe (COP) which operates from 200 kHz to 300 MHz.



a. Clamp-on current probe



b. Snap-on current probe

Figure 15. Current probes from EG&G.

Transmission Links

Fiber Optic Links

The Fiber Cable

Many different media are used to transmit information: e.g. wires, coaxial cables, wave guides and radio. For the highest quality signal transmission, hard-wired electrical connections form the sensors to the network analyzer are used. However, such wires can also pick-up part of the CW signal and give incorrect readings to the sensors. Furthermore, the presence of long electrical cables inside a facility can distort the normal EM field within the facility and may even introduce an inadvertent EM coupling path. As a result, the use of fiber optics links is often recommended.

Fibers optic systems need electro-optical transducers at each end of the transmission system. Despite the steadily declining cost of these components, they are still relatively expensive.

Weight is one of the main disadvantages of coaxial cables: the RG14 and RG19 cables weigh 350 and 1100 kg/km: a typical single-fiber cable weighs only 12 kg/km. This difference may become much more drastic in multichannel cables.

Noise immunity is often a problem in coaxial cables. They are sensitive to the electric and magnetic fields generated by machinery, lightning or EMP. Ground loops and oscillations are also severe problems in coaxial cables. Moreover any conductor acts as an antenna, either receiving or transmitting energy.

Fiber optics suffer from none of these effects, so they make an ideal transmission medium where EMI is concerned. A typical example is the communication link between the reference or measurement sensor of the CW system and the network analyzer. The use of fibers optic links eliminates filtering and grounding problems, and minimizes to a few µm the aperture sizes for bulkhead connectors in the shielding structure. An additional benefit is that the fibers are free from crosstalk: even if light is radiated by one fibers it can not be recaptured by other fibers.

Figure 16 compares the attenuation and bandwidth characteristics of two RG cables with those of typical fibers. The skin effect in a coaxial cable causes the attenuation to rise with the square root of the frequency, typically starting below 1 MHz. As a result, for very long coaxial lines, serious dispersion effects arise which must be corrected with filters.

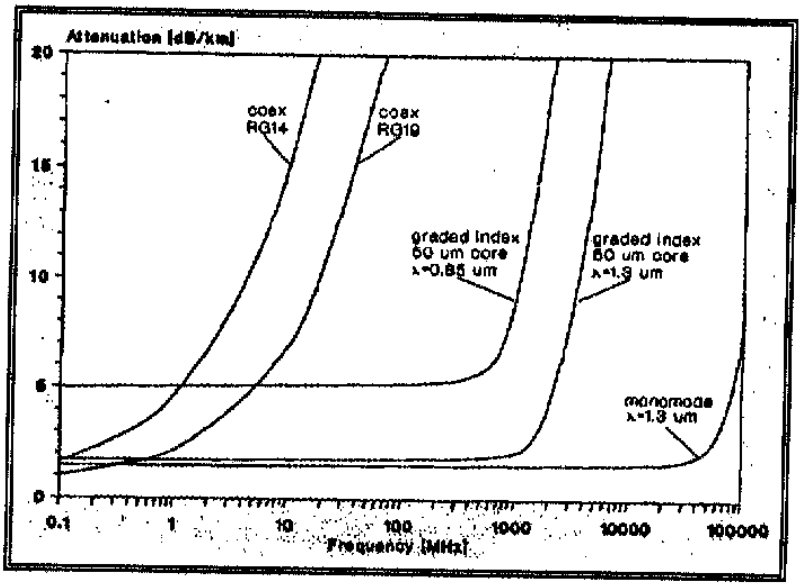


Figure 16. Attenuation of coaxial lines and fiber optics cables as a function of frequency.

Transducers

Transducers must be located at each end of the fiber optic cable to convert the electrical signals to modulated light beams and to then convert the light back to electrical signals. An example of such a system is provided by the Italian company, TESEO with their Analog Fiber Optic Muitilink (AFOM) system, as illustrated in Figure 17. The heart of this system is a mainframe based on an internal bus, micro-processor controlled, called SLOT-BUS. It is able to house. power and interface different modules, thus allowing mixed systems to be tailored for specific applications.

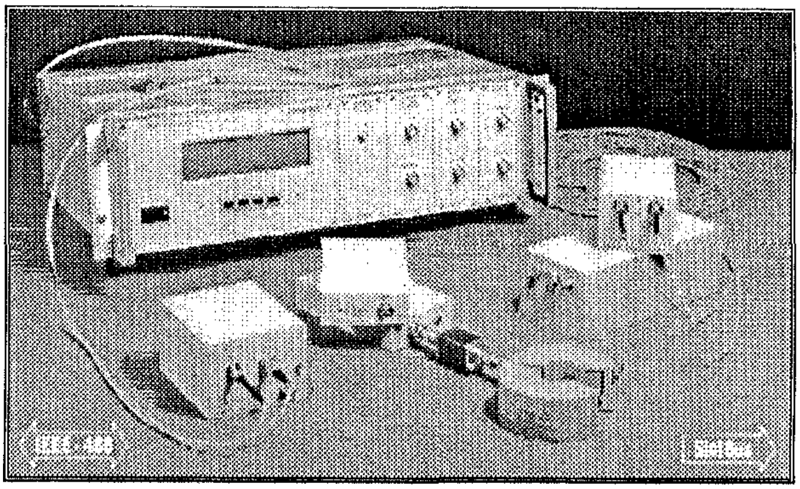


Figure 17. The TESEO AFOP fiber optic system.

A wide range of fibers optic plug-ins is available, providing a large selection of working modes (acquisition, telemetry, stimulation, EM field monitoring, audio and video transmissions), frequency ranges (from DC up to 1 GHz) and variable gain attenuation .

Each mainframe comes with an embedded IEEE-488 interface as well as keys for local operations: it lodges a large area backbit graphic display (LCD) to show the parameters of each plug-in and can house up to four plug-ins.

PLUG-INS

TESEO plug-in systems and electronic remote transceivers (satellites) are fiber optic communication systems for transmission and measurement of large bandwidth analog signals in hostile environments subject to electromagnetic interference.

A plug-in system consists of a base module fitting an AFOM-MF main-frame, a fibers optic cable for signals, a fibers optic cable for control if necessary, one or two battery powered, small sized, shielded (more than 200 V/m CW and 100 kV/m pulsed electromagnetic fields) satellites, and one or two battery chargers. Each plug-in can be individually managed by the microprocessor control system inside the mainframe.

Most satellites are remotely controllable via a dedicated control optic link. These satellites are powered by batteries which provide more than eight hours continuous operation. The maximum optic link length for standard models is l km.

The OAM acquisition plug-ins series offers clean waveform transmission from the satellite to the base unit over six decades bandwidth plus DC. Standard models range from DC to 1 GHz, with flatness better than ± 1. 5 dB over all the bandwidth. Instant bandwidth, low distortion and high signal-to-noise ratio output make these optics links extremely flexible. As an example of the electrical characteristics of several TESEO data acquisition plug-in units, consult Table 1.

Table 1. Electrical performance data for TESEO OAM Plug-in Units

Model	Indep. Ch/plug	Fraqu1ncy IOOIJO (CW)	Nominal output	Output	Input lo< nominal output	Input	: ni. 1 callbraHon	flb!• Cable type
OAMQ.1	2	DC+JOO ll&	IYpp	INC 5011	l+IOOVpp 6HlrangM	0111. IMll	NO	Mono (llgnoO
OAMOI	2	PC+IMl!z	IVpp	INC $011	l+500Vpp 9M,.fang91	BNC IMll	NO	Dual (Olgnld<I)
OAMI)f		4.Ht+ISMHI	IVpp	INC 50n	1+30Vpp 4"'-tangt:	INC 1M<l	NO	Mono lliQnall
OAMO.I	ii	W.11t>2 01111z.	OdBm	SMA 500	+1dlm dBllllPI	SMA $1111	IS	Dual l•lgn/clll)
OAM02	I	lkHz+IGl\i	OdBm	SMA 500	•"+1dBm 3dl1'•P1	SMA $0!1	Yli$	Dual lllgn/clrl)

Coaxial Cables

For cases where there is a minimal concern that the cable will conduct CW signals along the shield, or for cases when fiber optic cables are impractical (for transmission of RF energy, for example), coaxial cables can be used.

These cables should always be run close to a groundplane, so as to minimize any pick-up loop area, and if possible, the shields should be fitted with ferrite beads. Some special types of lossy-shield cables are also available.

In all cases, a general guideline is to minimize the use of these cables, and if they are used, to minimize the length of the cables.

Electrical Power

In a CW measuring system, electrical power must be provided to the following equipment:

- the RF power amplifier,
- the network analyzer and controlling computer,
- the analysis computer and printer/plotter,
- the fiber optics transmitter and receiver, and
- the E- and H-field sensors if they are active

It is important to insure that the CW excitation from the antenna cannot couple into the facility on the cable system which is used to provide electrical power to the above-listed components. Usually, this can be done by separating the power sources in to several parts.

For the CW antenna and the near-by power amplifier, a portable motor generator unit can be located near the amplifier to provide a source of "clean" power. Generally this is necessary, as the antenna should be located far from any perturbing buildings or other obstacles which will scatter the incident field. If there is a source of electrical power located near the antenna/amplifier location, it can be used to supply the needed amplifier power if an RF power line filter is used on the mains.

Often the network analyzer and other computer equipment can be connected to the electrical network of the facility being tested if the measurement equipment is located inside the facility. If the equipment is to be located inside a Faraday cage (as shown in Figure 8), it is important to be certain that the incoming power is properly filtered.

The power to the measurement end of the fiber optics transmitter and to the sensor is it is active is usually provided by battery sources. Usually, these batteries discharge rapidly, and in some tests, this is the limiting factor in trying to make a large number of measurements in a day's testing time. Careful consideration should be given as to the number of batteries needed and to possible test alternatives should all of the batteries fail.

Data Acquisition and Data Analysis Computers

The present-day capabilities of PC computers makes is unnecessary to use the older, larger and slower computers that have traditionally been used for data acquisition and analysis purposes, both for pulse and CW testing. For CW testing, the network analyzer can be controlled by a PC running a program written in Lab View. This program and its use is documented elsewhere [9].

Similarly, the initial data processing (plotting and correcting) of the raw data and the subsequent extrapolation analysis can be performed on a PC using the Advanced Signal Processing Program (ASPP) [10].

A typical measurement and control equipment configuration for CW testing is shown in Figure 18. Starting from the left of the photo, we see the following equipment:

- the laptop PC for the data analysis,
- the desktop PC for controlling the network analyzer
- a laser printer for both printed output and plots,
- the network analyzer
- a fiber-optics receiver (on top of the network analyzer), and
- an oscilloscope for off-line measurements of waveforms.

Other equipment, such as battery chargers, cable connectors, soldering irons, etc. are needed for such testing and should be included in an equipment list. As can be noted from this photo and the others of the CW system, all of the equipment needed for the test can be easily carried and installed by three people.

9. Nyffeler, Marcus, "Users Manual for the Lab View CW-DAS", NEMP Laboratory Spiez, 1994.
10. Tesche, F.M., "Users Manuals for the Advanced Signal Processing Program (ASPP)", August 13, 1994, Dallas, TX.

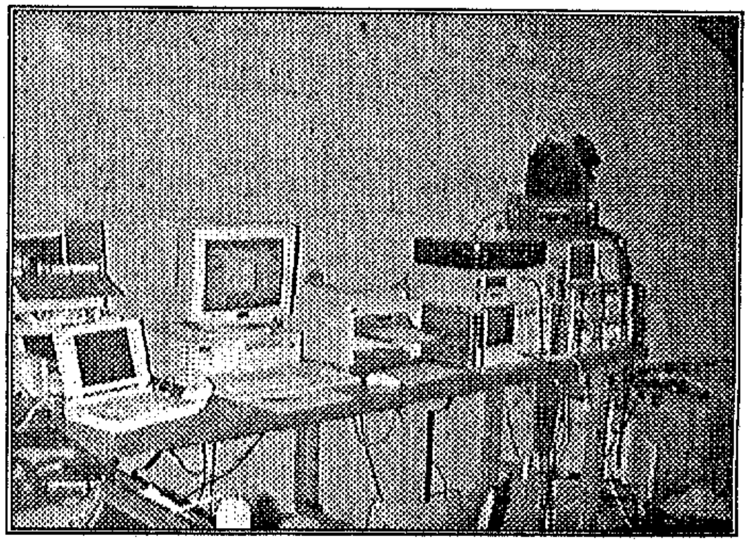


Figure 18. A typical CW test control area.

CW Test Planning

Definition of Test Objective

The first step in conducting a CW test is to identify the test object (facility, vehicle, etc.) and to define the overall objective of the test. As mentioned earlier, there can be several different objectives of such a test:

- to validate system hardness for acceptance of a new system,
- to assess the hardness of an existing system,
- to provide hardness surveillance data, or
- to study the behavior of hardness elements for design purposes.

Each of these objectives can lead to different test points and procedures. Consequently, it is important to have the goal of the test in mind from the start.

Site Survey

A second step in conducting a CW test is to perform a site survey. The blue prints or technical drawings of the site should be collected and studied. Experts in the construction of the system (architects, electrical design engineers, mechanical engineers, etc.) should be consulted and if necessary, brought to the site to assist in a detailed inspection of the system.

In an inspection of the site being tested, the following items should be examined and electrical construction details noted:

- the general EM shielding (or hardening) concept of the system,
- the nature of the electrical power penetrations into the system,
- the location and details of any communications into the system,
- the presence of any other well-defined non-electrical conducting penetrations (water pipes, etc.)
- the location of apertures or other physical entry points into the system,

- the importance of diffusive penetrations in the system walls, and
- the presence of filters and nonlinear protective devices in the system.

In addition to these physical details of the system, the current operators of the system should be contacted for their insight into operational characteristics of the system, such as

- the ambient EM noise level within the system,
- previous experience with randomly occurring system upsets of malfunctions,
- experience with lightning strike on or near the facility, and
- any other abnormal electrical features of the system that might have an impact on its HEMP.

The information gained in such a site serves will be used in defining the test points and the test procedure later.

