ADVANCE PROGRAM

REGISTRATION FORM

The IEEE Electromagnetic Compatibility Society

Proudly Presents

Emerging Technologies in EMC

Thursday and Friday, 26-27 April 2012

Escola Politécnica - University of São Paulo
São Paulo, Brazil

Program Agenda

26 APRIL 2012

9:30 am	**REGISTRATION** **REFRESHMENTS**
10:00 am	**Escola Politécnica - EPUSP Welcome** *Prof. José Roberto Cardoso, Dean of the EPUSP* **IEEE EMC Society Welcome** *Dan Hoolihan, Past President of the IEEE EMC Society*
10:15 am	**Reverberation Chamber Test Methodology for Traditional EMC Measurements** *Garth D'Abreu, ETS-Lindgren, Cedar Park, Texas*
11:15 am	**Measurement Uncertainty for Conducted and Radiated Emissions: An Analysis of a New Standard – ANSI C63.23** *Dan Hoolihan, Hoolihan EMC Consulting, Minneapolis, Minnesota*
12:15 pm	**LUNCH BREAK**
1:30 pm	**The "Ground" Myth for High Speed Signal Design and EMI/EMC Control** *Dr. Bruce Archambeault, IBM, Raleigh, North Carolina*
2:30 pm	**Radiated Emissions/Immunity: EMC Test Standards and EMI Antenna Analysis and Design** *Dr. Johannes Nordgaard, NASA/JSC, E3 Lab, Houston, Texas*
3:30 pm	**REFRESHMENTS**
3:45 pm	**Antennas for EMC – the Latest Designs and Capabilities** *Dr. Vicente Rodríguez, ETS-Lindgren, Cedar Park, Texas*
4:45 pm	**Combining EMC and Signal Integrity for Effective PCB Design** *Dr. Bruce Archambeault, IBM, Raleigh, North Carolina*
5:45 pm	**CONCLUDING REMARKS** *Carlos Sartori, Nuclear and Energy Research Institute IPEN-CNEN/SP*

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Program Agenda

27 APRIL 2012

9:30 am	**CHECK IN – REFRESHMENTS**
9:45 am	**IEEE EMC Society Welcome** *Dan Hoolihan, Past President of the IEEE EMC Society*
10:00 am	**Using Equivalent Emission Sources to Evaluate Component System Interactions** *Carlos Sartori, Nuclear and Energy Research Institute IPEN-CNEN/SP*
11:00 am	**Equipping Instrumentation and Control Engineers with the Right Knowledge to Address EMI Problems in Their Plants** *Philip Keebler, Electric Power Research Institute (EPRI) Knoxville, Tennessee*
12:00 pm	**LUNCH BREAK**
1:15 pm	**Automotive System and Component Level EMC Testing: CISPR 12, 25 and ISO 11451 and 11452** *Dr. Vicente Rodríguez, ETS-Lindgren, Cedar Park, Texas*
2:15 pm	**ISO/IEC 17025 – A Fresh Perspective from an Experienced EMC Lab Assessor** *Dan Hoolihan, Hoolihan EMC Consulting, Minneapolis, Minnesota*
3:15 pm	**REFRESHMENTS**
3:30 pm	**Development of the Reverberation Chamber for Wireless Applications** *Garth D'Abreu, ETS-Lindgren, Cedar Park, Texas*
4:30 pm	**Eliminating the Need for Exclusion Zones in Nuclear Power Plants: Where are the New Boundaries?** *Philip Keebler, Electric Power Research Institute (EPRI) Knoxville, Tennessee*
5:30 pm	**CONCLUDING REMARKS** *Carlos Sartori, Nuclear and Energy Research Institute IPEN-CNEN/SP*

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TECHNICAL PROGRAM

Presentation Abstracts – 26 April 2012

Presentation Title: Eliminating the Need for Exclusion Zones in Nuclear Power Plants: Where are the New Boundaries?
By Philip Keebler, Electric Power Research Institute (EPRI), Knoxville, Tennessee

Abstract: Since the first use of a hand-held walkie-talkie in a nuclear power plant, plant operators and instrumentation and control (I&C) engineers have been struggling with many electromagnetic interference (EMI) problems with I&C equipment. Plant personnel who must use walkie-talkies to communicate with other personnel within the plant have been burdened with where they are allowed to use walkie-talkies. Despite painted exclusion zone boundaries on floors around sensitive I&C equipment, EMI problems are still caused by the use of walkie-talkies and other wireless devices. Exclusion zones have proven to be ineffective in avoiding plant EMI problems. Plant personnel must have unlimited use of wireless devices, especially in the event of a plant emergency requiring communication with local and federal authorities. Recent EPRI research shows that providing the needed level of immunity to radiated electromagnetic threats requires a layered approach involving the design of circuits, enclosures, system cabinets, cable feed-throughs, and cables as well as the location of transmitter systems within the plant. This paper will present the results of an analysis of the radiated threats from the use of wireless devices of different power levels in addition to an analysis of practical levels of immunity that should be provided by the different layers.

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Presentation Title: Measurement Uncertainty for Conducted and Radiated Emissions – An Analysis of a New Standard – ANSI C63.23
By Dan Hoolihan, Hoolihan EMC Consulting, Minneapolis, Minnesota

Abstract: A new standard is nearing completion in the ANSI-ASC C6R Committee in the USA. The standard is *C63.23 – Guide for Electromagnetic Compatibility – Calculations and Application of Measurement Uncertainty*. This presentation will outline the material in the standard and go into detail on calculating the Measurement Uncertainty tables for radiated and conducted emissions. A number of International Standards for emission are starting to include Measurement Uncertainty in the standard requirements so it is essential to understand the MU principles and how to calculate your own lab's Measurement Uncertainty.

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Presentation Title: The "Ground" Myth for High Speed Signal Design and EMI/EMC Control
By Dr. Bruce Archambeault, IBM, Raleigh, North Carolina

Abstract: The term "ground" is probably the most misused and misunderstood term in EMC engineering, and in fact, in all of circuit design. Ground is considered to be a zero potential region with zero resistance and zero impedance at all frequencies. This is just not the case in practical high-speed designs. The one thing that should be remembered whenever the term "ground" is used, is that *"Ground is a place where potatoes and carrots thrive"!* By keeping this firmly in mind, many of the causes of EMC problems would be eliminated. The term "ground" is a fine concept at DC voltages, but it just does not exist at the frequencies running on today's typical boards. All metal has some amount of resistance, and even if that resistance was near zero ohms, the current flowing through a conductor in a loop creates inductance. Current through that inductance results in a voltage drop. This means that the metal ground plane/wire/bar/etc. has a voltage drop across it, which is in direct contradiction with the intention and definition of ground. This presentation discusses the origin of the word “ground”, what we really mean when we use the term “ground” and how to optimize our designs to achieve the overall goals for our reference strategy.

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Presentation Title: Radiated Emissions/Immunity: EMC Test Standards and EMI Antenna Analysis and Design
By *Dr. Johannes Nordgaard, NASA/JSC, E3 Lab, Houston, Texas*

Abstract: Electromagnetic Radiated Emissions (RE) from an electronic system can cause Radiated Susceptibility (RS) in other nearby electronic devices. All components of the electronic system radiate, and all parts of the electronic device receive, forming a transmitter/receiver pair. Electromagnetic Interference (EMI) between the system and device can cause electronic component degradation, damage, destruction, etc. and system disruption or failure. EMI emissions/immunity testing and analysis of the radiated emissions from and radiated susceptibility of an electronic circuit are reviewed. All components in the system/device are modeled and simulated as radiating/receiving antennas. The physics (phenomena) and math (models) of basic antennas are reviewed. The concept of radiation is discussed. The radiation integrals (describing the electric and magnetic effects of the antennas) are presented as THE unique particular solutions to the (coupled) Maxell and (uncoupled) Helmholtz field/wave equations (and the Conservation of Charge/Current) for all basic antenna types radiating in simple media (with homogeneous, isotropic, linear, and non-dispersive Constitutive Relations). Near-Field and Far-Field solutions to these governing equations are presented, which are the fundamental formulas on which the numerical computational electromagnetic (CEM) Method of Moments (MoM) technique is based. The interrelationships between antenna Analysis and Synthesis (Design) concepts are discussed. The near, immediate, and far fields radiated from a simple Hertzian dipole are found as an example. The physical characteristics of an antenna, e.g., radiation pattern, directivity/gain, input impedance/reflection coefficient, lobes/nulls, matching/VSWR, etc., are defined and discussed.

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Presentation Title: Antennas for EMC – the Latest Designs and Capabilities
By Dr. Vicente Rodríguez, ETS-Lindgren, Cedar Park, Texas

Abstract: The presentation is a basic introduction to different parameters of antenna theory. Gain, patterns, input parameters, antenna factor are introduced. After that the typical antennas used in EMC testing are introduced as well as their typical beamwidth. Beamwidth being a parameter which both the FCC and CISPR are concentrating on as they insist on the EUT being inside the cone of radiation of the antenna.

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Presentation Title: Reverberation Chamber Test Methodology for Traditional EMC Measurements
By Garth D’Abreu, ETS-Lindgren, Cedar Park, Texas

Abstract: This presentation will introduce the fundamentals of reverberation chamber operation and show how this measurement environment is being used for typical EMC measurements. Attendees will leave with a clear understanding of the basics and an appreciation of the advantages as well as the disadvantages of this increasingly popular test method.

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Presentation Abstracts – 27 April 2012

Presentation Title: Using Equivalent Emission Sources to Evaluate Component System Interactions
By Carlos Sartori, Nuclear and Energy Research Institute IPEN-CNEN/SP, Brazil

Abstract: The electromagnetic interference between the electronic systems or their components influences the performance of the systems. For that reason, it is important to model these interactions in order to optimize the position of the systems or their components. Many methodologies can be used for this purpose, such as numerical modeling and measurement techniques. The use of equivalent emission source models may be mentioned. They can be determined based on the multipolar expansion theory, and on measurement techniques, for instance, by applying large coils placed around the equipment to be evaluated. This approach allows achieving an integration of the magnetic flux density, reducing the constraints related to field sensor positioning inaccuracies. A brief presentation of this methodology, including some theoretical details and the measurement principle of antennas in which coils act like filters, sensitive to one specific component of the multipole, and some practical examples will be presented.

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Presentation Title: Equipping Instrumentation and Control Engineers with the Right Knowledge to Address EMI Problems in Their Plants
By Philip Keebler, Electric Power Research Institute (EPRI), Knoxville, Tennessee

Abstract: Instrumentation and control (I&C) engineers must possess a plethora of knowledge to do their jobs in today's existing nuclear plant. Many aspects of their jobs in the plant as they maintain existing analog I&C equipment and install new digital I&C equipment affect the EMC performance of the I&C equipment for which they are responsible. Electromagnetic compatibility (EMC) and electromagnetic interference (EMI) are two subjects that I&C engineers often struggle with. They must have at least a basic understanding of the topics within EMC and EMI to be effective in understanding, identifying, solving, and preventing EMI problems. Before they can utilize many of the basic EMC and EMI principles, they must first recognize the need for and value of effective and interactive EMI training programs designed specifically for I&C engineers. Building upon the basics, an effective training program should incorporate examples of different types of EMI problems in hands-on demonstrations which few training programs use. Effective training programs should also go way beyond understanding and applying EMC test methods for qualification of I&C equipment. EPRI is the leader in providing EMI training to domestic and global I&C engineers having started the training program in the late 1980s and making use of many real operating experiences and examples of challenges that today's I&C engineers face. This presentation will illustrate how EPRI presents the basics of EMC and EMI followed by consistent incorporation and use of new knowledge and practices from the EMC industry to effectively train today's I&C engineers to understand, identify, solve, and prevent tomorrow's EMI problems.

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Presentation Title: Automotive System and Component Level EMC Testing: CISPR 12, 25 and ISO 11451 and 11452
By Dr. Vicente Rodríguez, ETS-Lindgren, Cedar Park, Texas

Abstract: This presentation covers the basic standards for testing of automotive systems as well as automotive components. The presentation starts with an overview of the full system

component chamber and antennas requirement as well as a description of the test set up. After covering the full system testing, an overview of the component testing is provided concentrating on the anechoic chamber requirements for both immunity and emissions testing and the test set up geometries.

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Presentation Title: ISO/IEC 17025 – A Fresh Perspective from an Experienced EMC Lab Assessor

By Dan Hoolihan, Hoolihan EMC Consulting, Minneapolis, Minnesota

Abstract: The International Standard for Laboratory Accreditation is *ISO/IEC 17025 – General Requirements for the Competence of Testing and Calibration Laboratories.* This presentation will highlight the Administrative and Technical aspects of the Laboratory Accreditation standard. Experiences from over 200 lab assessments will be discussed including hints on what makes a quality EMC Lab as well as common Non-Conformities from labs around the world.

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Presentation Title: Development of the Reverberation Chamber for Wireless Applications

By Garth D'Abreu, ETS-Lindgren, Cedar Park, Texas

Abstract: Reverb Chambers have been in limited use for Immunity measurements for several decades. In the last five years there has been a surge in interest and an increase in the number of applications to which this method has been applied. This presentation will look at one of the most recent and challenging first steps in the development of a standardized method of over the air (OTA) testing of wireless devices.

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Presentation Title: Combining EMC and Signal Integrity for Effective PCB Design

By Dr. Bruce Archambeault, IBM, Raleigh, North Carolina

Abstract: EMC constraints for PCB design are often viewed as contrary to preferred design approaches for good high speed signal integrity (SI) design. This conflict is not necessary, and in fact, good *electromagnetic* design practices results in *both* EMC and SI effective designs! This presentation will discuss both the EMC and SI concerns, and how to create effective designs without compromising either EMC or SI. There are a number of design parameters, both on PCBs and in cable/connector designs that can improve both the SI quality and the EMC performance. Some of these issues include high speed differential signaling, immunity to external disturbances, and cross talk contamination within high speed buses.

SPEAKER BIOGRAPHIES

Dr. Bruce Archambeault is an IEEE Fellow and an IBM Distinguished Engineer at IBM in Research Triangle Park, NC. He received his B.S.E.E degree from the University of New Hampshire in 1977 and his M.S.E.E degree from Northeastern University in 1981. He received his Ph. D. from the University of New Hampshire in 1997. His doctoral research was in the area of computational electromagnetics applied to real-world EMC problems. Dr. Archambeault has authored or co-authored a number of papers in computational electromagnetics, mostly applied to real-world EMC applications. He is a member of the Board of Directors for the IEEE EMC Society and a past Board of Directors member for the Applied Computational

Electromagnetics Society (ACES). Within the IEEE/EMC Society he currently is the Technical Advisory Committee Chair and the Vice President for Conferences. He has served as a past IEEE/EMC-S Distinguished Lecturer. He is the author of the book “PCB Design for Real-World EMI Control” and the lead author of the book titled “EMI/EMC Computational Modeling Handbook”.

Garth D’Abreu is the Technical Manager of the RF Engineering Group at ETS-Lindgren in Cedar Park, Texas. He has primary responsibility for the design and development functions within the RF engineering group. The RF group provides technical support for ETS-Lindgren worldwide and is responsible for anechoic chambers, E Field generators, TEM cell device design and development, antenna design and absorber development. Mr. D’Abreu is the lead engineer for reverberation chamber design and testing and is responsible for the development of GTEM cells, products for EMP applications and wireless device test systems. He holds a BSc degree in Electronics & Communications Engineering, North London University, UK. He is a member of the IEEE EMC Society and has over 20 years experience in the RF industry.

Daniel D. Hoolihan is currently President of Hoolihan EMC Consulting, 32515 Nottingham Court-Box 367, Lindstrom, Minnesota, 55045. Dan is an iNARTE-certified engineer with a long career in EMC. He began by working in Control Data’s RFI/EMC lab in 1969. When the lab was spun off in 1984, Dan and a partner bought the lab and formed Amador Corporation. Dan served as the company’s COO until 1994 when the lab was sold to TUV America. He remained with TUV in a management capacity until 2000, when Dan again felt the entrepreneurial spirit and formed Hoolihan EMC Consulting. With his new company, Dan consults for commercial and private EMC labs in North America, Europe and Asia. Despite his busy schedule, Dan has been deeply involved in the IEEE EMC Society. He has served on the board of directors almost continuously since 1987. Dan was also president of the Society from 1998 to 1999, and served as chair of the 2002 IEEE Symposium on EMC. At a local level, Dan was one of the founding members of the Twin Cities EMC chapter in Minnesota. Today, in addition to his consulting business, Dan is the Chair of the ANSI accredited standards committee C63R and writes a column on EMC history for the EMC Society Magazine. Daniel Hoolihan received his bachelor’s degree in physics from Saint John’s University (Minnesota), his master’s degree in physics from Louisiana State University (Baton Rouge), and a master’s degree in business administration from the University of Minnesota (Minneapolis).

Philip Keebler is a Senior Research Engineer in the Power Delivery & Utilization Sector at EPRI with one focal area on electromagnetic compatibility (EMC). His responsibilities include, 1) conducting EMC research on end-use electronic loads including lighting, medical, and nuclear I&C equipment, 2) managing EPRI’s EMC Laboratory where emissions and immunity studies are carried out, 3) involvement in EMC standards development, 4) conducting EMC audits and troubleshooting for utilities and their customers, and 5) development and testing of solutions to electromagnetic interference (EMI) problems. Prior to joining EPRI in 1995, Philip worked with the North American Philips Company in the Consumer Electronics Division where he designed switch-mode power supplies, conducted EMC testing of television products, developed the first surge protection and characterization laboratory there, and studied failure mechanisms and rates associated with projection and direct view color televisions. Mr. Keebler also designed a low-noise power supply for Philips' first high-definition direct view television. Prior to working with Philips, Mr. Keebler studied high-voltage electronics and industrial plasma engineering at the University of Tennessee Plasma Science Laboratory in Knoxville, Tennessee where he conducted research on plasma ion-implantation for the Air Force Office of Scientific Research and the Army Research Office. Philip received his M.S. and B.S. in Electrical Engineering from the University of Tennessee (1990 and 1988, respectively). Philip is active in many professional organizations, including but not limited to IEEE, Illuminating Engineering Society of North America (IESNA), and the Association for the Advancement of Medical Instrumentation (AAMI), and is Chair of the TC-4: EMI Control within the IEEE EMC Society. Mr. Keebler was the editor of the IEEE Standard 1560 - *Standard for Methods of Measurement of Radio Frequency Power Line Interference Filter in the Range of 100 Hz to 10 GHz*, published by IEEE in 2005 and was the editor of a new standard on shielding effectiveness. Mr. Keebler is currently the Vice-Chair for two new ANSI C63 EMC standard projects regarding nuclear EMC.

Johannes Nordgaard (John Norgard) (Georgia Tech-B.S.E.E./1966/Co-Op; Caltech-MS/1967/Applied Physics; Caltech-PhD/1969/Applied Physics) of NASA/JSC is the Chief Engineer for Electromagnetic Environmental Effects (E3). Prior to joining NASA, Dr. Norgard was a Professor at the University of Colorado at Colorado Springs, the President and CEO of ElectroMagnetic Techniques (EMT), Inc., the Chief Scientist of ZeeWaves, Inc., and the Senior Research Scientist for the Radar Techniques Branch of the Sensors Directorate at the Rome Research Site of the Air Force Research Lab [AFRL/RRS (SNRT)]. He has also been a Distinguished Visiting Professor (DVP) at the US Air Force Academy in the Electrical & Computer Engineering Department. He has taught graduate and undergraduate courses in Electromagnetic Field Theory for over 30 years and was the Director of the Electromagnetics Laboratory at the University of Colorado. Before coming to the University of Colorado, he was a Professor in the Electrical Engineering Department at Georgia Tech and was a Post-Doctoral Fellow at the Norwegian Defense Research Establishment (NDRE) in Kjeller, Norway. He worked at the Jet Propulsion Laboratory (JPL) while studying at Caltech and was a Co-Op student at Georgia Tech while working at the Charleston Naval Shipyard (CNS). He has worked on numerous computational electromagnetic problems, including conformal antennas/apertures, strip lines/microstrips, waveguides/cavities and transmission lines, propagation of waves through various plasma media (polar ionosphere, rocket soundings), interaction and coupling of waves to wires (cross-talk, NEMP, and lightning), EMI, EMC, EMS/V, backscatter from clutter targets, ESD, HPM radiation, GPR, RF Tomography, and IR Metrology. He has developed a 2D thermal mapping technique using infrared thermography and microwave holography to measure electromagnetic fields and to verify and validate numerical CEM codes. He has been a Visiting Professor at the Tel-Aviv University and was a member of the technical staff of the Bell Telephone Laboratories. He is an Adjunct Professor at Syracuse University and at the University of Houston. He is a Fellow of IEEE for IR measurements of EM fields, a past member of the Board of Directors for the IEEE/EMC Society serving as the Vice President for Standards, on the Board of Physics and Astronomy for the National Academy of Sciences, Past Chairman for Commission A/Metrology of URSI, and an Associate Editor for the IEEE/EMC Transactions in the area of antenna metrology. He has authored several hundred technical papers, reports, and journal articles and has contributed chapters to four EM books.

Vicente Rodríguez attended The University of Mississippi (Ole Miss), in Oxford, MS, where he obtained his B.S.E.E. in 1994. During the fall of 1994, he joined the Department of Electrical Engineering at the University of Mississippi as a research assistant. During his tenure at the department, he completed his Master of Science and Doctorate degrees in the area of Engineering Science with an emphasis on Electromagnetic Theory in 1996 and 1999, respectively. In August 1999, Dr. Rodríguez joined the department of Electrical Engineering and Computer Science at Texas A&M University-Kingsville (formerly Texas A&I University) as a Visiting Assistant Professor. In June 2000, Dr. Rodríguez left the academic world when he joined EMC Test Systems (now ETS-Lindgren) as an RF and Electromagnetics engineer. During this time he was involved in the RF anechoic design of several chambers, including rectangular and taper antenna pattern measurement chambers, some of which operate from 100 MHz to 40 GHz. He was the principal RF engineer in the design and fabrication of the large Automotive/EMC/Satellite anechoic test chamber at INPE LIT in Brazil. In September 2004, Dr. Rodríguez assumed the position of Senior Principal Antenna Design Engineer, placing him in charge of the development of new antennas for different applications. Among the antennas developed by Dr. Rodríguez are new broadband double- and quad-ridged guide horns with a single lobe pattern and high field generator horns for the automotive industry. Dr. Rodríguez's interests include numerical methods in electromagnetics, especially when applied to antenna, EMC and RF/MW absorber design and analysis. Dr. Rodríguez is the author of more than twenty publications and holds patents for hybrid absorber and for a new double-ridged horn antenna. Dr. Rodríguez is a senior member of the IEEE and several of its technical societies including the AP, MTT and the EMC Societies. He is also a senior member of the Antenna Measurements Techniques Association (AMTA) and currently serves on its Board of Directors.

Carlos A. F. Sartori has been an Invited Professor at the Postgraduate Program of the Department of Energy and Automation Engineering of Escola Politécnica of University of São Paulo – EPUSP since 1999, and at the Nuclear and Energy Research Institute IPEN-CNEN/SP since 2006. He is also an Associate Professor at the Catholic University of São Paulo where he was the Vice-head of the Department of Electrical Engineering (1997-1998), and the Vice-Dean (2001-2004). He is a member of the IEEE EMC Society (SM'91), the IEEE South Brazil EMC Chapter Chair (2000-2009, 2011-2012), and a former EMCS Member of the Board (2000-2004). He is also a Member of the IEEE Education Society, International Compumag Society (ICS), and of the Brazilian Society on Electromagnetics (SBmag), where he was the Vice-president (1998-2002). His active research interest is applied electromagnetics and EMC, in particular, the time-domain modeling, lightning, crosstalk, reverberation chamber performance, failure detection, radiated equivalent source evaluation, and biological effects. He is registered professional engineer in the State of São Paulo -Brazil (1984), and he has been with the EMC Group of the IPEN CNEN/CTM-SP since 1991.

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Seminar Location

Auditório Francisco Romeu Landi
Escola Politecnica da Universidade de Sao Paulo
Av. Prof. Luciano Gualberto, trav. 3, 380
05508-010 Sao Paulo, Brazil

Parking Lot: There is a free parking lot in front of the Auditorium Building
http://www3.poli.usp.br/pt/acesso-rapido/mapas-e-meios-de-transporte.html

Seminar Organizing Committee

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Hosts
José Roberto Cardoso (EPUSP) and Carlos Sartori (IPEN/CNEN-SP)
IEEE EMC South Brazil Chapter
e-mails: sartori@ipen.br; sartori@pea.usp.br

REGISTRATION FEES

Deadlines	IEEE Members	Non-Members*
Received by April 6	**BR$ 50**	**BR$ 70**
Received from April 7 or on site (if space is available)	**BR$ 65**	**BR$ 85**
MEMBERSHIP: A credit of BR$ 10 may be applied on site to a one year E-membership in IEEE.		
STUDENT DISCOUNT: Full time students are eligible for a 50% discount off the registration fees. A valid student identification card must be presented on site to gain access to the program.		

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Registration Information

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IEEE Member: ***Y*** ☐ ***N*** ☐ ***Member Number:*** ______________________________

Full Time Student: ***Y*** ☐ ***N*** ☐ ***Student ID Number:*** ______________________________

Name of University or College: ______________________________

Registration by E-mail

Registration Total per Fees Above $ ______________________________

Check Enclosed in Amount of: $ ______________________________

Return to Registration Chairman:

André Kavaliéris Galvão
AK Telemedia – Director
Email: aktelemedia@gmail.com
Mobile Phone: 55-11-74077473, Office Phone: 55-11-24954437

NOTE: The registration fee includes refreshment breaks and access to the technical program for two full days. Lunch is NOT included and may be purchased by the attendees at the University Cafeteria. The organizing committee reserves the right to substitute speakers, restrict size, or to cancel the seminar. In the event the organizing committee cancels this event, registration fees only will be fully refunded. Individuals canceling their registration prior to April 6 will receive a full refund. No refunds will be made to individuals who cancel their registration after April 6. Substitutions are allowed.

Attendance is limited.

Registration will be confirmed on a first come, first served basis.

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Development of Wireless testing in Reverb Chambers

Garth D'Abreu
Director of RF Engineering

Dr. Michael Foegelle
Director of Technology Development

Yulung Tang
RF Engineer

Farris Alhorr
RF Engineer

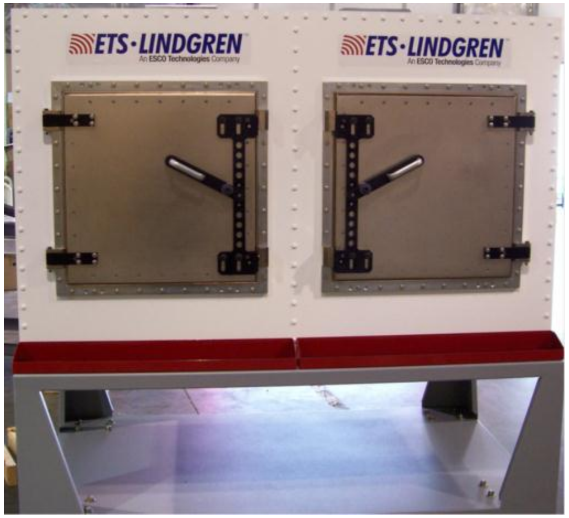
Jari Vikstedt
Senior RF Engineer

Agenda

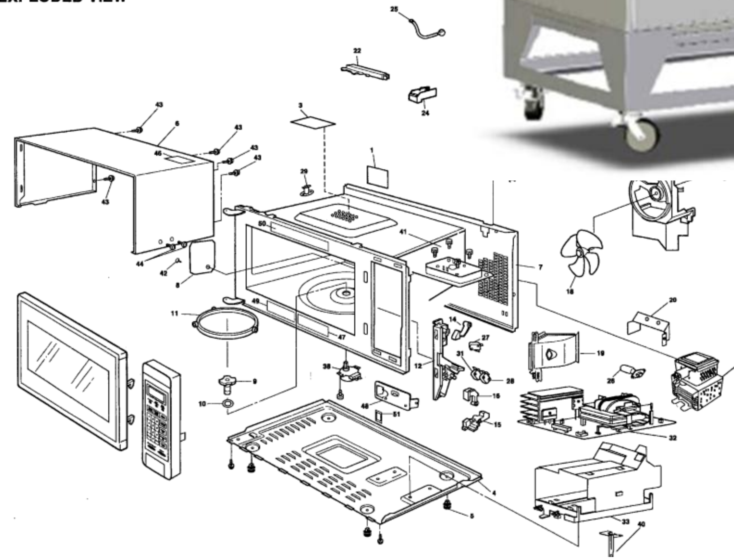
- **Introduction**
- Quick Overview of Chamber theory
- Wireless Testing
- MIMO
- Test data

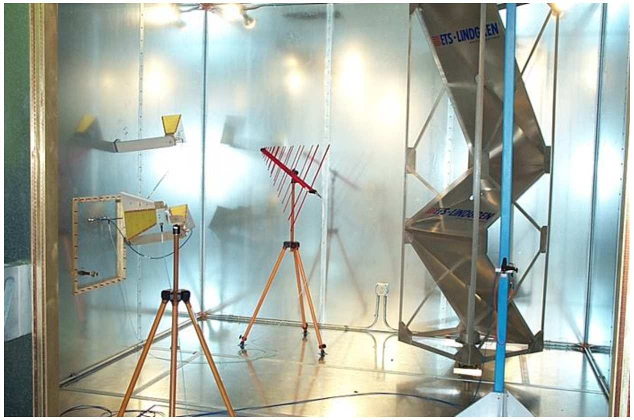
Introduction

- **Reverb chambers in Use …**



EXPLODED VIEW



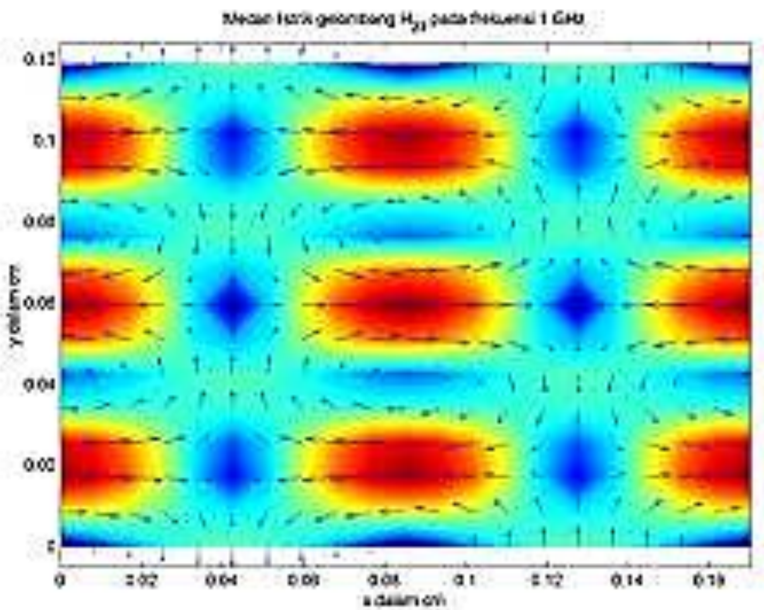


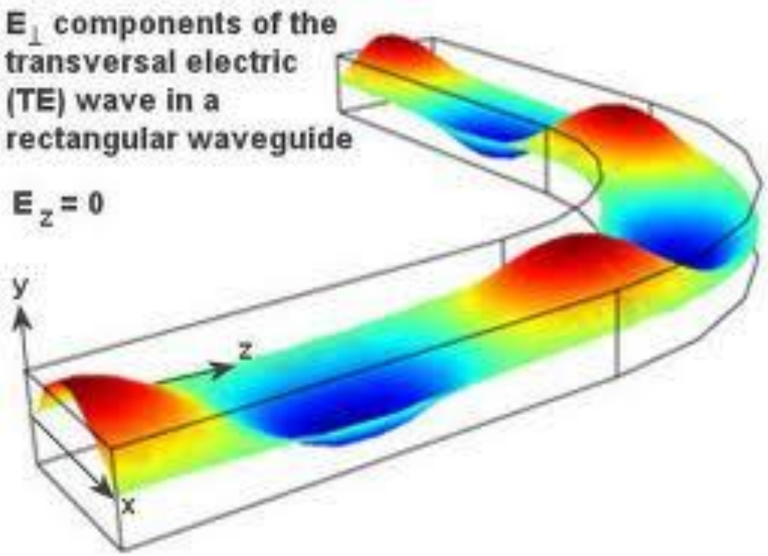
REVERB CHAMBERS - in more detail

- A reverb chamber is a cavity, into which RF energy in injected.
- It is bounded and supports resonant modes related to its dimensions.
- Through the use of boundary condition changes, a statistically uniform, homogeneous and isotropic environment is established.
- The environment is used to perform RI, RE, SE tests and measurements of wireless devices...

REVERB CHAMBERS - in more detail

- Mode indices:
  - 1st number = No. of half wavelengths in a direction (x)
  - 2nd number = No. of half wavelengths in b direction (y)





REVERB CHAMBERS - in more detail

- A reverb chamber is a 3D cavity, therefore supports Modes at frequencies dependant on the dimensions :

$$f_{l,m,n}(MHz)=150\sqrt{[(l/L)^2+(m/W)^2+(n/H)^2]}$$

- First Mode occurs when the index of the smallest dimension is Zero, (say n=0)

- Example : a chamber 4.8m x 3.5m x 3.05m
- $f_{1,1,0} = 150\sqrt{[(1/4.8)^2+(1/3.5)^2+(0)^2]} = 53.04MHz$

REVERB CHAMBERS - in more detail

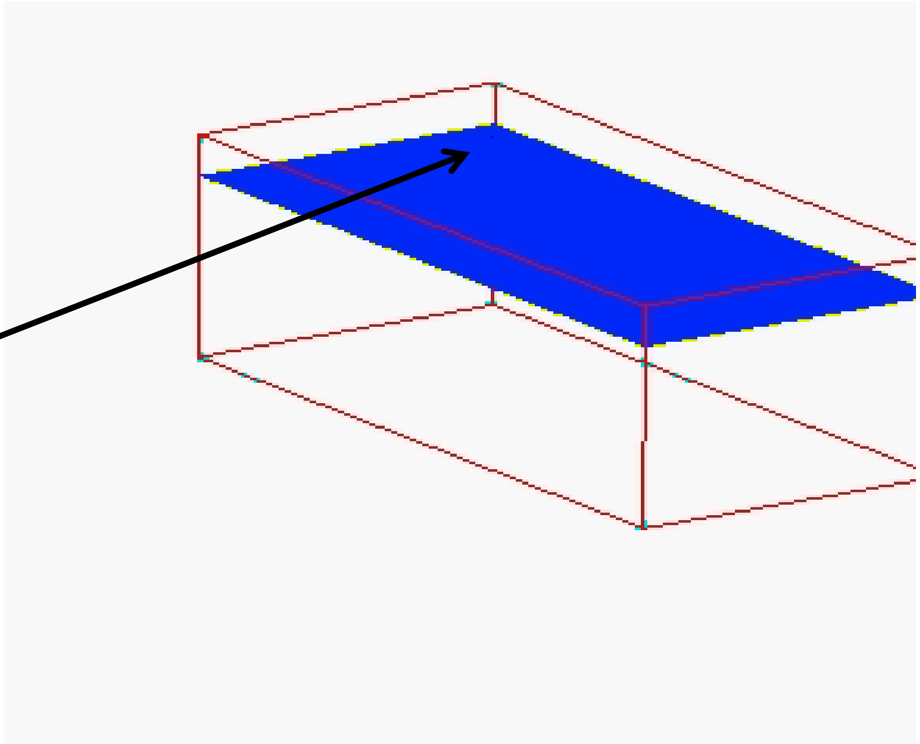
- **Basic operation:**
  - RF energy is fed into the chamber form the location of the transmit antenna.
  - The energy is reflected from the walls ceiling, floor and tuners in the empty chamber.
  - Energy is lost due to the losses in the surfaces in the chamber, including the losses in the DUT.
  - The efficiency of the tuners is reflected in the changes seen in the measured maximum and minimum $\bar{E}$ field.

REVERB CHAMBERS - in more detail

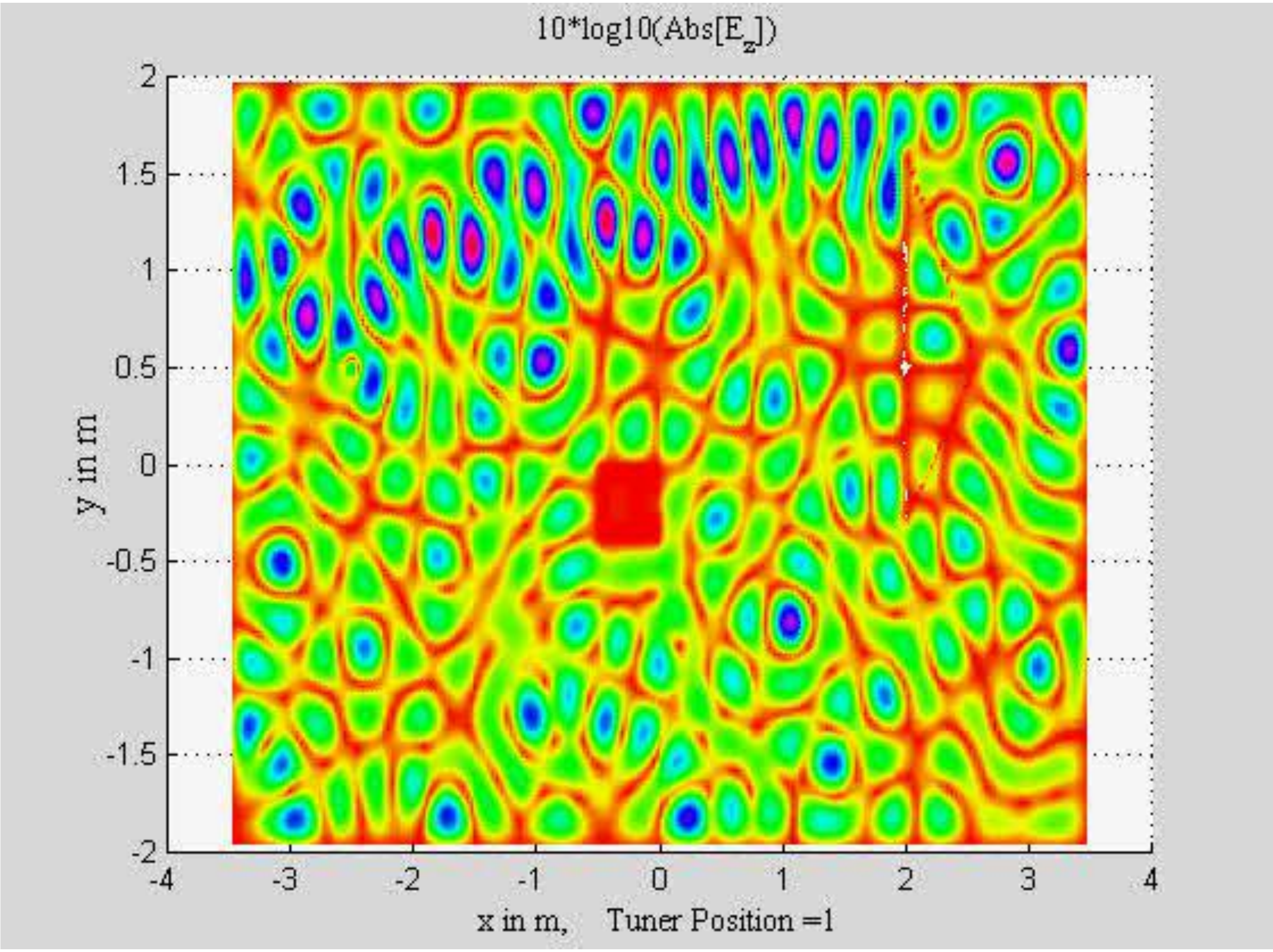
- **Lowest Test Frequency : Related to the shortest dimension of the cavity.**

- Example of standing wave in a cavity.
- Mode is a bounded field structure.
- Remains unchanged if unstirred…

Position of source antenna.

