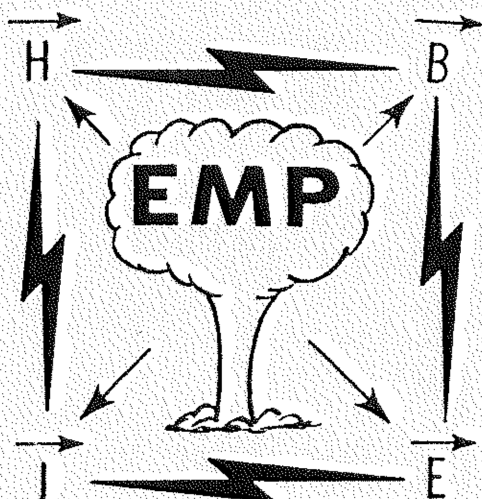
NEM 1980 RECORD

ABSTRACTS OF TECHNICAL PAPERS

Nuclear EMP Meeting
August 5 – 7, 1980

Disneyland Hotel, Anaheim, California



IN COOPERATION WITH THE FOLLOWING ORGANIZATIONS

THE INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS INC

ANTENNAS AND PROPAGATION SOCIETY

ELECTROMAGNETIC COMPATIBILITY SOCIETY

LOS ANGELES COUNCIL

THE U.S. NATIONAL COMMITTEE OF THE INTERNATIONAL UNION OF RADIO SCIENCE (USNC/URSI)

COMMISSION B: FIELDS AND WAVES

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THE ELECTROMAGNETICS SOCIETY

AND THE FOLLOWING GOVERNMENT AGENCIES:

HARRY DIAMOND LABORATORIES (ARMY)

NAVAL SURFACE WEAPONS CENTER

AIR FORCE WEAPONS LABORATORY

DEFENSE NUCLEAR AGENCY

TUESDAY 5 August 1980	WEDNESDAY 6 August 1980	THURSDAY 7 August 1980
0830 - 1130	**0900 - 1200**	**0830 - 1200**
HA-1 Panel On: Future EMP System Hardening Requirements South Ballroom	P-1 Plenary Session South Ballroom	ST-1 System Test and Analysis South Ballroom A
IN-1 Apertures North Ballroom A		AS-1 Assessment North Ballroom B
		IN-4 Antennas South Lounge
		IN-5 General Considerations & IN-6 Shielding North Ballroom A
1130 - 1330 Luncheon Center Ballroom		
1330 - 1700	**1330 - 1700**	**1330 - 1700**
HA-2 Panel On: System Hardening Approaches South Ballroom	HA-3 Panel On: EMP Design and Testing of Tactical Systems South Ballroom	HA-4 System Level and Component Hardening Techniques South Ballroom
SI-1 Parallel Plate Simulators and Miscellaneous Simulation North Ballroom B	SI-2 Localized Excitation and Source Region Simulation North Ballroom B	AS-2 Extrapolation North Ballroom B
IN-2 Transmission-Line Networks North Ballroom A	IN-3 Singularity Expansion Method North Ballroom A	IN-7 Cables North Ballroom A
EN-1 EMP and Lightning South Lounge	EN-2 SGEMP South Lounge	MT-1 Measurement Techniques South Lounge
1700 - 1900 No-Host Cocktail Party Magnolia C	**1700 - 1900** No-Host Cocktail Party Center Lounge **1900 BANQUET** Center Ballroom	

WELCOME TO ANAHEIM

On behalf of the NEM 1980 Conference Committee, the Permanent NEM Committee, IEEE, URSI, EMS, and cooperating government agencies, I welcome all of you to the NEM 1980 Conference. The meeting offers over 125 papers, presented by over 50 universities, agencies and/or contractors from six different countries. We have tried to make it a broad-ranging conference covering the entire spectrum of nuclear Electromagnetic Pulse (EMP) technology and hope that all of you find it useful for your needs.

I would particularly like to thank the NEM 1980 Conference Committee for all the hard work they have done to make this conference a success, and the Permanent NEM Committee under Dr. Carl E. Baum, for their guidance, help and gentle nudging.

The goals of NEM are to provide cross-fertilization of ideas, to renew acquaintances, to summarize the state-of-the-art, and to suggest future approaches for EMP hardening, hardness assessment and hardness maintenance. We hope you will find these goals supported by the presentations and surroundings of NEM 1980.

Looking ahead into the 1980's, a special session has been set up for Tuesday morning on "Future EMP System Hardening Requirements" to suggest hardening requirements in the 1980's. Congressional Representative Robert K. Dorman (R-Calif) has also agreed to be our banquet speaker. We hope you can attend both, and find them interesting and helpful.

Other special sessions on System Hardening Approaches (Tues. aft), a Plenary Session (Wed. morn), Tactical Systems (Wed. aft) and System-Level Component Hardening (Thurs. aft) also deserve your special consideration.

This conference was designed for you. I hope you will find it productive and it will lead to better understanding among us, a more mature consensus, and an impetus to future work.

Last, but not least, I hope you enjoy your visit to sunny California. Welcome, again, to NEM 1980.

Gene E. Morgan
Gene E. Morgan
Conference Chairman

NEM 1980

In cooperation with the following IEEE organizations

- Antennas and Propagation Society
- Electromagnetic Compatibility Society
- Los Angeles Council

In cooperation with the U.S. National Committee of the International Union of Radio Science (USNC/URSI)

- Commission B: Fields and Waves
- Commission E: Interference Environment

In cooperation with the following government agencies

- Harry Diamond Laboratories (Army)
- Naval Surface Weapons Center
- Air Force Weapons Laboratory
- Defense Nuclear Agency

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TECHNICAL PROGRAM

TUESDAY MORNING
AUGUST 5, 0830 - 1130

0830 Panel on
FUTURE EMP SYSTEM HARDENING REQUIREMENTS
Session HA-1
South Ballroom

Chairman: Gene E. Morgan,
Rockwell International

A select group of invited panelists will each present their views concerning the future EMP system hardening requirements and associated technology. The forum will then be opened up to the audience for comments and questions.

The guest panelists will each present a paper on requirements in their area of interest, as follows:

1. 0830 Strategic Missiles, Lt. Col. Jerry Allen, Chief, Nuclear Hardness and Survivability Division, Ballistic Missile Office (BMO), Norton AFB, CA

2. 0845 AF Research, Mr. John Darrah, Senior Scientist, Nuclear Technology, Air Force Weapons Laboratory (AFWL), Kirtland AFB, NM

3. 0900 Navy Aircraft, Capt. Russ Davis, USN, TACAMO Project Office, Naval Air Systems Command (NAVAIR), Washington, D.C.

4. 0915 Command, Control and Communications (C^3), Lt. Gen. Hillman Dickinson, Joint Chiefs of Staff Director for C^3 Systems (Paper presented by Major Roger C. Carro), Washington, D.C.

5. 0930 Navy Ships EMP Overview, Dr. Kurt Enkenhus, Director Nuclear Effects Division, Naval Surface Weapons Center (NSWC), White Oak, MD

6. 1000 DNA Research, Mr. Paul Fleming, Defense Nuclear Agency (DNA), Alexandria, VA

1015 Break (15 minutes)

7. 1030 Strategic Aircraft, Col. Thomas R. Meyers, Deputy Director Strategic SPO, Wright-Patterson AFB, OH

8. 1045 Space Systems, Col. Robert A. Oliveri, AF Space Division, El Segundo, CA

9. 1100 Tactical Army Systems, Dr. R. A. Pfeffer, U.S. Army Research and Development Command, Harry Diamond Laboratories, Adelphi, MD

10. Panel Discussion and questions

APERTURES
Session IN-1
North Ballroom A

Chairman: Tommy Tong, TRW

1\. 0830 Quasistatic Electromagnetic Penetration of a Spherical Shell Through a Circular Aperture, K.F. Casey, The Dikewood Corporation, Albuquerque, NM

2\. 0850 Low Frequency Magnetic Field Coupling Through a Circular Annular Aperture, R.M. Searing, Rockwell International, Anaheim, CA

3\. 0910 Shielding Effectiveness of Metallic Honeycombs, W.A. Bereuter, Kaman Sciences Corporation, Colorado Springs, CO; and D.C. Chang, University of Colorado, Boulder, CO

4\. 0930 Numerical Method for Electric Field Penetration Through Apertures, D. Binder, Hughes Aircraft Company, Culver City, CA

0950 Break

5\. 1020 Electromagnetic Penetration Through Apertures in a Conducting Cylinder, J.W. Williams and L. Simpson, Mission Research Corporation, Albuquerque, NM; and E.R. Carroll, Naval Surface Weapons Center, White Oak Laboratory, Silver Spring, MD

6\. 1050 NEMP Field Penetration in Cylindrical Apertures, T. Ruedy, J. Bertuchoz, and B. Wamister, Swiss Armament Technology and Procurement Group Technical Division 8, AC-Laboratory CH-3752 Wimmis, SWITZERLAND

TUESDAY AFTERNOON
AUGUST 5, 1330 - 1700

1330 Panel on
SYSTEM HARDENING APPROACHES
Session HA-2
South Ballroom

Chairman: Lennart Marin
The Dikewood Corporation

This panel will address the EMP hardening approaches appropriate to strategic systems. Topics considered are shielding, device hardening, hardness maintenance and assurance, and hardness verification. After the opening presentations the forum will be opened to the audience for comments and questions.

SIMULATION-I
Session SI-1
North Ballroom B

A. Parallel-Plate Simulators
Chairman: Dan F. Higgins, JAYCOR

1\. Analyses of Standing Wave Minima in a Model Simulator, D.J. Blejer
1330 and R.W.P. King, Gordon McKay Laboratory, Harvard University, Cambridge, MA

2\. A Study of a Resistive Sheet Bifurcating an Infinitely Wide Two-Parallel
1350 Plate Line, K.S. Kunz and D.V. Giri, LuTech, Inc., Berkeley, CA

3\. Electromagnetic Characteristics of the ATLAS I EMP Simulator, R. Fisher,
1410 EMA, D.L. Endsley, EG & G, and C.E. Baum, AFWL, NM

B. Miscellaneous Simulation
Chairman: Edward F. Vance, SRI

4\. Horn EMP-Simulator with Non-Linear Profile, N. Berkane, B. Besnault,
1430 J.Ch. Bolomey, Laboratoire des Signaux et Systèmes (CNRS - ESE), Groupe d'Electromagnétisme, FRANCE

1450 Break

5\. More Precise Timing of EMP Generators Can Offer Important Benefits,
1520 W.F.J. Crewson and C.H. Jones, Jr., Pulsar Associates, Inc., San Diego, CA

6\. A Transient High-Voltage Source for Direct Injection of Threat-Level
1540 EMP Current on Cables of Army Tactical Equipment, R. Gray and J. Sweton, U.S. Army Electronics Research and Development Command, Harry Diamond Laboratories, Adelphi, MD

7\. Development of Energy Distribution Concepts as Related to Electro-
1600 magnetic Field Waveforms, W. Motil and F. Sterk, TRW, Inc., Albuquerque, NM

8\. Planewave Spectral Densities for the Near- and Far-Zone Waves of
1620 Annular Radiators, J.S. Yu, Sandia National Laboratories, Albuquerque, NM

TRANSMISSION-LINE NETWORKS
Session IN-2
North Ballroom A

Chairman: Werner Stark
Kaman Sciences Corp.

1. On the Use of Single Line Models for Predicting Transmission Line
1330 Responses, F.M. Tesche, LuTech, Inc., Berkeley, CA

2. Characterization of B-52 Aircraft Multiconductor Cable Network,
1350 A.K. Agrawal, Mission Research Corporation, Albuquerque, NM; and T.K. Liu, LuTech, Inc., Berkeley, CA

3. EMP Induced Aircraft Internal Pin Currents Using a Single-Line Approxi-
1410 mation for Cable Bundles, W.J. Stark and J. Daffe, Kaman Sciences Corporation, Colorado Springs, CO

4. Experimental Characterization of Partially Degenerate Three-Conductor
1430 Transmission Lines Using Time-Domain Techniques, A.K. Agrawal and H.J. Price, Mission Research Corporation, Albuquerque, NM

1450 Break

5. Comparisons of Predicted and Measured Cable Harness Responses in a
1520 Transient EM Environment, J.A. Sawyer, Computer Sciences Corporation, Albuquerque, NM; and F.M. Tesche, LuTech, Inc., Berkeley, CA

6. Excitation of Multiline Shielded Cables in Close Proximity to a
1540 Flat Earth, M.H. Tesler, Booz, Allen & Hamilton, Inc., Tinton Falls, NJ

7. Analysis of the Shielding Effectiveness of a Multi-branch Cable in a
1600 RAMS Test Configuration, Y-B Yu, Rockwell International, Anaheim, CA

8. Upper Bounds on Cable Signals, W.A. Davis, Virginia Polytechnic
1620 Institute and State University, Blacksburg, VA

EMP/LIGHTNING ENVIRONMENT
Session EN-1
South Lounge

A. EMP
Chairman: Chris W. Jones
The Dikewood Corporation

1. 1330 Source-Region Environment Representation for a Surface Burst, J. Lam, The Dikewood Corporation, Santa Monica, CA

2. 1350 A Simple Conductivity Model for Late-Time Surface-Burst EMP, W.A. Radasky and K.S. Smith, JAYCOR, Santa Barbara, CA

3. 1410 SC Late-Time Implicit Code (SLIC): Theory, K.D. Granzow, The Dikewood Corporation, Albuquerque, NM

4. 1430 SC Late-Time Implicit Code (SLIC): Code Description, D. Rieb, R. Asbury, and K.D. Granzow, The Dikewood Corporation, Albuquerque, NM

1450 Break

5. 1520 The Effect of Atmospheric Heave - Generated MHD/EMP on Commerical Wireline Systems, I. Kohlberg and H. Root, GTE Products Corporation, Communications Systems Division, Needham Heights, MA

6. 1540 Cartesian-Coordinate Three-Dimensional Source-Region EMP Code, M. Bushell, U.S. Army Electronics Research and Development Command, Harry Diamond Laboratories, Adelphi, MD

B. LIGHTNING
Chairman: Jack C. Corbin, ASD

7. 1600 A Comparison of Lightning and Nuclear EMP Environments and Their Interactions with Aircraft, R.A. Perala, Electro Magnetic Applications, Inc., Denver, CO; M.A. Uman, The University of Florida, Gainesville, FL; and E.P. Krider, Institute of Atmospheric Physics, The University of Arizona, Tucson, AZ

8. 1620 Continuous Lightning Long Arc Attachment Testing for Graphite Composite Skinned Aircraft Using a 150 kw Tesla Coil, R.K. Golka, Project Tesla, Wendover AFB, UT

9. 1640 Spherical Lightning Current Distribution Model of MECA, R.M. Searing, Rockwell International, Anaheim, CA

WEDNESDAY MORNING
AUGUST 6, 0900 - 1200

PLENARY SESSION
Session P-1
South Ballroom

Chairman: Carl E. Baum, AFWL

1. SGEMP Technology: A State-of-the-Art Review, J. Gilbert, Mission Research
0900 Corporation, Albuquerque, NM; and C. Aeby, AFWL, Kirtland AFB, NM

2. Evolution and Trends of EMP Interaction, K.S.H. Lee, The Dikewood
0930 Corporation, Santa Monica, CA; and J.P. Castillo, AFWL, Kirtland AFB, NM

3. Common Approach to the Design of Complex Electronic Systems, C.E. Baum,
1000 AFWL, Kirtland AFB, NM

1030 Break

4. Engineering for High Reliability EMP Hardness, W.J. Karzas, R & D
1100 Associates, Marina del Rey, CA

5. The Impact of EMP Programs on the Development of Electromagnetism,
1130 P.L.E. Uslenghi, University of Illinois at Chicago Circle, Chicago, IL

WEDNESDAY AFTERNOON
AUGUST 6, 1330 - 1700

Panel on
1330 EMP DESIGN AND TESTING OF TACTICAL SYSTEMS
Session HA-3
South Ballroom

Chairman: Roger Oats, AWRE

Many national EMP programs in Europe and North America are devoted to tactical rather than to strategic systems. The panel will comprise speakers from several countries discussing their approaches to such issues as hardening design, test facilities, and instrumentation. After the opening presentations, the forum will be open to the audience for comments and questions.

SIMULATION-II
Session SI-2
North Ballroom B

A. Localized Excitation
Chairman: Paul Fleming, Hq. DNA

1. 1330 Development of Portable EMP Injection Techniques, E. Carroll, L. Libelo, and D. Koury, Naval Surface Weapons Center, Dahlgren, VA; K. Kunz, Mission Research Corporation, Albuquerque, NM; and M. Weinert, NBC Defense Research and Development Institute, Munster, F.R. GERMANY

2. 1350 Techniques for Simulating the EMP Response of the VLF/LF Dual-Wire Antenna on the E-4B, L. Marin, The Dikewood Corporation, Santa Monica, CA; and C.E. Baum and J.P. Castillo, AFWL, Kirtland AFB, NM

3. 1410 Simulation of the EMP Response of the TACAMO Aircraft with the Trailing Wire Antenna Deployed, J.L. Monroe and E.F. Laporte, Rockwell International, Anaheim, CA

4. 1430 Quasi-Static Magnetic-Field EMP Simulator Design Study, K.D. Granzow, J.P. Martinez, and K.F. Casey, The Dikewood Corporation, Albuquerque, NM

1450 Break

5. 1520 Interaction of Test Object with Small Localized Simulator, L.W. Chen, LuTech, Inc., Albuquerque, NM

B. Source Region Simulation
Chairman: Ian Smith, ISI

6. 1540 Measurement and Interpretation of the Response of a Slow Wave Structure (The Helix) in the Mark I HDL Aurora Source-Region EMP Simulator, M. Bushell, R. Manriquez, G. Merkel, W. Scharf, and D. Spohn, U.S. Army Electronics Research and Development Command, Harry Diamond Laboratories, Adelphi, MD

7. 1600 Simulation of Long Linear Antennas with Short Loaded Antennas in a Medium with Time-Varying Air Conductivity, M. Bushell, R. Manriquez, G. Merkel, W. Scharf, and D. Spohn, U.S. Army Electronics Research and Development Command, Harry Diamond Laboratories, Adelphi, MD

8. 1620 HDL Source-Region Simulation Program: The New Mark II Simulator, M. Bushell, R. Manriquez, G. Merkel, W. Scharf, and D. Spohn, U.S. Army Electronics Research and Development Command, Harry Diamond Laboratories, Adelphi, MD

9. 1640 The Use of Gases Other Than Air as Media in a Source-Region Simulation Scheme, C. Kenyon, G. Merkel, W. Scharf, and D. Spohn, U.S. Army Electronics Research and Development Command, Harry Diamond Laboratories, Adelphi, MD

SINGULARITY EXPANSION METHOD
Session IN-3
North Ballroom A

Chairman: Frederick M. Tesche, LuTech, Inc.

A. Theory

1\. Analytic Determination of the Transient Response of Loaded Thin-Wire
1330 Antennas Based Upon a SEM Representation, A. Hoorfar and D.C. Chang, University of Colorado, Boulder, CO

2\. EMP Interaction of Two Arbitrarily Orientated Thin Cylinders, T.H.
1350 Shumpert and L.S. Riggs, Auburn University, Auburn, AL; and D.M. Schmale, U.S. Army Missile Command, Missile Intelligence Agency, Redstone Arsenal, AL

3\. SEM Analysis of an Infinite Periodic Array, D.H. Herndon, E.W. Smith,
1410 and E.J. Dombroski, Harris Corporation, Melbourne, FL; and T.H. Shumpert, Auburn University, Auburn, AL

B. Extraction of SEM Parameters from Data

4\. SEM Parameter Measurement, K.S. Cho, C.A. Lin, and J.T. Cordaro,
1430 University of New Mexico, Albuquerque, NM

1450 Break

5\. On the Source of Parameter Bias in Prony's Method, J.R. Auton and
1520 M.L. Van Blaricum, Effects Technology, Inc., Santa Barbara, CA

6\. EMP Data Correlation Techniques, G. Bedrosian and R. Christie, The
1540 Dikewood Corporation, Baltimore, MD

7\. An Improved Algorithm for Representation of Frequency-Domain Data by
1600 Rational Functions, H.J. Price, Mission Research Corporation, Albuquerque, NM

8\. An Unbiased Method for the Estimation of the SEM Parameters of an
1620 Electromagnetic System, J.R. Auton, Effects Technology, Inc., Santa Barbara, CA

9\. Parameter Estimation from Noisy Transient Electromagnetic Measurements,
1640 D.T. Gavel, J.V. Candy, J.E. Zicker, Lawrence Livermore Laboratory, Livermore, CA

SYSTEM GENERATED EMP
Session EN-2
South Lounge

Chairman: Jim Gilbert, MRC

A. ENVIRONMENT & INTERACTION

1. Effects of an Ambient Gas on SGEMP, W.E. Hobbs and D.E.M. O'Dean, JAYCOR,
1330 Santa Barbara, CA

2. SGEMP Electron Dynamics Near an Edge, J. Dancz and R. Stettner, Mission
1350 Research Corporation, Santa Barbara, CA

3. Electromagnetic Emission from Electron Beams, H.S. Cabayan, Lawrence
1410 Livermore Laboratory, Livermore, CA

4. Determination of the EMP and SGEMP Response of Cylindrical Scatterers
1430 by Network Analogs, W.R. Zimmerman and E.B. Mann, The BDM Corporation, Albuquerque, NM

1450 Break

B. TESTING

5. Qualification Model Spacecraft Test Considerations, E.P. Chivington and
1520 R.H. Kingsland, TRW Defense and Space Systems Group, Redondo Beach, CA; D.C. Mounkes, Computer Sciences Corporation, Albuquerque, NM; and C.A. Aeby, AFWL, Kirtland AFB, NM

6. Screening, Categorization, and Classification for Nuclear Assessment
1540 of Satellites Using NHEP-S, J.F. Hunka, M.L. Van Blaricum, and A.R. Hunt, Effects Technology, Inc., Santa Barbara, CA

THURSDAY MORNING
AUGUST 7, 0830 - 1200

SYSTEM TEST AND ANALYSIS
Session ST-1
South Ballroom

Chairman: Gerry K. Schlegel, RDA

1. Air Launched Cruise Missile EMP Analysis, S.W. Kormanyos and E.J.
0830 Quenemoen, Boeing Aerospace Corporation, Seattle, WA

2. Determination of POEs and Cable Excitation From E-3A EMP Dipole Test
0850 Data, L. Marin, The Dikewood Corporation, Santa Monica, CA

3. E-4B System Level EMP Test, W.L. Curtis, Boeing Aerospace Company,
0910 Seattle, WA

4. TEMPAT II, Hardening Verification of TACAMO, R.V. Whiteley, Rockwell
0930 International, Anaheim, CA

0950 Break

5. Air Launched Cruise Missile EMP Direct Drive Test, C.A. Rolfe, Boeing
1020 Aerospace Company, Seattle, WA

6. EMP Assessment of the PATRIOT Candidate 150 kW Mobile Electric Power
1040 Plant, R. Garver, U.S. Army Electronics Research and Development Command, Harry Diamond Laboratories, Adelphi, MD; S.A. Clark, Jr., Technology Development of California, Arlington, TX; and J. Washington, U.S. Army Electronics Research and Development Command, Harry Diamond Laboratories, Adelphi, MD

7. Air Launched Cruise Missile EMP Free Field Test, A.M. Smith and S.W.
1100 Kormanyos, Boeing Aerospace Company, Seattle, WA

8. Electromagnetic Pulse Prediction Capabilities, W.A. Rabke, DNA; B.B. Gage,
1120 Boeing Aerospace Company; and E.L. Arnold, G.E. Tempo.