Measurement Points

From the review of the system design and characteristics, there should be several sub-systems that appear to be "mission critical" and which deserve a careful examination in the test. Identification of these sub-systems should then assist in the definition of the necessary measurement locations for the test. Of course, the choice of the measurements points also depends on the specific goals of the test, as listed above.

In selecting measurement points, remember that it is better to get just a few high-quality and useful measurements than to obtain hundreds of low-quality, noisy data that cannot be extrapolated or otherwise used for the desired purposes.

Measurement Quantities

Responses

Corresponding to each measurement location is a particular response that should be measured. These include

- E-field,
- H-field,
- conductor current, and
- load voltage

It should be remembered that these quantities are not independent. They are all interrelated and are governed by Maxwell's equations and the nature of the electrical conductors (boundary conditions) in and surrounding the system. The reason that we make a distinction between these four observable quantities is that sometimes it is more convenient to describe the problem using one particular variable as opposed to the others.

Reference

The CW test concept requires the measurement of a suitable response as a reference quantity for determining the system transfer function. This reference is usually located at a point external to the system being tested, and can be either an electric or magnetic field component, or perhaps an induced current on an exterior cable. An additional possibility for a reference quantity is the input current into the excitation antenna.

The purpose of the reference is to provide a means for defining the system transfer function. If an interior response S_1 is measured at a frequency ω, together with the reference quantity R_o, the transfer function *T(*ω) can then be defined as

$$T(\omega) = \frac{S_1(\omega)}{R_o(\omega)}$$

Once the transfer function is defined, the CW response inside the facility due to an external HEMP excitation can be calculated by multiplying the transfer function by the same electrical quantity used in for the reference which arises from the HEMP excitation. For instance, if the external reference is the x-component of the electric field, the HEMP response of an internal quantity S_1 is

$$S_1^{(HEMP)} = T(\omega) \times E_x(\omega) \; .$$

It is important to locate the reference sensor far from any and all objects that can contribute to scattering of the incident field.

Test Plan

Test plan contents

After developing an overall concept for the test, a test plan should be developed. This plan should be written in sufficient detail that a knowledgeable technician could take the plan and successfully carry out the test without having any previous knowledge of the site.

Such a test plan should have the following items:

- a summary of the overall test goals and objectives,
- definition of the HEMP threat (i.e., the stress),
- a statement of the data processing concepts, together with an example of how the data are to be processed,
- a listing of first priority test points and a definition of the measured response quantities,
- a contingency list of other test points or measurements should the first be completed early, or should some points be un-measurable.
- a list of all required test material,
- a list of all necessary personnel and their function(s) during the test,
- the results of a physical site survey (blueprints, etc.)
- a discussion of other issues pertinent to the test: security, personal safety, transportation requirements and other logistics,
- a schedule of events, and
- reporting requirements.

Flexibility of plan

A test is basically a learning experience. It is rare that what it conceived of in the pre-test planning will turn out exactly as expected during the course of the test. As the measurements proceed, new things are discovered about the system and different measurements may become apparent. As a result, additional measurements may be required to further explore the system behavior.

To account for this possibility, it is important to be able to change the test plan during the course of the test. The test plan is only an initial guide for the test. It should not be viewed at an unalterable plan. However, it should not be modified without due consideration and consultation with all knowledgeable participants of the test.

Test Conduct

The test director

The detailed requirements of the test plan provide guidance as to the direction of the test. The test director is responsible to insure that this guidance is followed.

No successful test can have more than one director. The test director should have the final authority for making decisions about the test, about deviations from the test plan, and for any other administrative actions. In the absence of the test director, a deputy test director should be appointed.

Daily meeting to review data

During the course of an extended test (longer than 3 days), a daily meeting with all of the test personnel in attendance should be held for the purpose of reviewing the past measurements and going over the measurements planned for the next day. This is important, as it lets everyone associated with the test understand the current test status, any difficulties with the test, and any needed test plan modifications.

Measurement of the data

Measurements should proceed according to the test plan, with changes to the test plan being approved only by the test director. As soon as a measurement is made, a plot of the raw data should be made and the plot entered into a test log book. This permits an immediate assessment of the quality of the data.

Frequent noise measurements should be made to verify that the measurements are being conducted properly and that there is a good signal-to-noise ratio for the test. Of course, such measurements should be planned ahead of time in the test plan document.

Concurrent measurement and analysis

During the test, the analysis of the test data and the extrapolation of the data to HEMP threat levels should be carried out. This is important, because the processing of the data can serve as a quality check on the data as they are being measured. It is much better to know there are difficulties with the data an hour or two after the measurement is made than at the end of the test when no remedial action is possible.

Moreover, real-time analysis can provide guidance to the test director for possible changes to the test plan, based on the results of the analysis.

Archiving of data

Test data is typically acquired from a network analyzer onto the measurement computer and then transferred to the analysis work-station for processing. This implies that there will then be two copies of the data on each of these computers.

During the data processing, the analysts will frequently find problems with the data. For example, at times the network analyzer will provide a "glitch" in the data, with a resulting invalid data point, and this will be edited out by the analyst. At other times, the header information of the data files may need to be edited. After such corrections to the raw data are performed, the data should be downloaded to a disk or tape for archiving.

Modification of plan

As mentioned above, it is important that the test be flexible enough to explore unexpected occurrences during the testing. If the test director decides to change the plan after consulting with others involved in the test, there should be a written documentation of the change, a discussion of the rationale of the change, and a description of the new measurements to be made. In a sense, this is like an "appendix" to the test plan, and it is very important, since after the testing is over, the test personnel are likely to forget why certain changes were made.

Data Analysis

The analysis of the test data should actually be conducted as the measurements are made, if personnel are available for this activity. If this is not possible, the processing should be made as soon as possible after the end of the test so as to not forget important aspects of the test.

The data analysis can take many forms, depending on the objectives of the test and the exact type of data analysis needed should be made clear in the test plan document. The analysis will usually involve one or more of the procedures described in the next section.

In conducting the analysis, documentation of the steps used is important. This documentation should be done in sufficient detail so as to permit another person to duplicate the analysis results if desired.

As the analysis is conducted, it should be remembered that that some, if not all, of the calculated results will be needed for the final report. Consequently, it is advised to try to develop "publication quality" plots from the onset.

Reporting

A final report documenting the test is usually required. This report is should be based on the test plan and follow the outline of the subjects contained in the plan. The details of any additional measurements or modifications to the plan should be described.

Completion of the report should be as soon after the test as possible, so as to not forget important details of the measurements or data processing.

Format

The test report should be a complete and stand-alone document which documents the entire test. Prior to writing the report, an outline should be written to guide the writer(s). A possible outline of a final report is as follows:

<u>Final Test Report Outline</u>

1. Foreword
2. Objective of the test
3. Definition of the HEMP threat environment
4. Description of test object
5. Test point summary and selection criteria
6. Details of the data processing
7. Testing details, equipment set-up and difficulties encountered
8. Summary of selected data
   - Examples of raw data
   - Examples of measured data
9. Information gained from the test
10. Summary and conclusions
11. Appendices
    - Presentation of the raw data
    - Presentation of the processed data

Notice that this report outline has the provision for presenting all of the raw and measured data in appendices at the end of the report. For long tests where many data records are obtained, these appendices may be separate volumes of the report. In the main body of the report, selected examples of the raw and processed data are to be presented to provide an overview of the system responses.

Presentations

In addition to formal reporting requirements, it is frequently required to present verbal briefings on the test results. Such briefings can follow the outline of the final report. Typically, presentations of length longer than 1 to 1 1/2 hours should be avoided.

Unforeseen Factors in Testing

Regardless of the amount of planning that goes into a test, there will always be difficulties that arise. Each test is different and has distinct features that come into play in determining how smoothly the test is run. It is impossible to predict exactly what will go wrong in a test, but rest assured that something will go wrong!

Experience over the past years of testing has shown that there are several overall areas of possible difficulty. These are listed below for future reference.

Personnel Safety

Perhaps the most important aspect of the test is assuring that it is conducted in a safe manner, with no unreasonable risks for the test personnel. Prior to the testing, a site safety survey should be conducted to identify potential hazards and ways of minimizing them. The test personnel should be informed of standard safety and first-aid procedures and an accident contingency plan developed in case there is an accident during the test.

Security Limitations

Security at the site is important, as many test facilities are military in nature. While this aspect of the test is very important, it can lead to unforeseen delays in the testing, due to the possible requirements of having guards continuously on hand, on the safeguarding of classified data and results, and the need for obtaining the necessary clearances for the personnel involved in the test.

Moreover, the measurement equipment, power supplies, probes, etc. must be constantly watched and controlled due to the possibility of theft at the test site. Every evening, this equipment must be moved and stored in a secure building or vehicle to prevent unauthorized use or removal from the test site.

Weather

Most CW tests are conducted outdoors and as a consequence, the weather plays an important role in the testing. Outdoor tests should be scheduled for times of the year when the weather is good. Nevertheless, rain coats and other rain gear should be included in the list of material for the test, and the test schedule should be constructed taking into account the possible delays of the test activities due to inclement weather.

Support Personnel

A list of the necessary support personnel must be developed at the start of the test. In addition to the staff actually conducting the measurements and performing the data processing, it is useful to have someone knowledgeable about security issues, another person to help with the general moving and set-up of equipment and assistance in communications. Generally, the requirement for extra support personnel will depend on the nature of the test and the details of the test facility. Frequently, personnel associated with the facility are available to assist in the test for non-technical activities.

Traffic

The presence of vehicular or pedestrian traffic in the vicinity of the test site can be a serious problem to the smooth operation of the test. The test site should be carefully examined for this possibility, and if it exists, a plan to reduce or eliminate this problem should be developed.

Animals

The presence of wild and domestic animals can pose non-trivial problems for testing. In past tests, small rodents have chewed through electrical cables, insects have invaded warm computers to find a home, rabbits have set-up housekeeping in a shielded tent-like enclosure, and livestock chewed and trampled fiber optics cables.

In conducting the preliminary site survey, the issue of animals affecting the test should be carefully examined and the necessary measures for controlling this potential nuisance should be developed.

Equipment Malfunctions

Notwithstanding the claims of the manufacturers, electrical measuring equipment is susceptible to changes of operation environment and to transportation. An equipment set-up that worked fine in the laboratory is almost guaranteed have problems when it is disassembled, transported and re-assembled in the field. The test director is well advised to allocate sufficient time for equipment check-out and repair during the test.

Murphy's Law

A final work of caution is advisable through the reiteration of Murphy's law which states that "If anything can go wrong in the test, it will". Unfortunately, this rather cynical view of testing seems to be true in every test. Although it is difficult to predict exactly what will go wrong, something will. A well-prepared test director will recognize this and will be sufficiently prepared for such problems.

CW Measurement Techniques

Introduction

In conducting a CW test, the following points must be considered:

- Unlike the transient test where the reference sensor response is used primarily to serve as a quality indicator of the incident pulse field, in CW testing the reference sensor response forms an important part of the system transfer function and it must be measured carefully,
- the reference sensor must be located properly, so as to be able to relate the measured CW response of the system under test to a similar response that would occur if the excitation were an incident plan wave, and,
- the resulting transfer function in the CW test must be measured in sufficient detail so as to permit the extrapolation of a transient waveform. This requires that both magnitude and phase be measured with a sufficient frequency sampling interval to provide an accurate inverse Fourier transform of the data.

This section will discuss these and other issues pertaining to the operation of a successful CW test.

CW Test Procedures

To insure that the CW test is conducted properly, there are a series of steps that should be performed in setting up the measurement equipment and conducting the measurements. As shown in Figure 19, these procedures consist of activities that pertain directly to the conduct of the test (labeled as "CW Test Activity"). The other analysis support tasks (denoted as "CW Data Processing Activity") serve to insure that the test configuration is correct, that the test data are of sufficient quality for the data analysis, and to finally perform the desired analysis on the measured CW data. Each of these functions will be discussed in this section.

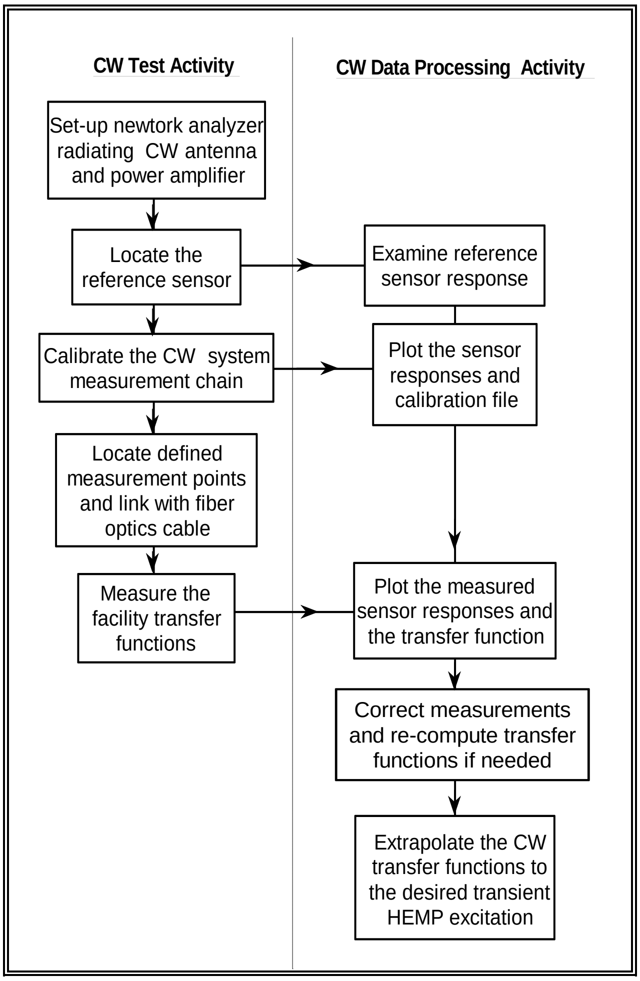


Figure 19. Test and analysis procedures or conducting a CW test.

Set-up of the Antenna and Measurement Equipment

The first step in conducting the CW test is to decide upon the location of the CW test antenna. In the direction broadside to the EMTECH antenna, the radiated EM field is primarily horizontally polarized. Thus, this CW antenna is suitable for simulating the effect of an incident horizontally polarized HEMP field.

