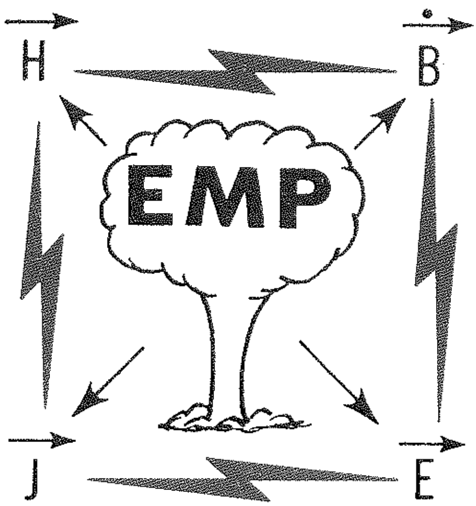
NEM 1978 RECORD

ABSTRACTS OF TECHNICAL PAPERS

Nuclear EMP Meeting
June 6-8, 1978
University of New Mexico Campus



Sponsored By:

IEEE Albuquerque Joint Chapter: AP-S, S-MTT, G-EMC
Department of Electrical Engineering and Computer Science, University of New Mexico

NEM 1978 - CONDENSED PROGRAM

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TUESDAY MORNING, JUNE 6, 0830-1150			
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IN-3	Apertures and Cavities A. Apertures B. Cavities	ED	103
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WEDNESDAY MORNING, JUNE 7, 0830-1150			
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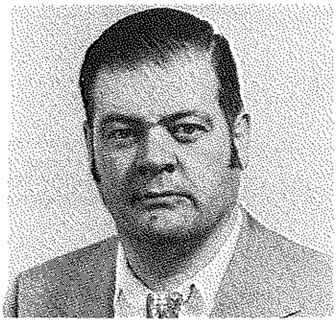
ED--Education Classroom Building



WELCOME
TO
ALBUQUERQUE

On behalf of the conference committee, the IEEE Joint Chapter: AP-S, S-MTT, and G-EMC, the Department of Electrical Engineering and Computer Science of the University of New Mexico, and the cooperating professional and governmental groups, I would like to welcome all the conference attendees to NEM 1978. I would particularly like to thank the conference committee for all the hard work they have done to make NEM 1978 a successful conference.

The previous NEM was held in 1973. Since the purpose of an NEM is to be a broad-ranging conference covering the entire spectrum of nuclear EMP related technology, and since this is the only major type of conference devoted primarily to this subject, it was felt that another such conference was perhaps overdue. Besides providing a cross-fertilization of ideas in the EMP community, an NEM also serves to bring the EMP community together to renew old acquaintances, introduce new members of the EMP community to the "old salts" and to the current state of the art, and provide an occasional kilometer stone (going metric you know) in summarizing the current state of the art. With the recent publication of the Joint Special Issue on the Nuclear Electromagnetic Pulse (IEEE Trans. Antennas and Propagation, January 1978, and IEEE Trans. Electromagnetic Compatibility, February 1978) providing a written review of the more basic and established aspects of EMP technology, this conference (NEM 1978) is in a position to provide a forum for launching some of the newer technology that is just beginning to be discovered.

So I wish you all a most productive conference. There are some exciting new ideas to be explored. Some progress has been achieved, and with everyone's help much more can be achieved.

Carl E. Baum

Dr. Carl E. Baum
Conference Chairman

NEM 1978

THE INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS, INC.
Albuquerque Section
Joint Chapter:
AP-S, S-MTT, G-EMC

Department of Electrical Engineering
and Computer Science
University of New Mexico
Albuquerque, New Mexico 87131

In cooperation with the following IEEE Groups/Societies:
- Antennas & Propagation
- Microwave Theory & Techniques
- Electromagnetic Compatibility

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In cooperation with the U.S. National Committee of the International Union of Radio Science (USNC/URSI):
- Commission B: Fields & Waves
- Commission E: Interference Environment

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In cooperation with the following government agencies:
- Harry Diamond Laboratories (Army)
- Naval Surface Weapons Laboratory
- Air Force Weapons Laboratory
- Air Force Office of Scientific Research

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The NEM 1978 is pleased to announce that the Air Force Office of Scientific Research (AFOSR) has provided a special financial support to the Conference for advancing the scientific research and technological development concerning the Nuclear Electromagnetic Pulse.

TECHNICAL PROGRAM

TUESDAY MORNING
JUNE 6, 0830-1210

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Room 101
Chairman: Don Wilton
University of Mississippi

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3.	0910	*An SEM Interpretation of Skin Current Injection Testing of the Transient Scattering Response of an Object*, by L.W. Pearson, University of Kentucky, Lexington, KY	24
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5.	0950	*Realizibility Considerations in Constructing Equivalent Circuits from the SEM Solution*, by B.K. Singaraju and C.E. Baum, Air Force Weapons Lab, Kirtland AFB, NM	26
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Education Class Room Building
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Chairman: J. Philip Castillo
Air Force Weapons Laboratory

MEASUREMENT TECHNIQUES
Session MT-1
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Room 104
Chairman: Ralph Partridge
Los Alamos Scientific Laboratory

HIGH ALTITUDE EMP
Session EN-1
Education Class Room Building
Room 105
Chairman: William Karzas
Research and Development Associates

TUESDAY AFTERNOON
JUNE 6, 1330-1710

SINGULARITY EXPANSION METHOD-II
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Education Class Room Building
Room 101
Chairman: Raj Mittra
University of Illinois at Urbana

APERTURES AND CAVITIES
Session IN-3
Education Class Room Building
Room 103
Chairman: Lennart Marin
Dikewood Industries, Inc.

SURFACE BURST EMP
Session EN-2
Education Class Room Building
Room 105
Chairman: Conrad L. Longmire
Mission Research Corporation

WEDNESDAY MORNING
JUNE 7, 0830-1150

TRANSMISSION LINE MODELING
Session IN-4
Education Class Room Building
Room 101
Chairman: Edward Vance
SRI International

HARDNESS VALIDATION AND CONFIDENCE
Session ST-1
Education Class Room Building
Room 103
Chairman: Gene Morgan
Autonetics

DATA PROCESSING TECHNIQUES
Session ST-2
Education Class Room Building
Room 104
Chairman: Werner Stark
Kaman Sciences Corporation

LIGHTNING PHENOMENA AND RELATION TO EMP
Session LT-1
Education Class Room Building
Room 105
Chairman: Gary Price
SRI International

WEDNESDAY AFTERNOON

JUNE 7, 1330

PLENARY SESSION
Session P-1
Student Union Building, Grand Ballroom
Chairman: John Darrah
Air Force Weapons Laboratory

THURSDAY MORNING
JUNE 8, 0830-1150

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Lawrence Livermore Laboratory

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Room 104
Chairman: Fred Tesche
Science Applications, Inc.

SYSTEM GENERATED EMP-I
Session IN-6
Education Class Room Building
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Chairman: Gerard Schlegel
Research and Development Associates

THURSDAY AFTERNOON
June 8, 1330-1650

EXPERIMENTAL EXTERIOR INTERACTION
Session ST-3
Education Class Room Building
Room 101
Chairman: Clay Taylor
Mississippi State University

ANTENNAS
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Education Class Room Building
Room 103
Chairman: Chen-To Tai
University of Michigan Radiation Laboratory

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4. 1430	*EMP Response of an Aircraft with a Trailing Wire Antenna Deployed*, by W.L. Curtis, Boeing Aerospace Company, Seattle, WA	145
5. 1450	*Transient Responses Induced on a Log-Periodic Antenna by an Electromagnetic Pulse*, by K.M. Lee, Mission Research Corp., Albuquerque, NM	146
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SIMULATION TECHNOLOGY
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Room 104
Chairman: Kelvin S. H. Lee
Dikewood Industries, Inc.

SYSTEM GENERATED EMP-II
Session IN-8
Education Class Room Building
Room 105
Chairman: Jim Gilbert
Mission Research Corporation

PROBING THE MYSTERIES OF COUPLING COEFFICIENTS IN THE SINGULARITY EXPANSION METHOD

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The proliferation of different types of coupling coefficients in the singularity expansion method has reached a stage where it sometimes presents a problem of considerable magnitude. A user who is not conversant with the fine points of Type-1, 2, X and Ω (or whatever other coupling coefficients that might be proposed in the future) can find it rather difficult to decide which type of coefficients to use under a given set of circumstances and whether an incorrect choice would introduce substantial errors.

One of the distinguishing features of the Type-1 coupling coefficients is the so-called "turn-on" time, which is taken to be the time when the incident pulse first reaches the scatterer, say t=0. The implication of this choice of the turn-on time is that in the process of computing the response waveform, the spatial integration is carried out over the entire surface of the scatterer beginning with the time t=0, and without allowing for the causal time delay. Following this procedure, one finds that the Type-1 SEM representation yields a response signal expressible in the form $\Sigma A_n \exp\{s_n t\}$, where A_n are independent of time. However, the other types of coupling coefficients, which introduce various degrees of time delays for the spatial integration result in a representation where the coefficients are time-varying, at least before $t=\tau$, where τ is the transit time of the incident wave as it sweeps past the scatterer. This important difference between the nature of A_n in the different types of coupling immediately raises the fundamental question: "Can these different types of coupling formulas all be correct, and do they yield identical results in the final analysis in spite of the obvious differences in their forms?" We may further ask, "Since the Type-1 form is the more desirable one from the point of view of equivalent circuit representation computation of the surface current on the scatterer, as well as for the evaluation of the far fields radiated by this current, could we find a way to avoid using the more complex form for the coupling, e.g., Type-2, without paying a penalty?"

In this paper, we examine both of these questions and show, in the first instance, that the conventional use of the Type-1 coupling coefficient can indeed be subject to errors, except perhaps in trivial cases.

The second and perhaps the most significant contribution of the paper is to develop a new representation of the incident field that allows one to use the Type-1 coupling formula in a correct manner such that the final results for the surface current and other desired quantities are consistent with those derived via the use of other types of coupling formulas.

Pseudosymmetric Eigenmode Expansion for the Magnetic Field Integral Equation and SEM Consequences

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A.D. Varvatsis
Scott Siegel

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Los Angeles, CA 90049

ABSTRACT

An eigenmode expansion for the magnetic field integral equation (MFIE) is derived which eliminates the requirement that an adjoint solution be explicitly sought. Instead, an orthogonality relation is determined which only involves the eigenmodes of the original MFIE operator. To promote confidence in the validity of the expansion, two analyses based on the expansion are presented which lead to known results. First, the expansion is applied to the problem of determining the surface current density induced on a perfectly conducting sphere by a plane wave and the known solution for this problem is duplicated by the expansion. The second analysis shows that for a general perfectly conducting body, the eigenmode expansion coefficient evaluated at the purely imaginary frequency corresponding to an interior resonance is zero. This result is necessary in order to relate the eigenmode expansion to SEM.

Viewing the SEM as a change of representation of the eigenmode expansion intended to facilitate the inverse Laplace transform of that expansion and taking advantage of our detailed sphere calculations, we obtained an important SEM result. We found that MFIE class 2 coupling coefficients give the wrong answer for the sphere. This result caused us to examine class 2 coupling coefficients corresponding to the electric field integro-differential equation (EFIDE). We examined the symmetric eigenmode expansion corresponding to that equation and found that EFIDE class 2 coupling coefficients also give the wrong answer for the sphere. Finally, we present numerical results that utilize our pseudosymmetric expansion and illustrate the capability of determining SEM quantities by patch zoning the MFIE.

"AN SEM INTERPRETATION OF SKIN CURRENT INJECTION TESTING OF THE TRANSIENT SCATTERING RESPONSE OF AN OBJECT"

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University of Kentucky
Lexington, KY

Recently [1], the Naval Surface Weapons Center, White Oak Lab, introduced a test scheme whereby transient skin currents are excited on an aircraft at rest over conducting ground by directly attaching a pulse generator to the surface of the structure. This alternative simulation technique has been termed Skin Current Injection Testing (SCIT). An anaylsis of data taken in this way on an A-6 aircraft indicates that certain of the resonant features of this structure are discernable from SCIT data.

In this presentation, we interpret the phenomenology of SCIT testing in terms of the Singularity Expansion representation for the current on the scatterer. It is shown that, indeed, the SEM resonances dominate in the response are contained in SCIT data and are, in principle, obtainable through Prony-type data analysis methods. Some guidelines are given to the allowable coupling mechanisms between the generator and the object so as to minimize corruption of the object resonance by the generator appendage. The possibilities and limitations which come to play in relating SCIT measurements directly to threat response are discussed. The possibility for performing SCIT measurements at the scale model level is discussed. The scale model measurements offer the potential of guiding full-scale system testing so as to narrow the data window required and hence reduce test costs.

REFERENCE

1. G. W. Bechtold, "Comparison of Predicted and Measured Aircraft Skin Currents", EMP Coupling Analysis and Validation Seminar, Air Force Academy, July 20-22, 1976.

*This work was sponsored by ONR Contract No. N00014-77-G-0362.

ON THE SINGULARITY EXPANSION METHOD APPLIED TO HORIZONTAL CROSSED WIRES OVER A GROUND PLANE

by

Terry T. Crow
Clayborne D. Taylor

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Mississippi State, MS 39762

Plane wave illumination of horizontal crossed wires (crude model of an aircraft) over a ground plane is considered. And a parametric study of the singularity-expansion-method parameters is performed. Using a numerical solution technique the natural frequencies, natural modes and coupling coefficients are obtained as the geometrical parameters are varied for a perfectly conducting ground plane. Also corresponding results are obtained from an approximation derived from transmission line theory. A lossy ground plane is considered in the transmission line formulation as well as a perfectly conducting ground and limited results are obtained for a single wire. Time domain results are presented for a unit step incident pulse.

REALIZABILITY CONSIDERATIONS IN CONSTRUCTING EQUIVALENT CIRCUITS FROM THE SEM SOLUTION

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In complex frequency plane there are various equivalent representations for an electromagnetic coupling problem. In the singularity expansion method (SEM) the response can be written in terms of the s plane singularities such as poles, branch cuts, etc. Circuit models can be constructed from the singularity expansion method representation which have the advantage of providing physical insight, computational convenience and low cost laboratory simulation among others. Both open circuit and short circuit boundary value problems can be treated in this fashion.

We have shown in an earlier work that it is possible to construct simple equivalent circuit representation from the SEM solution. In the present work, we investigate the conditions under which an equivalent circuit is realizable for a general problem and discuss an example.

SINGULARITIES OF THE IMPEDANCE FUNCTION OF THIN CYLINDRICAL ANTENNAS BASED ON A PERTURBATION METHOD*

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ABSTRACT

In a classical paper by Schelkunoff the impedance function of a cylindrical antenna was found by treating the cylindrical antenna as a non-uniform biconical antenna. We have modified Schelkunoff's calculation by using an average characteristic impedance corresponding to that of an inscribed biconical antenna. From the physical reasoning, as supported also by the induced EMF method, such a choice should yield a better approximation. The singularities of the impedance function is then found by a numerical analysis. In contrast to Tesche's result based on the integral equation method [IEEE Trans. AP-21, p. 53 (1973)] we found only two layers of zeros of the impedance function, corresponding to the poles of the input current function. While the first layer of the zeros is very similar to Tesche's the second layer does not resemble his higher-order layers. The work is now being extended to antennas of other shapes, such as prolate spheroidal antenna and rhombic antennas. An outline of this research will be described in this paper, including a reformulation of the integration of the differential equations pertaining to the theory of non-uniform transmission lines.

*This work was supported by the National Science Foundation under Grant ENG-75-17967 and by the Air Force Office of Scientific Research under Grant 77-3358.

A NETWORK MODEL FOR THE BICONICAL ANTENNA

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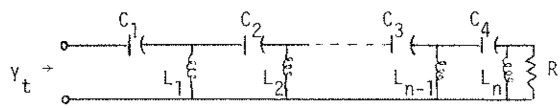
ABSTRACT

Tai [1] has shown that the input impedance at the center of a biconical antenna can be represented as a section of uniform transmission line terminated in a frequency-dependent admittance Y_t. The latter is a complicated transcendental function and does not lend itself to standard expansion techniques from which a network model may be derived. This paper presents a direct synthesis method from which a ladder network of the form shown below may be constructed from calculated values of $Re[Y_t(j\omega)]$.



Realizability is guaranteed by imposing the energy conservation principle and by utilizing the minimum phase character of the scattering parameter $S_{21}(s)$. The approximation problem involves least-square curve-fitting by a polynomial followed by a factorization step. The desired parameters of the network model are then obtained via the application of a straight-forward algorithm. Representative examples are presented.

[1] Tai, C.T., "The Theory of Linear Antennas", Chapter 8, R.W.P. King, Harvard University Press, Cambridge, Mass. (1956).

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CIRCUIT APPROACH TO THE FORMULATION OF EMP INTERACTION PROBLEMS

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The circuit approach is essentially a low-frequency method useful for wavelengths much greater than the overall dimensions of the system under consideration. When this assumption holds, the electrical response of the system can be described by the conventional circuit theory. This theory is expressed in two laws, the so-called Kirchhoff's current and voltage laws. These two laws take extremely simple mathematical form, namely, the form of algebraic and ordinary differential equations. For this reason the circuit approach quickly leads to simple and physically interpretable results. Besides the analytical ease with this approach, the circuit concept is a powerful tool for qualitative thinking, often shedding valuable light on the many electromagnetic interactions taking place within a complex system.

In this paper we will first discuss the relationship of Kirchhoff's circuit theory to Maxwell's field theory starting from Maxwell's equations in integral form. This relationship is then re-examined from the customary viewpoint of the electrical engineer through the use of vector and scalar potentials. We then proceed to derive the circuit properties of an object in infinite space with the aid of the complex Poynting theorem expressed in terms of current and charge densities on the external surface of the object. With this theorem the positive real (p.r.) characteristics of the driving-point impedance or admittance can be proved, the resonance condition can be established, and the damping of each resonant (natural) mode by radiation can be calculated. This theorem also leads, at the low-frequency limit, to the concept of energy functions in terms of which the Kirchhoff voltage law can be re-derived by the Lagrangian method. To end this paper we will briefly discuss the equivalent circuit representations of discontinuities in an otherwise uniform transmission line or waveguide, and the circuit description of the dynamic behaviors of several different kinds of modes, such as the waveguide modes, the cavity modes, the leaky modes, and the natural modes.

E M P SHIELDING AND ADVANCED COMPOSITE MATERIALS

Kendall F. Casey, Department of Electrical Engineering, Kansas State University, Manhattan, KS 66506

The use of advanced composite materials in aircraft construction is increasing and will continue to increase, since these materials possess a substantial strength/weight advantage over metals. In fact, advanced composites are expected to comprise 40% by weight and 80% outer surface coverage of the F-18 fighter. Since these new materials are not as effective as metals in electromagnetic shielding, it is important to assess the electromagnetic behavior of advanced composites in order to determine the increased shielding burden which may need to be borne by internal aircraft cabling and electronics.

In this paper we review some recent work on electromagnetic modeling of advanced composites and present data on electromagnetic field penetration of composite panels and of hollow bodies made of advanced composites. Two principal genera of materials are considered: graphite-epoxy composites, which behave like conductive media with conductivities in the vicinity of 10^4 mho m^{-1}; and "screened" boron-epoxy composites, which consist of a non-conductive anisotropic dielectric panel with a bonded wire-mesh screen embedded in one surface. The electromagnetic behaviors of these two types of advanced composites are very different, since the graphite-epoxy composite acts as a low-pass filter in the frequency domain, while the screened boron-epoxy composite has a high-pass characteristic. Furthermore, these behaviors are modified when an enclosed region is considered, because of the "low-pass" character of hollow bodies at frequencies below their internal and external resonances.

BOUNDARY CONNECTION SUPERMATRICES AND ELECTROMAGNETIC SHIELDING CALCULATIONS

Kendall F. Casey, Department of Electrical Engineering, Kansas State University, Manhattan, KS 66506, and Carl E. Baum, Air Force Weapons Laboratory, Kirtland AFB, NM 87117

A boundary connection supermatrix (BCS) is a matrix-of-dyadics operator which relates the tangential components of the electric and magnetic fields on one side of a planar shield structure to those on the other. The shield may be made up of many layers with sheet impedances between them; also, each layer can be inhomogeneous and/or anisotropic. The operator itself can be expressed as a product of operators of two separate types: these resemble the translation and refraction operators of geometrical optics.

The BCS can be developed for planar shields and then applied to the study of shields which are not planar, if their radii of curvature are large in comparison to their thicknesses. The usefulness of the BCS lies in the fact that it can greatly reduce the complexity of electromagnetic boundary-value problems involving complicated multi-layer shield structures, since it takes the shield structure automatically into account.

The BCS which has been described can be thought of as being an electromagnetic analog of the transmission matrix of two-port network theory, and it possesses properties similar to those of the T-matrx. Furthermore, alternate forms of the BCS exist which are analogous to other two-port matrices, e.g., the impedance and hybrid matrices.

In this paper we discuss the construction of the BCS and certain of its properties and limiting forms, and we present illustrative examples for some common shields. In addition, we discuss the formulation of integral equations for scattering and penetration of hollow bodies whose boundaries are described by the BCS.

EXTERNAL AND INTERNAL NEMP COUPLING TO A GRAPHITE EPOXY COMPOSITE AIRCRAFT*

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Because of their high strength-to-weight ratios, graphite-epoxy composite materials are finding increased usage in aircraft structural design, especially for aircraft skins. Two important issues relating to EMP coupling to a composite aircraft are addressed in this paper. The first issue concerns external coupling. Previous external coupling calculations for metallic aircraft have assumed the aircraft to be a perfect conductor. This is equivalent to assuming the aircraft skin surface impedance Zs to be zero. The problem relating to external coupling is therefore to determine Zs for composite skins and then to determine what effect this has on external coupling. The second issue concerns internal coupling. For composite skins, the problem is to determine diffusion through the skin and the induced voltages and currents on internal cables, and compare with the coupling levels induced via other POEs.