ASSESSMENT
Session AS-1
North Ballroom B

A. Probabilistic Aspects
Chairman: Chris Ashley, AFWL

1\. Statistical Interpretation of Component Test Results in EMP Hardening
0830 and Vulnerability Assessment, W.R. Graham and C.T.C. Mo, R & D Associates, Marina del Rey, CA

2\. Aircraft Probability of Survival as a Function of the Response Distri-
0850 bution, R.S. Carter, Boeing Aerospace Company, Seattle, WA

3\. A Statistical Approach to EMP Coupling Within a Communication Facility,
0910 F.J. Agee, P.H. Dittmer, W.G. Parsons, and R.L. Rothrock, The BDM Corporation, McLean, VA

4\. Proof of a Generalized Locasso Conjecture, R.M. Bevensee, Lawrence
0930 Livermore Laboratory, Livermore, CA

0950 Break

B. Component Thresholds
Chairman: Robert Pfeffer, HDL

5\. A New Method of Calculating Damage Margins, J.V. Locasso, Rockwell
1020 International, Anaheim, CA

6\. Bounding EMP Damage Threshold Prediction Uncertainties, D.L. Durgin
1040 and R.S. Shoup, Booz, Allen & Hamilton, Inc., Bethesda, MD

7\. An Investigation of the Predictive Capability of the Junction
1100 Capacitance Damage Model for Semiconductor Device Transient Failure, M.J. Vrabel, U.S. Army Electronics Research and Development Command, Harry Diamond Laboratories, Adelphi, MD

8\. Computer Simulation of Second Breakdown in Silicon-on-Sapphire Diodes,
1120 A.L. Ward, U.S. Army Electronics Research and Development Command, Harry Diamond Laboratories, Adelphi, MD

ANTENNAS
Session IN-4
South Lounge

Chairman: David Merewether, EMA

1\. Application of NEC and NET-2 Codes to Antenna Response Uncertainties,
0830 L.C. Martin, R.M. Bevensee, E.J. Bogdan, and G.J. Burke, Lawrence Livermore Laboratory, Livermore, CA

2\. Currents Induced on a Bare Cable Inside a Missile, T.C. Tong, A. Sankar,
0850 and P. Parhami, TRW Defense and Space Systems Group, Redondo Beach, CA

3\. End Correction for Coaxially Driven Monopole, M. Morris, Sandia
0910 Laboratory, Albuquerque, NM

4\. Theoretical and Experimental Response Analysis of an Inclined Antenna
0930 in a Time-Varying Air Conductivity Environment, R.P. Manriquez, U.S. Army Electronics Research and Development Command, Harry Diamond Laboratories, Adelphi, MD

0950 Break

5\. Experimental and Theoretical Response of an Oscillating Loop to an
1020 Electromagnetic Pulse in a Medium with Time-Varying Air Conductivity, M. Bushell, R. Manriquez, G. Merkel, W. Scharf, and D. Spohn, U.S. Army Electronics Research and Development Command, Harry Diamond Laboratories, Adelphi, MD

6\. Broadband and Transient Analysis of the VLF/LF Dual-Wire Antenna on
1040 the E-4B, L. Marin, The Dikewood Corporation, Santa Monica, CA; and J.P. Castillo, AFWL, Kirtland AFB, NM

7\. Transient Corona Effects on Wire Over the Ground, K.C. Chen, AFWL,
1100 Kirtland AFB, NM

8\. Estimating EMP Coupling to Shipboard Antenna Systems, L.C. Martin,
1120 R.M. Bevensee, H.S. Cabayan, and F.J. Deadrick, Lawrence Livermore Laboratory, Livermore, CA

9\. A Simple Model of Very-Low-Frequency CW Corona Loss on a Two-Wire
1140 Transmission Line, M.R. Wilson, US Army Electronics Research and Development Command, Harry Diamond Laboratories, Adelphi, MD.

GENERAL CONSIDERATIONS
Session IN-5
North Ballroom A

Chairman: J.P. Castillo, AFWL

1. The Electromagnetic Coupling and Aperture Penetration Into Complex
0830 Missile Geometries, K. Umashankar and A. Taflove, IIT Research Institute, Chicago, IL

2. An Efficient Technique for Solving Quasi-Static Problems for Irregularly
0850 Shaped Regions, M.D. Bradshaw, AFWL/University of New Mexico, Albuquerque, NM

3. The Use of Simple Coupling Models for Comparing Various EM Effects on
0910 an In-Flight Missile, D.F. Higgins and K.S. Smith, JAYCOR, Santa Barbara, CA

4. NH & S and EMC EM-Integrated Requirements, B.A. Daiken, Rockwell
0930 International, Anaheim, CA

0950 Break

5. Suggested Experiments and Their Rationale, M.I. Sancer, R & D Associates,
1020 Marina del Rey, CA

6. MX Guidance and Control Electromagnetic Specification Approach,
1040 D. Still and G. Palmer, Rockwell International, Anaheim, CA

SHIELDING
Session IN-6
North Ballroom A

Chairman: Lou Libello, NSWC

1. Multi-Layered Shielded Enclosures with Particular Reference to Bonding
1100 Between Layers, K.S.H. Lee, The Dikewood Corporation, Santa Monica, CA

2. Penetration of Electromagnetic Fields into Shielded Rooms via Room
1120 Shields and Particularly via Cable Entries, J.L. ter Haseborg and H. Trinks, Hochschule der Bundeswehr Hamburg, GERMANY; and R. Sturm, Wehrwissenschaftliche Dienststelle der Bundeswehr für ABC-Schutz, Munster, GERMANY

3. EMP Coupling to the Internal Circuits of Missiles and Torpedoes Through
1140 Hull Section Joints, P.R. Miller, Marconi Space & Defense Systems Ltd., ENGLAND

THURSDAY AFTERNOON
AUGUST 7, 1330 - 1740

SYSTEM-LEVEL COMPONENT HARDENING TECHNIQUES
Session HA-4
South Ballroom

Chairman: John Darrah, AFWL

1. Topological View of EMP Hardness Testing, W. Graf and E. F. Vance, SRI
1330 International, Menlo Park, CA

2. A Comparison of TACAMO EMP Currents Before and After Hardening, J. V.
1350 Locasso, Rockwell International, Anaheim, CA

3. Air Launched Cruise Missile EMP Hardware/Software Design, C. A. Rolfe,
1410 R. J. Marett, and A. M. Smith, Boeing Aerospace Company, Seattle, WA

4. TACAMO, Lessons in the Practical Application of EMP Hardening, J. L.
1430 Monroe, Rockwell International, Anaheim, CA

1450 Break

5. EMP Hardening of NATO Communication Shelter, A. Kleckzo, Rockwell
1520 International, Anaheim, CA

6. Computer Simulation of EMP Protection Circuit Transients, K. L. Williams,
1540 McDonnell Douglas, Huntington Beach, CA

7. Spark Gaps and Metal Oxide Varistors as Limiters for Fast Varying
1600 Electrical Transients, O. Busmundrud, Norwegian Defense Research
Establishment, Kjeller, NORWAY

8. Effective Telecommunication Signal Line Protection from Lightning and
1620 EMP, O. M. Clark and J. J. Pizzicaroli, General Semiconductor Industries,
Inc., Tempe, AZ

9. A Binding-Post Surge Arrester, R. J. Prochazka, U. S. Army Electronics
1640 Research and Development Command, Harry Diamond Laboratories, Adelphi, MD

10. Aircraft Control Cable EMP Transient Suppression Devices, L. D. Scott,
1700 A. Agrawal, J. Barnum, MRC, Albuquerque, NM; and T. K. Liu, LuTech, Inc.,
Berkeley, CA.

11. Absolute EMP Limiter, P. J. Madle, TRW Defense and Space Systems,
1720 Redondo Beach, CA

12. Design Parameters for Hybrid Terminal Protection Devices, R. V. Garner
1740 and C. Fazi, U. S. Army Electronics Research and Development Command,
Harry Diamond Laboratories, Adelphi, MD

EXTRAPOLATION
Session AS-2
North Ballroom B

Chairman: Jim Locasso, Rockwell International

1. 1330 Scale Model Measurements, V.V. Liepa, University of Michigan, Ann Arbor, MI

2. 1350 Surface Field Measurements on Scale Models in the Time Domain, H.S. Cabayan and J. Zicker, Lawrence Livermore Laboratory, Livermore, CA

3. 1410 E-3A Dipole Test Program Data Extrapolation Techniques, G. Bedrosian, The Dikewood Corporation, Baltimore, MD

4. 1430 EMP Extrapolation Functions for the TACAMO C-130 Aircraft, E.E. O'Donnell and P. Setty, Science Applications, Inc., Colorado Springs, CO

1450 Break

5. 1520 Extrapolation of Simulation Test Data for Aircraft with Large Penetration Areas, W.J. Stark, Kaman Sciences Corporation, Colorado Springs, CO

6. 1540 Uncertainties in Extrapolating EMP Test Data Taken on One Aircraft to All Aircraft of the Same Type, D.E. Merewether, R.B. Cook, and R.W. Cox, Electro Magnetic Applications, Inc., Albuquerque, NM

CABLES
Session IN-7
North Ballroom A

Chairman: Byron Gage, Boeing Aerospace Company

A. Currents on Cables

1. Current Density on a Cylindrical Scatterer Above a Ground Plane,
1330 G.I. Hoffer, Kaman Sciences Corporation, Colorado Springs, CO

2. A Corona Model for Predicting the EMP Response of Insulated Cables,
1350 R.A. Perala and S.R. Rogers, Electro Magnetic Applications, Inc., Denver, CO

3. Dielectric Breakdown of Cable Jackets by High-Voltage, Fast-Risetime
1410 Pulses, C. Berkley and J. Sweton, U.S. Army Electronics Research and Development Command, Harry Diamond Laboratories, Adelphi, MD

B. Cable Shielding

4. Cable Shields with Periodic Bonding, F.C. Yang, The Dikewood Corporation,
1430 Santa Monica, CA

1450 Break

5. Computer Model and Impulse Current Injections for Optimum NEMP Hardening
1520 of Cables, C.C. Lin and M. Ianovici, Swiss Federal Institute of Technology of Lausanne, SWITZERLAND; and J. Bertuchoz and B. Wamister, AC Laboratory of Wimmis, Swiss Dept. of Defense, SWITZERLAND

6. Shielding Tests for Braided Cables in the 100 MHz - 40 GHz Range,
1540 G.T. Smith, Rockwell International, Anaheim, CA

MEASUREMENT TECHNIQUES
Session MT-1
South Lounge

Chairman: Larry D. Scott, MRC

A. Sensors

1. Optimization of the ACD Sensors for Bandwidth and Pulse Response,
1330 G.D. Sower, EG & G Washington Analytical Services Center, Inc., Albuquerque, NM

2. The Radiation Response of Hardened Current Probes in the CASINO Spectrum,
1350 W.A. Seidler and C.E. Mallon, JAYCOR, Del Mar, CA

3. Development of a Ferrite Isolated Hardwired Data Link for SGEMP Testing,
1410 W.A. Seidler and H.T. Harper, JAYCOR, Del Mar, CA

4. Instrumentation for an Underground Nuclear SGEMP Experiment, R.H. Bonn,
1430 Defense Nuclear Agency Field Command, Kirtland AFB, NM

1450 Break

B. Miscellaneous

5. Shield Topology Concepts as Applied to EMP Data Links, G.D. Sower,
1520 EG & G Washington Analytical Services Center, Inc., Albuquerque, NM

6. Experimental Determination of Electromagnetic Pulse (EMP) Absorption
1540 on Complex Shapes, R.W. Burton, University of Colorado, Colorado Springs, CO; and R.M. Sega and V.M. Martin, USAF Academy/DFP, USAF Academy, CO

7. Collection and Processing Techniques for High Speed Transient EM Data,
1600 J.E. Zicker, Lawrence Livermore Laboratory, Livermore, CA

8. Processing of Data for E-4B EMP Test, M.A. O'Byrne, Boeing Aerospace
1620 Company, Seattle, WA

9. Improved Test Instrumentation/Recording Techniques, W. H. Cordova,
1640 Rockwell International, Albuquerque, NM

QUASISTATIC ELECTROMAGNETIC PENETRATION OF A SPHERICAL SHELL THROUGH A CIRCULAR APERTURE

K. F. Casey
The Dikewood Corporation
1009 Bradbury Drive, S.E.
Albuquerque, NM 87106

There exist five canonical problems relating to the quasistatic electromagnetic penetration of a conducting spherical shell through a circular aperture, the shell being immersed in a uniform field. These are

1. $\overline{E}_0$ perpendicular to the symmetry axis of the shell and aperture

2. $\overline{E}_0$ parallel to the symmetry axis, the shell being grounded

3. $\overline{E}_0$ parallel to the symmetry axis, the shell being uncharged

4. $\overline{H}_0$ parallel to the symmetry axis

5. $\overline{H}_0$ perpendicular to the symmetry axis

The solutions to problems 1, 2, and 4 may be found in [1], but problems 3 and 5 do not appear to have been solved previously.

In this paper the solutions of problems 1, 2, and 4 are reviewed and the new solutions of problems 3 and 5 are presented. In particular, a method will be presented for the solution of a previously unsolved class of dual series equations, which arises in connection with problem 5.

Numerical data are presented which illustrate the behavior of the penetrant fields and fluxes and of the equivalent electric and magnetic dipole moments of the aperture as functions of its opening angle. It is found that the penetration of the shielded region becomes comparable to that which would exist if diffusion penetration were present when the aperture area is greater than 0.04% of the total area of the shell and aperture.

Reference

[1] K.S.H. Lee, editor, EMP Interaction: Principles, Techniques, and Reference Data, AFWL-TR-79-403, Air Force Weapons Laboratory, Kirtland AFB, NM, December 1979.

Low Frequency Magnetic Field Coupling Through a Circular Annular Aperture

R. M. Searing
Rockwell International
3370 Miraloma Avenue
Anaheim, CA 92803

Low Frequency magnetic field coupling through a circular annular slot is investigated using static Green's function and the resulting integral equation for the aperture field distribution is solved by a combination of analytical and numerical techniques. The effective magnetic polarizability α_m of the equivalent dipole moment in the aperture is calculated and compared to the measured α_m from an electrolytic tank experiment. Within the range of slot width/diameter ratios of .01 to .5 (circular hole), the results show excellent agreement between theory and measurement. Additional measured valves of α_m are also presented for annular gaps about a square aperture.

SHIELDING EFFECTIVENESS OF METALLIC HONEYCOMBS

Dr. Wolfgang A. Bereuter
Kaman Sciences Corporation
P. O. Box 7463
Colorado Springs, Colorado 80933

and

Prof. David C. Chang
University of Colorado
Boulder, Colorado 80203

Air ducts in shielded enclosures form large apertures which are often covered by metallic honeycombs, i.e., an array of waveguides below cutoff. The shielding effectiveness (field transmitted into the interior of the enclosure versus incident field) of such honeycombs is given by the reflection of the incident field at the front face, the attenuation provided by the waveguides, and the reflection of the waveguide modes at the end of the waveguides. Often the first and last items are ignored, and only the waveguide attenuation is taken into account. This leads to counter-intuitive results.

In the analysis presented a simple expression for the shielding effectiveness of an infinitely large honeycomb is derived as a function of frequency and guide dimensions. The main tool employed is the Wiener-Hopf technique. Such an expression is a useful figure-of-merit analogous to that for the shielding effectiveness of infinitely large planar panels, i.e., the expressions derived are functions of the shielding material only, but not of the particular geometry of the finite enclosure.

NUMERICAL METHOD FOR ELECTRIC FIELD PENETRATION THROUGH APERTURES

Daniel Binder
Hughes Aircraft Company
Culver City, CA 90230

A numerical method of calculating the electrical field penetration through apertures was investigated. The method is purely electrostatic and is based on the well-known finite difference technique for solving Laplace's equation. It has been recognized that electrostatic methods (1) yield results that are consistent with more general methods for the far field (2). The finite difference technique has the advantage that it is applicable to any geometry, but it may be limited by the amount of computation required.

As a test case, the numerical method was used to obtain the potential distribution in a two-dimensional box with a single slit. The results were compared with Kaden's (1) result for a slit in an infinite wall. For zero wall thickness, Kaden's potential distribution obeys the equation

$$V^2 + Vy = \frac{(2V + y)^2}{x^2 + (2V + y)^2}$$

where V, x, and y are a normalized potential and normalized coordinates. The agreement between the numerical results and Kaden's potential varied with the number of divisions per slit width. For the far field, eight divisions per slit width yielded agreement within about 4%.

The numerical method was applied to a problem that relates to slotted antennas, where the coupling to the outside is a slit and the coupling to the electronics is around a bend. The results showed that the bend increased the electric field attenuation by one to three orders of magnitude.

(1) H. Kaden, "Wirbelstrome and Schirmung in der Nachtrichtentechnik," Springer-Verlag, Berlin (1959), p. 204.
(2) D. L. Jaggard, Interaction Note 323, "Transmission through One or More Small Apertures of Arbitrary Shape," September 1977, p.2.

ELECTROMAGNETIC PENETRATION THROUGH APERTURES IN A CONDUCTING CYLINDER

John W. Williams and Larry Simpson
Mission Research Corporation
1400 San Mateo Blvd., S.E. Suite A
Albuquerque, New Mexico 87108
and
E. R. Carroll
Naval Surface Weapons Center
White Oak Laboratory
Silver Spring, Maryland 20910

During the past three years a portable electromagnetic pulse (EMP) simulation technique has been developed as a potentially useful tool for hardness verifications of military aircraft in the field. In this paper we will present the results of a joint theoretical and experimental program in which aperture penetrations in a hollow conducting cylinder with internal bulkheads and wires were investigated as part of an effort to understand and improve the quality of the existing simulation technique.

The experimental portion of the program was conducted in the Naval Surface Weapons Center EMP simulator for aircraft (EMPSAC) facility at the Naval Air Test Station, Patuxent River, Maryland. A conducting cylinder 5 m in length and 0.47 m in diameter was subjected to illumination by the EMPSAC pulser and to excitation by direct injection from the portable pulser. The hollow cylinder contains bulkheads which define an internal cavity 3 m in length. A thin internal wire with various terminations at the interior bulkheads was located at several different positions within the cavity. One or two apertures of dimension 30.5 cm × 28.3 cm were opened to allow aperture excitation of the internal cavity and wire.

Predictions of internal wire currents were obtained with the THREDE finite difference code, which has been found in past studies to yield reasonably accurate estimates of exterior charge and current density for test objects in a free field EMP simulator. Several modifications to the existing computer code were necessary to model the experimental configuration. These changes included expansion of the mathematical problem space to provide increased spatial resolution and development of a thin strut formalism to allow inclusion of wires having a diameter less than individual cell dimensions. Comparisons are presented between measured and calculated internal currents obtained under both EMPSAC illumination and excitation by direct injection. Potential improvements in the portable simulation technique based upon these results are discussed in the concluding remarks.

NEMP FIELD PENETRATION IN CYLINDRICAL APERTURES

Ruedy T., Bertuchoz J., Wamister B.
Swiss Armament Technology and Procurement Group
Technical Division 8, AC-Laboratory CH-3752 Wimmis, Switzerland

From a NEMP standpoint, the behaviour of electromagnetic fields inside cylindrical apertures must be well understood for an effective hardening concept.

This problem has been investigated in an experimental program using a balanced transmission line EMP-simulator.
For various distances from the top opening peak amplitudes and time dependences of the electric and magnetic field inside the cylinder are measured.

Results of test configurations with different diameters and angles of incidence are compared with a simple analytical model for the geometry considered. This line of investigation will lead to an optimization of shielding requirements for buildings.

References

F. Gardiol

"Affaiblissement d'une onde électromagnétique dans un tuyau métallique", Pub. Ecole Polytechnique Lausanne, Novembre 1979

Mittra R.; Pearson W.

"Penetration of Electromagnetic Pulses through Larger Apertures in Shielded Enclosures", May 1976

Butler C.M.; Mittra R.; Rahmat-Samii Y.

"Electromagnetic Penetration through Apertures in Conducting Surfaces", IEEE-Ap 26, No 1, January 1978

ANALYSES OF STANDING WAVE MINIMA IN A MODEL SIMULATOR

Dennis J. Blejer and Ronold W. P. King
Gordon McKay Laboratory
Harvard University
Cambridge, Massachusetts 02138

The model parallel plate simulator approximates by a 1:10 scale the Alecs facility. Measurements of fields have been conducted in the model to detect the so-called "25 Mhz Notch" which occurs in Alecs. Detailed measurements of amplitude and phase in the parallel plate region of the model indicate that the "Notch" is a deep standing wave minimum which occurs in the electric and magnetic fields although at slightly different frequencies.

The measured fields are analyzed in terms of parallel plate waveguide modes. At the "Notch" frequency for the electric field of the model only the TEM and TM_{01} modes can propagate (TE modes are assumed to be negligible). The two modes are determined mathematically from the data and the real and imaginary parts are separated. The components of the TEM and TM_{01} modes display standing wave distributions which at certain locations in the simulator have equal and opposite amplitudes which mutually cancel to produce very deep minima in the total field.

The analyses are carried out for the fields of the model simulator with different terminations and for the case of a bifurcating metal plate located in the output region.

A STUDY OF A RESISTIVE SHEET BIFURCATING AN INFINITELY WIDE TWO-PARALLEL PLATE LINE

K.S. Kunz and D.V. Giri
LuTech, Inc., P.O. Box 1263, Berkeley, CA 94701

Abstract

This problem derives its motivation from the long standing issue of a magnetic field notch at the center of the ALECS facility [1]. On the scale model facility at Harvard, this notch in the magnetic field was duplicated and in addition, a corresponding electric field notch was also experimentally observed at a nearby location and slightly different frequency [2]. The modal decomposition of the measured field [2] enables one to conclude that these notches in the incident field are due to spatial interaction of TEM and TM_{01} modes traveling in forward and reverse directions. Consequently, there is a need for suppressing the TM_{01} mode and reduce TEM reflections as well.

In this paper, we have considered the problem of a resistive sheet bifurcating two infinitely long and infinitely wide plates that are separated by a finite distance. The resistive sheet is of finite width along the propagation direction and infinitely long in the transverse direction. The object of the problem is to consider a TM_{01} mode which has its axial electric field vanishing at the top and bottom plates and a maximum at the middle along the resistive sheet. Such an incident wave will couple strongly to the resistive sheet. By using the classical method of modal matching at two interfaces, along with the boundary condition on the resistive sheet, the relevant physical parameters like the attenuation constant, reflection and transmission coefficients are determined. The results of a parametric study will be presented. The usefulness of these results lie in optimizing the width and the resistance value of the resistive sheet for suppressing the undesirable TM_{01} mode.

---

[1] J.C. Giles, et al., "Evaluation and Improvement of the CW Performance of the ALECS Facility", ALECS Memo 10, September 1975.

[2] T.T. Wu, et al., "Experimental Studies on a Scale Model Parallel-Plate Transmission Line Type of EMP Simulator", ALECS Memo 18, 31 July 1979.

ELECTROMAGNETIC CHARACTERISTICS OF THE ATLAS I EMP SIMULATOR

by

Robert Fisher, EMA
David L. Endsley, EG&G
Carl Baum, AFWL

Submitted by:

Electro Magnetic Applications, Inc.
P. O. Box 8482
Albuquerque, New Mexico 87198
(505) 265-3538

Abstract

The construction of the ATLAS I (TRESTLE) EMP simulator was completed in 1979. This paper will describe the electromagnetic characteristics of this new simulator that was designed to test the in-flight response of large aircraft. The observed field in both the time and frequency domain will be described and our assessment of the effects of pulser asynchronism, wedge diffraction, and platform diffraction on the fields in the working volume will be discussed.

Measurements of aircraft skin currents and charges will be discussed and a comparison will be made between the simulator response and the response as measured on a scale model at the University of Michigan.

HORN EMP-SIMULATOR WITH NON LINEAR PROFILE

N. BERKANE, B. BESNAULT, J.Ch. BOLOMEY

Laboratoire des Signaux et Systèmes (CNRS - ESE)
Groupe d'Electromagnétisme
Plateau du Moulon - 91190 GIF-sur-YVETTE - FRANCE

This communication is devoted to the study of an EMP simulator consisting in a horn, the profile of which is non linear. This profile is determined in order to reduce the phase error due to the unavoidable phase front curvature in conventional linear horns (Fig. 1). For practical purposes the profile is choosen linear by parts (Fig. 2).

The simulator has been studied both numerically and experimentally. The numerical approach has been conducted by considering the simulator as a cascade of short sections of parallel plate waveguides. The calculated results have been experimentally checked on a reduced scale model. The measurement of the surface current on long conducting cylinders inserted in the simulator has provided a mean of estimating itsglobal behaviour in presence of a target. Indeed, experimental results can be compared to those exactly calculated for the same cylinders illuminated by a true plane wave.

This study is sponsored by THOMSON-C.S.F. and S.N.I.A.S..

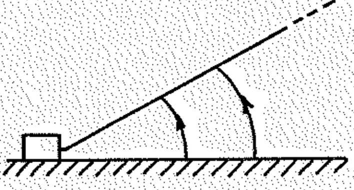

Figure 1

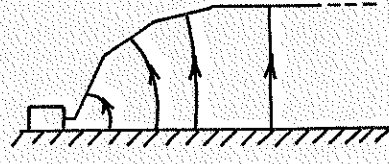

Figure 2

More Precise Timing of EMP Generators Can Offer Important Benefits

Walter F.J. Crewson
Carleton H. Jones, Jr.
Pulsar Associates, Inc.
11491 Sorrento Valley Rd.
San Diego, CA 92121

Dual channel fiber optically linked trigger systems have been recently installed at the HPD and TRESTLE EMP Test Facilities at the Air Force Weapons Laboratory in New Mexico. These systems have a command time precision (jitter) capability of 1nS per channel. The trigger signals to the Marx generators and the return firing confirmation signals are delivered by fiber optic lines. Use of fiber optics eliminates entirely any trigger-generated-transient difficulties from the control areas. The operation of these systems, including the capability to diagnose difficulties and locate them within the system from the operator's position using real time displays, is described. While the installation of these systems was intended primarily to provide a more reliable means of trigger control and operation for the EMP test operator, they provide the possibility of more important benefits for the conduct of EMP tests and analysis. First of all, properly extended, these systems will make it much easier to synchronize the firing of EMP generators with external events such as the system under test. It will be possible to fire the pulser so as to hit the most interesting time in a rapidly sequencing electronic system such as a computer. Another important advantage now brought into reach is the capability, using only electronic controls, of shaping the output pulse of an EMP generator in order to change the frequency content of the output pulse. In peaking circuit generators, the most popular in the United States, this can be accomplished by tight control of the timing between the charging of the main peaking capacitor arrays and the discharge of the main switches. This technique will give the test operator direct shot-to-shot electronic control of pulse shapes, including risetimes and pulse widths.