As shown in Figure 20, the angle of incidence of the simulated HEMP field, denoted by the angle ψ, is defined by the angle from the top (apex) of the antenna down to the facility under test. Thus, the location of the antenna relates to the angle

For the simulated EM field to appear as a plane wave, the antenna should be located as far from the facility as possible. Specifically, the distance *d* in Figure 20 should be larger than the typical dimensions of the facility under test. In addition, the distance d should be larger than the dimensions of the antenna. Often these requirements cannot be met, due to the large size of the facility. Reference [11] develops a calculational model for this antenna and discusses errors involved in this aspect of the simulation. It should be noted that this difficulty in the antenna placement occurs also in pulse testing.

11 Tesche, F.M. "Numerical Evaluation of the Radiating Characteristics of a CW Simulator for EMC and HEMP Testing", *Proceedings of the 9th International Zurich Technical Exhibition on EMC*, 12-14 March, 1991.

of incidence of the HEMP being simulated.

If the facility being tested is very large and the antenna cannot be located so that *d* is larger than the facility dimension, the CW test can be conducted using the PARTES concept discussed earlier. This will involve determining the principle points of entry (POE) of the facility and locating the antenna so that this part of the facility is suitable illuminated by the simulated plane-wave excitation from the antenna.

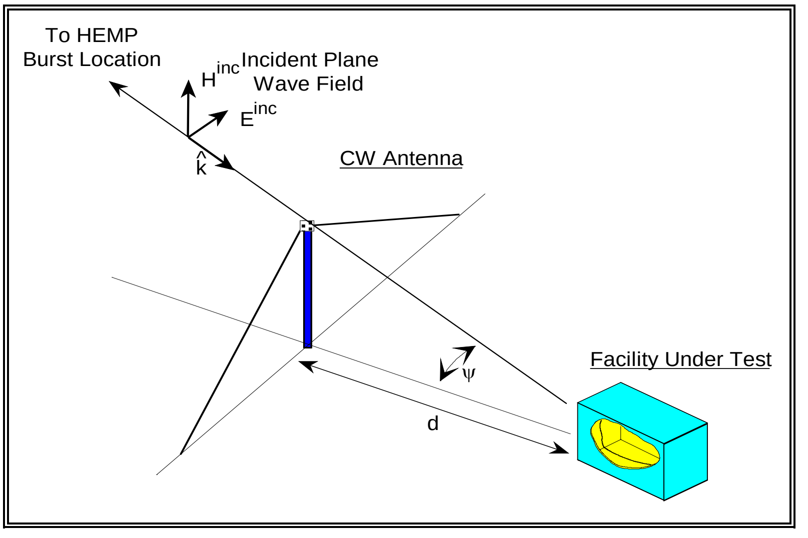


Figure 20. Relationship between the CW antenna and the Incident HEMP field.

In addition to the proper placement of the antenna, there is a need to locate the antenna power amplifier, the motor-generator unit and the measurement equipment (network analyzer). As discussed earlier, the locations of these equipment should be chosen in such a way that the EM fields produced by the antenna will not severely interact with the equipment and cause perturbations in the measured results. This implies that all conducting cables should be run close to the ground and in a direction so that they are orthogonal to the E-fields produced by the antenna. If possible, the measurement equipment should be located away from the facility or in a separate shielded enclosure to minimize the effects of direct EM interaction with the antenna fields.

Location of the Reference Sensor

A key aspect of the CW test configuration is the proper location of the reference sensor. The purpose of having a reference sensor measurement is to provide a way of relating the measured results in the facility using the CW antenna to the response that would be obtained if the excitation were an incident plane wave. Thus, it is necessary to understand how the reference sensor is excited. As shown in Figure 21, the response measured by the reference sensor consists of an incident wave contribution plus a contribution reflected from the ground. This resulting field is the total excitation field at the sensor. If the reference sensor is located far from the CW antenna, it can be seen that the direct and ground-reflected rays from the antenna apex (i.e., from the driving source on the antenna) will have about the same path length as will the contributions for the incident HEMP plane wave. In this case, the response of the sensor will be easily related to the response of a plane wave excitation. However, if the sensor is too close to the antenna, the sensor response for the CW case will be different form that of the plane wave excitation. A general rule of thumb is that the reference sensor should be located at a distance equal to several antenna lengths away from the antenna.

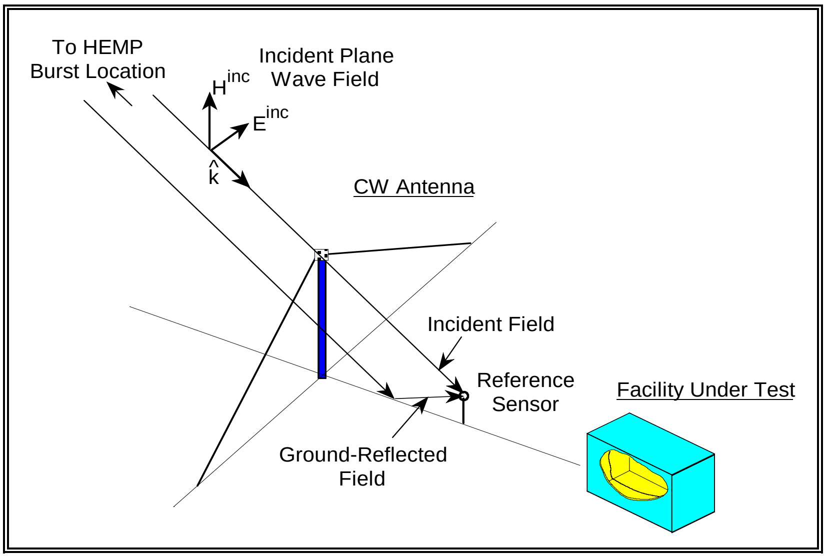
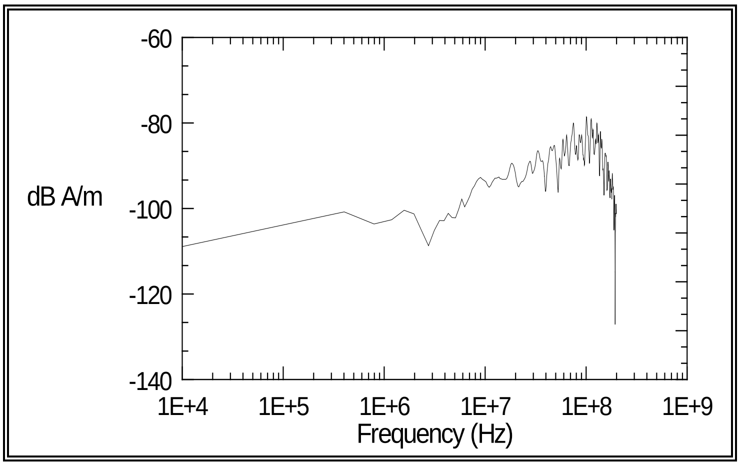


Figure 21. Incident and ground-reflected field contributions to the reference sensor excitations.

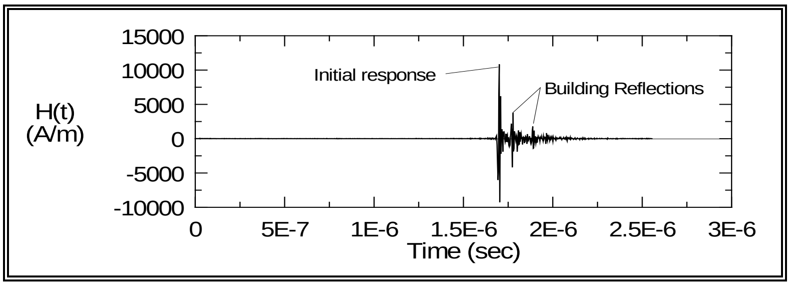
There is another important rule in locating the reference sensor: it should not be located close to other conducting structures which can contaminate the local EM fields. This implies that the reference should not be located too close to the facility under test

As an example of this, consider Figure 22a which illustrates the measured H-field reference sensor spectrum taken in an actual test. This response was taken using equally-spaced sample points and exhibits a very rapid fall-off of the response at high frequencies due to the sensor limitations. The resonances in the response are due to antenna resonances and reflections from near-by objects. The first null in this total field response due to the reflection in the groundplane occurs at about 200 MHz, and this also accounts for the high-frequency fall-off of the spectrum.

Figure 22b illustrates the delta-function response of this spectrum, obtained by taking the inverse Fourier transform of the spectrum. This transient response clearly illustrates the initial response of the sensor, arriving with a time delay determined by the antenna and reference sensor geometry and the details of the fiber optics cables. Later in time, smaller impulses arrive at the sensor. These have been reflected from a near-by building and should be eliminated if possible by moving the sensor further away from the building.



a.. Measured H-field spectrum.



b. Computed delta-function response from spectrum.

Figure 22. Measured reference H-field spectrum and its inverse Fourier transform.

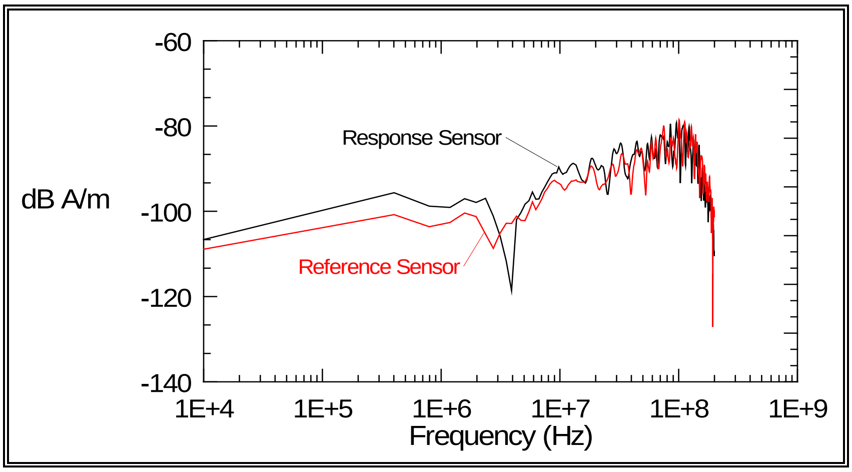
Calibration of the Measurement Chain

After the location of the reference sensor has been determined, it is necessary to calibrate the measurement chain. This is important, as it corrects for any differences in the sensor magnitude responses, but it also removes any unwanted phase shifts in the responses. These phase shifts amount to time shifts in the transient response, and can cause errors in data interpolation if they are present in the measured data.

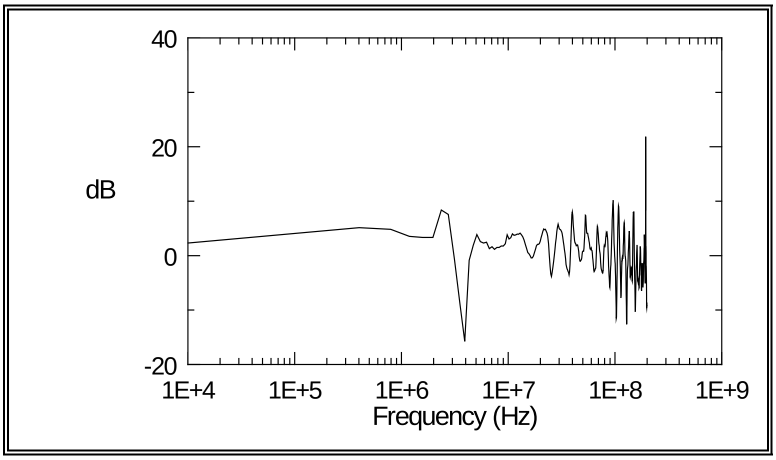
The calibration is accomplished by locating the measurement sensor next to the reference sensor and making a sweep of the spectrum. Figure 23a illustrates the results of such a measurement. Denoting the reference spectrum for the calibration process as $R_o(\omega)$ and the calibration response spectrum as $S_o(\omega)$, a transfer function between the two is defined as

$$T_o(\omega) = \frac{S_o(\omega)}{R_o(\omega)}.$$

This derived transfer function is illustrated in Figure 23b. Because the two sensors are not identical and because they are in slightly different locations, the transfer function $T_o(\omega)$ is not unity, but it has a variation to it. In addition, differences in the lengths and optical characteristics of fiber optics cables can contribute to these variation. If both sensors are of the same type, such variations should be small, and large variations indicate the possible presence of standing waves in the vicinity of the reference sensor, which is something to avoid.



a. Reference and response sensor spectra



b. Derived calibration function.

Figure 23. Measured sensor responses and calibration function.

Once the calibration transfer function $T_o(\omega)$ has been determined, a check of the calibration process should be performed. This involves making a new measurement of the reference sensor response, denoted by $R_1(\omega)$ and a new response sensor measurement, $S_1(\omega)$. With these measurements, a new, and corrected, transfer function is defined as

$$T(\omega) = \frac{S_1(\omega)}{R_1(\omega)} \frac{1}{T_o(\omega)}.$$

Ideally, this new transfer function should be identically 1. However, slight variations in the measurements will cause it to be different. Figure 24 illustrates this second transfer function and shows that it is close to unity. This calibration procedure and check of the calibration should be used for each test, and recalibrations should be performed routinely.

The calibration transfer function $T_o(\omega)$ must be applied to all transfer function measurements made using the calibrated sensors and the fixed system configuration.

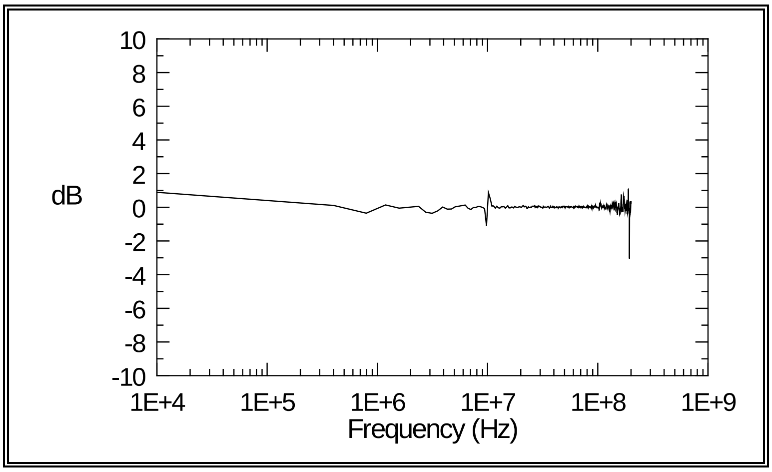


Figure 24. Measured transfer function, corrected by calibration file.