The properties of the graphite-epoxy composites are first discussed and the appropriate surface impedances are deduced. Numerical results are presented for externally induced surface current densities for various surface impedances. The effects of the composite material on the external coupling are examined. This is accomplished by using a three-dimensional finite-difference method of calculation of the induced responses exterior to the composite aircraft. From these results, we conclude that no discernible difference exists for external coupling results for aircraft skins having surface impedances between 0 and 1 ohm, and less than 6% difference in peak value is evident for a surface impedance of 10 ohms.

Numerical results obtained for external responses are then used to find the internal electromagnetic fields by making use of the surface transfer impedances. These internal fields are then used to calculate the short circuit currents and open circuit voltages induced on the internal cables. From the relative magnitude of these levels with respect to the levels induced via other POEs, a judgement is thereby made of the significance of diffusion coupling versus aperture coupling. The diffusion induced levels are found to be generally less than those associated with aperture or antenna coupling, but they are still significant and cannot be ignored in aircraft hardening.

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"Composite Plates - Their Surface Current and Charge Densities"

by C. L. Andrews, State University of New York at Albany,
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Modern composite materials are appearing as components of a large, and ever growing, number of important civilian and military systems. Consequently, detailed knowledge of the response of these materials to EMP, lightning, microwaves, etc., is becoming increasingly more significant. To help fill this need we have initiated a number of experimental studies. In one of these studies we have irradiated a set of thin square plates, each of a different type of composite, and measured both the induced surface charge and surface currents over both the front and rear faces. Each composite plate was then replaced by an aluminum plate of identical dimensions and the measurements were repeated. This provides a simple means for comparison of the response of the composites to that of the well known material aluminum. In addition the response characteristics of the different composites can also be compared to one another.

We shall show results obtained for three different types of composites each made into a square plate one wavelength on a side. Two of these composites are of the metal matrix type and the third consists of graphite fibers in tape form in oriented layers in epoxy. This is the so-called type 35-06-1. One of the metal matrix composites is fabricated of silicon carbide, 25% by volume, in 2024-aluminum alloy by standard power metallurgic techniques. The second consists of graphite fibers formed into the composite by liquid infiltration and hot pressing in 201-aluminum alloy.

We shall very briefly outline our other related studies on electromagnetic characteristics of composites.

Electromagnetic Properties of Non-Metallic Composite Materials: An Area Where Confusion Abounds. An Area which requires Fundamental Changes in EMP Analysis

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Non-metalic composite materials have been used to a minor degree in the F-14 and F-15 aircraft. The F-18 and AV-8B aircraft denote the major potions of the aircraft structure being built with a non-metallic material. Total composite material construction are being considered for aircraft for the 1990 timeframe. Only within the last year has adequate electromagnetic data been collected which allows initial prediction of composite aircraft susceptability.

The data reveals graphite/epoxy (g/e) composite material magnetic shielding (S_H) transparent below 0.2MHz progressing to opaqueness by 100 MHz. The sparce data regarding electric shielding (S_E) of a one dimensional joint (linear joint between metal and graphite/epoxy sections) and a two dimensional joint (doors and access panels) shows the inverse - S_E decreases as frequency increases.

Due to the tendency of describing things in the simplest terms, many incorrect notions abound about the very complex array of factors that constitute the electromagnetic properties of the many composite materials. Some of the primary parameters that determine the electromagnetic behavior of composite materials are:

MATERIAL (graphite/epoxy, boron/epoxy, Kevlar and fiberglass are the most common. Their shielding properties respectfully diminish.)

MATERIAL LAY-UP OR WEAVE (layers of parallel strands of graphite are far more susceptible than layers with fibers at 0,-45,+45,-90...degrees)

FREQUENCY

JOINT STRUCTURE (typical joints diminish g/e conductivity 1000X while well designed expensive joints diminish g/e conductivity 50X.)

EMP induced voltages and currents on wires in an all aluminum airframe, in an all g/e airframe, and in an aluminum/graphite/epoxy airframe with different type joints will be discussed. Moment codes which account for composite material frequency dependent intrinsic parameters (conductivity, permeability and permittivity) have had initial development. Tests are currently underway to corroborate code output. The EMP community may no longer develop codes for only metals or dielectrics which will not be applicable to future composite airframes.

ELECTROMAGNETIC SCATTERING BY ADVANCED COMPOSITE BODIES OF REVOLUTION

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Abstract

The electromagnetic scattering by advanced composite bodies of revolution can be effectively computed using unimoment technique [1]. The unimoment method decouples the interior and exterior regions associated with scattering or radiation problems. The interior region completely encloses the advanced composite medium. For the axial symmetric medium, the advanced composite can be characterized by the permittivity tensor of the form

$$\bar{\bar{\varepsilon}} = \begin{bmatrix} \varepsilon_{rr} & \varepsilon_{rz} & 0 \\ \varepsilon_{rz} & \varepsilon_{zz} & 0 \\ 0 & 0 & \varepsilon_{\phi\phi} \end{bmatrix}$$

Maxwell's equations can also be reduced to two coupled scalar partial differential equations [2]. With the appropriate functional for the variational formulation found, a finite-element algorithm is generated for the interior solution of the fields. The scattered field in the exterior region can be analytically represented by a truncated series expansion having unknown coefficients. By enforcing continuity conditions, the unknown scattering coefficients are obtained.

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HANAP2: An Important New Dimension in EMP Damage Assessment*

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HANAP2 (Hardness Assessment and Network Analysis Program) is a steady state frequency domain circuit analysis computer code which has the capability to compute the EMP-generated current and voltage required to burn out a semiconductor junction isolated from the input by an electrical network. The latest version was developed from the original code HANAP authored by Lt. R.A. Hanner formerly of AFWL/ELA. Among the features incorporated in HANAP2 are an improved damage calculation method, the latest semiconductor damage models or the provision for using experimental data, and the ability to monitor component arcing.

In the past, two methods were available for determining circuit hardness to electrical overstress damage. One method, manual analysis, is tedious, error prone and subject to the judgement of the analyst. The second option, use of large computer codes such as SCEPTRE and NET-2, is unwieldy, time consuming, expensive and oriented more toward TRE analysis.

HANAP2 helps remove the tedium and errors of manual analysis without the costs and difficulty of a large circuit analysis code. HANAP2 is easy to use, requires little computer processing time, and is essentially self-documenting. The analyst interacts with the code to assure correct, reasonable solutions. The code allows the user to analyze more complex circuits than is possible with manual analysis and to reduce the number of simplifications necessary. This capability is especially important in the analysis of frequency selective circuits and in the assessment of the damage effects of high frequency (>1MHz) EMP signals.

HANAP2 has been used to analyze many different circuit types and it has proven cost competitive with manual analysis techniques. Included among these circuit types are various broadband and frequency-selective communications circuits. HANAP2 has proven extremely useful in the case of frequency selective circuits. Both digital and analog control circuits have been analyzed including a servoamplifier. The out-of-band response of a transformer has been simulated in HANAP2 during the analysis of a power regulator circuit. The upset of a relay circuit has even been predicted using HANAP2.

Many of the analyses mentioned above could not have been performed accurately without the use of HANAP2 or a more sophisticated code. In addition, HANAP2 has enabled the analyst to include significant parasitics in his analyses. This has been important in resolving discrepancies between high frequency test data and analysis. In several instances, HANAP2 has yielded excellent agreement between simulation and test.

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UNDERSTANDING SECOND BREAKDOWN

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Although it is well known that damage of semiconductor junction devices from EMP pulses is generally initiated by second breakdown, the basic processes leading to second breakdown are little understood and controversial. This paper is a critique of some published models and a summary of the author's model and results. Only the reverse biased diode is considered.

The critical process in second breakdown is the transition from uniform current flow to a filamentary channel. This is often explained by the junction temperature exceeding the temperature for maximum resistivity for that doping. This has two fallacies: (1) resistivity is defined only when the current density is proportional to the field. In the depletion region the carrier velocities are saturated and have less temperature dependence than does the low field mobility, (2) a decrease of resistivity will not cause the current to constrict into a filament (a negative differential resistivity is required for current constriction). A second explanation of second breakdown is that the thermal generation current at the junction temperature quenches the avalanche current. Again there are two fallacies: (1) recombination rather than thermal generation occurs in the depletion region of a diode at current densities well below second breakdown, even at temperatures well above second breakdown. Moreover, the recombination-generation lifetime is small compared to the transit time across the depletion region (approximately 10^{-11} s per micron). However, thermal generation does occur in the highly doped, low field bulk regions and the thermal injection current is multiplied by avalanche into the negative-differential-resistivity current regime. (2) quenching the avalanche current in itself cannot lead to an increase in current. Higher fields are required for the same avalanche multiplication factor at higher temperatures, but higher thermal injection currents eventually reduce the required multiplication factor and space charge produces a more efficient field distribution and a drop in voltage with current increase.

Instead of the above criteria, and many variations thereof, it is proposed that the best simple, but general, criterion is that the mobile majority carrier density exceeds the doping density of the diode. (Since the velocity is saturated in the depletion region the corresponding current is readily calculated at each temperature.) This criteria reflects the onset of a saddle-shaped field distribution and the initiation of double avalanching, leading to a negative differential resistivity.

Results of second breakdown calculations for diodes with a wide variation of doping densities (intrinsic to 10^{17}cm^{-3}) and diode widths (less than 1 μm to over 20 μm) will be presented. Good agreement between the calculated the published experimental current vs. voltage and power to breakdown vs. pulse length will be presented for a few cases.

AVALANCHE OSCILLATIONS AND SECOND BREAKDOWN

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In the course of EMP vulnerability studies on the four-wire hand set used in the AUTOVON System, avalanche oscillations were observed in the reverse-biased T1DF606A diode (equivalent to 1N645) at stresses just below second breakdown. Oscillations were noted in the VHF/UHF range; current amplitudes greater than 1 A and voltage excursions of 50 V were observed. Earlier, computer studies[1] of second breakdown in the 1N4148 have shown various modes of avalanche oscillation at different current levels and load lines. In fact, avalanche oscillations have been computed for doping levels from intrinsic to $10^{17}cm^{-3}$ and for diode widths from 1 to 20 μm, which is the entire range of computation. Oscillations were later also observed in the laboratory with the 1N4148 but at a lower amplitude than the 1N645 equivalent. TRAPATT oscillations have been reported[2] for the Fairchild FD-300. One concludes that avalanche oscillations are quite prevalent in commercial diodes and should be considered in any assessment of EMP vulnerability of systems. This generated RF could couple internally to other parts of the circuit and by itself cause upset, or in combination with other components of the EMP transients cause upset and/or burnout.

One mode of avalanche oscillation that has been computed and observed is the relaxation mode. The time for a capacitor C to charge through a resistance R from V_{min} to V_B (breakdown) at an applied voltage V_o is

$$T = RC \ln\left(\frac{V_o - V_{min}}{V_o - V_B}\right)$$

Neglecting the breakdown time, it can be shown (using the excellent approximation that $\ln(1 + x) \cong 0.8\sqrt{x}$ for $x < 10$) that the frequency of a relaxing diode is given by

$$f = \text{Const.}\left(\frac{\sqrt{V_o - V_B}}{\sqrt{RC}}\right)$$

This equation has been verified by computer calculations over two orders of magnitude of R and C. The oscillations observed in the laboratory have been shown to be of the relaxation type since their frequency varies inversely with $\sqrt{C}$ (C includes the diode capacitance). Both calculations and experimental measurements have shown that the frequency of IMPATT oscillations decreases as the temperature rises. Since frequency changes can be measured much more accurately than voltage changes, the change of frequency is a superior diagnostic tool to voltage changes as a measure of the junction temperature of a reverse-biased diode.

It is anticipated that computer calculations for the 1N645 diode will be presented at the conference for comparison with laboratory measurements.

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HOLLOW SPHERICAL DIPOLE (HSD) SENSOR NEAR A GROUND PLANE

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The sensitivity of a Hollow Spherical Dipole D-dot sensor in free space is well known, being just $3\pi r^2$ with r the sensor radius. An interesting problem occurs when such a sensor is brought in close proximity to a conducting surface, such as a ground plane; what is the resultant effect on the sensitivity of the HSD? To solve this problem we use bispherical coordinates in the quasistatic (low frequency) case to obtain the charge distribution on the sphere induced by the EM fields for a fixed sphere-plane separation. We then integrate this charge over each half of the sphere to obtain the charge separations and thus the induced current output. The boundary value solutions to the bispherical coordinates are expressed as converging series solutions, and the integration is performed numerically. The resultant charge distribution on the sphere is shown for a particular value of separation, and the enhancement value of the sensitivity is stated. The variation of enhancement value with separation is also shown, which can give the needed correction factor if a sensor is used near a conducting surface.

ASYMPTOTIC CONICAL DIPOLE (ACD) SENSOR DEVELOPMENT

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A family of D-dot sensors has been developed using the theory of Baum presented in Sensor and Simulation Note 72. If we hypothesize a line segment of uniform charge per unit length normal to a conducting ground, we can generate the equations for the equipotential surfaces surrounding it. These surfaces will be "raindrop" shaped, with a point at the place where the line touches the plane. They will also bear azimuthal symmetry. If we now make a sensing element in the shape of one of these equipotential surfaces, in particular that surface which at its apex is asymptotic to a cone of 50-ohms characteristic impedance so that we can transition smoothly into a 50-ohm output coaxial cable, we have generated the ACD sensor. The equations governing the equipotential surface allow us to calculate the equivalent charge height and the capacitance and thus the sensor sensitivity. A line of these sensors has been built, from the ACD-1 with an equivalent area (sensitivity) of 1×10^{-4} square meters (0.220 inch high element) to the ACD-5 with a sensitivity of one square meter (22 inch high element). Both ground plane and double-sided free-field versions have been built and tested. These ACD sensors have a much smaller sensor capacitance, and thus greater bandwidth than the HSD D-dot sensors, and are now replacing them in many applications.

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BROADBAND, SENSITIVE AND NON-DISPERSIVE SENSORS FOR TRANSIENT EMP MEASUREMENTS

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The purpose of this paper is to introduce broadband, sensitive and non-dispersive sensors for transient electromagnetic pulse (EMP) applications. Antenna structures which are able to analyze the transient EMP need to be inherently broadband and non-dispersive. The new sensors proposed are a resistively loaded linear dipole and a resistively loaded TEM horn. The receiving transient EMP responses of the resistively loaded linear dipole and the resistively loaded TEM horn are investigated theoretically and experimentally using the FFT technique.

For omnidirectional measurements of transient EMP, one such sensor which has been successfully fabricated is an antenna which consists of three orthogonal dipoles with continuously tapered resistive loading. The receiving characteristics of the resistively loaded antenna indicate that the impulse shape of 70 ps duration is well preserved due to its excellent linear amplitude and phase response over a broad frequency range.

In another effort to attain increased directivity or increased antenna gain, a TEM horn with continuously tapered resistive loading has been considered as a broadband and non-dispersive sensor. With proper continuously tapered resistive loading, the receiving characteristics of the resistively loaded TEM horn is flat to ± 3 dB for the frequency range from 20 MHz to 6 GHz.

The theoretical and experimental results presented here indicate that the receiving transient responses of these antennas can be analyzed very well theoretically. Since their receiving transient responses are well behaved they should find wide applications as standard receiving antennas for the measurements of fast, time varying, EMP with minimal pulse-shape distortion due to nonlinear amplitude and phase characteristics.

RECENT DEVELOPMENTS IN RADIATION HARDENED SENSORS FOR USE INSIDE A NUCLEAR SOURCE REGION*

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In the past two years EG&G has designed and developed for the Air Force Weapons Laboratory a number of new sensors for measurement of electromagnetic quantities in the nuclear source region. This environment is very inhospitable for these measurements and causes interesting problems in the design of sensors**. Sensors for measuring magnetic fields, electric fields, conduction currents, and emission currents were designed, built, and used to experimentally study the System Generated EMP (SGEMP) effects on a model of a satellite in a recent underground nuclear test. Data provided by the sensors agreed well with pre-test predictions although some anomolous results were observed with the Parallel Mesh Dipole (PMD) E-field sensors. The PMD design was subsequently upgraded for better high-voltage characteristics. Another underground SGEMP experiment will be conducted soon; sensors have been built for this experiment. EG&G also has developed a number of new sensor designs for an EMP experiment on this upcoming underground nuclear test.

One of these sensors, the Inside Moebius Mutual (IMM) inductance sensor, also provides a fast-risetime, nonperturbative means of measuring the total current in a beam of charged particles. IMM sensors have been developed for the Los Alamos Scientific Laboratory for beam current measurements.

*Work supported by U. S. Air Force under contracts F29601-76-C-0034 and F2969-77-C-0055.

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BISPHERICAL DIPOLE (BSD) D-DOT SENSOR

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A new type of sensor has been developed for measuring EMP fields. This sensor measures the time rate of change of the displacement vector $\vec{D} = \epsilon\vec{E}$ in the same manner as the widely used HSD (Hollow Spherical Dipole) D-dot sensors, and like the HSD its sensitivity is well known in terms of its geometry; i.e., it is "calibrated by a ruler". The BSD sensor consists of a conducting sphere above a ground plane, suspended by its electrical connector post. The boundary value solutions to the field equations are readily obtained by means of the bispherical coordinate system. The solutions obtained for sensor capacitance, induced charge, sensitivity, etc., are in the form of series solutions which converge rapidly for even small shpere-plane separation. The accuracy of the solutions is dependent only upon the number of terms retained in the expansions.

The fabrication of the BSD sensors is very easy, requiring only a metal ball and a connector with a protruding center pin. Several sizes have been assembled and tested, with test results agreeing with theory to within the accuracy of the test equipment. Performance is comparable or better than any other D-dot sensor type, including the new ACD (Asymptotic Conical Dipole) sensors.

Development and Test of Small Passive Current Monitors for EMP and Lightning Testing

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Our laboratory has experimented with a variety of small, inexpensive monitoring devices to learn how a large number of test points can be monitored to obtain a small amount of information at each point. The investigation was begun to consider the problem of monitoring thousands of test points on an aircraft during a short EMP test program. It was expanded when questions concerning lightning effects on aircraft became interesting.

Two sensors, a wire current sensor and a skin current sensor were investigated and two signal processing circuits, one completely passive, the other requiring only a 15 volt battery were employed. Sensitivity and frequency response were measured. These devices were designed to obtain and retain one bit of information, whether or not a pulse of a specified amplitude occurred.

The first device consisting of a magnetic toroid pickup transformer coupled through a diode bridge to a computer core used as memory, see Fig. 1, detected and retained peak currents as low as ten amperes from damped sine pulses over the frequency range from 10 KHz to 10 MHz.

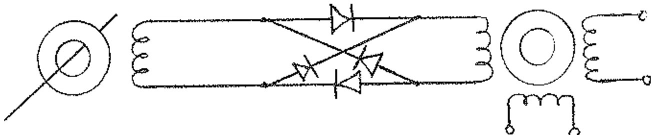

Figure 1

A surface current probe with the same signal processing was insensitive, sensing only 70 or more amperes per inch. The second signal processing circuit consisting of two darlington transistors driven by a 15 volt battery was constructed, Figure 2. This device was sensitive to 5 amperes per inch.

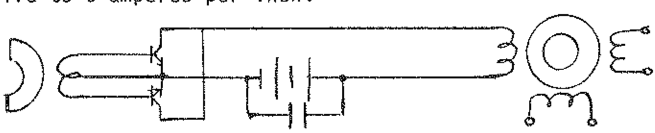

Figure 2

Preliminary design of a more complex circuit to measure pulse height to eight bit accuracy has been completed and conceptual design for an even more ambitious effort, a real time miniaturized transient recorder has been considered.

All of these designs as well as the results of test are presented in the paper.

A NEW PHASE-REFERENCED, CONTINUOUS WAVE (CW) MEASUREMENT AND ANALYSIS SYSTEM*

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Harry Diamond Laboratories has utilized and improved its CW test facility over the past six years. The present automatic network analyzer system is a direct result of experience gained using a simple, manual system.[1] Cost, accuracy, and ease of operation and maintenance were the criteria used to establish our present system.

We give a detailed description of the facility, including the transmit antennas, the network analyzer, and the interface between these units and an HP Programmable Calculator. (The network analyzer, designed and built specifically for the facility, employs sampling techniques which allow the probes to be located in test areas remote from the processing center.) We also describe the operation of the test facility to determine transmit and receive properties of antenna systems and discuss our method for obtaining time-domain equivalent circuits for the case of EMP excitation. We illustrate the application of the facility by showing the results obtained for several communication systems.

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*This work was funded by the Department of the Army under Project No. 1W162118AH75.

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RECENT DEVELOPMENTS IN WIDEBAND MICROWAVE DATA COMMUNICATION SYSTEMS

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Microwave data links continue to be one of the best systems for telemetering data out of EMP environments. In response to the challenge from other types of data links, principally fiber optic cables, the state of the art in the microwave systems is being continually improved. Past developments include the DLT-1 and the DLT-2 systems, both of which have now been in use for over two years. The DLT-1 is an improvement in the standard line of microwave systems, with a smaller transmitter package and improved system specifications, operating over up to 100 meters of dielectric waveguide (DWG). The DLT-2 system is a quite different type of system in that the microwave power source has been located in the receiver unit rather than in the transmitter, and is directed down the DWG to the transmitter for modulation. This results in a much lower battery capacity requirement and in a significantly smaller transmitter package, about the size of a one pound coffee can, with significantly extended battery life. The system specifications are also better than the DLT-1, but the DWG length is limited to about 15 meters, acceptable for some EMP and SGEMP testing.