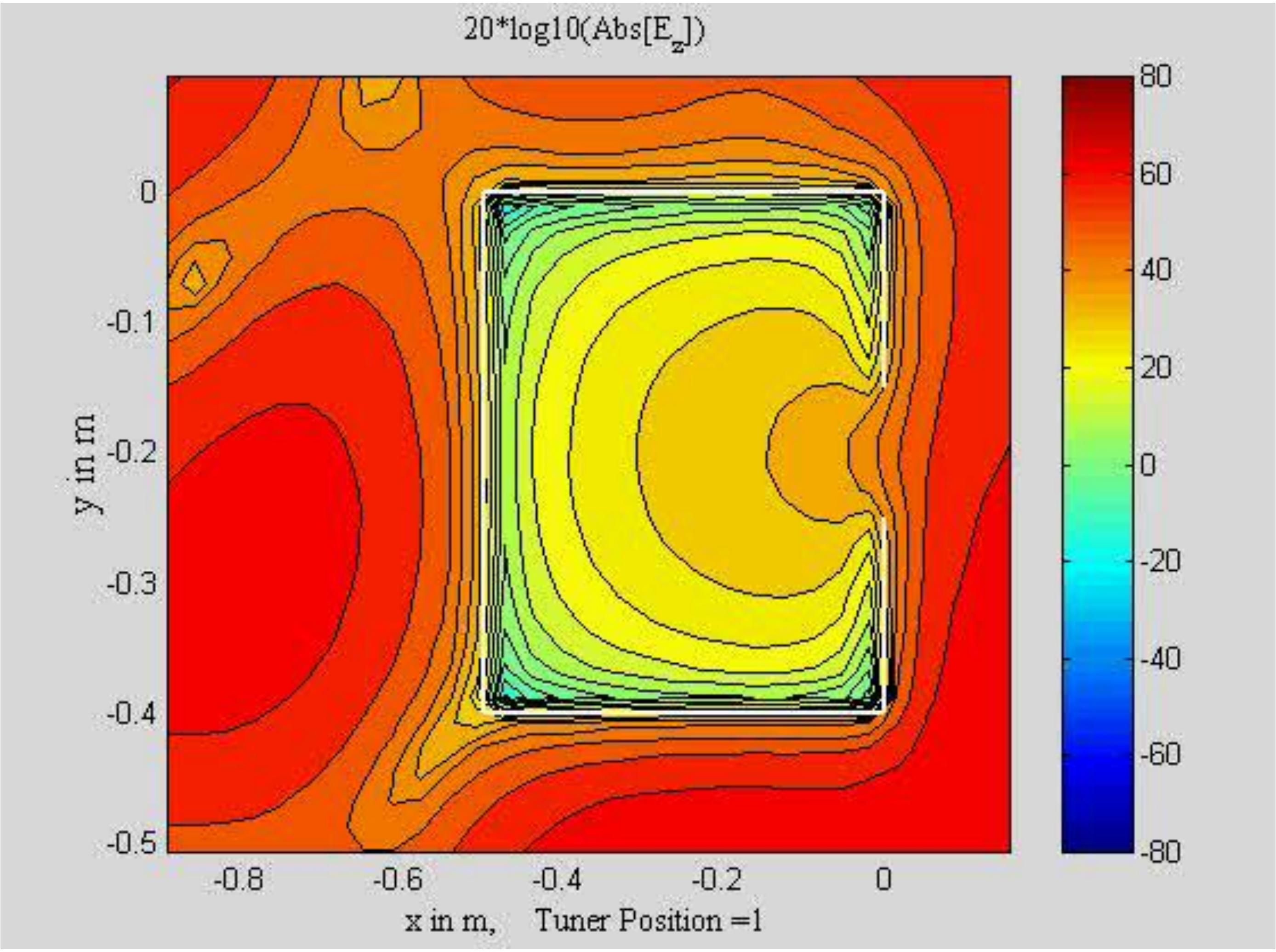


REVERB CHAMBERS - in more detail



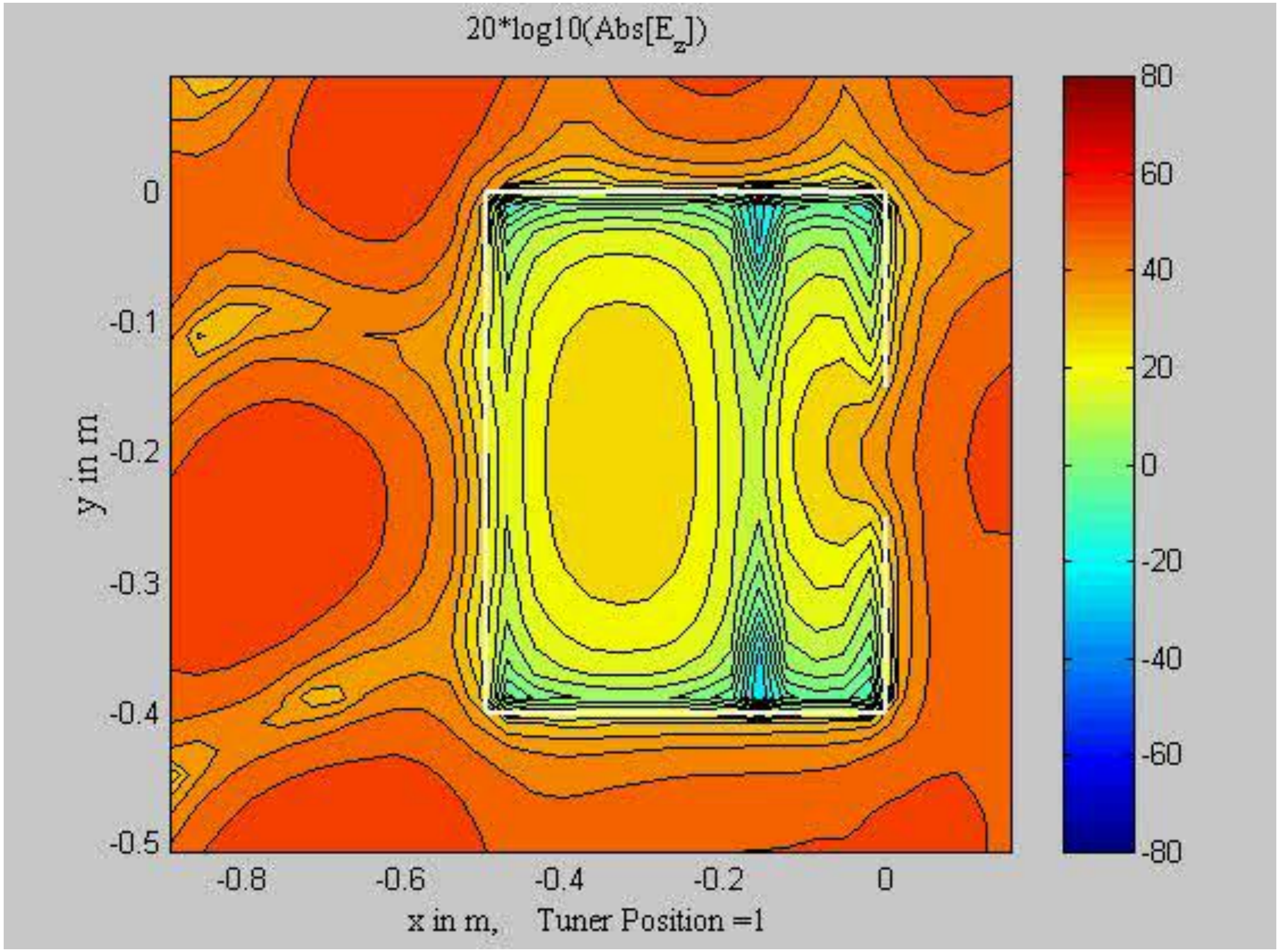
Courtesy Chuck Bunting, Oklahoma State University

REVERB CHAMBERS - in more detail



Courtesy Chuck Bunting, Oklahoma State University

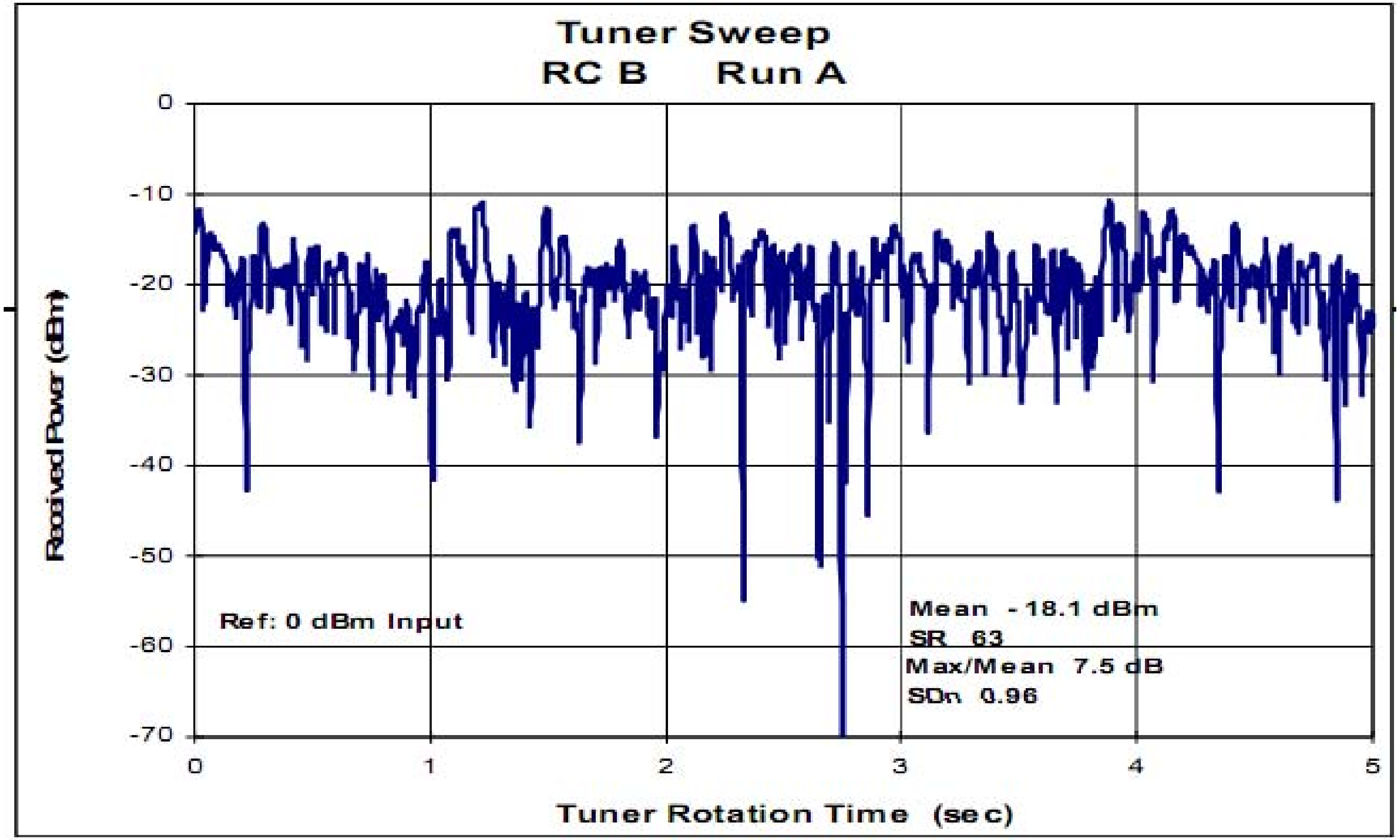
REVERB CHAMBERS - in more detail



Courtesy Chuck Bunting, Oklahoma State University

REVERB CHAMBERS - in more detail

- **Single tuner rotation.**



REVERB CHAMBERS - in more detail

- >60 modes should be available at lowest useable frequency (LUF).
- Chamber dimensions must be non-integer multiples of each other to maximize mode effectiveness
- EUT effective volume 4% to 10% of chamber volume
- Efficient tuners, (Z-fold) - length ~85% of chamber dimension, width is ~1/2λ at LUF.
- Software for data collection, interpretation and presentation is critical for efficient testing

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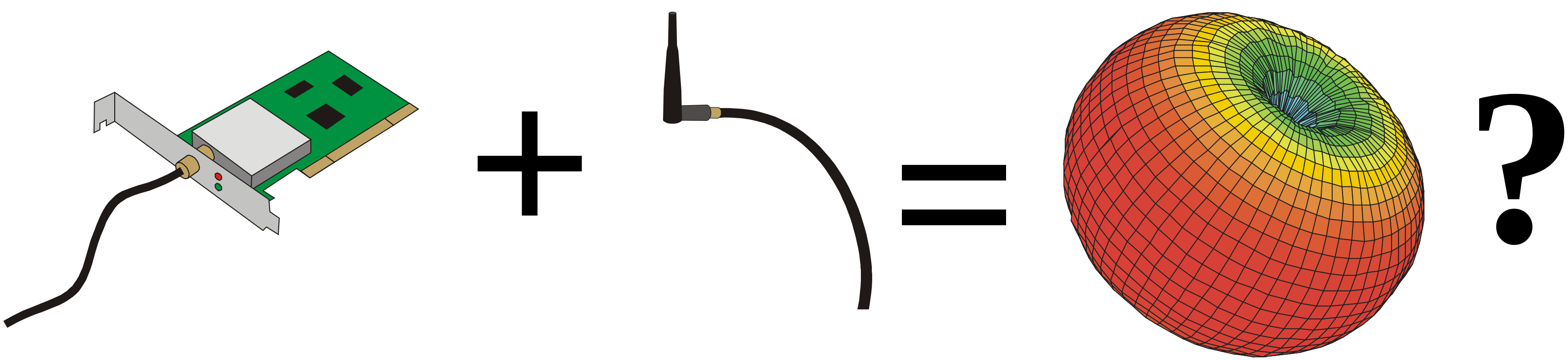
Agenda

- Introduction
- Quick Overview of Chamber theory
- **Wireless Testing**
- MIMO
- Test data

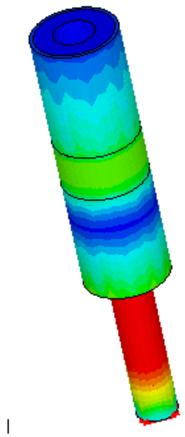
Introduction to OTA Measurements

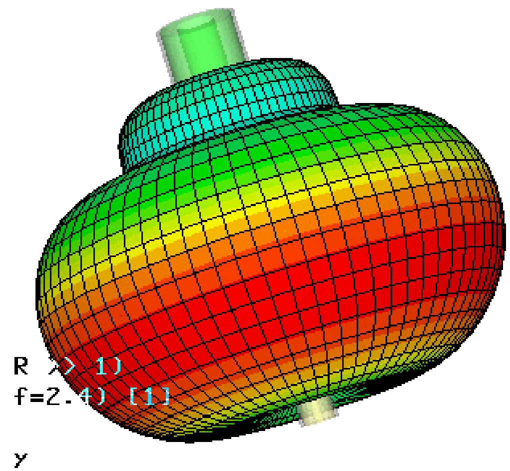
- **Over-The-Air simply means testing the EUT its radiated performance, which was long time ago characterized by its antenna characteristic with its conducted performance.**
- **conducted performance + antenna characteristic = OTA ?**



Introduction to OTA Measurements

- **End-fed sleeve dipole, measured passively, showing ideal pattern.**

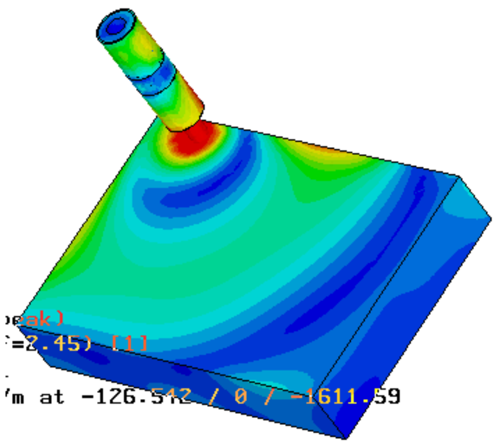


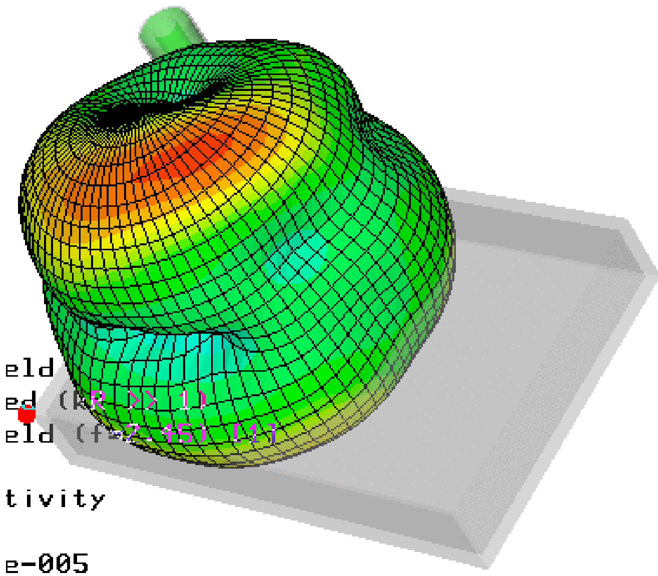


isolated antenna performance

Introduction to OTA Measurements

- **End-fed sleeve dipole mounted on EUT, showing performance degradation.**

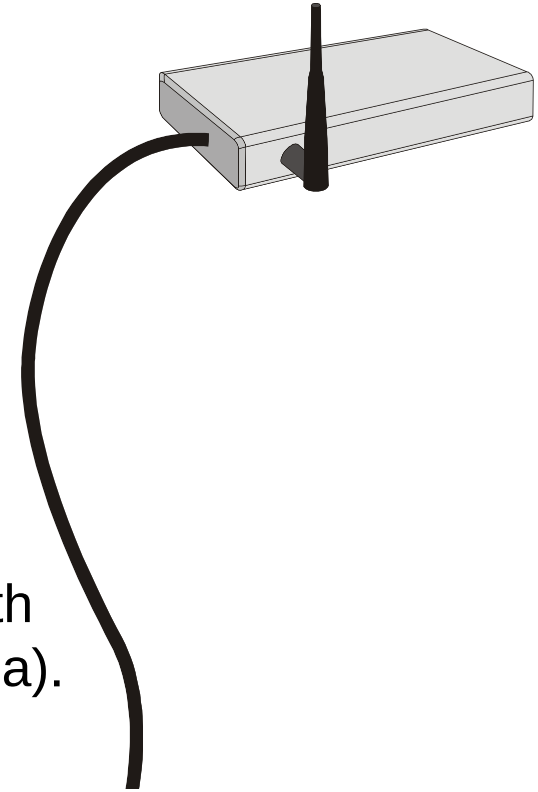




integrated EUT performance

The Antenna Assumption

- **Even if the antenna is tested passively within the body of the DUT so that the effect of the rest of the DUT on the pattern is accounted for, there are other issues:**
  - Cabled testing of DUT assumes antenna has a 50 Ω impedance. Mismatches between radio circuitry and actual antenna impedance can cause non-linear behavior in radio circuitry.
  - Near field coupling to objects typically found near DUT (tables, walls, hands, heads) can change both antenna impedance and radiation pattern.
  - Platform noise from electronics can interfere with the receiver through the antenna (and vice-versa).
  - Cable effects can still distort pattern.



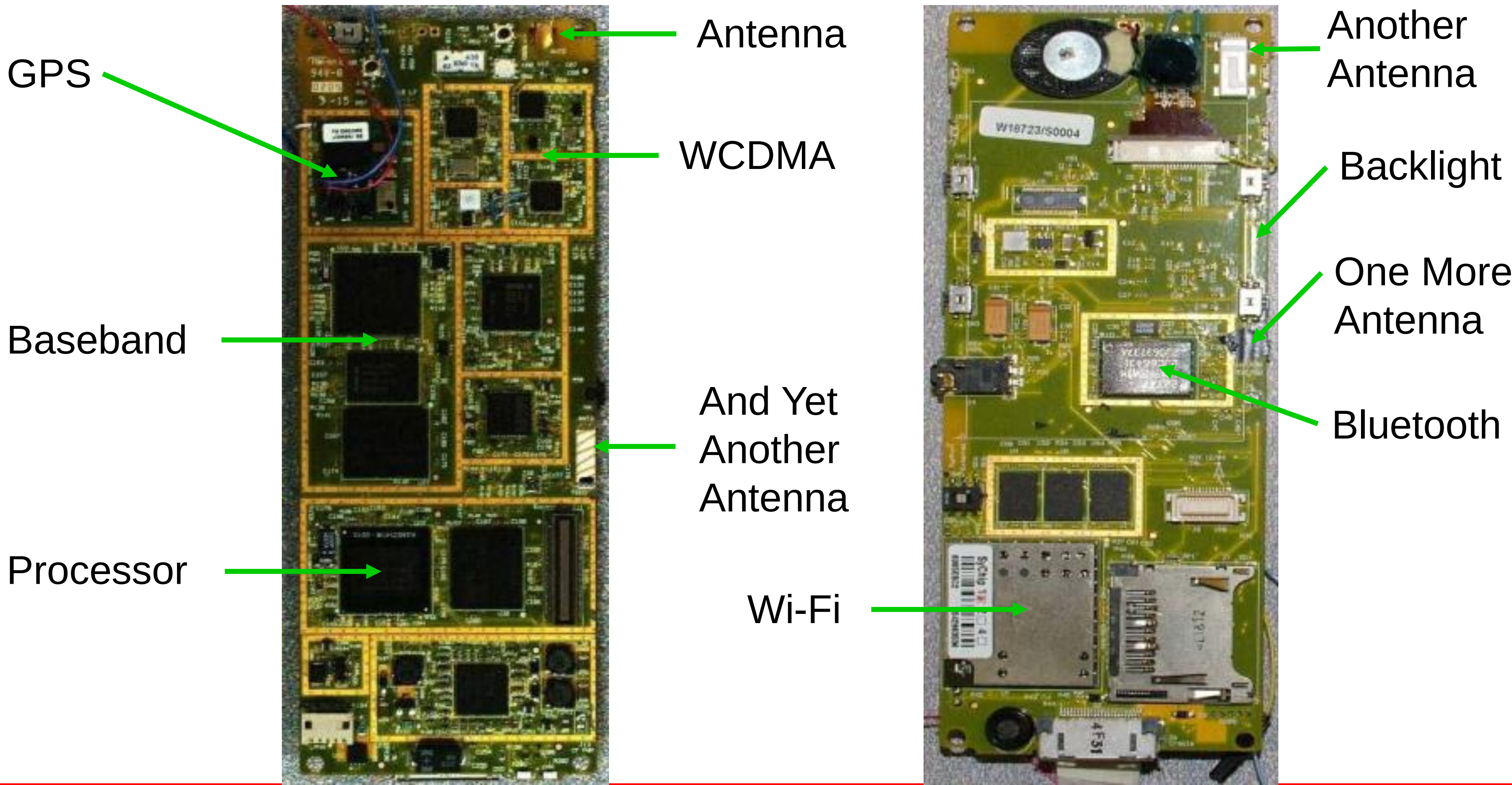
The Antenna Assumption

- **While this may hold for remote antennas or for electrically small devices, electrically large devices (laptops, etc.) generate radiation patterns that rarely match that of the antenna by itself.**

≠

The Antenna Assumption

- **Convergence of wireless technologies makes OTA testing issues even more important.**

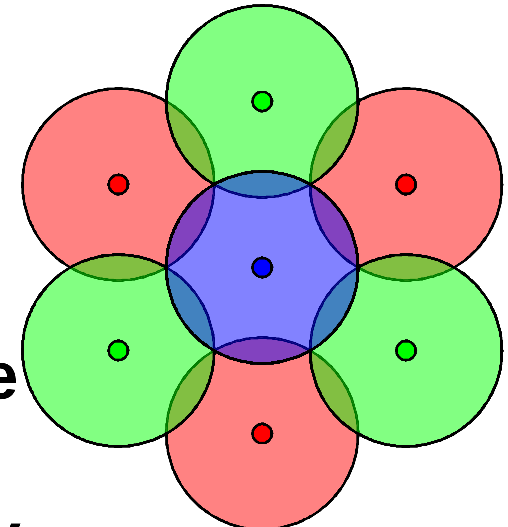


How much is a dB worth?

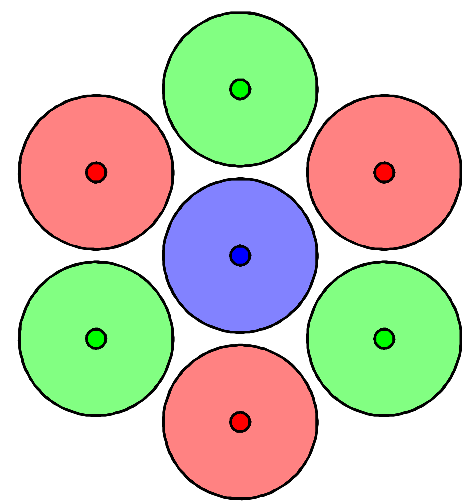
- Quality RF test and measurement can be expensive.
- Without an understanding of the issues involved, it can be difficult to justify the expense of performing TRP and TIS testing.
- However, the cost of poor testing (or worse yet, no testing) can be much more expensive in the long run.
- The resulting performance issues can result in customer service complaints, product returns, network “dead spots”, etc.

How much is a dB worth?

- Networks are typically designed with the fixed base stations or access points distributed so that the ranges corresponding to their link budgets overlap. Moving too far from one base allows roaming to the next one.



- While network link budgets are typically designed with a certain amount of safety margin, there will always be cases where users are at the limit of the link. Any loss in RF performance results in a lost connection.



Introduction to OTA Measurements

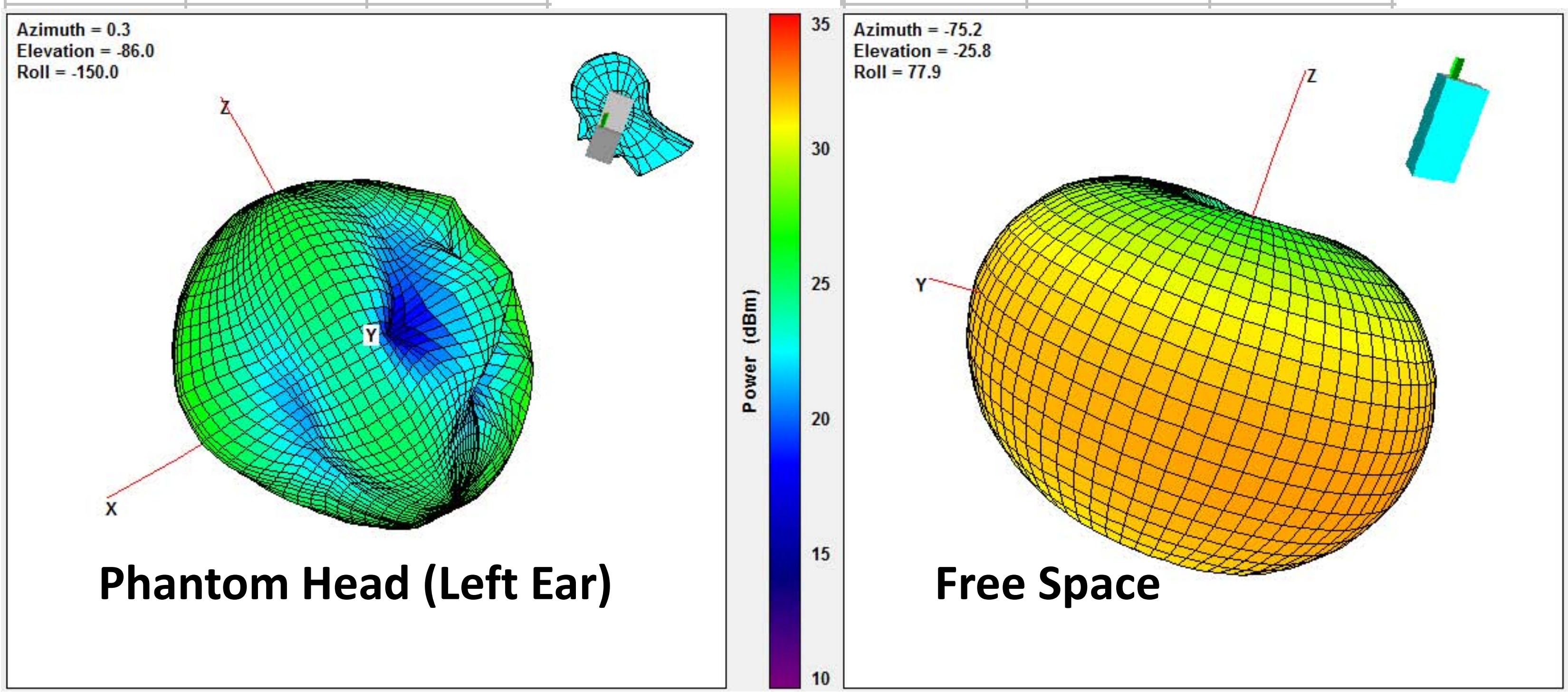
- **Obviously, conducted performance + antenna pattern does not represent EUT performance, due to**
  - Antennas size compared to EUT size.
  - Many antennas are integrated in one EUT.
  - EUT performance can be effected by near-field coupling, such as hands, head and etc.
- **OTA metrics are very important for service provider to plan their link budget and network topology.**
  - Based on Lee and Hata models, 2dB OTA performance reduction means 11% range length reduction in urban area.

OTA Performance Degradation due to Phantoms

- **For example of GSM900 TRP, about 5dB power reduction with phantom head in place.**

880.2	897.4	914.8
26.3971	26.4184	25.9903

880.2	897.4	914.8
30.1809	30.7449	30.4136



Introduction to OTA Measurement

- **Thus, it is important to characterize EUT's OTA performance.**
- **There are two ways to perform OTA testing, i.e.**
  - Anechoic Chamber method
  - Reverb Chamber method
- **These two methods will be introduced, with the focus on reverb method.**
- **The data measured from both methods will be presented and compared.**

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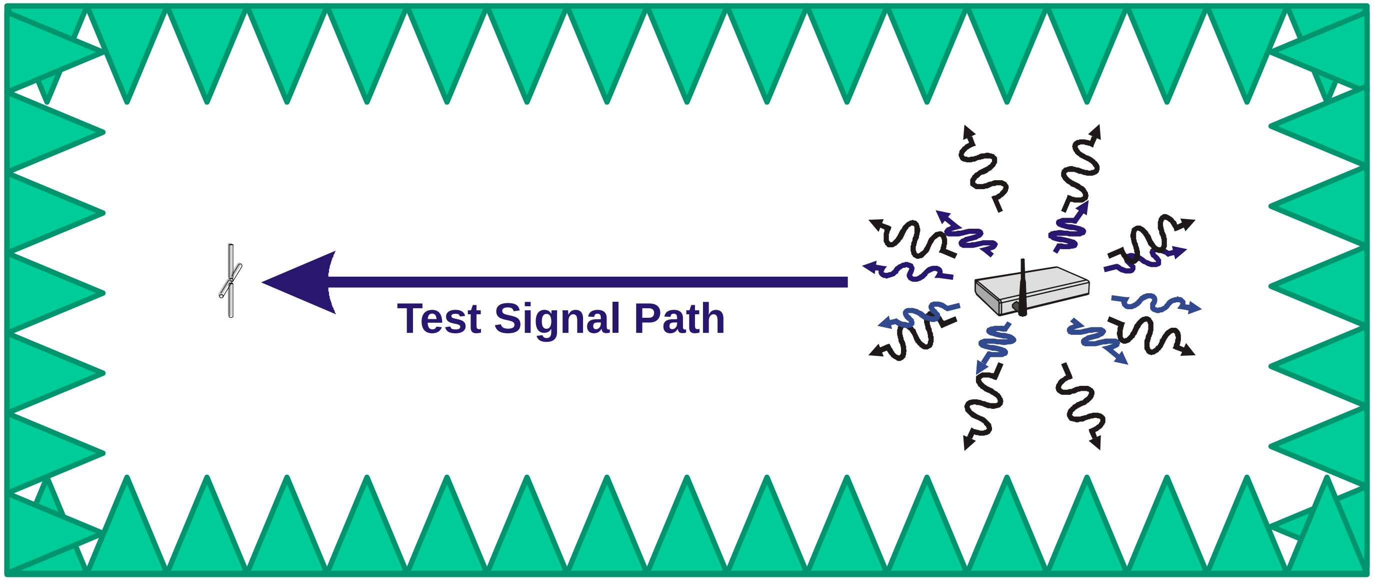
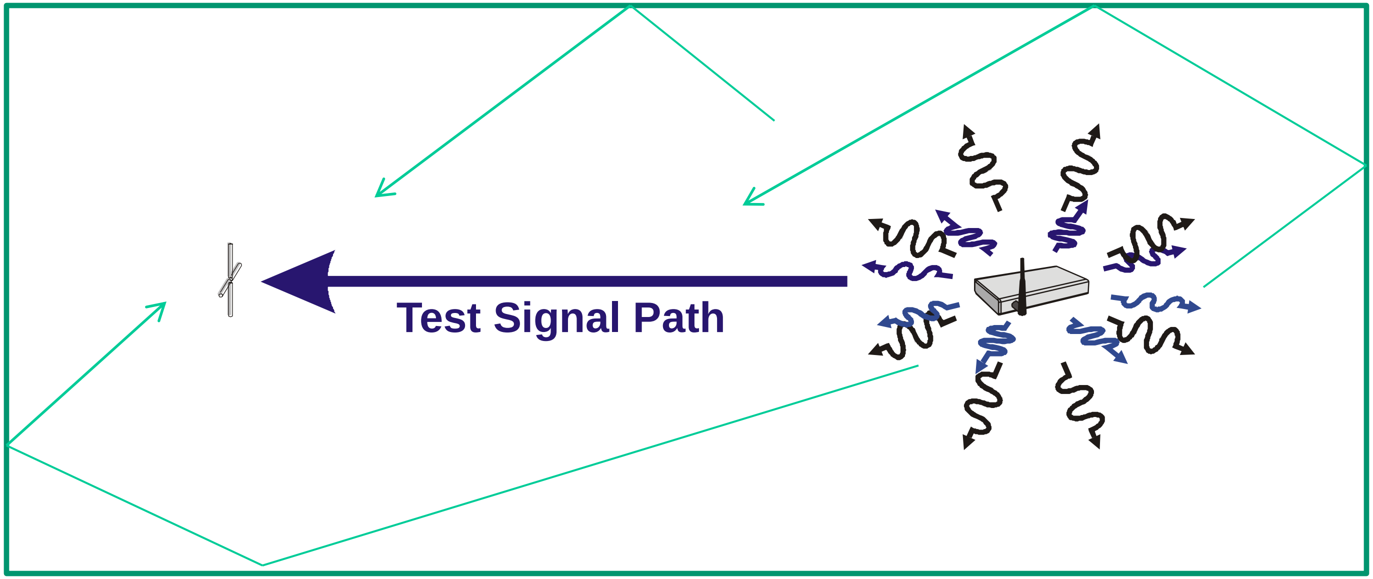
Anechoic Chamber Method

- The testing concept is simply to measure EIRP or EIS of the EUT as a function of its azimuth angle (ϕ) and elevation angle (θ).
- Then, the OTA metrics, TRP and TIS, will be the spherical integrals of EIRP and EIS.
- $TRP = \frac{1}{4\pi}\iint EIRP(\emptyset,\theta)\sin(\theta)\,d\theta d\emptyset$
- $TIS = \frac{1}{4\pi}\iint EIS(\emptyset,\theta)\sin(\theta)\,d\theta d\emptyset$
- Due to the sin (θ) term, EUT orientation will effect its final results.



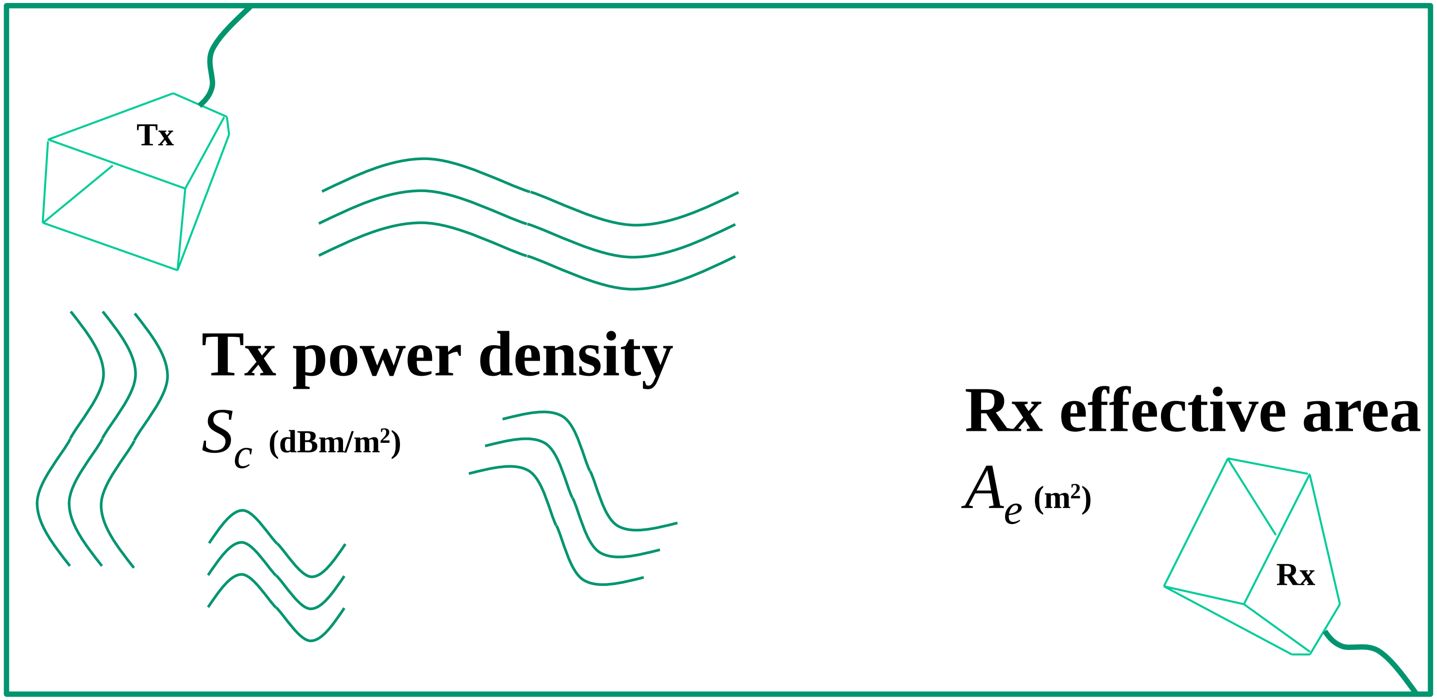
Reverb Chamber Method

- **Very different from anechoic chamber, in which we**
  - measure the signal in one direct path.
  - need absorbers to remove all the other reflected signals.
  - can accurately characterize antenna pattern.
- **In reverb chamber, we**
  - measure the signals from all the directions.
  - Not very concerned about EUT orientation.
  - do not obtain information of antenna pattern.



Chamber Transfer Function (A)

- **The chamber transfer function (P_R/P_T) has been deduced* by**
  cavity power density (S_c) and antenna effective area (A_e) .
- $S_c = f(P_T)$ (dBm/m²)
- $A_e = f(P_R)$ **(dBm)**



* Aperture Excitation of Electrically Large, Lossy Cavities, David Hill, IEEE Tran. on EMC, 1994 Aug.

Cavity Power Density, $S_c = f(P_T)$

- **Power density S_c is a function of injected transmit power P_T.**
- **Given the transmit power P_T, how much S_c can be generated?**
- **The injected P_T is not 100% converted into cavity power density S_c , due to cavity loss. The cavity loss is characterized by its quality factor *Q*.**
- $Q = \frac{\omega U_c}{P_T}$; ω **is angular frequency;** U_c **is stored cavity energy.**
- $U_c = \frac{Q\,P_T}{\omega} = W_c\,\boldsymbol{V}$ → $W_c = \frac{Q\,P_T}{\omega\,V}$

  W_c **is the cavity energy density;** V **is the cavity volume.**
- **Finally,** $S_c = \mathrm{c} \cdot W_c = \frac{c\;Q\,P_T}{\omega\,V} = \frac{f\,\lambda\;Q\,P_T}{2\pi f\;V} = \frac{\lambda\;Q\,P_T}{2\pi\;V}$ **.**

  c **is the speed of light.**

Antenna Effective Area, $A_e = f(P_R)$

- We know $A_e = \frac{G f^2}{4\pi}$
- Due to the statistical behavior of reverb chamber, the effective area A_e is averaged over all incident angles.
- In other words, the receive antenna can be regarded as fully isotropic in the environment of reverb chamber.

  That is, $G = 1$.
- Also, due to polarization mismatch, the effective area is half in one polarization; and half for the other polarization.
- Thus, $A_e = \frac{\lambda^2}{8\pi}$

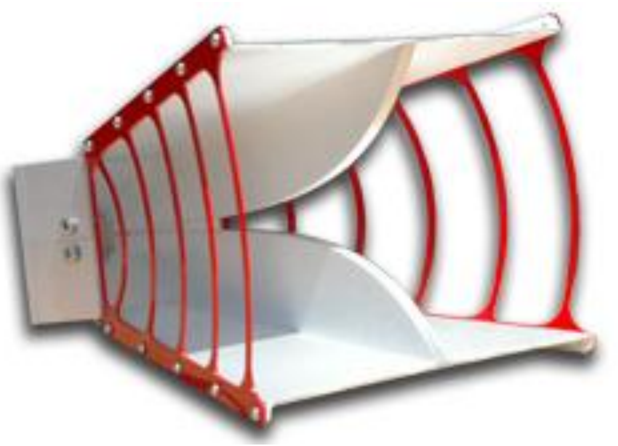
Chamber Transfer Function A, P_R/P_T

- $S_c = f(P_T) \rightarrow \quad S_c = \frac{\lambda \; Q \, P_T}{2\pi \, V}$
- $A_e = f(P_R) \rightarrow \quad A_e = \frac{\lambda^2}{8\,\pi}$
- $P_R = S_c \cdot A_e = \frac{\lambda \; Q \, P_T}{2\pi \, V} \cdot \frac{\lambda^2}{8\,\pi} = \frac{\lambda^3 \; Q \, P_T}{16\pi^2 \, V}$
- **Thus, the chamber transfer function is**

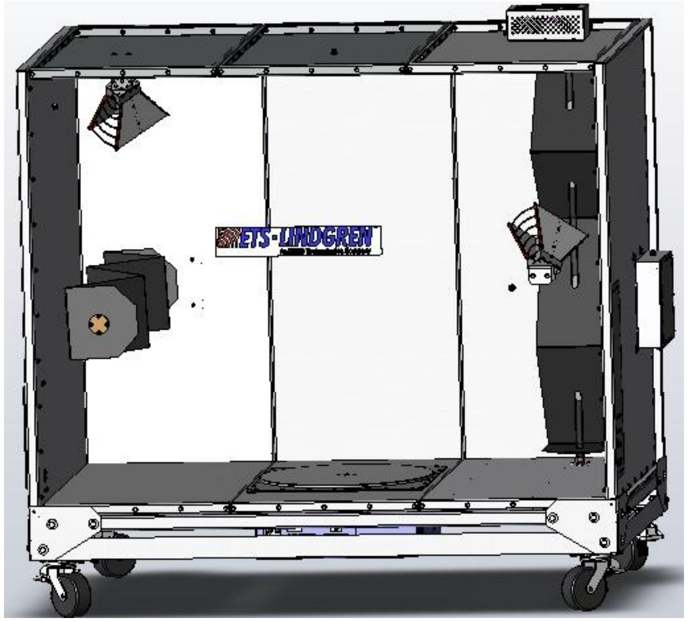
$$\frac{P_R}{P_T} = \frac{\lambda^3 \, Q}{16\pi^2 \, V}$$

Testing Setup

- TRP/TIS measurements were made in a AMS-7000 reverberation chamber .
- Its inside shield dimensions is approximately 2.0m x 1.5m x 1.2m.
- It uses two tuners, vertical and horizontal, with stepper motors.
- It is capable to support a test volume of 0.9m x 0.9m x 0.6m with a lowest operating frequency of 700 MHz.
- The antennas selected are ETS-Lindgren 3115, small dual ridge horns, operating from 700MHz to 18 GHz.



ETS-Lindgren 3115

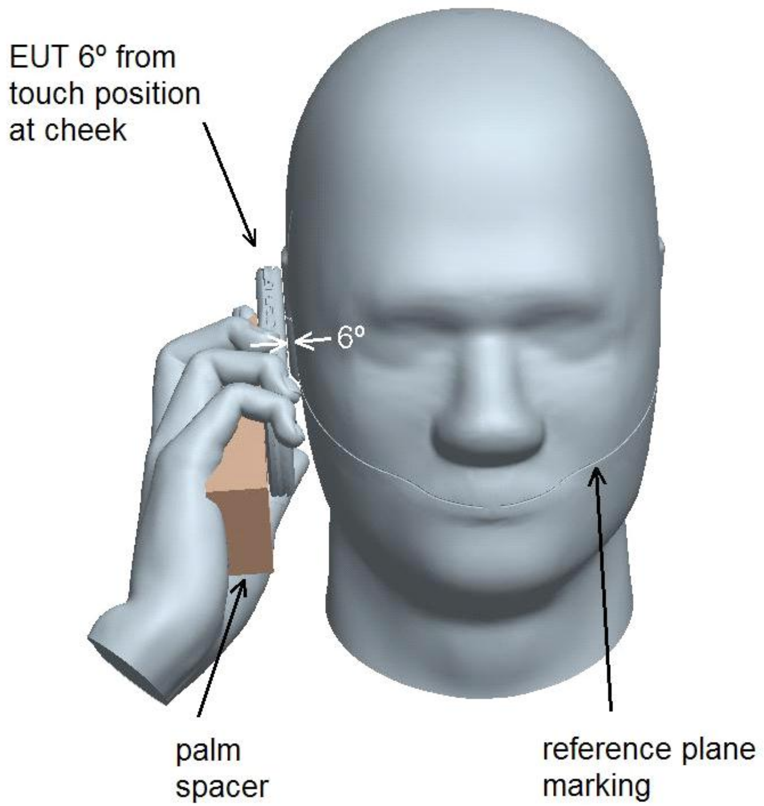


Testing Setup

- TRP/TIS measurements were made in accordance with the CTIA document provided by the Reverberation Chamber Sub-Group (RCSG090401).
- Two golden phones were tested, Nokia E71X GSM and LG VX9200 CDMA.
- Tests were done in both the anechoic chambers and the reverberation chamber.
- All tests were done automatically by ETS-Lindgren software, EMQuest™.

Standard Hand Phantoms – Accessories

- **What difference does the location and orientation of the DUT have on the measured TIS or TRP?**



Standard Hand Phantoms – Grips

- **What about the hand?**

Data Mode

PDA (Wide)

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Agenda

- Introduction
- Quick Overview of Chamber theory
- Wireless Testing
- **MIMO**
- Test data

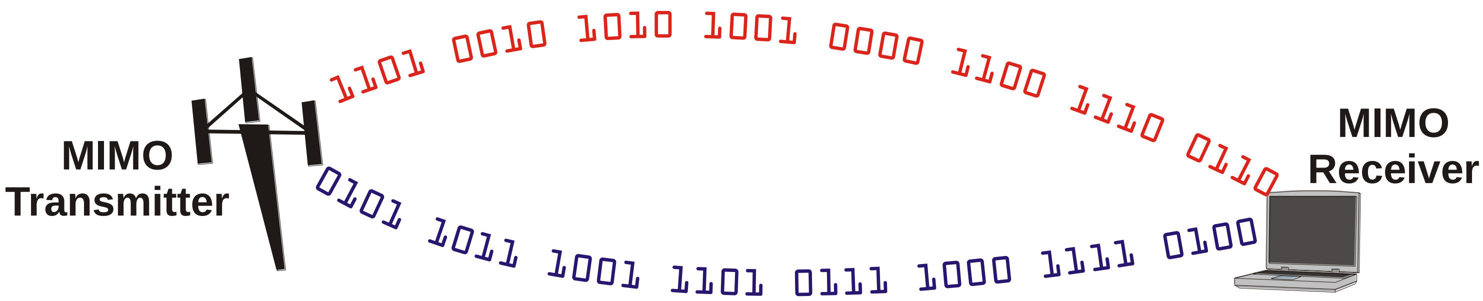
“Our standards are very high. We even have high double standards.”

The Meaning of MIMO

- **MIMO stands for *Multiple Input, Multiple Output* and refers to the characteristics of the *communication channel(s)* between two devices.**
- **In communication theory, a channel is the path by which the data gets from an input (transmitter) to an output (receiver).**
  - For Ethernet or USB, the channel is the cable used.
  - For wireless, the channel includes the RF frequency bandwidth, the space between antennas, and anything that reflects RF energy from one point to the other.
  - Often includes antennas and cables too.

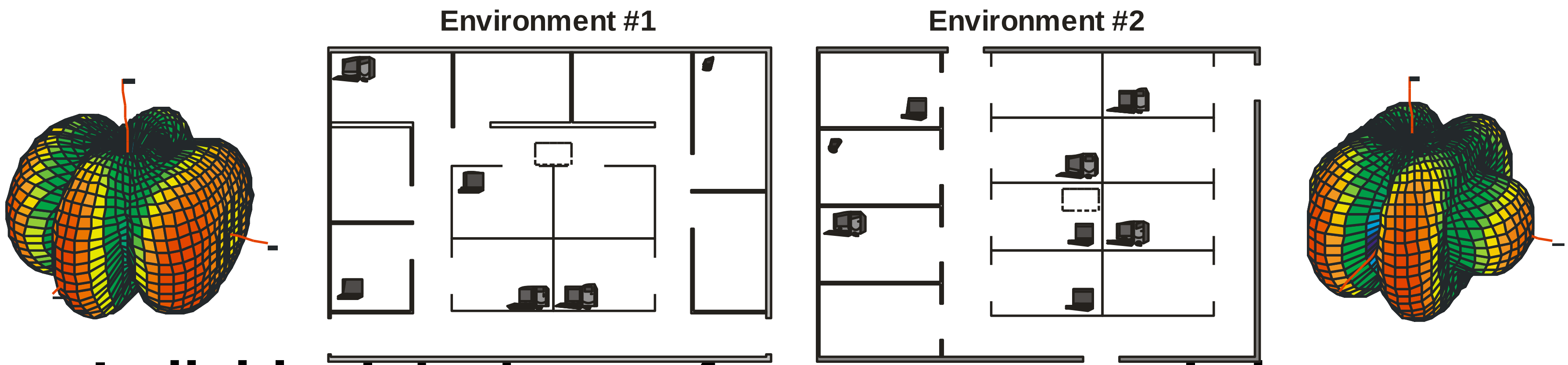
The Meaning of MIMO

- **"True" MIMO uses multiple transmit and receive antennas to increase the total information bandwidth through time-space coding.**
  - Multiple channels of communication (streams) share the same frequency bandwidth allocation simultaneously.