Limitations of Measurements

In developing a calibration procedure for the measurement chain, there are several limiting factors that should be remembered and taken into account. The dynamic range of the measurements can be limited by the following:

- noise of the fiber optic transmission system,
- insufficient bandwidth of the network analyzer, and
- amplifier gain setting.

These limitations can be understood and partially alleviated by making noise floor measurements with the amplifier turned off, changing the emission levels of the antenna by changing the amplifier gain, and by changing the network analyzer bandwidth.

Locate Measurement Points

The next step in the CW test procedure is to locate the desired measurement points (presumably within the facility or test object), instrument them with the previously calibrated sensor, and run the fiber-optic cables from the transducer near the network analyzer to the measurement location. In doing this, care should be used to insure that the shielding topology of the test object is not violated. For example, even though the fiber optic cables do not conduct electrical signals, if they pass through a door into a shielded enclosure, the door must remain open to let the cable pass. Such an open door constitutes a shielding violation and should be avoided.

Measurement of Transfer Function

With the internal measurement points instrumented, the measurement process can proceed, with the simultaneous measurement of the reference and the response sensors. Generally, the calibration transfer function $T_o(\omega)$ is applied to the these responses during the measurement process by the Lab View computer program the measurements, and as a result, there are three data files provided for each measurement:

1. the reference sensor spectrum,
2. the response sensor spectrum, and

3. the corrected transfer function.

As noted in Figure 19, simultaneous data analysis with the measurements should be performed, with plotting of these data files and a preliminary examination of the reasonableness of the results made. If there are any bad data points in either of the sensor responses, they should be edited out and a new transfer function calculated.

Data Processing for CW Testing

After the measurements of the transfer functions are completed, Figure 19 indicates that the remaining task is the processing of the measured data. Usually, for a CW test this will involve taking the measured (and corrected) transfer function spectrum and converting it to a transient, HEMP response of the system. To describe this extrapolation process, the signal flow diagram shown in Figure 25 can be used.

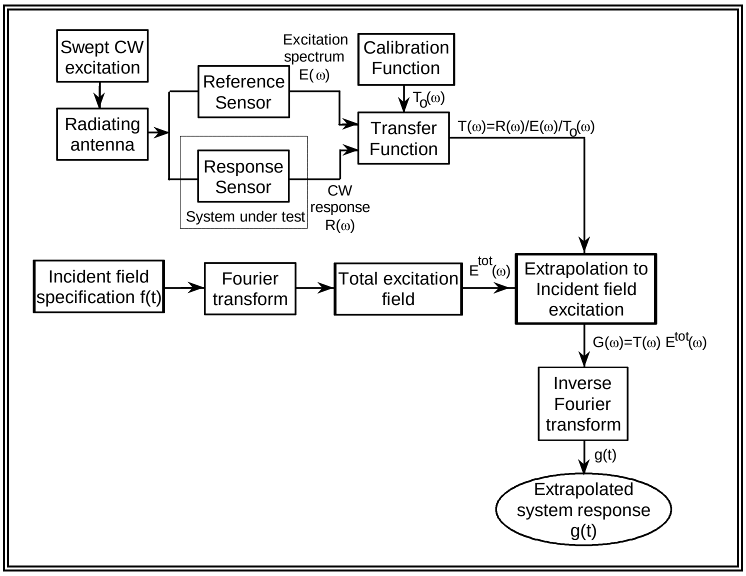


Figure 25. Analysis flow diagram for extrapolating a measured CW spectrum.

Data Processing Procedures

In the processing of the measured CW data, there are several key data processing procedures that are needed. These are all included in the ASPP program which may be used in a stand-alone mode for the processing. Some of the more useful data processing routines are descried below. For a more detailed description of these routines and example of their use, the reader is referred to the ASPP user's manual.

Fourier Transformation

A key requirement of the CW data analysis is to be able to perform a Fourier transform of a transient waveform to obtain its frequency-domain spectrum, or to perform the inverse transform to obtain a transient response from a spectrum. Normally, this is done by numerically integrating the appropriate Fourier integral in a process designated as the FIT.

An alternate approach is to use the fast Fourier transform (FFT) to perform this inversion. This latter approach is much more computationally efficient than the direct numerical integration.

Both of these procedures are available in the ASPP code and can be used for processing the CW data.

File Multiplication and Division

The measured CW transfer function must be divided by the correction function $T_o(\omega)$ and then multiplied by the spectrum of the excitation function. In the ASPP code, there is a general purpose routine to add, subtract, multiply or divide two data files to accomplish this requirement. These functions are actually complex-valued functions, so the arithmetic is complex.

Waveform and Spectral Generation

To generate specific waveform shapes or the corresponding spectra, the ASPP code provides a routine to define the following types of excitations

- Delta Function
- Step (Pulse) Function
- Single Exponential
- Double Exponential
- Damped Sine
- Damped Cosine

Data Filtering

At times in processing CW data, it may be desirable to filter the measured or computed spectra or the transient responses. The ASPP program provides several filter options:

- a bandpass filter for spectra,
- a causal (Hilbert) filter for spectra, and
- an averaging window filter for spectral or transient responses.

Each of these filters can be used to reduce or possibly eliminate the effects of noise or other difficulties in the spectral responses. However, care must be used in all filter operations, as part of the actual signal is also removed.

Time or Phase Shifting

At times, there can be a time delay (or a phase shift in the spectrum) introduced by propagation delays on cables, the system electronics, and by the difference in location of the two sensors. This can cause difficulties in data processing, as the phase of the signal will vary rapidly from +180° to -180°. To remedy this, the ASPP code provides the possibility of shifting the time origin of a transient response to $t = 0$.

Data Plotting

Finally, as noted in Figure 19, much of the quality assurance aspect of the CW testing involves the immediate plotting of the measured responses. The ASPP program provides this possibility. Both screen plots and paper (hard) plots can be generated.

Appendix A: Reflected and Transmitted Fields

Introduction

In performing CW testing on systems it is necessary to know certain components of the excitation fields. For above-ground fields, the excitation field consists of the incident plus ground-reflected fields. For buried systems, this excitation field is the field which is transmitted into the imperfectly conducting soil. This appendix provides mathematical expressions for these fields and illustrates some typical responses for HEMP waveforms.

Frequency-Domain Expressions for the Fields

The electric and magnetic fields produced by an incident plane wave striking an imperfectly conducting half-space is described in terms of the Fresnel reflection coefficients [12], [13]. With reference to Figure 4, an arbitrarily polarized incident plane wave of magnitude E_o is divided into a vertically polarized component and a horizontally polarized component. If the incident E-field vector makes an angle α with the plane of incidence (measured clockwise as seen by an observer looking towards the source), the vertically polarized component is given by $E^{inc} = E_o \cos\alpha$ and the horizontally polarized component is $E^{inc} = E_o \sin\alpha$.

By Snell's law, the reflected field has the vertical angle $\psi_t = \psi$, and the transmitted angle ψ_t is given by the expression

$$\cos\psi_t = \frac{jk}{\gamma_g}\cos\psi \ , \qquad \text{(A-1)}$$

where γ_g is the propagation constant in the soil given by

$$\gamma_g = \sqrt{j\omega\mu_o\left(\sigma_g + j\omega\varepsilon_g\right)} \, .$$

Because γ_g is a complex quantity, the transmitted angle ψ_t is also complex which implies that there is an attenuation of the fields propagating into the ground.

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12. Vance, E.F., *Coupling to Shielded Cables*, Krieger Publishing, 1987.
13. Jordan, E.C., and K.G. Balmain, *Electromagnetic Waves and Radiating Systems,*" Prentice-Hall, Inc., 1968.

The incident fields having angles of incidence (ψ and ϕ) shown in Figure 4 are expressed in the following way:

Vertical Polarization:

$$\vec{E}^{inc} = E_o \cos\alpha\left(\hat{x}\sin\psi\cos\phi - \hat{y}\sin\psi\sin\phi + \hat{z}\cos\psi\right) \times e^{-jkx\cos\psi\cos\phi} e^{jky\cos\psi\sin\phi} e^{jkz\sin\psi}$$

$$\vec{H}^{inc} = \frac{E_o}{Z_o}\cos\alpha\left(-\hat{x}\sin\phi - \hat{y}\cos\phi + \hat{z}\,0\right) \times e^{-jkx\cos\psi\cos\phi} e^{jky\cos\psi\sin\phi} e^{jkz\sin\psi}$$

Horizontal Polarization:

$$\vec{E}^{inc} = E_o \sin\alpha\left(\hat{x}\sin\phi + \hat{y}\cos\phi + \hat{z}\,0\right) \times e^{-jkx\cos\psi\cos\phi} e^{jky\cos\psi\sin\phi} e^{jkz\sin\psi}$$

$$\vec{H}^{inc} = \frac{E_o}{Z_o}\sin\alpha\left(\hat{x}\sin\psi\cos\phi - \hat{y}\sin\psi\sin\phi + \hat{z}\cos\psi\right) \times e^{-jkx\cos\psi\cos\phi} e^{jky\cos\psi\sin\phi} e^{jkz\sin\psi}$$

The reflected fields are related to the incident fields through the Fresnel refection coefficients which are determined by matching the appropriate field components across the air-earth interface. For the two polarizations, these reflected fields are expressed as

Vertical Polarization:

$$\vec{E}^{ref} = E_o \cos\alpha\, R_v\left(-\hat{x}\sin\psi\cos\phi + \hat{y}\sin\psi\sin\phi + \hat{z}\cos\psi\right) \times e^{-jkx\cos\psi\cos\phi} e^{jky\cos\psi\sin\phi} e^{-jkz\sin\psi}$$

$$\vec{H}^{ref} = \frac{E_o}{Z_o}\cos\alpha\, R_v\left(-\hat{x}\sin\phi - \hat{y}\cos\phi + \hat{z}\,0\right) \times e^{-jkx\cos\psi\cos\phi} e^{jky\cos\psi\sin\phi} e^{-jkz\sin\psi}$$

Horizontal Polarization:

$$\vec{E}^{ref} = E_o \sin\alpha\, R_h\left(\hat{x}\sin\phi + \hat{y}\cos\phi + \hat{z}\,0\right) \times e^{-jkx\cos\psi\cos\phi} e^{jky\cos\psi\sin\phi} e^{-jkz\sin\psi}$$

$$\vec{H}^{ref} = \frac{E_o}{Z_o}\sin\alpha\, R_h\left(\hat{x}\sin\psi\cos\phi - \hat{y}\sin\psi\sin\phi - \hat{z}\cos\psi\right) \times e^{-jkx\cos\psi\cos\phi} e^{jky\cos\psi\sin\phi} e^{-jkz\sin\psi}$$

where R_v and R_h are the Fresnel reflection coefficients for the vertically polarized and horizontally polarized fields, respectively. These coefficients are given in [12] as

$$R_v = \frac{\varepsilon_r\left(1+\dfrac{\sigma_g}{j\omega\varepsilon_r\varepsilon_o}\right)\sin\psi - \left[\varepsilon_r\left(1+\dfrac{\sigma_g}{j\omega\varepsilon_r\varepsilon_o}\right)-\cos^2\psi\right]^{1/2}}{\varepsilon_r\left(1+\dfrac{\sigma_g}{j\omega\varepsilon_r\varepsilon_o}\right)\sin\psi + \left[\varepsilon_r\left(1+\dfrac{\sigma_g}{j\omega\varepsilon_r\varepsilon_o}\right)-\cos^2\psi\right]^{1/2}} \qquad \text{(A-2a)}$$

and

$$R_h = \frac{\sin\psi - \left[\varepsilon_r\left(1+\dfrac{\sigma_g}{j\omega\varepsilon_r\varepsilon_o}\right)-\cos^2\psi\right]^{1/2}}{\sin\psi + \left[\varepsilon_r\left(1+\dfrac{\sigma_g}{j\omega\varepsilon_r\varepsilon_o}\right)-\cos^2\psi\right]^{1/2}} . \qquad \text{(A-2b)}$$

These plane wave reflection coefficients are complex functions of the earth parameters and the incidence angle ψ. The vertical reflection coefficient exhibits a more complicated behavior than does the horizontal coefficient. For low values of conductivity, the ground appears as a perfect dielectric, and a null in the vertical polarization coefficient appears for angles $\psi \approx 20°$ to $30°$, depending on ε_r. This corresponds to the Brewster angle, where there is no reflected field. As the ground becomes perfectly conducting, $\sigma \rightarrow \infty$, and the reflection coefficients in Eqs. (A-2) have the limits $R_v \rightarrow 1$ and $R_h \rightarrow -1$, as long as $\psi \neq 0$. For $\psi = 0$, both R_v and $R_h \rightarrow -1$.