A TRANSIENT HIGH-VOLTAGE SOURCE FOR DIRECT INJECTION OF THREAT-LEVEL EMP CURRENT ON CABLES OF ARMY TACTICAL EQUIPMENT

R. Gray and J. Sweton

US Army Electronics Research and
Development Command
HARRY DIAMOND LABORATORIES
Adelphi, MD 20783

Single-channel, audio communication in the US Army is typically transmitted over unshielded twisted pairs of field wire. These communication systems are common and often have many field-wire pairs as inputs. The short-circuit current that can be coupled to a tactically configured twisted field-wire pair excited by the electromagnetic pulse from a nuclear detonation can have a peak amplitude of several thousand amperes, a risetime in the order of 100 ns, and a fall time of between 1 and 2 μs. Exciting such large responses with radiating EMP simulators for purposes of EMP hardness verification is not possible. Therefore, a high-voltage, high-energy portable Marx generator has been designed and built for the purpose of providing direct-drive high-level current injection for hardness verification testing. The unique feature of this 22-kJ 400-kV generator is that its source impedance is never higher than 10 ohms even when the Marx is not conducting. It thus approaches the ideal voltage generator for most load conditions. This paper presents a description of this unique EMP hardness verification tool, the results of initial testing, and some alternate experimental uses such as a source for establishing the dielectric breakdown of in-place soil, corona losses on cables, and the ionization of earth around grounding rods.

DEVELOPMENT OF ENERGY DISTRIBUTION CONCEPTS AS RELATED TO ELECTROMAGNETIC FIELD WAVEFORMS *

W. Motil and F. Sterk
TRW Inc.
2425 Alamo, S.E.
Albuquerque, New Mexico 87106

The numerous EMP simulator facilities constructed in recent times have produced many different electromagnetic field waveforms. The traditional method for evaluating these waveforms is to examine the structure of each waveform's Fourier Transform. A relative merit for each waveform is normally obtained from the magnitude of the waveform's transform over some bandwidth of interest.

An alternate procedure for evaluating waveforms is being developed using energy concepts rather than just the amplitude of spectral components. The analysis starts with the conventional Fourier Transform of an electromagnetic field waveform and determines the Energy Spectral Density then sets forth a procedure for identifying the bandwidth where most of the energy is concentrated. The results of this process facilitate the evaluation and comparison of simulator waveforms.

In addition, the results suggest how an optimum waveform may be specified with regard to the response characteristics of the test article. The procedure is presented along with the rationale and some examples of its application.

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* This work was sponsored by the Defense Nuclear Agency under Contract DNA001-79-C-0361.

PLANEWAVE SPECTRAL DENSITIES FOR THE NEAR- AND FAR-ZONE WAVES OF ANNULAR RADIATORS

Jiunn S. Yu

Sandia National Laboratories
Albuquerque, New Mexico 87185

ABSTRACT

Electromagnetic waves have been represented by the weighted sums of spherical or cylindrical harmonic functions. They can also be approximated by the weighted sums of electric and magnetic dipoles. These decompositions are usually performed to facilitate the solution of boundary-value problems or the simulation of certain desired environments. For simulation technology, this paper considers the rigorous solutions of annular radiators that represent the electric and magnetic dipoles with finite radii. The initial solutions of these dipoles are in the form of Fourier transforms which converge very slowly. Rapidly convergent solutions are obtained through integrations along a branch cut in the complex plane of a spatial spectrum. Finally, the solutions are obtained as infinite series of polynomials in terms of spatial coordinates and the angular frequency of radiating source. All the three forms of solution are valid in both near and far zones. When the radii of dipoles approach zero, the solutions reduce to the well known dipole waves under point-source approximations. The planewave spectral densities are thus formally obtained to represent the annular radiators. Similar to time-modulated waveform envelops with a carrier frequency, certain physical insight and analytical convenience are enhanced by the planewave spectral densities. Examples on transient radiation and near-zone scattering are given for the utility of spectral densities.

ON THE USE OF SINGLE LINE MODELS FOR PREDICTING TRANSMISSION LINE RESPONSES*

by

F. M. Tesche

LuTech, Inc.
P.O. Box 1263
Berkeley, CA 94701
(415) 843-1504

Abstract

It has long been desired to reduce the complexity of a rigorous multiconductor transmission line analysis, for the purpose of modeling EMP propagation within a complicated electrical system, by using a single wire transmission line model. With this approximation, a multiconductor cable is replaced by a single wire transmission line with characteristic parameters appropriately chosen. By choosing the single line characteristics correctly, the single line current response can be made to approximate the bulk current (or common mode current) on the multiconductor line. From this bulk current, various schemes are then used to infer the response of an individual wire in the multiconductor line.

This paper examines several aspects of this problem: how to choose the appropriate single line parameters, how to relate the individual wire currents to the bulk current, and what type of accuracies can be expected in using a single line model.

*Work performed under contract F29601-78-C-0082 for Mission Research Corporation and the Air Force Weapons Laboratory.

CHARACTERIZATION OF B-52 AIRCRAFT MULTICONDUCTOR CABLE NETWORK

Ashok K. Agrawal
Mission Research Corporation
1400 San Mateo Blvd., S.E. Suite A
Albuquerque, New Mexico 87108

and

Tom K. Liu
LuTech, Inc.
P. O. Box 1263
Berkeley, California 94701

This paper presents the results of CW and transient measurements made on a multiconductor cable in a B-52 aircraft and in the laboratory. The multiconductor cable is modeled as a single-wire transmission line. The equivalent single-wire line represents the common-mode propagation on the cable. The equivalent single-line parameters are measured experimentally and compared with simple calculations. The single-line parameters are obtained from the measured multiconductor line parameters. The aircraft ribs and bulkhead penetrations are characterized and included in the model. A comparison of measured bulk current transfer ratios in the aircraft and laboratory along with calculated results is presented.

EMP INDUCED AIRCRAFT INTERNAL PIN CURRENTS USING A SINGLE-LINE APPROXIMATION FOR CABLE BUNDLES

Werner J. Stark and James Daffe
Kaman Sciences Corporation
P. O. Box 7463
Colorado Springs, Colorado 80933

We describe an analytical model which can be used to estimate pin currents at the input to electronic systems inside an aircraft. Cable bundles in the aircraft are represented in terms of a simplified single-line network allowing for cross-coupling between adjacent cable bundles. The network is driven at various segments by an approximation to the total electric field component along the segment. This electric field component is computed from the aircraft surface current at frequency components below 20 MHz, and from the incident field with some attenuation at higher frequency components.

The model was applied to compute pretest predictions for an airplane tested in an EMP simulator to aid in the test point selection and to perform a preliminary EMP hardness assessment of airplane systems. Comparisons of predicted and measured currents showed that the mean value of the prediction was approximately 2.5 dB too high with an uncertainty of ± 16 dB.

Comparison of computed and measured results indicated some simple model improvements such as better estimates of total fields driving the cable bundles, improved methods of computing pin currents from bulk currents, etc. The improvements were incorporated into the model and as a result the mean value for predictions was -.4 dB relative to test data, with an uncertainty of ± 11 dB.

EXPERIMENTAL CHARACTERIZATION OF PARTIALLY DEGENERATE THREE-CONDUCTOR TRANSMISSION LINES USING TIME-DOMAIN TECHNIQUES

Ashok K. Agrawal and Harold J. Price
Mission Research Corporation
1400 San Mateo Blvd., S.E. Suite A
Albuquerque, New Mexico 87108

In a recent paper[1], a method for the time-domain characterization of lossless multiconductor transmission lines with cross-sectionally inhomogeneous dielectrics was presented. This method is limited to lines with completely nondegenerate propagation; that is, all the modes have distinct propagation velocities. A knowledge of the modal velocities and the modal amplitudes (eigenvectors) is needed in order to obtain per-unit-length inductance and capacitance matrices from the characteristic-impedance matrix. Degeneracy among modes may occur due to symmetry. For partially degenerate propagation, where some groups of modes have the same propagation velocity in each group, the degenerate modes cannot be resolved in time.

In this paper, a method is presented for the characterization of lossless, partially degenerate three-conductor lines, together with experimental data. It is shown that for the degenerate case the product of the inductance and capacitance matrices can be diagonalized, and the voltage and current eigenvectors are mutually orthogonal to each other. Since modes with the same velocity travel together, only the sum of the modal voltage or current amplitudes for these modes can be measured. The individual modal amplitudes can be obtained from their sum by using the orthogonality properties of the modes. The results for a three-conductor line (over a ground plane) are in good agreement with independent frequency-domain measurements.

---

[1]A. K. Agrawal, H. M. Fowles and L. D. Scott, "Experimental Characterization of Multiconductor Transmission Lines in Inhomogeneous Media Using Time-Domain Techniques", IEEE Trans. EMC, Vol. EMC-21, No. 1, pp. 28-32, February 1979.

COMPARISONS OF PREDICTED AND MEASURED CABLE HARNESS RESPONSES IN A TRANSIENT EM ENVIRONMENT

By

Jerry A. Sawyer
Computer Sciences Corporation
1400 San Mateo Blvd. S.E.
Albuquerque, New Mexico 87108
505-265-9571

Frederick M. Tesche
LuTech, Inc.
P. O. Box 1263
Berkely, California 94701
415-843-1504

ABSTRACT

New applications of experimental and theoretical techniques have recently been used in obtaining data from the qualification model of a DoD communications satellite during exposure to transient electromagnetic fields which simulate the effects of a nuclear electromagnetic pulse in space. These new data make it possible to use the predictive capabilities of the general multiconductor transmission line analysis tools to help resolve questions arising during the tests; such as how is current shared between wires? How can individual wire currents be greater than bulk cable currents? What are the effects of branching in cable harnesses? Why does the frequency change between bulk and individual current measurements?

Reasonable answers to these questions are proposed by comparing measured and predictive results using a multiconductor transmission line analysis program (QV7TA). An experiment was conducted in the laboratory on a model representative of a cable harness located in a satellite cavity. The fields were generated by a parallel plate located a few centimeters above the cable bundle. Currents and voltages were calculated for the cable shields and conductors and were found to compare favorably with the experimentally measured values.

A discussion of improvements to the theoretical tools used in performing the above comparisons are delineated in the concluding section of the paper.

EXCITATION OF MULTILINE SHIELDED CABLES IN CLOSE PROXIMITY TO A FLAT EARTH*

M. H. TESLER
BOOZ, ALLEN & HAMILTON, INC.
COMMUNICATIONS AND INFORMATION TECHNOLOGY DIVISION

As part of a study to determine the adequacy of terminal protection designs, a model was developed to evaluate the EMP response of multiline shielded cables in close proximity to the earth. This paper presents salient features of that model development.

Initially, the field response of an infinitely long conducting sheath is determined, ignoring the effect of non-axial (circumferential) induced current distributions. It is shown that this approximation leads to results which become increasingly less accurate as the cable height approaches its radius. Exact results for parameters of interest are shown to be obtainable by postulating, for the exciting fields, an effective boundary different from the actual sheath boundary.

Continuing, the previously postulated effective boundary is used in the development of transmission line equations for the terminated sheath. The resulting expressions for the line excitation are shown to be consistent with other recent work which used quasi-static arguments to account for proximity effects.

Finally, the net current induced on the terminated cable sheath is used to determine the response of a symmetric distribution of internal conductors. Numerical results are presented.

* This work was performed for the TRI-TAC Office under Contract DAAB07-77-C-0022, Task Assignment 254.

Analysis of the Shielding Effectiveness of a Multi-branch Cable in a RAMS Test Configuration

Y. B. Yu
Rockwell International
3370 Miraloma Avenue
Anaheim, CA 92803

Although a number of papers and reports have been published on the theoretical and experimental characterization of the shielding effectiveness of a braided cable usually based on some variant of a basic tri-axial arrangement, they are limited to the cables without branch.

In practice, ordinary cables are often multi-branched. Since this measurement arrangement is useful for factory acceptance test purpose, it is desirable to develop the theory for a long cable with many branches. This presentation is to describe the analysis for a multi-branch cable with arbitrary branch conditions and terminations in the rapid attenuation measurement system (RAMS), developed by Rockwell International for cable shielding effectiveness measurement. The output of the computer code, RAMS developed according to the theory, is then compared with the analytic solution of a single branch cable with match junction and match terminations.

Upper Bounds on Cable Signals

William A. Davis
Department of Electrical Engineering
Virginia Polytechnic Institute and State University
Blacksburg, VA 24060

System hardening and design often involve extremely complicated geometries and equipments. In order to insure protection in such environments it is desirable to develop upper bounds on currents and voltages characteristic of worst case type analysis. This paper presents a brief summary of the modeling results for a wire behind a small aperture and methods of bounding the voltages and currents launched on the wire.

The coupling of aperture fields to a wire is modeled by voltage and current sources at a point on a transmission line. The first step is to bound the aperture fields and thus the transmission line sources. Jaggard and Pappas [1] have concentrated on this problem. Though their results are useful, they are not absolute bounds for small apertures. An alternate upper bound, which is not as tight, is to bound the aperture with an elliptical aperture which circumscribes the actual aperture.

The remaining portion of the problem may be bound with several assumptions made. Initially, the reflection coefficients are bounded above at the first discontinuities along the line. Neglecting phase cancellations, a bound is thus put on the received voltage or current at a termination. To account for transient fields, the bound may be stated as the sum of the bounds for each pole of the incident field behavior.

Results of this single wire problem will be presented in addition to preliminary results for multi-conductor systems. The latter is characteristic of wires near bulkheads and cable bundles.

1. D. L. Jaggard and C. H. Pappas, "On the application of symmetrization to the transmission of electromagnetic waves through small convex apertures of arbitrary shape," AFWL Interaction Note 324, Oct. 1977.

SOURCE-REGION ENVIRONMENT REPRESENTATION*

FOR A SURFACE BURST

John Lam
The Dikewood Corporation
Santa Monica, California 90405

The work of this report is performed as the first stage in the program of deriving an analytical representation for the electromagnetic environment in the source region of a nuclear detonation at ground level. The results are intended for use in studying the interaction of the source-region electromagnetic environment with missile-site installations. In this first stage of the program a simple, approximate, analytical solution of the electromagnetic field equations is sought. The Compton current and the air electrical conductivity are considered given quantities. By using the analytical techniques of perturbation expansion, interpolation and boundary-layer analysis, it is possible to construct simple, analytical formulas for the electromagnetic field components in air, at the ground and underground. The numerical accuracy of these formulas is tested by comparing the values of the electromagnetic field components calculated by them with those calculated by source-region environment computer codes.

*The work was performed under Contract No. F29601-79-C-0036.

A SIMPLE CONDUCTIVITY MODEL FOR LATE-TIME SURFACE-BURST EMP*

W. A. Radasky and K. S. Smith
JAYCOR
360 S. Hope Ave.
Santa Barbara, CA 93105

In this paper we will develop a simple model for predicting the EMP-related late-time air conductivity produced by surface nuclear bursts.[1] We will also use the model to study the variations of electron and ion conductivities produced by changing various air chemistry parameters.

Our model is partially based on curve fits of data produced by the SCX and LEMP computer codes for a nominal one megaton burst. Analytical fits are derived for the air ionization rate and electric field magnitude as functions of time and range for 10^{-6} to 10^{-1} seconds and 500 to 5000 meters. Also given is a fit for the initial ion density at 10^{-6} seconds as a function of range. A simplified three species air chemistry model is then used in conjunction with the given fits and the electron mobility and attachment rates of Longley and Longmire to solve for the electron and ion conductivities as functions of time and range. Our model is then verified by comparison to computed predictions of the SCX and LEMP codes.

The results of a brief study showing the impact on the air conductivity caused by varying several air chemistry parameters will be given. Of particular interest is the variation in the crossover time (the time at which the electron and ion conductivities are equal) caused by changes in water vapor content, electric field magnitude, and electron attachment rate. The study reveals a significant impact on air conductivity crossover time is caused by minor variations in water vapor content and electron attachment rate. Large variations in the electric field magnitude prove to be of lesser impact.

*Work supported by the Air Force Weapons Laboratory

[1]Smith, K. S. and W. A. Radasky, An Examination of the Behavior of the Late-Time Electronic and Ionic Conductivities Appropriate for Surface-Burst EMP Calculations, JAYCOR 200-80-191/2148, Janurary 1980

SC LATE-TIME IMPLICIT CODE (SLIC): THEORY

K. D. Granzow
The Dikewood Corporation
1009 Bradbury Drive, S.E.
Albuquerque, New Mexico 87106

The need to calculate EMP fields underground and inside shielded enclosures motivates a requirement for late-time EMP field calculations. The usual explicit solution schemes are impractical at late times due to the Courant condition (in simplistic form: $c\delta t < \delta x$). Hence, a totally implicit algorithm was developed for use in the coordinate system of SC (spherical polar coordinates above the ground and cylindrical coordinates below ground). The implicit scheme leads to a large set of linear equations (one equation at each grid point) that are solved simultaneously. The set of equations is characterized by a sparse matrix. These equations are solved directly by triangularization and back substitution. The difference equations are derived using an exponential difference scheme. The outside free-space boundary condition is applied by employing multipole theory in a manner similar to that used in SC.

SC LATE-TIME IMPLICIT CODE (SLIC): CODE DESCRIPTION

Declan Rieb
Ray Asbury
K. D. Granzow
The Dikewood Corporation
1009 Bradbury Drive, S.E.
Albuquerque, New Mexico 87106

The use of SLIC begins by computing the early-time fields using the SC code. While the retarded-time code SC is running, field values at a given real time are extracted and stored. These field values are used in SLIC as initial conditions. The coordinate system of SLIC is the same as that of the SC code. Provision is made in the code for the choice of a log or linear time grid. Typical spatial and time grids, as well as current code results will be discussed.

The Effect of Atmospheric Heave - Generated MHD/EMP on Commerical Wireline Systems

Ira Kohlberg and Henry Root
GTE Products Corporation
Communications Systems Division
Needham Heights, Massachusetts 02194

The MHD/EMP effect refers to the generation of electric fields in the ground due to perturbations of the geomagnetic field produced by nuclear detonations. In this paper we discuss the atmospheric heave component of the geomagnetic field change which is produced by X-ray heating of the E-region. An analytical model for atmospheric heave is developed which permits scaling of the geomagnetic field changes as a function of yield and height-of-burst, with application to multiburst effects. The atmospheric processes are complex but when attention is focused on predicting the damage or shutdown of specific types of communications hardware, a number of simplifications can be brought into play which make the problem manageable, while at the same time producing useful results. The derived threat signatures are applied to different types of communication wireline systems located in differing resistivity regions, through the mechanism of earth potential coupling.

The simplifying assumptions include (1) consideration of vertical variation of field quantities, (2) inclusion of only a vertical component of heave velocity and (3) the use of a homogeneous one-region ionosphere. Under these conditions only the horizontal component of the geomagnetic field changes; and the Cowling conductivity plays the dominant role in diffusion of the magnetic field from the ionosphere into the earth-ionosphere cavity. The analytical model produces results which are in good agreement with the Starfish data taken at Johnston Island, although it is recognized that comprehensive computer programs are necessary to more accurately evaluate geomagnetic changes at higher latitudes.

The large degree of heave and longer dwell times which are brought about by multiple bursts are used to estimate the impact of such time-related events on both coaxial and balanced pair type communication systems. The failure thresholds of these systems define, via the heave model, the necessary altitude and minimum yields necessary to cause damage or automatic shutdown of cable repeater power supplies.

Because the magnetic threat signal is felt over a wide geographic area many wireline links can be affected at the same time, promoting widespread routing problems in a communication switching network. An example of this communication vulnerability is provided.

CARTESIAN-COORDINATE THREE-DIMENSIONAL SOURCE-REGION EMP CODE

M. Bushell
US Army Electronics Research and
Development Command
HARRY DIAMOND LABORATORIES
Adelphi, MD 20783

In the on-going HDL source-region electromagnetic pulse (EMP) program, the short-circuit responses of antennas in a number of configurations that lend themselves to interpretation with a three-dimensional cartesian-coordinate finite-difference code were measured by subjecting them to a source-region-like EMP in the HDL Mark I Source-Region EMP Simulator. In the Mark I Simulator the electromagnetic field is produced by a long parallel-plate transmission line. The time-varying air conductivity is produced by the AURORA Flash X-Ray machine. The three-dimensional code, based on the Yee algorithm[1,2] as implemented by Holland,[3] was modified to include time-varying air conductivity and a thin-wire approximation.

The antenna configurations interpreted by the three-dimensional code include rectangular loops, capacitively end-loaded antennas, and antennas at 45° angles to the ground plane. An effort is underway to include continuous and lumped inductive loading in the code.

In the experimental procedure the short-circuit response was first measured without the presence to time-varying conductivity and then measured with the presence of time-varying conductivity (ionized air). The code will be discussed and comparisons with experimental measurements will be presented.

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[1]K. S. Yee, "Numerical Solution of Initial Boundary Value Problems Involving Maxwell's Equations in Isotropic Media," IEEE Trans. Ant. & Prop., AP-14, pp. 302-307, May 1966.

[2]C. L. Longmire, "State of the Art in IEMP and SGEMP Calculations," IEEE Trans. Nuc. Sci., NS-22, pp. 2340-2344, December 1975.

[3]R. Holland, "THREDE: A Free-Field EMP Coupling and Scattering Code," IEEE Trans. Nuc. Sci., NS-24, pp. 2416, December 1977.

A COMPARISON OF LIGHTNING AND NUCLEAR EMP ENVIRONMENTS AND THEIR INTERACTIONS WITH AIRCRAFT

R. A. Perala
Electro Magnetic Applications, Inc.
P. O. Box 26263, Denver, Colorado 80226

M. A. Uman
Department of Electrical Engineering
The University of Florida, Gainesville, Florida 32611

E. P. Krider
Institute of Atmospheric Physics
The University of Arizona, Tucson, Arizona 85721

The electromagnetic interaction of lightning with aircraft is assuming more importance for modern and future aircraft because of new technological developments which include the use of fly-by-wire systems, graphite-epoxy composite structures, and low level integrated circuit devices. This interaction is quite complex and includes the case when the aircraft is attached to a lightning channel as well as the case in which the aircraft is in the electric and magnetic fields of a close lightning. The interaction of transient electromagnetic fields with aircraft has received much attention in the NEMP community and interaction codes and methodologies developed for that purpose should be applicable for lightning interaction also.

In this paper lightning and NEMP environments are compared and the resulting requirements for interaction modelling are discussed. Specific attention is focussed on rise time, waveshapes, and spectral content for the various lightning processes such as preliminary breakdown, stepped leader, return stroke, J and K processes and the three stages of intracloud discharges, and NEMP. In addition for lightning, the importance of the attachment process and non-linearities such as streamering and corona are discussed and the requirements these impose upon interaction modelling are given.

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CONTINUOUS LIGHTNING LONG ARC ATTACHMENT TESTING FOR GRAPHITE COMPOSITE SKINNED AIRCRAFT USING A 150 KW TESLA COIL

Robert K. Golka
Project Tesla
Wendover AFB
Utah 84083

In conjunction with Air Force
Flight Dynamics Laboratory
Wright-Patterson Air Force Base

Recent advances in direct lightning strike testing has been in lightning attachment test techniques and generator development using a very large Tesla Coil (51 feet wide). Breakthroughs in simulated lightning attachment to small scale replica aircraft models which can be adapted to full size operational aircraft have been made in the past year. New high voltage long arc generator developments have succeeded in producing voltages in excess of 15 million volts and arc lengths in excess of 40 feet. The use of long arc attachment testing (arc lengths 20 - 40 feet) as compared to short arc (6 - 12 feet) testing yields some interesting dissimilarities. While in general the attachments with both aircraft (i.e. wing tips, vertical stabilizer, radome, etc.) are predominant, the percentage of strikes to the different extremities on the aircraft under test differ between long and short arc attachment tests. The long (slow rise times) arc attachment technique identifies inboard strike locations not identified by short (fast rise times) arc testing via Marx Generator techniques. The shortest path from the discharge arc electrode to the model extremity using the long arc does not govern the attachment points to the test specimen as it does when a short arc is used to conduct simulated lightning testing. The system just described may also have application as an ultra-high mega-volt source for particle beam weaponry.

Spherical Lightning Current Distribution Model of MECA

R. M. Searing
Rockwell International
3370 Miraloma Avenue
Anaheim, CA 92803

A 100 KA peak lightning strike to MX Missile IV stage produces an estimated 10 KA peak current internally flowing onto the MECA box shield. For study pruposes the MECA Box is modeled as a spherical shell. Using spherical stereographic projection onto a plane, the complex static potential field of two opposite line changes in a circular boundary is mapped to a spherical surface. The resulting imaginary component of the complex potential is proportional to the low frequency surface magnetic field H_S on the sphere for any arbitrary located entry and exit points. Multiple entry and exit points are handled by use of superposition of individual cases. Several cases are presented for consideration.

EVOLUTION AND TRENDS OF EMP INTERACTION*

K.S.H. Lee
The Dikewood Corporation
Santa Monica, CA 90405

J.P. Castillo
Air Force Weapons Laboratory
Kirtland AFB, NM

We begin with the definition of the EMP interaction problem from the viewpoint of a simple topological model. We then go on to identify the role of EMP interaction in system hardness design, verification, and maintenance. Next, a survey is given of the present-day knowledge of EMP interaction technology. The survey will address various methods of formulating and solving the EMP interaction problem, reference data on external and internal interaction, and their limitations and applicabilities. Outstanding issues such as errors in analytical modeling, nonlinear effects, etc. will be discussed. Finally, future trends of EMP interaction will be forecasted.

*The work was performed under Contract No. F29601-76-C-0149.