MIMO and the RF Environment

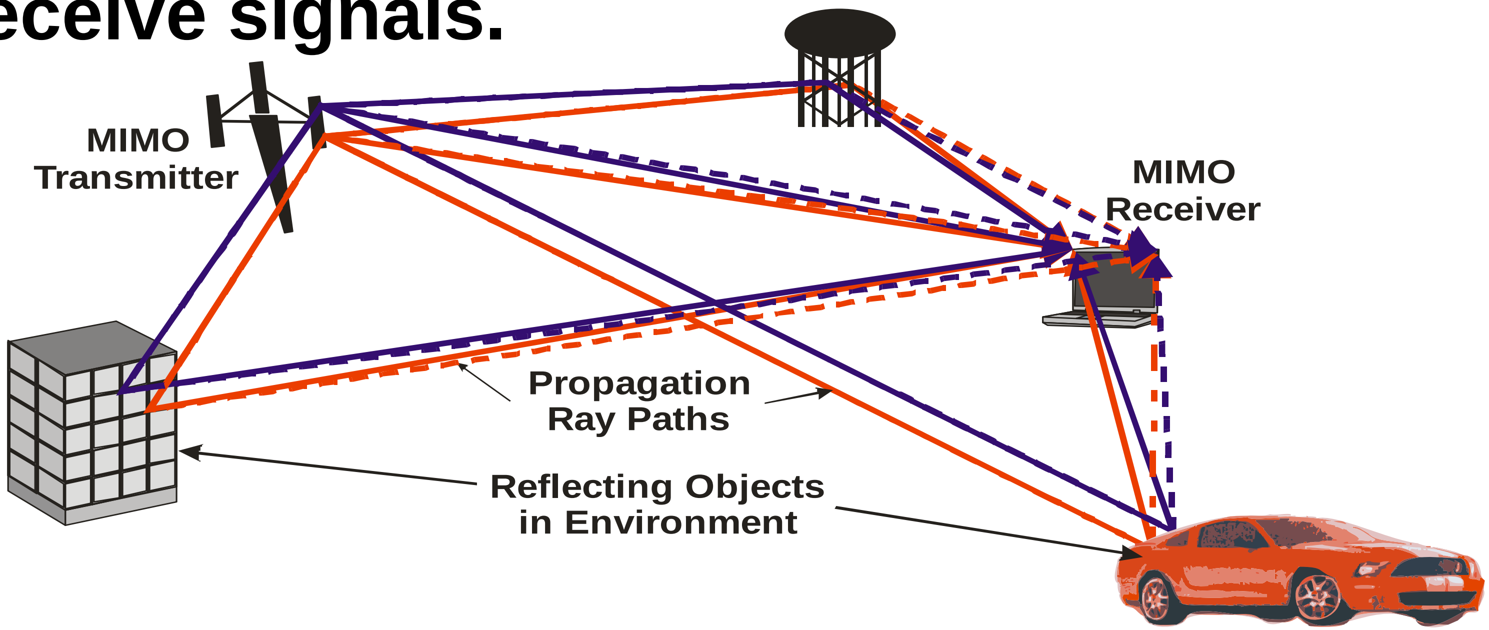
- For MIMO technologies, performance is a function of the system and cannot be restricted to the mobile device.



- Individual device performance can only be evaluated compared *in a given environment*.
- This implies the need for ***environment simulation***.

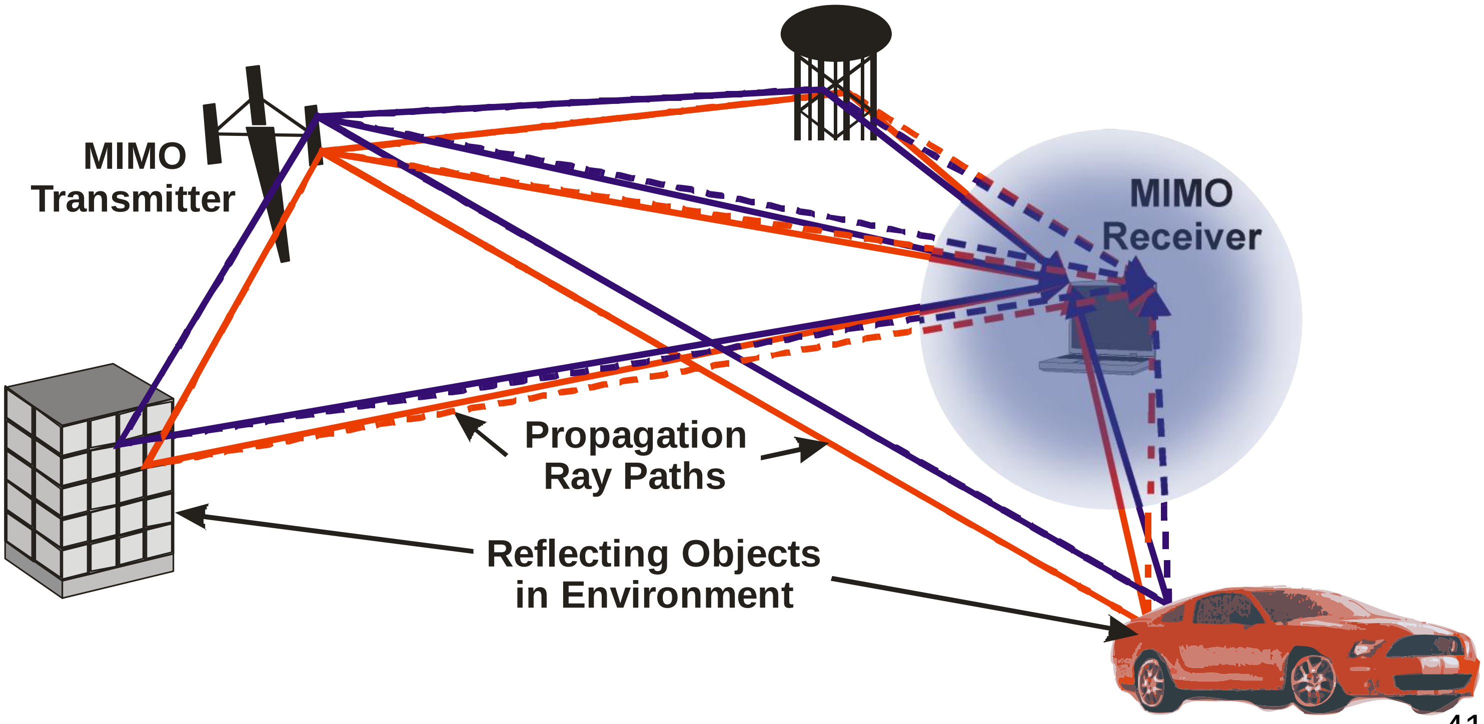
Spatial Environment Simulation

- **MIMO relies on a complex multipath environment to provide the information necessary to reconstruct multiple source signals that have been combined into multiple receive signals.**



Spatial Environment Simulation

- **The goal of the OTA Environment Simulator is to place the DUT in a controlled, isolated near field environment and then simulate everything outside that region.**



Spatial Environment Simulation

Spatial Environment Simulation

Spatial Environment Simulation

- **From inside the bubble, everything looks the same, even though everything outside the bubble is simulated.**

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Spatial Environment Simulation

- **Practical limitations may result in a low resolution picture of the environment.**
- **Using active spatial channel emulation provides motion simulation, etc.**

Spatial Environment Simulation

- **We may also only care about a portion of the environment.**
  - E.g. Most reflections cluster near the horizon.

Spatial Environment Simulation

- **For comparison, using a reverberation chamber averages out the spatial picture. The same signal comes from all directions.**

Spatial Environment Simulation

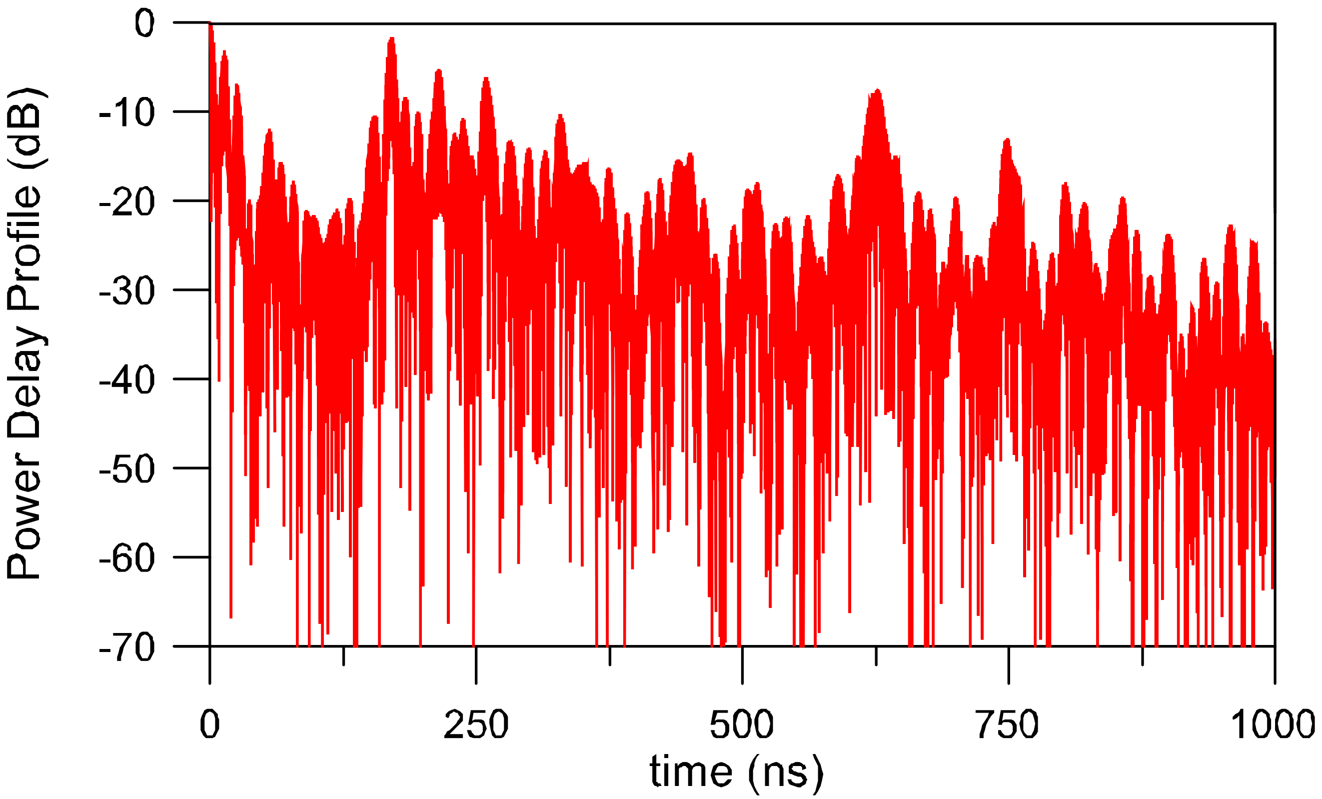
- **The proposed two antenna method is a very limited representation of the real world. It is uncertain what these test results mean.**

Spatial Environment Simulation

- **The two stage method uses antenna pattern data applied to a conducted channel emulation model.**

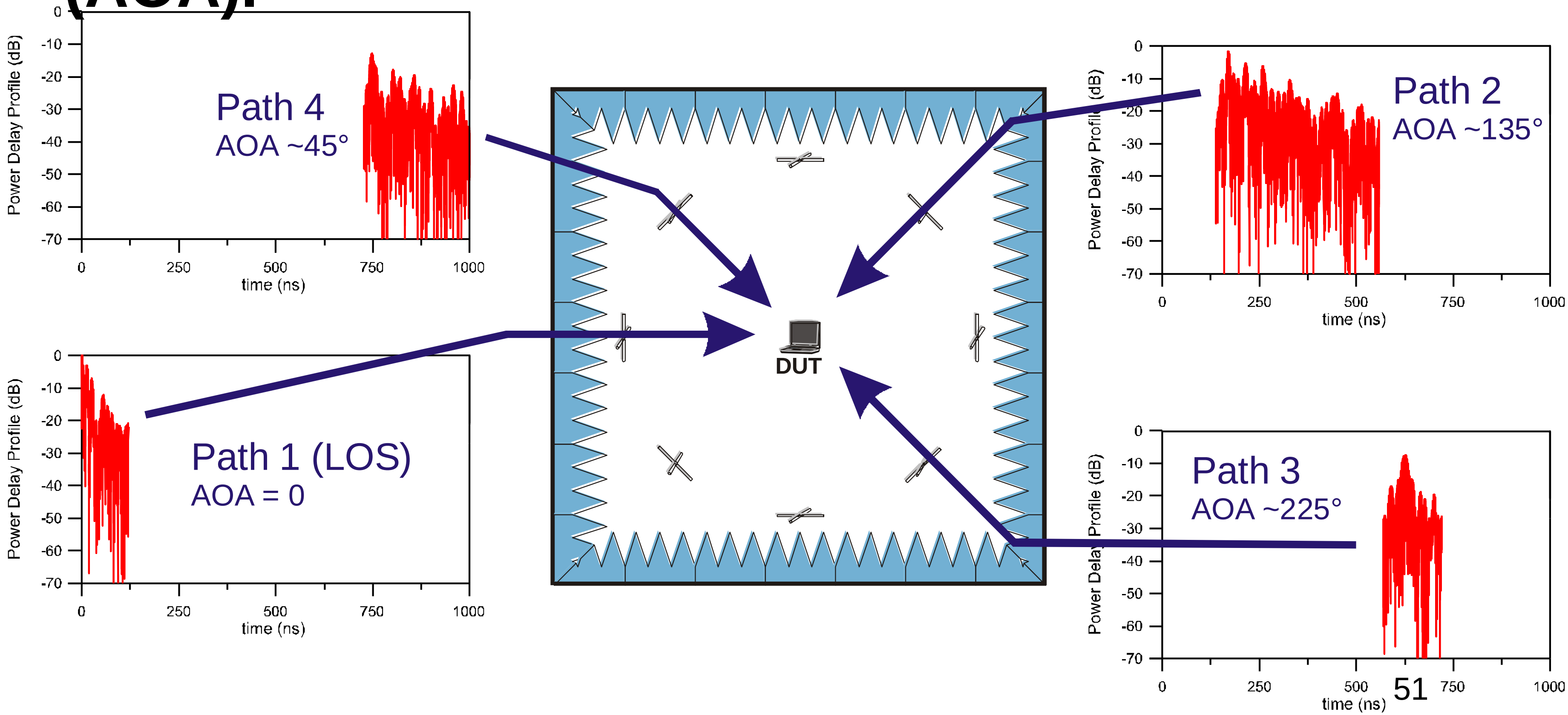
Spatial Environment Simulation

- **Example: Typical Multi-Path Power Delay Profile from a Real World Environment**



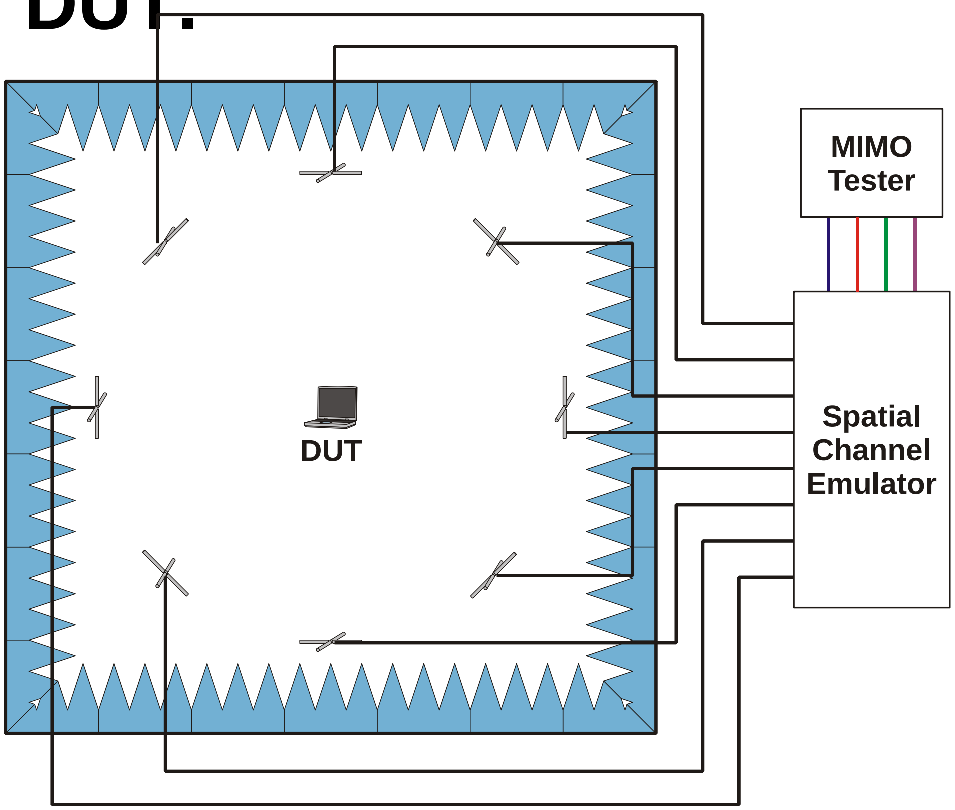
Spatial Environment Simulation

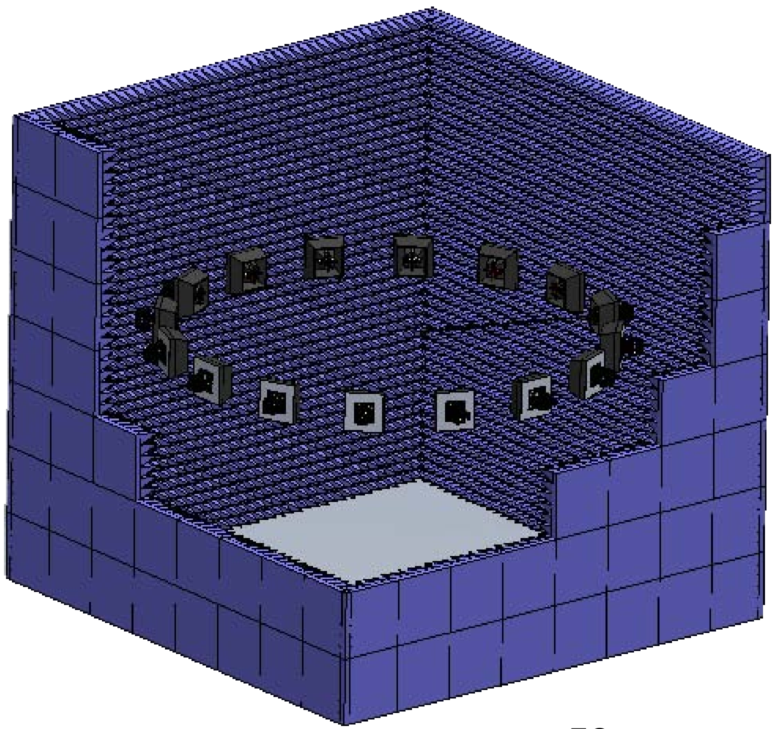
- **Using a fully anechoic chamber to isolate the DUT, a matrix of antennas arrayed around the DUT can be used to produce different angles of arrival (AOA).**



Spatial Environment Simulation

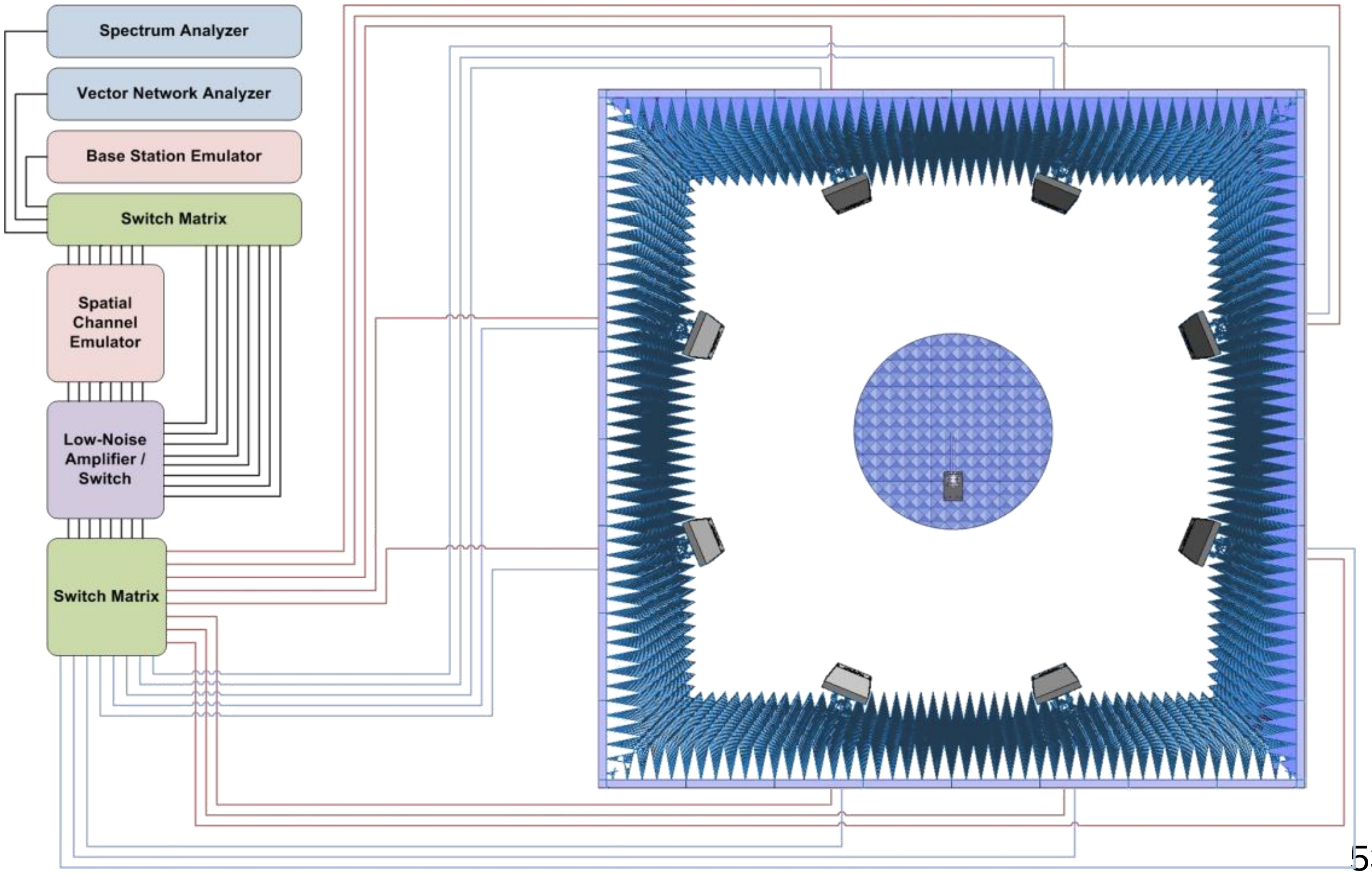
- A spatial channel emulator (a channel emulator with modified channel models) simulates the desired external environment between BSE and DUT.





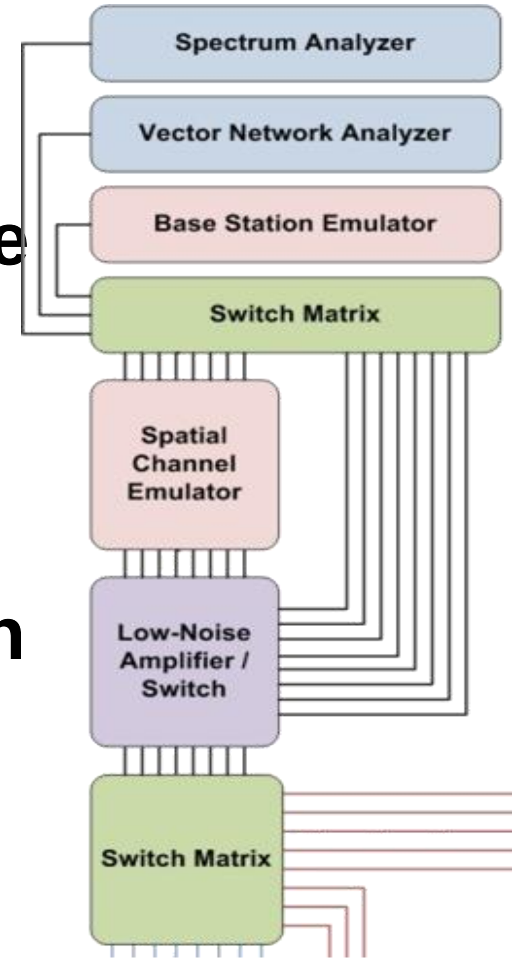
AMS-8700 Environment Simulator

- **The baseline provides only eight active elements, switchable between vertical & horiz.**



AMS-8700 Environment Simulator

- A base station with throughput testing options is used for MIMO.
- A VNA with multiple channels can be used for evaluating correlation of embedded MIMO antennas.
- A MAPS is provided for 3-D tests.
- An additional SISO-only antenna can be added for TRP/TIS.
- Other antenna configuration/test options are available.



AMS-8700 Environment Simulator

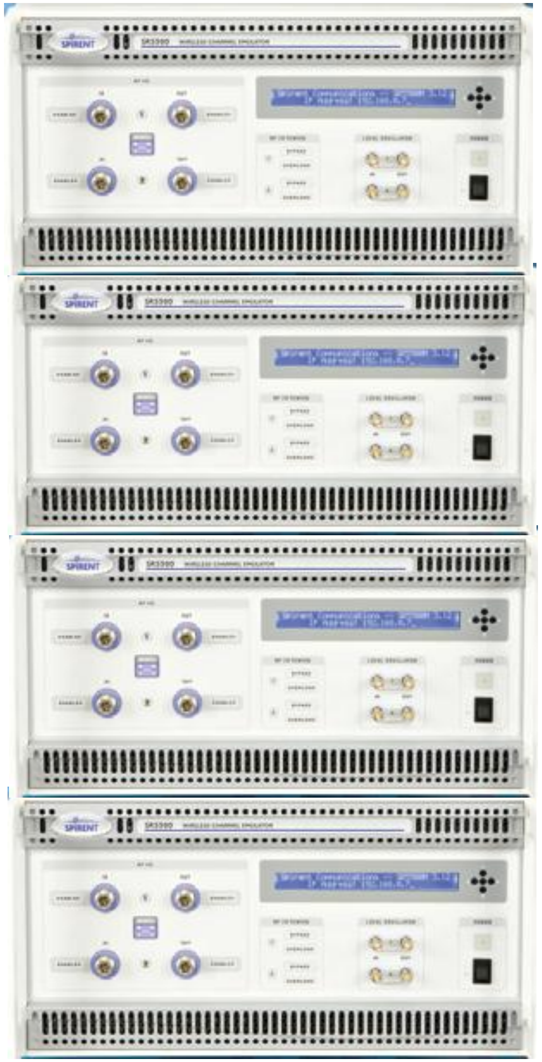
- **An eight channel low noise amplifier/switch combination is included to provide additional output power from the channel emulator.**
- **New independent switching feature allows control of output of each amp independently.**
  - Allows 8 vertical, 8 horizontal, or 4 dual polarized.

AMS-8700 Environment Simulator

- A channel emulator or emulators with a total of eight outputs is required for the baseline.
- The Elektrobit Propsim F8 provides 2x8 spatial channel emulation (developing 4x8).
- A full dual polarized, eight antenna system would require two Propsim F8s to provide the necessary spatial channel emulation.

AMS-8700 Environment Simulator

- Spirent supports MIMO OTA.
- Four SR5500s are required to produce a 2x8 spatial channel.
- 4x8 requires eight SR5500s.
- EMQuest support in place, but total capability set less than EB, primarily in validation arena.

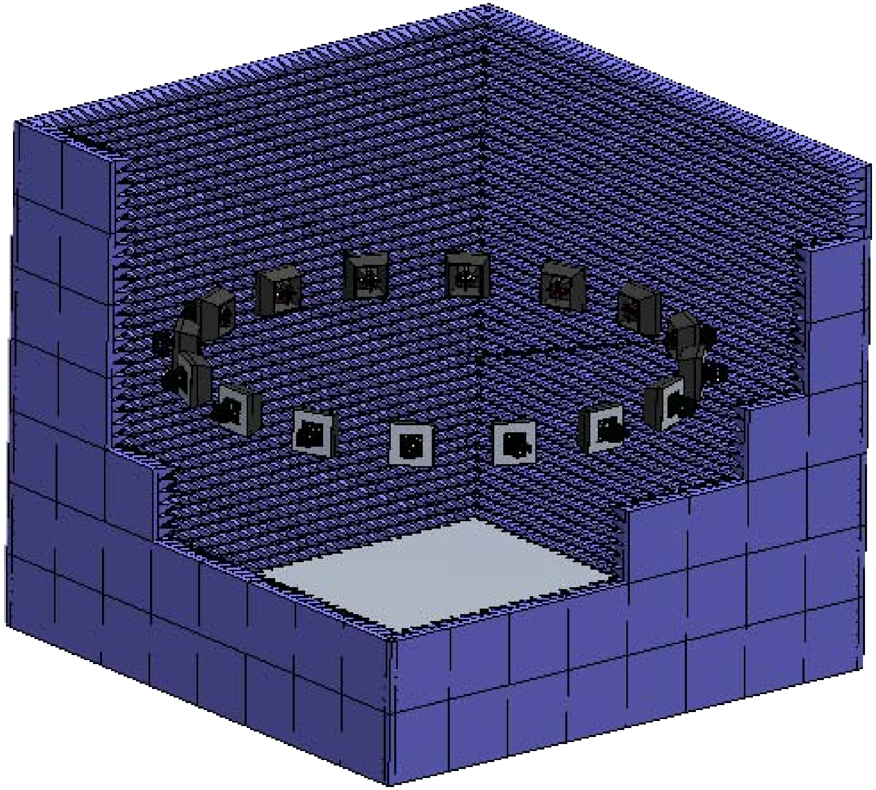


AMS-8700 Environment Simulator

- **Spirent’s new VR5 hardware provides equivalent port resources to Propsim in smaller package.**
- **One box should handle 4x8 scenario.**
- **Software support expected to be the same/similar to SR5500 engine.**

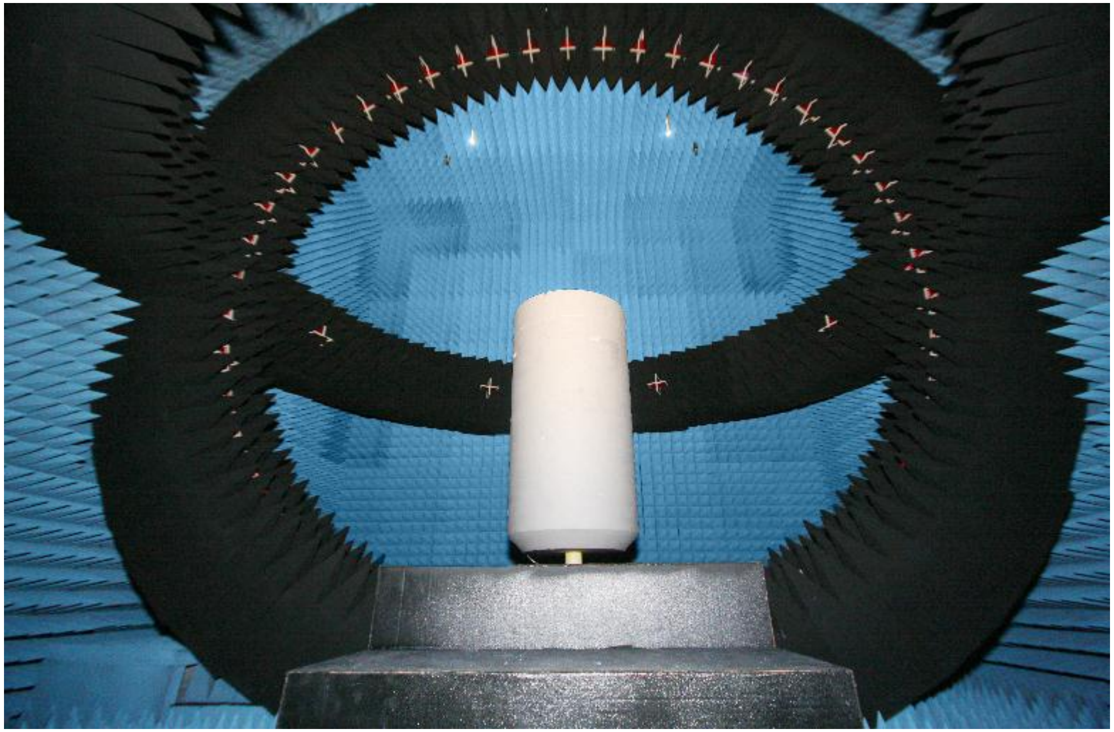
AMS-8700 Environment Simulator

- Additional antennas can be added (up to the available space on the ring) by adding the required number of channel emulators.
- Minor incremental cost to the chamber but multiplies the instrumentation cost.



AMS-8700 Environment Simulator

- An AMS-8900 can be combined with an AMS-8700 to allow high speed APM and TRP/TIS.
- Chamber cost is a fraction of overall system cost.
- User must weigh value of doing APM/TRP/TIS vs. having inactive channel emulator(s).



COST VERSUS BENEFIT

- **Performance comparison:-**
  - Anechoic Chamber – ***Pros***
    - Antenna pattern measurement
    - All measurements as a function of orientation
    - MIMO representation in time, delay, AOA
    - Multi use facility
  - Anechoic Chamber - ***Cons***
    - Cost of chamber, real estate and support instruments
    - Ratio of Chamber volume to test volume large
    - Range length consideration
    - DUT or measurement antenna rotation required
    - EUT and cable placement critical

COST VERSUS BENEFIT

- **Performance differences:-**
  - Reverb Chamber – Pros
    - Comparatively low initial chamber cost
    - Small space required for measurements from 700MHz
    - Ratio of Chamber volume to test volume small
    - Direct correlation to Anechoic chamber (TIS,TRP)
  - Reverb Chamber - Cons
    - No direction specific information
    - Not yet accepted in the CTIA standards
    - Limited representation of MIMO OTA environment

Key Differences - Reverb

- The field developed in a Reverb chamber is a chaotic field developed with the use of reflectors.
- Tuners make the boundary condition changes necessary to excite multiple modes.
- The test volume is characterized by measuring the ‘S’ parameters over a complete rotation of the tuner(s).
- This defines the correction factor to be applied to levels measured from the DUT.
- The number of Tuner positions equate to the number of measurement samples of the Ē field.

Typical REVERBERATION CHAMBER

- **Typical Chamber layout:**
  - Chamber with two Tuners (e)
  - Positioned at opposite ends
    - Creates large central test volume
    - Maximizes volume stirring with horizontal and vertical arrangement
    - Optimizes number of independent samples
  - Small Chambers (Wireless devices)
  - Support for Phantom

Typical AMS-7000 CHAMBER

Agenda

- Introduction
- Quick Overview of Chamber theory
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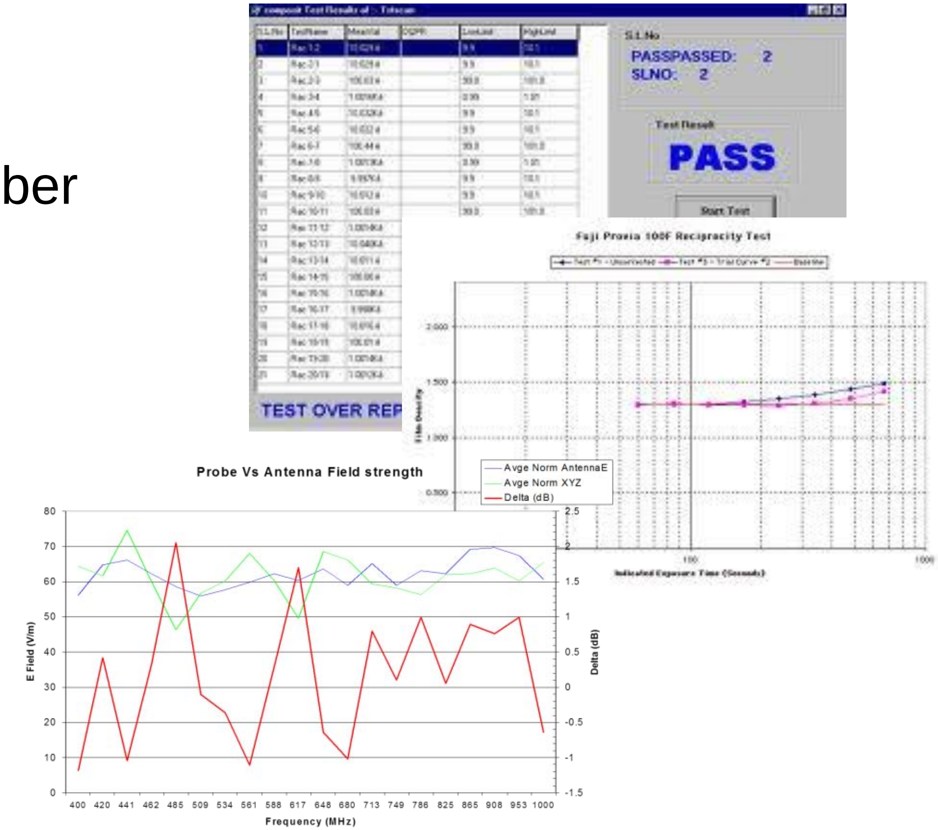
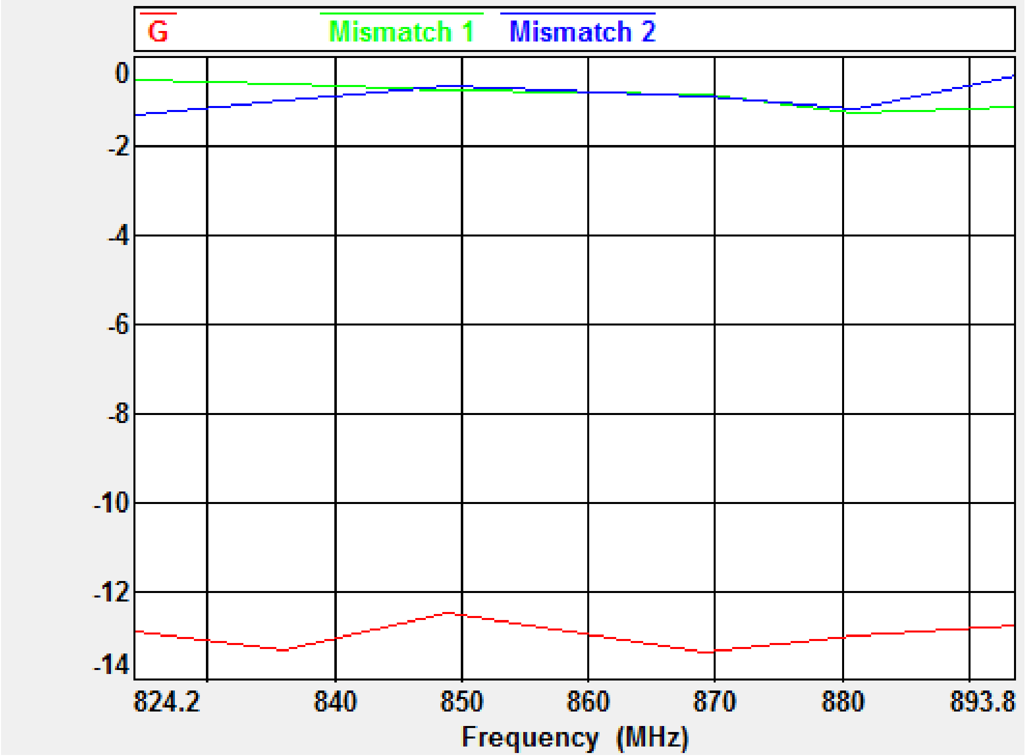
- **Test data**



Reverb Chamber Calibration

- Before EUT testing, calibration needs to be performed to find the chamber transfer function. This is simply a step of measuring S_{21} between the Tx and Rx antennas.
- as well as measuring the mismatch of the two antennas (S_{21} , S_{12})
- Here is an example of calibration data of GSM850.



Measured Results

- For GSM850, both TRP and TIS were measured.
- Between reverb and anechoic, the correlation is within 1dB for TRP, about 1.2dB for TIS.

GSM850	TRP (dBm)		
Freq (MHz)	824.2	836	848.8
Reverb	29.60	30.57	30.93
Anechoic	29.03	29.65	30.05
Delta (dB)	0.57	0.92	0.88

GSM850	TIS(dBm)		
Freq (MHz)	869.2	881.6	893.8
Reverb	-106.20	-106.42	-107.07
Anechoic	-107.28	-106.88	-108.31
Delta (dB)	1.08	0.46	1.24

Measured Results

- For GSM1900, TRP was measured.
- Between reverb and anechoic, the correlation is within about 1.5 dB.

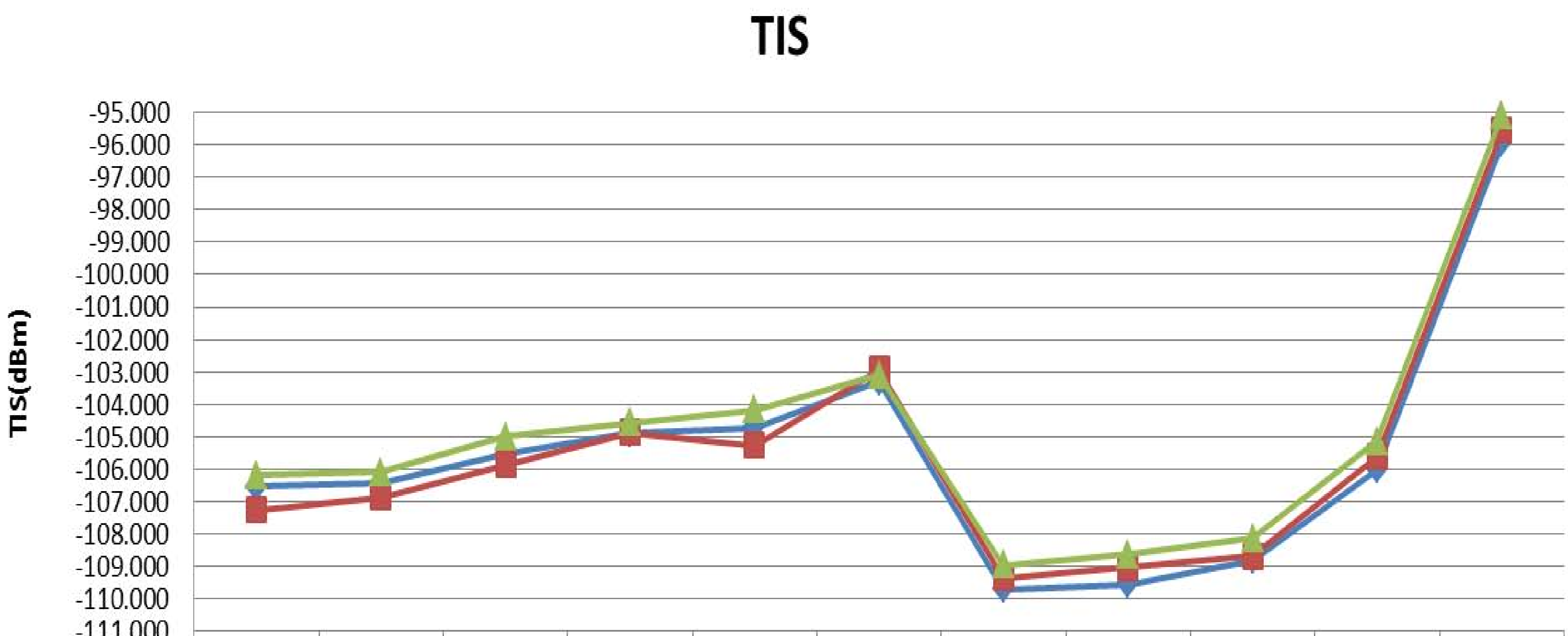
GSM1900	TRP (dBm)		
Freq (MHz)	1850.2	1880	1909.8
Reverb	27.60	27.88	27.83
Anechoic	26.45	26.46	26.49
Delta (dB)	1.15	1.42	1.34

Measured Results

- **For CDMA, TRP was measured at Cell band.**
- **Between reverb and anechoic, the correlation is within about 1.5 dB.**

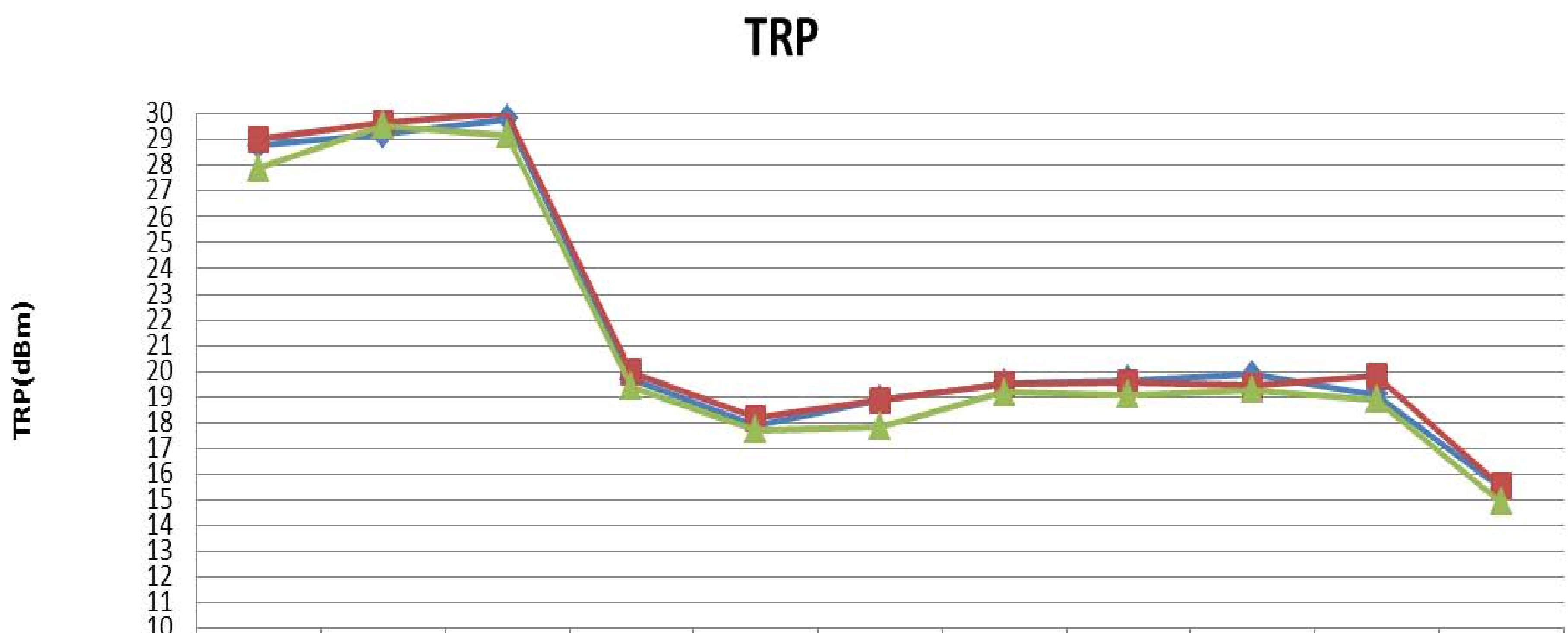
Cell	TRP (dBm)		
Freq (MHz)	**824.7**	**836.52**	**848.31**
Reverb	19.40	17.71	17.24
Anechoic	19.97	18.18	18.89
Delta (dB)	-0.57	-0.47	-1.65

Measured Results



	GSM850 LOW	GSM850 MID	GSM850 HIGH	CDMA2000	CDMA2000	CDMA2000	WCDMA V LOW	WCDMA V MID	WCDMA V HIGH	TD-SCDMA	LTE Band 13
AMS-8500	-106.556	-106.441	-105.543	-104.894	-104.728	-103.315	-109.717	-109.552	-108.818	-106.03	-95.9459
AMS-8923	-107.276	-106.875	-105.882	-104.877	-105.272	-102.922	-109.368	-109.033	-108.685	-105.610	-95.5624
AMS-7700	-106.19	-106.089	-104.992	-104.566	-104.167	-103.115	-108.967	-108.63	-108.129	-105.14	-95.0669

Measured Results



	GSM850 LOW	GSM850 MID	GSM850 HIGH	CDMA2000	CDMA2000	CDMA2000	WCDMA V LOW	WCDMA V MID	WCDMA V HIGH	TD-SCDMA	LTE Band 13
AMS-8500	28.7764	29.2290	29.8144	19.6902	17.9114	18.9081	19.5356	19.6551	19.8719	19.08	15.4582
AMS-8923	29.0295	29.6475	30.0507	19.972	18.1759	18.8872	19.4945	19.5611	19.437	19.8	15.5481
AMS-7700	27.9078	29.5594	29.1979	19.4083	17.7120	17.8397	19.181	19.087	19.287	18.9	14.923

Measured Results

- **Relationship between number of tuner steps and measurement uncertainty.**

Anechoic TRP:	28.4											Anechoic TIS	-105.8		
		Freq: 836MHz								Freq: 881MHz					
# Points	G	Mismatch 1	Mismatch 2	Correction Factor	Measured Power	TRP	TRP with 120pt correction factor		G	Mismatch 1	Mismatch 2	Correction Factor	Measured Power	TIS	TIS with 120pt correction factor
120	-8.18518	-1.37111	-1.2434	**-9.55629**	18.577	28.13329	same	120	-8.6934	-1.32721	-1.413	-10.02061	-95.5355	-105.55481	same
	-8.27191	-1.26895	-1.24423	**-9.54086**	18.541	28.08186	same		-8.77098	-1.24833	-1.41886	-10.01931			
	-8.19632	-1.36177	-1.24276	**-9.55809**	18.5257	28.08379	same		-8.71731	-1.31578	-1.42108	-10.03309			
100	-7.76225	-1.23992	-1.33625	-9.00217	18.7295	27.73167	28.28579	100	-8.43766	-1.41904	-1.61053	-9.8567	-94.9795	-104.8362	-105.00011
	-7.86135	-1.13207	-1.33901	-8.99342					-8.38723	-1.47443	-1.61394	-9.86166			
	-7.74387	-1.26176	-1.3383	-9.00563					-8.41137	-1.44616	-1.61324	-9.85753			
60	-7.88714	-1.16522	-1.28566	-9.05236	18.6162	27.66856	28.17249	60	-9.20415	-1.09708	-1.58829	-10.30123	-95.0379	-105.33913	-105.05851
	-7.87406	-1.18062	-1.29085	-9.05468					-9.06066	-1.24577	-1.58421	-10.30643			
	-7.87945	-1.166	-1.29476	-9.04545					-9.05885	-1.25059	-1.58582	-10.30944			
36	-7.62765	-1.65532	-1.38385	-9.28297	16.6891	25.97207	26.24539	36	-7.83735	-1.47102	-1.42164	-9.30837	-94.9795	-104.28787	-105.00011
	-7.6557	-1.64466	-1.38208	-9.30036	16.7215	26.02186	26.26236		-7.95305	-1.36136	-1.4155	-9.31441			
	-7.67826	-1.60197	-1.38324	-9.28023	16.7474	26.02763	26.30549		-7.91695	-1.35926	-1.41898	-9.27621			
30	-7.73475	-1.15268	-1.00119	-8.88743	19.0785	27.96593	28.63479		-8.68998	-1.1219	-1.31993	-9.81188	-94.1494	-103.96128	-104.17001
10	-6.61559	-1.0953	-0.969016	-7.71089	18.5658	26.27669	28.12209	10	-9.17645	-1.33709	-1.27146	-10.51354	-95.0346	-105.54814	-105.05521
	-6.49261	-1.16503	-0.961571	-7.65764	18.5222	26.17984	28.06306		-8.9721	-1.44673	-1.27027				
	-6.02507	-1.56	-0.961893	-7.58507	18.5255	26.11057	28.08359		-8.6553	-1.84281	-1.27174				

Summary

- **The Reverb chamber is :**
  - a proposed alternative method of performing TIS and TRP measurements of wireless devices.
  - Suitable for fast go/nogo type measurements as well as accurate qualitative measurements.
  - Removes the need to work with absorbers
  - Can be used for fast measurement of small wireless antennas
  - Being looked at as a potential alternative solution for a MIMO methodology.