For observer locations *in* the ground, the transmitted fields can be expressed in terms of a similar plane wave function, but using the Fresnel transmission coefficients. These fields are given as

Vertical Polarization:

$$\vec{E}^{\,t} = E_o \cos\alpha\, T_v\left(\hat{x}\sin\psi_t\cos\phi - \hat{y}\sin\psi_t\sin\phi + \hat{z}\cos\psi\right) \times e^{-\gamma_g x\cos\psi_t\cos\phi} e^{\gamma_g y\cos\psi_t\sin\phi} e^{\gamma_g z\sin\psi_t}$$

$$\vec{H}^{inc} = \frac{E_o}{Z_o}\cos\alpha\, T_v\left(-\hat{x}\sin\phi - \hat{y}\cos\phi + \hat{z}\,0\right) \times e^{-\gamma_g x\cos\psi_t\cos\phi} e^{\gamma_g y\cos\psi_t\sin\phi} e^{\gamma_g z\sin\psi_t}$$

Horizontal Polarization:

$$\vec{E}^{inc} = E_o \sin\alpha\, T_h\left(\hat{x}\sin\phi + \hat{y}\cos\phi + \hat{z}\,0\right) \times e^{-\gamma_g x\cos\psi_t\cos\phi} e^{\gamma_g y\cos\psi_t\sin\phi} e^{\gamma_g z\sin\psi_t}$$

$$\vec{H}^{inc} = \frac{E_o}{Z_o}\sin\alpha\, T_h\left(\hat{x}\sin\psi_t\cos\phi - \hat{y}\sin\psi_t\sin\phi + \hat{z}\cos\psi_t\right) \times e^{-\gamma_g x\cos\psi_t\cos\phi} e^{\gamma_g y\cos\psi_t\sin\phi} e^{\gamma_g z\sin\psi_t}$$

In these expressions for the transmitted fields, the transmission coefficients are given by

$$T_v = 1 - R_v \textit{ and } T_h = 1 - R_h \ .$$

The angle ψ_t is a complex angle, with cos ψ_t given by Eq.(A-1) and the function sin ψ_t is

$$\sin\psi_t = \sqrt{1-\cos\psi_t} = \sqrt{1+\left(\frac{k\cos\psi}{\gamma_g}\right)^2} \quad . \qquad \text{(A-3)}$$

The Excitation Fields for an Above-Ground System

From these general expressions for the plane wave fields incident, reflected and transmitted from the air-earth interface, it is possible to write the excitation fields for a system above the ground. We will consider only the E_x and E_z field components. The total E_z field component at height *z* = *h* and *y* = 0 is given by the sum of the incident and reflected fields for both polarizations. This is expressed as

$$\begin{aligned} E_x^{ex}(x,0,h) &= E^{inc} + E^{ref} \\ &= E_o\left[\begin{matrix}\cos\alpha\sin\psi\cos\phi\left(e^{jkz\sin\psi} - R_v e^{-jkz\sin\psi}\right) \\ +\sin\gamma\sin\phi\left(e^{jkz\sin\psi} + R_h e^{-jkz\sin\psi}\right)\end{matrix}\right] \\ &\times e^{-jkx\cos\psi\cos\phi} \end{aligned} \quad . \text{(A-4)}$$

Above the ground, the vertical E-field at a location (x, 0, z) is expressed as

$$\begin{aligned} \vec{E}_z^{ex}(x,0,z) &= E_z^{inc} + E_z^{ref} \\ &= E_o\cos\alpha\cos\psi\left(e^{jkz\sin\psi} + R_v e^{-jkz\sin\psi}\right)e^{-jkx\cos\psi\cos\phi} \end{aligned} \quad \text{(A-5)}$$

Notice that for a perfectly conducting ground $R_v = 1$ and $R_h = -1$.

The Excitation Fields for a Buried System

For observation locations below the surface z < 0, the excitation field at (x, 0, z) is

$$\begin{aligned} E_z^{ex}(x,0,z) &= \vec{E}^t \\ &= E_o\cos\alpha\cos\psi(1-R_v)e^{\gamma_g z\sin\psi_t}e^{-\gamma_g x\cos\psi_t\cos\phi} \end{aligned} \quad \text{(A-6)}$$

For conductivities in the range of σ_g = 0. 1 to 0.003 S/m and a relative dielectric constant of ε_r = 10 (typical values for a conducting earth), the term $|\gamma_g| >> k$ for frequencies over 1 MHz. Thus, the transmission angle ψ_t becomes

$$\begin{aligned} \psi_t &= \arccos\left(\frac{jk}{\gamma_g}\cos\psi\right) \\ &\arccos\left(\frac{jk}{\sqrt{j\omega\mu_o(\sigma_g - j\omega\varepsilon_g}}\cos\psi\right) \approx 90^o \text{ for } (\sigma_g >> \omega\varepsilon_g) \end{aligned} \quad \text{(A-7)}$$

For this case, the term $(1-R_v)$ in Eq.(A-6) becomes

$$1 - R_v \approx \frac{2}{\sin\psi}\sqrt{\frac{j\omega\varepsilon_o}{\sigma_g}}$$

and the propagation constant γ_g is approximately

$$\gamma_g \approx \frac{1+j}{\delta}$$

where $\delta = \sqrt{2/(\omega\mu_o\sigma_g)}$ is the skin depth in the ground. With these approximate expressions, the expression for the z-component of the E-field in the ground in Eq.(A-6) becomes

$$E_z^{ex}(x,0,z) \approx E_o \cos\alpha \cos\psi \frac{2}{\sin\psi}\sqrt{\frac{j\omega\varepsilon_o}{\sigma_g}} \times e^{(1+j)z/\delta} e^{-jk\,x\cos\psi\cos\phi}. \tag{A-8}$$

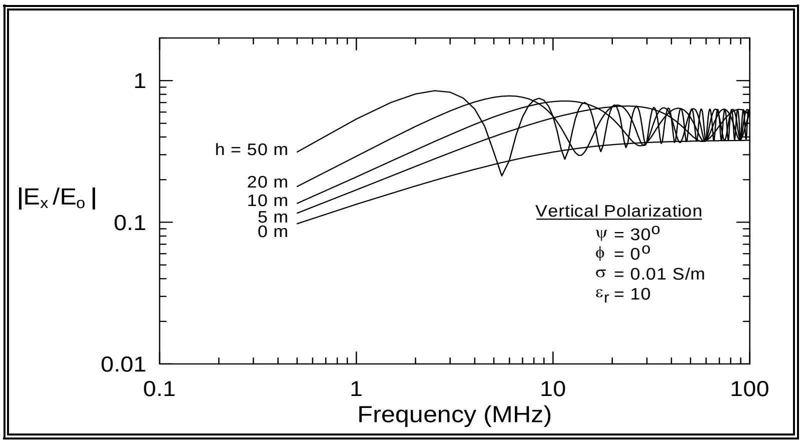
Transient Field Reflected from the Ground

In problems relating to lightning or the nuclear EMP, it is often necessary to find the fields above the earth in the time domain. This is especially important for problems involving a direct time domain solution for field coupling to lines or for problems involving nonlinear responses. One way of evaluating the transient fields is by the use of Fourier transform methods. For a specified incident transient field, the frequency domain spectrum $E_o(j\omega)$ can be determined either analytically or numerically. Then, the E or H-field spectra for the reflected or total fields evaluated at each frequency in the spectrum and the inverse Fourier transform evaluated. Generally, this last step is done by a numerical FFT.

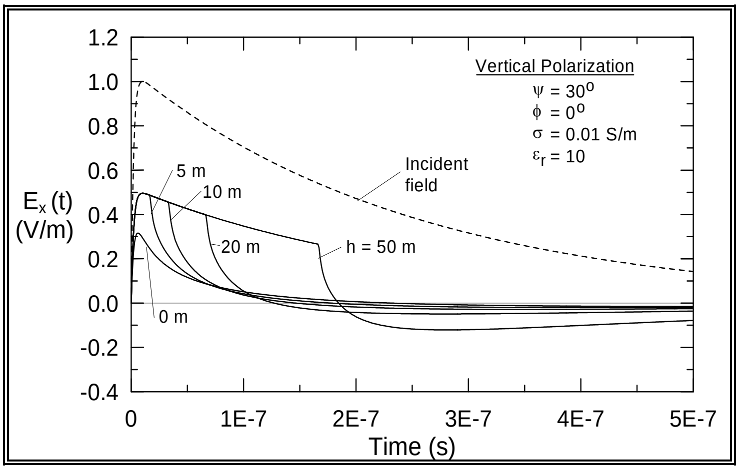
Transient Fields Evaluated by the FFT

As an example of the results provided by this procedure, consider the case of a vertically polarized incident field as shown in Figure 4, with the angles of incidence ψ = 30° and ϕ = 0°. This particular E-field will provide excitation field components in both the $\hat{x}$ and $\hat{z}$ directions. Using Eqs.(A-4) and (A-5), the E_x and E_z field components at different heights over an earth with σ_g = 0.01 S/m and ε_r = 10 can be evaluated as a function of frequency and the resulting magnitudes of the normalized responses are shown in Figures A-1a and A-2a.

For illustrating the transient responses of the E-fields, the double exponential incident waveform defined previously as $E^{inc}(t) = 1.05 \times \left(e^{-4\times 10^6 t} - e^{-4.76\times 10^8 t}\right)$ can be used. Figures A-1b and A-2b illustrate the behavior of the calculated transient excitation E_x and E_z components, along with the incident field. In the plots for the horizontal field, it is noticed that the reflected pulse from the ground plane tends to cancel the incident field, while for the vertical component, the reflected field adds to the incident field. The corresponding case for a horizontal polarization of the incident field is shown in Figure A-3. In this case, there is no vertical field component.



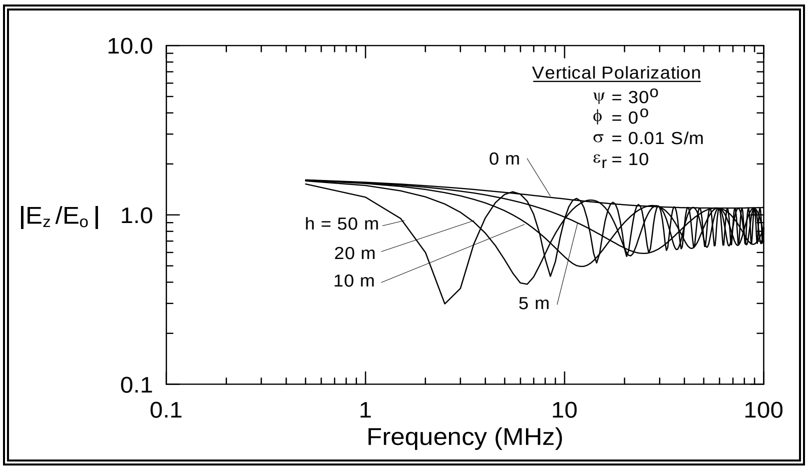
a. Spectral response



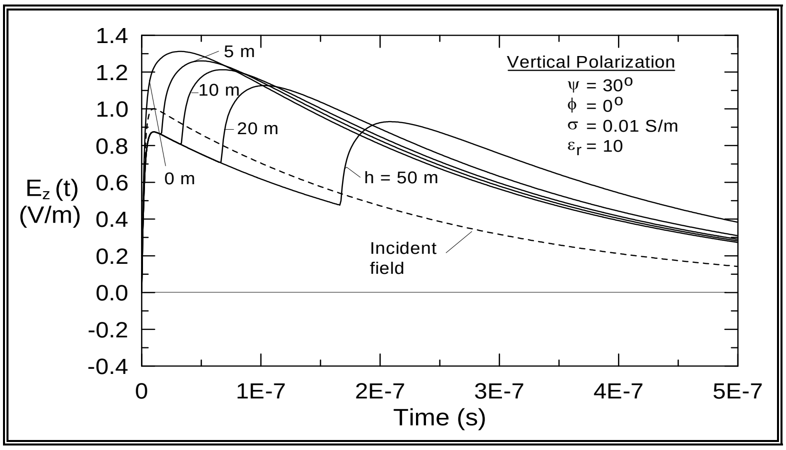
b. Transient response

Figure A-1. The total horizontal (E_x) field at different heights over a lossy ground for a vertically polarized incident field.

The use of Fourier transforms to obtain the transient fields is a relatively standard approach, and [12] contains additional results of a parametric study showing different E-field components above and in the earth, for variations in the observation height, angle of incidence and ground conductivity. In addition, variations in the frequency domain of the E-fields are illustrated.

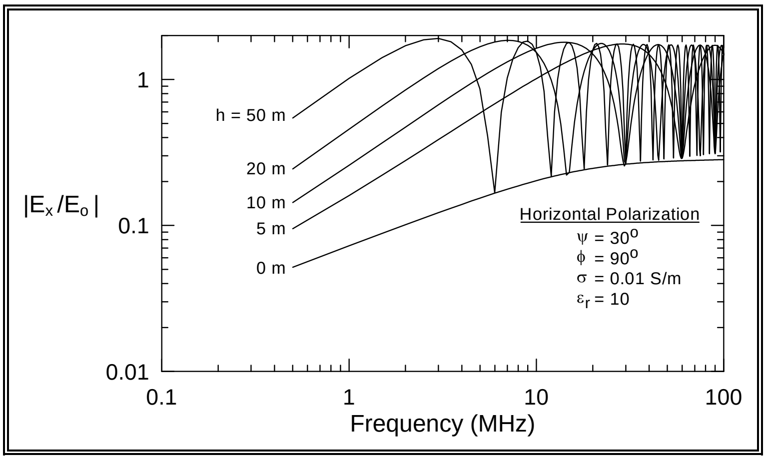


a. Spectral response

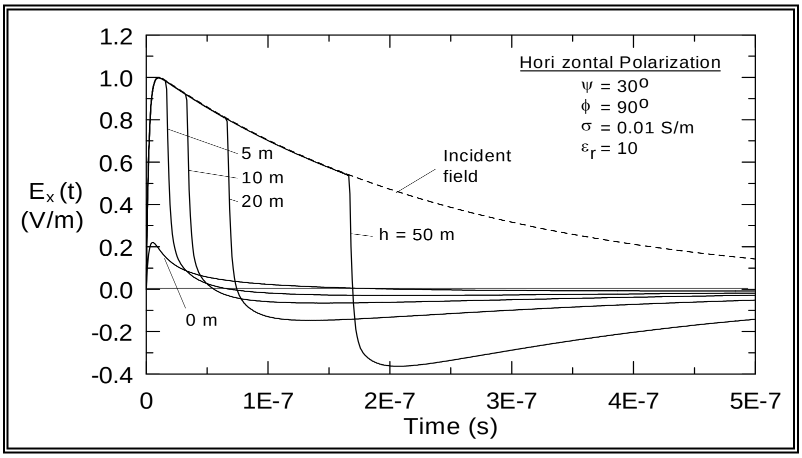


b. Transient response

Figure A-2. The total vertical (E_z) field at different heights over a lossy ground for a vertically polarized incident field.



a. Spectral response



b. Transient response

Figure A-3. The total horizontal (E_x) field at different heights over a lossy ground for a horizontally polarized incident field.