Common Approach to the Electromagnetic Design of Complex Electronic Systems

Carl E. Baum
Air Force Weapons Laboratory

Abstract

Complex electronic systems such as missiles, aircraft, communications terminals, etc., have various types of undesirable electromagnetic environments with which to contend. The nuclear EMP (outside the source region) and lightning are examples of exterior EM environments which must be excluded from (internal) electronic equipment. Certain electromagnetic compatibility (EMC) problems concern the isolation of particular electronic equipment in a system from other equipment because of the "large" electromagnetic "noise" emitted by one set of equipment. Sometimes one is concerned with preventing signals inside the system from being detected outside the system. The general problem is then one of controlling the transport of EM signals between various spatial domains which include internal parts of the system and the system exterior. The form of the problem is then seen to be topological involving various volumes and boundary surfaces.

In designing a complex system one needs to be able to design the parts of the system in such a manner that they will meet the desired system performance in the presence of specified EM environments. This requires that for the relevant system parts one needs appropriate specifications, design procedures, and test procedures which, when employed and passed, will result in the desired total system performance. Considering the specifications and associated tests for relevant system parts it is necessary that these be consistent with performance requirements of the total system. There then needs to be a way to quantitatively relate the specifications for the parts to the specifications for the whole, and in turn to the environment for the whole.

Stated another way the electromagnetic specifications must be related to each other through the general equations of electromagnetics, i.e., Maxwell's equations. It is well established that the electromagnetic response of a volume is governed by the values of appropriate electromagnetic parameters on surrounding (closed) boundary surfaces as well as any internal sources. This referencing of the EM response to sources and closed boundaries can be used to derive consistent forms of specifications and associated tests for a complete set of system parts as identified by the chosen system EM topology.

DEVELOPMENT OF PORTABLE EMP INJECTION TECHNIQUES

E. Carroll, L. Libelo, D. Koury
Naval Surface Weapons Center
Dahlgren, VA 22448 USA

K. Kunz, MRC*
Albuquerque, NM 87108 USA

M. Weinert
NBC Defense Research and Development Institute
Munster, F.R. Germany
(Foreign exchange assignment at NSWC; Apr 79 - Apr 80)

This program is directed toward development of low-cost, portable, sub-threat level EMP simulators for the purpose of complementing the capabilities of larger fixed site simulation systems for the Hardness Assurance, Maintenance and Surveillance (HAMS) of hardened systems. The initial experimental portion of this program was performed by the Naval Surface Weapons Center (NSWC), White Oak Laboratory and sponsored by the Defense Nuclear Agency (DNA). Supporting analyses have been performed by the Mission Research Corporation (MRC) under contract to NSWC. AWRE is also collaborating with NSWC in performing analyses related to this program.

This paper presents the results of preliminary SCIT (Skin Current Injection Techniques) tests performed by NSWC on A6E and A7E aircraft to emphasize the motivation behind the present program. For this program an operational A6E aircraft in an "on the ground" configuration was adopted to serve as the "test bed" for the studies. Using a high voltage transient pulser called the Delta System built by Pulsar Incorporated, San Diego, CA, a two-point (aircraft nose and tail) pulsed current injection mode was arrived at in collaboration with MRC. The external surface current excitation distribution and surface charge density distribution were measured for this SCIT stimulation. Utilizing EMPSAC, the NSWC fixed site, horizontal dipole, EMP simulator at the Naval Air Test Center (NATC) at Patuxent River, MD the A6E was irradiated on the ground with its fuselage parallel to the incident field and the external surface current densities and surface charge densities over the aircraft were measured.

Comparison of the external surface current and external charge density responses measured over the A6E has been carried out for the two stimulation modes (SCIT and EMPSAC). The results obtained via the two experimental approaches and their comparison with predicted responses provided by MRC using the THREDE code will be reviewed.

The study is presently being extended to investigate internal coupling phenomena.

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*Now with LuTech Corp., Albuquerque, NM 87108 USA

TECHNIQUES FOR SIMULATING THE EMP RESPONSE OF THE VLF/LF DUAL-WIRE ANTENNA ON THE E-4B

L. Marin*, C. E. Baum**, J. P. Castillo**

The presence of the VLF/LF dual-wire antenna on the E-4B is known to have a significant effect on the EMP excitation of the aircraft. The extreme length of the antenna makes it impractical to simulate the wire effects by direct illumination of the wires themselves. An approach based on current injections at the points where the wires exit/enter the aircraft appears to be the most feasible method. Three different aspects of the simulation problem will be discussed.

An analysis of the antenna response reveals that the EMP induced antenna currents consist of distinct pulses. In the first simulation scheme, each pulse is simulated using a separate simulation network. The interaction between the pulses is obtained by selecting the time when each simulation circuit is "switched on." The elements of the wave forming network are presented as well as the initial needed charge.

The antenna is designed to operate for frequencies between 16 kHz and 90 kHz. Any low-frequency content in the incident EMP will be picked up strongly by the antenna. The second aspect of the trailing-wire antenna simulation is therefore devoted to simulate the antenna's EMP response around its fundamental resonances. A circuit that accomplishes this task is presented. It should be pointed out that the periods of the simulated resonances are of the order of tens of microseconds and hence this simulation technique does not require the use of fast rise time generators.

The methods discussed above cover two important aspects of the trailing-wire antenna simulation. The third aspect deals with the simulation of the overall antenna response. A simple (but approximative) way of accomplishing this task is presented. The simulation is divided into two cases, namely: (1) the simulation of the total net current (common-mode current) injected to the aircraft from the two antenna wires, and (2) the simulation of the "loop current" (differential-mode current) in the loop formed by the two antenna wires and the aircraft. The first case simulates the induced charge density on the aircraft and, consequently, the electric-field penetration. The second case simulates the induced charge-less currents on the aircraft and, consequently, the magnetic-field penetration. The simulation techniques in each case are designed so that: (1) the simulated wire currents have the same "overall" spectral density for frequencies below 0.5 MHz, and (2) have the same total energy as do the wire currents calculated from an incident EMP.

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*The Dikewood Corporation, Santa Monica, CA 90405

**Air Force Weapons Laboratory, Kirtland AFB, NM 87117

SIMULATION OF THE EMP RESPONSE OF THE TACAMO AIRCRAFT WITH THE TRAILING WIRE ANTENNA DEPLOYED

J. L. Monroe

E. F. Laporte

ROCKWELL INTERNATIONAL
3370 Miraloma Avenue
Anaheim, CA 92803

ABSTRACT

A method for simulating the response of the TACAMO aircraft with the trailing wire antennas deployed has been developed and is being used in system testing of the TACAMO EC-130G. The method is based on analysis of the trailing wire antenna response to EMP excitation as seen at the aircraft. A capacitive discharge pulser system is used to excite the aircraft/antenna system with transients similar to those predicted by analysis. The design concepts for the pulser are shown, the test configuration is reviewed, and the system excitation is discussed.

QUASI-STATIC MAGNETIC-FIELD EMP SIMULATOR DESIGN STUDY

Kenneth D. Granzow
Joseph P. Martinez
Kendall F. Casey
The Dikewood Corporation
1009 Bradbury Drive, S.E.
Albuquerque, New Mexico 87106

The simulator geometry studied consists of current loops in pairs symmetrical about the equator of a sphere and lying on the surface of the sphere. The loop positions and relative loop currents were found that minimize r.m.s. error functions defined in terms of integrals over the volume and surface of spherical test volumes. The error functions were also minimized for various integer ratios of currents for the two-pair case. Results include the optimum parameter values, graphical representations of the error field, optimum loop positions for fixed current ratios, the sensitivity of the error functions to small changes in loop position and/or loop current, the driving point inductance and driving current requirements.

INTERACTION OF TEST OBJECT WITH SMALL LOCALIZED SIMULATOR

L. W. Chen

LuTech, Incorporated
5301 Central N.E.
Suite No. 1619
Albuquerque, New Mexico 87108

One of the more important simulator design questions is what one refers to as the simulator/object interaction. The object inside a simulator scatters fields which in turn are rescattered from the simulator back to the test object, thereby changing the ultimate response of the test object. This process can be viewed as a change in the kernel (Green's function) of an appropriate integral equation for currents or charges on the test object or as an infinite multiple-scattering sequence.

One would like to quantify the effects of this process so that the resulting errors can be kept down to an acceptable limit by making the simulator structure sufficiently distantly spaced from the test object. For the present discussion, changes in surface current and charge densities on the test object will be considered as the important measure of this error. However, depending on the specific shape and function of the test object, there are other parameters one might consider as well. Examples are inductance or capacitance changes in the test object and mutual inductances and capacitances to the simulator where appropriate for certain types of antennas; for such antennas one might also consider changes in open-circuit voltage and/or short-circuit current at their terminals. For apertures, on the other hand, one might consider changes in the equivalent dipole moments due to the simulator/aperture interaction mechanism.

Other kinds of changes associated with this effort are also observable at the driving terminals of the simulator. Specifically, the inductance of an H-field type and the capacitance of an E-field type of simulator will be changed by the presence of the object, and so parameters such as these should be considered.

Examples will be given to quantify the simulator/objective interaction in solving various canonical problems which have been published in the literature.

MEASUREMENT AND INTERPRETATION OF THE RESPONSE OF A SLOW WAVE STRUCTURE (THE HELIX) IN THE MARK I HDL AURORA SOURCE-REGION EMP SIMULATOR

M. Bushell, R. Manriquez, G. Merkel, W. Scharf, and D. Spohn

US Army Electronics Research and
Development Command
HARRY DIAMOND LABORATORIES
Adelphi, MD 20783

In a series of antenna response measurements in the Mark I HDL AURORA Source-Region EMP Simulator, we have studied the properties of a number of fundamentally different antenna configurations (such as: loop antennas, linear antennas, inductively-loaded antennas, and capacitively end-loaded antennas) when these antennas were subjected to an electromagnetic field in a medium with time-varying conductivity. In this paper, we describe the response of a more complicated slow wave structure antenna, the helix, when it is subjected to this environment. The ultimate goal of our work is to employ slow wave structures, such as a helix, in the construction of a simulator of the response of a long cable to the source-region EMP. By employing slow wave structures we hope to simulate physically long cables with much shorter slow wave structures. We are attempting to determine the fundamental similarities between the response of a slow wave structure, helix, etc., and a transmission line or cable to an EMP in a medium with time-varying conductivity. The experimental measurements and our equivalent circuit interpretation of the helical antenna measurements will be presented.

SIMULATION OF LONG LINEAR ANTENNAS WITH SHORT LOADED ANTENNAS IN A MEDIUM WITH TIME-VARYING AIR CONDUCTIVITY

M. Bushell, R. Manriquez, G. Merkel, W. Scharf, and D. Spohn

US Army Electronics Research and
Development Command
HARRY DIAMOND LABORATORIES
Adelphi, MD 20783

The HDL Mark I parallel-plate source-region EMP simulator, in its present configuration, has a test volume with a maximum dimension of 3 m (in the direction of the incident electric field vector). In the work presented here, we attempt to ascertain whether a "short" loaded antenna (dimensionally smaller than 3 m) could be employed to simulate the response of a much longer antenna to a source-region-like EMP. In this effort, the responses of a number of properly chosen inductively- and/or capacitively-loaded antennas were studied in the time-varying air conductivity of the Mark I EMP simulator. We used both simple linear short antenna theory and Harrington's method of moments to design loaded antennas that had approximately the same effective height and impedance as the antenna to be simulated over the frequency domain in question. The responses of the loaded antennas were then measured in the Mark I HDL simulator (with and without the presence of time-varying air conductivity). Due to the above-mentioned space limitations, measurements of long antenna response could not be made. Comparisons were made using computer models. Specifically, the response of the simulated long linear antenna to the same environment was calculated with Merewether's finite difference code, and the results compared to the measured responses of the loaded antenna. The measured responses of the loaded antennas have also been interpreted with equivalent circuits and with a finite difference code. The experimental and theoretical results will be presented.

HDL SOURCE-REGION SIMULATION PROGRAM: THE NEW MARK II SIMULATOR,

M. Bushell, R. Manriquez, G. Merkel, W. Scharf, and D. Spohn, US Army Electronics Research and Development Command, HARRY DIAMOND LABORATORIES, Adelphi, MD 20783.

In 1979, HDL conducted two very successful source-region EMP (electromagnetic pulse) simulation experiments in which the responses of a great number of antenna types, and also the response of a US Army AN/PRC-77 radio, were investigated. The time-varying air conductivity for these experiments was produced by the AURORA Flash X-Ray Facility. In AURORA, bremsstrahlung is produced in four thick tantalum targets by four synchronous 10-MeV electron beams. The bremsstrahlung then produces an EMP signal through the same mechanism as does a nuclear bomb. It induces Compton electron currents in the AURORA test cell chamber. As the Compton electrons are slowed down, they ionize the air and also produce an electromagentic field in the chamber. However, the Compton current is confined to a relatively small volume so that a relatively small electromagnetic field is produced. Also, the rise rate of the gamma radiation pulse is slower than desired. These two facts render the unmodified AURORA machine unsuitable as a source-region EMP simulator. The source-region simulation experiments which used the Mark I source-region simulator involved a large parallel-plate transmission line, Mark I (designed in cooperation with Dr. W. Crevier of MRC, Santa Barbara), that was positioned in the AURORA test cell.

In order to properly simulate coupling to relatively large systems, a traveling electromagnetic pulsed wave is required. Thus, a guided-wave structure is needed. Work has been done with a large (12 x 4 x 3 m) transmission line mounted laterally in the AURORA test cell. The line in the Mark I Simulator is driven by a 100-kV pulser which provides the appropriate propagating electric and magnetic fields. Simultaneously, AURORA is fired to provide a time-varying pulse of ionizing radiation. Unfortunately, these two effects are not independent. The time-varying conductivity creates a varying load on the pulser-line system and thus distorts the voltage pulse and, consequently, the electric field inside the line, resulting in a positive voltage pulse and a rising and overshooting E-field when the AURORA-produced air conductivity declines (the inductive kick). The change in load resistance cannot be entirely eliminated, since air conductivity is an essential feature of the environment to be simulated. In the Mark II source-region EMP simulator, the effect of the ionized air is minimized by allowing only the "work volume" to be ionized. This, in effect, results in two parallel transmission lines--the "master" line, which contains the work volume and undergoes ionization, and the "slave" line, which does not experience ionization. This effect can be achieved either by shielding the slave line or by filling it with some non-ionizing gas. The latter seems to be a more convenient approach. Another advantage of the master and slave line concept is that fringing fields in the AURORA test cell are desired and used. The work volume of the simulator can therefore be greatly increased. Theoretical interpretation of the operation of the Mark I simulator and the preliminary design of the Mark II simulator will be presented.

THE USE OF GASES OTHER THAN AIR AS MEDIA IN A SOURCE-REGION SIMULATION SCHEME, C. Kenyon, G. Merkel, W. Scharf, and D. Spohn, US Army Electronics Research and Development Command, HARRY DIAMOND LABORATORIES, Adelphi, MD 20783.

The most straightforward simulator for a source-region EMP would be one that produced the appropriate gamma pulse over the appropriate volume, and from which the proper fields and conductivity would naturally follow. However, even the best radiation source available (AURORA) is insufficient for this purpose for three reasons--its pulse rise is too slow by about a factor of ten, the irradiated volume (20m x 15m x 5m) is too small, and the metal walls of the test cell reduce the fields by shorting them out. As long as available radiation sources are limited as described above, there will be a need for an auxiliary source of pulsed fields and/or other devices or tricks to construct a satisfactory simulator. In any simulation scheme, it is usually not possible to obtain a precise mix of Compton electrons, time-varying air conductivity, and electromagnetic fields equivalent to the mixture produced by a real weapon. Actually, insight into the total response of a system to a source-region EMP can be obtained if the particular coupling mechanism could be enhanced over the other mechanisms.

It has long been realized that a nonattaching gas, such as N_2, can have useful properties in a source-region EMP simulation. In air, conductivity is limited by the attachment of electrons to the heavy oxygen molecules. By substituting nitrogen gas for air, the ratio of conductivity to ionizing radiation can be greatly increased. The production of a gas medium with time-varying air conductivity could very well be much more cost effective if a nonattaching gas such as N_2, Xe, Kr or A is substituted for air. The substitution of a nonattaching gas for air in a source-region EMP simulator does present a problem in that such gases have a tendency to form electron-depletion regions around negatively charged conductors. We have developed a method of minimizing the depletion layer formation with a grid structure and have measured the effectiveness of this technique. Noble gases that have a small addition of a complicated molecular gas such as CO_2 to cool down electrons have a behavior dominated by the Ramsauer effect; such gases have many intriguing physical characteristics that could make them a useful tool in source-region EMP interaction studies. Workers at HDL are investigating the possibility of tailoring the gas environment of a source-region EMP simulator to enhance various system interaction mechanisms.[1,2]

In the HDL Mark I source-region simulator the rise time of the displacement current is limited by the rise time of the parallel-plate transmission line. The rise time of the Compton current in the HDL Mark I source-region simulator is determined by the rise time of AURORA. The possibility will be discussed of employing the above "Ramsauer effect" gas mixtures with nonlinear conductivities in a source-region EMP simulator to enhance the rise time of the conduction current interaction $\sigma(E,t)E$. Preliminary calculations will be presented.

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ANALYTIC DETERMINATION OF THE TRANSIENT RESPONSE OF LOADED THIN-WIRE ANTENNAS BASED UPON A SEM REPRESENTATION

Ahmed Hoorfar and David C. Chang
Electromagnetics Laboratory
Department of Electrical Engineering
University of Colorado
Boulder, Colorado 80303

As it is well known in the EMP Community, the use of SEM representation is particularly useful in investigating the transient response of an antenna structure. A typical and interesting case is that of an unloaded as well as a loaded thin-wire dipole antenna. Analytical expression in the frequency-domain for the current induced on a thin-wire dipole antenna of radius a and half-length h has been previously obtained by Shen (IEE-APS, 16,5; 542-547, 1968) in terms of the current existing on an infinite antenna, plus the multiple reflections from the two ends. It has recently been shown that a modification of Shen's formula can yield a satisfactory result for a very broad frequency range under the condition, $(\ell n \frac{2h}{a})^2 >> (\ell n\ kh)^2$ where $k = \omega(\mu\varepsilon)^{\frac{1}{2}}$ is the free-space wave number (L. Rispin and D.C. Chang, University of Colorado, Scientific Report No. 38).

Equipped with these results, we have derived an analytical expression for the SEM poles of an <u>unloaded</u> thin-wire antenna; and uncovered the explicit expression for the current distribution of each mode, as well as the admittance function in terms of the product of modal functions. Excellent agreements with the numerical works for both the transmitting and receiving antennas were obtained.

In the present work, the problem is extended to include the transient response of a transmitting and a receiving, <u>loaded</u> thin-wire antenna. More specifically, when the load with impedance $Z(\omega)$ is located at $z = d$ on the antenna, we can show the positions of the SEM poles in the complex ω-plane can be determined from the modal equation:

$$D(\omega) = 1 - \Gamma^2(\omega)I_\infty^2(\omega;2h) + Z(\omega)f(\omega;d,d) = 0 \qquad (1)$$

where Γ is the reflection coefficient of an incident current wave onto the end of a semi-infinite antenna; $I_\infty(\omega;z-z')$ is the current at z on an infinitely-long antenna eminating from a source at z'. The function $f(\omega;z,z')$, which is given in terms of Γ and I_∞ is, in the absence of the load, the normalized current at z on the antenna due to a source at z'.

Results obtained for a resistive, a capacitive and an inductive center-loaded antenna compare very well with the numerical works of Liu and Mei (Radio Science, Vol. 8; No. 8,9; 797-804, 1973). In addition, for an off-centered-loaded antenna, a possibility of finding two different sets of SEM poles, each corresponding to resonances predominantly on one of the two segments of the antenna separated by the load, is discussed. The method can also be extended to a multiloaded thin-wire antenna.

EMP INTERACTION OF TWO ARBITRARILY ORIENTATED THIN CYLINDERS

T. H. Shumpert
Lloyd S. Riggs
Electrical Engineering Dept.
Auburn University, Alabama 36849

D. M. Schmale
U.S. Army Missile Command
Missile Intelligence Agency
Redstone Arsenal, Alabama 35809

The singularity expansion method description characterizing the scattering of an electromagnetic pulse by completely arbitrarily oriented cylinders will be presented. The problem will be cast in terms of a Pocklington type integrodifferential equation, and the Method of Moments employed to facilitate numerical investigation. Trajectories of the system complex natural resonances will be presented for a variety of scatterer orientations. It will be shown for this two-body problem that the fundamental resonances occur in pairs, and each pole of the resonant pair can be associated with either the symmetric or antisymmetric factorization of the problem [1]. In addition, for some configurations the resonant pole pair degenerates into a single pole of multiplicity two. The complete generality of the system geometry allows ready comparison to EMP-cylinder interaction problems treated by previous investigators [2], [3], [4], and therefore affords a deeper understanding of the scattering properties of cylinders.

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SEM ANALYSIS OF AN INFINITE PERIODIC ARRAY

D. H. Herndon, E. W. Smith, and E. J. Dombroski
HARRIS CORP.
MELBOURNE, FLORIDA

T. H. SHUMPERT
AUBURN UNIVERSITY
AUBURN, ALABAMA

The Singularity Expansion Method (SEM) is employed to determine the natural frequencies of an infinite periodic array. The natural frequencies of the surface are of interest since the periodic arrays are used as Frequency Selective Surfaces which are effectively filters. The currents and charges induced on the scatterers are treated using Floquet theory which is incorporated in a vector E-field integral equation. This problem contains branch cuts which affect the pole locations and trajectories. Data is presented to show the interaction of the branch cuts and poles. The SEM parameters are presented in the form of appropriate graphs and tables. In addition these data are compared with previously obtained data for multiple bodies.

SEM PARAMETER MEASUREMENT

K. S. Cho
C. A. Lin
J. T. Cordaro

University of New Mexico
Albuquerque, New Mexico

The singularity expansion method (SEM) parameters (natural frequencies, natural modes, and coupling coefficients) together with the incident field Laplace transform describe the natural response of a body to an EMP. There is some interest in computing these parameters from experimental data. Results from testing the method on transient data generated by a thin-wire code are given for an aircraft stick model. These results are compared with the parameters computed from scale model data and B-52 system level test data. It is shown that extra measurements can be used to improve parameter accuracy.

ON THE SOURCE OF PARAMETER BIAS IN PRONY'S METHOD

by

J. R. Auton
M. L. Van Blaricum

Effects Technology, Inc.
5383 Hollister Avenue
Santa Barbara, California 93111

Over the past several years the singularity expansion method (SEM) has provided a convenient way of characterizing the transient response of a scatterer. Prony's method[1] is a convenient numerical technique for solution of the inverse problem of characterizing the SEM description given a scatterer's transient response. Dudley[2] demonstrated that Prony's method is simply a technique for estimating the parameters of a linear system model and further demonstrated that these parameters are biased.

This paper shows that, strictly speaking, a transfer function cannot be defined for Dudley's model. In practice, the parameter values that cause the response of Dudley's model to most nearly match the response of the system being identified are used in a slightly different model, called the actual or true model[3], which has a well defined transfer function. This transfer function is then used as an estimate of the system transfer function. Hence, the parameter bias Dudley demonstrated is nothing more than the error incurred by transplanting parameter values of one model into another. This switch of models is not an accident or error but has definite advantages that compensate for the blight of biased parameter estimates. These advantages are discussed.

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EMP DATA CORRELATION TECHNIQUES*

G. Bedrosian and R. Christie
The Dikewood Corporation
Baltimore, Maryland 21210

Data correlation techniques find applications in the analysis of data from EMP simulation experiments. These uses include investigation of coupling modes in multi-conductor cables, POE tracing, noise filtering, and numerical expansion of EMP data in terms of poles in complex frequency space (the singularity expansion method).

Correlation techniques have been applied to the analysis of individual wire currents measured in a multi-conductor cable. Differential current modes were observed at two characteristic resonance frequencies.

Resonance structures which are particular to one POE can be used with some success to identify the dominant POE(s) for currents measured deep within a system. In order to accomplish this, it is helpful to construct digital filters which select only the particular frequency bands of interest.

Noise filtering is readily accomplished using autocorrelation techniques. In many cases, the autocorrelation of a measured signal reveals underlying structure not apparent in the original data. Because of the improved signal-to-noise ratio of the autocorrelation function, it is preferable to identify the poles in the singularity expansion of the original data by numerical analysis of the autocorrelation function.

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An Improved Algorithm for Representation of Frequency-Domain Data by Rational Functions.

Harold J. Price
Mission Research Corporation
1400 San Mateo, S.E.
Suite A
Albuquerque, New Mexico 87108

The representation of frequency-domain data by rational functions (ratios of polynomials) has many uses. For example, one may wish to determine system poles and residues from measured data, or one may wish to approximate an irrational function by a rational one.

Direct application of least-squares to this problem results in a nonlinear set of equations with their attendent difficulties. As pointed out by Brittingham *et al**, leasts-squares applied to a slightly modified problem results in a linear set of equations. In this paper, we apply eigenvalue methods to the modified problem and obtain better fits to the data than other methods. The development is done in a way which forces the resulting time function to be real.

In procedures of this type, some of the resulting poles represent increasing exponentials (right-half-plane poles). Using the algorithm described in this paper, it is possible to represent data so that all poles are in the left-half plane. Procedures to accomplish this are discussed.