- **This technology is developing...**

THANK YOU !

EMC Measurement Uncertainty

2012 – Seminar in Brazil – Daniel D. Hoolihan

BRIEF HISTORY OF EMC MEASUREMENT UNCERTAINTY

1977 – International standards bodies started to organize the concept of MU

1980 – First Recommendation on MU

1986 – First Recommendation was reconfirmed

1993 – Guide to the Expression of Uncertainty in Measurement (GUM) released

1995 – GUM is corrected and reprinted

2008 – ISO/IEC Guide 98-3 – Released and it cancels and replaces the 1995 GUM

EMC MEASUREMENT UNCERTAINTY

Measurement Uncertainty (MU) builds on the earlier definitions and use of:

- Error
- Tolerance
- Precision
- Effects
- Corrections

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Definition of UNCERTAINTY

Uncertainty (of measurement)

1. A **parameter**, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand;

2. **The spread of values** about the measurement result within which the value of the measurand may be expected to be found; and,

3. A **measure of the possible error in the estimated** value of the measurand as provided by the result of a measurement

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More MU Definitions

Type A evaluation (of standard uncertainty): method of evaluation of a standard uncertainty by the **statistical analysis of a series of observations.**

Type B evaluation (of standard uncertainty): method of evaluation of a standard uncertainty by means **OTHER than the statistical analysis of a series of observations.**

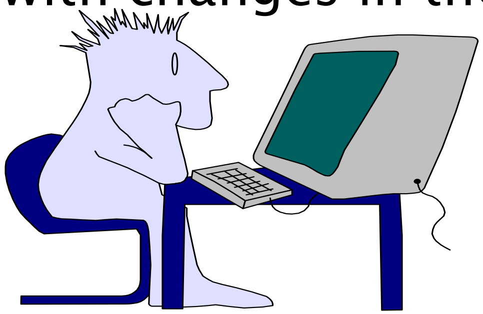
- data from calibration certificates
- manufacturer's specification data sheets
- previous measurement data
- experience with the operation of an equipment

Combined Standard Uncertainty

Standard Uncertainty: uncertainty of the result of a measurement expressed as a **standard deviation.**

Combined standard uncertainty:

standard uncertainty of the result of a measurement when that result is obtained from the values of a number of other quantities, equal to the **positive square root of a sum of terms**, the terms being the variances or covariances of these other quantities weighted according to how the measurement result varies with changes in these quantities.



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Coverage Factor and Expanded Uncertainty

Coverage factor:

numerical factor used as a multiplier of the **combined standard uncertainty** in order to obtain an expanded uncertainty.

- Note – In EMC, the coverage factor, k, is typically 2

Expanded uncertainty: quantity defining the interval about the result of a measurement within which the values that could reasonable be attributed to the measurand may be expected to lie with a high level of confidence.

Final Answer

Expanded Uncertainty =
Combined Standard Uncertainty x
Coverage Factor

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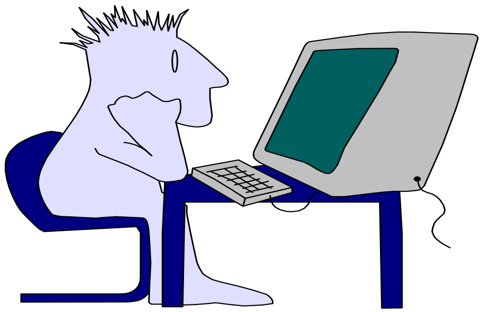
EMC MU - Concepts

-Errors of measurement may have two components

- a **RANDOM component**
- a **Systematic comp**onent

- In general, uncertainty is a result of RANDOM EFFECTS

- However, uncertainty may also result from imperfect correction for SYSTEMATIC EFFECTS



EMC MU – Concepts

RANDOM errors (RANDOM effects) arise from random variations of the observations

- every time a measurement is made under the same conditions, RANDOM effects from various sources affect the measured value

- thus, a series of measurements produces a scatter around a mean value

- since there can be a number of sources of variability in a measurement and their influence may change with each measurement, the scatter around the mean value can be reduced but never completely eliminated

EMC MU – Concepts

SYSTEMATIC ERRORS

- a systematic effect is an effect on a measurement result of a quantity that is not included in a specification of the measurand but the quantity influences the result
- they remain unchanged when the measurement is repeated under the same conditions
- their effect is to introduce a displacement between the value of the measurand and the experimentally determined mean value
- in general, the systematic effects cannot be eliminated but they may be reduced

EMC MU – Concepts

- **Components of uncertainty are evaluated by the appropriate method – A or B**
- Each is expressed as standard deviation and is referred to as a STANDARD UNCERTAINTY
- The STANDARD UNCERTAINTY components are combined to produce an overall value of uncertainty called the COMBINED STANDARD UNCERTAINTY
- EXPANDED UNCERTAINTY is the COMBINED STANDARD UNCERTAINTY multiplied by a coverage factor – k

EMC MU - Concepts

- The k factor is safety factor
- In engineering terms, it is the design factor to make sure the "fifty-pound bolt" will take at least "100 pounds of force before it fails."
- It is intended to increase the interval around the result of the measurement to increase the probability that the value of the measurand is within the selected interval
- The value of k is based on the coverage probability or level of confidence
- For EMC, the accepted value for k is 2 for a 95% probability of finding the value of the measurand within the interval

EMC Literature on MU

LAB34

– *The Expression of Uncertainty in EMC Testing*

- Published by the United Kingdom Accreditation Service
- It is FREE
- Contains examples of typical uncertainty budgets
  - Conducted Emissions (Conducted Disturbances)
  - Radiated Emissions/Radiated Field Strength
  - Measurement of Disturbance Power
- Released in 2002

EMC Literature on MU

International Standard on EMC-MU

CISPR 16-4-2 –

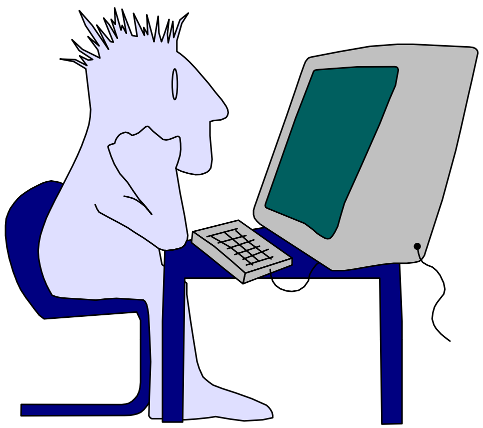
Specification for Radio Disturbance and Immunity Measuring Apparatus and Methods – Part 4-2: Uncertainties, statistics and limit modeling – Uncertainty in EMC Measurements

- Has three examples:
  - Conducted Disturbances
  - Radiated Disturbances of electric field strength
  - Disturbance Power Measurements

United States Literature on EMC MU

United States Department of Commerce

- National Institute of Standards and Technology
- NIST Technical Note 1297 – 1994 Edition
- *Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results*
  - Applies to all lab measurements
  - Easier to read than the "GUM"



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United States – ANSI/IEEE C63.23

The ANSI-ASC C63 Committee is developing a Standard on Measurement Uncertainty

- It is still in DRAFT form
- Its title is: *American National Standard Draft Guide for EMC – Calculations (Computations) and Treatment of Measurement Uncertainty*
- It addresses methods for estimating measurement uncertainty for EMC emission measurements in conjunction with ANSI C63.4
- Uncertainty Evaluation methods include Type A and Type B.

United States – ANSI/IEEE C63.23

Table of Contents

Example of Combined Measurement Uncertainty – Conducted Emission – 150 kHz to 30 MHz – 50 ohm/50 microhenry LISN

Source of Uncertainty	Value dB +/-	Probability Distribution Function/Type	Divisor	U(y) dB	$(U(y))^2$ dB
LISN Impedance	2.70	Triangular/B	2.449	1.10	1.215
Receiver Pulse Amplitude	1.50	Rectangular/B	1.732	0.87	0.750
Receiver Pulse Repetition	1.50	Rectangular/B	1.732	0.87	0.750
Mismatch	-0.89	U-Shaped/B	1.414	-0.63	0.397
Receiver Sine Wave	1.00	Rectangular/B	1.732	0.58	0.333
Attenuation LISN-Receiver	0.40	Normal 2/A	2.000	0.20	0.040
LISN Voltage Division Factor	0.20	Normal 2/A	2.000	0.10	0.010
Receiver Reading	0.05	Rectangula/B	1.732	0.03	0.001
Combined Standard Uncertainty					$\sqrt{3.496} = 1.87$
Expanded Uncertainty		Normal k = 2			3.74

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Example of Combined Measurement Uncertainty – Radiated Emission – 30 –300 MHz – biconical antenna – vertical polarization

Source of Uncertainty	Value dB	Probability Distribution/Type	Divisor	U(y) dB	$(U(y))^2$ dB
Site Imperfections	4.00	Triangular/B	2.449	1.63	2.667
Mismatch	-1.25	U-shaped/B	1.414	-0.88	0.781
Receiver Pulse Amplitude	1.50	Rectangular/B	1.732	0.87	0.750
Receiver Pulse Repetition	1.50	Rectangular/B	1.732	0.87	0.750
Receiver Sine Wave	1.00	Normal 2/A	2.000	0.50	0.250
Antenna Factor Calibration	1.00	Normal 2/A	2.000	0.50	0.250
Miscellaneous Factors	-	Various/B	Various	0.84	0.701
Measurement Distance Variation	0.60	Rectangular/B	1.732	0.35	0.120
Combined Standard Uncertainty					$\sqrt{6.269} = 2.50$
Expanded Uncertainty					5.00

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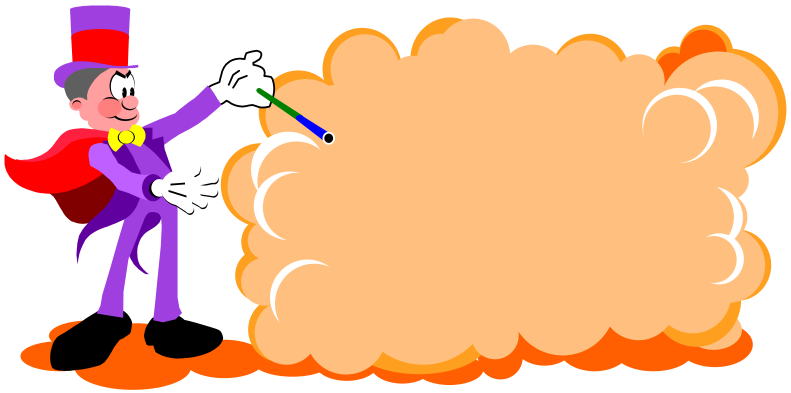
Cross References to EMC MU

CISPR 16-4-2 is referenced by:

- CISPR 16-1-1 – Edition 2.2
- CISPR 22 – Edition 5.2
- More coming in the future



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EMC Measurement Uncertainty

Summary

Type A factor – statistically-based

Type B factor – everything else

Standard Uncertainty = Standard Deviation

k is a coverage factor (normally 2) that increases the probability the measurement value will be found within the interval

Expanded uncertainty is two times the Combined Standard Uncertainty

The “Ground” Myth

Bruce Archambeault, Ph.D.
IEEE Fellow, IBM Distinguished Engineer,
Bruce.arch@ieee.org

Sao Paulo, Brazil
26 April 2012

IEEE

EMC SOCIETY

Introduction

- Electromagnetics can be scary
  – Universities *LOVE* messy math
- EM is not hard, unless you want to do the messy math
- Goal:
  – Intuitive understanding
  – Understand the basic fundamentals
  – Understand how to read the math

Electromagnetics
In the Beginning

- Electric and Magnetic effects not connected
- Electric and magnetic effects were due to ‘action from a distance’
- Faraday was the 1st to propose a relationship between electric lines of force and time-changing magnetic fields
  - Faraday was very good at experiments and ‘figuring out’ how things work

Maxwell

- Maxwell was impressed with Faraday’s ideas
- Discovered the mathematical link between the “electro” and the “magnetic”
- Scotland’s greatest contribution to the world (next to Scotch)

“Maxwell’s Equations”

- Maxwell’s original work included 20 equations!
- Heaviside reduced them to the existing four equations
  - Heaviside refused to call the equations his own
- Hertz is credited with proving they are correct

Maxwell's Equations are NOT Hard!

$$\nabla \times H = J + \frac{\partial D}{\partial t}$$

$$\nabla \times E = -\frac{\partial B}{\partial t}$$

Maxwell's Equations are not Hard!

- Change in H-field across space ~ Change in E-field (at that point) with time
- Change in E-field across space ~ Change in H-field (at that point) with time
- (Roughly speaking, and ignoring constants)

Current Flow

- Most important concept of EMC
- Current flow through metal changes as frequency increases
- DC current
  - Uses entire conductor
  - Only resistance inhibits current
- High Frequency
  - Only small part of conductor (near surface) is used
  - *Resistance* is small part of current inhibitor
  - ***Inductance*** is major part of current inhibitor

Inductance

- Current flow through metal => inductance!
- Fundamental element in EVERYTHING
- Loop area first order concern
- Inductive impedance increases with frequency and is MAJOR concern at high frequencies

$$X_L = 2\pi f L$$

Current Loop => Inductance

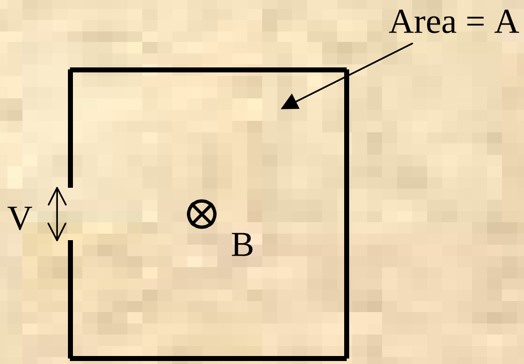
Courtesy of Elya Joffe

Inductance Definition

- Faraday's Law

$$\oint \overline{E} \cdot dl = -\iint \frac{\partial \overline{B}}{\partial t} \cdot d\overline{S}$$

- For a simple rectangular loop

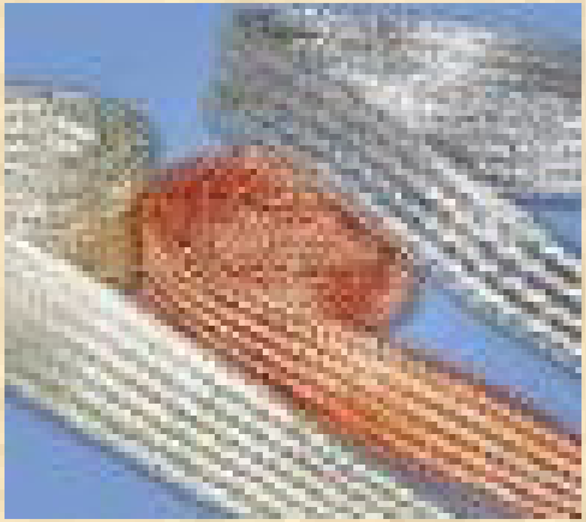


$$V = -A\frac{\partial B}{\partial t}$$

The minus sign means that the induced voltage will work against the current that originally created the magnetic field!

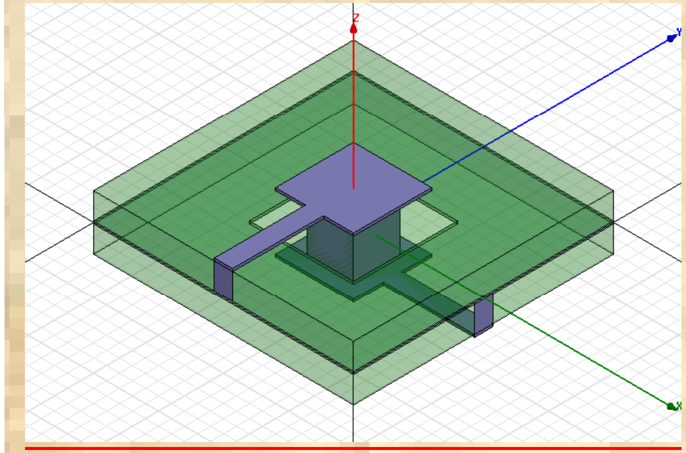
Given the Definition of Inductance

- Do these have inductance?



"Ground Strap"

SMT Capacitor



PCB Via

Not until return path for current is identified!

Self (Loop) Inductance

- Isolated circular loop

$$L \approx \mu_0 a \ln\left(\frac{8a}{r_0} - 2\right)$$

- Isolated rectangular loop

$$L = \frac{2\mu_0 a}{\pi} \ln\left(\frac{p + \sqrt{1+p^2}}{1+\sqrt{2}} + \frac{1}{p} - 1 + \sqrt{2} - \frac{1}{p}\sqrt{1+p^2}\right)$$

Note that inductance is directly influenced by loop ***AREA*** and less influenced by conductor size!

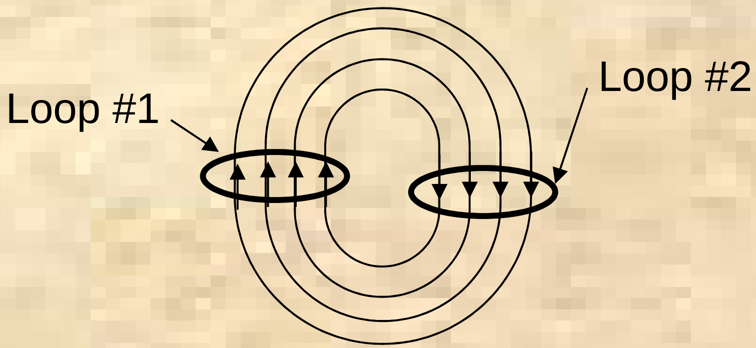
$$p = \frac{\text{length of side}}{\text{wire radius}}$$

Mutual Inductance

$$\Phi_2 = M_{21} I_1$$

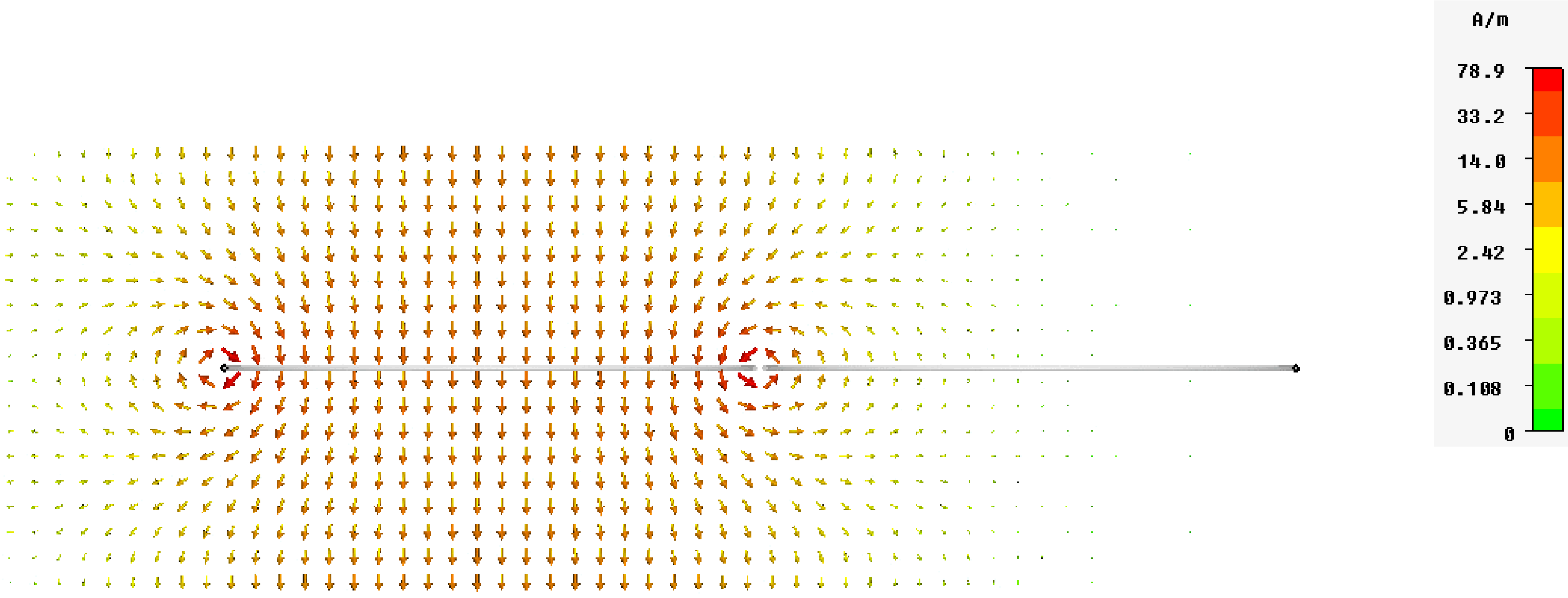
$$M_{21} = \frac{\Phi_2}{I_1}$$

How much magnetic flux is induced in loop #2 from a current in loop #1?

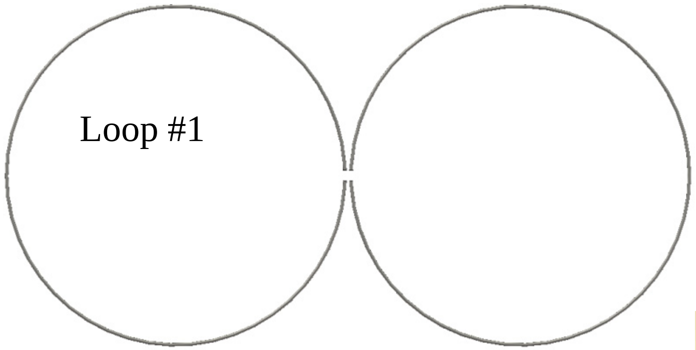


$$\Phi_2 = \int_{S_2} \vec{B}_1(r) \cdot \hat{n}\, dS_2$$

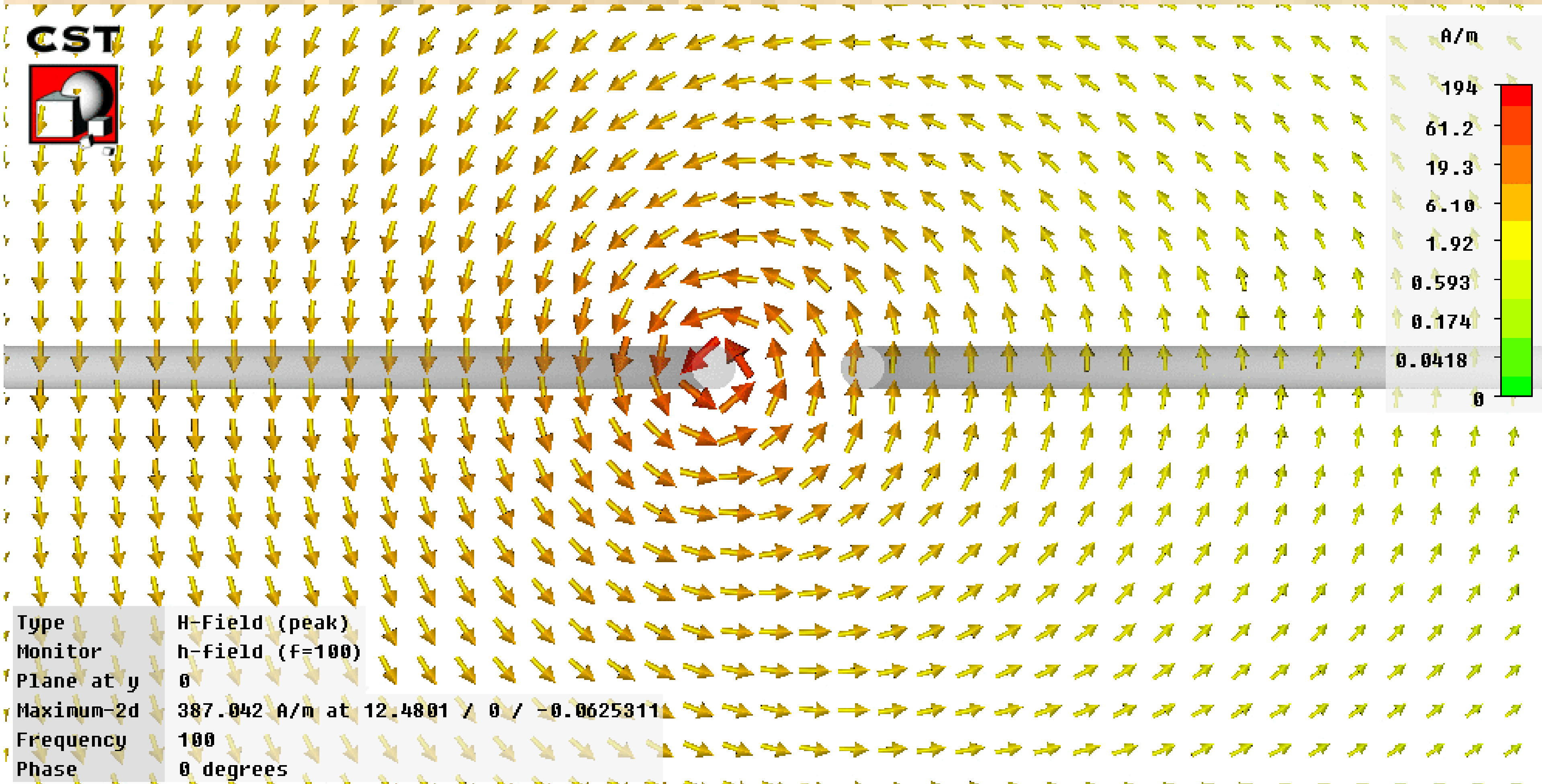
Flux from Current in Loop #1



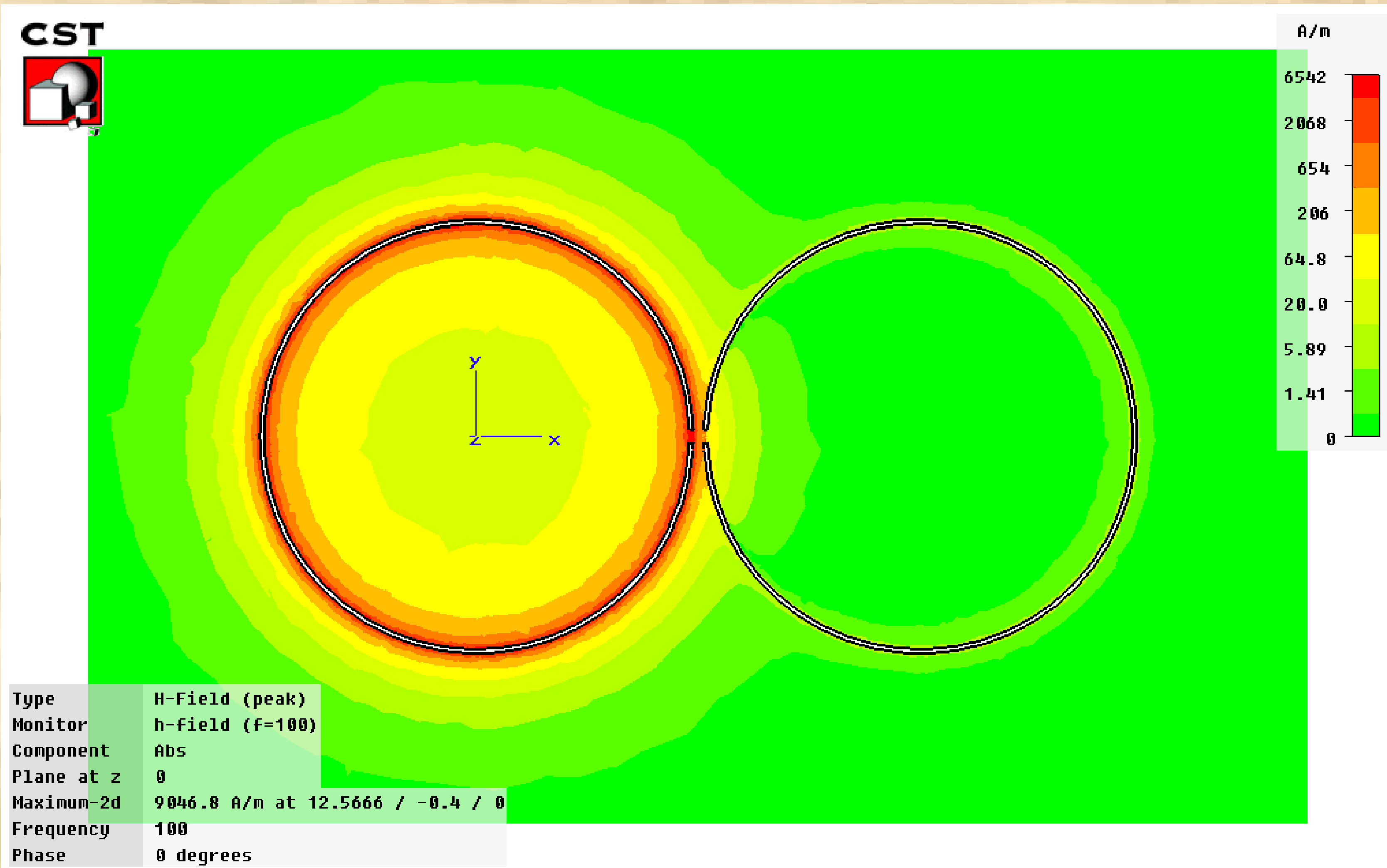
Type	H-Field (peak)
Monitor	h-field (f=100)
Plane at y	0
Maximum-2d	78.866 A/m at -12.2246 / 2.11637e-015 / 0.595706
Frequency	100
Phase	0 degrees

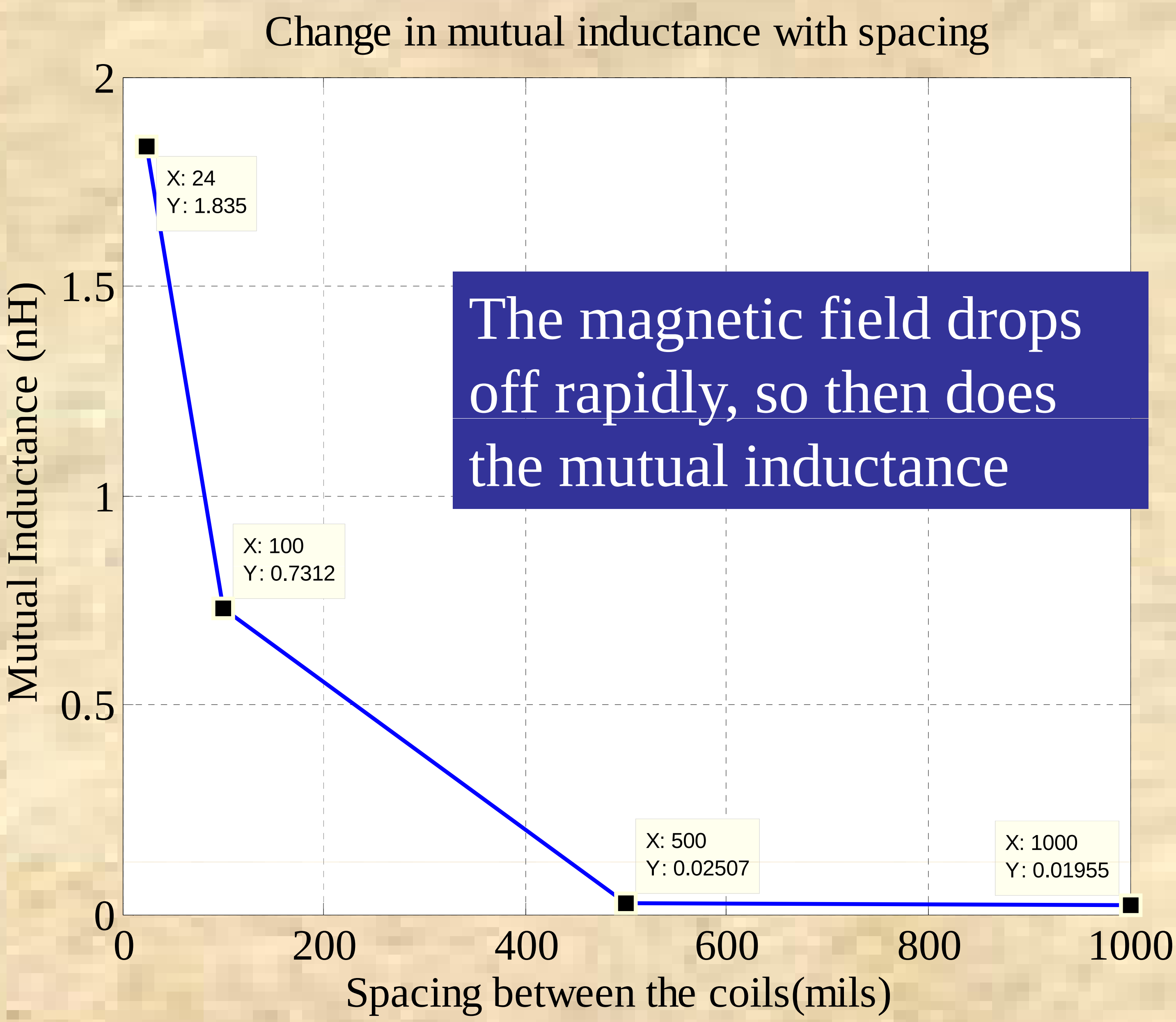


Flux from Current in Loop #1



Flux from Current in Loop #1

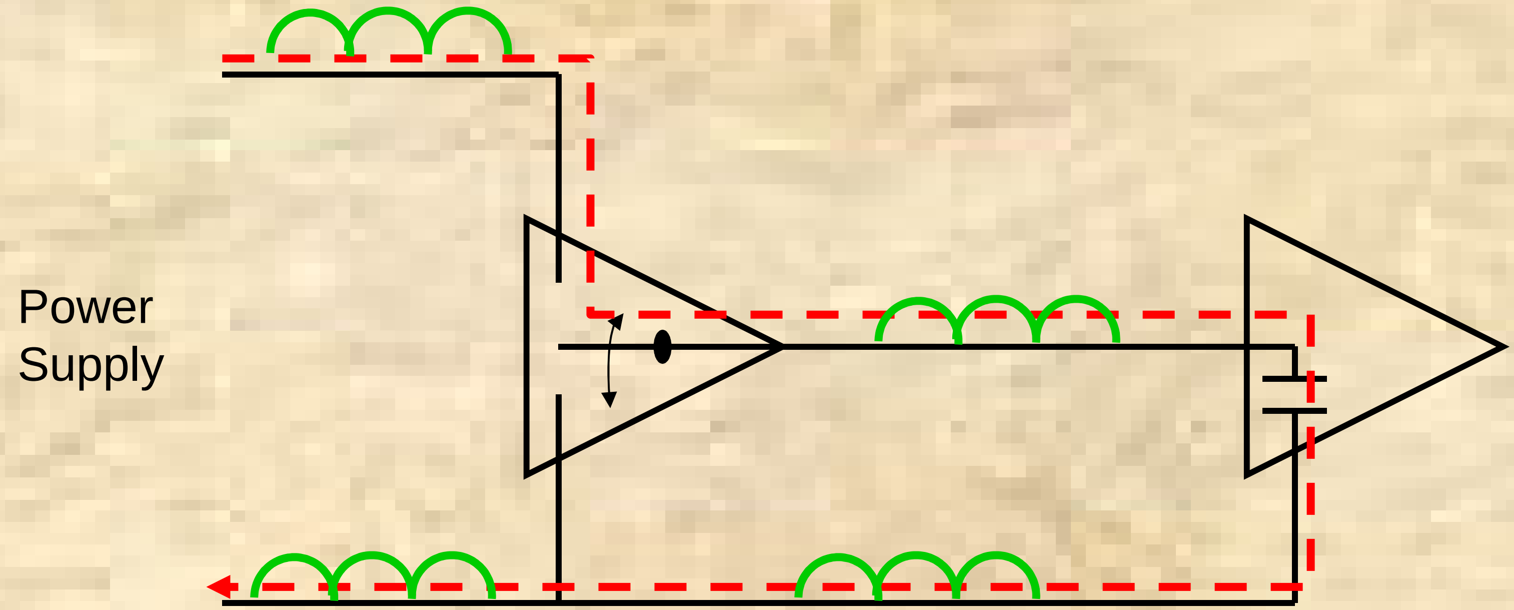



Change in mutual inductance with spacing
Mutual Inductance (nH)
2
1.5
1
0.5
0
0
200
400
600
800
1000
Spacing between the coils(mils)
X: 24
Y: 1.835
X: 100
Y: 0.7312
X: 500
Y: 0.02507
X: 1000
Y: 0.01955
The magnetic field drops off rapidly, so then does the mutual inductance

Partial Inductance

- We now know that a loop of current has inductance
- We now know that there must be a complete loop to have inductance
- But where do we place this inductance in a circuit?

Zero-to-One Transition
Where's the Inductance Go??

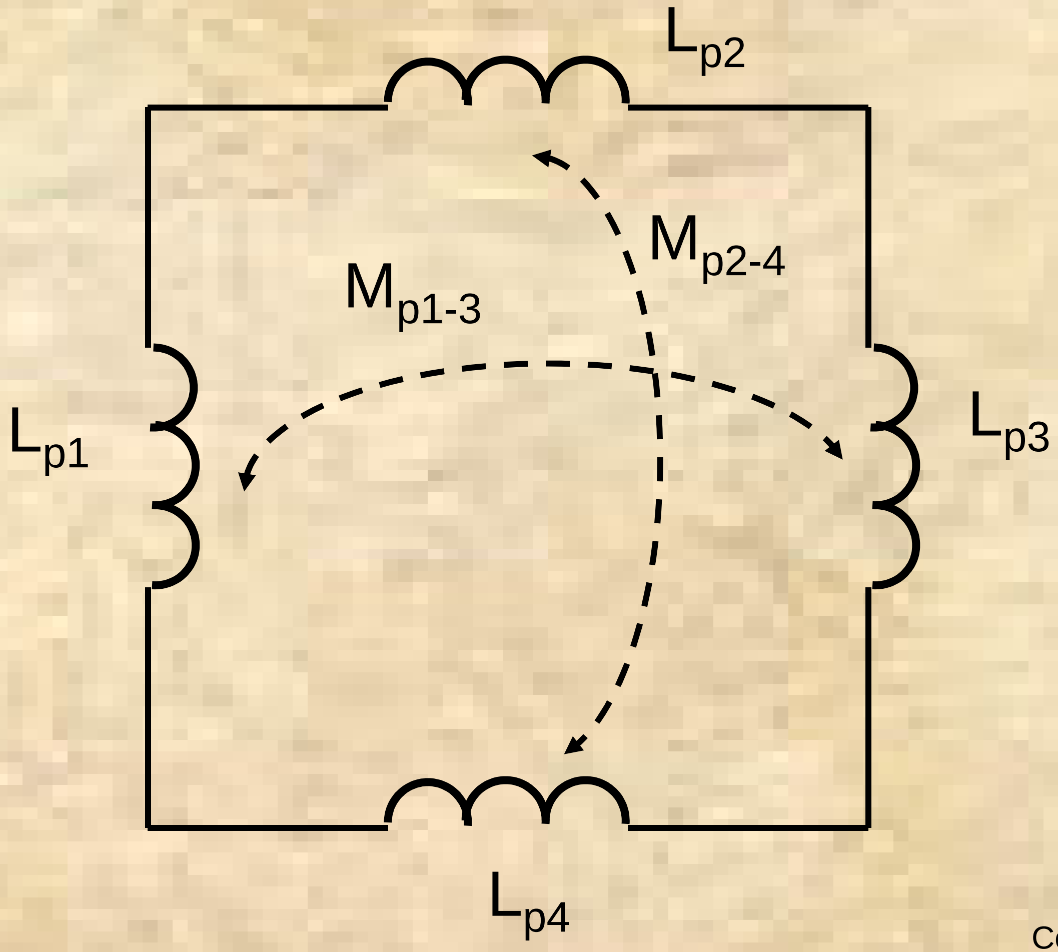


And how could you possibly calculate it?