Appendix B: Systems Containing Nonlinear Elements

Introduction

Although it is usually believed that a time harmonic analysis is not capable of being used for problems involving nonlinearities, there is a method which permits the determination of a nonlinear system response in an indirect manner. This method was illustrated for an antenna connected to a nonlinear load [14] and has been used subsequently by other researchers for a transmission network [15], [16]. This method uses a frequency domain analysis of the *linear* portion of the problem to develop a Thevenin or Norton equivalent circuit at the location where the nonlinear element is located. This equivalent circuit is then converted to a time domain equivalent circuit using a Fourier transform, and with the specified nature of the nonlinear device specified, a Volterra integral equation for the load response is found. This equation is solved by a time-marching procedure.

Development of the Volterra Integral Equation

As an example of this procedure, consider the simple transmission line shown in Figure B-1. The transmission line is assumed to have a nonlinear impedance load located at the x = $\mathcal{L}$ end of the line. For this nonlinear element, the *v-i* relationship is assumed to be of the form $v_t(t) = F[i_t(t)]$, where *F* is a nonlinear function. To the left of the load (at cut A-A' in the figure) the remaining portion of the line is a linear system, and may be described by the transmission line relations for a line having a length $\mathcal{L}$, a propagation constant γ, and characteristic impedance Z_c. Although the line is assumed to be excited by an incident field, the following development will also be applicable for a line having a lumped excitation source along the line.

As noted in Figure B-1, the linear portion of the line can be represented by an equivalent Norton circuit. In the frequency domain, the input admittance of this circuit is given by $Y_{in} = 1 / Z_{in}$, where Z_{in} is the input impedance of the line. The short circuit current is given by $I_{sc} = V_{oc} / Z_{in}$, where V_{oc} is the open circuit voltage of the line. Both V_{oc} and Z_{in}, or equivalently, I_{sc} and Y_{in}, can be measured or calculated using simple transmission line models.

The *v-i* description of the nonlinear element is provided in the time domain. To include in the analysis the excitation provided by the linear portion of the problem, the time harmonic functions I_{sc} and Y_{in} may be converted into the

14. Liu, T.K., and F.M. Tesche, "Analysis of Antennas and Scatterers with Nonlinear Loads", *IEEE Trans. AP*, Vol. 24, No.2, March 1976.
15. Djordjevic, A. R., T. K. Sarkar, and R. F. Harrington, "Analysis of Lossy Transmission Lines with Arbitrary Nonlinear Terminal Networks", *IEEE Trans. MTT*, Vol. 34, No. 6, June 1986.
16. D'Amore, and M.S. Sarto, "EMP Coupling to Multi-conductor Dissipative Lines with Nonlinear Loads Above a Lossy Ground", Proceedings of *the 10th International Zurich Symposium and Technical Exhibition on EMC*, pp 451-456, March 9-11, 1993.

time domain by a numerical Fourier transform. In this manner, the equivalent Norton circuit in Figure B-1 can be viewed as a circuit in the *time domain*, with a Applying Kirchoff's current law at the load and noting that the current through the internal admittance $i_y(t)$ is defined as a convolution operation $i_y(t) = y_{in}(t) * v_t(t) = y_{in}(t) * F[i_t(t)]$, the transient current through the load can be written as a nonlinear Volterra equation

$$i_t(t) = i_{sc}(t) - \int_0^t y_{in}(t-\tau)F[i_t(\tau)]d\tau . \qquad \text{(B-1)}$$

The solution for $i_t(t)$ from this equation is described in [1] and [3] and involves a time marching solution in which a nonlinear root-finding procedure must be employed in each time step. Assuming that $i_{sc}(t)$ and $y_{in}(t)$ are defined at temporal sample points t_n = *nΔt*, where *n* = 0, 1, … $n_{\max}$, the integral equation (B-1) at a time t_n can be written as

$$\begin{aligned} & i_t(n\Delta t) + y_{in}(0)F[i_t(n\Delta t)]\Delta t \\ & = i_{sc}(n\Delta t) - \sum_{k=0}^{n-1} y_{in}(n\Delta t - k\Delta t)F[i_t(k\Delta t)]\Delta t \quad n = 1, 2 \cdots n_{\max} \end{aligned} \qquad \text{(B-2)}$$

If the line is lossless and has a load impedance equal to the characteristic impedance at the *x* = 0 end, the frequency domain input admittance at *x* = $\mathcal{L}$ is $Y_{in} = 1/Z_c$, which is a purely resistive quantity. In the time domain, this admittance corresponds to an impulse function $y_{in}(t) = 1/Z_c\,\delta(t)$. Other representations for a more general function $y_{in}(t)$ will usually contain an impulse function at *t* = 0 plus later later-time contributions. In the discrete representation for the function $y_{in}(t)$, the term $y_{in}(0)\Delta t$ corresponds to the delta-function term.

Noting that the right hand side of Eq.(B-2) depends only on *past* values of t_n, this equation is of the form

$$i_t(t_n) + y_{in}(0)F[i_t(t_n)]\Delta t + K = 0$$

where K is a known constant. This equation may be solved for the unknown current at time t_n using a standard root finding algorithm [17].

17. Press, W. H., et. al., *Numerical Recipes*, Cambridge University Press, Cambridge, 1986.

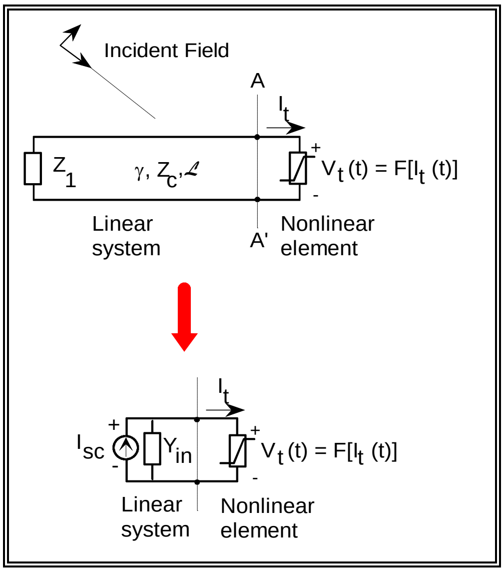


Figure B-1. Transmission line with a nonlinear load.

Example of a Single Transmission Line with a Nonlinear Load Impedance

As an example of such a calculation, consider the case of a field-excited transmission line over a perfectly conducting ground, as shown in Figure B-2. The line length is ℓ = 30m, the height over ground is h = 2 m, and the radius is a = 1 cm. The termination impedance at *x* = 0 is a *linear* load of $Z_1 = 50\Omega$. At the *x* = ℓ end, the *v*-*i* relationship for Z_2 is assumed to be a *nonlinear* function, modeled by a simple piece-wise linear relationship: Z_2 = 50 Ω for *i(t)* > 0 and Z_2 = 5000 Ω for *i(t)* < 0. Other more complicated representations of nonlinear elements are possible in this method, but this simple nonlinearity will serve to illustrate the response.

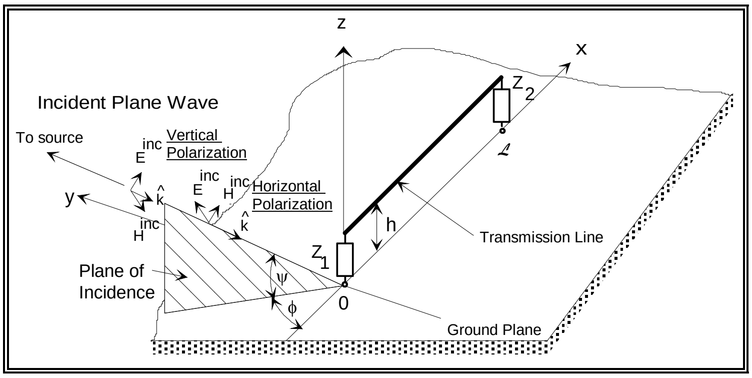
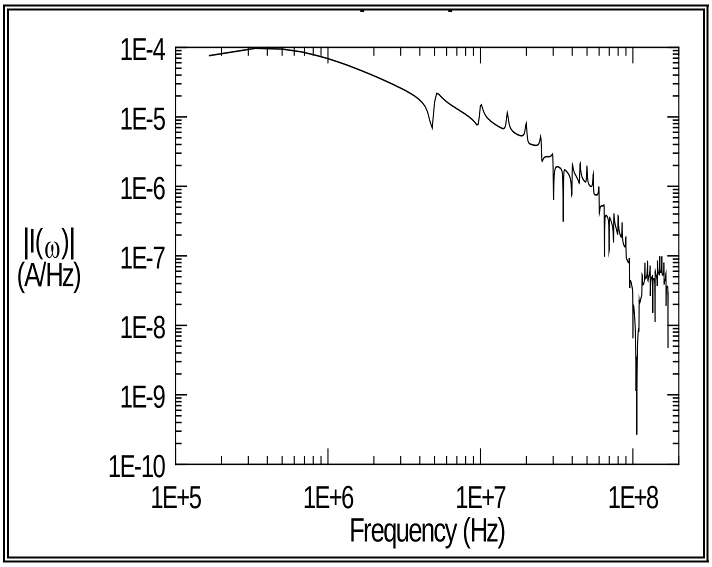


Figure B-2. A single-wire line over a perfectly conducting ground excited by an incident plane wave.

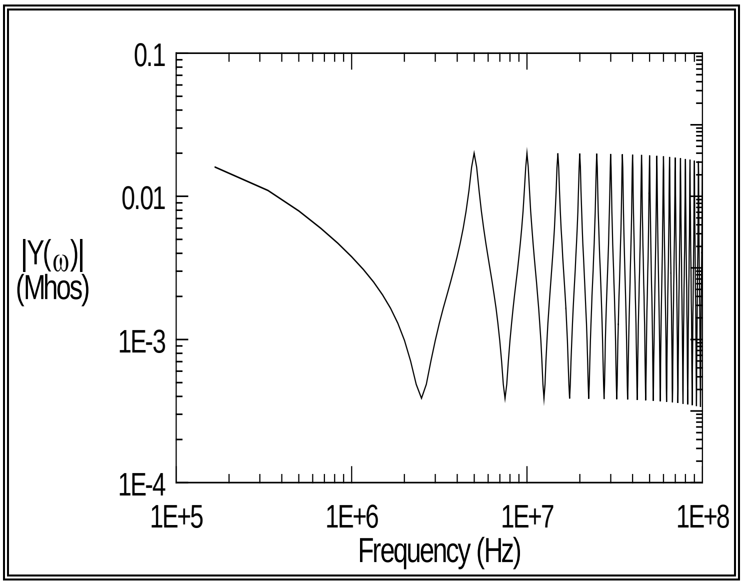
The line is illuminated by a vertically polarized plane wave waveform of the form $E^{inc}(t) = 52{,}500 \times \left(e^{-4\times10^6 t} - e^{-4.76\times10^8 t} \right)$, with angles of incidence ψ = 45° and ϕ = 0°. Thus, the excitation is typical of a electromagnetic pulse, with a peak E-field amplitude of 50 kV/m.

Using the frequency domain analysis presented in this chapter, the spectrum of the short-circuit current $I_{sc}(\omega)$ and the input admittance $Y_{in}(\omega)$ at the location

$x = \mathcal{L}$ can be calculated. Figure B-3 illustrates the magnitudes of these spectra. Note that in the spectrum for $I_{sc}(\omega)$, the spectra of the excitation field has already been included.



a. Short circuit current



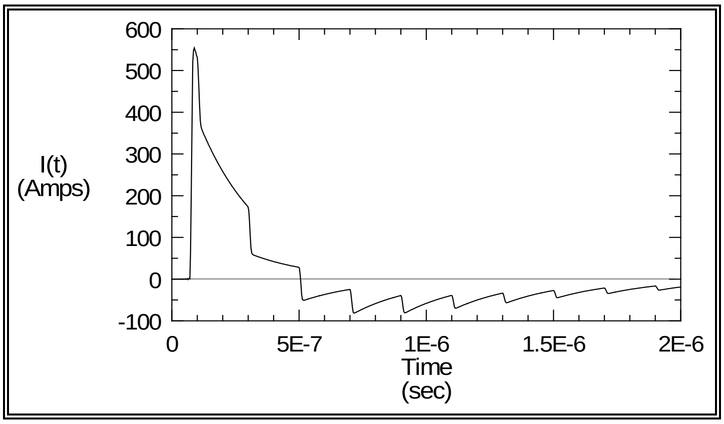
b. Input admittance

Figure B-3. Plots of the short circuit current spectrum (a) and the input admittance (b) at $x = \mathcal{L}$ for a field-excited transmission line as illustrated in Figure B-2.

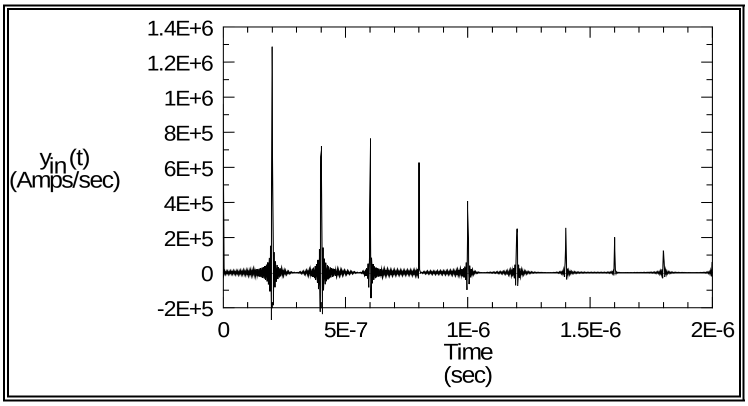
The corresponding transient responses are illustrated in Figure B-4. These waveforms are the Fourier transforms of the spectral shown in Figure B-3.

With these transient responses defined, Eq.(B-2) can be solved for the current through the nonlinear element, $i_t(t)$, at each time step, $n\Delta t$, by marching on in time. The corresponding load voltage $v_t(t)$ can then be easily determined by evaluating the nonlinear equation $v_t(t) = F[i_t(t)]$. These nonlinear responses are shown in Figure B-5. Notice that a large current flows through the nonlinear load in the positive direction when the load impedance is equal to 50 Ω.

However, when the sign of the current changes, the load impedance becomes 5000 Ω and the current is considerable reduced. The load voltage on the other hand, becomes large when the current is blocked.