More recent developments with improved modulation and demodulation schemes have led to significant improvements in the microwave systems' performance. Bandwidths of the DLT-1 and DLT-2 systems have been increased from the 130 to 180 MHz to the 350 to 400 MHz range, without any degradation in the dynamic range. The size of the transmitter packages has not been reduced, but the lower power requirements and the smaller size of the improved microwave components allows for larger battery packs with extended operating times. Another recent development is that of a balanced modulator microwave transmitter. The prototype tested shows a common mode rejection ratio of 50 dB to both fast and slow pulse inputs, and possesses a bandwidth of 350 MHz. This particular package has no amplifiers, attenuators, or calibration pulse generator in it, and so requires no batteries (totally passive) and is only about the size of a large "tuna fish" can. It can connect directly to the output connector of free-field EMP sensors and provides an absolute minimal perturbation of the environment. Other recent developments include remotely controlled attenuators which operate over low frequency fiber optic cables or over the microwave carrier channel of the DLT-2 type systems, thus eliminating the need for pneumatic controls.

DEVELOPMENTS IN FIBER OPTICS DATA LINKS

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EG&G began development of optical data links utilizing fiber optic cables in mid-1976. Since that initial system, EG&G has produced a number of high-technology systems designed to meet specific customer requirements.

Fiber optic systems research at EG&G has been directed to four major areas: sources, detectors, fibers, and amplifiers.

LED and LASER diode sources have been investigated and systems built using both. The optical detectors used have either been PIN or Avalanche devices depending on the specific system requirements. Numerous different fiber types and cable configurations have been used. These range from high-loss Galileo 19-fiber material to single fiber cables from DuPont and Corning. A lack of availability of wideband feedback amplifiers in the industry lead to an amplifier development effort. The result of that development is a wideband transimpedance amplifier used exclusively in all EG&G optical data links.

All systems delivered to date by EG&G have been custom designed systems tailored to the specific mechanical and electrical requirements of the customer. Increasing customer interest in an off-the-shelf system has lead to the development of the EG&G ODL-2 optical data link. The ODL-2 is a 10 kHz to 130 MHz system operating with 100m of single fiber cable. Both transmitter and receiver are self-contained units with internal batteries for a nominal 8 hour continuous operating time. The receiver contains an integral battery charger for charging both the transmitter and receiver batteries. The transmitter has both single-ended and balanced inputs, internal calibration generator and an integral manual attenuator. The transmitter package is a steel cylinder 4.5 inches in diameter and 6 inches long designed for operation in EMP fields up to 100 kV/m.

Present work in optical data acquisition systems is directed toward extending bandwidth and dynamic range as well as incorporating remote control features and interfacing to the IEEE 488 bus (HP GPIB). A system bandwidth exceeding 250 MHz over a 15 meter optical fiber has been demonstrated.

THE EMP ENVIRONMENT DUE TO NEUTRONS FROM A HIGH ALTITUDE NUCLEAR SOURCE

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ABSTRACT

The usual early-time EM pulse generation by a high altitude nuclear source is primarily due to prompt gamma ray interactions within the atmosphere. Neutrons also induce electrical sources (distribution of currents and ionization) within the atmosphere. These neutron induced sources occur on a time scale long compared to prompt gamma effects and produce a later-time (lower frequency) EM signal. Calculation of the generation of the neutron induced sources is described. The associated EMP environments have been computed by finite difference solution of Maxwell's curl equations using the two-dimensional computer code HAPS. Alternate calculations based on an integral representation of the fields in terms of the sources have also been considered. The time and frequency domain character of this EMP environment has been determined for a generic neutron source.

PAIR PRODUCTION EFFECTS ON HIGH-ALTITUDE EMP*

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The effects of pair production on the source terms and electric fields due to a high-altitude burst have been investigated. Compton scattering is normally treated in environment codes at observer altitudes of 20-50 kilometers. Calculations have been completed for monoenergetic 1.5 and 7 MeV sources, as well as for a hypothetical spectrum, which included the injection of sample electrons and positions due to pair production and Compton scattering. Modifications to the resulting sources and fields are evaluated.

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EMP REFLECTION FROM A MOVING CONDUCTIVITY FRONT*

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The gamma rays from a high-altitude nuclear burst interact with the atmosphere and create a downward-moving conductivity front traveling at the speed of light. It is possible then that the upward-moving EMP from the ground reflection of one nuclear burst can be reflected from the downward-moving conductivity due to a second nuclear burst. A question has arisen concerning frequency enhancement of EMP reflected in this way. It is the purpose of this paper to investigate the magnitude and time variation of the reflected wave.

Since the moving conductivity travels at the speed of light, it is not difficult to show that if the conductivity were an infinite step (analogous to a perfectly-conducting, moving surface) the reflected EMP, regardless of the incident waveshape, would be an impulse. In effect, the moving surface integrates the incident pulse to create the reflection and considerable frequency enhancement can occur.

In the actual situation, the conductivity is finite and varies with time, space, and the net electric field, so that analysis of the time-variation of the reflected wave is considerably more complex. By use of Maxwell's equations in retarded time, and by means of linear combinations of electric and magnetic fields to separate inward and outward moving waves, an analytic solution is obtained. It will be seen from the analysis that the magnitude of the reflection is still related to the time integral of the incident pulse; however, the time variation of the reflection is strongly related to the time variation of the conductivity. Although some frequency enhancement occurs, the amplitude of the wave reflected from the conductivity front is small compared with that of the upward-moving incident wave.

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Scaling Long-Distance MHD/EMP Effects: Preliminary Evaluation

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The effects of the long-time MHD/EMP signals produced by a nuclear detonation is of importance to long-line cable systems. Terrestrial magnetic field disturbances can cause shutdown of these long-lines. Initial interest has focused on single burst evaluation of MHD/EMP signals where cable systems are close to the sub-detonation point. More recently, interest is being focused on Multi-burst MHD/EMP effects, where strong reinforcement of these long duration signals may occur. This is so even though the peak magnetic field (B_m) from a single detonation observed at long distances may be low. Although the prediction of the MHD/EMP magnetic field waveform for a single burst is not yet adequately understood, it may be necessary to develop system assessments for a multi-burst environment in which numerous events occur at long distances.

This paper describes an approximate time-domain scaling technique which relates the electric field at the earth's surface to weapon parameters, geophysical conditions, and distance between detonations and observer. The principal aim of this work is to illucidate the important physical parameters which contribute to the long-distance magnetic waveforms and related electric fields. Referring to Starfish data where long-distance magnetic field waveforms are similar with quasi-periods (T_p) ranging from 2-10 seconds, it is shown that a two-layer earth conductivity model is sufficient for predicting electric fields, in contrast to using more complex 3-layer earth models necessary for longer-periods associated with magnetic storms. The use of the two-layer earth model permits an analytic time-domain expression to be derived for the peak electric field in terms of B_m, T_p, conductivities of the first and second subsurface earth layers, and thickness of the first layer. Application of the model to Starfish data appears to give results which are in reasonable agreement with measurements. Limitations of the model are also discussed.

In addition to the earth coupling aspect of the problem, the scaling of B_m is developed. Based on an impulsive electromagnetic source model (demonstrated using a theory of plasma expansion in a magnetic field) and the Starfish data observed at long distances, an approximate formula is developed for B_m as a function of local Alfven velocity V_A, yield-to-mass ratio of the weapon, and great circle distance. The dependence of V_A on altitude, sunspot number, and time-of-day then provides the dependence of B_m on these parameters.

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EXPERIMENTAL INVESTIGATION OF THE ABSORPTION OF ENERGY FROM AN EMP BY A PLASMA WITH A HIGH COLLISION FREQUENCY

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In previous work reported elsewhere, we have observed experimentally the propagation of an electromagnetic pulse (simulating an EMP) through a plasma. This work has been done in a machine constructed especially for this purpose in The University of Arizona Plasma Laboratory. In this initial work, we observed the absorption of energy from this pulse by the plasma over a distance of about 3 pulse lengths and the resulting change in the pulse wave shape. The parameters of the plasma were such that collisions played no significant role. A theory was developed by one of us based on the swarm model, which predicted the experimental results to about ±20%. In this paper, we report on a continuation of this work into the regime where collisions are important. We find that a much larger fraction of the pulse energy is absorbed from the pulse in a distance of about 1.5 pulse lengths. Considerable distortion of the pulse wave shape occurs. The ability of the swarm model to predict this behavior will be discussed.

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OBSERVATION OF LOW FREQUENCY ENERGY TAIL FOLLOWING IN THE WAKE OF AN EMP EMERGING FROM A PLASMA

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In an experimental device at The University of Arizona Plasma Laboratory, the propagation through a plasma of an electromagnetic pulse (simulating an EMP) may be studied. Recent observations have shown that a significant amount (10-20%) of the initial energy of the pulse exits the system on a time scale much longer than the time duration of the EMP. Typically, we observe the EMP emerging from the plasma followed by a signal that persists for about 25 times the rise plus fall time of the initial pulse. The frequency spectrum of this energy tail has a maximum frequency at least an order of magnitude lower than the maximum frequency of the initial pulse. This experimental evidence indicates that a plasma mechanism exists which couples energy from the pulse into low frequency modes. Care has been taken to distinguish between signals attributable to system geometrical and impedance mismatches, and those directly attributable to plasma effects. We emphasize that this data is very preliminary, and that the mechanism for energy conversion has not yet been identified.

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SURFACE EMP EFFECTS IN THE HIGH-ALTITUDE X-RAY SOURCE REGION

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Preliminary results of one-dimensional studies of the EMP effects near surfaces exposed to X-rays at high altitude are reported. These studies treat the electrons emitted from the surface due to the incident X-rays, as well as the surrounding plasma. This plasma may be one that exists before the X-ray pulse arrives, or that generated by the scattering of the X-ray produced photo electrons in the 50-100 kilometer altitude regime. The plasma is treated using a swarm model. Preliminary studies of ion effects are also reported.

ILL- POSED AND WELL-POSED PROBLEMS IN SYSTEM IDENTIFICATION

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The objective of this paper is to demonstrate how different formulations published in literatures regularize the ill-posed system identification problem. The different techniques presented shall include the different Wiener filters and the various stochastic extensions of the ill-posed system identification problem. The latter include Maximum Entropy Spectral Analysis, Maximum Likelihood Estimation and The Minimum Variance Method.

[For details please see Scientific Report No. 2 on Air Force Cotract F33615-77-c-2059, Air Force Weapons Laboratory, December 1977.]

LICATION OF PRONY METHOD TO SGEMP DATA ANALYSIS*

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A method based on the Prony algorithm[1] has been applied to find the modes and amplitudes of response to electrical and photon excitation of various satellite-like structures.

Whereas the method can clearly find the correct modes in perfect data records (those free from the effects of the driver term and noise), there is a legitimate question whether the Prony fit to a noisy data record includes the modes that would exist in the absence of noise[2,3]. As an alternative to a mathematical proff of uniqueness, we made use of the fact that the same modes should appear in data records for different sensors under a single excitation, and in some cases for various excitations. The method was applied first to find the modes (poles in complex plane). A validated set of modes deduced from various records was then used to find the excitation amplitudes (residues) for each excitation and sensor. The same method was applied to the output of finite-difference calculations to predict the response.

Examples of the application of the method to known waveforms, with and without superimposed random noise, electrical excitation, and photon test data will be shown.

The techniques used to enhance the visibility of the actual poles (as distinct from noise artifact poles) were:

1. Proper pre-smoothing of data
2. Over determining the fit (excess of points over poles)
3. Safe interval between driver and fit time window
4. Choice of data window wide enough to represent at least one cycle of lowest beat frequency.

References

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ABSTRACT

POLE MEASUREMENTS FOR THE ATHAMAS I PIPE TEST

BY

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During the pipe test at the ATHAMAS I facility, the current density response of a metal cylinder to EMP was recorded. According to the singulaity expansion method, this transient response can be characterized by poles and residues contributed by the cylinder and by the incident field. Poles and residues have been calculated for both the response and incident field. Some poles can be identified as corresponding to natural modes of the pipe. Others match the incident field poles. Most poles in the incident field are shown to be due to ground reflection.

PENCIL-OF-FUNCTION METHOD ---- BETTER THAN THE WIENER FILTER ?

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The pencil-of-functon method regularizes the ill-posed system identification problem with respect to the location of the poles and not with respect to the measured waveform as is done in current system identification methods. It is because of this reason it is possible not only to estimate the error inthe location of the poles but also the statistics about the pole locations given the statistics of the noise. Numerical results shall be presented to demonstrate this claim.

LOW-FREQUENCY MAGNETIC FIELD PENETRATION INTO A COCKPIT VIA WINDSHIELDS

by

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When the surface current densities induced by the nuclear electromagnetic pulse (EMP) on the exterior of an aircraft are known, it is possible to find the fields induced inside the aircraft. This analysis is concerned with the fields or surface-current densities induced inside an aircraft cockpit. The configuration of an aircraft cockpit leads naturally to the analysis of electromagnetic cavities. For EMP interactions, the cockpits are undersized cavities; i.e., their linear dimensions are far below the lowest order resonant wavelength. Since the cockpits are not completely closed, the penetration of the low-frequency components actually dominates. The mathematical analysis of the low-frequency magnetic components of cavity excitation via aperture has been given by Lee, Yang and Chen (ref. 1). The objective of this investigation is to apply the analysis of Lee, et al., to specific cockpit configurations, in particular, the cockpit of an E-4 aircraft.

In the process of computing the low-frequency fields inside the cavity, it is necessary to find the normal component of the magnetic fields at the aperture of the cavity or the windows of the cockpit. We have chosen an equivalence current method to estimate H_n, the normal magnetic field. This approach yields the distribution of the H_n, which is more significant than the usual magnetic polarizability $\underline{\underline{\alpha}}_m$ especially in the cockpit study where the apertures, or windows, while small compared to wavelength, are not small in comparison to the linear dimensions of the cavity.

The generic study of a finite, semicircular cone is given, because this geometry best describes the cockpit of an E-4 aircraft. The results of this study are all expressed in terms of simple elementary functions such as transcendental functions, exponentials, polynomials or fractional powers of the variables or parameters. Specific results are given for an E-4 cockpit.

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AN EXPERIMENTAL STUDY FOR THE USE OF THE BETHE HOLE THEORY FOR WIRES BEHIND APERTURES *

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The Bethe hole theory was originally developed to model electromagnetic coupling through electrically small apertures in planes. In the assessment of EMP vulnerability, this theory is presently used to model aperatures in three dimensional bodies and planes with wires behind the aperatures. This use of the Bethe hole theory has not been validated. In this paper, two theories (developed by previous authors) that use Bethe hole theory to find the current on a wire behind an aperture in a plane and a wire at the center of a cylinder with aperture are used to predict experimental results.

The experimental measurements were obtained at the LLL Transient Range facility. These measurements were conducted for a wire behind an aperture in a plane and a cylinder. The effect of varying the apertures' shape and sizes along with the wires distance behind the aperture were studied in the case of the plane. In the case of the cylinder the effect of varying the aperture shapes and size along with the cylinder's diameter were studied. For some cases the numerical and experimental results are in good agreement but in others the agreement is very poor.

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INTERACTION OF A GROUND EMP WITH A CIRCULAR APERTURE IN AN INFINITE CONDUCTING SCREEN

by

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When EMP strikes the earth the transmitted wave is attenuated due to the conductivity of the earth and the shape of the EMP is altered. The boundary conditions at a circular aperture are different than at an aperture in air. G.H. Price describes the ground wave in a paper, "Subsurface HEMP Field Calculations," (AFWL Theoretical Note #232). Using a Fourier Transform and neglecting the high frequencies, an approximation is made for the wave in the presence of an infinite unbroken conducting screen. Then, a circular aperture is assumed with free space on the shadowside. Oblate spheroidal coordinates are used to find a potential on the shadow side of the aperture. Because of the conductivity of the earth, the magnetic field is not the gradient of a potential on the incident side of the aperture. However, a particular solution is found which when added to the general solution is sufficient to satisfy all the boundary conditions. Simple analytical expressions are given for the fields on the screen, along the axis, in the aperture and for large distances from the aperture.

FIELDS IN A RECTANGULAR CAVITY EXCITED BY A PLANE WAVE ON AN ELLIPTICAL APERTURE

by

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Leigh-Wei Chen has given expressions for the fields in rectangular cavity ("On Cavity Excitation Through Small Apertures," AFWL Interaction Note #45). He assumes that the frequency is small and the aperture is small and the aperture is symmetrically placed in the center of the cavity. Other authors have found complicated expressions for the diffracted fields of a circular aperture. In this paper we derive relatively simple expressions for the fields due to an elliptical aperture and then find the fields excited in a rectangular cavity by these fields. The frequency is assumed small so that a quasi-static approach is used. Tables are given for the fields along the axis, on the screen and in the aperture. The screen is illuminated by a wave of arbitrary orientation and arbitrary polarization. The aperture is in arbitrary position and arbitrary orientation in the cavity. The integrals involve Bessel Functions of fractional order which can be readily evaluated. There is no assumption of far fields so that the dipole approximation is not used. Hence, the fields are good in the neighborhood of the aperture. To avoid infinite resonances, a non-perfect conducting wall is assumed. The response to a simple model of EMP is given in terms of a Fourier Integral.

EMP PENETRATION THROUGH DOOR/HATCH SEAMS

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The solution of the problem of electromagnetic pulse (EMP) penetration through the seams of a door or hatch is constructed from the solution of the complementary problem of a loop with the aid of Babinet's principle. The complementary loop problem is solved by the asymptotic antenna method in which the expansion parameter is $2 \ln$ (loop's perimeter/loop's wire radius). The effects of hinges, latches and conducting gaskets are also treated. For electrically small seams magnetic and electric polarizabilities are presented, while for seams of arbitrary electric size maximum magnetic flux penetration is calculated.

A COST-EFFECTIVE TECHNIQUE FOR EVALUATING SHIELDING EFFECTIVENESS OF ENCLOSURES *

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The determination of the shielding effectiveness of metal enclosures is essential for formulating an effective hardening program for the interior system electronics. A well designed shielded enclosure provides the first envelope of protection against the incident free fields. Too often, an inadequate knowledge of the shielding provided by the enclosure may lead to the costly practice of overhardening the interior system. In this paper, we describe a simple cost-effective technique that we use at LLL for evaluating shielding effectiveness of enclosures. We will also present some preliminary test results concerning the behavior of the shielding properties as the "fill factor" changes ("fill factor" is the percentage of the volume inside the enclosure randomly filled with metal equipment racks). These results can be significant in evaluating internal coupling behavior of communications facilities.

The method basically relies on scale model tests of wire mesh enclosures. In order to demonstrate this capability, an empty wire mesh box was tested at the Transient Range at LLL. The box is made of copper wire mesh (#40) and is 2 ft. by 2 ft. at its base and 1 ft. high. The ambient vector fields (both E and H) are measured with appropriate probes at three different locations in the box. The time histories are Fourier transformed and the shielding properties for various vector orientations are evaluated as a function of frequency.

The previous measurements are repeated for fill-factor values of 24 and 32%. The Prony Poles (i.e., natural modes of the physical system) of the responses are evaluated in order to examine their migration in the complex frequency plane as a function of fill factor.

From the results we have so far, the following conclusions can be made:

1. Predictions based on comparing peaks of transient responses overestimate the shielding effectiveness; a frequency domain analysis is necessary.
2. The internal fields peak at those frequencies that correspond to the resonant frequencies of the box; predictions based on test procedures such as in MIL-STD-285 will overestimate the shielding capabilities of enclosures.
3. There is marked improvement in shielding properties with increasing fill-factor.
4. The largest field components inside the enclosure correspond to those having the same polarization as the incident field.
5. It is possible to extract the Prony poles from the data. However, no noticeable trend is observed with changing values of fill-factor.

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GENERIC STUDY OF AIRCRAFT AVIONICS BAYS/ELECTRONICS COMPARTMENTS*

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This report presents two theoretical models for the aircraft avionics bays/electronics compartments. The first model is a large rectangular cavity excited by the electromagnetic pulse (EMP) field via small hatch door cracks. The second model deals with the EMP energy coupling into an aperture-backed rectangular cavity through the avionics-bay-door slits which have dimensions as large as the cavity size. By solving the quasi-static boundary-value problem and utilizing the eigenfunction method in the calculation of the penetrant cavity magnetic field through apertures, simple transfer functions in predicting the EMP field coupling to cables inside the avionics bays are hence obtained.

*This research was sponsored by the Air Force Weapons Laboratory, Kirtland AFB, New Mexico.

Transients in Coaxial Waveguides with Discontinuities

by

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Integral equation formulations are developed for the radial component of electric field at the discontinuities introduced by placing an annular septum (disk) on the inner conductor of a coaxial waveguide and by placing choke-like wave constrictions within a coaxial waveguide. The formulations for the electric field include the dominant mode and an infinite series of higher-order modes. A procedure is employed to obtain rapid convergence of the resulting Bessel function series and numerical solution techniques are employed to obtain a solution for the electric field component. The field distribution in the vicinity of the discontinuity may be calculated from the electric field solution. Values for the capacitance and impedance introduced by the discontinuities are obtained. These values are compared to results presented in Marcuvitz's Waveguide Handbook which were obtained by Julian Schwinger and associates who solved similar integral equations using variational techniques.

The transient response of the two discontinuities to a square pulse input is obtained by Fourier integral techniques. These calculations are compared to results obtained by time domain reflectometer measurements on actual structures. It is possible to use the analytical/numerical techniques employed here to treat a variety of coaxial waveguide discontinuities. Such work should ultimately lead to the capability to analyze the responses produced by injecting transient waves into somewhat complex cavities by means of coaxial cables.