Courtesy of Dr. Clayton Paul

Total Loop Inductance from Partial Inductance

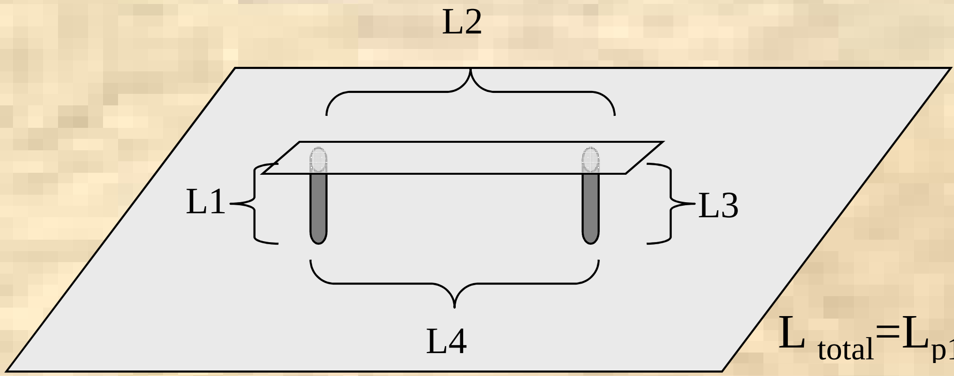
$$L_{total} = L_{p1} + L_{p2} + L_{p3} + L_{p4} - 2M_{p1\text{-}3} - 2M_{p2\text{-}4}$$



Courtesy of Dr. Clayton Paul

Partial Inductance

- Simply a way to break the overall loop into pieces in order to find total inductance



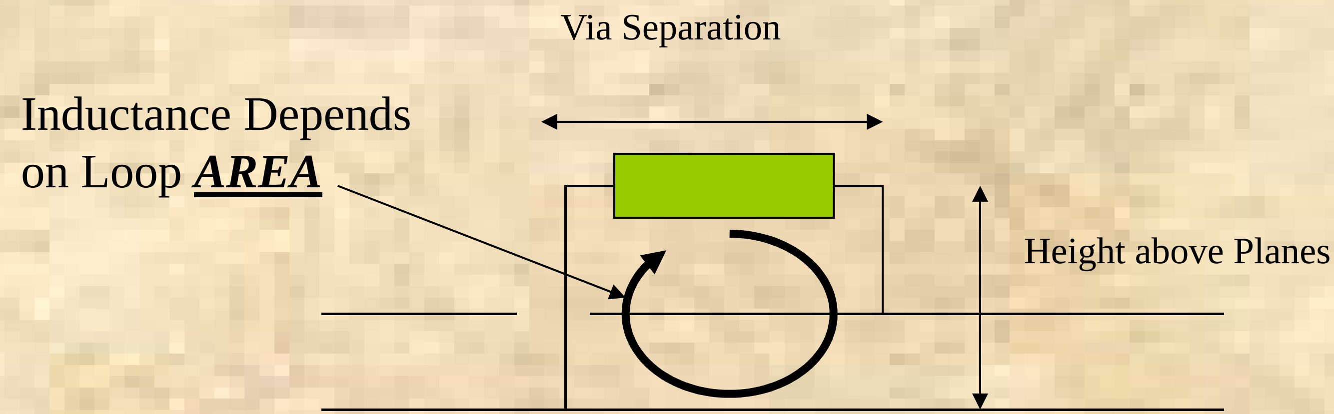
$$L_{total} = L_{p11} + L_{p22} + L_{p33} + L_{p44} - 2L_{p13} - 2L_{p24}$$

Important Points About Inductance

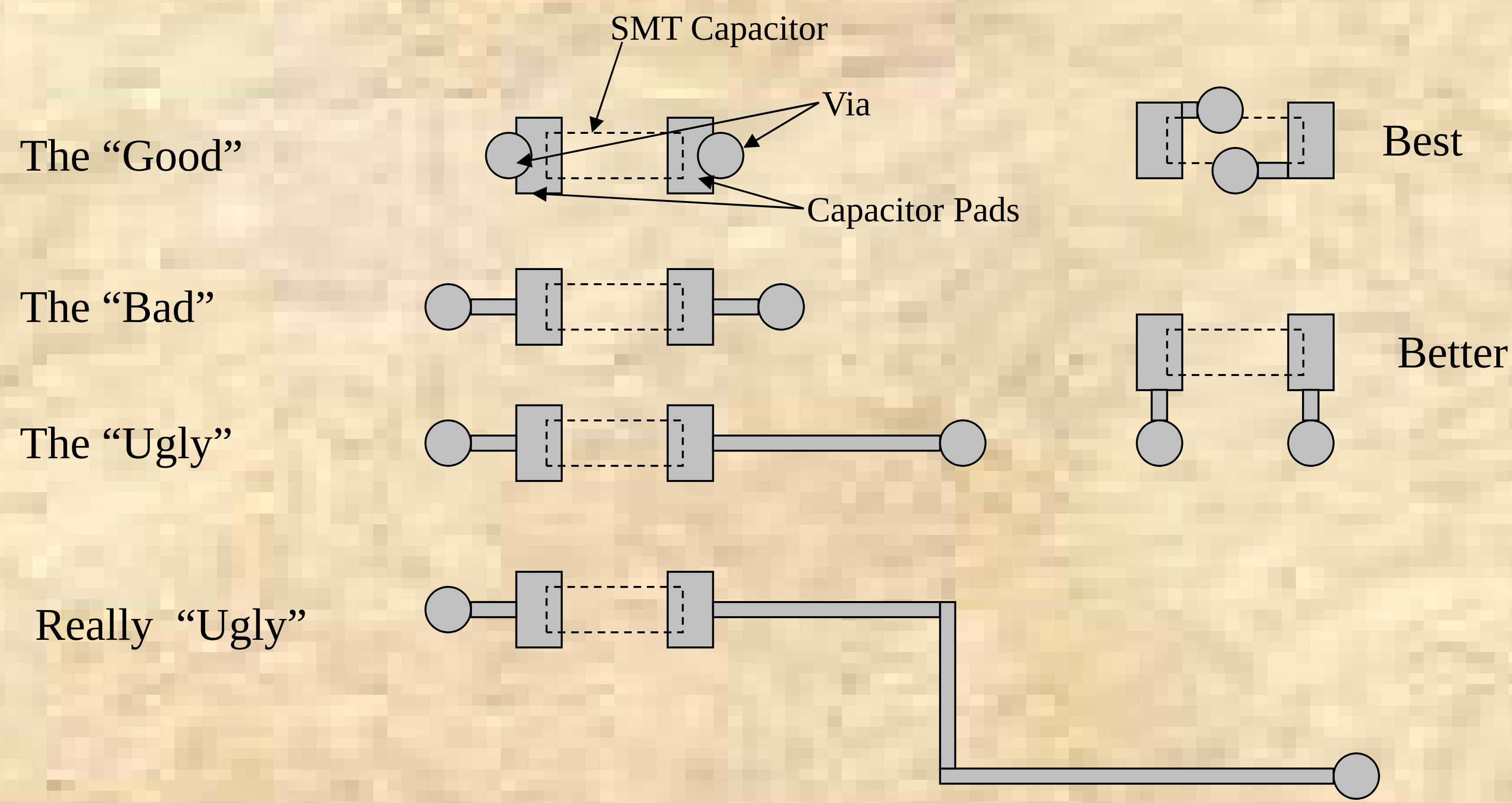
- Inductance is everywhere
- Loop area most important
- Inductance is everywhere

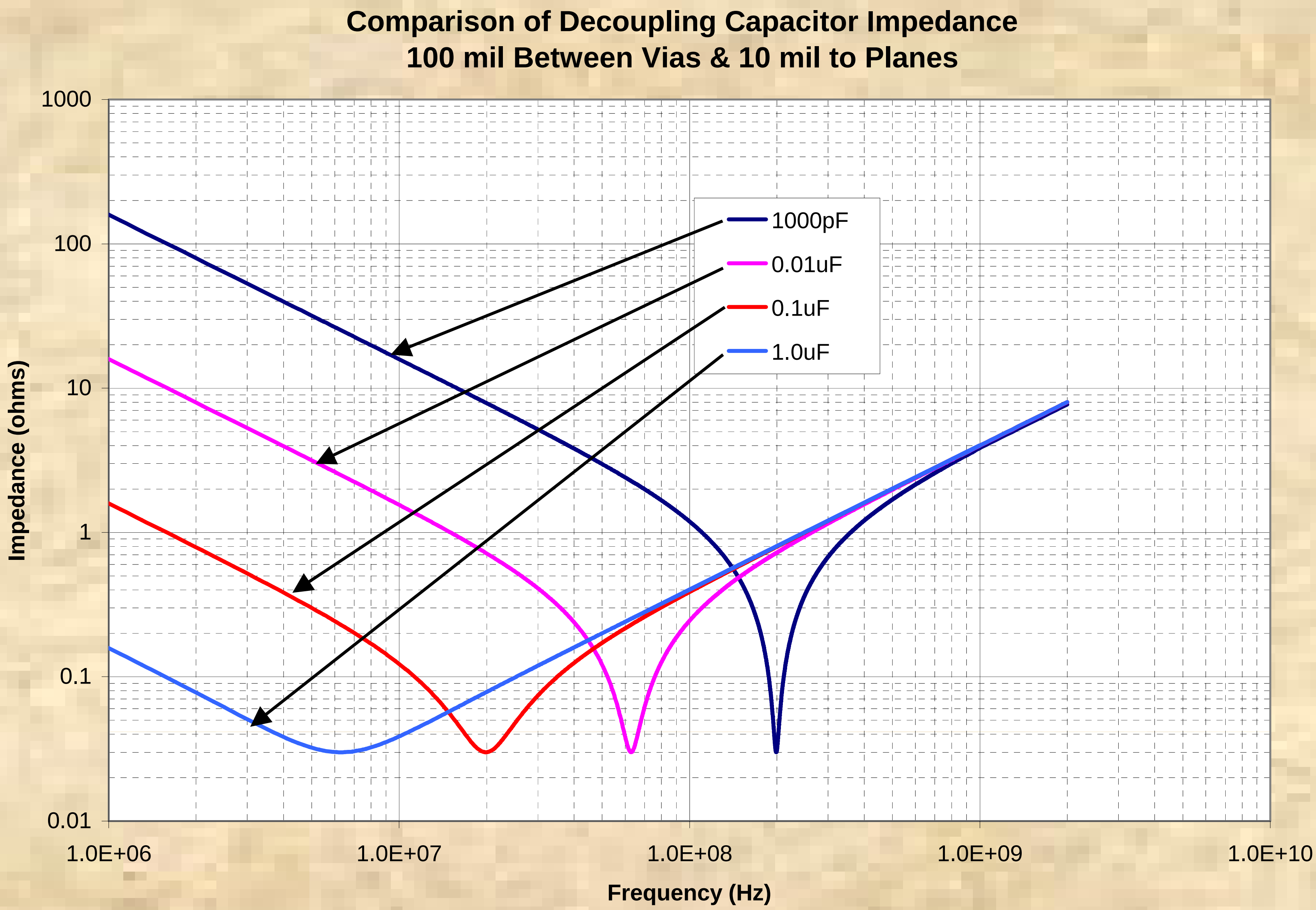
Decoupling Capacitor Mounting

- Keep as to planes as close to capacitor pads as possible



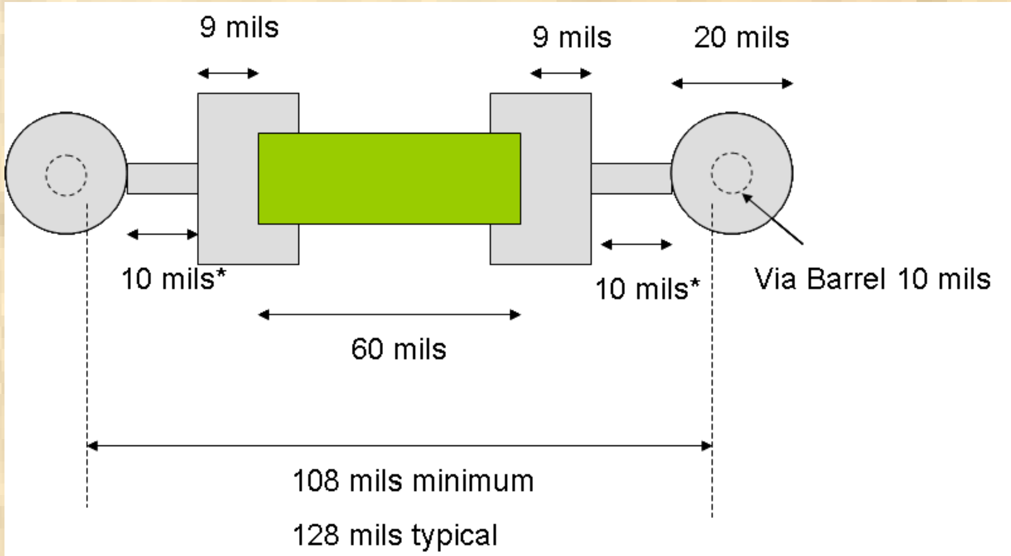
Via Configuration Can Change Inductance



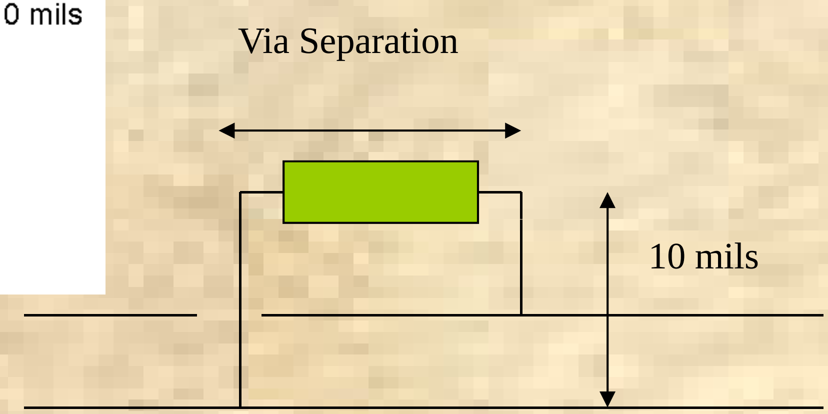


Comparison of Decoupling Capacitor Impedance
100 mil Between Vias & 10 mil to Planes
1000
100
10
1
0.1
0.01
Impedance (ohms)
1000pF
0.01uF
0.1uF
1.0uF
1.0E+06
1.0E+07
1.0E+08
1.0E+09
1.0E+10
Frequency (Hz)

Comparison of Decoupling Capacitor Via Separation Distance Effects



0603 Typical Minimum Dimensions



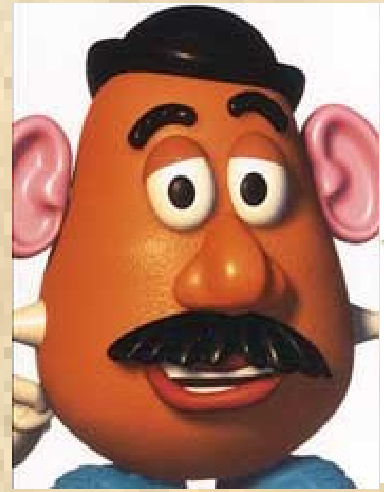
Connection Inductance for Typical Capacitor Configurations

Distance into board to planes (mils)	0805 typical/minimum (148 mils between via barrels)	0603 typical/minimum (128 mils between via barrels)	0402 typical/minimum (106 mils between via barrels)
10	1.2 nH	1.1 nH	0.9 nH
20	1.8 nH	1.6 nH	1.3 nH
30	2.2 nH	1.9 nH	1.6 nH
40	2.5 nH	2.2 nH	1.9 nH
50	2.8 nH	2.5 nH	2.1 nH
60	3.1 nH	2.7 nH	2.3 nH
70	3.4 nH	3.0 nH	2.6 nH
80	3.6 nH	3.2 nH	2.8 nH
90	3.9 nH	3.5 nH	3.0 nH
100	4.2 nH	3.7 nH	3.2 nH

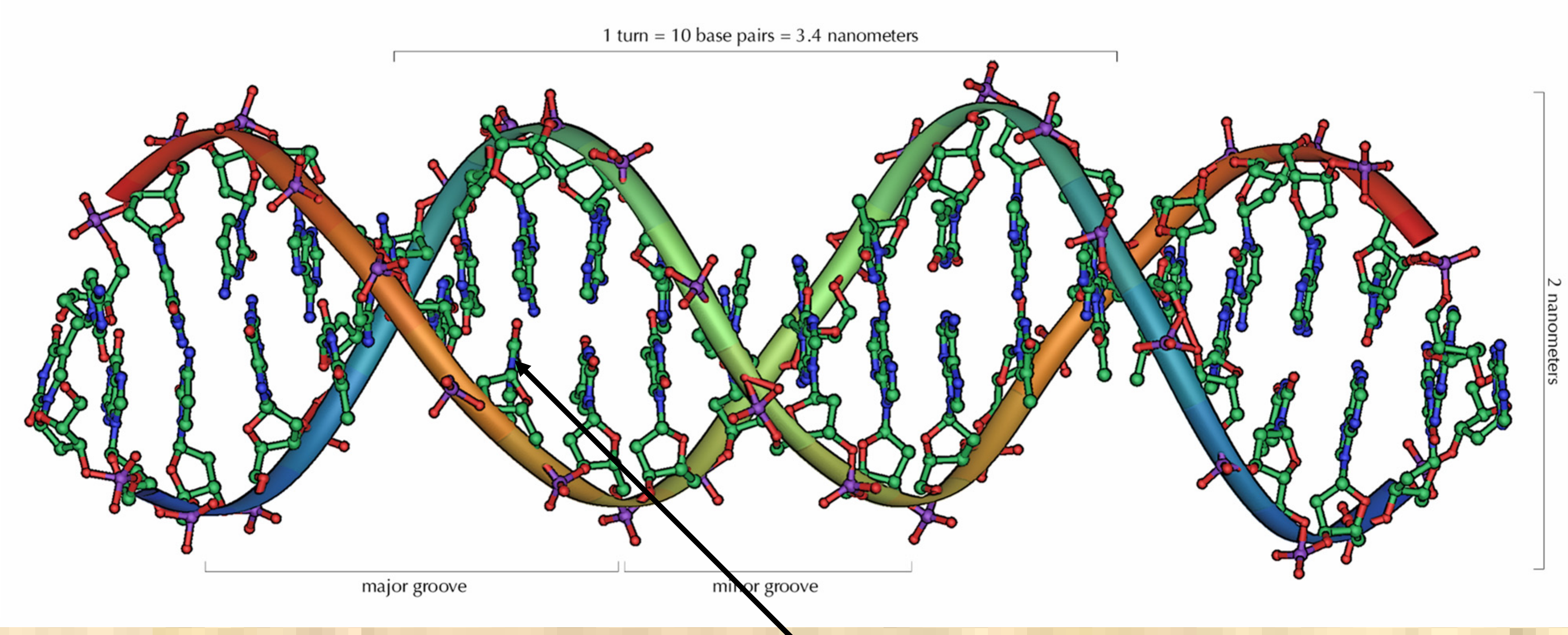
‘Ground’

- **Ground is a place where potatoes and carrots thrive!**
- ‘Earth’ or ‘reference’ is more descriptive
- Original use of “GROUND”
- Inductance is everywhere

$$X_L = 2\pi f L$$




News from the Human Genome Project

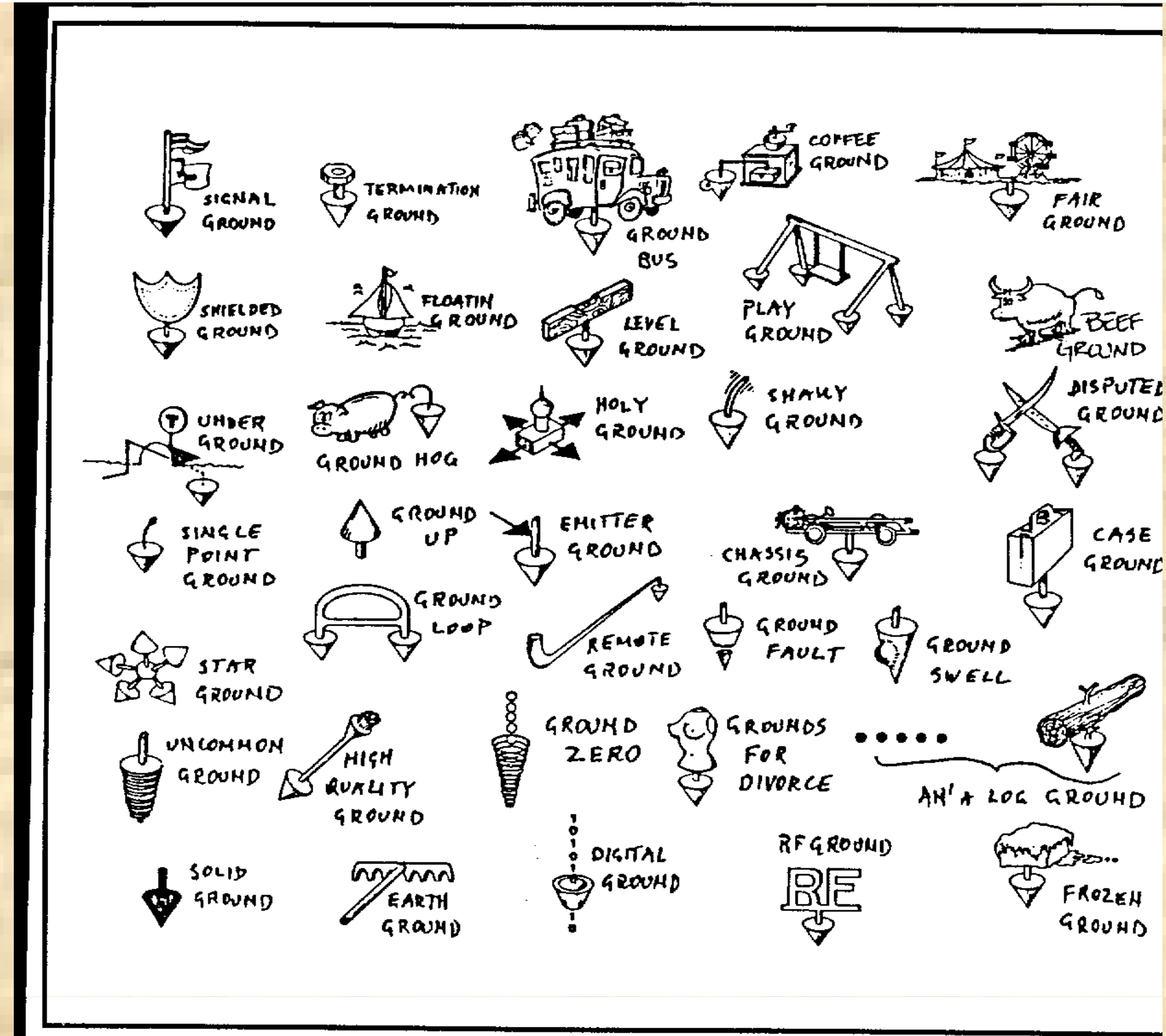


<u>"GROUND" is good</u> gene

What we Really Mean when we say ‘Ground’

- Signal Reference
- Power Reference
- Safety Earth
- Chassis Shield Reference

Circuit “Ground” | Chassis “Ground” | Digital “Ground” | Analog “Ground”

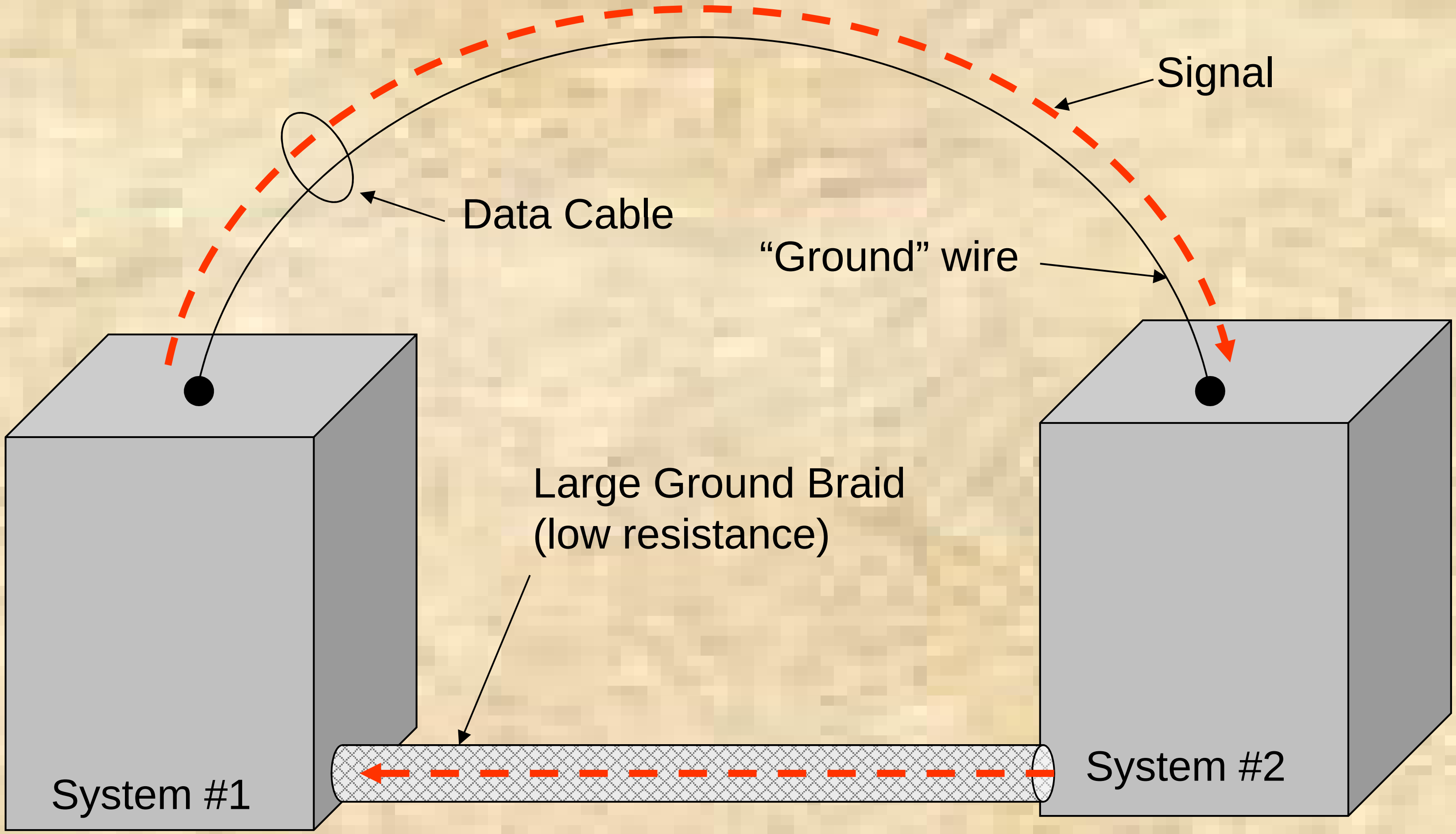

SIGNAL GROUND
TERMINATION GROUND
GROUND BUS
COFFEE GROUND
FAIR GROUND
SHIELDED GROUND
FLOATIN GROUND
LEVEL GROUND
PLAY GROUND
BEEF GROUND
UNDER GROUND
GROUND HOG
HOLY GROUND
SHAKY GROUND
DISPUTED GROUND
SINGLE POINT GROUND
GROUND UP
EMITTER GROUND
CHASSIS GROUND
CASE GROUND
GROUND LOOP
REMOTE GROUND
GROUND FAULT
GROUND SWELL
STAR GROUND
UNCOMMON GROUND
HIGH QUALITY GROUND
GROUND ZERO
GROUNDS FOR DIVORCE
AN' A LOG GROUND
SOLID GROUND
EARTH GROUND
DIGITAL GROUND
RF GROUND
RF
FROZEN GROUND

Current Path

- Current will ALWAYS follow the path of least ***impedance***
  - Low frequencies → lowest ***resistance***
  - High frequencies → lowest ***inductance***
  - Change over ~ 100 KHz

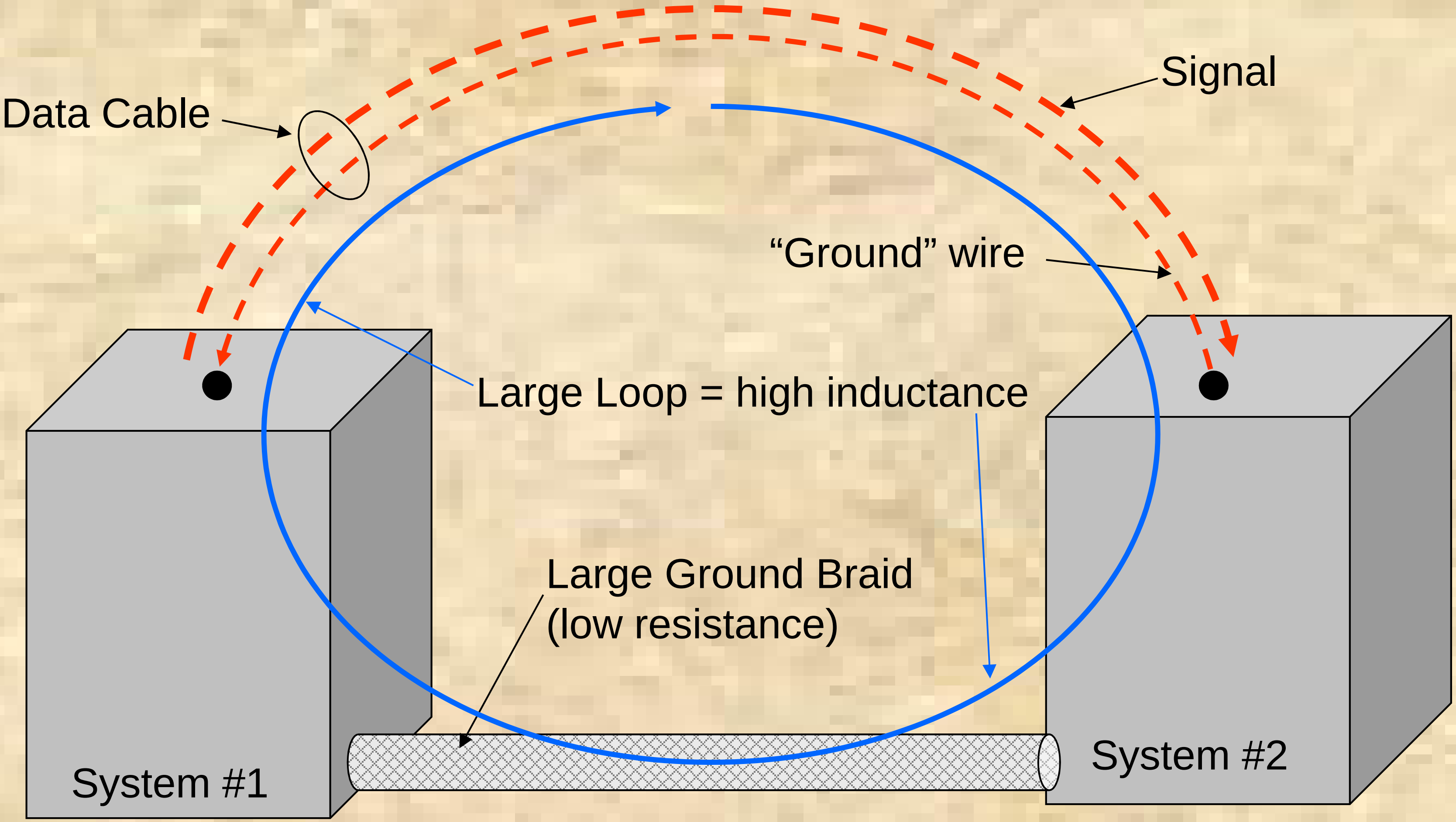
Low Frequency Return Current

Path of Least RESISTANCE



High Frequency Return Current

Path of Least Inductance

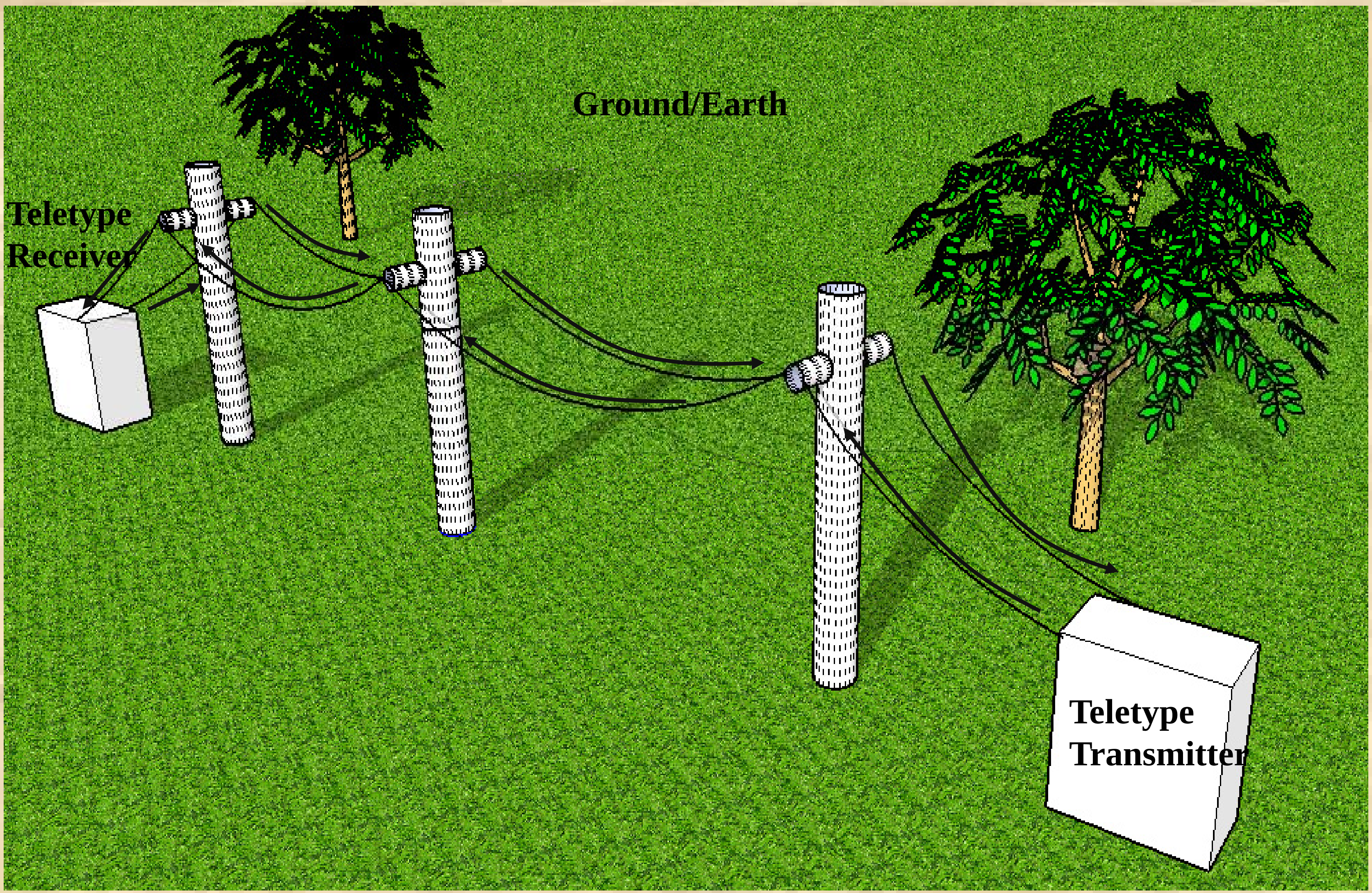


‘Grounding’ Needs Low Impedance at Highest Frequency

- Steel Reference Plate
  - 4 milliohms/sq @ 100KHz
  - 40 milliohms/sq @ 10 MHz
  - 400 milliohms/sq @ 1 GHz
- A typical via is about 2 nH
  - @ 100 MHz Z = 1.3 ohms
  - @ 500 MHz Z = 6.5 ohms
  - @ 1000 MHz Z = 13 ohms
  - @ 2000 MHz Z = 26 ohms

Where did the Term "GROUND" Originate?

- Original Teletype connections
- Lightning Protection


Ground/Earth
Teletype
Receiver
Teletype
Transmitter

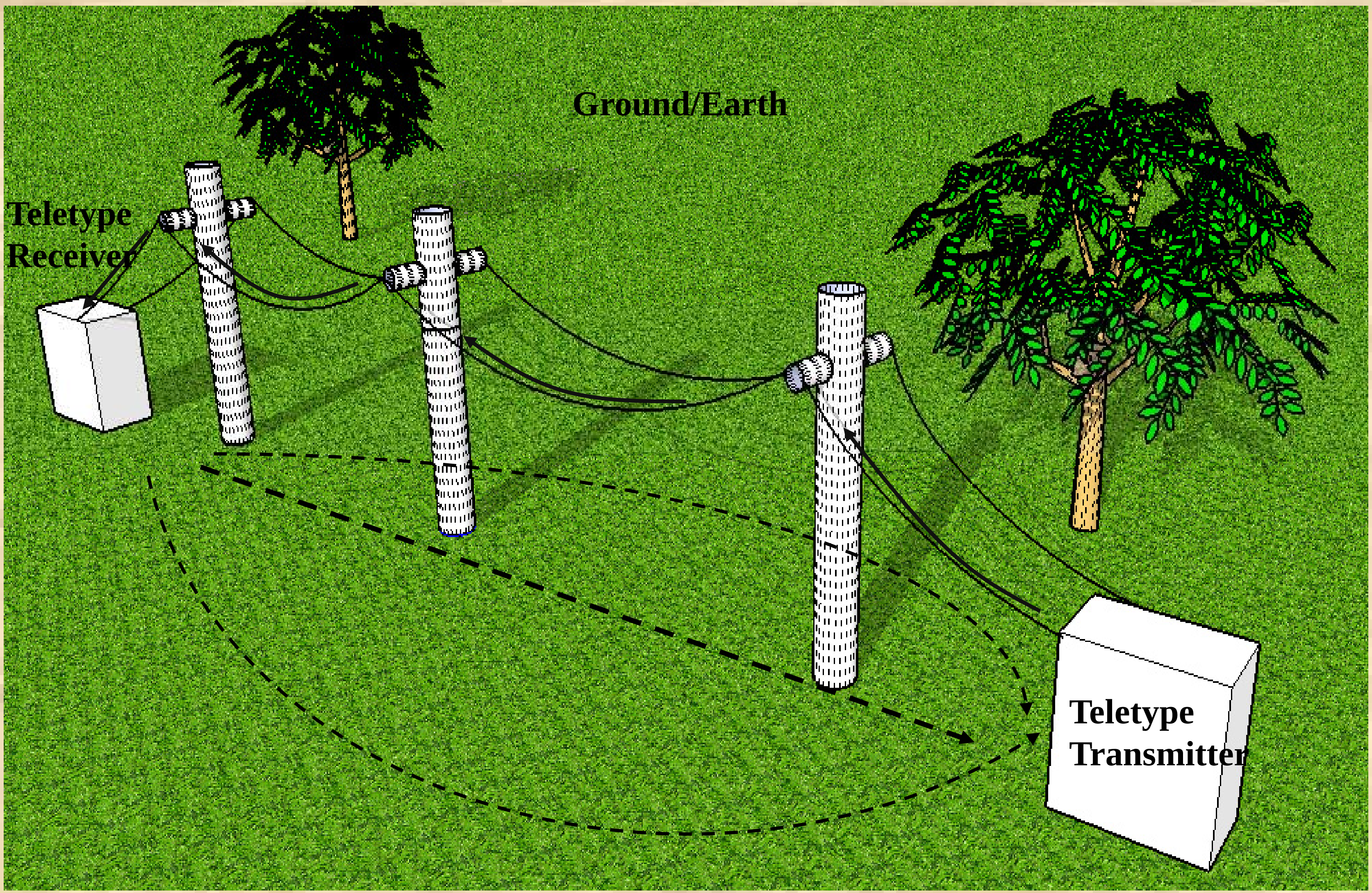

Ground/Earth
Teletype
Receiver
Teletype
Transmitter

FIG 7

Lightning striking house

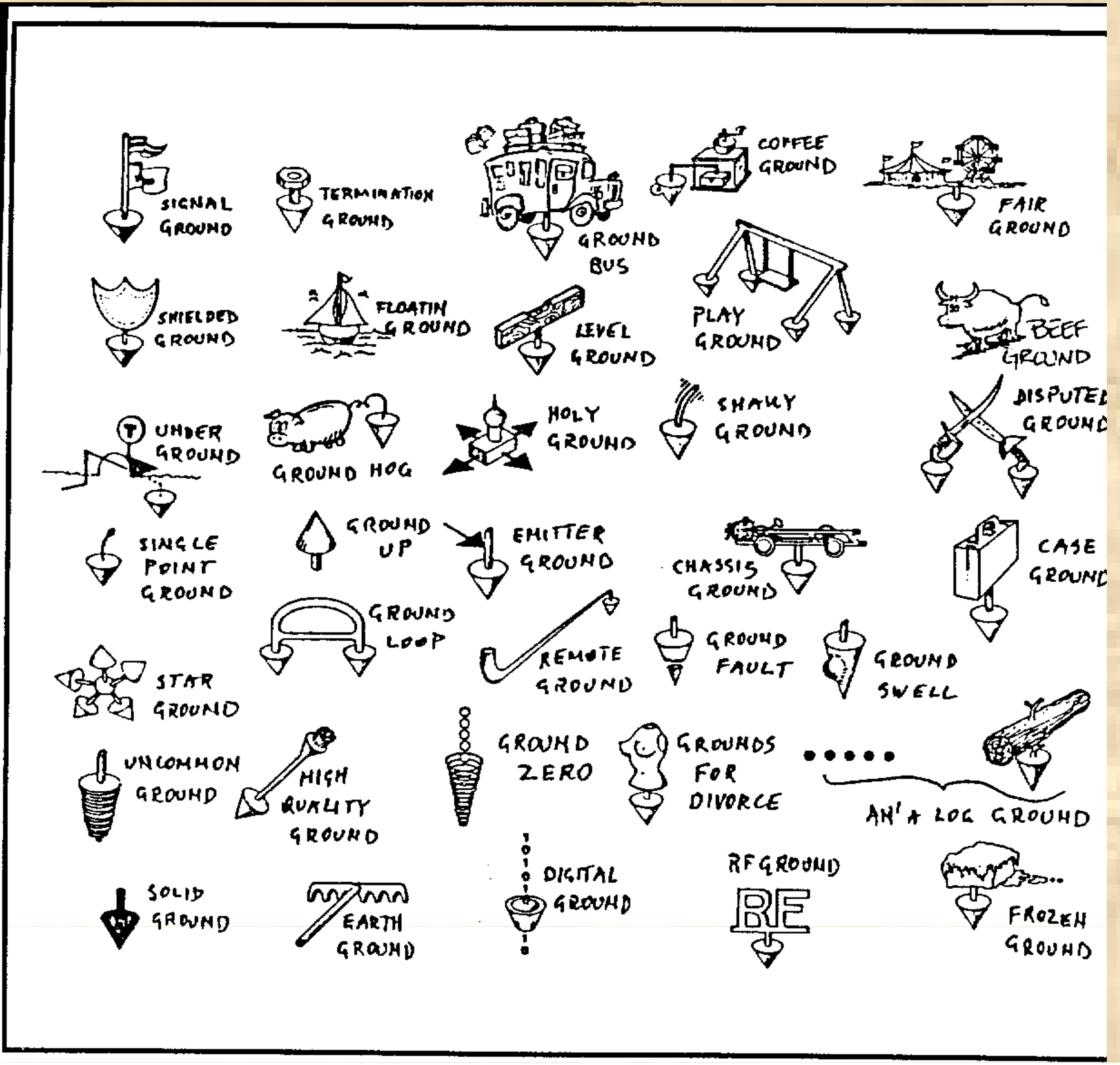
Lightning effect without rod

Lightning effect with rod

What we Really Mean when we say ‘Ground’

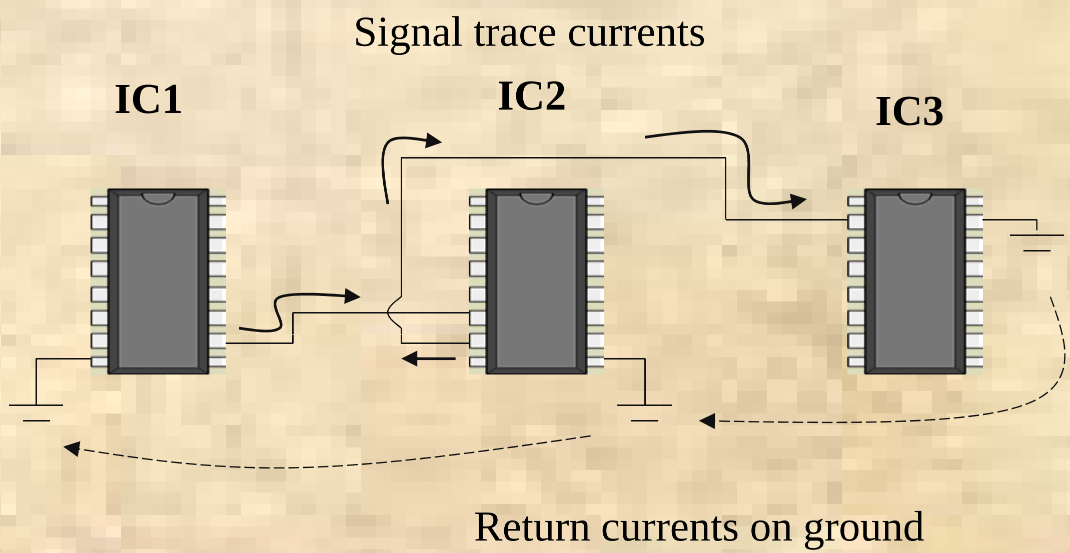
- Signal Reference
- Power Reference
- Safety Earth
- Chassis Shield Reference

Circuit “Ground” Chassis “Ground” Digital “Ground” Analog “Ground”