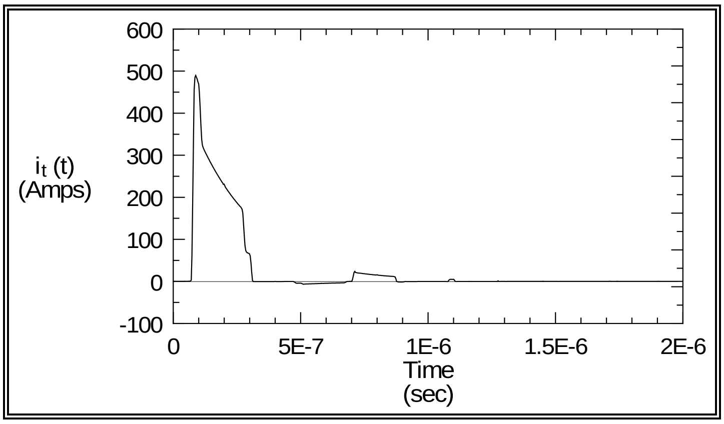


a. Short circuit current

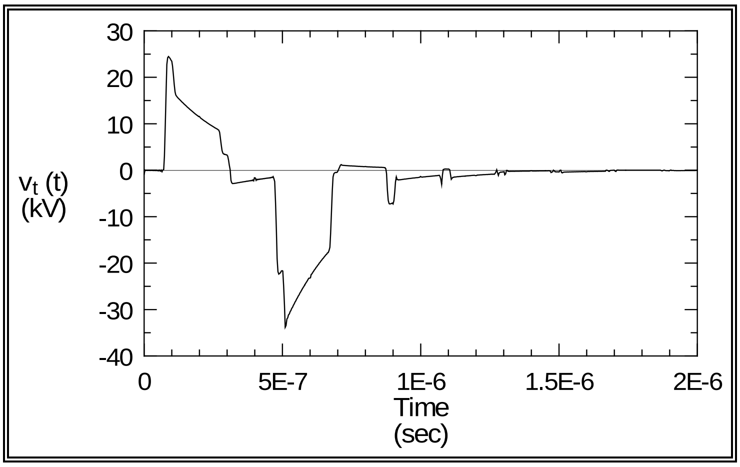


b. Surge admittance

Figure B-4. Plots of the transient short circuit current (a) and the surge admittance (b) at $x = \mathcal{L}$.



a. Load current



b. Load voltage

Figure B-5. Plots of the transient load current across the nonlinear load (a) and the corresponding transient load voltage (b), as computed from the frequency domain data.

This treatment of nonlinear loads can be extended to the case of a general linear N-port network with different nonlinear loads at each of the output ports. This network could be considered to be a transmission line network as in [3], or any other system which is described by the short-circuit admittance parameters y_{ij}. The relevant Volterra equation for the n-vector of load currents [*i(t)*] is given by the matrix integral equation

$$[i(t)] = [i_{sc}(t)] - \int_0^t [y(t-\tau)][F(i_t(\tau))]d\tau \,, \qquad \text{(B-3)}$$

where [*y(t-τ)*] is an n × n matrix whose elements are the Fourier transforms of the corresponding elements of the y matrix in the frequency domain and $\left[i_{sc}(t)\right]$ is an n-vector containing each of the transient Norton current sources for the network. This matrix equation is solved by a time-marching procedure in the same manner as was done for the scalar equation.

As noted in [3], a dual equation can be developed for the nonlinearly loaded system involving the open circuit voltage $v_{oc}(t)$ and the input impedance $z_{in}(t)$ of the system. This alternate expression involves the nonlinear *i-v* relationship for the load as $i_t(t) = G(v_t(t))$, where G is a nonlinear admittance function. In this manner, the Volterra equation for the scalar case is

$$v_t(t) = v_{oc}(t) - \int_0^t z_{in}(t-\tau) G(v_t(\tau)) d\tau , \qquad \text{(B-4)}$$

with a similar matrix equation for the N-port case.

Appendix C: HEMP Survivability Assessments

Overview

Once the HEMP-induced stress within a system has been determined, either through system testing or by analytical models, it in necessary to determine the effects of this stress on the system operation. Because the confidence in the accuracy of calculated results from analytical models is considerably lower than that obtained from testing, measured stresses are usually preferred in performing this task.

In order to determine the system survivability, the degree of susceptibility of the mission critical equipment first must be determined. To do this, one must define an interface between the equipment and the external portion of the system which interacts with the incident HEMP environment. There are many choices for this interface. For example, consider a HF radio system on an aircraft which contains digital electronics, as well as electrically robust components in the high-power RF section. Practical considerations of component susceptibilities suggest that the semiconductor devices will be the components most likely to fail, so that the stress/susceptibility comparison interface might be located at the terminals of these components. Another possibility might be to locate the interface at the connector pins of the cable harnesses or other wiring as they enter in to the boxes (enclosures) comprising the HF system. Still another interface could be at the topological penetration points of a global shield surrounding the radio unit and where penetrations of the HF antenna, the power system, and digital controls, can be defined.

The electrical stresses at each of these interface points will be different, because they are all at different locations within the system topology. Similarly, each of these interfaces will have different susceptibility levels. The goal is to select the interface location which maximizes the confidence in the resulting survivability estimates of the system, while at the same time, providing realistic testing and analytical requirements. The following appendix discusses several possible choices of interface.

Pin-Level Susceptibility Analysis

The choice of the interface being located at the pins of connecting cables implies that it is necessary to evaluate the susceptibility of the system at these points. There are several existing models which can be used to predict failure thresholds of electronic components [18]. These models can be combined together with circuit analysis methods to estimate the failure threshold of a piece of electronic equipment. The basic approach to performing this analysis is as follows (see Figure C-1):

18. Wunsch, D.C., and R.R. Bell, Determination of Threshold Failure Levels for Semiconductor Diodes and Transistors Due to Pulse Voltages, *IEEE Trans. Nuclear Science, Vol.* NS-15, No. 6 , December 1968.

1. For each connector pin, develop an electrical schematic of the interface circuit component.
2. Identify the vulnerable circuit components based on analyst's experience and judgment.
3. Calculate component damage thresholds using a semiconductor device model.
4. Based on interface circuit characteristics estimate the power at the connector pin required to produce component damage.

The difficulty with this approach is in its practical application to complex systems. A modern aircraft system, for example, includes a very large number of electrical components. A typical aircraft may have several thousand electronic boxes, each of which having electrical connectors with 10's of pins. At the system level, the analyst must then address tens of thousands of circuits. Each circuit is examined, simplified and the vulnerable component identified. A failure power threshold is then calculated for the component. The damage threshold is usually based on electrical and thermal induced breakdown failure mechanisms.

Susceptibility analysis is analogous to stress prediction in that the size and complexity of the problem limit the accuracy which can be achieved. For a single circuit, careful circuit analysis and measurement of component parameters can result in a fairly accurate estimate of the failure threshold of a given component. The failure threshold prediction will have an uncertainty of less than a factor of 10 [19]. However, if the estimate is based on generic device characteristics or manufacturers data sheets, the uncertainty in predicted failure threshold will be closer to a factor of 100 [2].

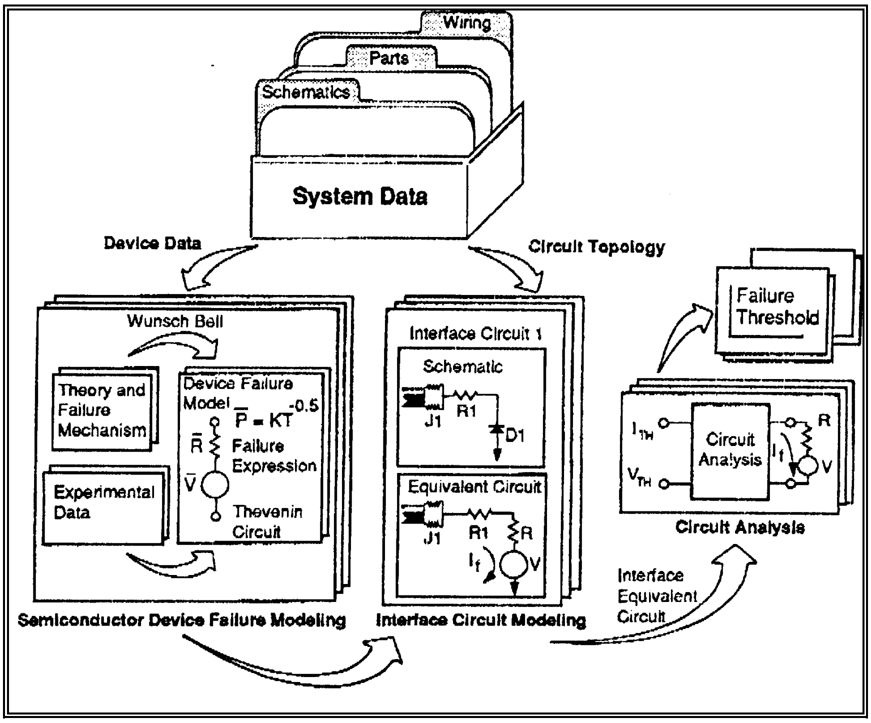


Figure C-1. Analysis elements of pin-level failure threshold analysis and evaluation.

Errors and uncertainties in the susceptibility analysis generally arise from three sources: the semiconductor device model, the interface model and circuit

19. Techniques to Improve EMP Failure Threshold Analysis, DNA Report, DNA 82.H324.6 003, January 15, 1982.

analysis. Those associated with the semiconductor device model are usually the most significant. Device modeling errors are usually due to the incorrect use of device parameters. The device failure model uses certain parameters to estimate failure power. For a given device, these parameters may be obtained from the manufacturers data sheet or from a data base of typical device characteristics. Using either of these sources results in large errors in failure threshold prediction. Measurement of device characteristics for the specific manufacturer's device results in the least error. Interface circuit analysis errors have various sources, including the following:

1. Errors in circuit simplification
2. Single frequency versus transient analysis
3. Single pin versus multiple pin excitation
4. Idealized model elements; i.e., lack of parasitic elements
5. Considering only linear responses
6. Incorrect assumed source impedances
7. Failure to include operating signal levels

Usually uncertainties in circuit analysis are small and can be reduced by using more sophisticated and expensive techniques.

It is important to summarize the limitations on the capability to predict failure thresholds for electronic systems.

1. When the stress/strength comparison interface is at the pins of cables entering box enclosures, HEMP hardness cannot be verified with acceptable confidence. The large number of pin on an aircraft make it impossible to measure stress and strength at each pin. Sampling of the pins on an aircraft results in the situation where it is impossible to have high confidence that a significant number (100's) of pins declared hard by analysis will not, in fact, fail under HEMP stress.
2. The existing failure threshold analysis methods only address permanent damage. Mission failure due to upset malfunction must be considered in hardness verification. This can only be done by conducting a system level
3. For a small number (100's) of well defined circuits, failure thresholds can be predicted with reasonable confidence. However, when this technique is applied at the system level, the large number of circuits and components (10,000's) require the process to be simplified, resulting in large uncertainties.
4. If HEMP hardness is based on semiconductor device characteristics, then the component becomes a hardness critical item (HCI). At the present time, many end users of systems do not specify semiconductor devices in detail, but rather, they procure equipment by "form, fit and function". If semiconductor components become HCI, the end users of the system would have to modify the present system maintenance procedures. In addition, it appears that the semiconductor device characteristics which determine failures are not normally controlled by manufacturers. Thus additional semiconductor specifications and controlled production lines would be required for systems hardened at the pin interfaces.

The significance of these limitations is that failure threshold predictions are not applicable to the following situations. (See Table C-1). These include the following:

1. Hazard Analysis - During the planning of a system level test, the system owner sometimes expresses a concern about the possibility of damaging mission essential equipment. Of course, the test is intended to determine if hardening deficiencies lead to damage or upset, but nonetheless, it is sometimes necessary to provide the system owner with an estimate of what items of equipment could be damaged during high level testing. As noted above, the best source of data to answer this question is measurement of the equipment's minimum strength. However, if experimental data are not available, equipment thresholds can be estimated by analysis.

2. Preliminary Hardness Design - Before detailed hardware designs exist, it is often useful to make preliminary estimates of equipment strength. This activity supports hardening allocations. The amount of protection (stress reduction) needed for various classed of equipment is estimated based on an estimate of equipment strength and the required design margin. If there is a data base of measured strength for the type of equipment of interest, it would be better to refer to that data than to use analysis to estimate strength.

3. Hardness Screening - In this case, the analyst attempts to identify which items of equipment require hardening and how much hardening is required. This situation occurs when the system under consideration includes government furnished equipment (GFE The system developer may be reluctant to apply a minimum strength requirement which may have been procured without any strength requirements. Analysis is then used to estimate failure thresholds and to then determine hardening requirements. The same limitations noted above apply to this case . When implemented on a large scale, there are large uncertainties, and low confidence in the results.

4. System Assessments - It is not useful to assess system hardness by analysis. For a large number of pins, the uncertainties in threshold predictions (factor of 100), together with the uncertainties in stress prediction at the pin (factor of 100) result in unrealistically high design margins. The designer either unnecessarily over-hardens or has a very low confidence in the prediction of what pins are hard.

Equipment permanent damage failure thresholds are best determined by test. The most reasonable approach is to specify a minimum required strength for various classes of equipment and to perform 100% testing to verify the specification. In those cases where it is not possible to test a piece of equipment to determine its strength, analysis can generate an estimate of the damage threshold. The quality of this estimate is usually inversely proportional to the scope (number of circuits) of the analysis. For a small number of circuits, it is possible to characterize the circuit and the component in sufficient detail to produce a reasonable estimate of the failure threshold.

In summary, for following points must be stressed for pin-level susceptibility analysis:

- Selecting the HEMP hardening interface at the component or pin results in a loss confidence in hardness verification. In addition, hardness maintenance becomes impractical.
- Existing threshold analysis techniques do not predict system failure due to upset. A system level test is required to verify hardness to upset. If upsets occur and the hardening interface is at the pin, the difficulty and cost of correcting the problem will be great.