DIFFUSIVE ELECTROMAGNETIC PENETRATION INTO CAVITIES

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Electromagnetic energy can penetrate into a cavity not only through apertures in the cavity surface, but also by means of diffusion through the cavity walls. The diffsuive penetration comes about because the conductivity of the walls, albeit high, is not infinite. At low frequencies for which the wall thickness is less than the skin depth, the diffusion mechanism is known to be an effective means for penetration by the magnetic field, while penetration by the electric field is negligibly small by comparison. At higher frequencies for which the wall thickness is larger than the skin depth, most of the incoming electromagnetic energy is shielded out by reflection and attenuation losses due to the cavity walls. Thus, diffusion penetration is of concern mainly for the low-frequency magnetic field.

In this paper the physics of shielding by a metallic enclosure will first be considered at an elementary level. Simple working formulas will be given, both in frequency and time domain, to calculate the cavity fields for certain simple-shaped enclosures. These simple formulas will then be generalized so as to be applicable to general-shaped enclosures. Finally, the great difference (order of 100 dB) in shielding effectiveness between enclosures and planar slabs will be discussed.

GAMMA-RAY INDUCED COMPTON CURRENTS IN THE GROUND*

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Gamma rays entering the ground from above induce Compton currents in the ground. In addition, some of the Compton electrons leave the ground and create an electron flux moving away from the surface. Both the ground currents and surface currents are important in estimating EMP effects within the ground and at the surface.

The Compton electron fluxes have been calculated by a modified Monte Carlo procedure for gamma-ray energies in the range 0.75 MeV to 6.0 MeV and gamma-ray entrance angles from grazing incidence to vertical incidence.

It has been found that the currents can be approximated by simple analytic expressions as a function of both gamma-ray energy and incidence angle. These empirical expressions greatly ease the computational burden when EMP calculations are performed.

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Improved LEMP Outer Boundary with Finite* Ground Conductivity

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LEMP2 is a computer code which calculates the electric and magnetic fields resulting from a surface burst. In the past, the numerical solution was obtained by a finite difference approximation to Maxwell's equations in the air and ground. This solution was carried out to a radius sufficiently large that the source currents and air conductivity were essentially zero. Beyond this radius, the fields were obtained analytically, on the assumption that the ground conductivity was infinite. This assumption overestimates the high-frequency content of the fields outside of the source region.

An analytic method has been devised which incorporates ground conductivity. The electromagnetic fields resulting from multipoles located at the origin are obtained analytically by Sommerfeld's method for a finitely conducting half space. The amplitude of the multipoles is determined from a Legendre expansion of numerically calculated fields exterior to the source region.

A finite-difference method has also been devised to treat finite ground conductivity.

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PRELIMINARY CHARACTERIZATION OF THE VERY LATE TIME EMP EFFECT*

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A preliminary survey of the very late time EMP effects has been conducted. Most of the extant work concerns high altitude bursts, but it appears that for relatively hard systems that might be subject to direct attack on fixed sites, that ground and low altitude bursts would determine their survivability criteria, at least for the ground installations. In particular, this seems to be true for [redacted] ground systems when only very late time EMP is considered. This paper will attempt to establish that thesis in a preliminary fashion. Certain hand calculations of the magnetotelluric effect of ground bursts will be presented in evidence. Some values for the short circuit current and the open circuit voltage are calculated for two types of loops in the vicinity of a ground burst. The horizontal loop is a circular loop in the ground plane with the burst at the center of the loop. The vertical loop is a wire in the ground plane going out from the burst point and grounded at the outer end. The loop is closed by the ground currents. Crude time histories of the short circuit current and open circuit voltage are presented. These solutions are for negligible ground conductivity as far as its effect on the magnetic field is concerned. However, effects of finite conductivity on the field perturbation are discussed in the light of a solution for infinite ground conductivity. Some ideas for further study will be offered.

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AN IMPLICIT CLOSE-IN COUPLING ALGORITHM*

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An explicit finite difference code, A3D, was developed a number of years ago to solve the EMP close-in coupling problem. The algorithm used in the code is based on second-order accurate spatial derivatives throughout the mesh and at all boundary surfaces. The time derivatives, however, are currently calculated using an explicit, first-order accurate exponential finite difference scheme. Since the Courant condition must be satisfied to ensure stability of the difference equations, this method of time derivative evaluation is extremely restrictive for many problems of interest.

This situation has been improved by the development of a new finite difference scheme that is fully implicit and is unconditionally stable so that the time step can be determined by the accuracy required to resolve the physics problem under consideration rather than by stability requirements. The new calculation retains the use of second-order accurate spatial derivatives and, in addition, employs second-order accurate exponential time differencing.

To facilitate the solution of the implicit equations, an operator-splitting technique has been used to reduce the calculation to an alternating direction, implicit scheme. The resulting algebraic equations are tri-diagonal and are solved by the well-known two-pass method.

After writing Maxwell's equations in operator form in curvilinear coordinates and splitting the operators into simpler tractable operators, one finds that, due to the source terms, the resulting operators are not commutative. This has two implications: First, the operators must be applied in the proper sequence. Second, a second-order error is introduced into the finite difference calculation. If left uncorrected, this error was found to introduce bounded oscillations into the calculated electromagnetic fields. A method was discovered to remove this error from the calculation, thereby removing the numerical oscillations in the fields.

A two-dimensional code has been written to test the method. The code is unconditionally stable and compares very well with a two-dimensional version of A3D.

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*This work supported by the United States Air Force Weapons Laboratory.

STATUS OF AFWL UGT ANALYSIS TECHNIQUES*

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Various techniques have been developed and refined at AFWL over the last few years for use in the analysis of several underground nuclear test events. These include various means of specifying source terms; one-, two-, and three-dimensional environment calculations; and multi-dimensional coupling analysis for various geometric configurations. This paper describes methods used to facilitate some typical calculations (boundary conditions, treatment of small structures, etc.) and summarizes the present capabilities and limitations in this area. A majority of this work is based on the use of the AFWL codes CLASP(1-D) and A3D (2 and 3D).

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SPECIAL COMPUTATIONAL METHODS

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The usual approach to numerical solution of the e.m. field equations is, of course, the well-known "leapfrog" finite-difference scheme. Alternative methods include implicit solutions of conventional finite-difference equations and characteristics methods. Advantages of these latter methods include better stability and more physical orientation of the problem formulation. The implicit scheme is similar to the explicit "leapfrog" method, but all fields are defined at the same times. Ordering the differenced form of the field equations and the unknown fields in some reasonable fashion creates a coefficient matrix for the unknown fields which is large, but whose elements are identically zero outside a comparatively narrow diagonal band. The system of equations so represented can be solved by Gaussian elimination methods in which only the in-band elements need be considered. The computational labor involved in the implicit method is, in fact, large. For moderately sized grids, however, the large permissible time-step size balances this cost.

Characteristics methods for solving systems of hyperbolic partial differential equations requires integration on curves or surfaces associated with the propagation of wavefronts. The process of "integrating along characteristics" is attractive from a physical standpoint because it is connected with notions of causality, and attractive from a numerical standpoint because the original partial differential equations take on the form of convenient relations for the variations of fields along the directions of characteristics. In one dimension, the characteristics are families of straight lines and the characteristic equations have the form of ordinary differential equations. An analogous result appears for the three-independent-variable EMP problem, except that the characteristic equations involve derivatives in two directions along 2-d characteristic surfaces.

The characteristic equations that replace the original set of field equations can readily be differenced. The sets of implicit equations obtained are solved by standard methods, and are sometimes more satisfactory, because of the causality considerations implicit in their development, than equations generated by more straightforward use of the original field equations.

Details of the above two special methods are presented in the paper, together with a comparison of computational results, for an example geometry that might be encountered in a UGT coupling problem.

CALCULATION OF THE TRANSMISSION LINE PARAMETERS FOR A POWER CHANNEL CONTAINING TWO CONDUCTING RAILS*

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The transmission line parameters, inductance, capacitance, characteristic impedance, and the speed of light, were solved for a power channel with two conducting rails along the inside. The parameters were found for the channel both filled with air and partially filled with dielectric. Solutions were obtained through a matrix approximation to the appropriate Fredholm integral equation of the first kind. In addition, magnetic and electric field coupling factors were calculated for the inner rails.

The dielectric was simulation by an equivalent surface charge density. This charge density was calculated by dividing the channel and rail surfaces into a finite number of linear unit charge densities and summing the effects of these charges on single sections of the dielectric surface.

The electric field coupling parameter is the ratio of the electric flux from infinity which terminates on the inner rails to the total electric flux. The magnetic field coupling parameter expresses the magnetic flux that links each of the conductors per unit of current on the channel. In addition, a dimensionless quantity which relates the air conductivity, σ, to the transmission line parameter G was calculated.

*This work supported by the Air Force Weapons Laboratory under Contract No. F29601-76-C-0148.

SOLUTION OF THE TRANSMISSION LINE PROBLEM FOR A POWER CHANNEL CONTAINING TWO CONDUCTING RAILS*

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The Boltzmann form of the Transmission Line (TEM) equations describe the behavior of forward and backward moving voltage waves. Moving down a transmission line in finite steps, the Boltzmann equation yields the attenuation of the wave over the (time and space) step, the reflection of the wave over the step, and accounts for the source terms at each location. This technique allows for load impedances anywhere along the line as well as any desired termination impedance. A subroutine has been written which solves these equations in a stepwise fashion.

Once the transmission line parameters (L, C, Z_O and c) and the external field-coupling parameters have been calculated, the response of the line to any source can be readily obtained. Results for a typical calculation will be presented.

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PREDICTIONS OF THE NONLINEAR RESPONSE
OF BURIED CABLES CLOSE TO A NUCLEAR BURST*

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ABSTRACT

Close to a nuclear burst, intense fields can alter the response of buried cables by causing puncture of the dielectric sheath on an insulated cable and by driving the soil itself into a nonlinear conductance mode.

In this paper, the transmission line formulation of the buried cable problem is reviewed, the expected effect of dielectric puncture and soil nonlinearities on the cable parameters is described and, finally, predictions are presented in which analytical models of the nonlinear cable parameters are utilized in a real time finite-difference computer code to illustrate the expected response of buried cables.

From the parameter studies presented, the most significant nonlinear effects are determined and the principal sources of uncertainty in the predicted responses are isolated.

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MULTICONDUCTOR TRANSMISSION LINE ANALYSIS FOR EMP APPLICATIONS

by

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Continued interest in the EMP interval interaction area has led to the development of a technique for analyzing the behavior of a complex network of interconnected multiconductor transmission lines, subject to transient excitation. Using the concept of a linear graph, the transmission line network can be represented by a number of transmission tubes connected at various junctions. These are analogous to the branches and nodes of a conventional circuit, except that in the transmission line case, each tube may consist of N individual wires, and a junction represents the connection of many individual wires.

On each tube, the conventional multiconductor transmission line theory can be applied to derive relationships between forward and backward propagating current (or voltage) waves. At each junction of the network, forward and backward waves may be related by current (or voltage) reflection coefficients, which are functions of the line parameters and interconnections. With both sets of relationships, an overall matrix equation for the currents at every wire of each tube, at each junction can be derived. Known as the BLT equation, this equation can be solved at a number of frequencies to obtain the transient response of the network by Laplace methods, or SEM concepts may be employed.

This paper will discuss in more detail the above concepts, illustrate the form of the BLT equation for some simple networks, and indicate directions of future work in this area.

MULTICONDUCTOR TRANSMISSION LINE RESPONSE: A COMPARISON OF THEORETICAL AND EXPERIMENTAL RESULTS

by

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In a companion paper by T. K. Liu, et al., an analysis technique for determining the time harmonic response (and also the transient response, using transform methods) of a general, multiconductor transmission line network has been described. In order to verify that the analysis and the corresponding numerical methods are correct, a number of simple network configurations have been examined and will be discussed in this paper.

The verification of the accuracy and validity of the analysis for more complicated, multiconductor networks employs experimental data provided by Mission Research Corp., in Albuquerque. The MRC data, which clearly exhibit the multi-velocity nature of wave propagation on the multiconductor line, correlate very well with similar data calculated using the multiconductor network theory. These data comparisons will be illustrated and reasons for the minor discrepancies between the theoretical and experimental results will be suggested.

EXPERIMENTAL CHARACTERIZATION OF MULTICONDUCTOR TRANSMISSION LINES IN INHOMOGENEOUS MEDIA USING TIME DOMAIN TECHNIQUES

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An effective method for the time domain characterization of lossless multiconductor transmission lines with inhomogeneous dielectrics is presented. Lines of this type are characterized by multiple propagation modes with unequal velocities. Time domain reflectometry is used to obtain the characteristic impedance and the modal velocities of the line. The pulse or step function response of the line is used to obtain the modal amplitudes which in turn determine the velocity matrix. The appropriate multiconductor transmission line equations involving inhomogeneous dielectrics are solved to obtain the per-unit-length inductance and capacitance matrices in terms of the characteristic impedance and velocity matrices. The method is concise and complete and identifies the propagation modes in a way that permits direct physical interpretation of the results. The experimental results for a four-conductor transmission line are presented and are found to be in good agreement with independent frequency domain measurements within the accuracies of the measurements.[1]

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*This work was applied towards graduate course work at the University of New Mexico.

[1]Fowles, H. M., A. K. Agrawal, L. D. Scott and L. T. Simpson, Cable Parameter Study, Final Technical Report, Mission Research Corporation, to be published.

TIME DOMAIN ANALYSIS OF MULTICONDUCTOR TRANSMISSION LINES WITH BRANCHES IN INHOMOGENEOUS MEDIA

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An effective method for computing the time domain response of lossless multiconductor transmission lines with branches in a cross-sectionally inhomogeneous dielectric media is presented. Lines of this type are characterized by multiple propagation modes having different velocities. The theory of wave propagation on lossless multiconductor transmission lines with inhomogeneous dielectrics is used to obtain the modal amplitudes on the uniform sections of the line. The scattering matrix for the junction is used to compute the transmitted and reflected waves in the different branches at the junction. Each mode arriving at the junction excites multiple modes in all branches. The method described in this paper identifies all propagation modes in all branches of the line and leads to the direct physical interpretation of the results. The method is general and can be applied to either partially or completely nondegenerate cases. Experimental results for a six-conductor transmission line having a single branch are found to be in good agreement with the results computed using the described method.

SINGLE-LINE MODELING VERSUS MULTI-CONDUCTOR MODELING

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Over the years modeling of EMP interaction with complex systems have been refined in an attempt to reduce uncertainties in response predictions. While much progress has been achieved in areas such as external coupling, environment, and penetration coupling (including apertures) one area still remains difficult: internal interaction. Modeling large complex cable systems, which frequently exist, with techniques that assure great accuracy (such as complete n-wire models) becomes unfeasible. In particular, data collection for accurate input parameters to the n-wire model is most unfeasible.

This paper presents an alternative to this dilemma which, for the particular application addressed here (an aircraft cable system), is no worse than a multi-conductor solution with simplifications forced by constraints of time and manpower. Predictions will be shown, using a single-line model, for a cable system representative of a small segment of an aircraft internal cable system. These predictions will be overlayed on test measurements along with n-wire model predictions for this cable. Measurements show considerable detail in resonances due to multimodes. The n-wire model predicts great detail, but with 6 to 20 dB lack of comparison due to the inability to input model parameters that exhaustively characterize the cable system. The single-line model also compares within 6 to 20 dB but with much less resonant detail. For this particular application the two modeling approaches appear to be comparable in their ability to predict the interaction on the cable. The computer usage was approximately a factor of 10 less for the single-line solution and the analyst time was less. A modeling approach that would combine the capability of the n-wire model to depict only major multimodes and the simplicity of the single-line model with minimal input and computer usage would be an asset to the EMP community.

ON THE ELECTROMAGNETIC FIELD EXCITATION OF UNSHIELDED MULTICONDUCTOR CABLES

by

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Certain simple unshielded multiconductor cables are considered to be illuminated by electromagnetic plane wave fields. Using three independent formulations-quasistatic circuit theory- a study of the currents that are introduced in the terminations is made. Questions of accuracy, ranges of validity and general trends are addressed.

An Improved Transmission Line Model For Buried Insulated Cable

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The problem of coupling to buried insulated cables has been of interest in the EMP community for several years. At present, modal solutions[1] and equivalent transmission line models[2,3] have been developed. Existing transmission line models do not agree with the modal solutions over the wide frequency range of interest to EMP analysts.

The research reported here describes a transmission line model which agrees quite well with the modal solutions, and which is very simple and inexpensive to use. The model enables the evaluation of each separate element in the incremental equivalent circuit and allows a more accurate estimation of the dielectric voltage. The research is an extension of recent work in insulated linear antennas.[4]

A simple extension of this work is also applied to the problems of eccentric insulated antenna and of a wire over a ground plane.

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"ABSTRACT"

Validating EMP Hardness of the Minuteman Launch Facilities

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This paper presents the system testing approach required to validate the EMP Hardness of the Minuteman ICBM Force. The In-Place EMP Validation Program is the final phase of a three-phase EMP program for the MM ICBM Force.

The first phase implemented in 1968 was the Assessment Program whose objective was to determine if the fielded MM force was survivable to EMP threats and what hardening would be required. The following phase was the hardening program and was conducted in conjunction with the MM force upgrade. The purpose of the hardening program was to prevent the propagation of current transients from various threats into protected areas of the launch facility. The approach utilized included EMP surge protection, decoupling, filtering, shielding, circumvention, and subsystem hardening. The final phase of the validation program commenced in 1972 and is to be completed in June 1978. The purpose of the validation program is multi-fold: substantiate the survivability of the upgraded force to EMP threats, develop mathematical models, make survivability predictions and provide a baseline of data and test procedures for hardness maintenance.

The paper presents the system level methods of conducting the validation program. Discussion will include the determination of critical circuitry and fragilities, field test methodology, test data analysis, extrapolation techniques, and assessment methodology. Specific examples relating to latest system tests conducted at the Wing VI Launch Facilities at Grand Forks AFB, North Dakota will be presented.

HARDNESS EVALUATION IN THE PROTOTYPE PHASE: The Approach to the TACAMO EMP Assessment Test (TEMPAT)

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TEMPAT 1 was conducted during the summer of 1977 for the purpose of determining what hardening might be required. The TACAMO system tested is a prototype of a modification which increases the communication capability of the system. The AFWL horizontally and vertically polarized dipole facilities were used.

The hardness was evaluated by sampling the coupled bulk currents at mission critical boxes; extrapolating these to appropriate levels and configurations; and comparing to threshold bounds measured by current injection. An error analysis was used to define an adequate system design margin. Test points not sampled are assumed to be in the same distribution as the sampled points so that the tail of the sampled distribution could be used as a measure of system hardness.

CONDUCTIVE PULLEY ASSEMBLY FOR EMP HARDENING OF CONTROL CABLE PENETRATIONS

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Control cables that penetrate an airplane hull provide a strong coupling mechanism to bring EMP energy inside a shielded region. The importance of this penetration type was demonstrated in Boeing direct drive tests and in EC-135 tests in AFWL simulators. Several hardening methods were considered for the E-4B airplane. One practical problem encountered is the length of cable travel--up to 60 inches in the case of the rudder trim cable. Conductive pulley assemblies were developed to solve this problem and provide a path of low inductance L and resistance R to ground at the pressure hull. An extensive laboratory program was undertaken to demonstrate the adequacy of these devices.

Design analysis was based on a linear R-L circuit model of the pulley assembly. This simple circuit was incorporated as a hardening fix in the over-all computerized coupling model and a parametric study was carried out to evaluate maximum allowable values of R and L.

Early testing showed that the resistance of the rolling lubricated contact surfaces in the pulley assembly was nonlinear, decreasing with increasing current. Data will be presented to show this effect in direct current and pulse measurements made while the control cable was driven in a realistic motion cycle. Static measurements of the transfer impedance (R and L) were made with network analyzer and milliohmmeter instrumentation. Also, mechanical measurements were made to evaluate breakout drag force of the pulleys.

Many different designs (in terms of materials, bearings, springs to tension the pulleys) were tested. Mechanical requirements for low drag led to choice of a ball bearing assembly on an axle. A standard airplane control system steel bearing with conductive lubricant within a raceway pressed into an aluminum pulley was found to provide satisfactory performance. Two types of design were used: a twin idler pulley assembly to be installed at the pressure bulkhead and a replacement pulley assembly for use where control cables change direction at the penetration. The production model idler pulley assembly was put through a complete environment qualification test. Results of these tests and comparisons with model calculations establish the adequacy of the pulley design and construction.

HARDNESS ASSURANCE AND VERIFICATION: QUANTIFYING PROPER TEST AND REDESIGN INVESTMENTS

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The EMP test planner is charged with the responsibility for what to test, to what level, and with what equipment. He is required to define the value of the test in terms of what change in hardness confidence will occur if implemented. He often feels compelled to suggest a design modification which would result in a higher confidence hardness in lieu of testing. Thus, the test planner must be an expert in EM and circuit theory, reliability analysis, test hardware, system design and analysis—and resource allocation methodology.

EMP test planning requires identification of the critical system elements and their failure modes. Since the purpose of the test is to determine actual hardness reliability and confidence, pretest analysis must be quantified on the basis of less than firm estimates. Conclusions must then be reached based upon sensitivity analysis. Failure mode effects and criticality analysis (FMECA) is a formalized technique which is applicable to this problem. Its procedure is based upon network analysis, and uses logic diagrams and failure probabilities to derive system failure sensitivities. The important application of this process is not in quantifying the system failure likelihood based upon firm subsystem reliabilities, but in identifying <u>changes</u> in system failure likelihood as a function of subsystem failures—sensitivity. Comparison of such sensitivities to subsystems allows identification of critical EMP paths and the high priority EMP tests.

Suggestions for elimination of these critical paths by redesign are quantitatively justifiable based upon relative costs of testing versus design modification costs as a result of such deliberations.

Important to note is the tendency on the part of the design community to parallel important functions to provide peacetime reliability and availability through redundancy. Such a procedure can result in decreased EMP hardness confidence since it also provides redundant points-of-entry, of which a failure in any one causes system failure.