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AN UNBIASED METHOD FOR THE ESTIMATION OF THE

SEM PARAMETERS OF AN ELECTROMAGNETIC SYSTEM

by

J. R. Auton

Effects Technology, Inc.
5383 Hollister Avenue
Santa Barbara, California 93111

To the author's knowledge all identification methods capable of providing unbiased estimates of the parameters of a linear system are iterative. Some of these methods require a large number of iterations to converge to the unbiased solution or may not converge at all. The iterative method presented in this paper offers a possible means of insuring and hastening convergence. The method is a modification of the adaptive method[1]. This hastening of convergence is accomplished by the use of adjustable filters in the parametric model of the system undergoing identification.

Similar to Prony's method[2], the present method may be used to find estimates of poles that characterize a given transient response. However, in contrast to Prony's method, it is an iterative technique that does not suffer from the problem of biased parameters. Dudley[3] indicated that the source of the noise sensitivity of Prony's method is the bias in the parameters. This implies that any technique that provides unbiased estimates should be relatively insensitive to noise. Numerical examples are presented to demonstrate this method's insensitivity to noise.

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PARAMETER ESTIMATION FROM NOISY TRANSIENT ELECTROMAGNETIC MEASUREMENTS

D. T. Gavel, J. V. Candy, J. E. Zicker
Lawrence Livermore Laboratory, Livermore, CA 94550

The study of EMP phenomenon has promoted the development of techniques to investigate transient electromagnetic response data. Characterization of the EMP transient response information is necessary to evaluate the performance of that system in a hostile environment. An efficient technique to characterize this performance is to fit an electromagnetic model to the data.

In this paper we describe the performance of three different signal processing techniques applied to parameterize a body from noisy experimental electromagnetic transient response data. We briefly describe the techniques which range from the well-known Prony method to the more sophisticated extended Kalman filter and finally to the highly sophisticated maximum likelihood identifier. We compare the performance of these algorithms and discuss their tradeoffs.

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EFFECTS OF AN AMBIENT GAS ON SGEMP*

W. E. Hobbs and D. E. M. O'Dean
JAYCOR
360 S. Hope Ave.
Santa Barbara, CA 93105

In this paper we will present a new model for estimating the high frequency SGEMP when the photo-induced boundary layer has translational symmetry. Although it is constrained by geometry, the model makes no assumptions about the currents. It therefore gives some insight into the physical processes involved and we will show its application by examining the effects of an ambient gas on the EM fields produced by photoemission. This analysis has application to missile-radiation coupling problems in the X-ray deposition region (50-100 km).

We begin with the wave equation for the magnetic field. This equation is greatly simplified by the introduction of the retarded time appropriate to the incident X-ray pulse as in the vacuum SGEMP analysis.[1] The result is a one-dimensional wave equation which can be reduced to quadrature using a Green's function. If the irradiated surface can be assumed to be a good conductor, we may use image currents. In this case, two of the integrals are trivial and the solution has an agreeable physical interpretation. The solution is simply a contour integral along the points in space and time which contribute to signals at the point and time of interest.

The surface signal is conveniently given by a single convolution integral in either space or time. If we take this surface solution and assume that the SGEMP width is much wider than the boundary layer and that the currents parallel to the surface may be ignored, then the integral reduces to the familiar electric dipole moment.[1]

The question arises as to what is the effect of introducing an ambient gas to the situation. The photoelectrons will ionize the gas creating their own plasma. The plasma electrons themselves will be strongly accelerated by the surface normal electric field so that avalanching will occur to produce additional low energy secondary electrons. When the gas density is greater than some critical density, the build-up of secondary electrons will exceed their convection into the surface. When this occurs space-charge limiting will not occur and the photoelectrons will continue propagating outward. The detached boundary layer leaves a dense plasma in its wake and this insulates the surface from continued strong EM radiation. In addition to the normal energy loss as the boundary works against its own electric field, it is continuously losing energy to ionization. The photo-boundary thus dissipates.

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*Work supported by the Defense Nuclear Agency

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SGEMP Electron Dynamics Near an Edge

John Dancz and Roger Stettner
Mission Research Corp.
735 State Street
Santa Barbara, California 93101

The dynamics of SGEMP generated electrons is studied, theoretically, near a 270° right elbow edge. Such geometries are important in characterizing SGEMP sources across gaps and other structures. Such studies will also yield analytical tools useful in providing models of SGEMP edge effects in sophisticated numerical codes. The basic methodology used was to assume a one-dimensional charge distribution above the top surface of the edge to simulate the SGEMP layer, analytically determine the resulting electrostatic potential in all space via a conformal mapping and the method of images, and then numerically determine the resulting dynamics of SGEMP generated electrons emitted with a $\cos\theta$ distribution in the specified electrostatic fields.

It was found that the electrons which succeed in going over the edge tend to originate within a few SGEMP layer thicknesses of the edge for the assumed charge distributions we investigated. Electrons which do go over the edge, though, tended to travel distances much larger than the SGEMP thickness. The behavior of these latter electrons was also characterized by an analytical model of the dynamics of a particle moving in a purely non-central potential, e.g. a potential which depends only upon the angle, θ, which the electron traverses around the edge.

ELECTROMAGNETIC EMISSION FROM ELECTRON BEAMS

H. S. Cabayan
Lawrence Livermore Laboratory, Livermore, CA 94550

Relativistic electron beams radiate energy covering the electromagnetic spectrum from radio wave frequencies up and including gamma rays. For a given current amplitude, the proportion of the energy in each type of radiation depends on the energy of the electrons.

In this paper, radiation from electron beams in the radio wave and gamma ray portions of the spectrum will be examined. Simple approximate formulae for quantities of interest will be derived and applied for hypothetical beam parameter values. The intent is not to derive rigorous relations but rather approximate levels that will help point out problems that may arise in instrumentation implementation and other electromagnetic compatibility (EMC) issues.

Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore Laboratory under Contract No. W-7405-ENG-48 and sponsored by the Defense Nuclear Agency under Subtask Code X99-QAXVD-403 "System Testing", Work Unit Code 02/Electron Beam EMP Applications.

DETERMINATION OF THE EMP AND SGEMP RESPONSE OF
CYLINDRICAL SCATTERERS BY NETWORK ANALOGS

W. R. Zimmerman and E. B. Mann
The BDM Corporation
1801 Randolph Road S.E.
Albuquerque, N.M. 87106

Abstract

The calculation of the external response of a cylindrical scatterer to EMP and System Generated EMP (SGEMP), generated by direct illumination of the system by nuclear-weapon induced ionizing radiation, has often been a necessary step in the determination of EMP and SGEMP induced transients at electronic interfaces. At present, external response calculations are often carried out by either solving numerically the integral forms of Maxwell's equations or by direct numerical integration of the differential form of Maxwell's equations.

In this paper an electrical circuit representation of Maxwell's equations will be discussed[1,2,3] for problems possessing azmuthal symmetry. This network analog, suitable for implementation or any large generalized circuit analysis computer program will then be used to determine the external response of cylindrical scatterers and resistively loaded dipole antennas to EMP and SGEMP external sources.

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QUALIFICATION MODEL SPACECRAFT TEST CONSIDERATIONS*

E. Paul Chivington and Richard H. Kingsland
TRW Defense and Space Systems Group
Redondo Beach, California 90278
(213) 535-3006

D. Cord Mounkes
Computer Sciences Corporation
Albuquerque, New Mexico 87108
(505) 265-9571

Charles A. Aeby
Air Force Weapons Laboratory
Kirtland AFB, New Mexico 87115
(505) 264-9056

SUMMARY

We describe the development and execution of an SGEMP test program on a qualification model spacecraft. This introductory paper was written because of the major effort that turned out to be required to implement such a program and describes many of the practical solutions employed. The objectives of the program were to:

1. Test certain features of hardened spacecraft as actually employed on the qualification spacecraft.
2. Evaluate limited testing for the purpose of SGEMP validation.
3. Gain experience using real spacecraft hardware.

TEST REQUIREMENTS

Short of a full simulation of the threat environment, limited testing may satisfy a subset of the hardness validation needs. To an extent, these limited test methods can be correlated with the hardening design features of the spacecraft. As an example, one way of designing a hardened spacecraft would be:

1. Develop an analytical model of the spacecraft to predict the coupled energy and determine hardening required.
2. Have a well connected spacecraft structure so that currents will not concentrate on cables.
3. Shield all electrical cables and boxes sufficiently to reduce cavity field and replacement current induced cable shield currents below the direct injection of signal wires.
4. Use interface protection on pins where the direct injection energy may cause circuit failure.
5. Use an upset tolerant electronic design so that transients do not adversely affect spacecraft mission.
6. Test the hardening features employed.
7. Validate the model developed in 1.

This test program will address each of the hardening design features.

LESSONS LEARNED

The completed paper will discuss the lessons learned in preparing for and testing a spacecraft. Below is an example of the types of problems encountered.

*work supported by Air Force Weapons Laboratory

Hardware Configuration

The qualification model spacecraft is a representation of the spacecraft design early in the development program and may not be representative of the final production. Some of the differences of significance for our testing were:

- o No full complement of solar panels. Only one panel was built for testing. For full body tests of the spacecraft, a simulation of the solar panels was to be constructed.
- o Thermal Blankets - A set of test thermal blankets had existed but were largely in unusable condition. Because the blankets are dielectric with aluminum film backing, they may exhibit both spacecraft charge up and electromagnetic shielding properties.
- o Antennas - The spacecraft did not normally communicate through a radiated link during testing. However, a hardwire link would interfere with the electromagnetic configuration of the spacecraft.
- o Hardening Design Changes - The qual model does not necessarily use high reliability parts or go back and incorporate all subsequent design changes.

SCREENING, CATEGORIZATION, AND CLASSIFICATION FOR NUCLEAR ASSESSMENT OF SATELLITES USING NHEP-S

by

J.F. Hunka, M.L. Van Blaricum, A.R. Hunt

Effects Technology, Inc.
5383 Hollister Avenue
Santa Barbara, California 93111

The number of possible analysis sites which must be addressed when performing an assessment of the nuclear hardness of a satellite system, or any complex electronic system, requires that careful consideration be given to which satellite elements are evaluated and in what order and to what degree they will be analyzed. A satellite system with typically sixty-thousand pieceparts has potentially a million analysis sites when all the nuclear weapons effects are considered. Practically, each element can not be analyzed individually. Thus, screening procedures are needed to reduce the analytical burden to a tractable level.

The NHEP-S Methodology is a systematic set or procedures designed to minimize oversights in the design and hardness assessment of satellites. The methodology contains screening procedures which require elimination of elements based on functional considerations first, classification and grouping of similar elements for common analysis next, and finally, elimination of groups of elements by comparison of their performance with that of all groups.

This paper presents the classification and categorization techniques which were developed as part of the general screening procedures in the NHEP-S Methodology. Specific examples and discussions will be given of the classification and categorization process used for the indirect nuclear effects (SGEMP, DEMP) analysis of a complete satellite subsystem.

This work supported by DNA, Contract #DNA001-78-C-0307.

AIR LAUNCHED CRUISE MISSILE EMP ANALYSIS

Stephen W. Kormanyos
Edward J. Quenemoen

Boeing Aerospace Company
P. O. Box 3999 M/S 44-66
Seattle, Washington 98124

The Air Launched Cruise Missile (ALCM) is a strategic missile launched from a B-52 some distance from its target. The ALCM then flies a planned route to its target using an on-board computer in conjunction with inertial and terrain matching navigation systems.

The Boeing Comapny has designed the AGM-86B Air Launched Cruise Missile to comply with stringent government electromagnetic pulse environments. As a part of the EMP qualification, a missile level analysis was done.

After briefly summarizing the EMP requirements and the missile design features to satisfy these requirements, the paper describes in detail the three part ALCM EMP analysis.

The first part was to demonstrate that the electromagnetic field environment adjacent to the navigation guidance and control and engine segment equipments have a peak amplitude 30 dB lower than the combination of incident and scattered fields resulting from the specified free field EMP. All missile penetrations were analysed. The missile seams were found to be the dominant penetration.

The second part was to demonstrate that internal ALCM equipments are capable of withstanding equipment case currents of six amps/inch at frequencies between 100 KHz and 100 MHz without upset or damage of internal components. In this analysis the internal EM fields and internal transients due to these fields were calculated for all ALCM equipments. Safety margins were determined and tabulated.

The third part was to calculate the magnitude of the interface transients appearing at internal equipments as the missile is illuminated by the specified EMP. This analysis consisted of external coupling, penetration coupling, and internal coupling.

All three parts of the analysis utilized the PRESTO EMP analysis computer codes.

The paper details the approach taken for these analyses and tabulates the results.

In addition, the correlation of the analyses results with subsequent missile level direct drive and free field tests is discussed.

DETERMINATION OF POEs AND CABLE EXCITATION FROM E-3A EMP DIPOLE TEST DATA

L. Marin
The Dikewood Corporation
Santa Monica, California 90405

The E-3A EMP Dipole Test was conducted at the HPD/VPD-II test facilities during 5 months in the summer and fall of 1978. During this test, special experiments were performed to establish the major POEs of the E-3A and the excitation mechanisms of different cables.

The test procedures used during the POE identification experiment and the results obtained from the experiment will be presented. It was found that cables penetrating the pressure hull are very important means through which electromagnetic energy can penetrate into the aircraft. It was also found that most cables are mainly excited through mutual coupling to cables penetrating the pressure hull rather than through some other mechanism. Results for the current distribution along cable runs and the distribution of currents in different wires in a wire bundle will also be discussed.

E-4B SYSTEM LEVEL EMP TEST

Walter L. Curtis
Boeing Aerospace Company
P. O. Box 3999
Seattle, WA 98124

The E-4B consists of a Boeing 747 aircraft that has been modified to serve as an airborne command post and hardened against EMP. The Complete hardened system was EMP tested in the HPD and VPD II simulators at Kirtland Air Force Base, New Mexico during the period of February through June 1979. This paper will provide a summary description of the tests which were conducted, how the tests were performed, and the test results obtained.

There were over 2000 pulse response measurements made which consisted primarily of open-circuit voltage measurements but also included bulk current, short-circuit current, surface current density and normal E-field measurements. The test points were chosen to cover all locations, wire routing, wire shielding types and some to correspond to points used in a previous EMP test on an unhardened 747. Measurements were taken to show effects of aircraft configuration, orientation of the aircraft and polarization of the incident pulse. Tests were also made to check linearity by using different pulser levels. In addition, both simulated power on and actual power on tests were made. Finally, a series of tests were made with individual EMP hardening fixes degraded in order to show the effectiveness of the various hardening measures.

The results of the test showed that the average peak open circuit voltage measured at points inside the pressure hull was only .5 volt.

TEMPAT II, HARDENING VERIFICATION OF TACAMO

R. V. Whiteley

ROCKWELL INTERNATIONAL
3370 Miraloma Avenue
Anaheim, CA 92803

ABSTRACT

The TACAMO EMP Assessment Test (TEMPAT) II is now being performed to evaluate the EMP survivability of the TACAMO EC-130 with prototype hardening installed. The planning, organization, and structure of this test has been developed to meet the test objectives and yet allow flexibility in testing to accommodate the unexpected. This approach results in a high quality program with minimum risk. The critical elements of test planning and performance of TEMPAT II are reviewed in this presentation.

AIR LAUNCHED CRUISE MISSILE EMP DIRECT DRIVE TEST

Charles A. Rolfe

Boeing Aerospace Company
P. O. Box 3999 M/S 44-66
Seattle, Washington 98124

The Air Launched Cruise Missile (ALCM) is a strategic missile launched from a B-52 some distance from its target. The ALCM then flies a planned route to its target using an on-board computer in conjunction with inertial and terrain matching navigation systems.

The Boeing Company has designed the AGM-86B Air Launched Cruise Missile to comply with stringent government electromagnetic pulse environments. As a part of the missile EMP qualification, a direct drive test was run.

After briefly summarizing the EMP requirements and the missile design features to satisfy these requirements, the paper describes in detail the ALCM EMP direct drive qualification test performed during August-September 1979 at the Boeing Company, Seattle, Washington.

The EMP pulses were injected at the selected mission critical interface circuits via breakout boxes. The missile was tested in the following test modes:

a. Power on/specification level

b. Power on/twice specification level

c. Power off/specification level

d. Power off/twice specification level

The missile was monitored for upset or failure.

During power on testing, during which the missile was operated in a simulated free flight mode, the monitoring was done in real time by using the flight test instrumentation system and receiving station.

There were 140 test points, trapezoidal and damped sine pulses were used, each pulse was applied 10 times, both positive and negative trapezoidal pulses were used.

The test pulse generation, missile monitoring techniques, and test results are discussed in the paper.

Title: EMP Assessment of the PATROIT Candidate 150kW Mobile Electric Power Plant

Samuel A. Clark, Jr.
(Formerly of Harry Diamond Laboratories)
Technology Development of California
624 Six Flags Drive
Arlington, Texas 76011

Robert Garver
U.S. Army Electronics Research and Development Command
Harry Diamond Laboratories
Adelphi, Md 20783

AND

James Washington
U.S. Army Electronics Research and Development Command
Harry Diamond Laboratories
Adelphi, MD 20783

Abstract

The candidate 150kW Mobile Electric Power Plant for PATROIT has been assessed for vulnerability to electromagnetic pulse (EMP) induced transients. The assessment included field tests of the generator and loads with field-cable layout using the Repetitive Electromagnetic Pulse Simulator (REPS) and Vertical EMP Simulator (VEMPS), cable-driving experiments, and circuit analysis using the NET-2 computer code. The purpose of the field tests was not only to determine the transients to critical circuits but also to determine the dominent means by which the transients were coupled to the circuits. After careful design and construction of the power distribution unit, load shelters, and cable shield terminations, it was determined that the dominant coupling to the control circuits in the generator was via aperatures in the generator housing.

It was also determined that engineering measures taken to make the turbine engine survive in the engine compartment environment of a commercial truck tractor enhanced the survivability of most of the control circuits to EMP.

AIR LAUNCHED CRUISE MISSILE EMP FREE FIELD TEST

Alan M. Smith
Stephen W. Kormanyos

Boeing Aerospace Company
P. O. Box 3999 M/S 44-66
Seattle, Washington 98124

The Air Launched Cruise Missile (ALCM) is a strategic missile launched from a B-52 some distance from its target. The ALCM then flies a planned route to its target using an on-board computer in conjunction with inertial and terrain matching navigation systems.

The Boeing Company has designed the AGM-86B Air Launched Cruise Missile to comply with stringent government electromagnetic pulse environments. As a part of the missile EMP qualification, a free field test was run.

After briefly summarizing the EMP requirements and the missile design features to satisfy these requirements, the paper describes in detail the ALCM EMP free field qualification test performed during September-October 1979 in the ALECS at the AFWL.

There were three test phases: Mission Completion, Transient Measurements, and Intentional Hardness Degradation.

During the first phase, Mission Completion, the Air Vehicle was operated in simulated free flight. Missile power was supplied by turning the missile DC generator with a hydraulic motor which in turn was driven by a hydraulics cart. Non-conductive hydraulic hoses were used. The missile status was monitored in real time using a fiber optics data link. The missile status monitoring criteria, the hydraulic power system, missile status monitoring system, in process checks, success criteria, and test results are discussed.

During the second phase, Transient Measurements, 53 measurements were made at equipment interfaces. Open circuit voltage and short circuit current measurements were made. The data was collected using a high bandwidth fiber optic link, was recorded on the AFWL DASET-B system, and reduced on the AFWL ADSET system. The paper discusses the test point selection criteria, the data collection system, in process checks, corrections applied to the data, success criteria, test results, and correlation of the test results and the pre-test analysis.

During the third phase, Intentional Hardness Degradation, eight test points were monitored using the same techniques as in phase 2 during eight hardness degradations. The degradations are discussed and the resulting changes in safety margins are tabulated.

The ALCM passed all the tests. High design margins were observed.

ELECTROMAGNETIC PULSE PREDICTION CAPABILITIES

LCDR W. E. Rabke, CEC, USN
EMP Effects Division
Defense Nuclear Agency
Washington, DC 20305

Edward L. Arnold
Consultant, GE-TEMPO
816 State Street
Santa Barbara, California 93101

Byron P. Gage*
R&D Associates
4640 Admiralty Way
Marina Del Rey, California 90291

Abstract

Electromagnetic pulse (EMP) simulation experiments conducted in 1978 under sponsorship of the Defense Nuclear Agency have provided an excellent data base for evaluation of various EMP response prediction techniques and experimental simulation approaches. The experiments were conducted at a major United States military communications center in Hawaii, and sufficient data were obtained to establish confidence of predictions when applied to nuclear EMP assessments. Several different simulators were used. Pulse simulation sources were the Transportable Electromagnetic Pulse Simulator (TEMPS) and a low-level Repetitive Pulse Generator (RPG). A newly developed stepped frequency continuous wave radiator (CWR) was employed to evaluate the technique of using a non-interfering low-level radiator to determine a transfer function from which a pulse response can be obtained using Fourier techniques.

*Currently with Boeing Military Airplane Co, Seattle, WA

Statistical Interpretation of Component Test Results in EMP Hardening and Vulnerability Assessment

William R. Graham

Charles T.C. Mo

R&D Associates
Marina del Rey, California 90291

Since the nuclear weapon-generated electromagnetic pulse (EMP) does not occur in the natural environment, systems, subsystems, and components cannot obtain an engineering legacy of exposure and hardness to EMP through ordinary practice. To meet the need for EMP hardening, some system designs have been implemented, and even more proposed, that depend for their EMP hardness upon the ability of components, sometimes numbered in thousands, to withstand levels of electrical stress greater than the levels that they encounter in peacetime operation. This places the burden of proof of EMP hardness at the component level. In determining the vulnerability of thousands of components, without the benefit of frequent system-wide exposure in the EMP environment, it has been proposed that special purpose component testing be used to establish a statistical basis on which component hardnesses and hence system hardness are then characterized.

In this paper, we delineate the need, use, and limitation for statistical schemes in characterizing component and system hardness, and we present several simple examples. Outlined and illustrated are relations and linking procedures among the testing and prediction schemes, the data quality and quantity, and the confidences in the results. Some answers are of immediate practical interest.

Then, we present a generalized and yet extremely simple conceptual scheme that handles in a clear way many relevant statistical problems. The scheme explicitly separates and relates the a posteriori data-based information and the *a priori* logic and physics. We emphasize that all different types of data statistics and their assumptions and quantifications can be used in the scheme described.

Following this, we give another slightly more complicated example to illustrate the power of the scheme in reducing and clarifying complicated problems into conceptually straightforward data requirements and calculations. Finally, we suggest several important areas worthy further investigation.

AIRCRAFT PROBABILITY OF SURVIVAL AS A FUNCTION OF THE RESPONSE DISTRIBUTION

Robert S. Carter
Boeing Aerospace Company
P. O. Box 3999
Seattle, WA 98124

The response of the E-4B aircraft wiring to an excitation from the AFWL HPD/VPD II EMP simulators has been measured. These measured responses were compared with responses calculated from a transmission line model of the wiring excited by aircraft penetrations. Voltage and current were grouped by shielding type and wire routing and response error histograms were determined for each class. The mean value, standard deviation, and maximum error were found for each error histogram. These statistics were used to formulate the response probability density function. Density functions considered in the analysis included lognormal, truncated lognormal, and asymmetric log-normal. Chi-square tests of the goodness of fit were performed to assess the likelihood that the variate follows the particular distribution being considered.

A safety margin probability density function was calculated by forming the correlation of the response probability density function and a lognormally distributed threshold variate. The dependence of the safety margin distribution on the particular response distribution used in the correlation is discussed. The dependence of the probability of survival on the response distribution is also considered, where the probability of survival is found by integrating the safety margin probability density function from zero to infinity.

A STATISTICAL APPROACH TO EMP COUPLING WITHIN A COMMUNICATION FACILITY

AUTHORS: Dr. Forrest J. Agee, Dr. Phil H. Dittmer, Mr. William G. Parsons and Mr. Ronald L. Rothrock

The BDM Corporation, 7915 Jones Branch Drive, McLean, VA 22102

ABSTRACT:

The DNA Project APACHE assessments of PACOM Command, Control, Communications and Computer installations included a simulated HEMP test at NAVCAMS EASTPAC as a validation phase. This TEMPS test at the largest and most complex communications facility in PACOM provided a sampling of the currents and voltages coupled into communications and computer equipment. These data were used in the APACHE program to quantify the prediction errors associated with state-of-the-art assessment methods. In this paper the data have been analyzed in another way to define the distribution of currents and voltages that can be expected to occur from HEMP in facilities for which long external penetrations are either not present or have been attenuated by terminal protection technology. The APACHE test data base included hundreds of individual measurements, quantification of test errors, and a classification of test points by communications element that make the data base especially useful for this kind of analysis. The methodology and some applications are discussed that include an approach to treating an EMP problem for which the specific layout of communications gear, and cabling are not well defined. The approach includes a means of computing probability of survival for equipment in structures of varying degrees of shielding.

PROOF OF A GENERALIZED LOCASSO CONJEXURE

R. M. Bevensee
Lawrence Livermore Laboratory, Livermore, CA 94550

This Conjexure concerns the reliability interval R and confidence C_x in that reliability of a sum of N random variables $X = \sum x_i$ given the R-reliability intervals at confidences C_i of the x_i. The x_i are assumed to come from normal populations $N(0, v_i)$ of zero means and unknown variances v_i. Samples $x_{i1}, \ldots, x_{in}$ are taken in each i-population and the sample variances

$s_i = \sum_{j=1}^{n} x_{ij}^2/n$ and covariances $s_{ij} = \sum_k x_{ik}\, x_{jk}/n$ are calculated.