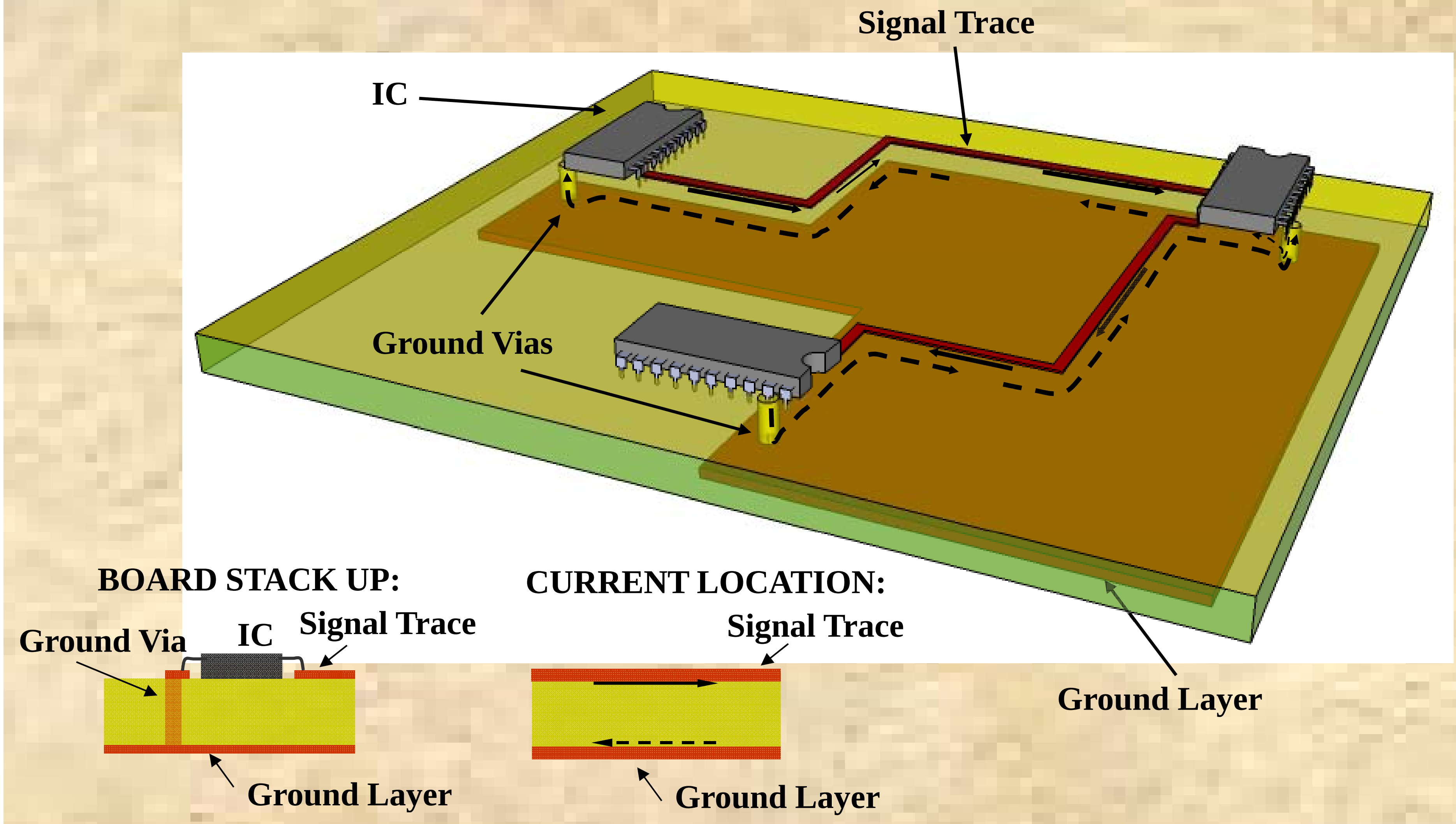


SIGNAL GROUND
TERMINATION GROUND
GROUND BUS
COFFEE GROUND
FAIR GROUND
SHIELDED GROUND
FLOATIN GROUND
LEVEL GROUND
PLAY GROUND
BEEF GROUND
UNDER GROUND
GROUND HOG
HOLY GROUND
SHAKY GROUND
DISPUTE
GROUN
SINGLE POINT GROUND
GROUND UP
EMITTER GROUND
CHASSIS GROUND
CASE
GROUN
GROUND LOOP
REMOTE GROUND
GROUND FAULT
GROUND SWELL
STAR GROUND
UNCOMMON GROUND
HIGH QUALITY GROUND
GROUND ZERO
GROUNDS FOR DIVORCE
AN' A LOG GROUND
SOLID GROUND
EARTH GROUND
DIGITAL GROUND
RF GROUND
RF
FROZEN GROUND

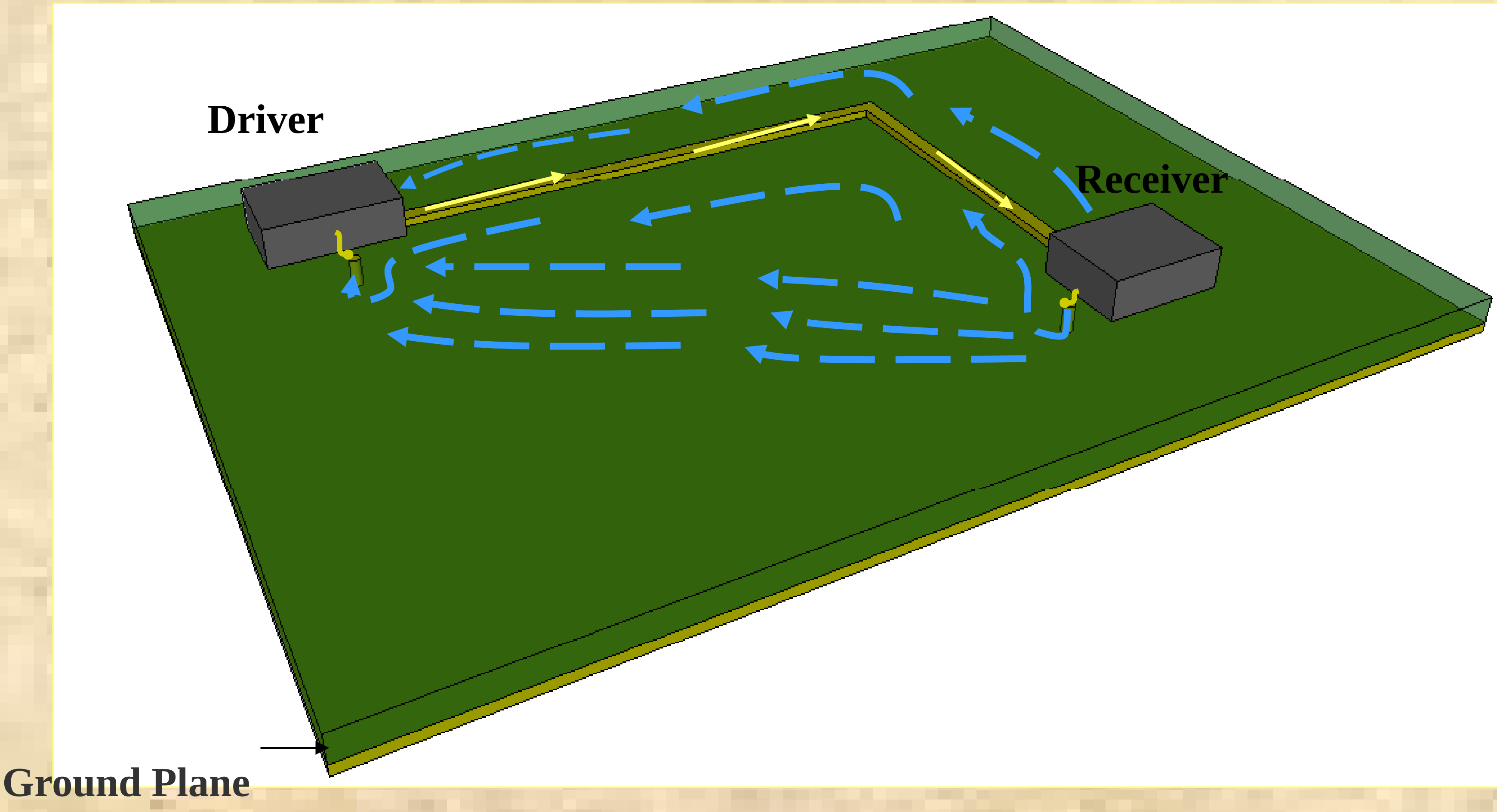
Schematic with return current shown



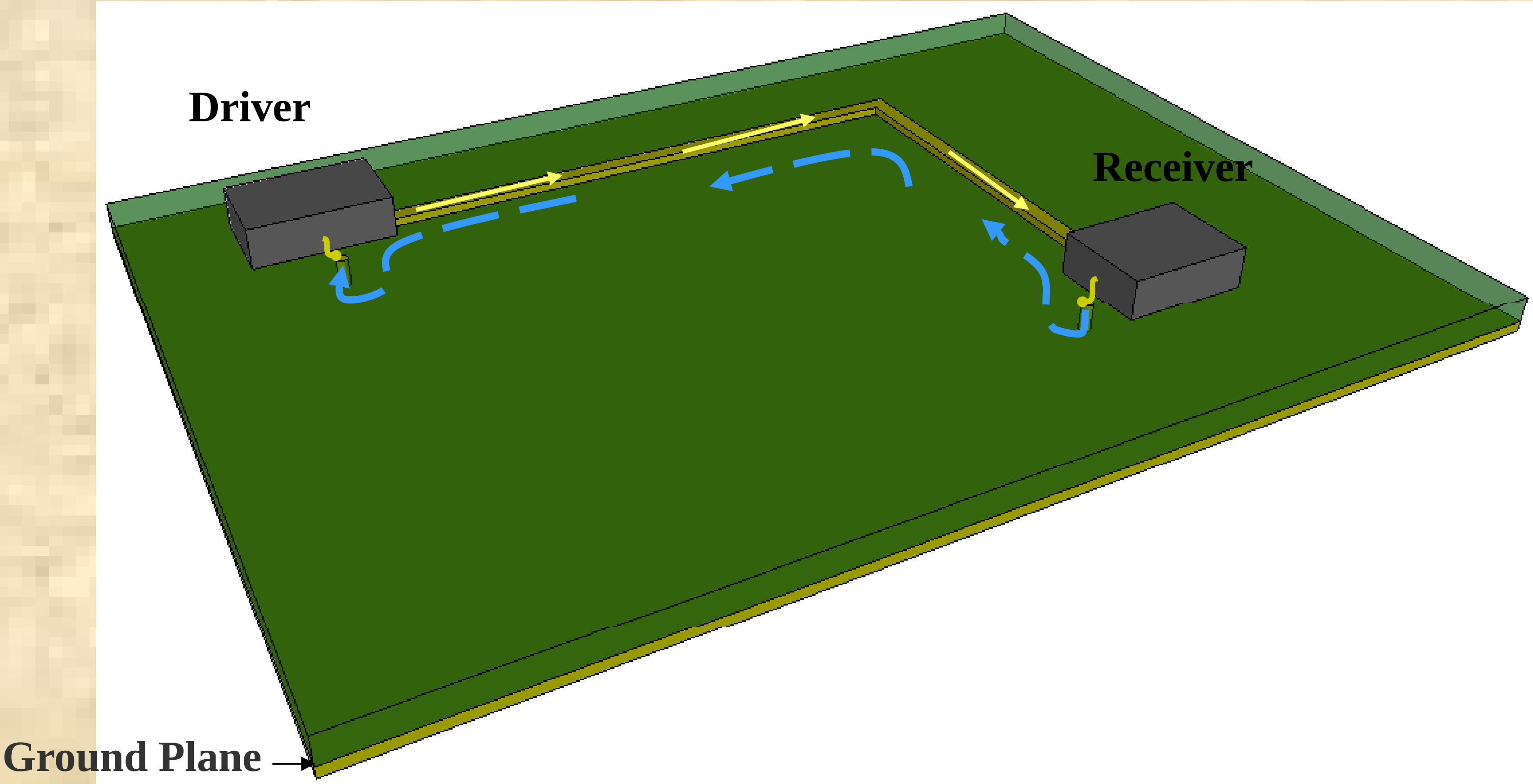
Actual Current Return is 3-Dimensional



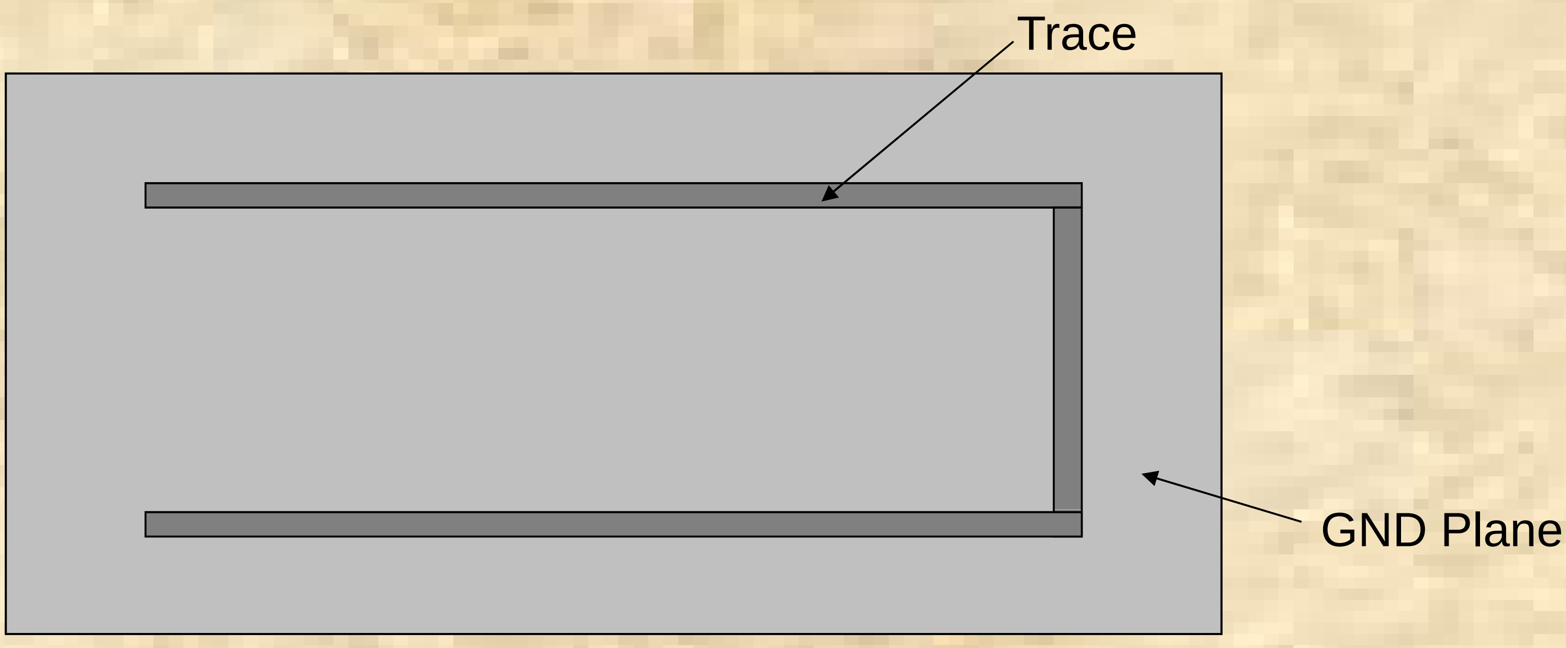
Low Frequency Return Currents Take Path of Least ***Resistance***



High Frequency Return Currents Take Path of Least ***Inductance***



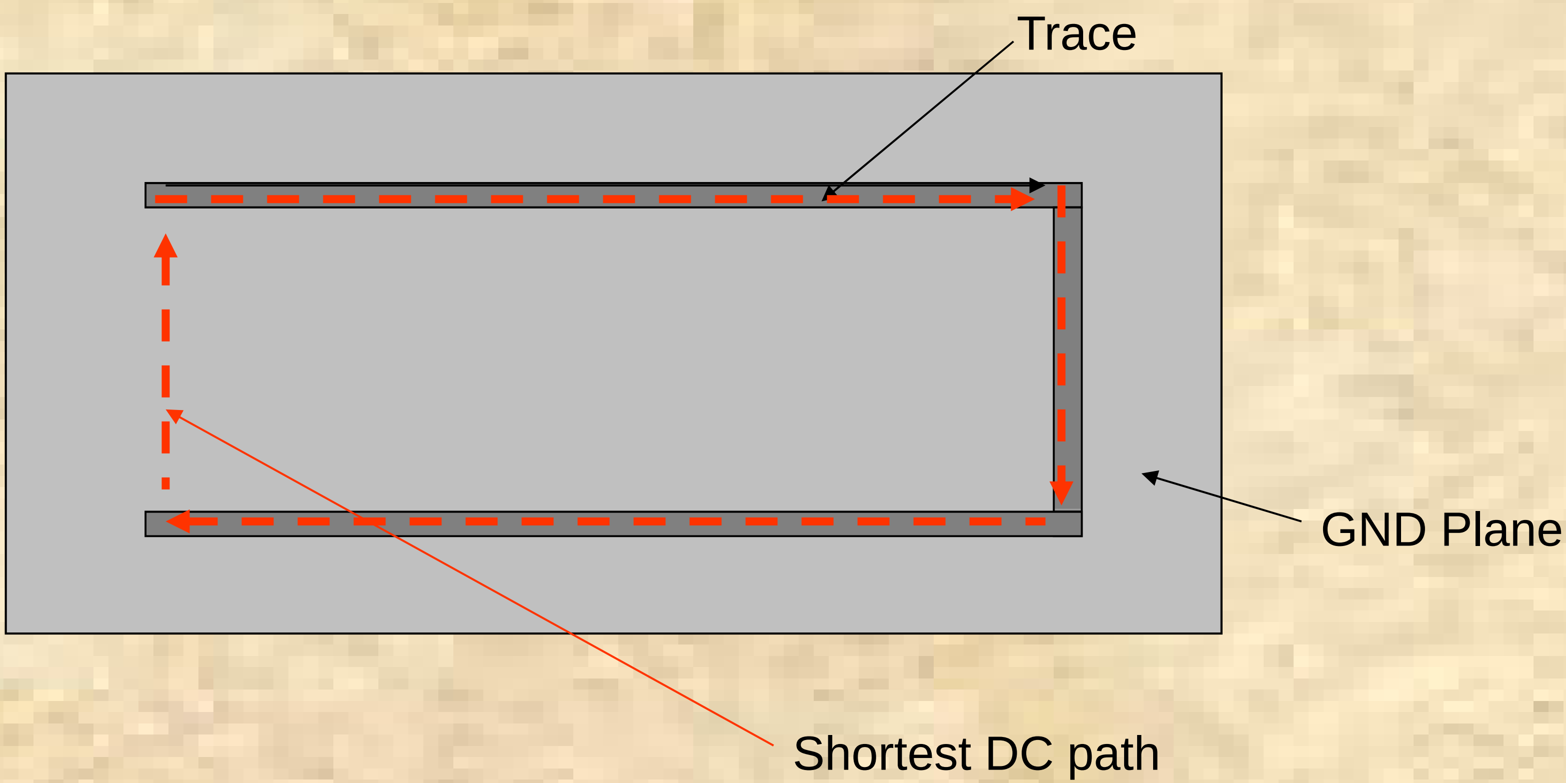
PCB Example for Return Current Impedance



22" trace

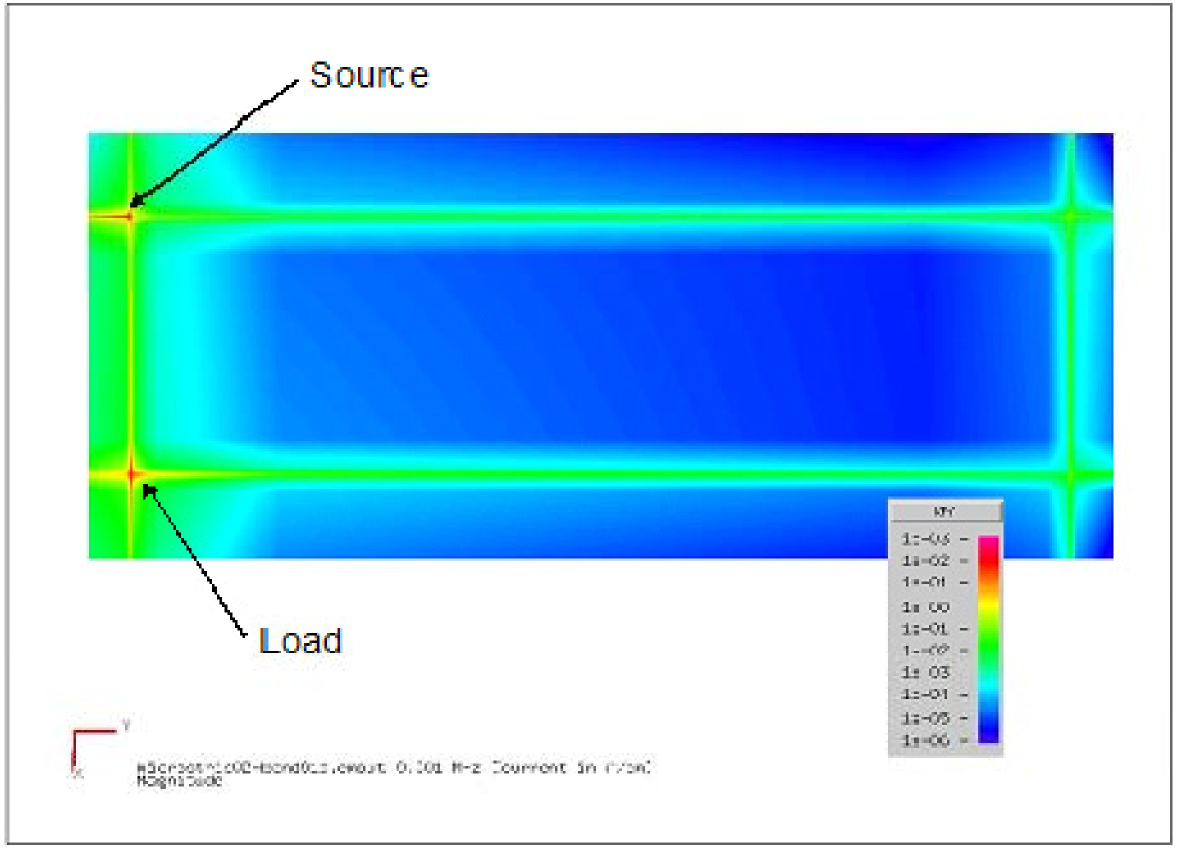
10 mils wide, 1 mil thick, 10 mils above GND plane

PCB Example for Return Current Impedance

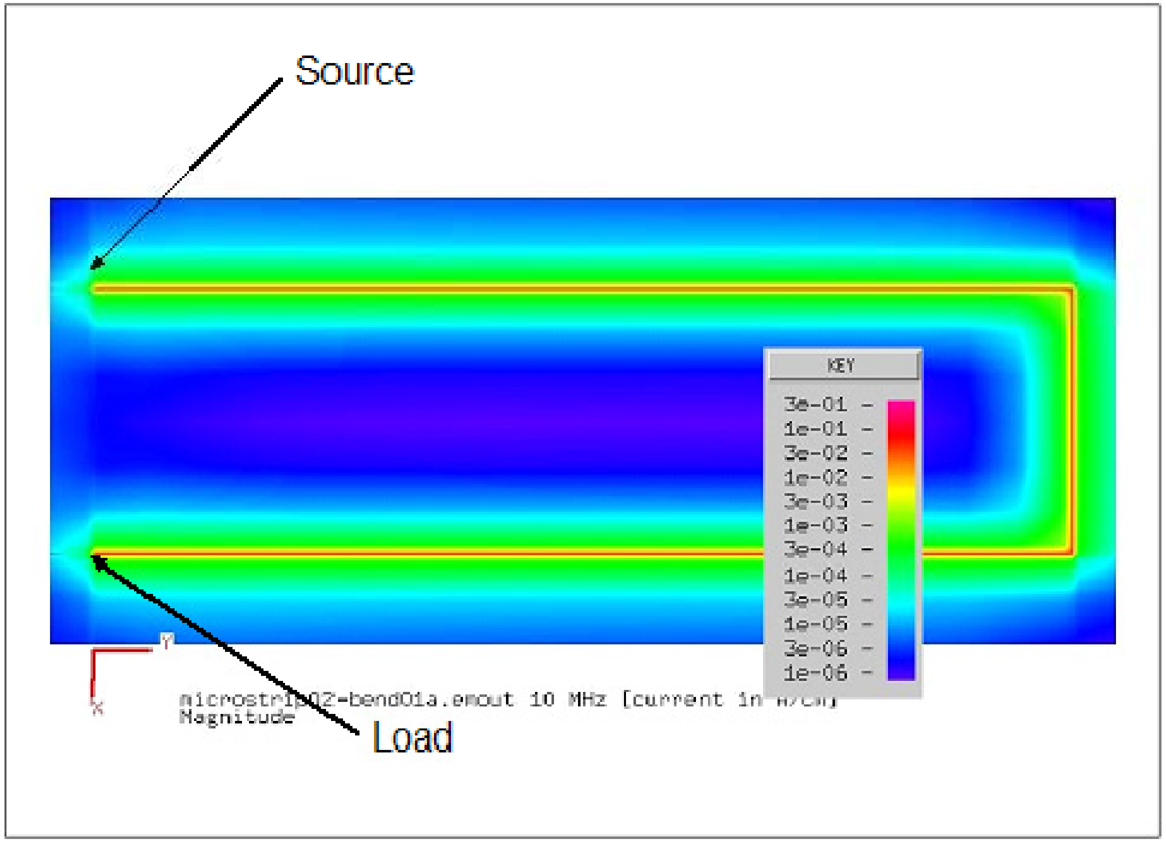


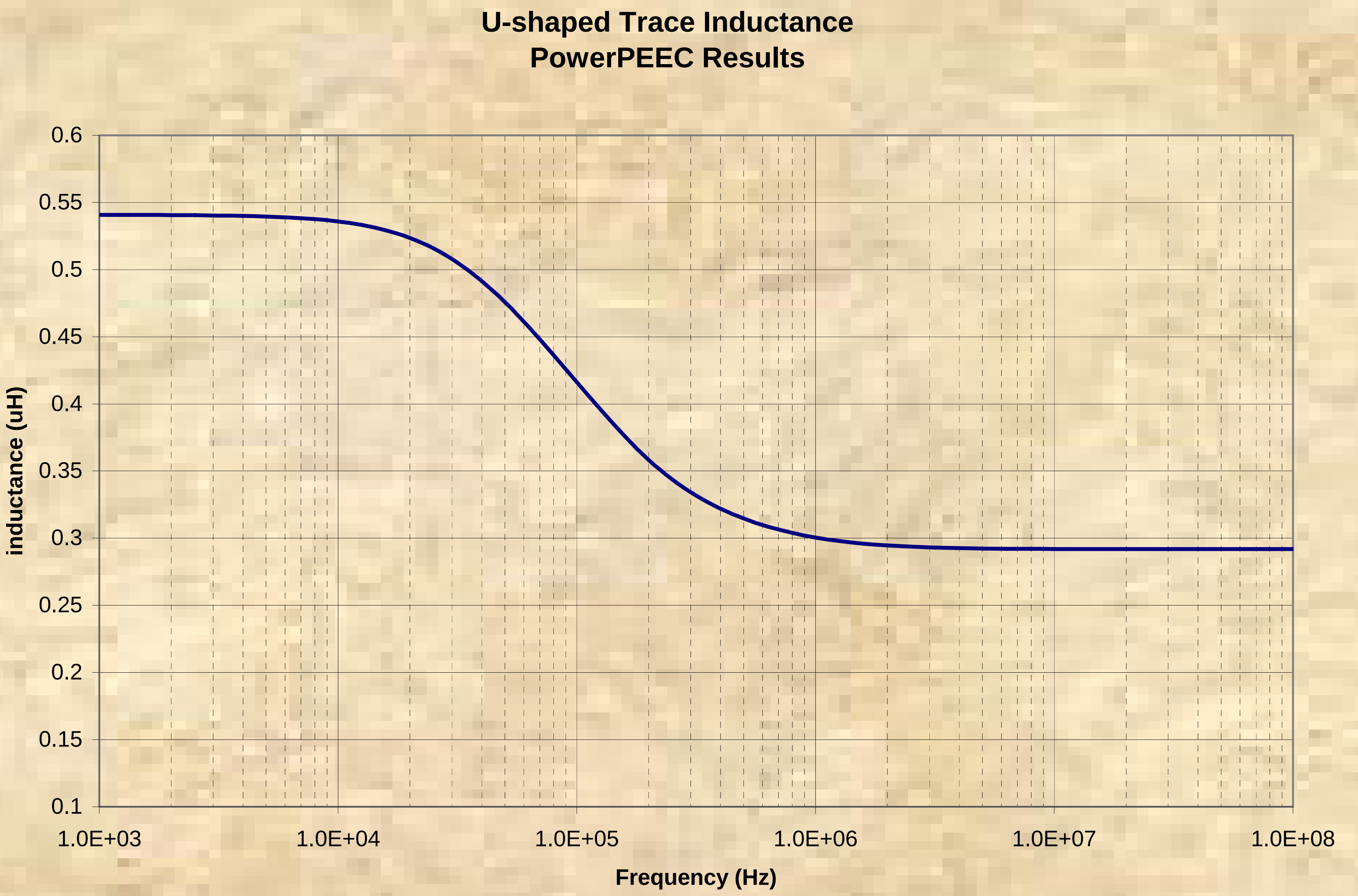
For longest DC path, current returns under trace

MoM Results for Current Density
Frequency = 1 KHz

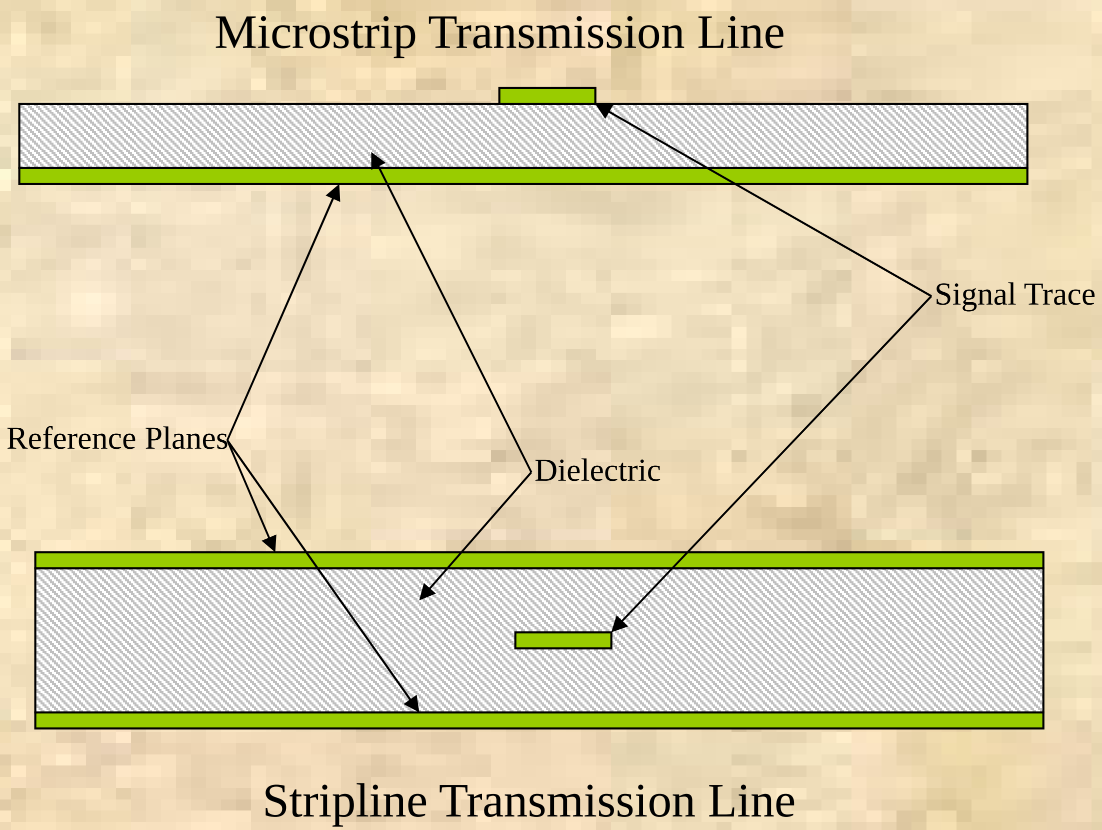


MoM Results for Current Density Frequency = 1 MHz

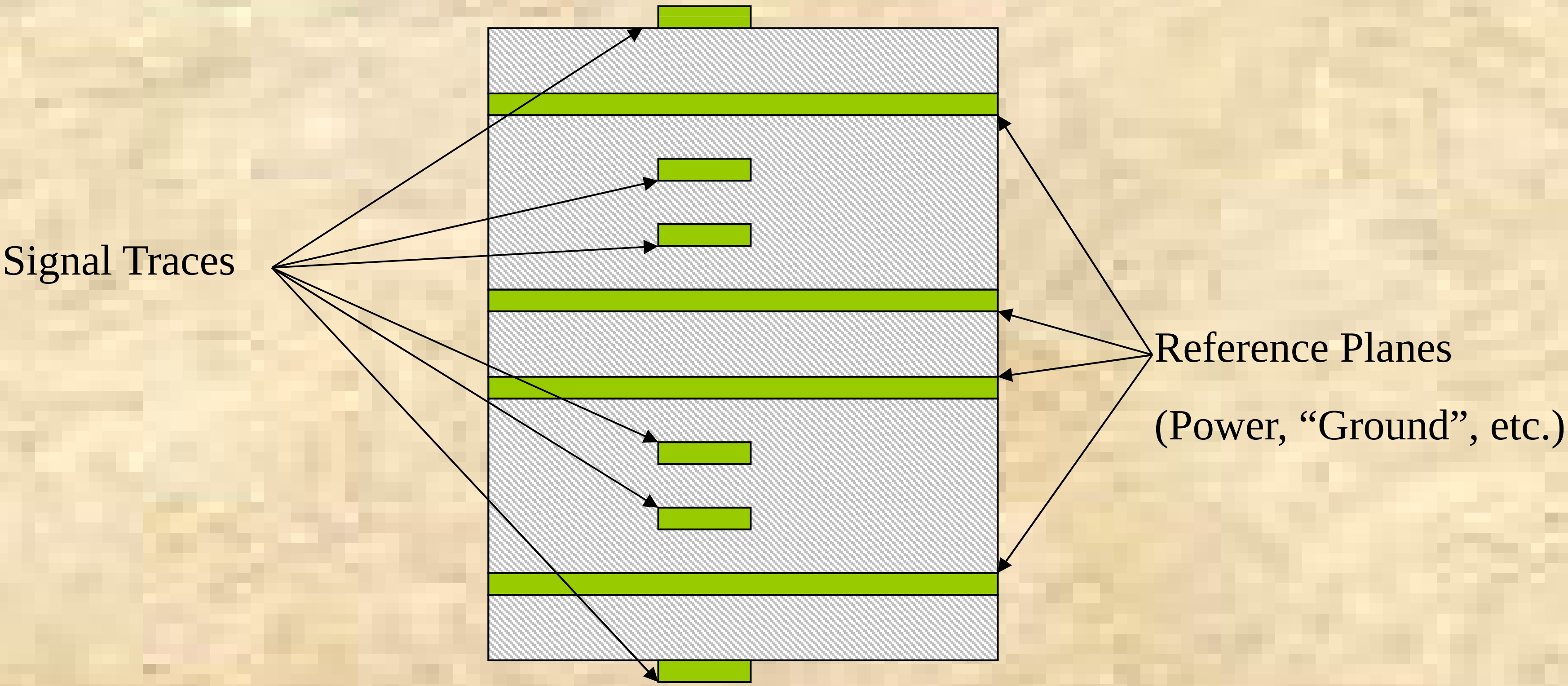



U-shaped Trace Inductance
PowerPEEC Results
inductance (uH)
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
1.0E+03
1.0E+04
1.0E+05
1.0E+06
1.0E+07
1.0E+08
Frequency (Hz)

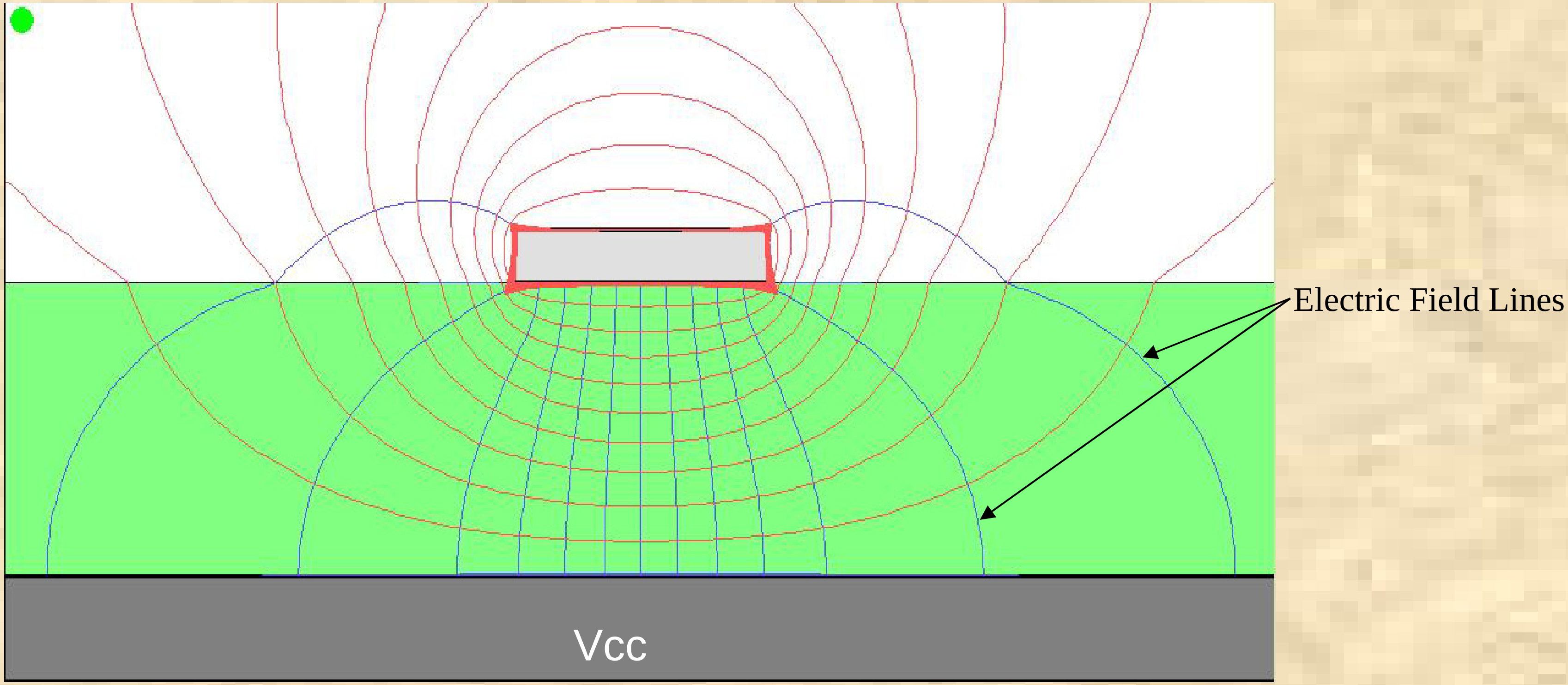
Traces/nets over a Reference Plane



Traces/nets and Reference Planes in Many Layer Board Stackup



Microstrip Electric/Magnetic Field Lines
(8mil wide trace, 8 mils above plane, 65 ohm)

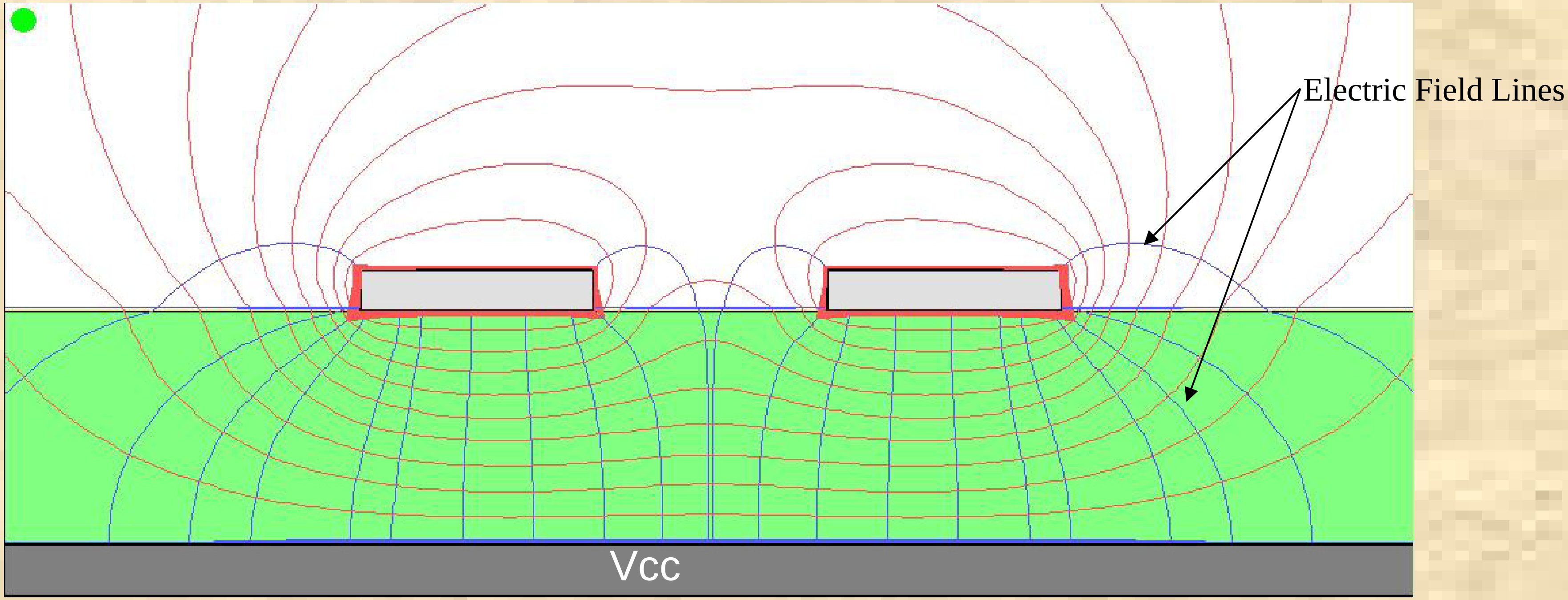


Courtesy of Hyperlynx

Microstrip Electric/Magnetic Field Lines

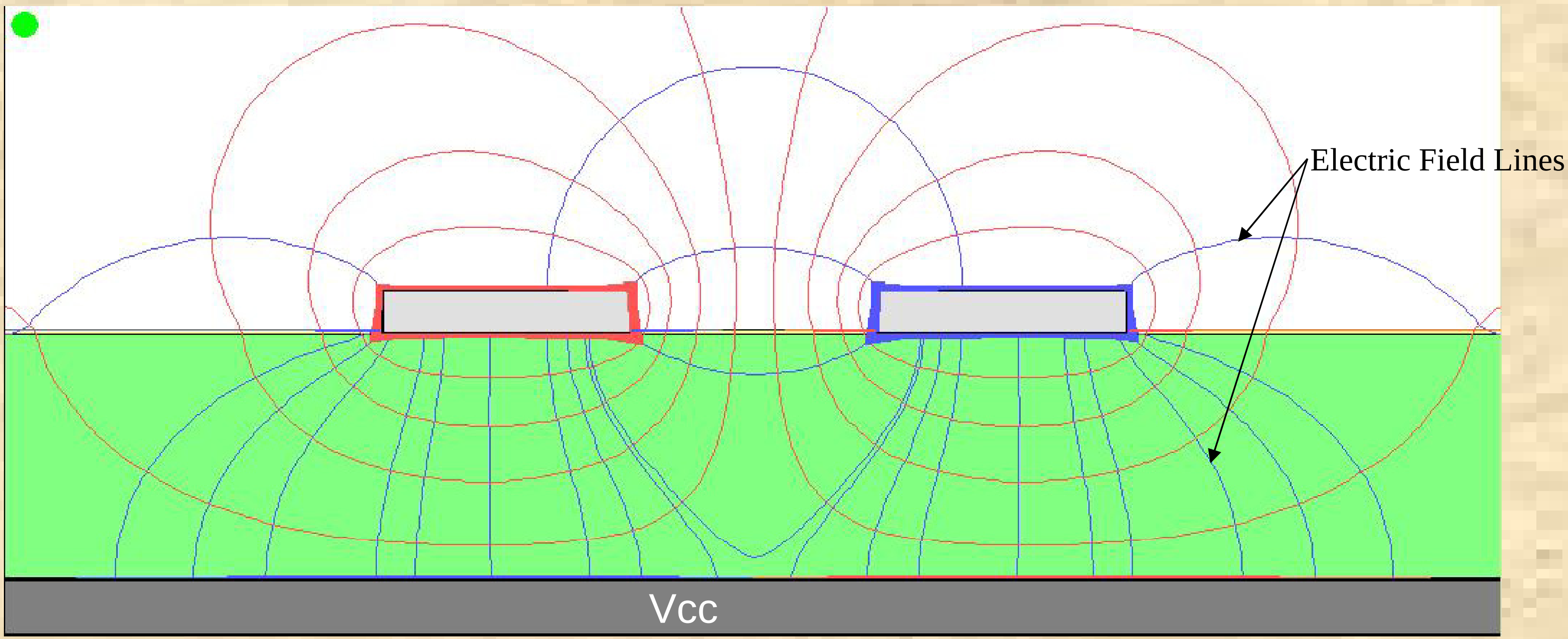
Common Mode

8 mil wide trace, 8 mils above plane, 65/115 ohm)