This paper shows why the FMECA techniques are an essential tool for hardness assurance and validation, how they are best applied, and some interesting results of successful application to a DoD C^3 system.

Statistical Relationship Between Testing and Predictions of EMP Interaction

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Investigating the general relationship between EMP testings and predictions, we first show that such a relationship must be statistical in nature due to the many uncontrollable and uncertain elements and the shear complexity of the problem. Then, we devise a theoretical framework that decomposes the overall problem into a number of different stages. For each stage, we identify the input information required, delineate the output information produced, and outline the nature of the effort needed. In particular the methodology used is explicitly specified and the difficulties encountered, of both physical and mathematical origins, are pointed out. While we have suggested ideas and commented on the extent of efforts needed to resolve some of these difficulties, in this report we can merely indicate others as being open questions. In short, for the general EMP testing-prediction problem we have spelled out the ingredients needed to arrive at a final assessment and have outlined the ideas and procedures for making use of these ingredients.

To the part of the statistical relationship between EMP coupling test data and prediction results, we have devoted a detailed effort. Based on a linear model that links the subsystem level black box points to their dominant points of entries (POE), we have developed a statistical formalism that enables one to calibrate the uncertainties in the theoretical (analytical or computational) prediction capability by the uncertainties in the test data under simulated EMP environments. Thus, the calibrated prediction capability then will be used to predict, with quantified estimates of confidence levels and intervals, the statistical behavior of the system responses at that subsystem level to a threat EMP stress. Following this formalism, we use a simplified example to illustrate how the procedures are applied and implemented. In the example test data and prediction results are statistically compared and aggregated to yield an EMP coupling assessment that has quantified confidence measures. Such a coupling assessment, combined with the other subsequent ingredients outlined in the general theoretical framework, could be used either forwardly to facilitate the overall assessment or backwardly to specify the amount of hardening required for improving the unsatisfactory coupling parts.

Reliability-Confidence Algorithms
for Assessing Complex Systems

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ABSTRACT

Consider the question of whether the threshold of failure of a given system is greater than a specified level of stress (the threat) expected in a certain harsh environment. Suppose it is proposed that the difference between the threshold and the threat is at least M dB (M for margin). It is reasonable to ask what is the probability that this proposition is true. Suppose it is further proposed that this probability is greater than or equal to a certain value R. Then we say the reliability of the first proposition is R. (If M = 0 then R is also the reliability of the system at that stress level.)

In statistical terms, [R,1] is a confidence interval for the binomial (or hypergeometric) parameter p. A further question is, what is the confidence level to be associated with this confidence interval? In the actual assessment of a complex system only incomplete data is ever available from which to estimate the reliability R. Moreover the data which is available is usually contaminated by error from several different sources. Consequently the confidence C(R) warranted by any proposed value of R > 0 must in actual practice always be less than unity. This confidence level is rigorously calculable as a function of the experimental data (and other supplementary information) available to support the estimates M and R. When this confidence is calculated, it is in practice often found to be sufficiently less than unity (typically .9 or less) to require that the confidence level accompany any advertising of the estimates M and R.

For these reasons the algorithms used to calculate C(R) from experimental data are very important in the assessment of systems. For complex systems, RC (reliability-confidence) algorithms have improved considerably in the past few years. However, they still contain theoretical weaknesses. Further work is required to eliminate these weaknesses.

This paper examines RC algorithms currently in use for EMP assessment of complex systems. It discusses the weaknesses of these algorithms, and describes further work needed in this area.

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ABSTRACT

A STRUCTURED APPROACH TO TEST POINT SELECTION FOR AN EMP SYSTEM TEST

By Mr. William H. Cordova, Rockwell International, Nuclear Effects Engineering, 3636 Menaul Blvd N.E., Suite 211, Albuquerque, New Mexico

This paper examines the mechanics of structuring an EMP system test with emphasis on the test point selection process. With the realization that EMP system test programs differ in terms of goals and objectives, three categories of test program are examined. These are: (1) an Analysis Support and Model Verification System Test Program, (2) A Hardness Assessment Related Test Program, and (3) A Hardened System, Hardness Verification Test Program. Programmatic differences are examined in detail as related to the test program structure and alternately as related to the test design and test point selection. Although the approaches discussed apply, in general, to the design of most EMP System Test Programs, the subject material is inclined towards aircraft EMP test programs.

Many variables affecting the test program design and test point selection process are examined. Among these are: test program objectives, test vehicle considerations (e.g., surface coatings, surface materials, equipment and cable layouts, etc.), system modes of operation, configurations/orientations, experiment categories, types of measurements, simulation facilities, instrumentation system and limitations, data acquisition rates, deterministic test variables, configuration controls, and test controls.

The material presented shows how a structured test program requires a thorough knowledge of how the test data is to be applied to satisfy the program objectives and also requires an understanding of the mechanics of running a test. The importance of test point selection algorithims and prioritization schemes is exemplified.

ABSTRACT

COMMENTS ON THE SELECTION OF EMP DESIGN MARGINS

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It is generally necessary to select design margins fairly early in an EMP hardening program in order to provide concrete goals for the equipment designers. Once selected, few considerations have more significant and long lasting impact on the hardening program than the design margins.

The availability of high quality design techniques and design solutions means nothing if too low a margin requirement renders them apparnetly unnecessary. Conversely, cost, weight, and possibly reliability penalties accrue to programs with too high a margin requirement. Despite their importance, design margins to date have been picked judgementally without the benefit of any but the most cursory analysis.

This paper attempts to identify the major factors which enter into the selection of design margins. It presents one view of how these factors add up to a design margin. An attempt is made to identify those factors which can be quantified in a typical program and those which most probably cannot.

It is believed that part of the variation in viewpoints on design margins stems from differing, but unspoken, treatment of the basic factors noted above; this leads to unnecessary disagreements which vanish when communication is more complete. This paper begins the process of identifying these factors so that the true issues in selecting design margins can be better highlighted.

E^3 ENGINEERING
THE STRUGGLE FOR COMBAT READINESS IN AN ELECTROMAGNETIC WORLD

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Electromagnetic environmental effects (E^3) influence the combat effectiveness of all land, sea, and air deployed electronic systems. Therefore, it is imperative that E^3 be addressed adequately in the life cycle of military systems so as to ensure continued operation in a glutted, and sometimes hostile, electromagnetic world.

For some years problems of radio frequency interference (RFI) and electromagnetic interference (EMI) have prevented electromagnetic compatibility (EMC) of electronic systems with their environment. Safety of ordnance (HERO), fuels (HERF), and of people (RADHAZ) are important when it is necessary to be and to operate in the vicinity of high power transmitters. Electronic systems and weapon systems also exhibit special electromagnetic vulnerabilities (EMV) when near such transmitters. Lightning has long been a threat to be reckoned with. In this nuclear age, the electromagnetic pulse (EMP) is still another threat to the sustained mission effectiveness of military systems. From the standpoint of electronic system performance, each of these are but specialized manifestations of a composite electromagnetic environment in which a sytem must function. Taken as an ensemble, the composite environment produces electromagnetic environmental effects (E^3) which impair in some manner the functioning of electronic systems.

Over the past several years the Navy has been trying to understand how to better control these E^3 in a cost-effective manner. Under orders of the Chief of Naval Material, the TESSAC (Tactical Electromagnetic Systems Studies, Action Council), chaired by the Head, Tactical Electromagnetic Program Office (ELEX-095), set up six technical teams to survey the status of our ability to understand the environment, to engineer and to test for system operability in that environment, and to procure and maintain systems with assured operability. The technical teams surveyed the E^3 specialty areas of EMC, EMV, EMP/Lightning, Safety, ECCM, and Power Systems. Summary reports were synthesized from these specialty surveys, including: a synopsis of current capabilities and deficiencies; a plan for achieving E^3 engineering in the acquisition cycle; a plan for R&D needed to make up identified deficiencies in technology, testing capability, specifications and standards, and personnel training; and a plan for monitoring and maintaining continuing operability of electronic systems during their deployment and use.

E^3 engineering is the combined application of E^3 specialties so as to achieve sustained system performance in a composite electromagnetic environment. This does not mean that the various electromagnetic specialties are to be melded into one. Rather, it implies the integration and coordination of the application of their technologies. Such an effort has some very definite implications for EMP in the future in the Navy, and for those who are engaged in EMP related research and engineering.

PRACTICAL ASPECTS OF EMPLOYING TRANSIENT DIGITIZATION AND RECORDING SYSTEMS FOR FIELD TEST PROGRAMS*

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The AFWL Data Acquisition System for EMP Tests (DASET) represents a significant improvement in field test data gathering and recording capability.

The use of this system for seven months for recording data from the AFWL Horizontally-Polarized Dipole (HPD) Upgrade Testing Program has provided extensive experience which can benefit future users of this type of automated digital recording system.

Specifically, the following areas are discussed:

a. Data recording limitations
b. Operational data cycle
c. System self check (auto-cal)
d. DASET/Microwave characterization (284 test)
e. Statistical accuracy

Using data acquired during the HPD Upgrade Testing Program, each area is addressed with emphasis on the inherent system characteristics and their impact on successful acquisition of quality test data.

*This work was sponsored by the U.S. Air Force under Contract F29601-76-C-0064.

LARGE EMP DATA ACQUISITION/ANALYSIS SYSTEMS,
A BRIEF HISTORY AND UPDATE

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EMP testing in large facilities is usually very expensive and tests are performed on a very tightly scheduled basis. There has always been a lot of interest in improving data acquisition/analysis systems to improve data reliability, accuracy, throughput and, consequently, lower the cost per shot. These efforts have been complicated by several unique aspects of the EMP testing scenario, specifically:

(1) Physical size of the facilities makes sensor to recorder traceability difficult;
(2) Several data records must be "time tied" before a test point can be verified;
(3) The working environment is poor;
(4) The data acquisition is done at a location physically distant from data reduction.

Several generations of test systems have evolved over the years to attack this problem. This paper will give a brief history of this evolution up to the present "daset/adset" system and show how the various systems performed when judged against the following criteria:

(1) Data Reliability
    (a) Traceability
    (b) System Calibration/Verification
    (c) Recording Format
    (d) Q.C.
(2) Accessibility of Data Base
(3) Accuracy
(4) Time Between Acquisition and Analysis
(5) Human Engineering
    (a) Working Environment
    (b) Ease of Operation
(6) Shots/Day
(7) O&M Requirements

In addition, the present system will be described in detail to show how the data acquisition and analysis facilities have been tied together in a distributed network of computers, how extensive use is made of software verification of data, and how human errors are minimized through good system design.

The paper will end by discussing possible future system improvements such as fiber optic data links, CCD recorders, etc.

The test systems described here were developed by and for the Air Force Weapons Laboratory. Current improvements are being performed under contract F2960177C-0014.

EMP DATA PROCESSING ERROR ANALYSIS*

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This paper describes the results of a statistical analysis of data processing errors associated with electromagnetic pulse (EMP) test data. Results are presented for both time and frequency domains. Two different sets of data processing procedures are addressed: those associated with the processing of oscilloscope data photographs, and those associated with the processing of data acquired by the DASET (Tektronix R7912 Transient Analyzer) data acquisition system. Mathematical models, derived from the statistical analysis, which estimate ninety (90) percent confidence limits at a ninety (90) percent confidence level are presented. Limitations on data dynamic range imposed by data processing errors are also discussed.

*Work supported by Contract F29601-76-C-0064 for the AFWL.

DETERMINISTIC ERROR ANALYSIS AS A TEST PLANNING AND ON-SITE ANALYSIS TOOL

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The utility of a deterministic error model, developed as a part of an aircraft test program, is illustrated for system test planning and analysis. The model's greatest strength lies in its ability to provide real time error estimates. Six sources of measurement error have been identified as being significant contributors to overall measurement error in a test program with rigorous quality control [1]. The resulting model has been implemented as a user-available algorithm on a mini-computer.

For a given set of six user-specified time domain errors, exercise of the algorithm on a given data set results in the calculation and graphical presentation of the frequency-dependent overall error. The accuracy of the error model has been cross-checked by comparison with statistically derived error estimates also obtained as a part of the aircraft test program referred to above.

Examples of the use of the algorithm are given in two situations:

1) test planning activities, in which the algorithm is used to perform trade-off studies between required data frequency bandwidth and quality control constraints, and

2) on-site data analysis during testing, in which the algorithm is used to accept or reject data on the basis of meeting specified frequency bandwidth - error level requirements.

The first situation is illustrated using predicted aircraft response data, and the second situation is illustrated using real response data taken in the ATHAMAS-I EMP simulator (F-111, SPS, and TACAMO external response data).

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APPLYING DIGITAL SIGNAL ANALYSIS TECHNIQUES TO DIGITIZED EMP/SGEMP WAVEFORMS

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Experimental data recorded by photographing and digitizing an oscilloscope trace into coordinate pairs generally contains various errors. One of the more obvious errors occurs in the zero base line shift of the data. This may be due to the uncertain width of the scope trace, incorrectly setting the (0,0) point in the digitization process, etc. These errors gravely affect a waveform when the digitized data is proportional to the derivative of the measured quantity and must be integrated before calibrations can be made. Some simple and straightforward methods of integrating, interpolating, and bandpass filtering are applied to sample derivative data, particularly the OWL Exploding wire SGEMP experiment, to better represent the structure and for more reasonable comparison to prediction data. Time and frequency domain waveforms of idealized and experimental signals are presented.

DATA SIGNAL TO NOISE RATIO ESTIMATED BY THE MOMENT METHOD (1)

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Many military systems are tested with EMP simulators not completely representative of the specified threat environment. In order to estimate the coupled signals in the actual threat, measurements are often extrapolated with various transfer functions (2). However, the validity of the extrapolation is critically dependent on the signal-to-noise ratio of the measurements (3). The purpose of this paper is to present an analytic method of estimating data signal-to-noise ratios.

The effect of random additive errors introduced by the analog-to-digital conversion process cannot be removed by additional data processing. Therefore some model indicating frequency bandwidths with acceptable signal-to-noise ratios is desired. Unfortunately, straightforward mapping of random time domain errors to estimates of frequency domain modulus and phase errors presents a formidable analytic problem. However a simple formulation is available using the statistical method of moments (4).

The moments method was used to obtain (5) the mean and standard deviation of the modulus and phase of a Fourier transform, and the transfer function modulus and phase obtained from two Fourier transforms. The noise model was assumed to be uncorrelated with a zero mean and a finite second moment. Expressions for the mean and standard deviation are shown.

A significant finding of the analysis is that the mean of the modulus is biased while that of the phase is unbiased. Numerical examples are presented. A typical result using a damped sine with a noise standard deviation equal to one percent of peak limits the frequency domain bandwidth below three times resonance. The standard deviation is best interpreted using non parametric statistics since an acceptable fit to common parametric distributions could not be found.

Recommendations for evaluating data contaminated by noise and means for reducing input noise are presented.

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LIGHTNING WAVEFORM MEASUREMENT

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This paper describes a remote controlled instrumentation system that is capable of measuring the current waveform of a lightning strike. An AFWL CPM-1A current probe was used as a sensor. The output signal from the sensor was recorded using high speed digital techniques. The equipment installation and shielding are described with the aid of block diagrams and installation photographs. Lightning current waveforms are shown along with a photograph of the actual lightning strike.

A TEST TECHNIQUE FOR MEASURING NATURAL AND SIMULATED LIGHTNING PHENOMENA

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A joint AFFDL/NASA lightning research program was conducted at Kennedy Space Center in July and August of 1977 as part of Project Thunderstorm (TRIP-77). A NASA Learjet aircraft was instrumented with E and H field antennas, field mills, and skin current sensors to obtain near field lightning data. Special cable runs were installed to record induced voltages and currents within the aircraft. This paper describes the measurement system used to gather in-flight data and the subsequent use of the system for ground tests. A description of the various sensors on the aircraft and their characteristics are given in relation to the natural phenomena measured. In addition, the equipment and generators used for the ground tests to simulate various parameters of the natural phenomena are described. Comparisons of in-flight and ground test data are given.

TEST DATA FROM NATURAL AND SIMULATED LIGHTNING PHENOMENA

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Ground-based lightning simulation test data are compared to in-flight data recorded on a NASA Learjet aircraft under a joint AFFDL/NASA lightning research program. The program (TRIP-77) was conducted at Kennedy Space Center during July and August 1977. The relationship between simulated test data and that obtained in the natural environment are emphasized. The parameters discussed are the electric field, the magnetic field, and the aircraft skin currents produced by laboratory tests and by natural lightning. Comparisons are made in both the time and frequency domains in order to characterize the lightning/aircraft interaction.

THE EFFECT OF SOIL CONDUCTIVITY AND INSULATION DIELECTRIC STRENGTH UPON LIGHTNING DAMAGE TO BURIED INSULATED CABLES*

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Some communication or power systems can have large networks of buried insulated conductors, whose total length can approach thousands of miles. Although they are buried, these cables are still significantly exposed to cloud-to-ground lightning strokes. With such large lengths of buried cable in a system, problems associated with the initial cost, development, and maintenance become significant. Fault isolation and maintenance for long cables may be quite difficult and expensive. It is thus incumbent upon the system designer to incorporate expected lightning damage into his design criteria and maintenance plan.

The problem addressed in this paper is the predicted effects of soil conductivity and the cable insulation dielectric strength upon cable damage. The cloud-to-ground lightning stroke peak current is treated in a well known statistical manner, and thus the expected cable damage is described statistically.

A rather simple nonlinear time varying circuit model is employed to calculate cable damage. When a stoke is incident upon the earth, it ionizes a region (which is roughly hemispherical) near the surface of the earth. To a first approximation, this region is regarded as an unipotential volume. If the cable is in this volume, a potential will develop across the insulation. The size and impedance of the unipotential volume is a function of the soil resistivity, its dielectric breakdown, and the time varying current flowing into this volume from the lightning stroke, and is therefore represented as a time varying nonlinear resistor. The cable insulation forms a time varying coaxial capacitor whose outer conductor is the ionized soil region, and whose inner conductor is the cable conductor. A nonlinear resistor accounts for the cable insulation breakdown. The cable characteristic impedance is represented by a resistor determined by well known methods.

The model is used to predict the expected number of damaging strokes per 100 miles for cables having insulation dielectric strengths of 210, 550, and 1000 kV, and for soil resistivities ranging from 25 to 1000 ohm-m. The current which flows down the cable is also predicted.

It is shown that significant lightning protection is provided by increasing the cable insulation dielectric strength, and that the protection is a significant function of soil resistivity. Of course, high voltage cables are initially more expensive, but this cost would have to be traded off against the reduced fault isolation and maintenance costs.

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Lightning Effects on Air Force EMP Instrumentation

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The effects of nearby lightning on Air Force EMP sensors are being studied at Langmuir Laboratory near the summit of the Magdalena Mountains of central New Mexico. About 60 thunderstorms develop each summer within a 10 km radius of the summit and lightning frequently strikes the mountain ridge. The paths and nature of the discharges are determined by use of video cameras and recorded onto magnetic tape. The mountain top is often enveloped in clouds and the flashes are then obscured. Three arrays of low frequency microphones provide location information on the in-cloud portions of the discharges.

A vertically scanning, 3 cm cloud physics radar provides a quantitative digital record of the location and intensity of the precipitation echoes lying within a 10 km range of the Laboratory. Electric and Magnetic field vector changes for each stroke are recorded with high time resolution. Changes in $|E|$ of the order of 30 kV m^{-1} are commonly recorded for nearby discharges.

Minimizing Lightning Effects On An Electromagnetic Signal Detector

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A detection system is being developed to detect electromagnetic signals. Because incorrect operation caused by lightning is a major concern, various designs are being incorporated in the system to minimize lightning effects. These include antenna, band pass filters, amplitude selection, protection circuitry, shielding, and power line isolation. The deployment configuration is also an important factor. The detection system is being field tested to determine lightning effects.

ELECTROMAGNETIC COUPLING ANALYSIS OF A LEARJET AIRCRAFT IN A LIGHTNING ENVIRONMENT

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As an adjunct of the AFFDL/NASA lightning research program (TRIP-77), an electromagnetic coupling analysis of the NASA Learjet aircraft was developed and applied to predict and interpret magnitudes and waveforms of induced voltage and current transients on selected aircraft cables and circuits. This paper describes the modeling techniques used to calculate the external induced skin current density for arbitrary lightning sources, the penetration fields that produce voltage sources on interior cables and circuits, and the circuit responses to these sources. Measured in-flight test data and simulated lightning ground test data are compared with model predictions.

A HIGH VOLTAGE TEST FACILITY FOR FUTURE LIGHTNING TEST REQUIREMENTS

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Existing lightning induced voltage tests are defined only for that part of the lightning stroke that delivers the high current (up to 200,000 amps) to an airframe. This test (called the Transient Analyzer Test) does not account for induced electronic transients that may appear in airborne electronics due to the lightning channel E-fields and other significant lightning generated transient fields.

In anticipation of the future test specifications that will address their E-field problem, the McDonnell Douglas High Voltage Laboratory has developed high voltage generators, instrumentation, and test techniques, to support this type of testing.

Tests have been performed upon simulated airframes to study the effects of these lightning type of E-field transients upon airframe wiring and upon composite structures. Data is presented to show the strong interaction of test configurations with the resultant data.

A REVIEW OF THE LITERATURE ON LIGHTNING AND LIGHTNING PROTECTION AS RELATED TO EMP HARDENING

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This paper presents a summary of the extensive material that has been collected and reviewed by the author while engaged in lightning and EMP studies over the past 5 years. Topics include lightning generation research, lightning protection techniques and combined lightning and EMP protection studies. A selected bibliography is provided with a commentary on the more pertinent references, particularly in the area of terminal protection devices. Both U.S. and Foreign literature is discussed and a guide to information sources is provided.