Assuming 1) no knowledge of each probability distribution $p_i\,(\nu_i)$ of the i^{th} variance as a random variable, except, perhaps, that it is bounded above and below by $(\nu_i)_{max}$ and $(\nu_i)_{min}$, 2) all the $(\nu_i)_{max}/s_i$ are equal, as are the $(\nu_i)_{min}/S_i$, and are equal to $(\nu_x)_{max}/s_x$ and $(\nu_x)_{min}/s_x$, respectively, and 3) the same number of sample values n of the x_i for each i-population we prove the following:

If $(-e_i, e_i)$ is an R-reliable interval for x_i at confidence C_i and $(-E, E)$ the R-reliable interval for $X = \sum x_i$ at confidence C_x then

$\left(C_i\right)_{max} \geq C_x \geq \left(C_i\right)_{min}$ provided $E^2 = e_1^2\left(1+\beta_1\right) +\text{---}+ e_n^2\left(1+\beta_n\right)$,
with $\beta_i = \sum_{j\neq i} s_{ij}/s_i$ assumed ≥ -1.

This inequality among the confidences is true even if the x_i are correlated, in which case some β_i do not approach zero as n approaches infinity.

For the special case of $\left(C_i\right)_{max} = \left(C_i\right)_{min} = C$ Locasso's Conjexure* -- that $C_x \geq C$ for $E^2 = \sum e_i^2$ at common reliability level R -- is only true if $\sum e_i^2 \geq \sum e_i^2\left(1+\beta_i\right)$, which could only occur if one or more of the β_i were ≤ 0. (The β_i are constrained by $s_x = \sum_i s_i\left(1+\beta_i\right) > 0$.)

Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore Laboratory under Contract No. W-7405-ENG-48 and sponsored by the Defense Nuclear Agency under Subtask Code R99-QAXEC-301 "Data Collection and Evaluation", Work Unit Code 83.

*J. V. Locasso, "The Confidence in Combinations of Imperfectly Known Variances", Prob. and Stat. Notes, Note 9, Air Force Weapons Lab, 8 July, 1977.

A NEW METHOD OF CALCULATING DAMAGE MARGINS

James V. Locasso
Rockwell International
3370 Miraloma Avenue
Anaheim, California 92803

ABSTRACT

Accurate EMP damage margins are important because they can affect hardening requirements and hence hardening costs. Margins calculated to date have generally been quite conservative because there has been no known way to accurately compare broad band EMP threat spectra to the usual damage thresholds. The latter are generally a function of frequency, and any one given threshold is meant to apply only in a narrow range of frequencies.

This paper introduces the concept that components of the EMP threat spectra can be weighted to make them "damage equivalent." Under certain assumptions of junction heating, it is shown that the familiar threshold curve (threshold versus frequency) is a valid current weighting function. The "damage equivalent" current leads to margins which are larger and less conservative than would normally be calculated.

The derivation depends on certain assumptions, and experimental verification is needed. The results are intuitively appealing, however, and deserve further consideration.

BOUNDING EMP DAMAGE THRESHOLD PREDICTION UNCERTAINTIES*

D.L. Durgin and R.S. Shoup
Booz, Allen & Hamilton Inc.
4330 East West Highway
Bethesda, Maryland 20014

ABSTRACT

The EMP assessment and protection of existing and new weapon or C^3 systems requires knowledge of the inherent electrical overstress failure thresholds of electronic systems. During the past ten years various theoretical and/or experimental techniques have been developed to provide estimates of the EMP failure thresholds of electronic devices, circuits and subsystems. The current approach entails the use of small sample pulse test results or empirical models derived using the existing experimental data base to predict thresholds for untested devices. Since these device/circuit level predictions are frequently used in conjunction with EMP coupling analyses to make hardening allocation decisions and to design EMP protection, the statistical uncertainties associated with these predictions must be understood. This paper presents a brief overview of the evolution of electronic device EMP failure models and describes the results of a detailed analysis of the uncertainties associated with the models currently used on such programs as the B-52, APACHE and F-16.

The information presented includes the following:

(1) A description of the theoretical basis for and limitations of each model algorithm currently in use, specifically including the relationships used for diodes, transistors and integrated circuits.

(2) A discussion of the experimental data base that has been developed to support assessments and model development, specifically including a description of the data base contents including device types, sample sizes, key parameters, etc.

(3) A quantitative evaluation of the uncertainties associated with each level of the device failure threshold determination hierarchy, i.e., the use of large sample test results, the use of small sample test results, the use of empirical models and the use of derivative (semi-empirical) models.

This paper will discuss the advantages and limitations associated with current analytical techniques and will present a recommended approach for determining device EMP damage thresholds. Finally, areas requiring improvement will be identified and approaches to accomplishing these improvements will be summarized.

* This work was sponsored by the Defense Nuclear Agency.

AN INVESTIGATION OF THE PREDICTIVE CAPABILITY OF THE JUNCTION CAPACITANCE DAMAGE MODEL FOR SEMICONDUCTOR DEVICE TRANSIENT FAILURE

Michael J. Vrabel

US Army Electronics Research and
Development Command
HARRY DIAMOND LABORATORIES
Adelphi, MD 20783

For all the difficulties engendered in its use, semiconductor device damage data are an integral part of many programs of EMP vulnerability assessment and hardening. Experimental damage data, which are generated only as a result of dedicated efforts, can be expected to be available for only a minor fraction of all semiconductor devices. This has spurred efforts to develop predictive damage models, in order to bypass the tedious experimental requirements for generating damage data. The predictive ability of the best of these models, the junction capacitance damage model, is investigated in detail.

Central to this study is a library of experimental damage data for 46 silicon device types, comprising bipolar transistors and diodes tested at the 10, 1, and 0.1 μs pulse durations. These are devices from the front-ends of a number of Army systems and represent radio, field-wire, and cable functions with operating ranges in the dc to microwave region. Of the 46 experimental devices comprising 68 junction types (with E-B and C-B junctions treated as distinct for all transistors), sufficient published manufacturer's data was available for the damage modeling of 11 junctions. These were supplemented with measured parameters for 27 junction types. No measurable difference was observed between the model's predictive capability using the experimental parameters and that using manufacturer's model parameters. The ratios of experimental power to damage (for all tested pulse durations) to predicted value span a range from 0.00077 to 18--a skewed distribution, with 59% of all predicted values being overestimates of the power to damage.

With only 16% of the test-device population having sufficient published parameters to allow the junction capacitance damage model to be used, it is a valuable exercise to develop alternative, simpler, damage models--not so much as a substitute for the junction capacitance model but rather as a standard for comparison. The first considered was the dc power rating model. It was based on the supposition that there is some correlation between dc power ratings and transient power to damage. No distinction was made in the development of this model between forward or reverse dc ratings. The resultant model was applicable to 88% of the test-device population (based on published parameters) and demonstrated an agreement with the experimental power-to-damage data that was approximately a factor of 2 to 3 times poorer than the junction capacitance model. A second model was developed based on the manufacturer's rating of devices as high power or low power. This model considered the entire population of bipolar transistors and diodes (excluding microwave devices) as equatable to either of two devices with damage constants of 0.089 and 6.1 $W\text{-}S^{1/2}$. This model was applicable to 90% of the test population and demonstrated the same level of correlation with the experimental damage data as the junction capacitance damage model.

COMPUTER SIMULATION OF SECOND BREAKDOWN IN SILICON-ON-SAPPHIRE DIODES

A. L. WARD

U.S. Army Electronics Research and Development Command
Harry Diamond Laboratories
Adelphi, MD 20783

The HDL electrothermal-mode[1] computer program has been used to simulate second breakdown of a silicon-on-sapphire diode described by Baruah and Budenstein.[2] The diode is 30-μm wide and doped to $N = 1 \times 10^{16}$ cm^{-3}. Constant-temperature static characteristics have been calculated for 300, 350, 400, and 500 K. First breakdown occurs at 60 V and second breakdown (maximum voltage) at 410 V at 300 K and at 70 V and 440 V, respectively, at 500 K. Avalanche oscillations[3] are calculated in the range of current densities of from 5×10^3 to 5×10^4 A/cm^2. The frequency varies from 5 to 20 GHz, depending on the current density and temperature. The oscillations affect the second-breakdown transient.

It is shown that the current density cannot exceed $Ne\, v_{sat}$ until the avalanche field at the NN^+ junction is reached; then the holes neutralize the space charge of the excess electrons. When negative resistance is attained, the field drops rapidly except at the P^+N and NN^+ junctions.

Besides constant-temperature simulations, calculations have been made with extrapolated-temperature distributions. The resulting static current/voltage characteristics are but little different from the isothermal ones. Therefore, the static characteristics at various temperatures may be used[4] to calculate power versus time to breakdown curves with confidence.

Comparison of calculated results with experimental measurements will be presented.

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1. A.L. Ward, "Understanding Second Breakdown," NEM 1978 Record, p.37.

2. A. Baruah and P. P. Budenstein, "An Electrothermal Model for Current Filamentation in Second Breakdown of Silicon-on-Sapphire Diodes," Proceedings of the 1979 Electrical Overstress/Electrostatic Discharge Symposium, RAC/RADC pp. 126-132.

3. A. L. Ward and C. Fazi, "Avalanche Oscillations and Second Breakdown," NEM 1978 Record, p. 38.

4. A. L. Ward, "Doping Profiles and Second Breakdown," Proc. 1979 EO/ESD Sym. pp. 109-115.

APPLICATION OF NEC AND NET-2 CODES TO ANTENNA RESPONSE UNCERTAINTIES*

L. C. Martin, R. M. Bevensee,
E. J. Bogdan and G. J. Burke
Lawrence Livermore Laboratory, Livermore, CA 94550

This paper presents an approach which utilizes two large computer programs and work on circuit modeling to analyze the problem of uncertainties in EMP coupling to an antenna system. The Numerical Electromagnetic Code (NEC)** is the principal tool which provides the variation of antenna performance parameters with ground effects. NET-2, a powerful circuit and systems simulation program, is then used in several ways. First, the optimization solution feature provides an approximation of antenna impedance and effective height with circuit parameters. Second, the transient response capability of NET-2 is used in a direct input-output manner with a specified input and load. Finally, the Monte Carlo solution feature of the program demonstrates the significance of uncertainties when parameters are specified by distribution entries. The approach is illustrated by application to a case of a "whip-on-box" antenna system with several cases for comparison.

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**"Numerical Electromagnetic Code (NEC)-Method of Moments," Naval Ocean System Center, Technical Document 116, prepared for Naval Electronics Systems Command (ELEX 3041), G. J. Burke and A. J. Poggio, Lawrence Livermore Laboratory, 18 July 1977 (also Report AFWL-TR-76-320).

Currents Induced on a Bare Cable Inside a Missile

T. C. Tong, A. Sankar and P. Parhami
TRW Defense and Space Systems Group
Redondo Beach, California, 90278

Abstract

Recently TRW has developed a unique approach to calculate the current induced on an arbitrary bare cable inside a missile due to an EMP source. In this approach we modeled the missile by an open-ended conducting tube of finite length. The tube is illuminated by an arbitrary EMP source. By using Kao's[1] method we formulated this scattering problem in terms of a pair of pseudo-coupled E field integral equations in the frequency domain. The integral equations which involve only one-dimensional integration were solved readily by method of moments for the surface currents. Once the surface currents were known, the transient fields inside the missile were obtained by performing a Kirchhoff type integral and a Fourier transform. Assuming that the bare cable was small and did not perturb the field, we could use the computed field as the excitation source for the bare cable. To compute the current induced on the cable, a time-domain E field integral equation was formulated for an arbitrary curved thin-wire in free space. The integral equation was then solved by the finite element method[2]. Both computer programs have been developed, and good numerical results were obtained and will be presented.

1. C. C. Kao, "Three Dimensional Electromagnetic Scattering from a Circular Tube of Finite Length," J. of App. Phys., Vol 40, Nov., 1969.

2. A. Sankar and T. C. Tong, "Finite Element Application to Transient Scattering Problems, "TRW technical report prepared for Air Force Office of Scientific Research, Washington, D.C., AFOSR-TRW-79-002, October 1979.

End Corrections for Coaxially-Driven Monopoles

Marvin E. Morris
Applied Biology and Isotope Utilization Division 4535
Sandia National Laboratories
Albuquerque, NM 87185

ABSTRACT

Experiments with monopole antennas are often performed with only one or several drive geometries because of time and expense limitations. In order to correlate admittance measurements made with one drive geometry to those made with other drive geometries, end corrections are necessary. In this paper, the admittance of a coaxially-driven infinite monopole over an infinite ground plane is accurately calculated from integral equation formulations of the exact boundary value problem for a wide range of parameters. Differences of these admittances can be added or subtracted to correct for drive geometry changes in finite antennas that are not too short.

THEORETICAL AND EXPERIMENTAL RESPONSE ANALYSIS OF AN INCLINED ANTENNA IN A TIME-VARYING AIR CONDUCTIVITY ENVIRONMENT

R. P. Manriquez

US Army Electronics Research and
Development Command
HARRY DIAMOND LABORATORIES
Adelphi, MD 20783

The interaction of an inclined antenna immersed in an electric field with a time-varying air conductivity medium can be modeled with a simple lumped-parameter network. The "method of moments" developed by Harrington was implemented to obtain the circuit model for this directional antenna. A time-varying resistor across capacitors in the network model was incorporated to account for the time-varying air conductivity. At the AURORA Flash X-Ray Facility, a typical experiment was performed. The HDL Mark I source-region simulator transmission line was fired simultaneously with the AURORA Flash X-Ray Machine and the response of the inclined antenna was measured. The theoretical and experimental results will be presented.

EXPERIMENTAL AND THEORETICAL RESPONSE OF AN OSCILLATING LOOP TO AN ELECTROMAGNETIC PULSE IN A MEDIUM WITH TIME-VARYING AIR CONDUCTIVITY

M. Bushell, R. Manriquez, G. Merkel, W. Scharf, and D. Spohn

US Army Electronics Research and
Development Command
HARRY DIAMOND LABORATORIES
Adelphi, MD 20783

Linear and loop antennas are probably the most fundamental antenna structures. Our success in describing linear oscillating antennas by employing a Foster equivalent circuit with time-varying resistors across the capacitors has motivated us to employ a similar approach to the description of oscillating loop antennas. Of course, in the case of a loop antenna the impedance at low frequencies is inductive and not capacitive. In a typical experimental procedure, the HDL Mark I source-region simulator transmission line was first fired by itself so that the response of the loop could be measured in free space. Next, the parallel-plate transmission line was fired simultaneously with the AURORA Flash X-ray machine so that the oscillating loops were subjected to a time-varying EMP in a time-varying air conductivity. The response of the loops has been interpreted with a number of equivalent circuits and with a finite difference code. The experimental results and the theoretical interpretation will be presented.

BROADBAND AND TRANSIENT ANALYSIS OF THE VLF/LF DUAL-WIRE ANTENNA ON THE E-4B

L. Marin*, J. P. Castillo**

The response of the VLF/LF dual-wire antenna on the E-4B is analyzed both in the frequency and in the time domain.

A superposition procedure is used for frequencies below 0.5 MHz in which the original problem is split into two transmission-line (differential-mode current) problems and two antenna (common-mode current) problems. An equivalent circuit for the antenna is derived which places in evidence the combined antenna- and transmission-line properties of the two wires. Results for the two important quantities in the Norton equivalent circuit of the antenna, namely, the input admittance and short-circuit current are presented for different polarizations and angle of incidence of an incident plane wave.

The aircraft is electrically small for frequencies below 0.5 MHz and so its influence on the antenna response can be accounted for by using lumped network parameters. For frequencies above 0.5 MHz, the resonances of the aircraft itself influences the antenna response. A stick model for the aircraft is used to account for the major longitudinal aircraft resonances. Results are presented for the antenna wire currents induced by an incident plane wave of different polarizations and angles of incidence. The results show a very rapid frequency variation of the induced wire currents. This rapid variation is attributed to the extreme lengths of the two antenna wires.

The transient response of the antenna wires is calculated from the frequency-domain results. The antenna response both to a delta function incident pulse and a double exponential pulse are presented. It is found that the wire currents consist of distinct pulses. The magnitude and waveshape of the two initial pulses are presented in detail.

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*The Dikewood Corporation, Santa Monica, CA 90405
**Air Force Weapons Laboratory, Kirtland AFB, NM 87117

TRANSIENT CORONA EFFECTS ON WIRE OVER THE GROUND

K. C. CHEN
Air Force Weapons Laboratory
Kirtland AFB, NM 87117

Military aircraft, such as TACAMO and Airborne Command Post, employ long VLF trailing wire antennas. These antennas are required to survive exposure to nuclear electromagnetic pulse environment. During such an exposure the electric field on the trailing wire antenna can be considerably greater than the breakdown electric field of the air, which results in corona around the wire. As a first step in understanding wires with corona, the Air Force Weapons Laboratory set up a wire over a copper wire mesh ground plane facility at Kaman Sciences Corporation. A high voltage pulser is used to drive this transmission line up to 90 Kv. Baum's electric and magnetic field sensors are situated on the ground plane to measure the corona effect. The recorded signals clearly show the onset of the corona which is characterized by a dip in the measured data. Corona data for different wire types, e.g., Aluminum, Copper; for a range of voltage levels; and for both polarities; have been collected.

A nonlinear corona model based on a transmission line equation with a nonlinear capacitance per meter is developed. First, a general solution for the nonlinear transmission line equations is obtained. Second, the pulse velocity is deduced from the measured data as a function of pulse magnitude. Relationship between line current and voltage is studied. Townsend's electron avalanch theory is also applied to interpret the test data.

ESTIMATING EMP COUPLING TO SHIPBOARD ANTENNA SYSTEMS*

L. C. Martin, R. M. Bevensee, H. S. Cabayan
and F. J. Deadrick
Lawrence Livermore Laboratory, Livermore, CA 94550

The large size and extreme complexity in the electromagnetic response behavior of a surface ship presents a difficult problem for estimations of EMP coupling phenomena. This paper discusses techniques and presents some results pertaining to the estimation of EMP induced coupling levels for certain shipboard antenna systems and structures. The techniques discussed include the following: 1) The prediction of specific response levels based on use of data modules for external coupling of EMP to generic system structures, 2) the combined use of a transient electromagnetic range facility and scale models of ships, and 3) the synthesis of equivalent circuits with network response predictions.

The emphasis is on the use of the reduced-scale ship models in order to provide the type of responses required for hardening considerations. Scale-model tests on the transient range aid in establishing the accuracy and limitation of such ship model measurements as tools for predicting voltages and currents on the shipboard systems. Data is presented for comparison of techniques and thus illustrates some of the accuracy and flexibility of the scale model approach. Results from tests on a 1/48 scale model indicate time domain response peaks generally are within ± 6DB when compared to full-scale measurements.

*This work was performed under the auspices of the U. S. Department of Energy by the Lawrence Livermore Laboratory under contract No. W-7405-ENG-48 and was sponsored in part by the Defense Nuclear Agency, Subtask Code R99-QAXEC-301, and by the Naval Ocean Systems Center, MIPR-N660018OMP00014.

A SIMPLE MODEL OF VERY-LOW-FREQUENCY CW CORONA LOSS ON A TWO-WIRE TRANSMISSION LINE

Monti R. Wilson
US Army Electronics Research and
Development Command
HARRY DIAMOND LABORATORIES
Adelphi, MD 20783

A simple analytical model of very-low-frequency CW transmission line power loss to corona is the subject of this paper. Basically, the corona ionization creates a conducting ion stream between conductors. The line power loss to ohmic heating of this shunt conductance is traditionally called P, the watts/m loss one can conveniently calculate over 1 m of line length. Models proposed previously in the literature are quantitatively unsatisfactory to explain the P measurements of Holm[1]. I have found a simple model for calculating P that has one free multiplicative parameter, P_A, to be determined from a single data point. My model well predicts P in all seven of Holm's experiments. Such a model provides an improved basis for correlating semi-empirically P data in this restricted region of low-voltage corona. Furthermore, this model provides indirect information regarding electron attachment inside the corona sheath, since P_A is an attachment event number parameter that naturally arises in an equilibrium ion transfer approach to the ion supply of the conducting ion streams. Finally, the CW calculations provide coarse grain information concerning the steady corona electron avalanching, information which is also useful in certain transient corona studies.

So far, the study of this model has isolated two distinct regions over which parameter P_A can be treated as a voltage independent constant: (1) $P_A \ll Q$ and (2) $P_A \simeq Q$ where Q is the electron avalanche gain exponent (e^Q). Region 1 is weak attachment and region 2 is the equilibrium avalanche quenching limit. Further measurements would be required to verify the transition region between regions 1 and 2.

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[1]R. Holm, Arch. f. Eleckt., 18, 567 (1927).

THE ELECTROMAGNETIC COUPLING AND APERTURE PENETRATION INTO COMPLEX MISSILE GEOMETRIES

Korada Umashankar and Allen Taflove
IIT Research Institute
10 West 35th Street
Chicago, IL 60616

The general electromagnetic coupling and shielding problems have been difficult to treat because of the complicating effects of apertures, curvatures, corners, and complex internal contents of structures. Only canonical structures and simple aperture shapes have been studied previously in an attempt to gain insight into coupling mechanisms using analytical and method of moment (MOM) numerical approaches. A powerful alternate approach is the (FD-TD) Finite Difference-Time Domain method (A. Taflove, "Time Domain Solutions for Electromagnetic Coupling", IIT Research Institute Final Technical Report, RADC-TR-78-142, June 1978) which allows computation of the penetrated internal EM fields by direct modeling of realistic complex geometries, apertures, and internal contents.

In order to treat coupling problems more effectively, new hybrid techniques have been developed which involve combining the FD-TD method either with the MOM or some other appropriate technique. The hybrid FD-TD/MOM approach which will be presented, is based on a novel use of the so-called, "field equivalence theorem" due to Schelkunoff. In the hybrid FD-TD/MOM method, the coupling problem is analyzed in two steps by treating the relatively simple external and the relatively complex internal regions separately. The method involves first, determination of an equivalent short-circuit current excitation in the aperture region of the structure which is obtained by solving an exterior problem (using MOM) with the aperture being closed for a given external illumination. The computed equivalent current excitation in the aperture region is next utilized as sources to illuminate the interior region and the penetrated interior fields are computed by the FD-TD method. The computed interior fields for an aluminum cylinder with one open end are compared with available experimental and numerical results to demonstrate validity of the technique. The hybrid FD-TD/MOM method has been successfully applied to a complex nose cone model with interior material contents (A. Taflove and K. R. Umashankar, et al, "Evaluation of Time Domain Electromagnetic Coupling Techniques", IIT Research Institute Final Technical Report to RADC, March 1980). The hybrid method based on Schelkunoff's "field equivalence theorem" is also applicable when coupled wires or material bodies are present and coupled strongly to the aperture. The results of the application of the hybrid MOM/MOM approach to "a finite wire scatterer behind a narrow slot perforated conducting screen" are also compared with available data.

An Efficient Technique for Solving Quasi-Static Problems for Irregularly Shaped Regions

Dr. Martin D. Bradshaw
AFWL/University of New Mexico

Abstract

The Method of Summary Representation is a mathematical technique which combines finite-difference and analytical procedures to produce matrix solutions at specific internal grid-points in terms of the known boundary conditions of the region. By using concepts similar to those employed in Diakoptics, which is used in circuit analysis, complicated geometrical problems can be reduced to a system of simpler problems which are coupled together through the common boundary conditions. When these unknown internal boundary values are considered as matrices, application of an extended Summary Representation technique produces a system of matrix equation which reduces the original problem to a solution of only these internal boundary value matrices. The total solution is then easily written down directly. The technique produces a characteristic coefficient supermatrix which has properties which allow the resulting matrix equation to be solved in convenient form by the special properties of the supermatrix inverse.

The procedure will be illustrated with two problems utilizing rectangular geometry in which the number of internal cells is of the order of 6 to 12. (An internal cell is defined as one of the smaller regions into which the original region is subdivided.)

THE USE OF SIMPLE COUPLING MODELS FOR COMPARING VARIOUS EM EFFECTS ON AN IN-FLIGHT MISSILE

Daniel F. Higgins and Kenneth S. Smith
JAYCOR
360 S. Hope Ave.
Santa Barbara, CA 93105

Various military systems, such as an in-flight missile, may be exposed to a number of potentially damaging electromagnetic effects. These include various types of nuclear EMP, SGEMP, and source region radiation effects, in addition to natural effects such as lightning. A hardened missile may be required to survive all of these effects. Some protective features, such as EM shielding can reduce the importance of many of these effects, but it is useful to have some means of comparing the relative importance of all such drive mechanisms so that protective measures can be properly allocated.

This paper describes a method of comparing the various EM effects that might be seen by an in-flight missile. The currents induced on a raceway cable shield by various external effects are first estimated. A transmission line model is then combined with typical shielding parameters (e.g., transfer impedance and transfer admittance) so that the resulting currents and voltages inside the shield can be calculated. Parameter variations, such as the external current spatial distribution along the raceway and transmission line dielectric losses at high frequencies, will be discussed. The currents and voltages coupled through the shield can then be compared to those created internally by penetrating radiation (x-rays and γ-rays). The radiation driven internal response is also calculated using a simple transmission line model.

The end result is thus currents and voltages at some common point inside a shielded system. These signals can be directly compared even though the sources of the EM signals may be quite different and the signals have arrived at the comparison point after different coupling paths.