TABLE C-1

Uses for Susceptibility Analysis

USE	COMMENT
Hazard Analysis. Analysis is used to identify equipment which may be damaged by testing.	The system program office may request a pretest analysis to identify what equipment may be damaged by high level simulation. Sensitive equipment may be then decoupled.
Hardening Decision. Analysis is used to estimate amount of stress reduction required to achieve desired margin.	In early hardening design phase, items supplied by the customer (government furnished equipment (GFE)) are sometimes identified for use in the system. Analysis is then used to obtain a back-of-the-envelope estimate of strength to support initial hardness allocation. Assumptions can lead to overhardening.
Hardening Screen. Analysis is used to identify which items of equipment require hardening.	Basic limitation in accuracy of the process means that for a system with a large number of pins (10,000), a significant number (100) will be incorrectly declared.
System Assessment. Analysis is used to estimate a system's probability of survival.	Uncertainties in susceptibility analysis together with uncertainties in stress estimates combine to produce very low confidence in results of analysis.

Susceptibility Analysis Based on Topological Considerations

The problems arising from having too many interface points to adequately monitor, and in having large uncertainties in the susceptibilities at these locations, can be substantially reduced by choosing the interface to be located at one of the topological shields comprising the system. For a multiply shielded system, there might be several choices for this interface. A key principle in designing a hardened system using topological shielding concepts is to minimize the number of penetration points into a shielded volume [20]. Thus, when a system is constructed in this fashion, it is feasible to test and analyze each penetration point without incurring extreme cost penalties.

The implementation of a topologically-based susceptibility analysis of a system principally involves measured data. The analytical techniques are generally not useful for stress predictions or for susceptibility estimates. The general procedure for this type of assessment is as follows:

1. Topological Definition - The first step is to determine the system shielding topology, including all of the shielded and unshielded volumes, and the shielding surfaces. Specific shielded volumes containing mission essential equipment should be identified.
2. POE Identification - With the topology defined, the next step is to locate and identify all POEs entering into the shielded regions, paying special attention to those volumes containing the mission essential equipment identified in step 1.
3. Stress Definition - At each of the defined POEs, a suitable measure of the HEMP-induced stress must be identified. This can be in the form of a current on a cable, a voltage between a cable shield and a case, or in some cases, an electromagnetic field quantity. It is at this

20 Tesche, F.M., "Topological Concepts for Internal EMP Interaction," *IEEE Trans. EMC*, 20 (1), February 1978.

point that some of the analytical coupling and penetration models discussed previously might be of use. This is to help guide the system analyst toward the right choice of stress quantity, not to actually evaluate the stress.

4. Stress Estimation - Once a suitable stress quantity has been defined for each of the POEs into the shielded volume, its value for an HEMP excitation must be estimated. This is done by performing a system-level test, using either the pulse or CW testing approached discussed earlier, with an appropriate extrapolation being done to yield HEMP threat-level stresses. At this stage of the process, there are uncertainties introduced into the stress, due not only to the difficulties with extrapolation as discussed earlier, but also due to a lack of knowledge of the angle of incidence and polarization of the incident HEMP field.

5. Susceptibility Estimation - The next step is to estimate the susceptibility of equipment attached to each of the POE's. As discussed earlier, this cannot be done by analysis because the system is too complex to model. Measurements are required. This may be accomplished by developing a suitable driver for each POE and then individually exciting each POE, making certain that the driving levels exceed the estimated stress for the POE. If a quantitative estimate of a hardness margin for the POE is desired, the experimental POE excitation should be increased to the point where a system failure is observed, and this drive level recorded. Additional errors are introduced into the assessment procedure at this point, as well. These arise from the fact that the POEs are tested one at a time, while the HEMP excitation of the system is simultaneously applied to every POE Furthermore, the exact waveshape of the POE excitations may not be like those found for the HEMP excitation. For example, several damped sine excitations are frequently applied to conducting POEs instead of a broad-band HEMP response.

6. Stress/Susceptibility Comparison - The final step in this process is the comparison of the estimated stress levels at each of the POEs with the measured susceptibilities. For those POEs where the measured susceptibilities are larger than the stress, the POE is hard, and a hardness margin can be estimated. For those POEs which gave rise to equipment failure during the susceptibility testing, the POE is not hard, and there is a corresponding negative hardness margin. Retrofit hardening measures are then called for.

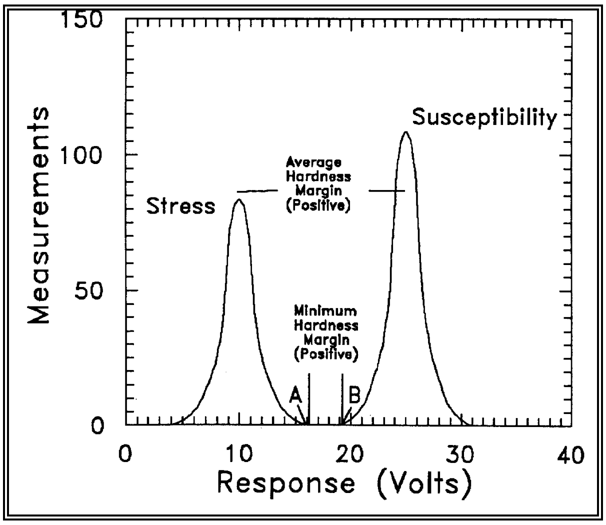
A hypothetical example of the relationship between the stress and the susceptibility level at a POE is illustrated in Figure C-2. It is supposed that for a particular POE in a system, a suitable observable for defining the stress is a voltage. Measurement and extrapolation of the HEMP-induced stress at this POE provide a nominal estimate of 10 volts. This number is uncertain, however, due to the measurement, extrapolation, and environmental uncertainties previously discussed. Consequently, the stress is represented by a distribution of possible voltages, having a most likely value of about 10 volts, but with a shape which is generally unknown. The susceptibility of equipment attached to the POE can be defined in a similar manner, using a distribution function. Uncertainties in the measurement process also provide a distribution function describing the probable system susceptibility. Its shape is also unknown.

In the case shown in Figure C-2a, the POE stress distribution is well below the susceptibility distribution, and this particular POE would be considered hard. The overall system would be considered hard if every POE behaved in this manner. For this POE, it is possible to define an average hardness margin as indicated in the figure. Note that this depends only on the mean values of the stress and susceptibility levels. The highest stress in the distribution, denoted by "A" in the figure, and the lowest level of susceptibility, denoted by "Bl', are seen to be separated by a non zero voltage, indicating that there is a minimum hardness margin (which is positive in this case).

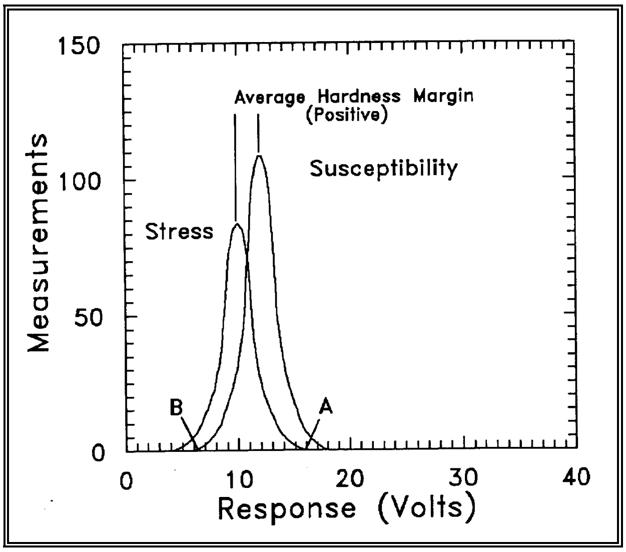
Because the shapes of the stress and susceptibility distributions are unknown, the exact voltage values at "A" and "B" are also unknown. Given a finite number of measurements of the susceptibility of the equipment, or estimates of the errors in the stress, these distributions can be fit to one of several mathematical models which can then be used to estimate the values in the tails of these distributions. An alternate approach is to use analytical models to estimate the range of expected deviations in these distributions. Needless to say, this leads to additional uncertainties in the minimum hardness margin. For a sure-hard system, it is desired to have these tails of the distribution be well separated to insure hardness. This leads, perhaps, to over hardening of the system, but one that has a high degree of confidence in the hardening.

Figure C-2b illustrates the case where the stress and the susceptibility distributions for the POE overlap. Here the average hardness margin is still positive, indicating that the POE is hard. However, the high end of the stress distribution, "A", is well within the susceptibility distribution, indicating that the minimum hardness margin is negative. In this case, the system is only marginally hard. The corresponding case of a sure unhard system is shown in Figure C-2c, where the stress distribution is clearly larger than the susceptibility.

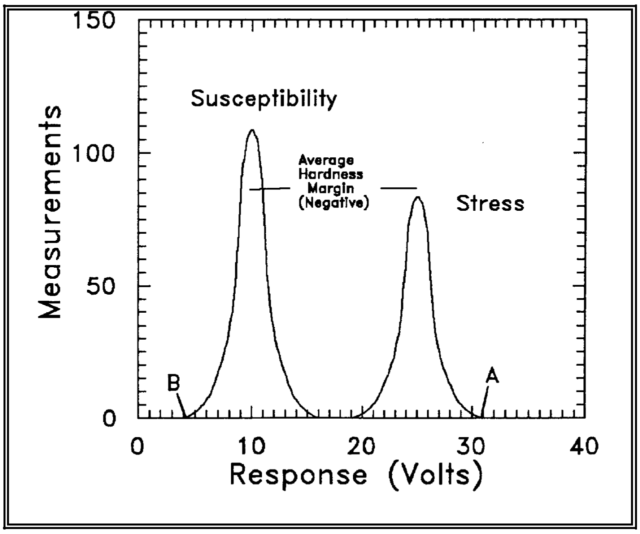
This approach to survivability estimation is capable of providing results that are significantly more accurate than does the pin-level interface method. Of course, a prime prerequisite for its use is that the system be built with topological shielding concepts guiding the design. The application of this method to a system not build with a well controlled topology is not possible, for the same reason that the pin-level approach fails: there are too many pins to be adequately treated. This points out one of the benefits of designing and constructing a system in a topological manner.



a. A sure-hard system



b. A marginally-hard system.



c. An unhard system

Figure C-2. Hypothetical stress-susceptibility distributions for a POE.

Appendix D: Waveform Norms

Introduction

Once a set of system responses have been measured, corrected, extrapolated, or filtered, something must be done to characterize them in a way that will be useful for assessing the overall behavior of the system in the HEMP environment. Simply presenting several thousand plots of spectra or transient waveforms in a test report is not useful. The resulting responses must be further analyzed, categorized, and archived.

One way to summarize the similarities and differences between different waveforms is to define several observables that can be easily calculated, and which have a bearing on the system response to HEMP. The peak amplitude and the largest rate of rise of a transient waveform immediately come to mind. Baum [21] has introduced the concept of a waveform norm for this purpose, and has described in detail the mathematical properties of such norms. More loosely, the term "norm" is often used as being any scalar quantity that characterizes the waveform. With such norms defined, various waveforms can be compared and contrasted, not by their detailed time histories, but by these simpler (and fewer in number) quantities. The following norms are useful for such an analysis. In this discussion, it is assumed that the time domain waveform is represented by f(t).

1. Peak Amplitude - The peak amplitude norm is simply the largest absolute value contained in f(t). This quantifier has the relationship with the rest of the waveform that on a continuous point-by-point comparison, it has the maximum value.
2. Maximum Rate of Rise - The derivative of the function f(t) is computed numerically from the measured waveform by computing the slope using neighboring points. A new function f ′(t) is obtained, and then its peak value is found.
3. Total Impulse - This function, defined as $\int f(t)\,dt$, is not a true norm as defined in [1], but is a scalar observable and, as such, can be used for waveform comparisons. It is equal to the total area of the waveform curve, and thus may be positive, negative, or zero.
4. Peak Value of the Impulse - In performing the numerical integration of f(t) to obtain the total impulse, the largest absolute value is stored as the integration proceeds. This scalar quantifier is

21 Baum, C.E., "Extrapolation Techniques for Interpreting the Results of Tests in EMP Simulators in Terms of EMP Criteria", *AFWL Sensor and Simulation Notes*, Note 222, March 20, 1977.

again not a norm in the mathematical sense, but is useful for waveform comparisons.

5. Rectified Impulse - This quantifier, defined as, $\int |f(t)| dt$, is similar to the total impulse, but with the absolute value of the function being used.
6. Action Integral - The action integral,; $\int f^2(t)\, dt$ is proportional to the energy contained in the waveform.
7. Square Root of the Action Integral - This scalar quantifier is the Euclidean norm, defined as $\sqrt{\int f^2(t) dt}$.

These waveform norms are summarized in Table D-1, along with relationships between the value of the norm and possible adverse effects in electrical systems. These norms have been applied to measured data from a number of different aircraft systems. It has been found that the strongest correlations occur between the peak value and the action integral norms. The weakest correlation is between the peak value and the impulse integral, which is not a true mathematical norm.

Although is it relatively easy to compute these scalar observables, is it not as easy to decide what to do with them, nor to say what level of a particular norm quantity might be dangerous to equipment in a system. Variations in the norm values can be used to develop a statistical view of possible system responses.

TABLE D-1

Waveform Observation Quantities for Stress Characterization

QUANTITY	DEFINITION	FAILURE MODE AND CRITICAL PHENOMENON
Peak Value	$[I(t)]_{max}$; $[V(t)]_{max}$	Toggling of digital circuits Dielectric breakdown Some junction breakdown phenomena
Rate of Rise	$[\frac{\partial}{\partial t} I(t)]_{max}$; $[\frac{\partial}{\partial t} V(t)]_{max}$	Mutual coupling between wires Reactive circuit elements Toggling of digital circuits Voltage breakdown
Total Impulse	$\int_0^\infty I(t)dt$; $\int_0^\infty V(t)dt$	Toggling of digital circuits
Peak Impulse	$\left[\int_0^\infty I(t)dt\right]_{max}$; $\left[\int_0^\infty V(t)dt\right]_{max}$	Toggling of digital circuits
Rectified Impulse	$\int_0^\infty \lvert I(t)\rvert dt$; $\int_0^\infty \lvert V(t)\rvert dt$	When oscillatory waveforms can be rectified and stacked together Some junction heating
Action Integral	$\int_0^\infty I^2(t)dt$; $\int_0^\infty V^2(t)dt$	Adiabatic thermal failure modes Bulk heating, resistor heating Metalization burnout

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