THE ROLE OF ACADEMIA IN THE DEVELOPMENT OF EMP TECHNOLOGY

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The systems engineer assigned to design a military communication system that is required to withstand certain levels of EMP radiation must have ready access to the necessary tools for reliably estimating the EMP penetration and vulnerability of a complex system to a high level of transient electromagnetic radiation. Although electromagnetics is recognized to be a mature field, the DOD management realized very early that large gaps still existed in the technology for accurately assessing the EMP vulnerability of practical communications systems. This, in turn, prompted the defense organizations to develop a network of contractual arrangements with leading academic institutions in the U.S., sponsoring basic research in EMP at these universities. The universities responded by embarking upon an extensive research program directed toward developing practical tools for the designer working in a government or industrial laboratory and engaged in the task of hardening command, communication and control systems for the military. Thanks to the tremendous foresight of the government planners, these programs were viewed as long-range, and consequently were ideally suited for the university environment. Significant advances have been made in the EMP program in the areas of electromagnetic radiation, coupling, time-domain analysis and measurements. What is more, some of the fundamental theories developed under the basic research programs in EMP have found useful applications in many other areas: electromagnetic compatability and lightning protection. The university research laboratory with its EMP technology program has had yet another salutory effect. It has given the research students at these laboratories an exposure to practically significant, real-life problems that require the development of innovative, theoretical approaches — an excellent training procedure that has prepared the students for a post-graduation career. The AFWL note series, e.g., the Interaction Notes, are internationally acclaimed as leading publications in electromagnetics; they are a testimonial to the high ratio of productivity to research dollars invested in the program. To summarize, the EMP program has proved to be mutually beneficial both for the government and for the university and is an excellent example of university contribution to government projects and long-range DOD support of basic research with application to military problems.

A Review of the Status of EMP as a System Level Problem

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Since modern weapon systems contain thousands to hundreds of thousands of pins and wire segments, and many more electronic components than wire segments, it is clear that it can be extremely difficult and time consuming to understand accurately what is happening when EMP interacts with the system. Further, systems are not identical nor static. Electronic modifications are frequent and sizable. The authors will deal with a view of the dimensions of the system, questions, problems and strategy for dealing with it.

THE INTERACTION OF AN ARBITRARY E. M. PULSE
WITH A CONDUCTING CYLINDER OF INFINITE LENGTH

I. L. Gallon

A phenomenological argument is presented which suggests that the current response of the cylinder may be separated into two components, one proportional to the incident field, the other proportional to the integral of the field. The δ-function response of the cylinder is developed in transform space and a combination of analytical and numerical techniques are used to justify the above ideas, which in this case lead to an approximate δ-function (which proves to be insignificant) plus an approximate step function. The extension to arbitrary fields then follows by superposition. The mathematical content is simplified by considering normal incidence, a simple argument producing the correction for angle. The admitted zero errors in previous work are found to be larger than indicated.

OVERVIEW OF A DATA BASE FOR ENGINEERING PREDICTIONS OF EMP EXTERNAL COUPLING*

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A significant number of EMP interaction and coupling problems involve estimates of EMP-induced signals flowing into systems on purposeful or inadvertent antennas. Many such structures have sufficient commonality of form that certain fundamental or "canonical" models can be used for engineering estimates of EMP external coupling to the real structure.

This paper describes an engineering Data Base generated at the Lawrence Livermore Laboratory and includes a set of such models with a large amount of data presented in a form suitable for rapid engineering estimates of coupling levels. The Base is non-specialist, user-oriented.

The data modules comprising the Base consist of time and frequency domain data and provide estimates of responses such as total energy, power, voltage, and current for various dimensions and loading conditions. The canonical models include straight wires and loops (in free space and above ground planes) whips and loops (on boxes and cylinders), and whips in special configurations. Some data is also presented for representative or scale models (i.e., whip on a tank) for comparison. Examples of data presented in the modules are given.

The Data Base has been generated both experimentally and computationally. The experimental work was performed on the Transient Electromagnetics Range at Livermore, while most of the computations were done with the general purpose time-domain computer code WT-MBA/LLL1B. Use of both the Range and the code is described and general capabilities and limitations are included.

The technique for obtain various "worst-case" EMP parameters (incident wave direction and polarization, antenna length L, antenna size relative to surrounding geometry, load position and impedance, etc.) is discussed. The philosophy for a Range model is to approximate the worst-case load and other parameters, then choose worst-case ratio of configuration/antenna size, and then maximize the EMP response of interest relative to resistive load. From this modular data one can estimate worst-case EMP response of many real-life systems through external antennas.

The Data Base has been validated for many real-life antenna configurations relative to field test data.

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MATRIX ITERATION IN METHOD OF MOMENTS

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Some applications of matrix iteration in the method of moments will be presented. They are designed to save either computer storage space or computing time, depending on the problem.

(a) In order to save storage, only the largest matrix elements, corresponding to interactions within physically delineated and (as far as possible) optimally chosen sub-sections of the scatterer and occurring in square sub-matrices down the diagonal of the complete interaction matrix, are stored. The consequent storage reduction, which can amount to over 95 per cent in some cases, enables large objects to be treated.

The resulting approximate matrix is factorised and a first approximate solution obtained which gives the currents which would be distributed over each sub-section in the absence of the others. The exact solution (for the whole scatterer), correct to the desired accuracy, is then obtained by iteration, utilising the minor elements which describe the interactions between sub-sections. These elements are not stored in core but recalculated when required in each iteration. Alternatively, they might be stored on disc. The increase in computing time, resulting from recalculation of unstored elements, need not be large if the number of iterations can be kept down.

(b) Problems in which computing time (but not storage) can be saved by iteration are:-

(i) a small geometric change to an already-solved system;

(ii) solving for a frequency close to one for which a solution is known.

Using (b)(ii) it is possible to proceed through the frequency domain performing an occasional (necessary) matrix inversion while obtaining solutions for intermediate frequencies by iteration.

A physical interpretation of iteration in cases (a) and (b)(i) is derived and the convergence of the scheme considered. A method is described and applied which improves convergence; this works most effectively in cases (for example near a resonance) where normally a large number of iterations would be required.

Several examples will be demonstrated.

INTERACTION OF FULL-SCALE TEST OBJECTS IN AN NEMP SIMULATOR ENVIRONMENT

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One of the RDT&E activities in NEMP (Nuclear Electromagnetic Pulse) is to predict and measure NEMP-induced responses on the surface of a test object. Most efforts on prediction are motivated to facilitate empirical measurements for verifying analytical tools. When responses are adequately correlatable between prediction and measurement, they can then be properly treated as equivalent sources for further studies on the NEMP penetration toward the complex interior of a test object.

This paper is intended to summarize the results of two full-scale test objects. One is a conducting pipe 10 m in length and 1 m in diameter. The other is a salvaged version of F-111 aircraft. Both were tested in the ATHAMAS-I Simulator at KAFB. Before testing, a prediction code developed by Richmond was selected to compute bulk currents of "thin-wire" models. Both the pipe and F-111 were modeled into "thin-wire" structures. Bulk currents of the models were calculated by assuming that their illuminating fields are the principal field components actually measured in the simulator.

The relative simplicity and efficiency of the prediction code for facilitating optimal instrumentation settings were reached under a set of assumptions and approximations discussed in ATHAMA Memos 14 and 15. Evaluation of the predicted and measured results indicate that they agree to a factor of about 2.5 or better around the first resonances of test objects. Also for the two test objects studied, the ATHAMAS-I simulator may be considered as the equivalent of a"free-space" environment for the first resonance regions to within a factor of 2.5. Pertinent examples are numerically compared for the two test objects, and suggestions for attempting to extend the present conclusions to larger aircraft such as E-3A or E-4 will be made.

Formulation of Electromagnetic Pulse External Interaction Above a Lossy Earth/Comparison of Numerical Results with Experimental Data for the Special Cases of Free Field Interaction and Interaction Above a Perfectly Conducting Ground

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ABSTRACT

Both the electric field integro-differential equation (EFIDE) and the magnetic field integral equation (MFIE) for the determination of the surface current density induced on a perfectly conducting object above a lossy earth are derived. The resulting equations are then decomposed so that the source terms and operators are represented as the sums of three terms. For either the EFIDE or the MFIE, equating one of the source terms with one of the operator terms describes free field interaction, equating the sum of two of the source terms with the sum of two of the operator terms describes interaction above a perfectly conducting ground, and equating the sum of all three source and operator terms describes interaction above a lossy earth. In this decomposition, the calculation of any of the source terms is algebraic for plane wave incidence; however, the calculation of the third operator term that changes a perfectly conducting earth to a lossy earth requires the evaluation of Sommerfeld integrals. We assure the computational tractability of these Sommerfeld integrals by presenting them in well studied forms.

Finally, we demonstrate the capability of patch zoning the MFIE by presenting a comparison of numerical computations with experimental data. Utilizing the first term in the described decomposition, calculations for the induced surface current density are compared to the density measured on exactly the same aircraft model. Utilizing the first two terms, we compared calculated and measured current densities induced on a finite perfectly conducting cylinder above and parallel to a perfectly conducting ground.

ESTIMATING THE BULK SURFACE CURRENT OF FAT CYLINDERS DUE TO AN EMP

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A method is described which estimates the bulk skin current waveform at the centre of a fat cylinder due to a double exponential EMP. The estimate can be made very quickly from the equations given, the cylinder dimensions and the electric field parameters. The simplicity of the method means it can readily be applied without specialised knowledge, but with sufficient accuracy for many engineering applications.

The method is based on the observation that the bulk centre current of cylinders excited by a step change field strength, is approximately a damped sinusoid[1]. A damped sinusoid is fitted to the initial part of the normalized current for a range of cylinder fatnesses, and this allows the response of any cylinder to be estimated. The bulk cylinder current due to other excitation functions is obtained from the step function data, by formulating the cylinder transfer function in the complex frequency domain and calculating the time domain current for the new excitation. A general solution for double exponential excitation is given, which can easily be applied to any cylinder and any double exponential EMP. Comparisons with a computer model show[2] that the peak current can be estimated to within 20% for cylinder fatnesses ranging from $6 < \Omega < 15$. A method of estimating the bulk cylinder current at any position on the cylinder is given; this is a simple extension of the sinusoidal current distribution for thin cylinders.

An extension to the method using the equivalent RLC circuit is shown, this enables the dipole open circuit voltage and the current in a loaded dipole to be found. The equivalent circuit values are calculated directly from the step function data.

The method is similar to the singularity expansion method (S.E.M.) in which the time domain response is given as a series of damped sinusoids[3]. In this case only one damped sinusoid is used which is not an SEM derived result but a curve fit to the initial part of the step function response, and which the dominant damped sinusoid in the SEM solution doesn't fit particularly well. The SEM gives exact solutions whereas this method is approximate, but more simply applied to different cylinders and waveforms.

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CALCULATION OF SURFACE CURRENT DISTRIBUTIONS ON AIRCRAFT STRUCTURES

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Surface current distributions on aircraft structures have been calculated by means of the AWRE wire-grid modelling code 'CHAOS 3'. This uses the Method of Moments, overlapping triangular basis functions and a Galerkin type solution of the Electric Field Integral Equation. The program is capable of inverting large dense matrices and up to 750 wire segments may be used. Modelling in considerable detail is therefore possible. Initial calculations are in frequency - domain with ready conversion to time-domain depending on the particular drive function required.

Surface current distributions for more simple geometrical structure have previously been presented. These were compared with alternative solutions using patches and the Magnetic Field Integral Equation, and also with experiment. (References (1), (2)).

Two aircraft have been studied, the British Jaguar strike-aircraft with a fixed swept wing and the US F111 swing-wing fighter-bomber. In each case the incident plane wave was propagating normally to the axis of the fuselage with the E-field either parallel or perpendicular to this axis. Excitation was of the form $E(t) = A(e^{-\alpha t} - e^{-\beta t})$.

Results for the F111 have been compared with the finite-difference calculations and experimental results published by Holland (3). Waveforms are similar in magnitude and shape. Possible future developments of the current programme will be outlined.

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STICK MODEL CHARACTERIZATION OF THE EXTERNAL ELECTROMAGNETIC INTERACTION OF AIRCRAFT

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This paper presents a simple method for estimating the external electromagnetic interaction of an aircraft. The aircraft is modeled by eight thin, perfectly-conducting stick segments representing the fuselage, wings, and empennage; the important global features of the external surface of the aircraft are thereby retained while, at the same time, the mathematical difficulty of the problem is greatly reduced. Junction conditions (continuity of quasi-static potential and conservation of current) are enforced on the structure, resulting in a small linear system of equations for the unknown coefficients in expressions for the total currents on the stick segments. This system is solved analytically, and the poles of the solutions occur at the (real) aircraft resonance frequencies. Radiation losses at the resonances are calculated by finite, two-dimensional numerical integrations over the natural modes. The expressions for the segment currents are then expanded in Mittag-Leffler series and the poles are shifted into the complex plane to account for radiation damping. The total linear charge densities on the segments are found immediately using the continuity equation. Thus, simple approximate analytical expressions are obtained for the external-interaction transfer functions.

Detailed results are presented for the E-4 and EC-135 aircraft. Comparisons are made with scale model measurements performed at the University of Michigan. The frequency-domain transfer functions are transformed analytically to the time domain, and results are presented for a typical electromagnetic pulse incident on the EC-135.

EVALUATION OF TYPES 3A AND 3B SYSTEM RESPONSE EXTRAPOLATION USING EXPERIMENTAL DATA*

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Testing of an F-111 airframe and the PIPE test object in the ATHAMAS-I simulator during the Upgrade Program provided a unique opportunity to evaluate the type 3 simulator-to-free-flight extrapolation methods created by Baum.[1] Previous surface current and charge density measurements had been made on this airframe in the ARES simulator,[2] and measurements were made on scale models of the F-111 at the University of Michigan Surface Field Measurement Facility.[3] Type 3A (incident field) and type 3B (surface response) extrapolation functions were formed among data from the three facilities, both with associated type 3C errors.[4]

It is found that the principal errors in the extrapolation process are due to inadequate spectral output of the ATHAMAS-I and ARES simulators, limited dynamic range of the measurements, and the complex structure of the electromagnetic fields in the ATHAMAS-I simulator. While the first two sources of error could be reduced with a better quality pulser and multiple measurements of the same quantity, the final source of error cannot be overcome without the use of type 4 extrapolation (in which the excitation of each penetration is extrapolated individually).

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IMPLEMENTATION OF THE 3C EXTRAPOLATION METHODOLOGY FOR THE EC-135 AIRCRAFT

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This was the first application of the 3C extrapolation methodology to a system. The extrapolation to criterion for each aircraft orientation was calculated by taking the geometric mean of the extrapolation ratios which were the ratios of University of Michigan (U of M) scale model data to aircraft response data. Thus, only four functions (one for each aircraft/simulator orientation) were used to extrapolate all the wire currents to the criterion level. This extrapolation method resulted in technically sound computations of system margins and high confidence error intervals.

Several problems were overcome in developing the mechanics for implementing the 3C methodology, the more difficult of which are discussed below. The first problems encountered were the result of truncated ranges for both the EC-135 measured field data (0.1 MHz to 50 MHz) and the U of M scale model data (2.0 MHz to 20 MHz). The U of M data were analytically extended on both the low and high frequency ends to conform to the range of the EC-135 data. In addition, analytic tails were added to all frequency domain data just prior to the calculation of a Fourier inverse transform to reduce the effects high frequency truncation. This resulted in high quality Fourier inverse transforms.

The use of the geometric-mean method of generating extrapolation functions resulted in some interesting facts. The mechanics of the geometric mean calculation were such that irregularities in amplitudes were smoothed out, but irregularities in phase were enhanced. In spite of the lack of good phase information, only a 6 dB uncertainty was observed in the time domain peak values. On the other hand, the geometric mean minimized the effects of apparent noise spikes in the measured field data by virtue of its smoothing characteristic.

ON THE LOCATION OF POEs USING TRANSMISSION LINE MEASUREMENTS

by

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The concept of locating points of entry (POEs) in the skin of an aircraft, through which EMP energy can penetrate, by means other than a visual inspection, has been under discussion for a number of years. Candidate techniques include making various transmission line measurements with the aircraft in an EMP simulator (such as ARES), using portable or localized simulators to excite only a portion of the aircraft, and using the concepts of reciprocity (as in the "sniff test" concept).

Recent testing of the Navy TACAMO aircraft provided an opportunity to investigate one of the proposed POE search techniques and verify its usefulness in locating POEs. The method studied involved making early time, time of arrival measurements of energy flow on transmission lines within the aircraft to attempt to locate one or more regions on the line which are strongly excited by the POEs.

Results of this investigation show that, whereas it is possible to determine the early time direction of energy flow on a transmission line, it may be difficult to use this method effectively to locate POEs. The reasons for this conclusion will be discussed in this paper.

SMALL EMP SIMULATOR BASED ON BALANCED ELECTRIC AND MAGNETIC DIPOLE MOMENTS

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Small EMP simulators are being studied for potential application in systems hardness maintenance surveillance. Two basic types are considered for generating certain EMP fields to locally illuminate systems of interest. One is to generate desired fields within the simulator structure. The other is to produce fields external to the simulator.

This paper summarizes some analytical results obtained recently for a small simulator whose exterior fields are to consist of predominantly those of electric- and magnetic- dipole moments. By maintaining a proper relationship between the two moments, the simulator fields can have a unique feature that is consistent with the P cross M concept developed in SSN 125. Briefly, its field is distributed in an axially symmetric cardiod pattern and is almost purely transverse-electromagnetic around the axis of maximum radiation. This desirable feature is shown to be "realizable" if the simulator were made vanishingly small.

"Practical" EMP simulators of this type are necessarily of finite size, and are electrically large when operated in higher frequencies. A parametric study of a transmission-line type simulator has been made to evaluate the electric and magnetic dipole moments based on quasi-static definitions. Higher-order moments have also been evaluated to study their degradation effects on the unique property of pure dipoles.

Some results for enhancing the P cross M condition for relatively "large" simulators are discussed in the space-time and frequency domains. Also the relationship between quasi-static definitions and spherical-harmonic solutions is established for the purpose of characterizing analytical performance parameters. Possibilities of physically realizing this type of simulators are also discussed.

PROPAGATION ALONG A RECTANGULAR BONDED WIRE MESH LOCATED OVER THE GROUND

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A rectangular mesh of intersecting parallel wires located over a lossy half space has been analyzed using a general Floquet expansion for the doubly periodic structure. A mode equation for the unknown propagation constant is obtained by setting the determinant of the current coefficients equal to zero. The mode equation must be solved numerically, but the convergence is rapid when appropriate current and charge conditions are applied at the wire junctions.

When the half space is a perfect electric (or magnetic) conductor, by image theory the model yields the antisymmetric (or symmetric) waveguide modes of a pair of rectangular bonded wire meshes. The quasi-TEM mode which is of interest in parallel plate EMP simulators is analyzed in detail. Numerical results for the propagation constant and the field distribution are generated to illustrate the dependence on the various parameters (mesh dimensions, frequency, direction of propagation, etc.).

When the half space parameters are those of a lossy earth and the mesh is located close to the earth, the model can be used to study surface wave propagation over a ground screen. This surface wave is important in vertical dipole EMP simulators where both the source and the test object are located over the ground screen. Because of the lossy earth, the surface wave suffers attenuation and the propagation constant is complex. Numerical results are generated to illustrate the dependence of the phase velocity and attenuation rate on the ground screen parameters.

ELECTROMAGNETIC EQUIVALENCE OF A LOADED WIRE CAGE AS COMPARED TO A HOLLOW CYLINDER

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The various types of hybrid simulators used in the study of electromagnetic pulse and other interaction problems consist of complex physical geometries. From many practical considerations, quite often thin wire grids or thin wire cages are employed to replace conducting surfaces of the simulators. The rigorous analytical treatment of the complex simulator geometries is even more difficult; to understand the nature of the electromagnetic radiation and the fields generated, simple canonical geometries can be used.

This paper discusses a preliminary investigation of the electromagnetic equivalence of an infintely long loaded thin wire cage as compared to a loaded circular cylinder or a loaded hollow circular cylinder. For these comparative models using the impedance boundary condition, matrix-integral expressions for the current induced and scattered fields are obtained, and specializing them to a concentric wire cage gives rise to simpler expressions. Based on the currents induced on the structure and the corresponding fields radiated, a field equivalence is established to obtain the equivalent radius and equivalent sheet impedance of a circular cylinder. Both the scattering and the antenna problems are considered as a function of frequency in the quasi-static and asymptotic ranges. The results of this study are useful both in the analytical and computational nature of the hybrid simulator problems.

ATHAMAS I (HPD) PULSER ASYNCHRONISM AND ITS EFFECTS

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Three characteristics of the fields produced by the ATHAMAS I facility degrade its simulation capabilities, namely

1. lack of high frequency ($\gtrsim$20 MHz) repeatability;
2. presence of a spectral "valley" that varies as a function of position;
3. asymmetric field distributions.

These characteristics have their source in the HAG-II C pulser used to excite the ATHAMAS I antenna array. This pulser employs two symmetric pulser halves or subsystems, charged to opposite polarity, that are switched by two symmetrically separated output switches. When these switches fire synchronously or nearly synchronously (within 1 ns or less of each other, an event that occurs approximately once in every 100 shots), none of the above problems are visible for frequencies up to 250 MHz, the upper limit currently applied to ATHAMAS I operation. When the switches fire asynchronously (the majority of shots, approximately 80%, have asynchronism times ranging from 2 to 6 ns), all of the above problems are visible for frequencies well below 250 MHz.

The assertion that the above three field characteristics are the result of pulser asynchronism is based on the fact that a simple theoretical model of pulser asynchronism, using experimentally derived inputs, can predict the gross features of all three field characteristics. This note presents the field characteristics in more detail, develops the simple asynchronism model, extracts the necessary model inputs, and predicts the important features of the field characteristics. It concludes with a discussion of how asynchronism effects limit testing and what measures are available to circumvent the asynchronism problem.