The paper will present several examples and numerical response comparisons, although the emphasis will be on how relatively simple analysis tools can be used to make such comparisons.

*Work sponsored by the Defense Nuclear Agency

NH&S and EMC EM-Integrated Requirements

Bruce A. Daiken
Rockwell International
3370 Miraloma Avenue
Anaheim, CA 92803

Abstract - This paper describes the method used to integrate the EM (Electromagnetic) portions of the NH&S (Nuclear Hardening and Survivability) and EMC (Electromagnetic Compatibility) requirements of the Missile X Guidance and Control System.

EMP (Electromagnetic Pulse), and SGEMP (System Generated Electromagnetic Pulse), Lightning and EMC are all related by their EM parameters. The objective of the EM-Integration is to take advantage of the overlap of EM parameters to eliminate redundant efforts of analysis, design and tests, and to take advantage of hardening and protection commonalities. Complete cost savings are realized by combining analysis, test plans, tests, and test reports by using EM-Integrated requirements.

EM-susceptibility requirements of EMP, SGEMP, lightning and EMC were combined into a single set of four curves at the subsystem interface. The four curves are electric field, magnetic field, coupled voltage, and coupled current.

The EM-Integration Method includes a method to derive the internal generated interference of a system. This internal generated interference is added to the external MIL-STD-461 specified susceptibility EMI levels to create the combined EMC part of the EM-Integrated requirements envelope.

How to use the new EM-Integrated requirements in NH&S and EMC analysis and tests and how to select common protection design is discussed. Examples are given using the EM-Integrated requirements to determine the EM Safety Margin for circuits where upset or burnout thresholds are known.

Suggested Experiments and Their Rationale

Maurice I. Sancer
R&D Associates
Marina del Rey, CA 90291

It is argued that EMP coupling analysis alone, cannot be relied upon to determine subsystem excitation. The argument is based on a reciprocity proof which shows that the coupling problem can be viewed as an equivalent antenna problem. For systems of moderate complexity, the equivalent antennas are considerably more complex than are intentional antennas which are considered beyond analytic treatment. For these intentional antennas it is routinely required that their patterns be measured before they are fielded.

Accepting the need for experiments leads to the difficult task of identifying specific experiments. This task is first addressed by discussing the relationship between laboratory experiments and full system experiments. Next, three sets of laboratory experiments are described along with the objectives they would accomplish. The first set of experiments would provide a data base to examine existing and proposed procedures for the interpretation of full system-level EMP simulation tests in terms of threat. The second set of experiments would examine the adequacy of incidence and polarization angles that have been included in past and proposed system-level tests. The third set of experiments would examine whether external coupling quantities can be combined with measured quantities (transfer coefficients) to determine subsystem excitation. A positive result has the potential to facilitate the determination of system response to a variety of threat scenarios while a negative result implies that the analytic, numerical, and experimental capabilities that have been developed for the determination of external coupling quantities are not useful for predicting internal subsystem response. Some data exists which indicates that transfer coefficients can be measured and it will be presented. Finally, secondary purposes for the experiments will be discussed.

MX G&C ELECTROMAGNETIC SPECIFICATION APPROACH

Duncan Still/Gordon Palmer
Rockwell International
3370 Miraloma Avenue
Anaheim, CA 92803

Abstract - The approach taken to implementing electromagnetic requirements into the specifications for the MX Guidance and Control System, requires consideration of all electromagnetic environments, EMP, SGEMP, lightning EMR and EMC. Specifications cover the entire frequency range appropriate for these environments; dc to GHz. Protection levels are driven by the most severe environment in a given portion of the frequency spectrum. This allows specific electromagnetic protective features to attenuate several electromagnetic effects, thus allowing a more efficient and lower cost hardening approach.

Electromagnetic shield environments are specified in terms of transfer impedance, both for cable shields and connectors. Electronic box case shield requirements are specified in terms of current density attenuation through the shield. Conducted electrical noise interface transients are specified at interface connector pins and are specified in terms of equivalent Norton or Thevenin sources. Supplemental requirements include use of low Z coatings to minimize SGEMP electron emission, restrictions upon the SGEMP direct injection in missile cables, specific bonding, isolation and referencing requirements.

This set of requirements provides an optimum LCC approach to specifying and implementing electromagnetic protection into MX. This approach utilizes each protective element to its maximum limit allowing it to protect against several EM environments, and ensures that the entire spectrum of electromagnetic threats is properly protected. This approach has cost benefits along with minimization of missile weight.

MULTI-LAYERED SHIELDED ENCLOSURES WITH* PARTICULAR REFERENCE TO BONDING BETWEEN LAYERS

K.S.H. Lee
The Dikewood Corporation
Santa Monica, CA 90405

Recently, the theory of inductive shielding [1] has been applied to derive simple engineering formulas to describe the magnetic field that penetrates into a single-layered shielded enclosure of arbitrary shape [2]. In this paper we extend the previous work to enclosures of multi-layered shields and investigate the effect of electrical bonding between the shields on the shielding effectiveness of the enclosure.

We will first solve the boundary-value problem of two concentric spherical shields using the theory of inductive shielding, and then generalize the results to a multi-layered shielded enclosure of arbitrary shape. The results will be interpreted in terms of equivalent circuits by means of which we introduce the concept of bonding between the shields. The effect of bonding will be evaluated by solving simple circuit problems. Finally, we will show the corresponding results for a multi-layered cylindrical shield.

[1] R.W. Latham and K.S.H. Lee, Canad. J. Phys., 46, 1745 - 1752, 1968.

[2] K.S.H. Lee and G. Bedrosian, IEEE Trans. on Ant. and Propag., AP-27, No. 2, 194 - 198, March 1979.

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Penetration of Electromagnetic Fields into Shielded Rooms via Room Shields and particularly via Cable Entries

J.L. ter Haseborg +), R. Sturm ++), H. Trinks +)
+) Hochschule der Bundeswehr Hamburg, Postfach 70 08 22, 2000 Hamburg 70
++) Wehrwissenschaftliche Dienststelle der Bundeswehr für ABC-Schutz, 3042 Munster, West Germany

The interfering influence of impulsive electromagnetic fields - caused by e.g. lightening flashes, strong radar beams, nuclear EMP - in the inside of shielded rooms is investigated. Such external interferences enter the shielded room either direct via the shielding or via the cable entries.

Partly the cable entries are protected by arresters. With sufficiently intense external interferences these arresters are activated. In dependance of the threshold of response of the arrester a current impulse, coupled via the cables, runs over the cable loops, which are laid in the inside of the shielded rooms. As a result, particularly magnetic interference fields H(t) occur.

These interference fields H(t) and the subsequent, induced voltage signals U(t) in secondary loops are calculated theoretically. For this purpose assumptions are made on the intensity and frequency of the coupled currents with various given current branchings. A superposition of such current branchings with a high degree of symmetry leads to substantial compensation of the fields, while with a strongly asymmetrical arrangement particularly heavy interferences are caused. These results elucidate the variable efficiency of centrally earthed conductor systems with coaxial return, and of widely spread decentralized earth connection.

Electrically conducting division walls in the shielded rooms lead to a partial shielding of the unavoidable interference fields. The shielding effect of plane grid shieldings (Cu, Al, Fe) in dependance of mesh grid and diameter of wire is calculated and discussed.

Possibilities are described how to complete and confirm the theoretical results by means of experimental methods.

Ref. R. Sturm: EMP-Induced Currents and Fields in Shelters 3rd Symposium and Technical Exhibition on Electromagnetic Compatibility, Rotterdam, May 1-3, 1979

EMP COUPLING TO THE INTERNAL CIRCUITS OF MISSILES AND TORPEDOES THROUGH HULL SECTION JOINTS

P.R. Miller,
Marconi Space & Defence Systems Ltd.,
Chobham Road,
Frimley,
Camberley,
Surrey,
GU16 5PF
ENGLAND.

In the majority of missiles and torpedoes, the hull takes the form of a metal cylinder built up from a number of sections that are connected to each other by circumferential joints. It is common practice to include inside these weapons a cable form that runs along the length of the cylinder close to these joints. This cable form carries the services of the weapon.

However, as the joints must possess finite impedances, this manufacturing process provides a good path for EMP to be coupled into the cable form and eventually into the internal circuits of the weapon.

In this paper it is postulated that this coupling path can be initially characterised by a single, simple, joint transfer impedance that relates the voltage induced on the internal cable to the current flowing on the weapon hull. Time domain methods to measure this joint transfer impedance are described and analysed and results from measurements using these methods are then used to predict the energy coupled into the cable form using a transmission line formulation. The predictions are backed up by practical measurements carried out in an EMP simulator. Agreement is shown to be very good.

Once confidence has been obtained in the coupling theory, it can then be used to investigate the general properties of EMP coupling into weapons of this type. Such an investigation is carried out in this paper where the parameters varied are:

(1) The length and diameter of the cylinder.

(2) The value of the joint transfer impedance.

(3) The tightness of coupling of the cable to the joint.

The results of this investigation are presented in the form of coupled energy level contours.

Finally the influence on the coupling coefficient of any bonding straps that are connected across the joints is considered.

Topological View of EMP Hardness Testing

W. Graf and E.F. Vance
SRI International, 333 Ravenswood Ave., Menlo Park, CA 94305

System topology was first introduced as an aid to the analysis of the system response to incident EMP.[1] It has since evolved into a powerful tool for simplifying very complicated systems into elements such as transmission lines, antennas, cavities, apertures, etc. that are amenable to analysis.[2]

The concept of shield topology is also extremely useful in designing system hardness.[3] The designer can synthesize a shield topology that will restrict penetration of EMP and lightning effects to a tolerable level. In order to verify system hardness to EMP various tests in accordance with standards such as IEEE 299, MIL-STD 285, 461 and 462 are usually performed. The topological concepts developed for EMP and lightning protection system design become important tools for the understanding and proper application of these tests.[4]

Two kinds of tests are generally performed, emission and susceptibility. Each of these tests is performed with conducted and radiated energy. In the topological sense these tests verify the integrity of the zonal boundaries. Since these boundaries (i.e., the shields) are never perfect in practice, it is important to perform tests which indicate that the desired level of shielding effectiveness is preserved. In that sense, standard tests sometimes turn out to be insufficient. For example, at low frequencies (below about 100 MHz or so), the predominant excitation of a shielded box will occur via the interconnecting cables, but MIL-STD 461 and 462 do not specify the arrangement of the cabling. Therefore clever test engineers can arrange the connecting cables such that the equipment will pass the test, even though in the actual installation environment it will fail.

In the topological view the connecting cable shields are part of the equipment or cabinet shield, and they must be subjected to the same tests as the equipment shield to verify the integrity of that zonal boundary. For instance, in a radiated susceptibility test, in addition to illuminating the "box", current must be injected onto the connecting cable shields at low frequencies to verify that the different zones are kept separate and that a "noisy" zone does not contaminate a "quiet" zone.

1. C. E. Baum, How to think about EMP interaction. Proceeding of the 1974 Spring FULMEN Meeting, AFWL (April 1974).

2. F. M. Tesche, Topological Concepts for Internal EMP interaction. IEEE Trans. Ant. and Prop. Vol. EMC-20 pp. 60-64, (February 1978).

3. E. F. Vance, J. E. Nanevicz, and G. A. August, Technical Inputs and EMP Design Practices for Intrasite Cabling of Telecommunication Facilities. Final Report, Contract DAAG-39-76-C-0021 SRI Project 4587, SRI International, Menlo Park, California (June 1977).

4. E. F. Vance and W. Graf, Topological View of EMC Susceptibility Testing. Proceedings of the 1980 Spring FULMEN Meeting, AFWL (March 1980).

A COMPARISON OF TACAMO EMP CURRENTS BEFORE AND AFTER HARDENING

James V. Locasso
Rockwell International
3370 Miraloma Avenue
Anaheim, California 92803

ABSTRACT

DATA has been taken on the TACAMO aircraft EMP response in several tests ranging from a direct drive test in 1975 to the HPD/VPD-II tests of 1980. In this 6 year period the TACAMO has been hardened by (a) a set of POE Closures at the pressure hull, and (b) a later set of hardening modifications inside the hull. Direct comparisons of the data are limited because of changes in test method, test points and TACAMO configuration.

This paper presents a comparison of the different data sets using a cumulative plot of current magnitudes. Hardening improvements show up clearly and can be approximately quantified. Data for other aircraft are also presented for their general interest.

AIR LAUNCHED CRUISE MISSILE EMP HARDWARE/SOFTWARE DESIGN

Charles A. Rolfe
Robert J. Marett
Alan M. Smith

Boeing Aerospace Company
P. O. Box 3999 M/S 44-66
Seattle, Washington 98124

The Air Launched Cruise Missile (ALCM) is a strategic missile launched from a B-52 some distance from its target. The ALCM then flies a planned route to its target using an on-board computer in conjunction with inertial and terrain matching navigation systems.

The Boeing Company has designed the AGM-86B Air Launched Cruise Missile to comply with stringent government electromagnetic pulse environments. Minimizing cost, volume, and weight while complying with requirements were the criteria used to provide our present design, compliant with all electromagnetic pulse requirements.

This paper presents a detailed description of the AGM-86B hardware and software designs selected to ensure compliance with free field and derived requirements. We describe the missile structure shielding design, the cable/electrical equipment shielding design, the interface circuit protection design, and the missile software upset protection design. We also describe developmental testing leading to the selected design.

This design has been validated by qualification analyses, missile level direct drive qualification testing performed at Seattle, and missile level free field qualification testing performed at the AFWL.

TACAMO, LESSONS IN THE PRACTICAL APPLICATION OF EMP HARDENING

J. L. Monroe

ROCKWELL INTERNATIONAL
3370 Miraloma Avenue
Anaheim, CA 92803

ABSTRACT

The TACAMO EC-130 aircraft and communications platform have been EMP hardened using a successive layered approach. The results of this hardening experience reveal practical challenges that must be considered in hardening of complex airborne systems. This summary of TACAMO hardening reviews the critical elements of the EMP design and highlights the challenges encountered in actual application.

EMP Hardening of NATO Communication Shelters

Andrew Kleczko
Autonetics Strategic Systems Division
3370 Miraloma Avenue
Anaheim, CA 92803

Abstract - The approach taken by Autonetics to EMP hardening the 23 NATO Communication Shelters throughout Western Europe used a combination of limiting/filtering and shielding. This technique is usually more effective than any one technique alone. Shielding alone could require shielding effectiveness ratios between 60 db and 120 db which are difficult to achieve throughout operational systems. Filters, by themselves, can be exceedingly heavy when used on lines normally required to handle high power throughout or when designed to filter high-energy transients. Surge protection devices (especially ESA's) can generate high-frequency reflections along the line due to the sudden "short circuit" created during their breakdown.

Prior to development of the hardware, preliminary analysis effort was required to provide hardness improvement requirements. The EMP hardening approach began with shelter hardening design, a susceptibility analysis of interface circuits, and a coupling analysis of antennas and cables, from which needed hardness improvements were developed, implemented, and ultimately verified through tests.

Utilizing the system functional analysis and susceptibility analyses along with the cable coupling predictions and antenna response calculations, hardness margins were then obtained and various hardening improvements were then designed and implemented.

Autonetics has designed and built the EMP Penetration Panel which houses the EMP Hardening Protection devices at the shelter interface. Autonetics has also designed and developed EMP Free Field Threat Level Pulser and a portable Array which will be used to conduct an EM Free Field and a EMP Direct Drive Tests on the NATO Communication Shelters, antennas, and power generators.

Title: Computer Simulation of EMP Protection Circuit Transients

Author: K. L. Williams

Company: McDonnell Douglas
5301 Bolsa Avenue
M/S 14-3
Huntington Beach, CA 92683

A computer simulation of the LC-zener EMP protection network was developed to determine the network attenuation characteristic, which is used in determining buried circuit upset thresholds. The computer simulation is useful as an alternate to the previously accepted method. The previous method assumed that the voltage to the load had the form of an undamped sine wave with peak to peak amplitude of twice the maximum zener voltage. The simulation shows that there is less high frequency content and therefore less capacitive coupling to buried circuitry than previously thought. To aid the analysis of magnetic coupling the computer simulation calculates successive values of the current through the LC Branch of the network.

The computer simulation uses a HP 9825 and was developed in such a way that the source voltage, zener voltage, source resistance, zener resistance, initial voltage to the load, initial current, inductance, capacitance, pulse width of the source voltage, and delta t can all be input allowing maximum versatility. The output of the simulation is a graph which is drawn on the HP9862A plotter which shows Vin, Vo, and I as a function of time.

During EMP qualification testing of one system the computer generated graphs of Vin for the LC-zener circuit were compared with actual Vin traces seen during testing. The comparisons show the computer simulation to be a very close approximation to the actual network characteristic.

SPARK GAPS AND METAL OXIDE VARISTORS AS LIMITERS FOR FAST VARYING ELECTRICAL TRANSIENTS

by

O Busmundrud
Norwegian Defence Research Establishment
P O Box 25
N-2007 Kjeller, Norway

The performance of some commonly available spark gaps and metal oxide varistors as limiters for EMP produced transients has been investigated. Transients with rates of voltage rise higher than 200 kV/μs have been used.

The measurements show that the performance of the limiters is determined to a large extent by the length of the connecting wiring. The wiring should not exceed a few cm in length.

For spark gaps no direct relationship between the static striking voltage and the striking voltage for transients with a high rate of voltage rise was found. It is shown that varistors may be better than spark gaps in limiting peak voltages.

EFFECTIVE TELECOMMUNICATION SIGNAL LINE PROTECTION FROM LIGHTNING AND EMP

O. MELVILLE CLARK

and

JOSEPH J. PIZZICAROLI

General Semiconductor Industries, Inc.
P.O. Box 3078
Tempe, Arizona 85281

Transient voltages in telecommunication lines caused by lightning are characterized by microsecond rise-times and with peak currents of up to several kiloamperes. Nuclear Electromagnetic Pulse (NEMP) can produce peak currents also in the kiloampere range but with nanosecond rise-times, which is several orders of magnitude faster than lightning. Gas surge arrestors uniquely coupled with silicon transient suppressors have demonstrated effective clamping of both lightning and EMP to low, safe levels. The slower acting spark gap diverts the bulk of the energy while the fast acting silicon suppressor clamps the residual voltage spike.

Impulse striking voltage for the gas surge arrestor is developed across the series resistor and inductor along with the silicon suppressor. An inductor of only 10μH will build up several thousand volts required to fire the gap for fast rise-time EMP and also slow down the wave front to reduce inductive effects in the silicon suppressor package.

Evaluation of the peak power and energy consumed by the components under simulated field surge conditions shows that overstressing does not occur and that good reliability for assemblies can be expected. In the event of overstress, fail-short will occur to protect the system. A review of design considerations will include circuit operating voltage, insertion loss, phase angle distortion, rise and fall time, and transient voltage threat, all of which determine component electrical parameters and physical layout for optimum performance.

Protector assemblies as described above have been designed into several military programs including the Airborne Command Post, TENLEY, GMF, and ULCS.

A BINDING-POST SURGE ARRESTER

R. J. PROCHAZKA

US Army Electronics Research and
Development Command
Harry Diamond Laboratories
Adelphi, MD 20783

Field telephone wires are frequently terminated at system/shelter entry panels by means of standard binding post connectors. When EMP and lightning protection of the system's electronics is required, surge arresters (spark gaps) can be applied between ground and the signal lead of the binding post: typically, via several feet of wiring. However, this circuit arrangement reduces the effectiveness of conventional spark gaps which are inherently limited by a large leakage voltage. Besides, the problem is further complicated by the spark gap's lead inductance. To compensate for this circuit behavior, secondary protective components are cascaded with the spark gap; the selection of components will depend on the ability of the spark gap to efficiently suppress EMP and lightning transients.

Since the binding-post provides a penetration point for transient signals and is also used at the interface for radio-wire communication equipment, a prototype gas-tube binding-post has been developed which can reduce the problem arising from conventional arrester circuitry: excessive leakage voltage. The gas tube binding-post is designed as two concentric cylinders. As a coaxial assembly, the internal cylinder is the center electrode of the coaxial gas tube, and also the signal carrying conductor of the binding-post; the external cylinder is the ground electrode of the coaxial gas tube, and an excellent heat sink for the gas tube.

The binding-post surge arrester (BPSA) appears to be an effective method for protecting equipment that has binding posts as inputs for single wires. It is basically a feed-thru assembly, as are all binding-posts, but in addition the BPSA is a self-contained gas tube with zero lead inductance; consequently, the effectiveness of this surge arrester is enhanced.

This paper will discuss the prototype design, supporting laboratory experiments, and data comparing the effectiveness of the BPSA with other surge arrester assemblies.

Aircraft Control Cable EMP Transient Suppressing Devices

Larry Scott, Ashok K. Agrawal and John Barnum
Mission Research Corporation
1400 San Mateo Boulevard, S.E.
Suite A
Albuquerque, New Mexico 87108

and

Tom Liu
LuTech
Post Office Box 1263
127 University Avenue
Berkeley, California 94701

On many aircraft there are a significant number of conducting control cables. EMP energy, after penetration of the aircraft hull, will couple to various wire bundles as well as control cables. Although the control cables may not be connected directly to electronic equipment, induced currents on them can couple energy to nearby electrical cables and thereby damage important electronic equipment. In the past, several techniques have been tried to suppress these induced currents on control cables with little apparent success. In this paper we present a systematic study of this problem, both experimentally and analytically, to evaluate the effectiveness of various transient suppression devices currently used and contemplated.

The devices discussed in this paper are evaluted both analytically and experimentally in the laboratory. These include dielectric insertion devices (DIDs), ferrite beads, lossy dielectrics, DID in in a waveguide, etc. Indications from EMP simulation tests point to the fact that DIDs may not be very effective in suppressing transients on control cables. The same is reported for shorting pulleys.

These transient suppression devices are primarily characterized in the laboratory by measuring the characteristics of a transmission line loaded at periodic intervals with the devices. The losses introduced by the various devices on the line are compared in this paper. Furthermore, the attenuation per unit length of the periodically loaded line is also calculated for comparison. Experimental and analytical results for all the transient suppressing devices considered are presented with suggestions for improving their effectiveness.

ABSOLUTE EMP LIMITER

P. J. Madle, Senior Member IEEE

TRW
Defense and Space Systems
Redondo Beach, CA 90278

ABSTRACT This paper describes a generic approach to the EMP protection of hardened shielded ground facilities from surges propagated along long external conductors such as power or communications cables. It is noted that the EMP/lightning protection is usually achieved by a non-linear shunt device, such as a spark-gap, which diverts surge current to the shielding shell of the facility and by a filter which integrates or reflects energy. These surge protection devices must be capable of protecting the equipment in the facility against multiple events, such as caused by lightning, high altitude burst (HAB) nuclear events or surface burst (SB) nuclear events which would occur in a set of scenarios pertaining to the specific facility and the system of which it is a part.

Certain other scenarios are possible in which larger EMP/lightning surges may be induced in the external conductors. SB nuclear events occurring very close to the long external conductors, "super-lightning" strikes on the conductors and "near-miss" SB nuclear attacks on the facility are examples of such scenarios. These scenarios are characterized by damage to the conductors or to the power or communication systems of which they are a part. Following such an event the conductors could no longer be used for their intended purpose, therefore, at these surge levels, there is no necessity for the surge arrestors, spark gaps or filters to survive in operable condition. If they fail they must however do so in a manner that continues to protect the equipment in the facility.

It is suggested that the EMP/lightning protection devices should be provided as two cascaded sets. One, designed for multiple operation, and probably consisting of a gas-filled spark gap and filter, should be preceded by an Absolute Limiter, designed for single-shot operation at a higher surge level. The Absolute Limiter could consist of a solid-dielectric spark gap, and a section of coaxial line of reduced diameter leading to the gas-filled gap and filter noted above. Solid-dielectric spark gaps operate at essentially constant voltage even at very short times whereas the firing voltage of gas-filled gaps rises rapidly at the shorter times. A parallel arrangement of the two types of gaps can be designed in which the gas-filled gap will fire at all input rates associated with normal lightning, HAB or SB events but where the solid-dielectric gap will fire for the extreme input rates of "super-lightning," "near-miss" SB or other events of extreme magnitude. The solid-dielectric gap can be designed to fail shorted after firing thus providing permanent protection after such an event, unless the current delivered exceeds that required to volatilize the conductor. The eventual outcome of the operation of an Absolute Limiter would be that the conductor would be opened by volatilization or shorted to ground by the solid-dielectric gap or both after an extreme event thus providing continuing protection for the equipment in the facility.

DESIGN PARAMETERS FOR HYBRID TERMINAL PROTECTION DEVICES

by

Robert V. Garver & Christian Fazi
U.S. Army Electronics Research &
Development Command
Harry Diamond Laboratories
2800 Powder Mill Road
Adelphi, MD 20783

ABSTRACT: A hybrid terminal protection device (HTPD) consists of a shunt spark gap to reflect high energy followed by a shunt semiconductor limiter to reflect the energy leaking past the spark gap. Two factors are requiring the HTPD to be used more than in the past. Integrated circuits with lower damage thresholds are being used more in systems, and the long transients of low altitude EMP require protecting devices that can withstand higher energy. The HTPD art requires that an inductor or a delay device be placed between the spark gap and the semiconductor limiter to prevent the limiter from hogging the current of the transient, keeping the voltage too low to initiate conduction in the spark gap, and burning itself (the limiter) out. But the HTPD art provides no design equations for selecting the inductor, and it does not describe current redistribution after limiting, which can in time lead to other modes of HTPD damage. Design parameters for the HTPD will be presented as well as sample applications for protecting a tactical radio transmitter VMOS transistor and protecting the WD-1 field wire radio input with long transients on the line.