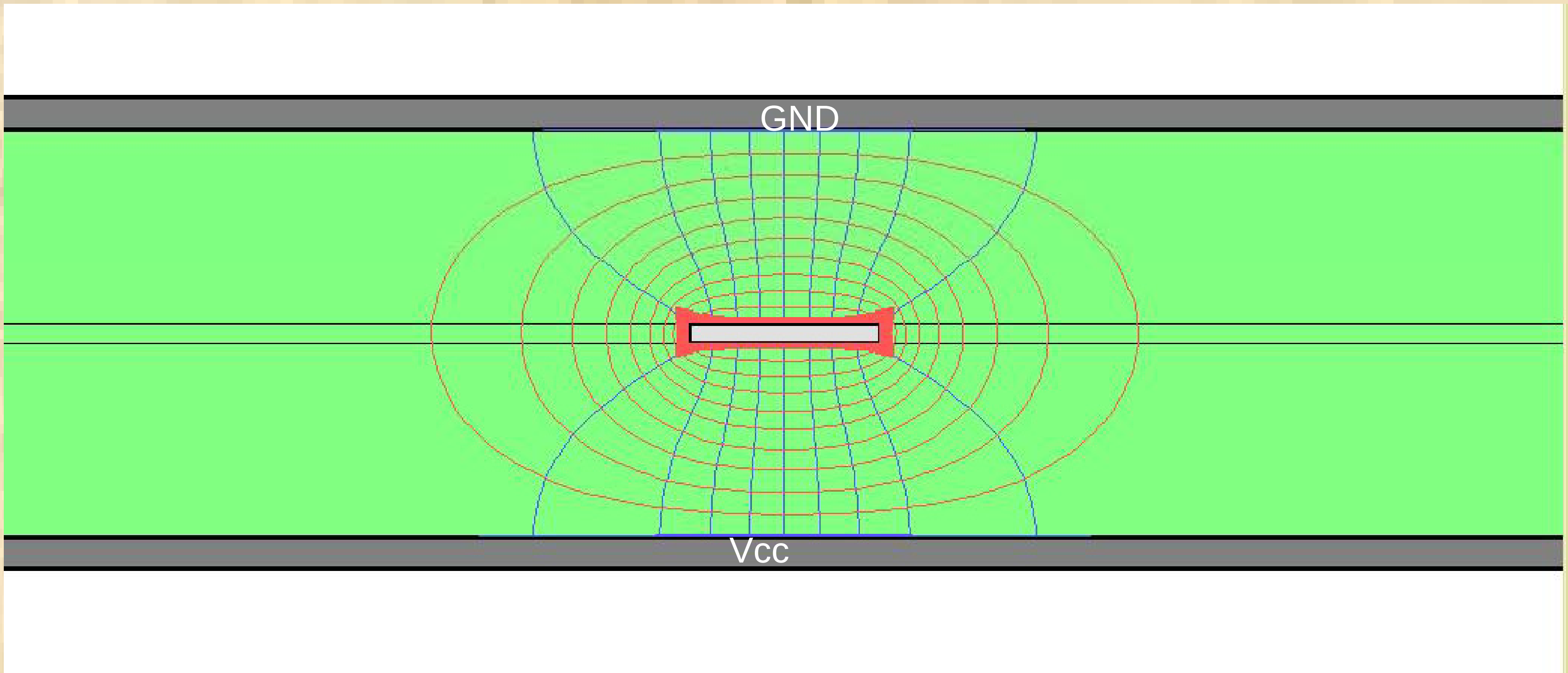
Courtesy of Hyperlynx

Microstrip Electric/Magnetic Field Lines
Differential Mode
8 mil wide trace, 8 mils above plane, 65/115 ohm)



Courtesy of Hyperlynx

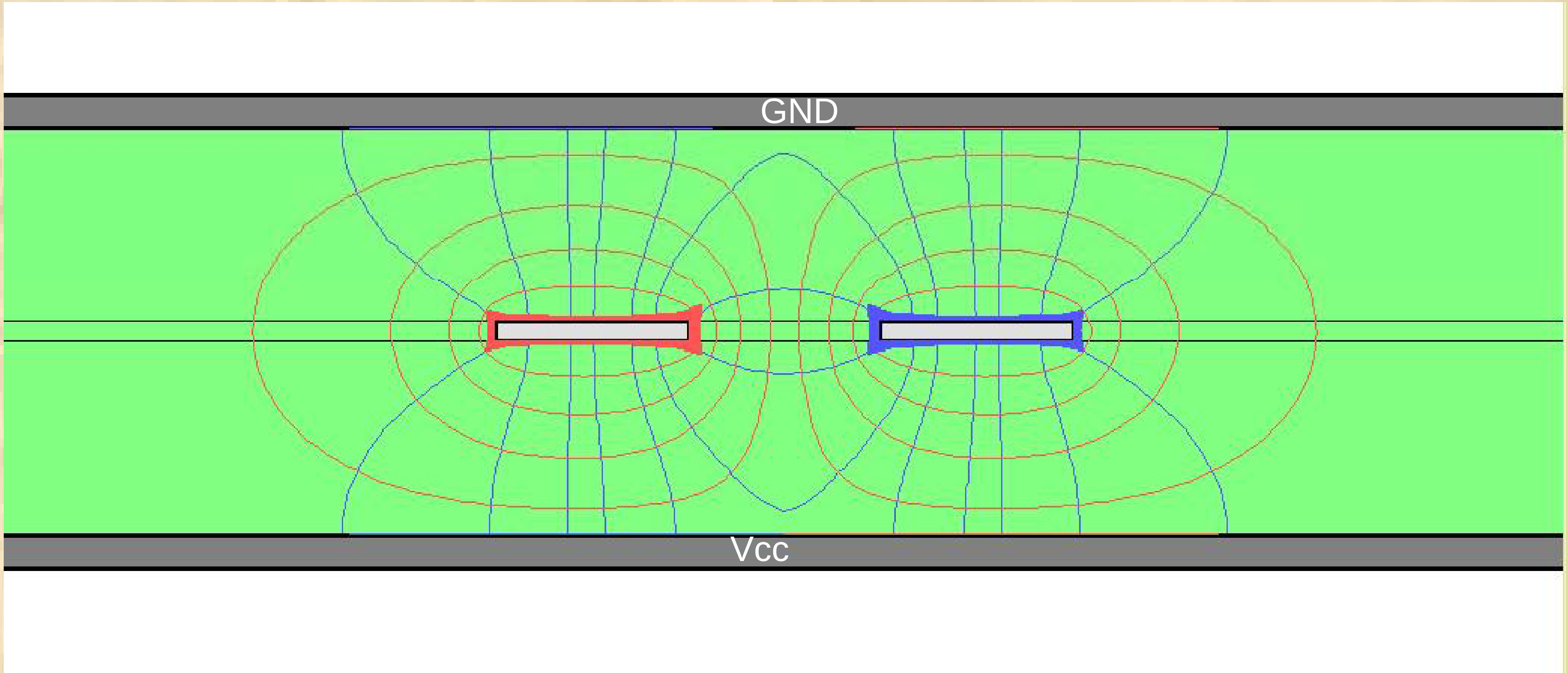
Electric/Magnetic Field Lines
Symmetrical Stripline



Courtesy of Hyperlynx

Electric/Magnetic Field Lines

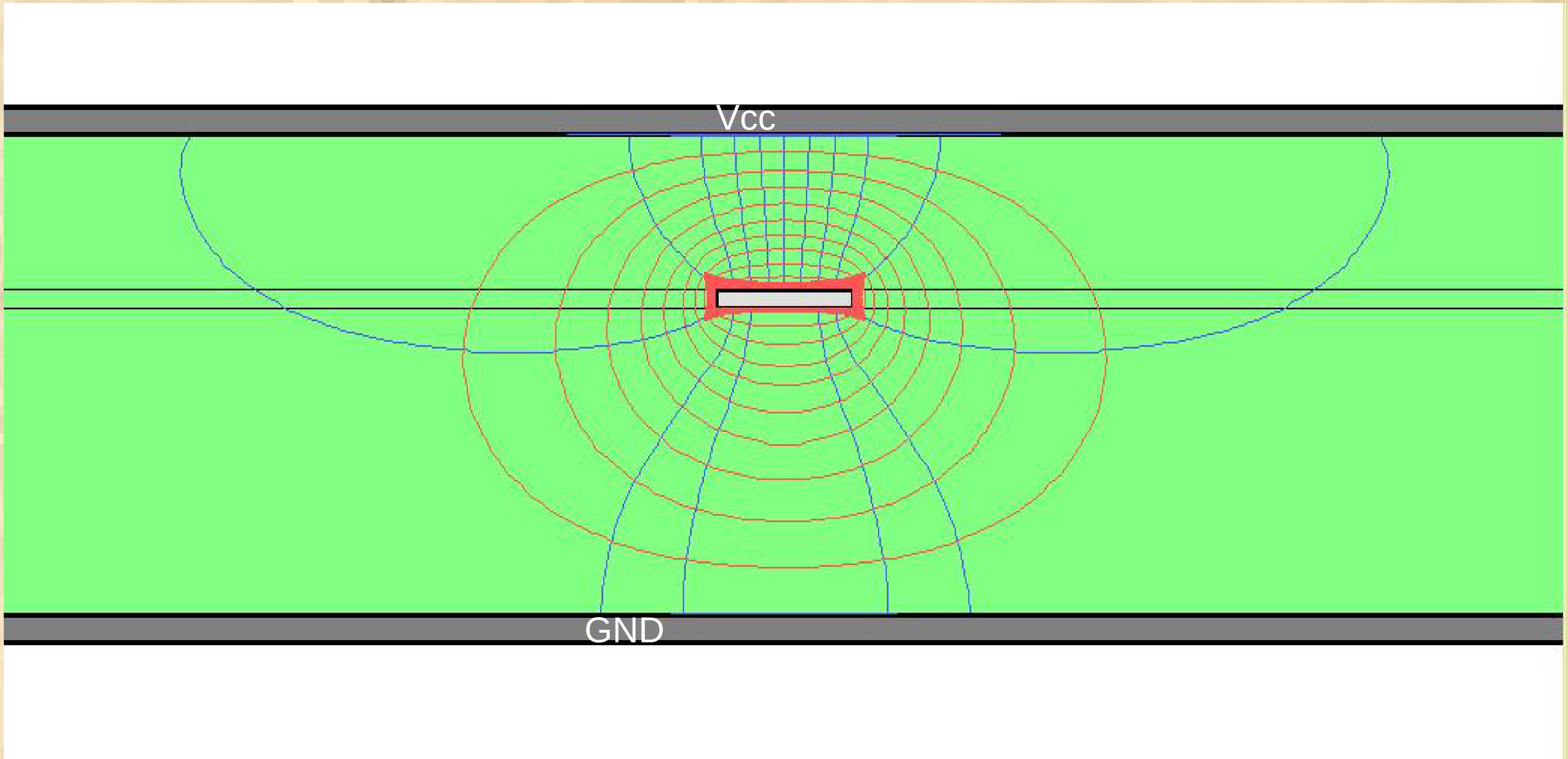
Symmetrical Stripline (Differential)



Courtesy of Hyperlynx

Electric/Magnetic Field Lines

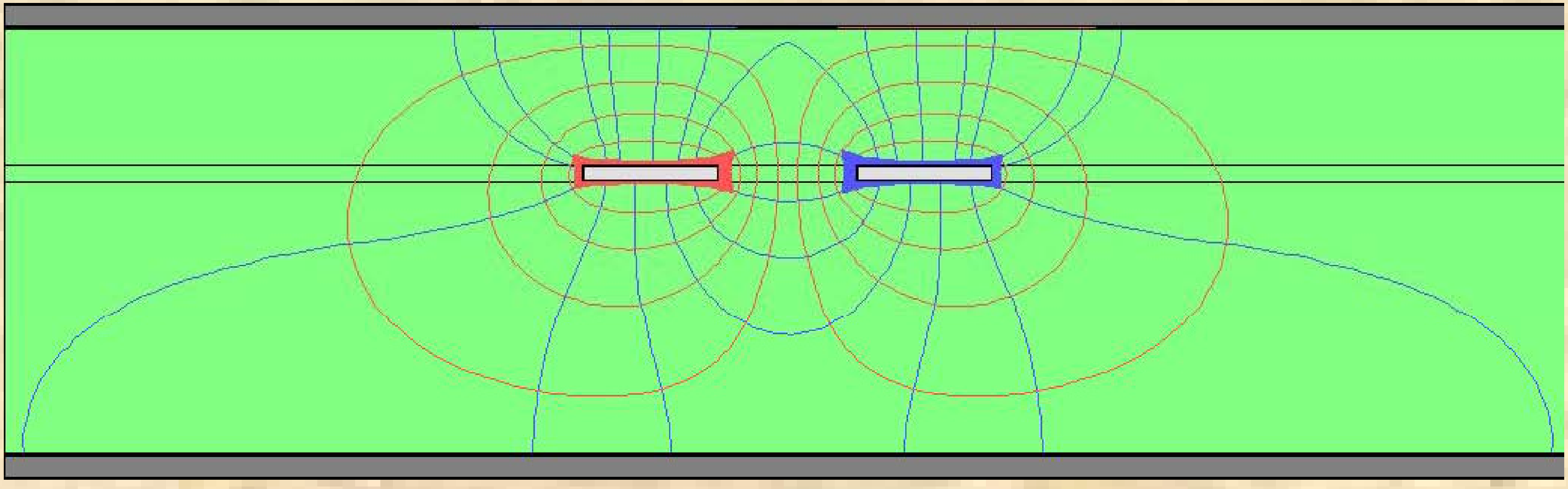
Asymmetrical Stripline



Courtesy of Hyperlynx

Electric/Magnetic Field Lines

Asymmetrical Stripline (Differential)



Courtesy of Hyperlynx

What About Pseudo-Differential Nets?

- So-called differential traces are NOT truly differential
  - Two complementary single-ended drivers
    - Relative to ‘ground’
  - Receiver is differential
    - Senses difference between two nets (independent of ‘ground’)
    - Provides good immunity to common mode noise
    - Good for signal quality/integrity

Pseudo-Differential Nets Current in Nearby Plane

- Balanced/Differential currents have matching current in nearby plane
  - No issue for discontinuities
- Any unbalanced (common mode) currents have return currents in nearby plane that must return to source!
  - All normal concerns for single-ended nets apply!

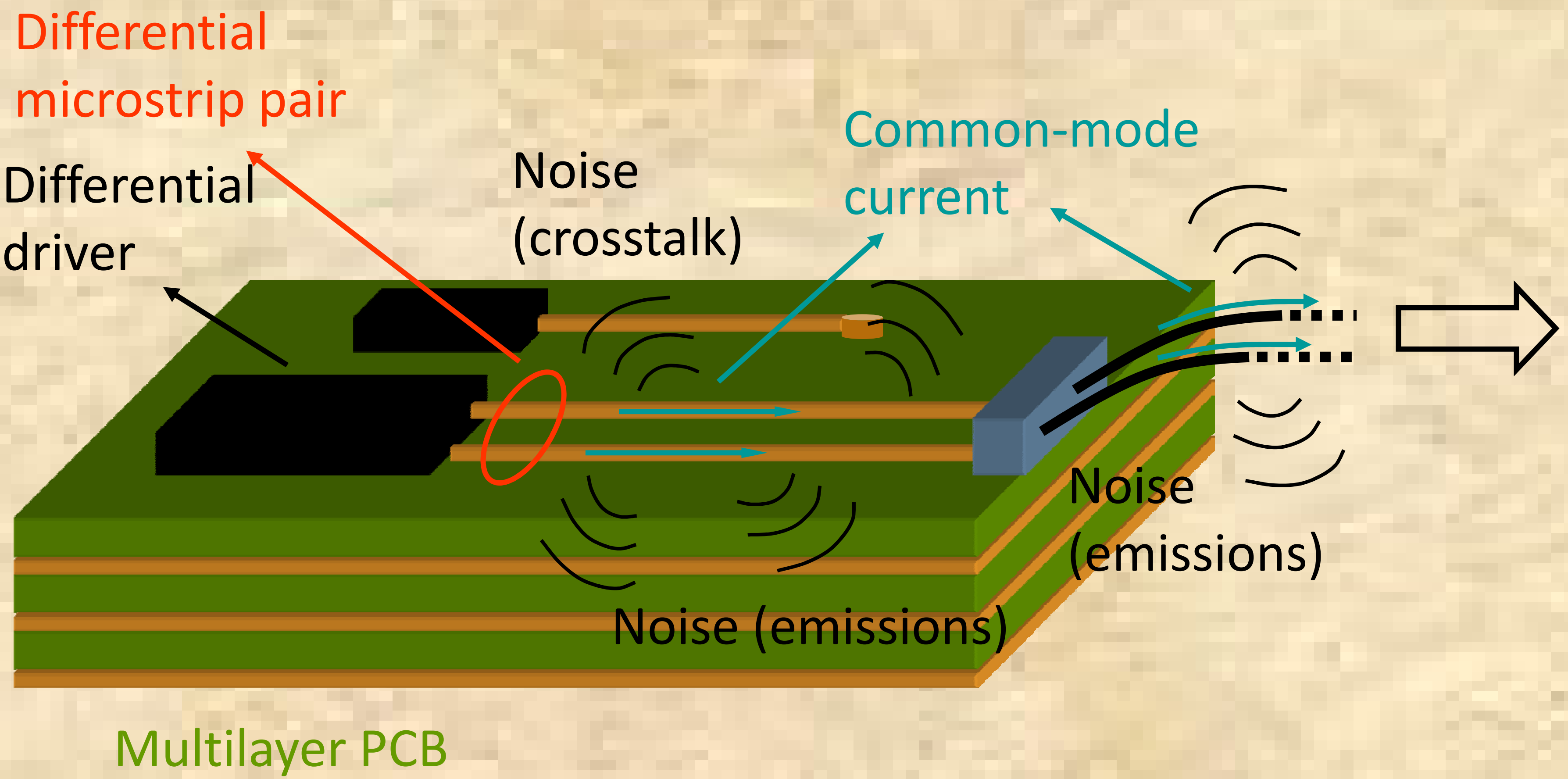
Pseudo-Differential Nets

- Not really ‘differential’, since more closely coupled to nearby plane than each other
- Slew and rise/fall variation cause common mode currents!

Why Control Common Mode Noise in Differential Pairs?

- Common Mode Noise is inevitable in differential pairs
  - Skew
  - Rise/fall time mismatch
  - Asymmetry in channel
- Common mode noise is a big problem in EMC!
- Common mode noise can increase differential crosstalk

Common-Mode Noise on PCB



Ground Myth Summary

- **THERE IS NO SUCH THING AS *"GROUND"***
- Define which *reference* type is needed
- Plan the return current path
  - Avoid split reference planes & changing reference planes

Radiated Emissions/Immunity:
EMC Test Standards
EMI Antenna Analysis/Design
(Intentional/Unintentional)

Johannes Nordgård

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University of Colorado

Air Force Academy

Colorado Springs

Air Force Research Laboratory

KAFB/GAFB

NASA/JSC

Houston

IEEE Standard Definitions 145-1983

- **Antenna**
  - **Current Carrying Device (usually metallic conductor ~ free electrons)**
  - **For Transmitting/Receiving EM Waves**
    - **Transducer [Converts Current(Internal) to Waves(External), visa-versa]**
- **<u>Changing</u> Current (Ex: Pulse(Transient) / AC(SS)]**
  - **Accelerating/Decelerating Electrons Radiate?**
    - **Intentional Radiation (Radio/TV/Cell/GPS/Radar/Etc)**
      - **Aerials**
        - **Wire (1D/2D/3D) ~ Grid**
        - **(Linear) Dipole/Monopole (Electric) ~ *Herttzian Dipole***
        - **(Circular) Loop (Magnetic)**
      - **Apertures (Dual)**
        - **Slot**
        - **Horn**
        - **Dish (NASA Deep Space Network)**
      - **Arrays**
    - **Unintentional Radiation (EMI Problems)**
      - **Everything (Electronic) Caries Current**
      - **Everything (Electronic) Radiates**
      - **Everything (Electronic) is an Antenna**
        - **"Radiation Rule" [Shield(Cage)/Cancel/Pairs-Clooe)] ~SNR**

Outline

- I: Introduction
  - NASA (S/C Problems ~ Radiation/Antenna Examples)
- EMI/EMC Problem/Solution
- Compliance Checks ~ Limits
  - II: Test Techniques (MIL-STD) ~$$$
    - Radiation/Conduction (Wireless/Wired) ~(2)
    - Emissions/Immunity (Susceptibility/Vulnerability) ~(2) 1wk/mode
  - III: Analysis/Design ~20 dB Penalty! (Error Margin)
    - Radiation ~ TX/RX Antennas (Intentional/Unintentional)
    - THE Unique “Radiation Integrals” ~ Greens Function(Weight/Sum)
      - Analytical (Exact/Asymptotic) Antenna Answer (Solution: >100y Old)
      - Numerical (CEM) M&S ~ Canonical(V&V) / Hi-Fi Models
        - MoM (Source Method: Based on Solution to ME) OATS
        - FDM/FEM/TLM/etc (Field Method: Based on ME +BC) A/C

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    - **Radiation ~ TX/RX Antennas (Intentional/<u>Unintentional</u>)**
    - **THE Unique "Radiation Integrals" ~ Greens Function(Weight/Sum)**
      - **Analytical (Exact/Asymptotic) Antenna Answer (Solution: >100y Old)**
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        - **MoM (Source: Based on Solution to ME)** **OATS**
        - **FDM/FEM/TLM/etc (Field: Based on ME +BC)** **A/C**

I: Introduction

- **NASA Examples**
  - **Test Missions**
  - **Test Sites**
  - **Test Articles**
  - **Test Types**
- **Design/Redesign (SS Retired ~ "Orion" Planned)**
  - **Emerging Technologies**

I: Intro ~ Test Missions

- **NASA**
  - **JPL ~ (Pasadena, CA)** **Unmanned Missions**
  - **JSC ~ (Houston, TX)** **Manned Missions**
  - **KSC ~ (Cape Canaveral, FL)** **Launch Site (SS)**

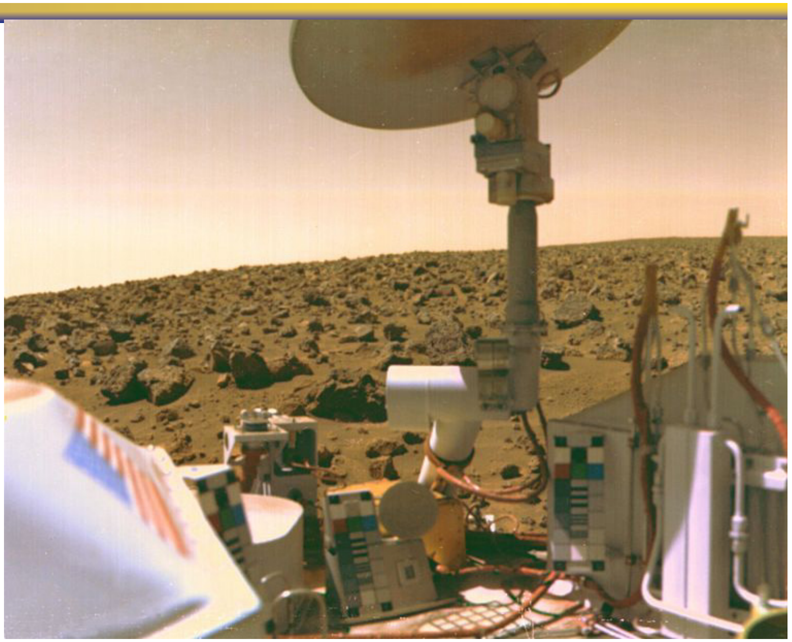
  - **MSFC ~ Test Support (Huntsville, AL)**
  - **GSFC ~ Test Support (Cleveland, OH)**

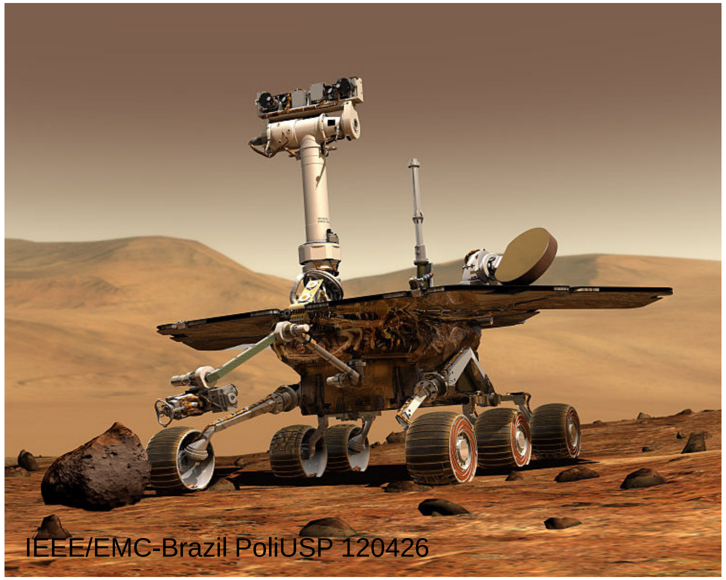
I: Intro ~ Test Sites

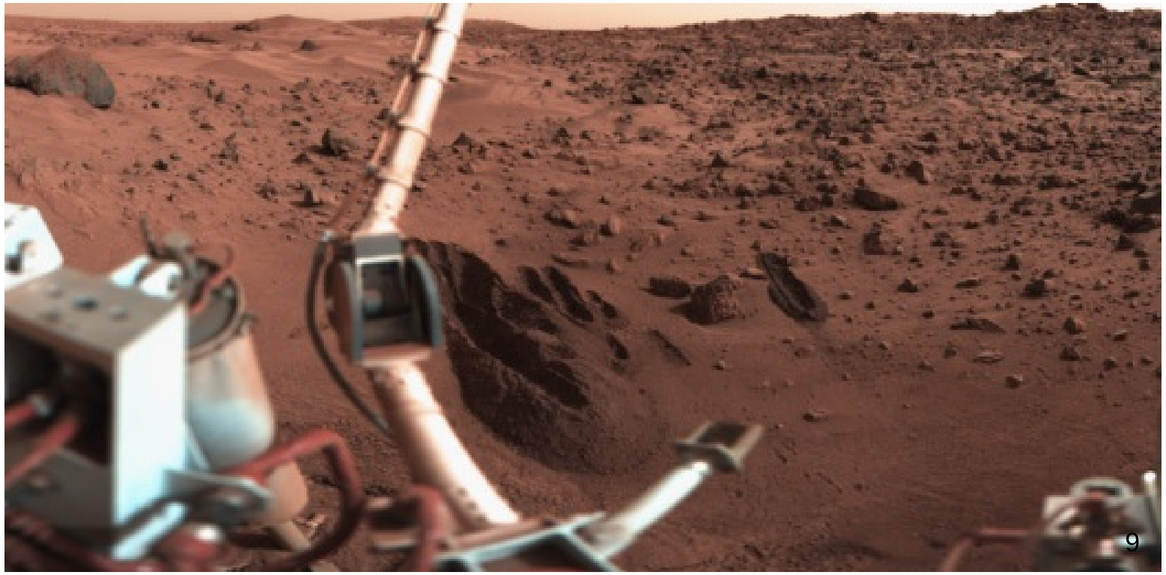
- **NASA**
  - **KSC (Assembly/Check-Out/Launch ONLY)**
  - **JSC~ISS(SS)**
  - **JSC/SPF(GSFC)~Orion (Emerging Technology/Testing)**
  - **JPL~Probes**
- **AF**
  - **EAFB~C130/C17 (Drop Tests)**
- **Army**
  - **YPG/CPAS (Parachute Assembly)**
  - **WSMR/LAS (Launch Abort)**
- **Navy**
  - **Retrieval**

I: Intro ~ Unmanned

- **NASA/JPL ~ Unmanned Missions**
  - **Planetary Probes**
    - **Fly-Bys (Inner/Outer Planets)**
    - **Landers (Mars)**
    - **Rovers (Mars)**
  - **EMI (Internal)**

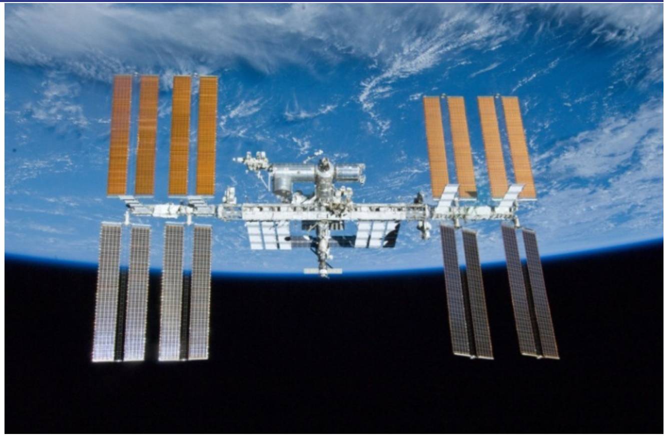




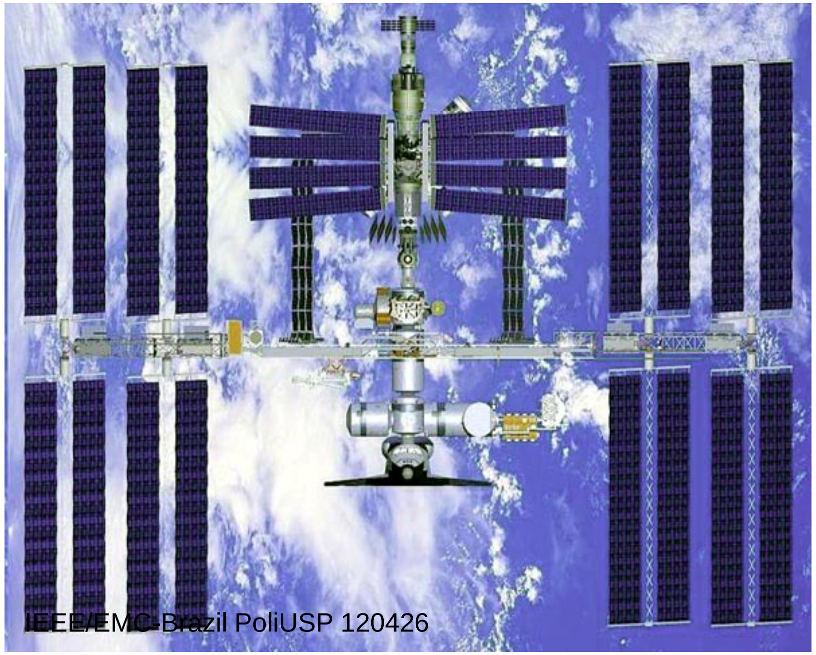


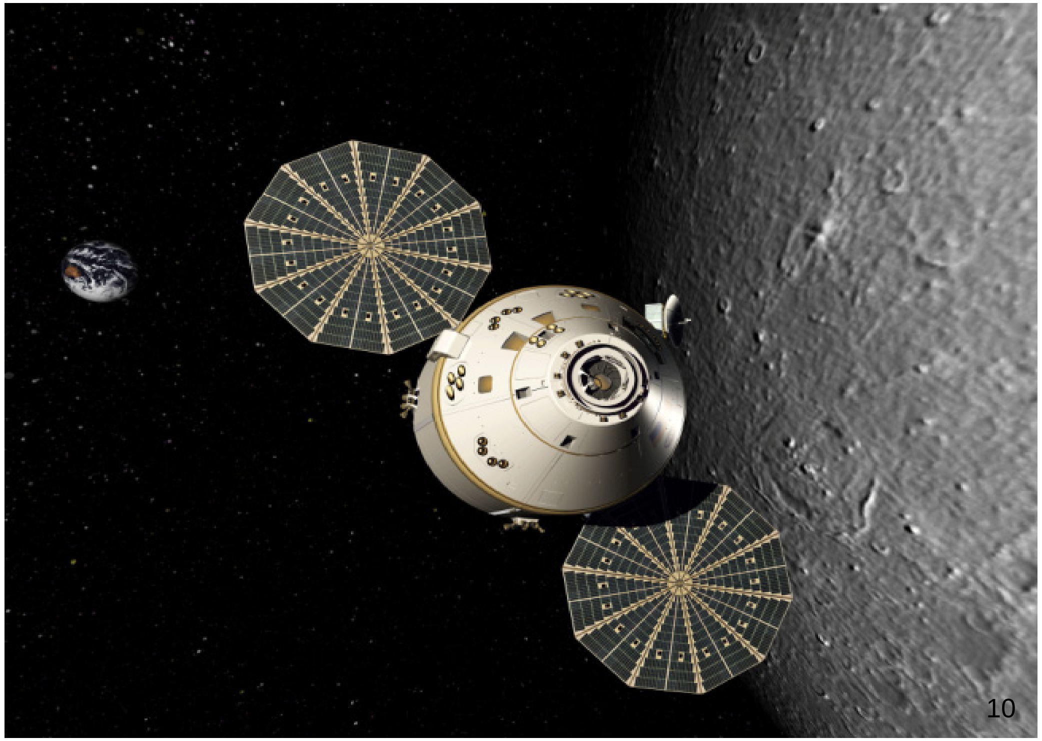
I: Intro ~ Manned

- **NASA/JSC ~ Manned Missions**



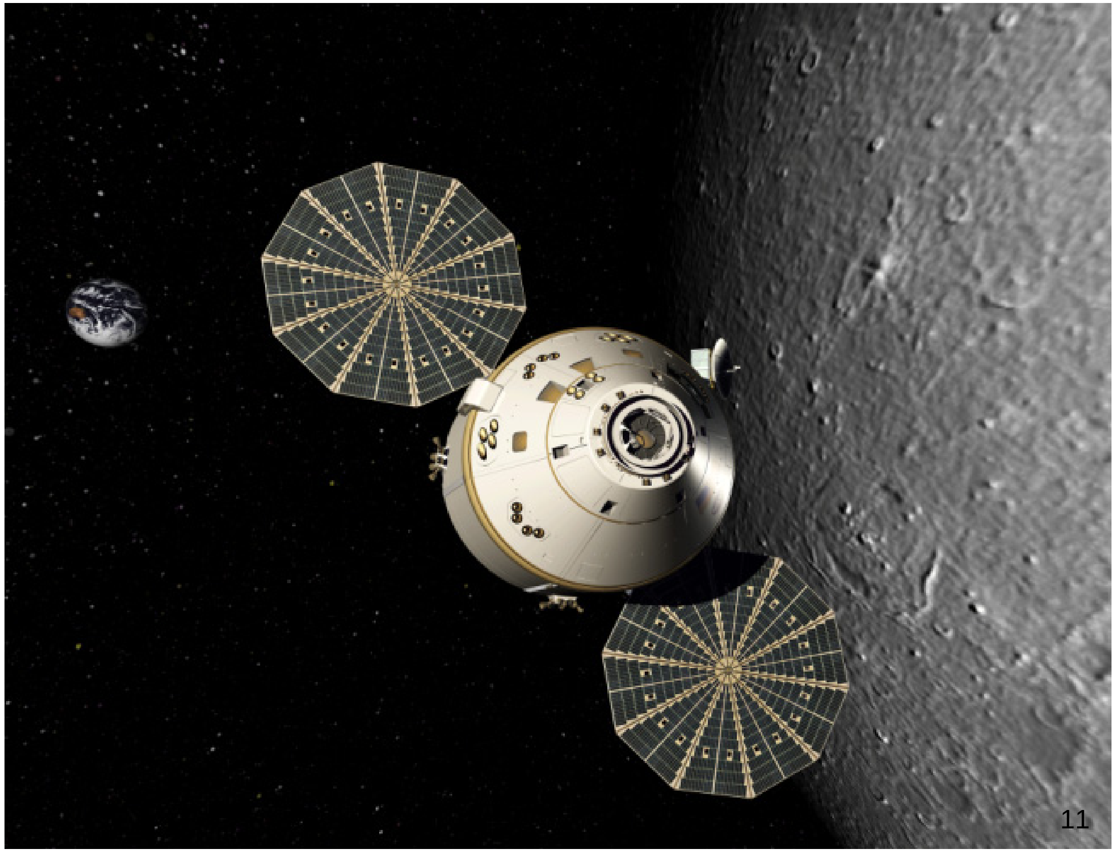
  - **Short Haul: Earth2LEO (ISS) (200-300km)**
  - **Long Haul: ---> Moon/Mars(Asteroids)**
    - **STS/SS~Discontinued**
      - **Cost/Safety/Utility/Maintenance**
    - **STS/Orion Capsule (~Apollo ~Parachute Landing)**
  - **EMI (Internal/External)**





I: Intro ~ Emerging Technologies

- **Design/Redesign (Emerging Technologies) ~ Retesting!**
  - **Weight (60K$/Kg to LEO) ~1.5B$/Launch (135) Payload <22,700 Kg**
  - **Light/Strong? Materials (Background Radiation / Micro-Meteorites)**
    - **Carbon Fiber-Composites**
    - **Carbon Nano-Tubes**
    - **FO**
    - **Spray-On Shields**
    - **Flexible Fuel Tanks**
    - **Modules (Crew/Service)**
    - **Plasma Thruster**
    - **Etc.**



I: Intro ~ EMI/EMC

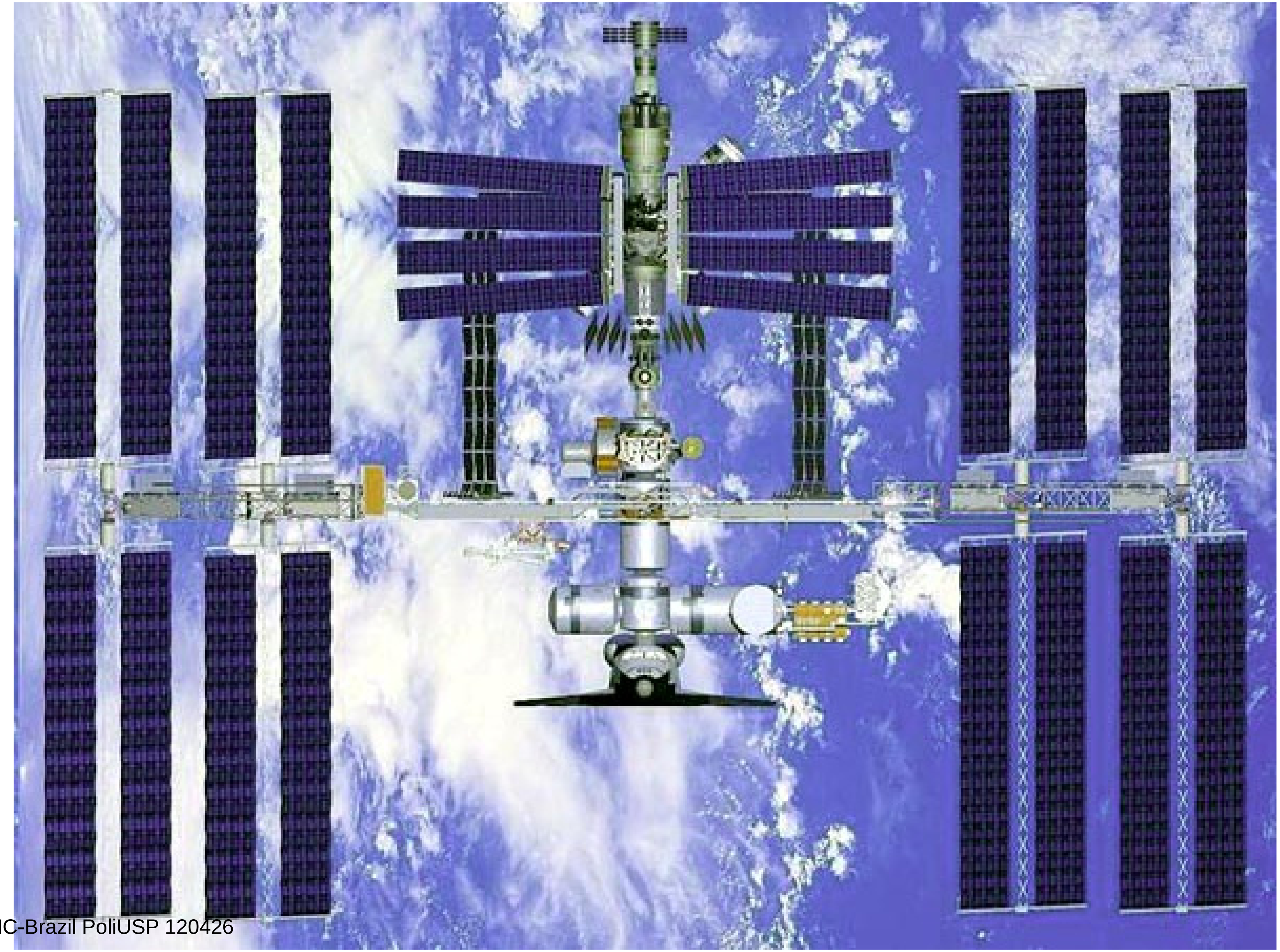
- (Problem) EMI –> EMC (Solution)
  - Wires (Metal/Conduction)
  - Wireless (Air/Radiation) ~ Radio/TV/Cell-Phones/NAV
- Emissions/Immunity (Hazards) ~ Cranes/Robonaut/Lightning
  - Susceptibility
  - Vulnerability (Waiver)

- Standards (MIL-STDs)
  - CE/RE (<Limits ~ DUT/Listen)
  - CS/RS (Degradation/Disruption/Damage/Destruction ~ DUT/Watch)
- Compliance ~ Voluntary/Required
  - Testing (1^{st})
  - Analysis (2^{nd}) ~ 20dB Penalty! (Predict Experimental Expectations)

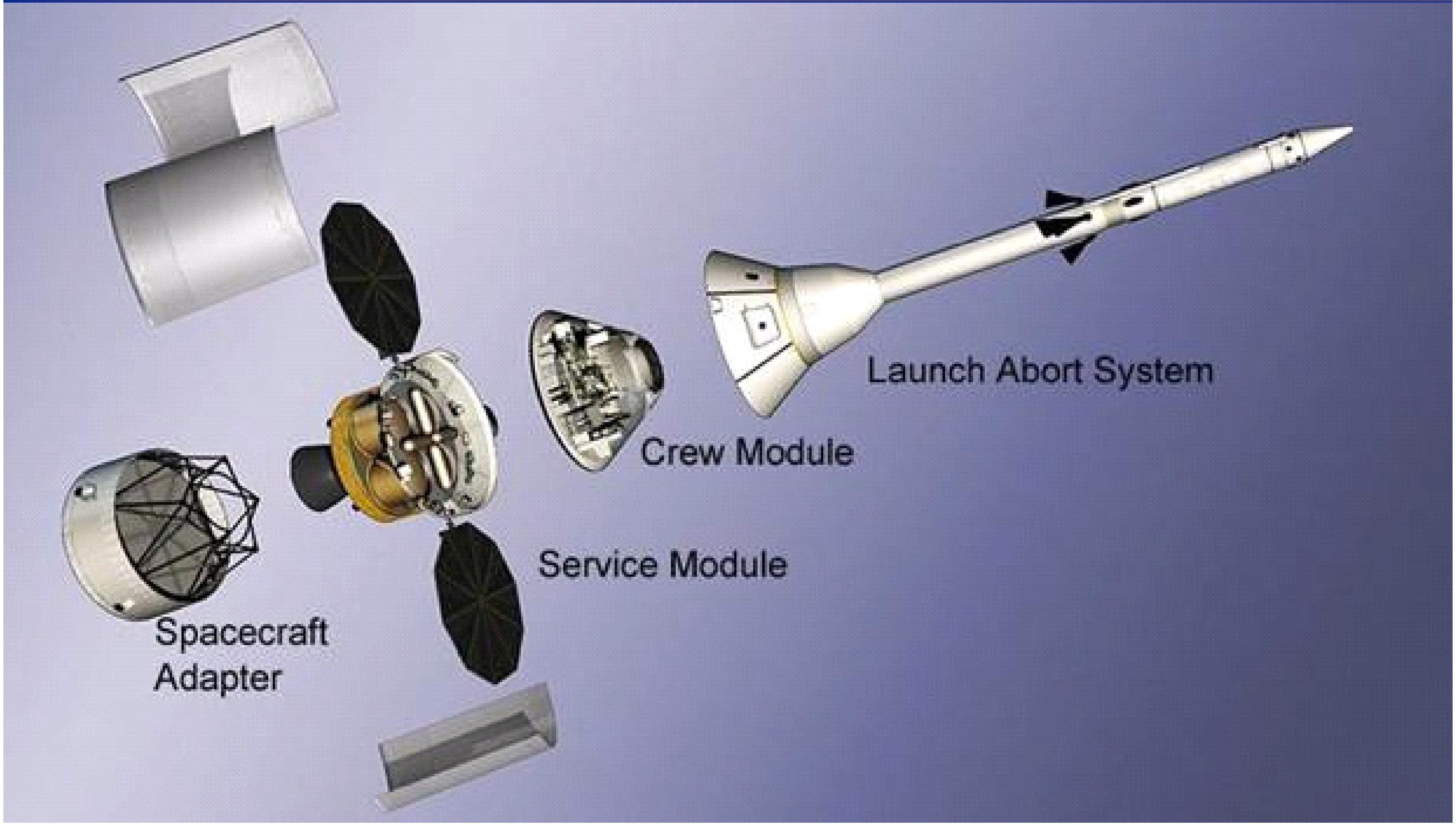
I: Intro ~ Test Articles

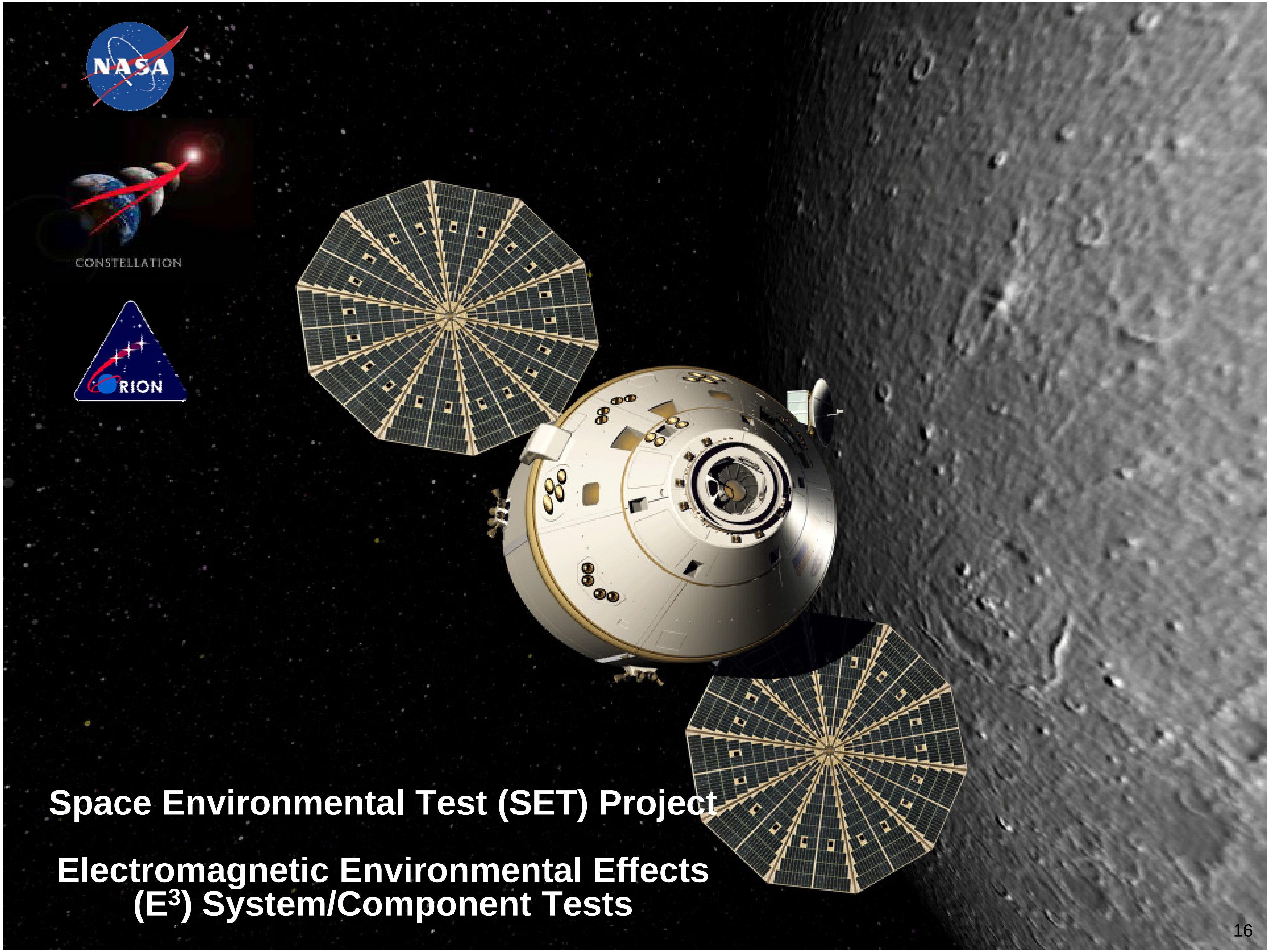
- **NASA**
  - **International Space Station (ISS) ~ Commissioned until 2020 (~100B$)**
    - **Repairs (Harsh Environment)**
    - **Ungrades (Emerging Technologies)**
    - **New Science Experiments**
  - **Space Shuttle (SS) ~ Retired**
    - **Russian Replacement**
    - **Industrial Vehicles**
  - **Orion Capsule**
    - **Crew Module (CM) ~ Crew Exploration Vehicle (CEV)**
    - **Service Module (SM)**