HORIZONTALLY-POLARIZED DIPOLE (HPD) PULSER (HAG-II) VARIABILITY*

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Use of the HAG-II Pulser in support of the AFWL HPD Upgrade Test Programs produced field reference data for more than 2,000 pulser firings. Analysis of this and other test data has identified both short-term (shot-to-shot) and long-term pulser variabilities which are attributable to asynchronous firing of the two series output switches, variations associated with the pulser use factor, and variations in peak amplitude which correlate with pulse risetimes.

Field reference sensor and test data will be used to demonstrate these variations. (A separate paper will discuss the asynchronism problem.) The factors involved in these variations will be discussed, and the implications of these variations for future programs will be presented. Benefits of improved reference field measurements will be described.

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HEMP SIMULATOR/COMMUNICATION FACILITY INTERACTION*

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ABSTRACT

Simulators that are used to simulate the EMP threat from high altitude nuclear explosions reproduce only a portion of the threat field. This simulated threat field in turn interacts with communication facilities in a non-threat-like manner. In order to use simulators in assessment programs, test results must be analyzed to define HEMP survivability.

Scale modeling has been used to define simulator/site interaction for specific assessment test programs.[1,2,3,4,5] Here scale modeling techniques are used to define the interaction with a generic communications facility and a horizontal dipole simulator. These results are compared with scale model HEMP excitations. In general the results show that for facility excitations the waveforms for the two excitation methods may be quite different. However, the spectral content are within a few dB of each other except when the simulator directly straddles a facility penetration.

The results show that a non-threat field simulator can be used to test communication facilities in a HEMP threat manner if the simulator location is chosen to minimize non-threat-like excitations. Applications will be presented.

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*This research was sponsored in part by the Defense Nuclear Agency, Program Element NWED 62704H.

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Magnetic and Electric Contributions to Quasi-Static SGEMP and Scattered Electromagnetic Fields

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In this report, we identify and resolve a basic idfficulty in finding the system generated electromagnetic pulse (SGEMP) fields that has caused ambiguities of the same order of magnitude as the fields' leading terms. The difficulty is the hitherto unrecognized absence of one condition for determining the quasi-static electric contribution to the surface SGEMP fields and its full reconciliation with the magnetostatic contribution. The results apply as well to any low-frequency electromagnetic scattering problems involving highly conducting scatterers.

In resolving the difficulty, after exhibiting its existence and delineating its significance, we conceive and make use of two mathematical conjectures. One is the decomposition of a tangential vector field on a two-dimensional closed simple surface into a "surface-divergenceless", or magnetostatic, part and a "surface-curlless", or electrostatic, part; the other is the requirement of "surface-curllessness" of a surface current were it to generate a magnetostatic field parallel to the surface on that surface. The first conjecture is critical to the validity of our methodology and solution. Its proof is reduced to the solvability of a generalized wave equation on a curved surface, unexpectedly the same formal equation obyed by the relativistic electromagnetic four-potentials in a curved spacetime. The second conjecture simplifies the calculation greatly but is not critical. Except for some special cases, it is not proved; but neither is any counter example found.

With these conjectures, we show that the electric and magnetic contributions to the quasi-static fields fall out separately from the general formalism and reconcile fully with each other to yield the whole fields. The results are that the electrostatic part of the surface current is driven by the driving electrostatic field and is "surface-curlless"; the magnetostatic part is driven by the driving magnetostatic field component perpendicular to the highly conducting surface and is "surface-divergenceless"; furthermore, only scalar field mechanisms are needed to exploit away-from-surface conditions in determining and reconciling the two parts. Finally, the application and significance of the results are illustrated by several simple but practically interesting problems. The illustrations show that the relative amplitudes of the electrostatic and the magnetostatic parts of surface currents (and thus the ambiguities removed by obtaining them correctly) vary from zero to infinity in the cases often encountered.

PREDICTIONS OF CURRENTS ON A MODEL SATELLITE EXPOSED TO X RAYS

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In this paper we present calculations of the response of a scale model of the DSCS-II satellite exposed to X rays under conditions which result in a high degree of space-charge limiting. The methodology used in these was to perform one- and two-dimensional calculations of the photoelectron motion in the vicinity of emitting surfaces. We then insert the electric dipole moment adjacent to emitting surfaces and the magnetic dipole moment, created by circulatory current flow at the boundary between emitting and non-emitting surfaces, into two- and three-dimensional finite difference electromagnetic models of the model satellite. The electromagnetic model is a hybrid of straightforward finite difference techniques on a grid coarse compared to the fine detail of the satellite structure and local electrostatic and magnetostatic models of gaps and struts on the satellite. Comparisons between the calculations of the electromagnetic resonances in the hybrid model and those observed in current injection testing of the model are shown as well as comparisons between the calculated and observed currents under X-ray exposure.

* Work supported by U.S. Air Force under Contract F29601-76-C-0034.

HIGH-ENERGY ELECTRON-BEAM CHARGING AND BREAKDOWN EFFECTS IN DIELECTRICS*

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A series of experiments to examine the effects of charging dielectric materials with high-energy electrons was performed at the RADC/HANSCOM AFB Dynamitron facility. Preliminary experiments with cables indicated that dielectric breakdown could be induced by high-energy electrons and that the radiation response of the cable could be altered somewhat by prior exposure to electrons. To examine the dielectric phenomena in some detail, slabs of teflon and fiberglass of two thicknesses were exposed in vacuum to monoenergetic electrons at various energies ranging from 0.5 to 1.2 MeV. The charge buildup, breakdown, and signals coupled to wires during breakdown were measured.

Slabs of dielectrics with electrodes on both faces were exposed to electrons with the back electrode grounded. The front electrode could be left floating or could be grounded. The time integral of the current to the grounded electrode, which is proportional to surface charge density, was measured in the experiments.

Multiple breakdowns were observed in almost every test condition. The data indicated that, with the front electrode floating, breakdowns occur with discharge potentials of 5 to 27 kV. Tests with an external power supply indicate that the breakdowns occurred across the surface. With the front electrode grounded, the discharge potentials exceeded 10^5 volts.

Coupled currents were measured in a 35-cm-long wire traversing the vacuum chamber behind the sample holder. The results from the Dynamitron response and from subsequent laboratory measurement show that substantial current can be coupled during this charge.

The results of the experiment can be explained by considering the deposition of charge and the conductivity of the dielectric exposed to a high-energy electron beam.

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A STUDY ON ELECTRON BACKSCATTER CONTROL FOR A SYSTEM GENERATED ELECTROMAGNETIC PULSE (SGEMP) FACILITY*

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The severity of photoelectric emissions from SGEMP test facility structures at the Arnold Research Organization (ARO) 4 meter test facility is examined. Results are generalized to larger facilities for fluence levels less than 10^{-3} cal/cm^2. Three passive control techniques are shown to reduce the majority of facility emissions to acceptable levels and localize the region requiring active control. Passive controls consist of 1) Coating surfaces with low Z coatings; (2) Reducing the structure's x-ray cross section; and (3) Collimating the x-ray source. Active emission control is shown to be nontrivial to design. Secondary electrons generated on any charged surface of an active control grid may accelerate electrons into the test volume possibly creating a problem more severe than the photoelectric emission.

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* Work supported by Arnold Research Organization

** Currently employed by Jaycor

MEASUREMENTS AND CALCULATIONS OF
SGEMP STRUCTURAL CURRENTS IN A SATELLITE MODEL

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SGEMP structural currents were measured at various locations on a simplified reduced-scale model of the DSCS-II spacecraft (built at IRT Corporation) exposed to photons from an exploding-wire source at the OWL-II facility at Physics International. The model was designed to incorporate the principal electrical features of the spacecraft. The exposures took place in a 4-m-diameter, 6-m-long cylindrical steel tank evacuated to a pressure below 10^{-4} torr. Data were taken at numerous locations on the model in three exposure orientations, with the model exposed head-on, sideways, and at an oblique angle relative to the photon direction. The exposure fluence and spectrum were monitored by a magnetic spectrometer (Ref. 1) and by forward-biased total emission diodes located at the rear of the exposure tank. Typical peak emission currents at the model were in the vicinity of 100 amp/m^2(Aℓ).

Calculations were performed at JAYCOR with the MEEC-3D computer code (Ref. 2). One problem with the exploding-wire source is the lack of reproducibility of pulse parameters — intensity, time history, and (to a lesser extent) spectrum. Calculations were therefore performed to determine the effects of utilizing the actual pulse parameters, as opposed to using average pulse parameters. The difference in the computer interior structural currents was found to be relatively small; surface currents and fields were more strongly influenced by pulse-to-pulse variations. This agrees with the experimental findings.

Reasonable agreement between calculations and measurements was obtained on peak current and field intensities. The characteristic structural current signatures observed at various locations on the model were less closely matched by the calculations.

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PLASMA TRAPPING OF SGEMP*

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In this paper we will present the theory and simulation of electromagnetic radiation generated by photoelectric emission from a metal and then trapped near the surface by an ambient plasma. This analysis has application to missile-radiation coupling problems in the X ray deposition region.

For the analytic work the EM fields are described by Maxwell's equations, the boundary layer as a source current, and the plasma as a constant density reactive medium. The equations are written in the retarded time appropriate to the incident X ray pulse. The equations reduce to a wave equation which may be solved in terms of a Green's function. When there is strong space-charge limiting the boundary layer may be assumed to decouple and the solution at the surface may be written in terms of a simple convolution integral. This solution indicated that there will be surface fields and currents which oscillate with a frequency near the plasma frequency and whose amplitudes decay slowly. This is in sharp contrast with the vacuum SGEMP analysis[1] which shows a single pulse radiated off into space.

To consider the nonlinear effects of the plasma in more detail we have developed and implemented a numerical simulation model. Here the photo-electrons are modeled by an ensemble of macro-particles and the plasma by the cold fluid equations. For cases of interest this numerical algorithm produces qualitatively the same results as the analytic work described above.

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*Work sponsored by the Defense Nuclear Agency (DNA) and monitored by the Air Force Weapons Laboratory, Air Force Systems Command, United States Air Force, Kirtland Air Force Base, New Mexico 87117.

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DEMONSTRATION OF EMP SYSTEM LEVEL FLIGHT TESTING

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A system level EMP illumination test was completed on the TACAMO EC-130 aircraft including configurations with a long trailing wire extended 1000 feet. The EM field was obtained from the vertically polarized dipole (VPD) facility of AFWL. The free field was determined by measurements made from a hot air balloon platform.

Surface charge density, current density, internal cable currents and long wire currents were measured while approaching and leaving the facility along a radius vector and broadside. The aircraft was exposed when positioned approximately 1700 feet out at 500 feet altitude. Aircraft position was recorded by ground range cameras and altitude determined from the copilot's flight log.

Data obtained indicated that the aircraft response pole constellation was changed little when the long wire was extended except for the addition of one pole pair at 500 kHz reflecting the long wire length. The long wire did provide drive to all aircraft response poles as evidenced by clear pulses at 2 μs intervals. Incident field strengths were on the order of hundreds of volts per meter.

TACAMO POE CLOSURE EVALUATION BY FLIGHT TESTING

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EMP hardening kits for the TACAMO EC-130 aircraft were evaluated by comparison of transient current measurements during inflight EMP illumination of the aircraft at the NSWC horizontal dipole facility at NAS Patuxent (EMPSAC) both before and after installation.

Field strengths on the order of 3 kV/m were experienced directly over the pulser at 500 feet above sea level. The wave form of the incident field contains a null due to reflection of the primary pulse from the ground.

The data obtained from the test support the concept of flight testing for comparative purposes. The reflected wave problem was not serious in that the spectral amplitude at the notch and its higher harmonics did not go to zero because of 1/r attenuation and ground losses.

EC-130 SCALE MODEL EM RESPONSE MEASUREMENTS

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ABSTRACT

Much of the information about the EM and consequently EMP response of an aircraft can be obtained from measurements using small scale versions of the target. Such measurements are capable of providing the desired data at the fraction of the cost of the corresponding full scale measurements, and have the added advantage of being performed in a carefully controlled EM environment. It is therefore possible to produce the precise characteristics of the illumination, as regards direction of incidence and polarization, and to simulate either a free space situation or a case of nearby lossy or perfectly conducting ground.

Over the last three years we have, at The University of Michigan, made measurements on scale models of EC-135, E-4, F-111 and are presently making measurements on EC-130 (TACAMO) and E-3A (AWACS) models. Although to some extent measurements have almost become a routine, we are continuously updating our measurement capabilities, especially as regards the accuracy of the data and the frequency coverage. A description of the surface field facility is presented, including the anechoic chamber, the new 20:1 bandwidth illuminating antenna, the sensors used and the analog and digital instrumentation. The facility is operated over 225-4250 MHz range and when using, for example, 1:100 scale models, a 2.25-42.5 MHz full scale coverage is achieved.

Sample measurements are presented for simple shapes such as spheres and cylinders, but most data is presented for the EC-130 aircraft covering 1.5-59.0 MHz.

COMPARISON OF SCALE MODEL MEASUREMENTS WITH EMP FIELD TEST DATA FOR THE TACAMO C-130 AIRCRAFT

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ABSTRACT

In a recent EMP simulation test of the TACAMO C-130 aircraft performed at the Air Force Weapons Laboratory Horizontally Polarized Dipole (HPD) Facility, skin current and charge density measurements were made at six locations on the fuselage, wings, horizontal and vertical stablizers. Also, the University of Michigan Radiation Laboratory obtained charge density and skin current data at corresponding locations on C-130 scale models. These scale model measurements have been extrapolated via Fourier analysis and compared to the responses obtained in the field test at HPD.

Field test measurements, data acquisition and reduction processes are described, and results are presented in time and frequency domains.

SURFACE CURRENTS AND CABLE VOLTAGE INDUCED BY HARMONIC ELECTROMAGNETIC WAVES INCIDENT ON AN AIRCRAFT

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Abstract

Results of measurements of surface currents induced on aircraft "Draken" by vertically polarized, harmonic electromagnetic waves of frequencies 773 kHz and 10.09 MHz are reported and shown to be in good agreement with simple theoretical estimates. The separation of the current in a circulating an a capacitive part and its concentration to edges are discussed, and an equivalent network is used to analyse the influence of grounding the aircraft, as well as impedance measurements in an opened grounding wire.

The relative antenna height (relative modulus of induced voltage divided by strength of incident electric field) was measured for a cable inside an aircraft, as a function of frequency in the range 2-18 MHz, and the resulting voltage waveforms are determined for an assumed high-altitude EMP pulse and a few assumed functions describing the variation of the phase with frequency.

ABSTRACT

COMPARISON OF MEASURED AND CALCULATED EXTERNAL COUPLING

DATA FOR THE EC-135

by

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This paper presents some comparisons between calculated and measured external coupling data from the EC-135 program. Measurements from the ACHILLES II (SRF) simulator and from the scale model experiments will be included. Data will be presented for free space and ground based configurations. The effect of the HF wire antennas will be considered.

ABSTRACT

Results of the AFWL/TACAMO Experimental Program

BY

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AND

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This paper presents some results of an experimental program with the object of obtaining the EMP response of the TACAMO aircraft. These experiments included exterior measurements of current and charge densities using the ATHAMAS I (HPD) to excite the aircraft as well as scale model measurements, interior measurements, and measurements on the VLF/LF antenna during a flyby of the ACHILLES I (VPDI). Time and frequency domain data plots will be presented together with a discussion of the measurement techniques used.

Surface Field Measurements on Scale Models in the Time Domain *

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A series of time domain experiments involving EM interactions with scale model cylinders, crossed cylinders, and a 1/100 scale 747 aircraft have recently been completed at the Lawrence Livermore Laboratory's Transient Electromagnetic Range for the Air Force Weapons Lab. The induced transient surface current and charge densities due to a 330 psec. wide EM impulse were measured at several locations using miniature field probes developed by AFWL. Measurements were made for the models in free space and in the pressure of a near-by perfectly conducting ground plane.

The experimental techniques used in making these scale model tests, the associated processing equipment, and the problems encountered in making these measurements will be discussed in this paper. Results are analyzed in both the time domains and the frequency domains which show how the response of the models change as they approach a perfect ground plane.

The complex natural frequencies in the responses are also evaluated in order to examine their migration in the complex frequency plane as a function of the ground plane proximity. These results are compared with previously reported numerical results.

* This work was performed under the auspices of the U.S. Department of Energy under contract #W-7405-ENG-48.

"EMP - AN ULTRASONIC SIMULATION?"

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Ultrasonic simulation of electromagnetic radiation propagation and scattering has been successfully carried out for the last two decades. Pulse and CW signals have been employed in radar cross-section and glint work. Impulse response has also been simulated. This leads one to suggest that electromagnetic pulse and its related effect of induction of surface currents, on the air frames or enclosures of electronic system, and the subsequent interference and malfunctioning of such systems can indeed be simulated in controlled laboratory environment at 10 to 25 percent the cost of, and in less than 30-40 percent of the time, required for actual full scale or model electromagnetic simulation. Surface wave phenomena on air frames, ground effect of the fuselage, and shadow effects have been successfully simulated for both horizontal and vertical polarization. This further supports the above premise that ultrasonic underwater simulation of EMP is indeed a real attractive technique and is worth a try since every other technique is more expensive, time consuming and only approximate whereas ultrasonic simulation would be an exact analog simulation of the full scale case.

EMP RESPONSE OF AN HF ANTENNA BY USING MEASURED TRANSMIT PROPERTIES OF THE ANTENNA*

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The transmit characteristics of an antenna give all the information needed for the determination of its receive properties provided that certain conditions are met on the load and generator.[1] This reciprocity between transmission and reception applies to antennas in free space, and we show experimentally that it can be extended to electrically long antennas in the presence of a finitely conducting ground.

We measured the radiated CW field from a ground-based, vertically-polarized HF antenna over the operating frequencies of the antenna. We use this measured transmit property to compute the transient response of the log-periodic antenna and show excellent agreement with the measured transient response.

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*This work was funded by Defense Nuclear Agency Program under Subtask G37KAXEX475.

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AIRCRAFT HF ANTENNA RESPONSE IN HPD/VPD

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ABSTRACT

HF antenna measurements made during the TEMPAT I test in HPD/VPD showed characteristic signatures attributable, in part, to non-linear electrical surge arrestor (ESA) response. Significant correlations exist between antenna-related measurements made in different test configurations that also appear, in some cases, in internal cable response data. This observation may be of value in planning tests on other aircraft systems, interpreting test data, in evaluating HF antennas as points-of-entry and in developing methods of hardening antennas.

RESPONSES OF THE HF FIXED-WIRE ANTENNAS ON THE E-4 AND EC-135 AIRCRAFT

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In calculating the response of the HF fixed-wire antennas on the E-4 and EC-135 aircraft, it is necessary to account for coupling with the currents and charges on the aircraft surface, since the external aircraft resonances occur within the same frequency regime as the resonances of the antenna. The aircraft bodies are modeled as conjunctions of thin sticks which, while not very detailed models, nevertheless exhibit the overall resonance behavior of the aircraft. The HF antennas themselves are modeled as transmission lines driven against the aircraft fuselages. Analytical expressions are obtained for the effective heights and the input impedances of the antennas as functions of frequency. These results are used to find analytical expressions in the time domain for the open-circuit currents and short-circuit voltages induced on the HF antennas by a typical high-altitude nuclear electromagnetic pulse (EMP). Sample calculations are presented for both aircraft and for several angles of incidence of the EMP. It is found that (1) coupling between two HF antennas is very weak, (2) the input impedance is completely dominated by the transmission line formed by the antenna wire and the fuselage, and (3) the aircraft resonances have only a slight effect on the antenna responses.

EMP RESPONSE OF AN AIRCRAFT WITH A TRAILING WIRE ANTENNA DEPLOYED

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The surface currents and charges due to an incident EMP are found on a 747 aircraft with a VLF/LF dual trailing wire antenna deployed. The antenna consists of two wires trailing behind the aircraft. One wire trails straight out from the aft end of the fuselage up to a kilometer in length and the second wire is attached to the bottom of the fuselage, trails about 7 degrees below the first and is up to about 8 kilometers long. The method of solution involves a modification of a detailed method-of-moments solution of a wire grid model of the aircraft by combining it with a transmission line solution for the trailing wires. The solution thus preserves the details of the aircraft geometry and its connection with the trailing wires. The paper shows the details of solution and presents some typical results in both the frequency domain and time domain for an incident EMP.

TRANSIENT RESPONSES INDUCED ON A LOG-PERIODIC ANTENNA BY AN ELECTROMAGNETIC PULSE *

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EMP coupling to a Log-periodic (LP) antenna can be quite significant when the operating frequency range of the antenna is within the principal EMP frequency spectrum. Previous analysis of properties of LP antenna was conventionally carried out in the frequency domain using either a circuit-and-array approach[1] or a wave-propatation approach.[2] A recent computer modeling of LP antenna has also been reported.[3] It appears to be difficult to use these methods to analyze the problem when the LP antenna is immersed in a time-varying medium. In this paper, a time domain approach is introduced that may be used for the transient analysis of antenna arrays. The method has been applied to calculate the induced response of a six-element LP antenna(designed for operation in the frequency range of 30 to 76 MHz) to an incident EMP. The numerical results are compared with those reported in reference 3 and the measured data reported in reference 4.

The approach to the problem is outlined as: 1) the exterior problem, which is concerned with the coupling between antenna elements, is treated by using a modified two-dimensional finite difference technique to solve Maxwell's equations in space. Utilizing appropriate boundary conditions, the multiple scattering effects are included at each time cycle; 2) the interior problem, which is concerned with the coupling through the transmission line, is treated by solving the familiar two-wire line equations in the time domain, with the antenna elements as discrete loads; and 3) the interior and exterior coupling are related by making use of Kirchhoff's current and voltage laws at the antenna-transmission-line junctions. The load to the LP antenna is also included in this manner.