SCALE MODEL MEASUREMENTS

Valdis V. Liepa
Radiation Laboratory
Department of Electrical and Computer Engineering
The University of Michigan
Ann Arbor, Michigan 48109

ABSTRACT

The surface current and charge data measured on scale models in anechoic chambers provide an important input to the program of hardness assessment of aircraft. These data are used for simulator pre-test analyses and as a data base for extrapolation of the simulator data to the free space environment. They are used in verification of computations and numerical codes, and as sample data for extraction of characteristic poles from frequency domain data in SEM studies.

The purpose of this presentation is to provide to the present and the potential users of University of Michigan scale model data an overview of what these data are, how they are obtained and presented, and their limitations and shortcomings. The measurement facility and its operation is described, including the anechoic chamber and its instrumentations that cover 118 to 4400 MHz. For example, on full scale this represents a 1.18 to 44.0 MHz coverage when a 1:100 scale model is used.

Sample measurements are presented from the just completed B-52 and F-16 programs, and surface current data are shown for the first time anywhere for the upper main fuselage and the right power unit of the U.S.S. Enterprise.

SURFACE FIELD MEASUREMENTS ON SCALE MODELS IN THE TIME DOMAIN

H. S. Cabayan, J. Zicker
Lawrence Livermore Laboratory, Livermore, CA 94550

In order to provide a data base for comparison with calculation and additional insight into test object/simulator interactions, time-domain measurements have been performed of surface current and charge induced on three scale-model test objects at the LLL transient range simulator. The objects include a cylinder, a crossed-cylinder, and a 1:100 scale-model 747 aircraft. Responses were measured for objects in a simulated free-space environment and in the proximity of a perfectly conducting plane. The measured time-domain data are Fourier transformed to the frequency domain, and analyzed via a linear least-square estimator algorithm to extract the complex natural frequencies of the structures.

In this paper, the test object and experimental set-up will be described. The time-domain and frequency-domain results in addition to the pole analysis will be presented. Finally, the data will be compared to CW data obtained at the University of Michigan and to available numerical predictions.

Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore Laboratory under Contract No. W-7405-ENG-48.

E-3A DIPOLE TEST PROGRAM DATA EXTRAPOLATION TECHNIQUES*

G. Bedrosian
The Dikewood Corporation
Baltimore, Maryland 21210

Two basic extrapolation techniques were used in the E-3A Dipole Test Program: overall surface response extrapolation with associated error estimates (TYPE 3C) and POE-specific extrapolation (TYPE 4). In addition, an incident field extrapolation function (TYPE 3A) was generated for comparison using simple double-exponential function approximations for both the criterion and simulator incident fields. The incident field extrapolation function displays common features of all of the extrapolation functions.

The direct method of extrapolating data is to transform the data to the frequency domain, multiply by the appropriate extrapolation function, and transform back to the time domain. The disadvantage of the direct method of extrapolation is that two numerical transforms are required.

An alternative extrapolation method requires minimal computation. The measurements can be categorized by their dominant resonance frequencies. The scalar ratios of extrapolated to measured peak values (in the time domain) within each category are very similar. Thus, measurements within each category can be extrapolated using a single scalar extrapolation factor.

The errors associated with extrapolation can be ascribed to three sources: measurement or instrumentation errors, data processing errors, and fundamental extrapolation error. The fundamental extrapolation error is the result of simplifying assumptions in the extrapolation method itself. The total extrapolation error is not small, and leads to significant uncertainty in conclusions drawn from extrapolated measurements.

*The work was performed under Contract No. F29601-78-C-0082.

EMP EXTRAPOLATION FUNCTIONS FOR THE TACAMO C-130 AIRCRAFT

By

Edward E. O'Donnell
Prem Setty
Science Applications, Inc.
2860 S. Circle Drive, Ste 2224
Colorado Springs, CO 80906

During the TACAMO EMP Assessment Test (TEMPAT I) ground and airborne surface response data were obtained for the C-130 aircraft. In addition, scale model data were obtained by the University of Michigan Radiation Laboratory [1].

Using these data, a set of symmetric and antisymmetric extrapolation functions [Type 3B, Ref 2] and surface response errors have been derived for ground tests in the Horizontally Polarized Dipole facility and flight tests near the Vertically Polarized Dipole facility. Three methods for determining the extrapolation functions were used:

1) Using HPD as the simulation and scale model data as the criterion

2) Using HPD as the simulation and the flight test data as the criterion

3) Using flight test as the simulation and the scale model data as the criterion

Data will be presented for all three methods. Average extrapolation functions for HPD range between 0.4 and 10 over the frequency range of 10^6 to 10^8 Hz, and for the flight test, the average value of the extrapolation function is approximately 100. The uniformity of the flight test functions indicate that flight tests may be a promising method of EMP simulation for aircraft.

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EXTRAPOLATION OF SIMULATION TEST DATA FOR AIRCRAFT WITH LARGE PENETRATION AREAS

Werner J. Stark
Kaman Sciences Corporation
P.O. Box 7463
Colorado Springs, Colorado 80933

The process of computing the pin level EMP response of aircraft systems is an important step in assessing hardness of these systems to an incident EMP. When the responses are obtained from simulation test data, various extrapolation techniques must be applied to compute the response to a specified EMP environment. Test data consisting of pin currents on internal cables are a strong function of the external geometry of the aircraft, and a common extrapolation technique is to compute extrapolation parameters in terms of surface response characteristics of the aircraft [1].

In some instances, particularly for a hull hardened aircraft, the ports of entry (POE's) for EMP penetration are electrically small and numerous, and one usually computes an extrapolation function from an average of surface extrapolation parameters. These extrapolation parameters can vary considerably over the surface of the aircraft, and can result in large error bounds for extrapolated data.

When an aircraft contains several large penetration areas such as an open bomb bay, unshielded cockpit windows, etc., the extrapolation errors can be reduced if the extrapolation functions are taken as an average over the penetration area, rather than as an average over the whole aircraft. In this paper we describe how such major penetration areas can be identified, and how the extrapolation can best be accomplished using a combination of surface and field extrapolation parameters for appropriate frequency ranges. The extrapolation technique is illustrated by comparing extrapolations of test data from a ground based simulator with test results from an "in flight" simulator.

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[1] Carl E. Baum, Extrapolation Techniques for Interpreting the Results of Tests in EMP Simulators in Terms of EMP Criteria, Air Force Weapons Laboratory Sensor and Simulation Notes, Note 222, March 1977.

UNCERTAINTIES IN EXTRAPOLATING EMP TEST DATA TAKEN ON ONE AIRCRAFT TO ALL AIRCRAFT OF THE SAME TYPE

by

D. E. Merewether
R. B. Cook
R. W. Cox

Electro Magnetic Applications, Inc.
P. O. Box 8482
Albuquerque, New Mexico 87198
Phone: (505) 265-3538

Abstract

During an EMP test of an aircraft, a large number of wire current measurements will be made that will allow assessment of the EMP survivability of that particular aircraft. However, usually our interest is in the more general question of the survivability of any aircraft of that same type. This extrapolation requires assumptions about the similarity of the aircraft that are often taken for granted. In this paper, we focus attention on the question of how much the differential voltage on a pair of wires within a cable would depend upon the relative location of the pair within the cable. Since there is always at least that much uncertainty in the cable geometry, the variation observed here is a lower bound on the uncertainty in the aircraft-to-fleet extrapolation process.

We have approached the problem in two ways: first, by making a Monte Carlo type of analysis of the variation in response of nine simplified cables made up of straight conductors, loaded on each end with almost balanced loads. Secondly, we have examined a small sample of measurement cable responses taken in a single aircraft on "almost identical" cables. The results of these two studies will be presented and the results compared.

CURRENT DENSITY ON A CYLINDRICAL SCATTERER ABOVE A GROUND PLANE

GARY I. HOFFER
Kaman Sciences Corporation
P.O. Box 7463
Colorado Springs, Colorado 80933

Results are reported here of a calculation of the current density induced on an infinitely long, perfectly conducting circular cylinder parallel to a perfectly conducting infinite ground plane by an electromagnetic plane wave with the electric vector parallel to the cylinder axis. This study was motivated by a desire for a better understanding of the magnitude and distribution of EMP-induced current on an aircraft parked on the ground. Bombardt[1] has calculated the current density for a cylinder over ground for the case when the distance from the cylinder to the ground plane is much greater than the cylinder radius. Taylor[2] has determined the circumferential distribution of an arbitrary current on a cylinder above ground in the static limit. The solution presented here involves the replacement of the ground plane with a second cylinder representing the image. The problem then becomes nearly identical to that of electromagnetic scattering from two parallel cylinders, a subject treated by many authors. The formulation used is similar to that employed by Olaofe.[3] The incident field was expanded in Bessel functions and the scattered field in Hankel functions. The axial current density on the cylinder surface is calculated, and currents from the direct and reflected waves are superimposed. The resulting expression for the current density is examined in the limit $ka \ll 1$, $kd \ll 1$ where k is the wavenumber, a is the cylinder radius and d is the separation between the cylinders. The resulting approximation for the current density is:

$$K(k,\theta) \approx \frac{E_o}{Z_o ka}\left[\frac{\sin(kd\cos\beta)}{\ln(d/a)}\left(1 + 2\sum_{n=1}^{\infty}(a/d)^n\cos(n\theta)\right) + 4\sum_{n=1}^{\infty}\frac{i^{n+1}(\tfrac{1}{2}ka)^n}{(n-1)!}\left(\cos(n(\theta+\beta)) - (-1)^n\cos(n(\theta-\beta))\right)\right]$$

where E_o is the incident electric field magnitude, Z_o is the impedance of free space, θ is the azimuthal angle on the cylinder measured from the line connecting the centers of the cylinders, and β is the incidence angle of the field measured from the same line. This result is identical to that of Bombardt (Ref. 1, Eq. 29) except for the summation over the terms $(a/d)^n\cos(n\theta)$. These terms lead to a circumferential distribution similar but not identical to that found by Taylor.[2]

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A CORONA MODEL FOR PREDICTING THE EMP RESPONSE OF INSULATED CABLES *

By

R. A. Perala and S. R. Rogers

Electro Magnetic Applications, Inc.
1990 So. Garrision Street
P. O. Box 26263
Denver, Colorado 80226

(303) 989-2744

Insulated cables often provide points of entry for EMP induced energy into facilities or equipments of various kinds. These cables may be either elevated above the earth's surface or they may lie directly on the surface.

Linear results for the EMP induced voltages show that air breakdown can occur in the vicinity of the cable. This corona has been largely neglected in previous analyses. In this paper, a simple corona model is presented and results for both elevated and surface cables are given for several angles of incidence and polarization and for the cable both within and out of the source region.

The corona is basically treated as a conducting sheath which exists around the cable dielectric. The sheath's thickness and conductivity are time varying and nonlinearly dependent upon the cable voltage and any incident radiation. The sheath conductivity is determined from a nonlinear air chemistry formulation which includes the effects of electrons, positive and negative ions, attachment rates, avalanche rates, and recombination. The nonlinear sheath is then treated as a second conductor in a transmission line formulation.

*Work sponsored by Harry Diamond Laboratories under Contract DAAK21-80-C-0004

DIELECTRIC BREAKDOWN OF CABLE JACKETS BY HIGH-VOLTAGE, FAST-RISETIME PULSES

C. Berkley and J. Sweton

US Army Electronics Research and
Development Command
HARRY DIAMOND LABORATORIES
Adelphi, MD 20783

Coupling codes used to predict the energy coupled to long surface cables exposed to tactical EMP excitation show that the voltage developed between the shield of the cable and ground is of sufficiently high amplitude to cause dielectric failure of the cable jacket. The level at which a fast-rising voltage transient may cause jacket failure is therefore of interest since such failures can significantly alter the coupling calculations. This paper presents experimentally obtained data on the dielectric breakdown of cable jackets to high-voltage, fast-risetime pulses. Samples of RG-8, RG-21, RG-22, RG-58, and WD-1 fieldwire were stressed to breakdown with voltage pulses having a zero to peak risetime of 30 ns. The data presented also include the effect of jacket breakdown to multiple pulses, kinked and scuffed samples, polarity reversal, and data on samples of the same type of cable from different manufacturers.

CABLE SHIELDS WITH PERIODIC BONDING*

F.C. Yang
The Dikewood Corporation
Santa Monica, CA 90405

A two-layered cable shield with periodic bonding and excited either discretely or distributedly is analyzed. It is found that the bonding straps improve the overall shielding effectiveness of the cable shield at certain frequencies, but degrade the effectiveness at others. In the case of distributed excitation, the effective transfer parameters of a two-layered cable shield can generally be calculated from simple circuits. These circuits can be easily extended for multi-layered cable shields.

*The work was performed under Contract No. F29601-78-C-0082.

COMPUTER MODEL AND IMPULSE CURRENT INJECTIONS FOR OPTIMUM NEMP HARDENING OF CABLES

C. C. Lin and M. Ianovici, Swiss Federal Institute of Technology of Lausanne, Dept. of Electrical Engineering, Ch. de Bellerive 16, 1007 Lausanne, Switzerland.

J. Bertuchoz and B. Wamister, AC Laboratory of Wimmis, Swiss Dept. of Defense, 3752 Wimmis, Switzerland.

Abstract

One possible approach is presented for the optimization of cable shielding against Nuclear EMP. The protection study performed to determine the EMP response of transmission cables consists of a combination of analytical methods and laboratory testing. The first step is the development of a cable coupling computer model. Both aerial and buried coaxial cables with multi-layer shields are considered. The model is assumed to be linear and the transmission line theories[1,2] are applied to compute the cable response in the presence of an incident EMP. The internal voltages and currents are determined via the surface transfer impedance of cable-sheaths. A comparison between the analytical and the experimental results in the case of a 6 m lenth aerial cable is presented. The second step of the study is the surface transfer impedance measurements by impulse current injections in short cables. A measuring system composed of a triaxial fixture fed by a current pulser (150 kV) and followed by a transient recording equipment has been developped. The advantages in determining the transfer impedance by impulse current injections are 1) the possibility of measuring the heavyly shielded cables (which is difficult in CW testing) and 2) the fact that the measured results include the realistic transient behaviour of saturable ferromagnetic materials used in the cable shield constructions. The third step of the study is the EMP simulation on long cables by impulse current injections. This step assumes that the EMP induced sheath currents are already known. The transfer impedance measured by the triaxial impulse current injection system is combined with the analytical method to compute the internal voltages and currents for a given transient sheath current so that the non-linear behaviour of ferromagnetic shield is taken into account. The combination of these three steps appears to be a very efficient technique in the optimization of cable shielding.

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Shielding Tests for Braided Cables in the 100 MHz - 40 GHz Range

Garland T. Smith
Rockwell International
3370 Miraloma Avenue
Anaheim, CA 92803

Electromagnetic shielding tests, in the past, have been very thorough in determining "shielding effectiveness" or transfer impedance" characteristics of braided shields up to 100 MHz. However, many new government documents are specifying requirements up to 40 GHz.

This paper presents the results of testing a multiconductor cable including a double layer of metallic overbraid in the frequency range 100 MHz - 40 GHz.

The test technique consisted of radiating cable samples with a transmitting antenna and measuring core wire currents with a spectrum analyzer. The cable sample was exposed in two configurations, one with the outer shields intact, and the other with the shields removed to expose the core conductors. The difference in the two measurements is indicative of the shield effectiveness.

OPTIMIZATION OF THE ACD SENSOR FOR BANDWIDTH AND PULSE RESPONSE

by

Gary D. Sower

EG&G Washington Analytical Services Center, Inc.
1400 San Mateo SE
Albuquerque, New Mexico 87108

ABSTRACT

The Asymptotic Conical Dipole (ACD) family of D-dot sensors has become the accepted sensor for measuring electrical fields from EMP and lightning away from the source region. Recent investigation of these sensors shows that they do indeed have very good response characteristics, much better than those of any other D-dot sensor. However, they do exhibit an "overshoot and ringing" response to a step-field input, of about ten percent. Analysis of this effect has identified its cause and thereby a method to eliminate it. The result is an ACD sensor which has a "maximally flat" response, exhibiting both the maximum possible bandwidth and minimum possible pulse risetime, with no overshoot and ringing.

The Radiation Response of Hardened Current Probes in the CASINO Spectrum

by

William A. Seidler and Charles E. Mallon
JAYCOR, Del Mar, CA

The radiation responses of seven radiation hardened current probes (ICIX3[1], SCIX4A[1], SCIX1A[1], SCIX2A[1], SCIX3A[1], and F-32-8[2]) have been compared to that from two unhardened probes (a Tektronix CT1 probe and a Singer 91550-2) in a CASINO spectrum. Hardened probe responses varied from 8.2×10^{-14} C/rad (ICIX3) to 1.9×10^{-15} C/rad (SCIX4A), while the unhardened probes had a response of 7×10^{-14} C/rad. Measurements were limited by the ability to shield the probe interior from radiation driven currents striking the case. Sensor cables (0.075" semirigid aluminum coax) were found to contribute $3.6 \pm 1.1 \times 10^{-16}$ C/rad-cm to the radiation responses.

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[1]A product of EG&G.

[2]A product of Fischer Custom Communications.

Development of a Ferrite Isolated Hardwired Data Link for SGEMP Testing

by

William A. Seidler and Howard T. Harper
JAYCOR, Del Mar, CA

A ferrite isolated hardwire data link has been developed for use in SGEMP tests where the test object must appear electrically isolated from the vacuum tank. Isolation times greater than 1 μsec have been achieved at 63 kV using a 1.8×10^{-4} H inductor constructed of CN20* ferrite material. Isolation time is defined as the time when the test object voltage is reduced to 50% of its open circuit voltage. Two high frequency effects, electromagnetic shock formation and current leakage caused by the nonlinear variation in permeability with current amplitude and frequency, have been examined. Such nonlinear effects have been found to be sufficiently low in amplitude to not impact the isolation of the data link.

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*CN20 is a trademark of Ceramic Magnetics, Inc.

Abstract

Instrumentation for an Underground Nuclear SGEMP Experiment

Major Russell H. Bonn
Defense Nuclear Agency Field Command
Kirtland AFB, New Mexico 87107

In 1980 an elaborate full scale model of the DSCS III satellite was subjected to photon exposure from a vertical line of sight (VLOS) nuclear explosion. The scope of the experiment included measurements of prompt SGEMP singles and long term (minutes) survivability data. This report discusses the development to support this experiment, including SGEMP sensore, cabling, grounding, and shielding.

SHIELD TOPOLOGY CONCEPTS AS APPLIED TO EMP DATA LINKS

by

Gary D. Sower

EG&G Washington Analytical Services Center, Inc.
1400 San Mateo SE
Albuquerque, New Mexico 87108

ABSTRACT

Data links, both microwave and fiber-optic, are used in EMP test programs to transmit wideband analog data from sensors on and in test objects to recording/processing systems. The data link transmitters are of ten fastened to the exterior of the test object and thus subjected to both the simulator environment and to the test object response. The data link transmitters must therefore be impervious to the couple into the signal data paths. A method for ensuring the hardness of such data transmitters is described which is based on the two-layer shield topology concept. This method defines two volumes within the transmitter, the outer of which is shielded so the maximum open-circuit voltage possible from the external fields is less than from normally existing voltages occuring in this region, such as on digital controls. The inner volume, which contain the circuitry carrying the data signals, is shielded from the outer volume so the maximum induced noise signal is much less than the smallest data signal of interest.

EXPERIMENTAL DETERMINATION OF ELECTROMAGNETIC PULSE (EMP) ABSORPTION ON COMPLEX SHAPES:

R. W. Burton, Professor of Electrical Engineering, University of Colorado, Colorado Springs, Austin Bluffs Parkway, Colorado Springs, CO 80907

R. M. Sega, Instructor of Physics, USAF Academy/DFP, USAF Academy, CO 80840

V. M. Martin, Instructor of Physics, USAF Academy/DFP, USAF Academy, CO 80840

It has been demonstrated that the induced surface currents resulting from incident electromagnetic radiation produce I^2R heating detectable through thermographic techniques. A method is developed to predict the distribution of electromagnetic energy absorbed by an object as a function of its particular geometry. Intense areas of detected I^2R heating can then be identified in relation to the entire object.

Previous studies have utilized simple geometric shapes in theoretical and experimental analyses. These shapes have included the flat plate, sphere, cylinder, cross-dipole, and combinations thereof, providing a data base from which the present experimental techniques have been qualitatively compared. The experimental results utilizing thermographic techniques show that the distribution of induced surface currents resulting from an impinging electromagnetic wave are detected in real time through thermography. Complex shapes including aircraft models are also examined to determine the effect on the electromagnetic energy absorption distribution as a function of orientation relative to the incident angle of the impinging wave. The dependence of frequency on absorption distributions is investigated using frequencies of 2.8, 10 and 94 GHz. All model surfaces are of a composition having a coating of high emissivity on an insulating layer such that incident electromagnetic energy is reradiated through surface current production minimizing the thermal conduction interior to the surface. Maximizing the surface phenomena of absorption then provides for the accurate determination by thermography of localized energy absorption from the impinging wave.

The use of infrared radiations and scaled down modeling of complex shapes provides the researcher or engineer with an accurate and rapid method of examining an entire object with respect to the anticipated electromagnetic energy absorption. The technique developed allows for exceptional cost effective simulation of potential design alterations of the geometric factors involved in the location and possible redistribution of absorbed electromagnetic energy.

COLLECTION AND PROCESSING TECHNIQUES FOR HIGH SPEED TRANSIENT EM DATA

J. E. Zicker
Lawrence Livermore Laboratory, Livermore, CA 94550

Instrumentation that can digitize analog signals with frequencies into the Gigaherz range has proved useful in acquiring transient electromagnetic field data. The digital processing of this type of data requires knowledge of signal processing techniques, the acquisition instrumentation and the characteristics of the experiment. The results of this combination of specialties are several data processing algorithms that prove useful in analyzing transient electromagnetic data. Some of the methods used are digital filtering and least mean squares estimation.

The acquisition instrumentation tends to introduce measurement noise and spurious data points. The measurement noise can, for example, drastically affect the various methods of estimating the frequency spectra from the time domain data. One parameter estimation technique may work well for one problem and poorly for another.

We present the practical methods and the techniques gained from experience on two different problems. The two problems both involved the measurement of transient electromagnetic fields. The data was collected with two different acquisition systems. In both cases we were able to reliably eliminate or compensate for the unwanted effects introduced by the acquisition instrumentation through improved experimental or signal processing techniques. We concentrate primarily on the estimation of the frequency spectrum.

Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore Laboratory under Contract No. W-7405-ENG-48.

PROCESSING OF DATA FOR E-4B EMP TEST

Myles A. O'Byrne
Boeing Aerospace Company
P. O. Box 3999
Seattle, WA 98124

Approximately 2000 pulse response measurements were made during the E-4B System Level EMP Test conducted from February to June 1979 at the AFWL HPD/VPD facilities. This paper describes the processing scheme used to obtain final time domain data to which complete frequency-dependent calibrations had been applied and discusses the rationale behind the approach taken.

The data was acquired and processed initially by the on-site acquisition and processing systems (DASET/ADSET). Subsequent to the test, nominally corrected time data and frequency dependent calibration data were used in Seattle to produce the final time domain data.

The following were of chief concern in the processing task and are discussed in the paper:

The presence in many data sets of both significant late time response (>100 μsec) and early time character which required sweep rates of 20 ns/div.

The choice of transform algorithms to give the required flexibility in specifying frequency range.

The limitations imposed by digitization noise at high frequency and by truncations and offsets at low frequencies.

The effect of the frequency-dependent corrections and the range over which their application was valid.

The formats used to display the finally-processed time and frequency data (overlayable scales, log time plots).

ABSTRACT

IMPROVED TEST INSTRUMENTATION/RECORDING TECHNIQUES

By Mr. William H. Cordova, Rockwell International Corporation, Nuclear Effects Group, 2340 Alamo S. E., Suite 309, Albuquerque, New Mexico 87106.

This paper describes improvements in test instrumentation/recording techniques which can be used to enhance the signal-to-noise dynamic range and to extend the valid frequency limits of measured EMP signal responses. With the major emphasis today being the assessment of systems/equipment to criteria threat environments, and due to the lack of threat level simulators, it has been necessary to extrapolate measured responses to criteria levels to support such assessments. Previous assessments have nonetheless found it difficult to develop valid extrapolation transfer functions which span the total EMP frequency range. This has generally been due to equipment signal-to-noise dynamic range limitations as well as instrumentation bandwidth frequency limitations.

During the recent TACAMO (TEMPAT-II) EMP Assessment Test, Rockwell International developed and demonstrated some innovative instrumentation/recording techniques using conventional EMP test instrumentation which provide improved signal-to-noise dynamic range as well as extend the valid frequency limits of signal response Fourier transforms. These new techniques support the development of broadband extrapolation transfer functions and promise significant reduction in frequency domain data error margins.

Described are the effective use of multiple transient digitizers (scopes), sequential triggering, optimization of sweep speed and vertical sensitivities, simultaneous recording of integrated and non-integrated vehicle response data, simultaneous recording of integrated and nonintegrated environmental reference data, and use of a broadband fibre optics data link.

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