The numerical results calculated using present analysis are seen to agrre quite well with that calculated by a different method,[3] and the measured data given in reference 4.

It is easy to generalize the method reported here to calculate the transient response of LP antenna in a time varying medium. Antenna arrays other than LP structure can also be analyzed using this method.

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*Work sponsored by Harry Diamond Laboratories, Adelphi, MD., under contract DAAG-39-77-G-0178.

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RESPONSE OF SCATTERERS IN COMPLEX ENVIRONMENTS

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Most EMP predictions are for isolated objects. In many cases such predictions are sufficient for EMP hardening purposes. The question often arises, however, as to how the response will change if the object in question is placed within an environment that contains many other objects (scatterers) that are randomly positioned within a volume of interest. There is then the possibility that a certain amount of enhancement of the EMP induced currents and voltages on the object might ensue. One will be interested to know the degree of enhancement and the associated probability. In order to study these effects, a simple experiment was performed at the Transient Range at LLL. The receiving properties of a monopole were evaluated in the immediate vicinity of randomly placed monopoles of similar dimensions. The results from this experiment were deemed to be of interest because of their applicability to treating--for example--whip antennas on ships, antenna arrays next to ground communications facilities, and to antenna arrays on planes and missiles.

A 40.cm long monopole was placed in the center of 1 m x 1 m grid. The response of this monopole is measured as N other monopoles are randomly placed on the grid. For each N, 20 repetitions of random placements were performed. The set-up was illuminated with a vertical E-field of 100 psec rise time and 300 psec width at half-max.

From this rather initial experiment, some tentative conclusions can be drawn. In general, some enhancement of EMP induced energy levels in receptors is to be expected when such a receptor is placed within a cluttered area; however, the probability of such an occurance is low. In fact, the probability of enhancement decreases as the number of scatterers increases. The mean value, on the other hand, is found to drop monotonically as the clutter around the receptor is increased. The variance of the response also decreases as the number of scatters increases. These findings seem reasonable since a random collection of non-intentional energy receptors (non-intentional antenna), as might be found around a complex ground station, would not be expected to be an efficient antenna array for the EMP.

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*This work was performed under the auspices of the U.S. Department of Energy under contract #W-7405-ENG-48 and sponsored by DNA Subtask R99QAXEB088, Work Unit 76: Experimental Coupling Model Verification for Generic Structures.

SOME OPEN QUESTIONS IN OPEN WAVEGUIDE PROBLEMS

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Open parallel-plate waveguides are often used as EMP simulators, and an understanding of the excitation of fields in such waveguides is helpful in designing these simulators. The conventional approach for representing the fields in open structures is in terms of an integral over the continuous spectrum. Such an integral typically runs along the branch cut of the integrand of the Fourier transform representation for the fields, and may be extremely time-consuming to evaluate numerically. This fact has prompted many researchers to investigate the possible use of highly efficient, leaky-wave representation for the field expansion. A systematic procedure for converting the original continuous spectrum representation for the field in an open waveguide into a series expansion of leaky-wave modes has been discussed in a number of publications, including a text by Collin. However, the continuous spectrum representation for an open, parallel-plate waveguide comprises an infinite number of branch cuts, as opposed to a single one for the dielectric slab waveguide discussed in Collin.

Consequently, for the open waveguide case, it becomes necessary to critically examine the problem of making the best possible choice between the infinitely many possibilities for wandering in and out of upper and lower Riemann sheets, corresponding to the infinite number of branch cuts in the spectral representation. A thorough understanding of this problem is a prerequisite for computation of the leaky-wave poles in the appropriate Riemann sheets. In this paper, we address ourselves to this important question and present a systematic procedure for deforming the original path of integration for the continuous spectrum representation. We show exactly in which Riemann sheet we have to search for the leaky-wave poles and demonstrate that one of the seemingly obvious choices for the deformed contour is also the one that would lead to an erroneous result.

MEASURED ELECTRIC FIELDS IN A MODEL SIMULATOR

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An experimental study of the interior electric field of a model EMP parallel-plate, transmission-line simulator will be discussed. The dimensions of the structure are chosen to give a characteristic half-line impedance of 100 Ω. Archates Memo 1 cites a height to half-width ratio of $h/a = 1.2335$ and a height to length ratio of $h/b = 0.94$ for a 200 Ω full-line impedance, parallel-plate geometry [1]. The study is conducted at the single frequency $f = 626.5$ MHz which yields a ground plane to parallel plate separation of $kh = 4.5\pi$ for the model. These dimensions imply a frequency range in which simple TEM transmission-line theory does not apply.

Measurements of the electric field are conducted along the ground plane, the underside of the parallel plate, and throughout the three-dimensional region comprising the working volume. Diagrams of the surfaces of constant phase, magnitude, and the standing-wave pattern are being developed. Measurements of the induced current and charge densities on single and crossed thick cylinders in the simulator working volume are also being conducted. These results will be compared with current and charge densities on cylinders excited by an ideal plane wave (Kao theory) and by a nearly plane wave field (dipole and corner reflector).

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SPATIAL MODAL FILTERS FOR SUPPRESSSION OF NON-TEM MODES IN PARALLEL PLATE SIMULATORS

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CW measurements in the ALECS facility [1] have detected what has been referred to as the 'notch problem'. Specifically, the transfer function from source to field displays significant notches at specific frequencies, e.g., an order of magnitude dip in amplitude around 24 MHz. There appears to be some evidence to believe that this 'notch' is due to the excitation and propagation of non-TEM mode(s). It is interesting to note that the dispersion distance [2] calculations of the frequency of a non-TEM mode excitation is also about 24 MHz. All of these considerations point toward the need for a technique of suppressing the non-TEM propagating mode(s).

In this paper, we shall present a method of suppression in the form of a spatially distributed modal filter. The chief requirement of such a modal filter is that it should essentially be decoupled from the TEM mode and should load or damp the non-TEM modes. So, if one places resistors on a TEM equipotential surface [3,4] along the axial and transverse directions, such a 2-dimensional array will have minimal effect on the TEM mode. However, for the TE modes, some of the transverse field couples to the transverse resistors and in the case of TM modes, the axial component of the electric field couples to the axial resistors and some of the transverse electric field couples to the transverse resistors. Initially, one may think of locating such a mode filter in the output section, not too close to the terminator, since non-TEM modes are evanescent there. It is also desirable for such a mode filter to be away from the working volume to avoid its coupling with the objects. An implicit problem in this context is the identification of the presence of non-TEM modes in the available experimental data. Finally, it is to be emphasized that such a filter has more experimental potential than analytical.

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Self-Consistent Formulation of Scattering Problems in a Simulator Environment

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Many electromagnetic diffraction problems involve composite configurations that comprise the scatterer per se and perturbing environmental effects. Examples are provided by a scatterer placed in a parallel plane waveguide, as in a simulator, or on or near a ground surface. In most instances, it is easier to calculate the scattering properties of the object in isolation than to deal with the composite geometry. Under these circumstances, it is desirable to formulate the overall scattering problem in a manner that exhibits separately the unperturbed problem and then furnishes corrections by self-consistent interaction with the perturbing environment. A general Green's function formalism to this end is reviewed[1]. It involves the self-consistent combination of the unperturbed Green's operator and an interaction operator. Specific application is then made to the low-frequency scattering by an obstacle placed inside a waveguide environment such as a simulator. Diffraction by the obstacle in free space can be characterized in terms of induced electric and magnetic dipole and higher order multipole moments, which are corrected self-consistently by accounting for interaction with the induced currents in the waveguide walls[2]. As an illustrative example, results are presented for a spherical obstacle inside a rectangular waveguide.

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A SIMPLE TECHNIQUE FOR OBTAINING THE NEAR FIELDS OF ELECTRIC DIPOLE ANTENNAS FROM THEIR FAR FIELDS

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A procedure has been developed which yields the near field electric and magnetic components of an axially and lengthwise symmetric electric dipole if the far field components of the same are known. In particular, it has been shown that if E_{f_θ}, i.e., the θ component of the far field is known, all other components of the electric and magnetic fields including their near fields can be determined. This procedure is shown to have been applicable both in time and frequency domains. In frequency domain the near field components can simply be obtained by integrating the far fields with respect to time.

An example involving the fields of a resistively loaded dipole antenna driven by a step function generator is discussed.

The Analysis of Loaded Antenna Structures

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It is common to use resistive loading for wave shaping and for damping out waves reflected from structure discontinuities on EMP simulators. This paper reports on recent work in determining the natural frequencies and modal current distributions for biconical antenna structures. Both loaded and unloaded structures are considered.

A recent analysis [1] of a biconical simulator has shown that the use of discrete loading to approximate continuous loading can introduce effects not predicted by the uniform loading model. It is thus desirable to introduce the lumped loading model at the outset in the design of such simulators. To this end, a characteristic equation for a loaded structure with point loading is derived in terms of the poles and modal currents of the unloaded structure. It is anticipated that this result may make tractable the multi-variable problem of analyzing a structure with many discrete loads chosen to simulate continuous loading. It is hoped that some insight will also be gained into the synthesis problem of using loading to obtain the desired frequency characteristic.

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THE AFWL VERTICALLY-POLARIZED DIPOLE II (VPD-II) EMP SIMULATION FACILITY*

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EG&G recently completed the integration and checkout of the newest of the AFWL EMP simulators, the VPD-II. This facility, designed by EG&G based on the work of Baum in Sensor and Simulation Note 81 and Baum and Kehrer in ATHAMAS Memo 4, consists of a resistively-loaded conical antenna over a ground plane. The antenna is driven by a five-million-Volt marx generator built by Physics International. A 100-meter diameter area for parking aircraft to be EMP tested is centered 100-meters from the antenna apex. Pulser control and reference sensor data recording are accomplished in a van with internal shield room which is parked in a below-ground bunker to eliminate scattering of the fields into the test area. Room is also provided in this bunker for the data recording van (DASET).

This paper describes the theoretical basis for the antenna design, the calculated currents and voltages on the antenna, the mechanical design features of the facility, and general facility aspects. (Field mapping data are presented in another paper.)

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CHARACTERISTICS OF VERTICALLY-POLARIZED DIPOLE ANTENNAS*

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Since 1970, three resistively loaded vertically-polarized dipole (VPD) EMP simulator antennas have been designed, built, analyzed, and measured by EG&G for the Air Force Weapons Laboratory (VPD-I and VPD-II) and the Naval Surface Weapons Center (NAVES-II). Sensor and Simulation Notes 81 and 213 by Baum and Singaraju provide the basic analytic tools for analyzing antennas of this geometry. EG&G has extended these analytic tools to more closely match the as-built facilities and used them to prepare waveform predictions at several locations. To evaluate these predictions, electric and magnetic field measurements were made at the same or similar locations in the real facilities.

Comparison of predicted and measured waveshapes shows good agreement and confirms that fields generated by resistively-loaded conical antennas over a good ground plane are predictable and well-behaved.

This paper presents an overview of the analytic and experimental techniques, typical predicted and measured waveforms, and conclusions concerning these three vertically-polarized dipole facilities.

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Comparison of Four Treatments of Space-Charge Limiting*

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A comparison is made of four different methods of treating space-charge limiting for satellite structures. The test object is a simple cylinder, 1-m in diameter and 0.75-m in length, exposed end-on to a 2 shake pulse of 5 keV blackbody X rays under conditions resulting in high space-charge limiting. All calculations are performed with the two-dimensional SGEMP code, MAD2; results are characterized in terms of the radiated electric field at a distance of 1-m from the cylinder.

The first calculation is a brute-force treatment, i.e., the usual particle method with a very fine spatial mesh near the cylinder. This result establishes a standard against which the approximate methods can be evaluated. The dipole method makes use of a planar one-dimensional calculation to obtain a prescribed source. Using this method, calculated radiative fields are too low at the peak by a factor of two, and are characterized by ringing at late times. The other two methods are based upon the adiabatic approximation. In the ordinary boundary layer method, the steady-state, half-cell voltage is used to suppress creation of low-energy electrons. For the large mesh size chosen, this method also gives a radiative result too low by a factor of two. In the dynamic boundary layer method, the half-cell voltage is coupled to the electromagnetic algorithm. This method gives good agreement with the brute-force results after dipole saturation; at early times, a large overshoot results from the adiabatic assumption.

Comparisons are made of the accuracy, cost, and difficulties associated with each of the methods. Improvements to the dipole and boundary layer methods are suggested, and implications for three-dimensional calculations are summarized.

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†Work performed while at Science Applications, Inc.

Analytical Electrical Models of Dual-Spun Satellite Interiors for Mode Prediction

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In trying to understand some of the internal data taken during the recent SKYNET current injection tests, and the associated photon experiments, it became evident that some simple analytic basis was necessary. The data clearly shows the internal fields and currents to be oscillating in time at specific frequencies. This leads one in a rational way to view internal responses of satellites—in particular the SKYNET satellite—in terms of modes of the specific satellite structure.

Here we present the steps we took toward understanding the internal electromagnetic characteristics of satellites in terms of simple analytic modal models. Our discussion will be restricted to the first few modes for axisymmetric excitations of dual-spun-like structures. The method of analysis will be to begin from very simple, relevant structures and then increase the structural complexity. Some of the satellite structures discussed are not completely closed electromagnetically, but contain gaps which allow the interior of the satellite to communicate with the exterior. The areas of these gaps are small, however, in comparison with the total area of the structure. As a consequence radiation energy losses from the interior of the satellite to the exterior are small for all the internal modes reported. The internal responses are therefore manifested as practically undamped oscillations. This internal situation can be contrasted with an analysis of the currents on exterior structures where radiation damping can be appreciable. These gaps and interior struts and panels essentially load the internal structure of the satellites giving rise to modal frequencies that can be appreciably lower than one might expect from the cavity dimensions alone.

Most of the analysis of these lower frequency modes can be made using simple lumped parameter circuit models. Detailed lumped-element modeling has been used in the past[1] to determine internal peak currents in SKYNET but the elements giving rise to the characteristic modes were not investigated. Loaded transmission line models, however, appear to more accurately represent the physical situation. In many cases the accuracy of the lumped parameter models in predicting the resonant frequencies can be estimated by a comparison of the gap capacitance with the internal distributed capacitance. The TOM2D finite difference code was used to validate the analytical models. In addition, the analytical predictions are compared against actual SKYNET current injection test data.

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PIMBS-II *

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The AFWL is sponsoring development of a low-level photon source for System Generated EMP (SGEMP) effects investigations of space systems. The source employs a 4 module Marx generator with peaking capacitors feeding unique reflection converter X-ray diodes through low inductance output switches. Each module is capable of delivering 1.25 MA peak current to the diode resulting in 110 KV peak accelerating potentials. The system generates a 350 joule radiation pulse of 65 nsec pulse width and 30 nsec rise time. Total conversion efficiencies of 0.6% are attained from 60KJ stored energy and 45KT electron beam energy.

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Equivalent Surface Currents
And Their Possible Use for SGEMP Simulation

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Abstract

Recently [1,2] some of the practical aspects of the DIES [3] concept have been examined. One result [2] is that several electric dipole positions are needed for accurate simulation.

In this paper, consideration is given to replacement of the bulk of the external environment by an equivalent electric surface current layer [4]. It is demonstrated that a magnetic layer is not required. Also, it is shown that the current layer is determined entirely by charge motion exterior to the layer.

Results are given for a circular cylinder with a specific volume current distribution.

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CURRENT TRANSPORT IN A DIELECTRIC LINED CAVITY*

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An electron beam was injected into a 30 x 15 cm cylindrical aluminum cavity evacuated to a pressure of 0.1 μm. Dielectric materials 0.3 cm thick (>> electron range) covered the side walls of the cavity. The electron beam was uniform to 20% over 730 cm^2, current density 18 amp/cm^2, mean energy 77 keV. With a dielectric lining the cavity current transported through the cavity increased by a factor of five. Current risetime decreases by a factor of 2.8 indicative of a threshold phenomena.

Results of experiments and theoretical predictions imply that a plasma is released by the dielectric irradiated at an average 10^{-3} cal/cm^2. This plasma may be produced by the non linear heating of a released gas layer over the surface of the dielectric by fields near 1.5×10^6 v/m.

* Work supported by AFWL

+ Currently employed by Jaycor, Del Mar, CA.

++ Work performed while at Science Applications, Inc.

SGEMP RESPONSE
OF
AN X-BAND WAVEGUIDE

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On a spacecraft waveguide connections between an antenna and a receiver or transmitter are generally considered to be adequate for protecting the internal electronics from SGEMP fields generated on the external surfaces. This paper provides an estimate of the SGEMP seen at a load which is produced by the direct interaction of the photon flux with the waveguide walls. The analysis indicates that a differentially induced signal can be produced in the waveguide itself. This signal, with the bulk of its spectrum above the waveguide cut off frequency, can propagate to a load at either end of the waveguide. The model calculations are normalized to a fluence of one calorie per square centimeter. The peak power delivered to the load is $\sim$ 3000 watts. The total energy is $\sim$ 4 microjoules. The power and energy scale as the square of the fluence.

AIR PRESSURE DEPENDENCE OF PHOTON INDUCED CABLE RESPONSE*

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A wide selection of coax, pair and multiconductor cables was exposed to photon pulses from PIMBS I-A and CASINO. The response of all cables irradiated in vacuum could be explained by electron motion across gaps[1]. The sign of this signal was negative, corresponding to gaps, between shield and insulator, in all cables except RG62, which has a deliberate gap around the center conductor.

At atmospheric pressure the current was larger and mostly of opposite polarity. The magnitude tended to decrease with successive pulses, remained smaller after one-week undisturbed storage, and was augmented by mechanical flexing. The current appeared largest at ~ 100 torr pressure in most cables as expected from air conduction in ionized air. All these features agree with a model in which preexisting trapped charge is neutralized by air conductivity[2,3]. This model does not explain the sign and the relatively large value of the current after many pulses, including exposures at ~100 torr in which an asymptotic response is seen after one pulse.

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*This work performed under AFWL Contract F29601-77-C-0102.

THE EFFECT OF DIELECTRIC CHARGING ON THE SGEMP RESPONSE OF SPACECRAFT

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The SGEMP response of a satellite can be strongly influenced by initial charging produced by the natural electron environment or artificial electron environment associated with a nuclear burst. The satellite can be charged as negatively as an entity by the lower energy portion of the environment (Ref. 1), in which case the electrons emitted by x rays can be accelerated from the object. The satellite can also be differentially charged by higher energy electrons which penetrate spacecraft dielectrics and become imbedded in the dielectrics (Ref. 2). The differential charging can produce large static fields which can severely perturb the trajectory of electrons emitted by the x rays and, therefore, perturb the x-ray response. This effect is particularly severe for SGEMP responses within the spacecraft. Finally, the x-ray pulse could conceivably cause a spontaneous release of stored charge during or after the x-ray pulse.

The purpose of this paper is to explore perturbation in the SGEMP response caused by differential charging. Calculations have been performed which describe the build up of charge in dielectric within the spacecraft interior resulting from both the natural and nuclear electron environments. The resulting static fields are used as initial conditions in SGEMP response calculations for selected geometries to quantify perturbation in the SGEMP response resulting from the differentially charged dielectrics. Effects of x-ray fluence, spectrum and time history are explored. The 2-D SGEMP code ABORC is used to perform the response calculations (Ref. 3).

Finally, calculations are performed in which a dielectric within an enclosure is initially uncharged and is allowed to charge as a result of electrons emitted by the x-ray impacting on the dielectric. Perturbations in the x-ray response resulting from the presence of the dielectric liner are explored.

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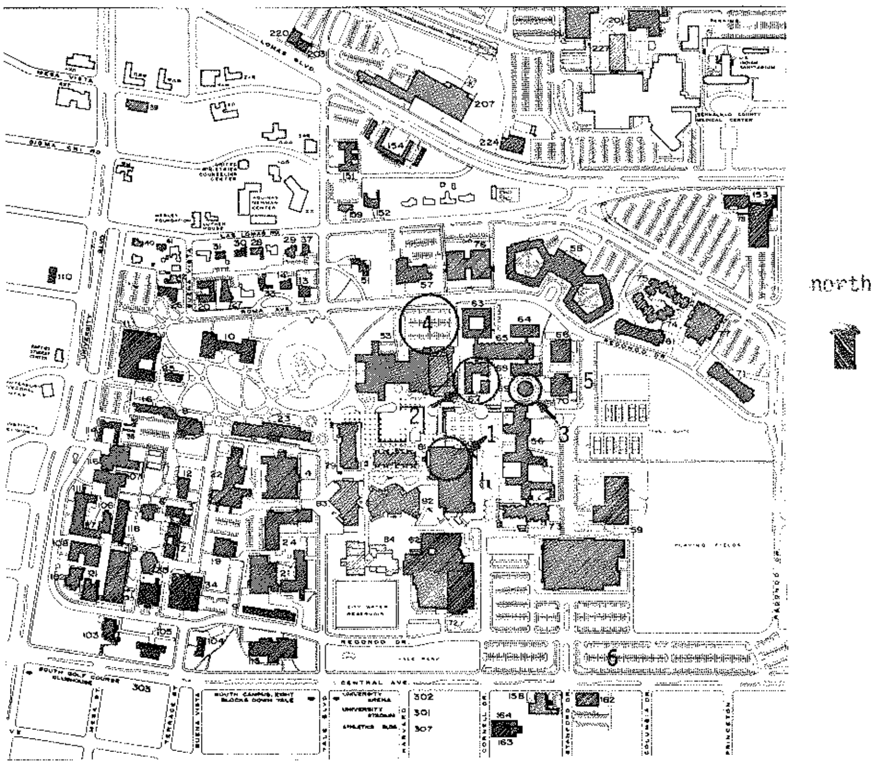

Legend:

1 - New Mexico Union-Plenary Session
2 - Education Classroom Building--All other technical sessions, registration, and information
3 - KIVA for gathering of tired feet
4&5 - Parking Lots