I: Intro ~ ISS/SS (Existing)



I: Intro ~ Orion (Planned) Carbon Composites





Space Environmental Test (SET) Project

Electromagnetic Environmental Effects (E[3]) System/Component Tests

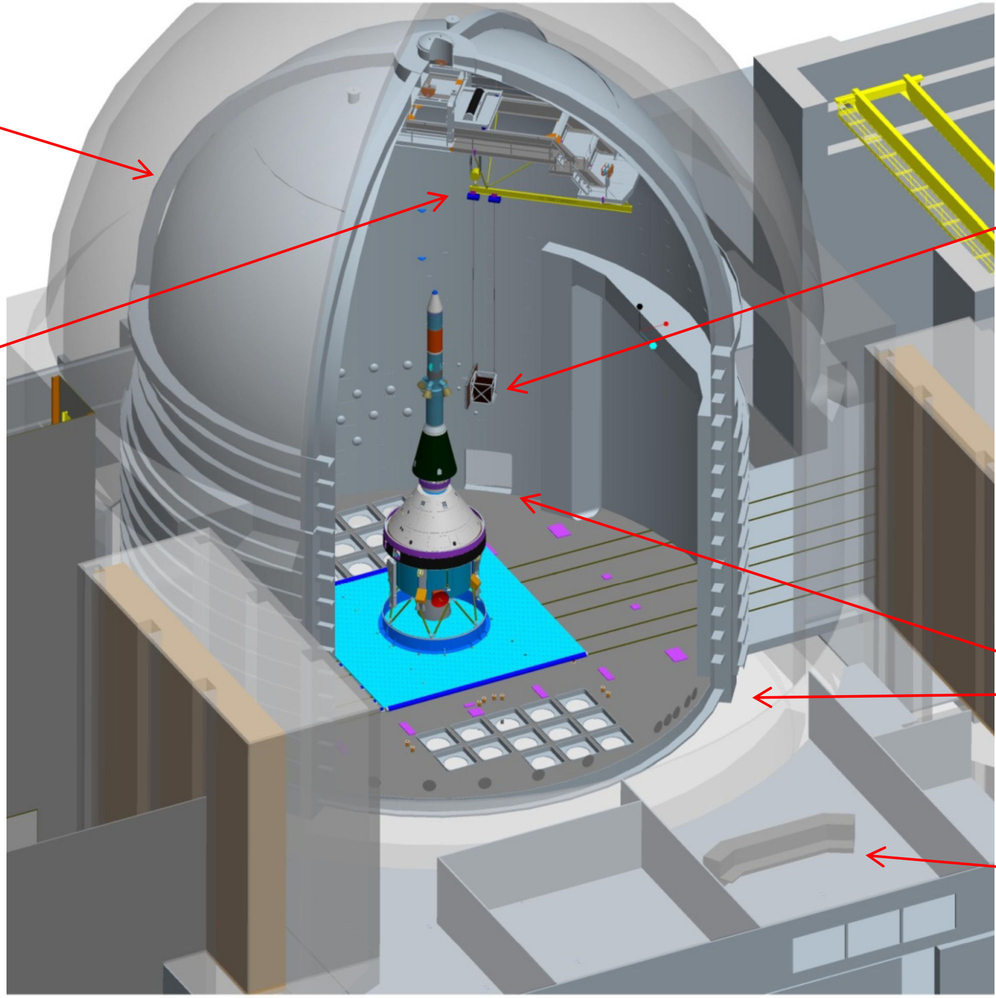
I: Intro ~ Tests

- **System Level (Integrated)**
  - **Full Size (Space Qualified)**
  - **Scale Models (Prototypes)**
    - **Thermal/Vac**
    - **Acoustics**
    - **Vib**
    - **EMI**

Ex 1: Plumbrook SPF
E^3 Tests (Emerging Testing)

Chamber

Lifting and Positioning Assembly

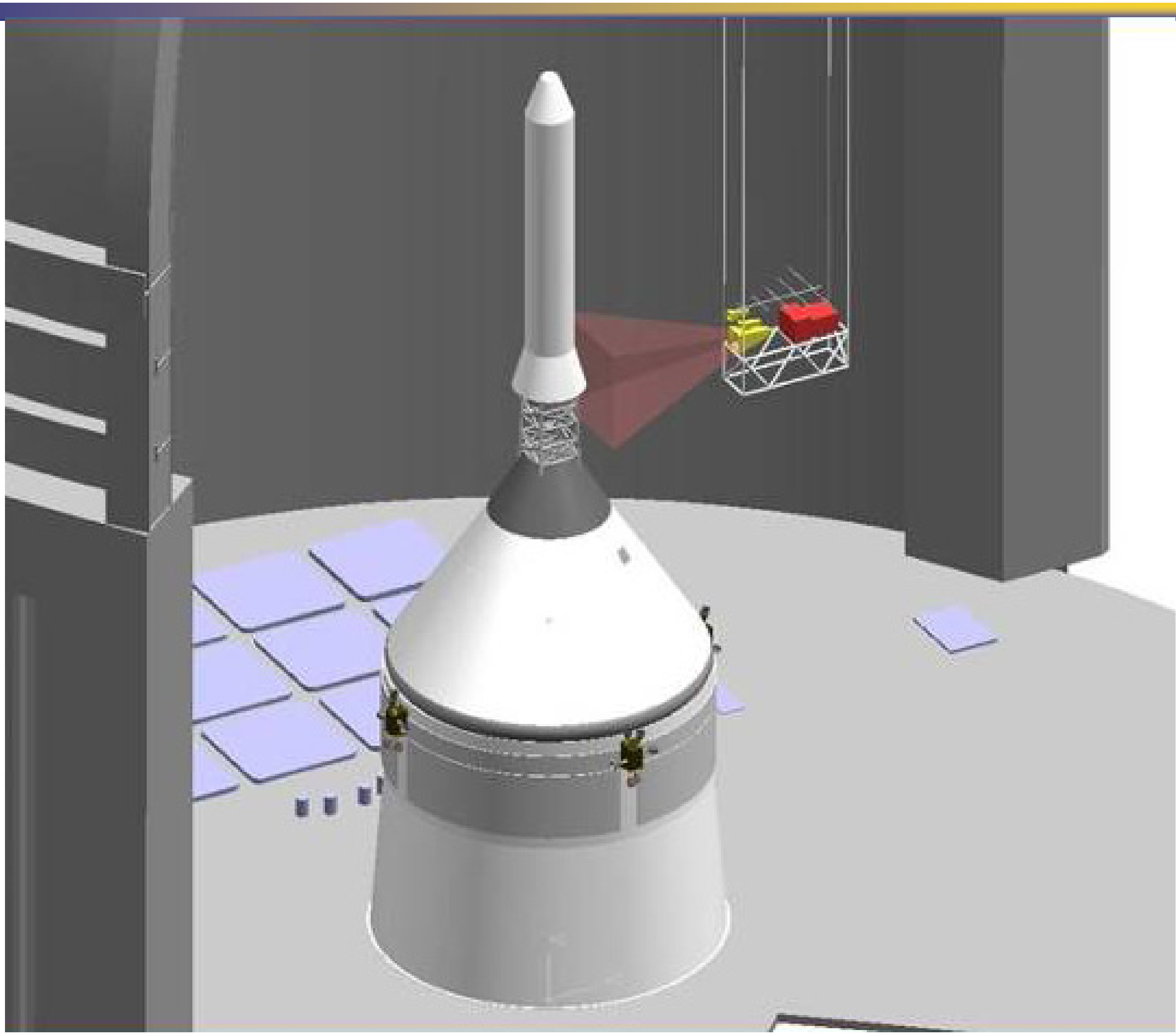


RF Pallet, including:
- RF Signal Generation
- RF Sensing and Measurement

Safety System

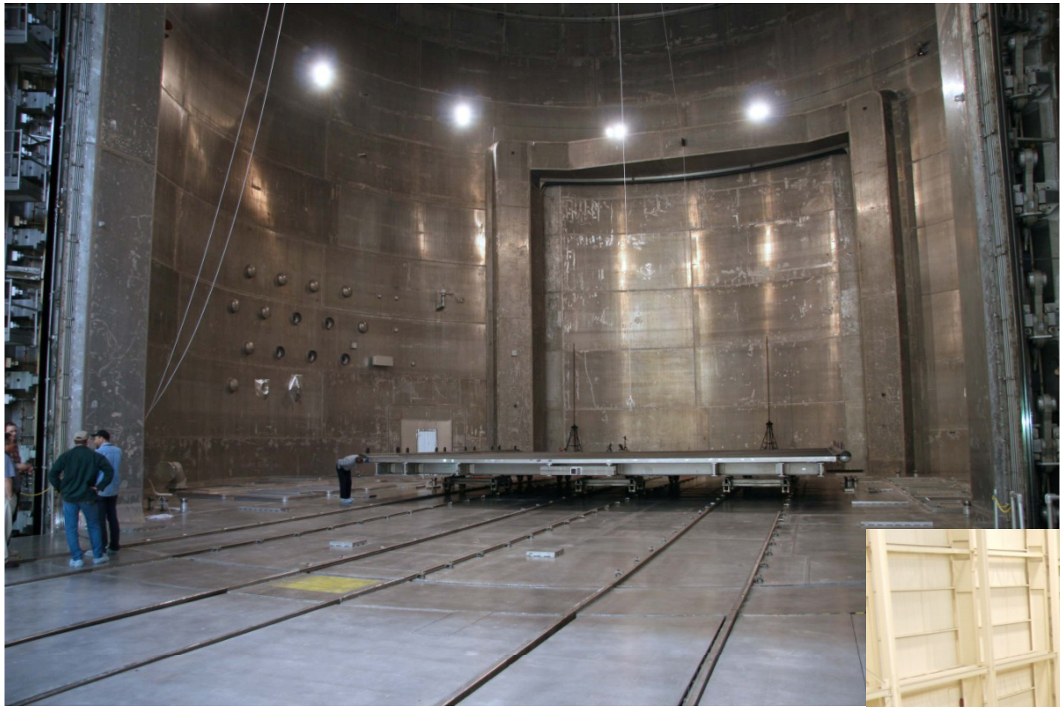
Control and Data Recording

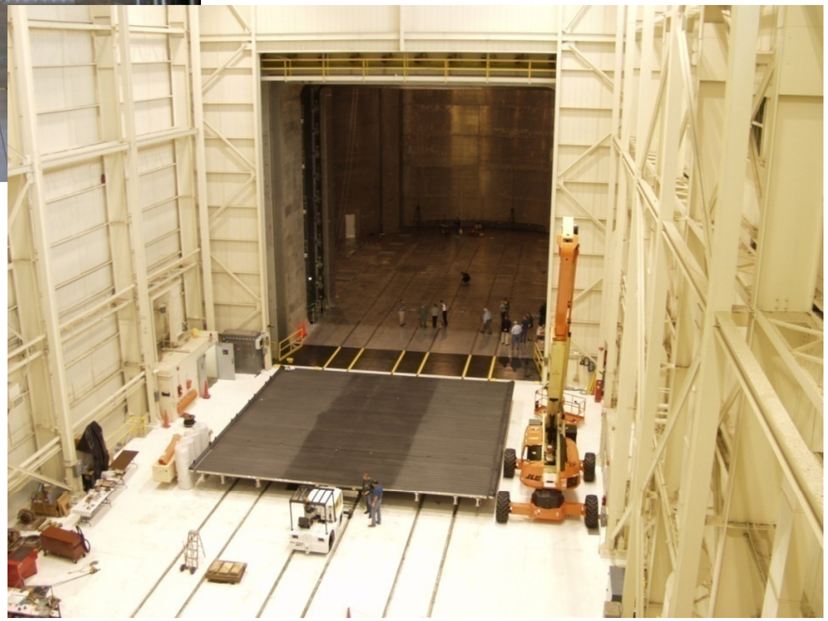
RE/RS
(Polar Crane)



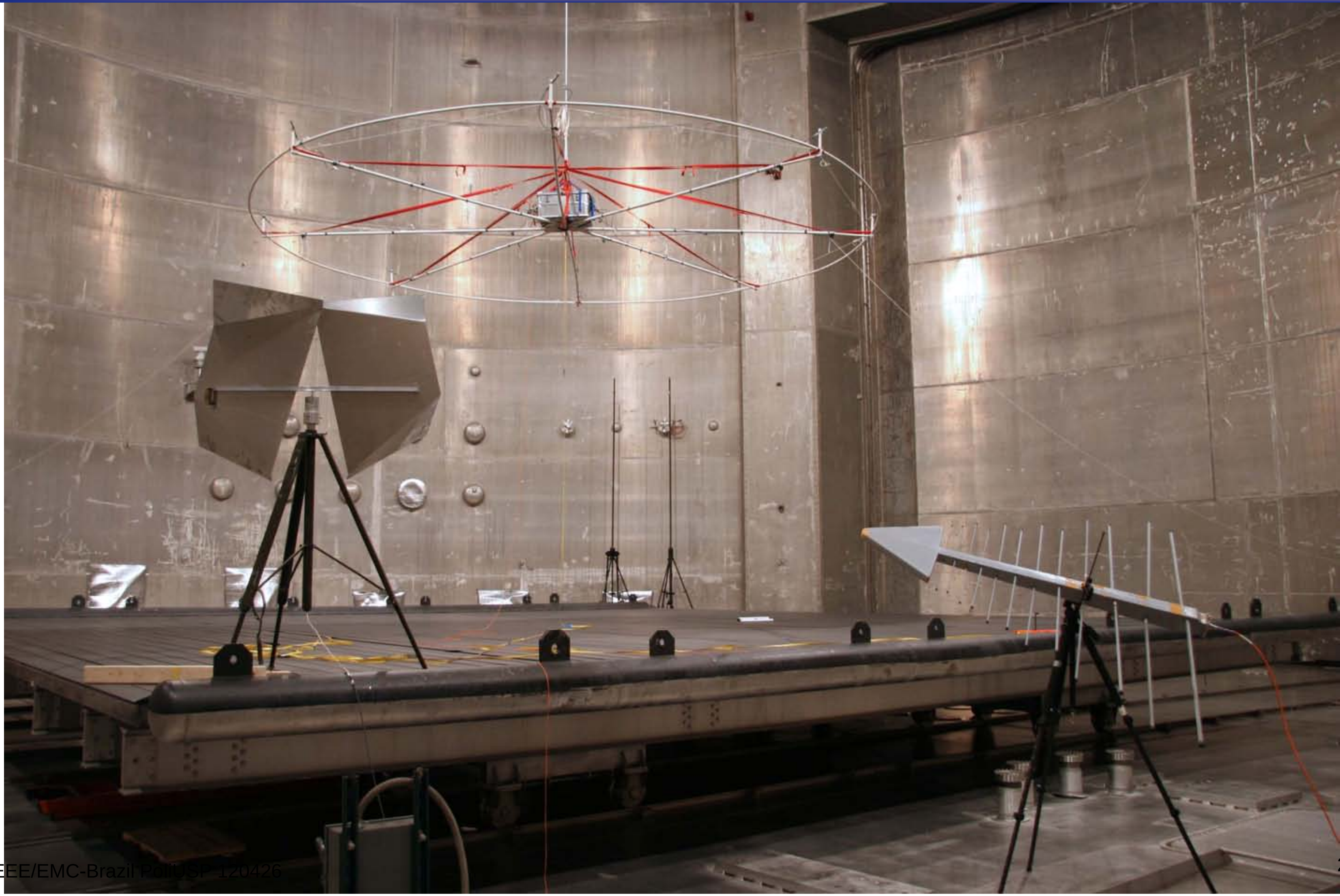
E3 System in SPF

Cryo-Floor / Sled in SPF Chamber (Linear Crane)





NIST Field Probe Test Configuration Reverberation Chamber



Ex 2: NASA/JSC Facilities Outdoor/Indoor Test Ranges

Building 14 - Outdoor Antenna Range

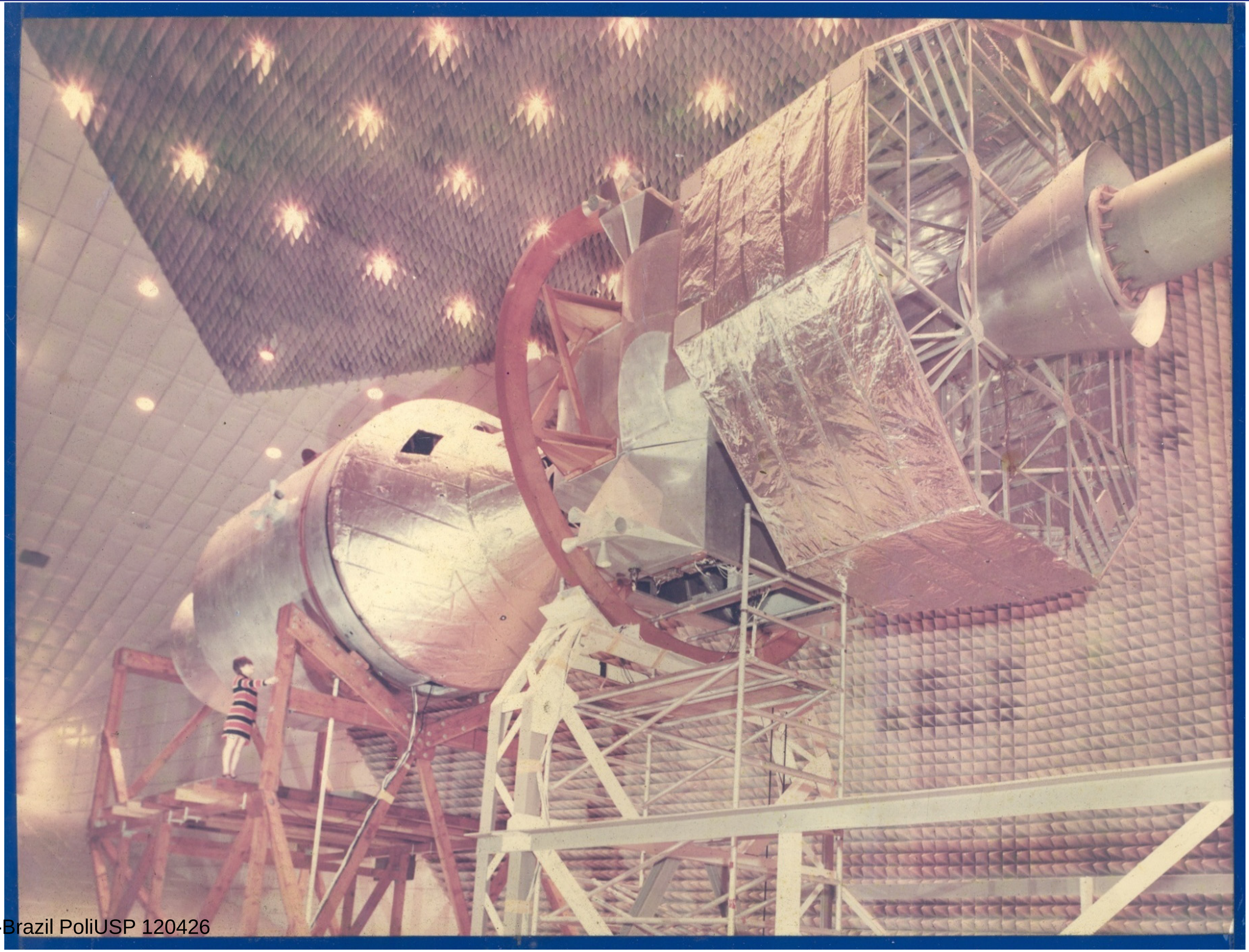
Morpheus Lander
(Flex Tanks)

Morpheus Test
(Take Off)

Morpheus Test
(Hover)

MCC

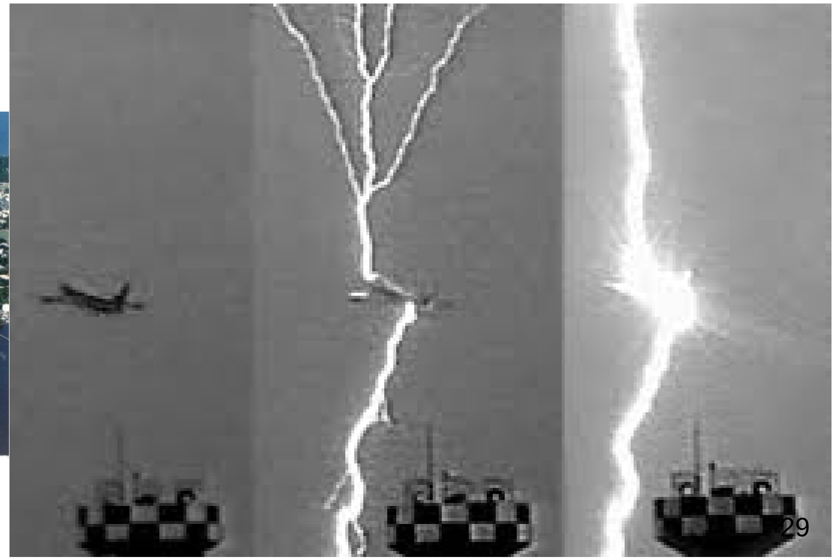
Ex 3: Tapered Anechoic Chamber (Original Apollo Tests)



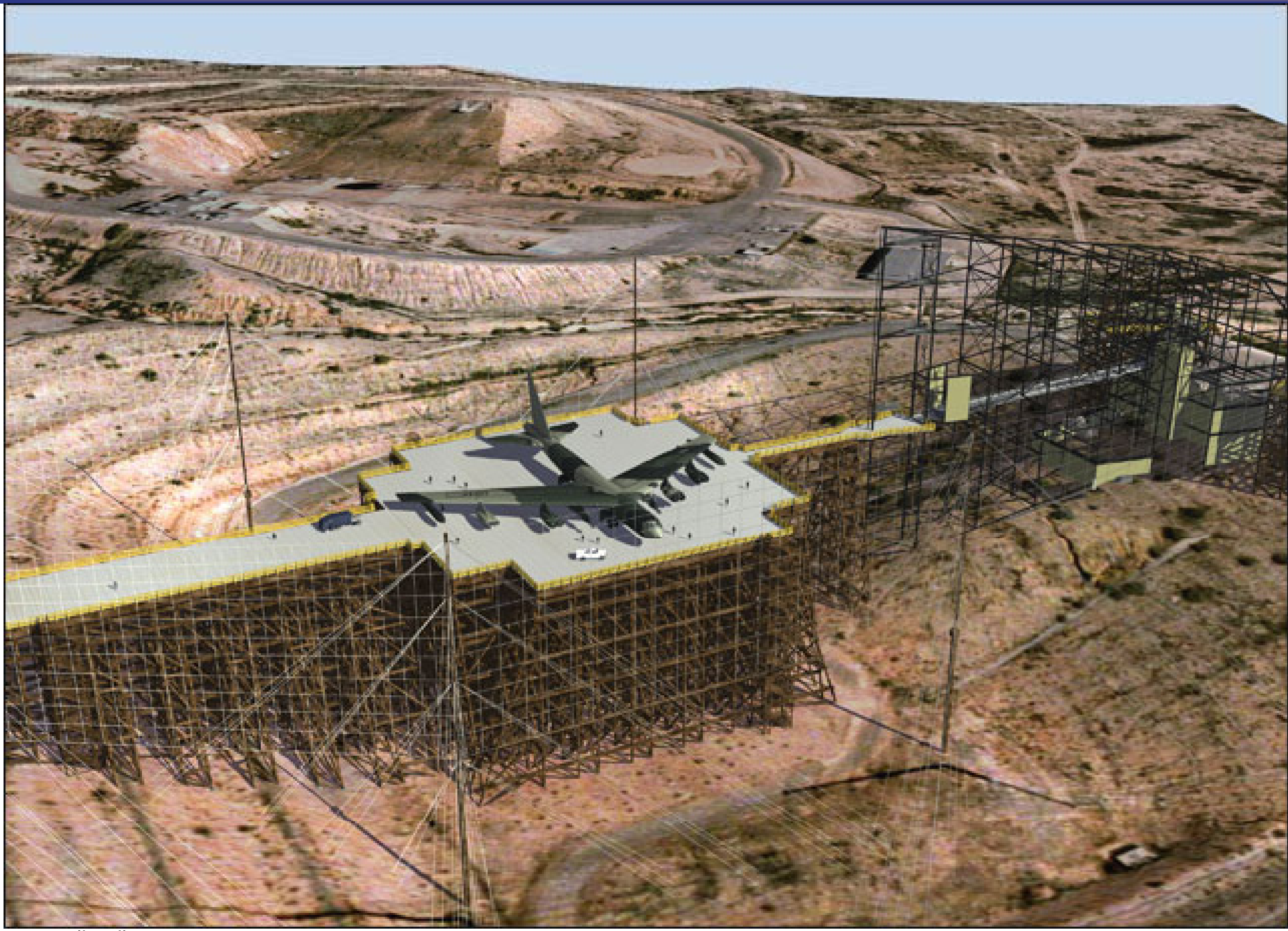
Ex 4: Semi-Anechoic Chamber (Robonaut I/II/III)

Ex 5A: Lightning (A/C)

- **Indirect Lightning Interactions**
  - **A/C (Military/Commercial)**
    - **Ground**
      - **Hanger**
      - **Taxiway**
      - **Runway**
      - **Pedestal**
    - **Air***
      - **1/1000h**

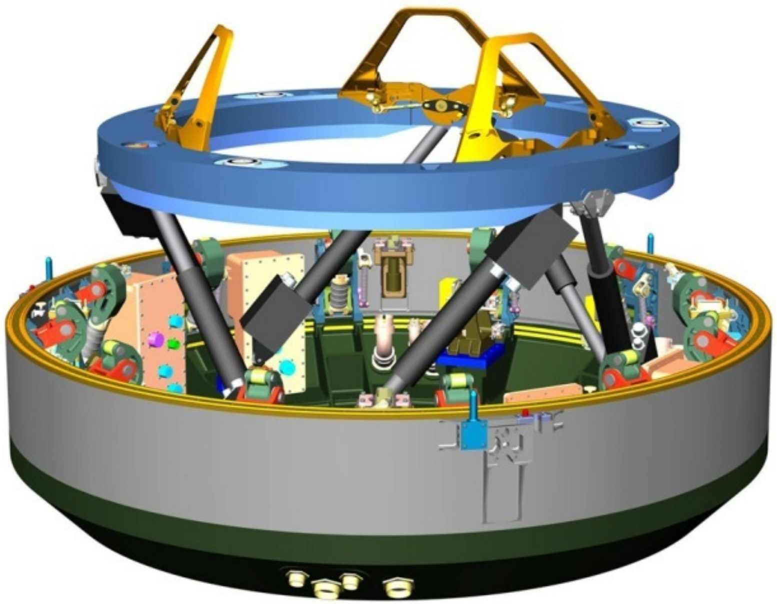


EX: Lightning/(N)EMP Pulser KAFB

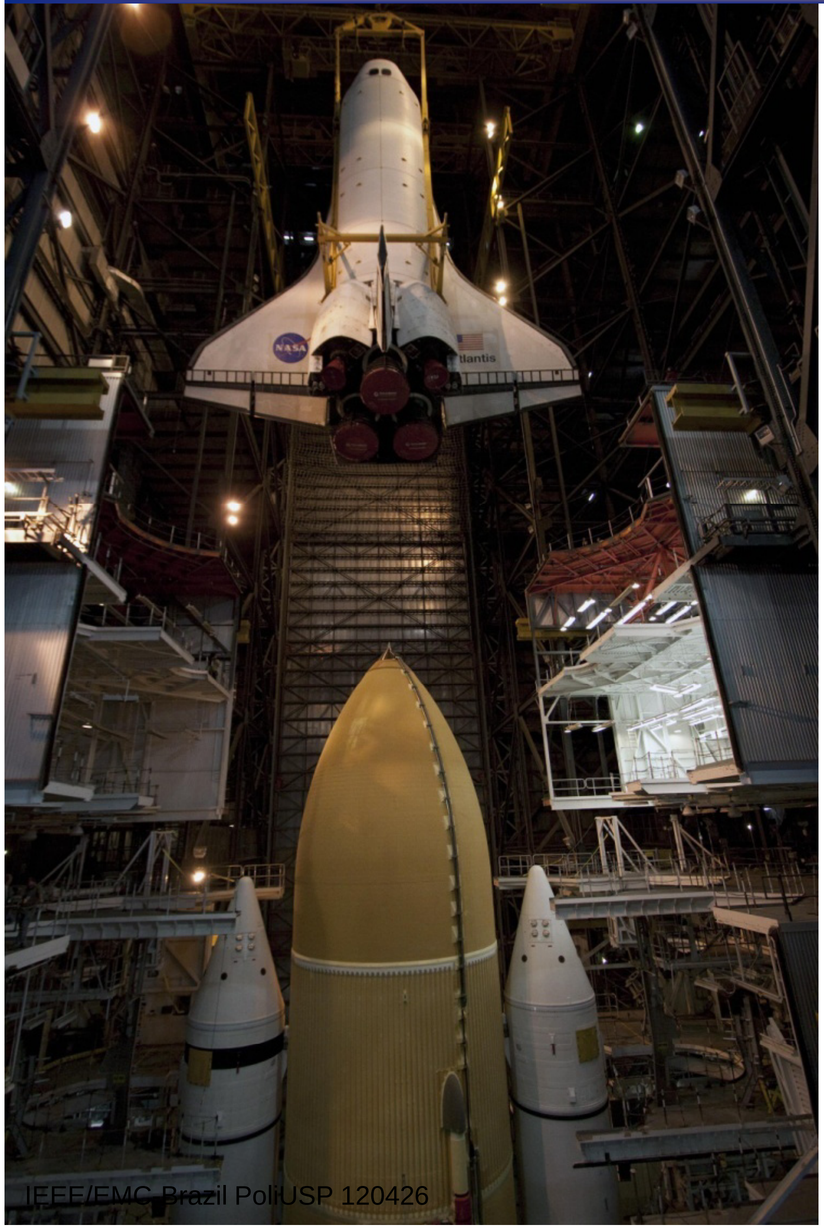


Ex 5B: Lightning/ESD (S/C)

- Indirect Lightning Interactions
  - S/C (SS/ISS)~Orion
    - Ground*
      - VAB
      - Crawler
      - Pad (Old/New)
    - Air* (Launch/Landing)
    - Space* [Docking (iLIDS)]~Ionosphere(F-Layer)
      - Spacecraft Charging (Negative)
      - ESD



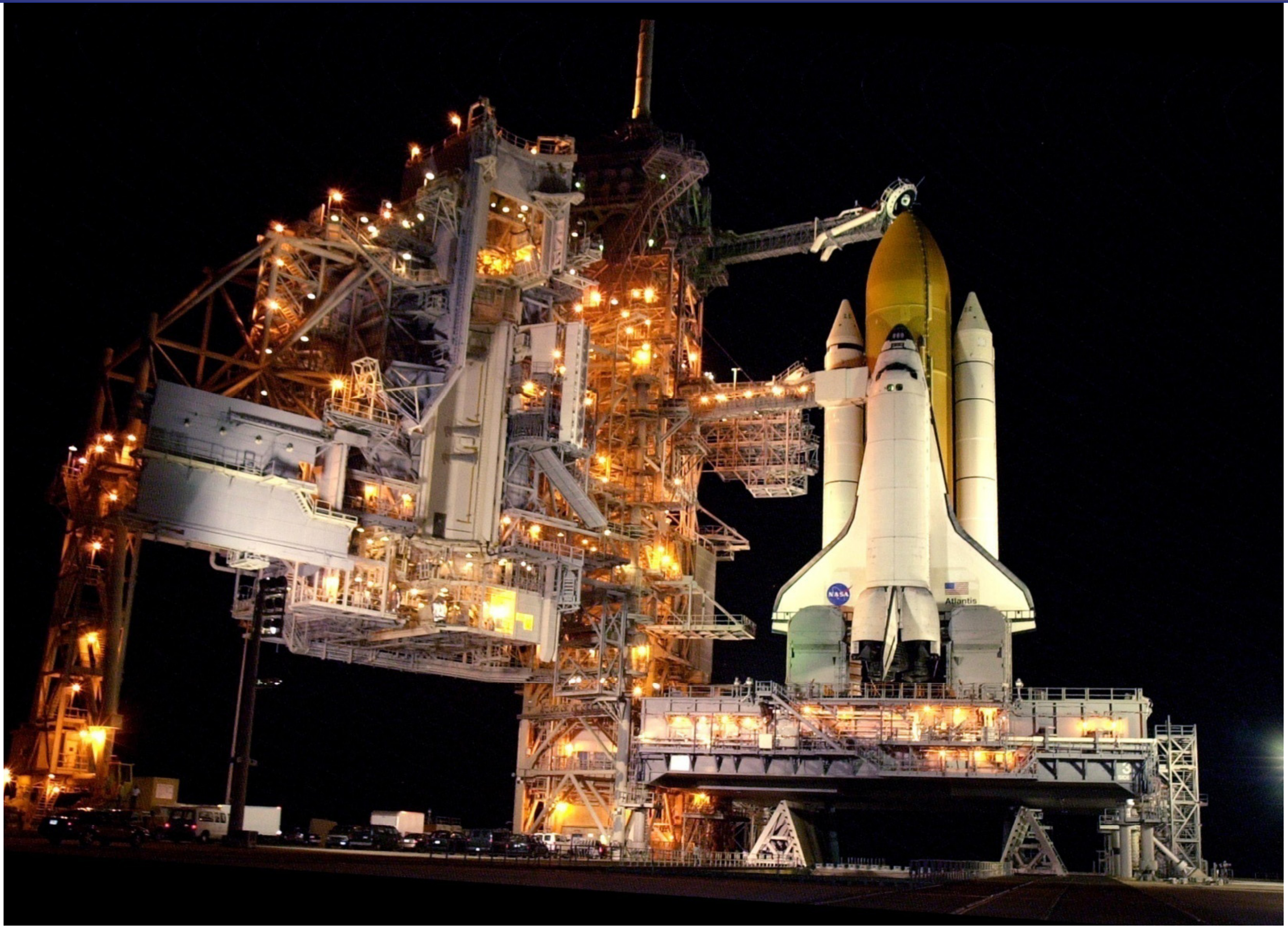
VAB (SS)



Crawler (SS)

Crawler (SS)

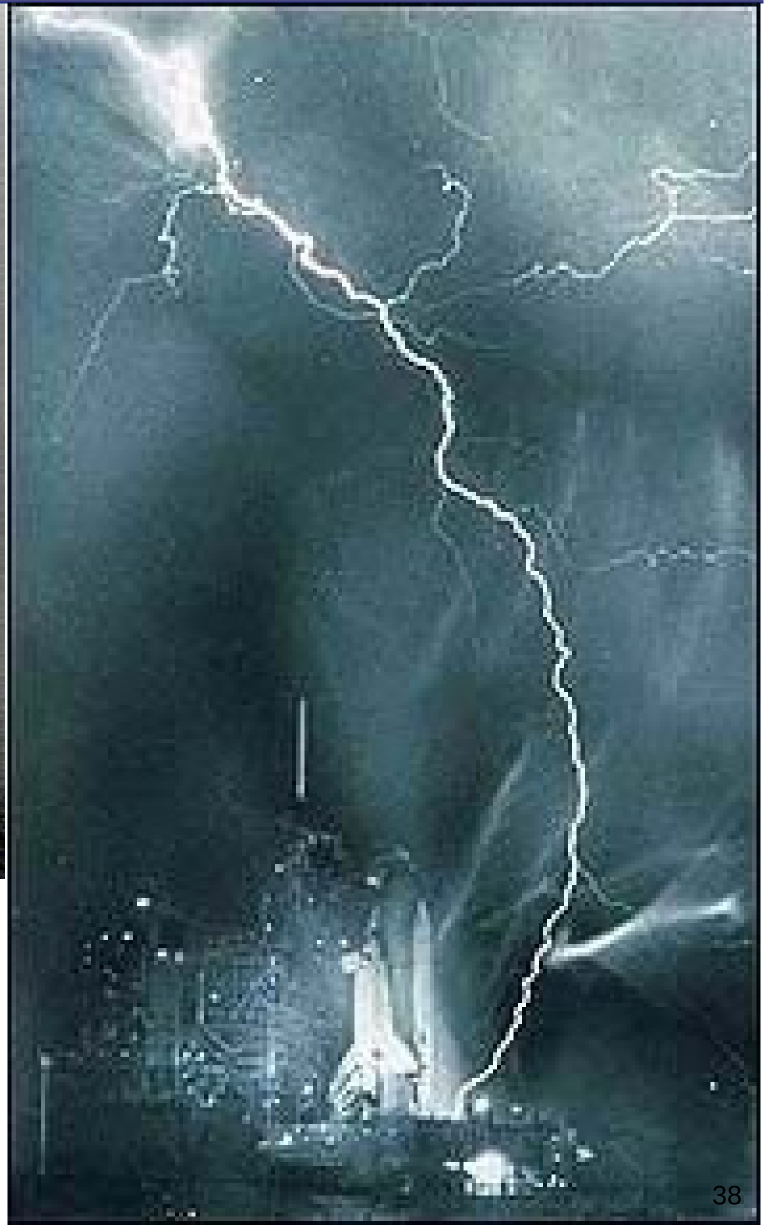
Pad 39 (SS)
KSC Tower



Pad 39 (SS) Lightning Rod

Pad 39 (SS)
Direct Lightning Strike

Pad 39 (SS)
Direct Lightning Strike



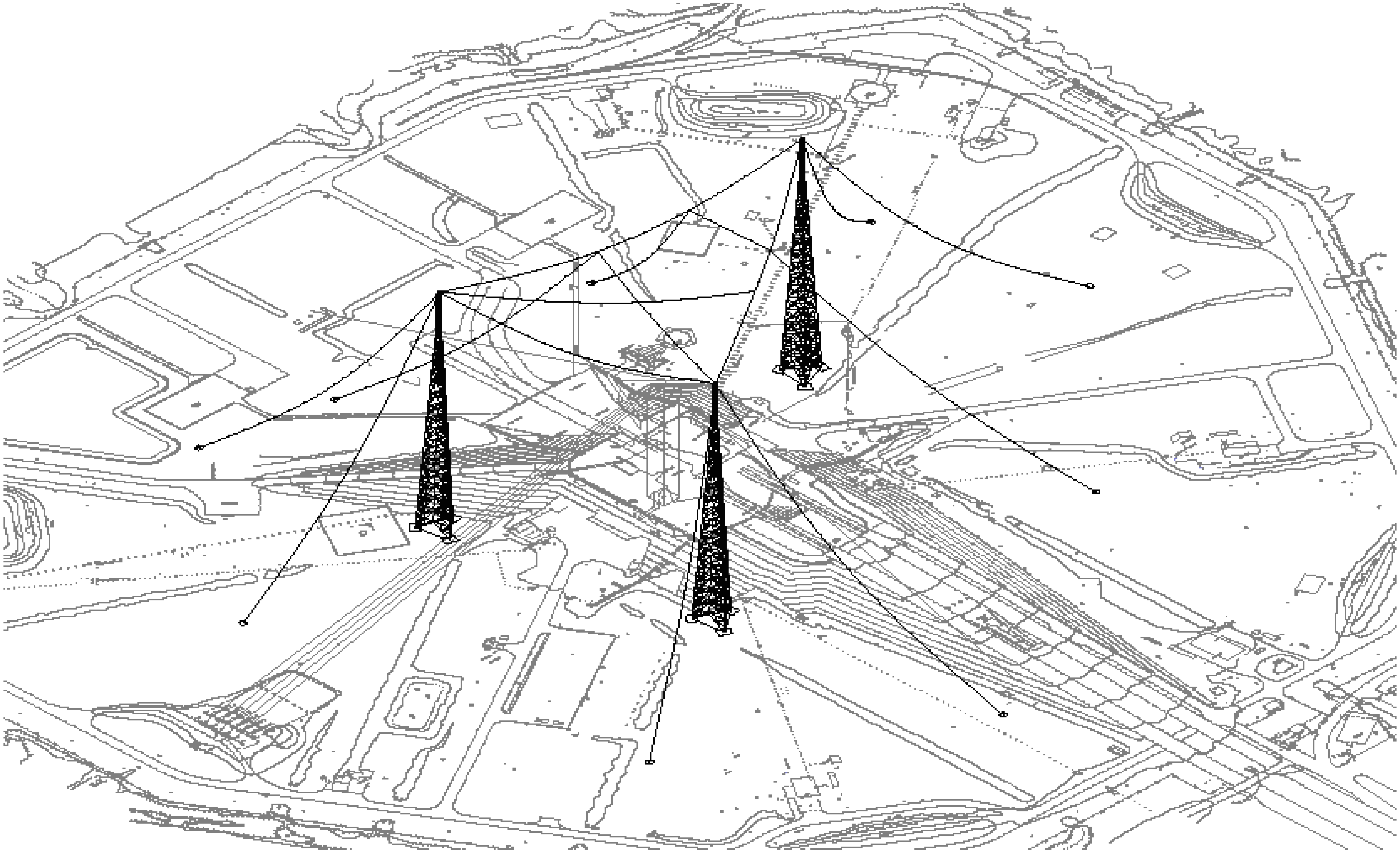
3 Day Delay ~ SoF

Close Call

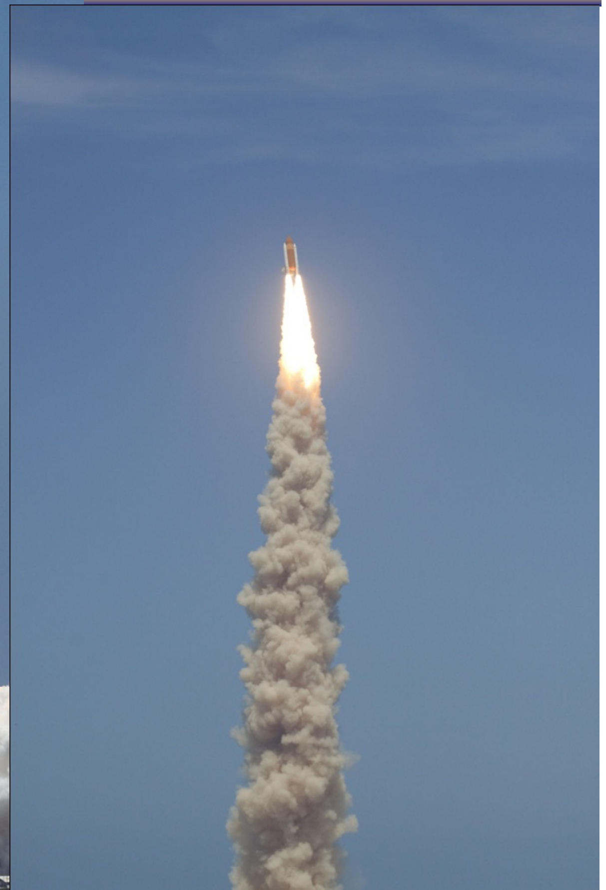
Pad 39 (A&B)~Old/New Hubble Repair (Rescue?)

Pad 39B
Catenary Lightning Protection

Pad 39B
Catenary Lightning Protection



Ex 6: Launch
Direct Lightning Strike



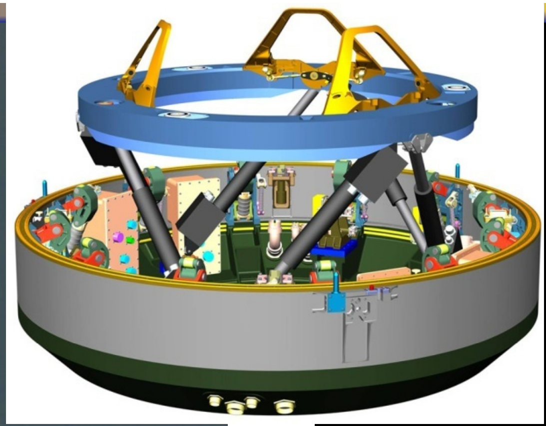
Direct Strike

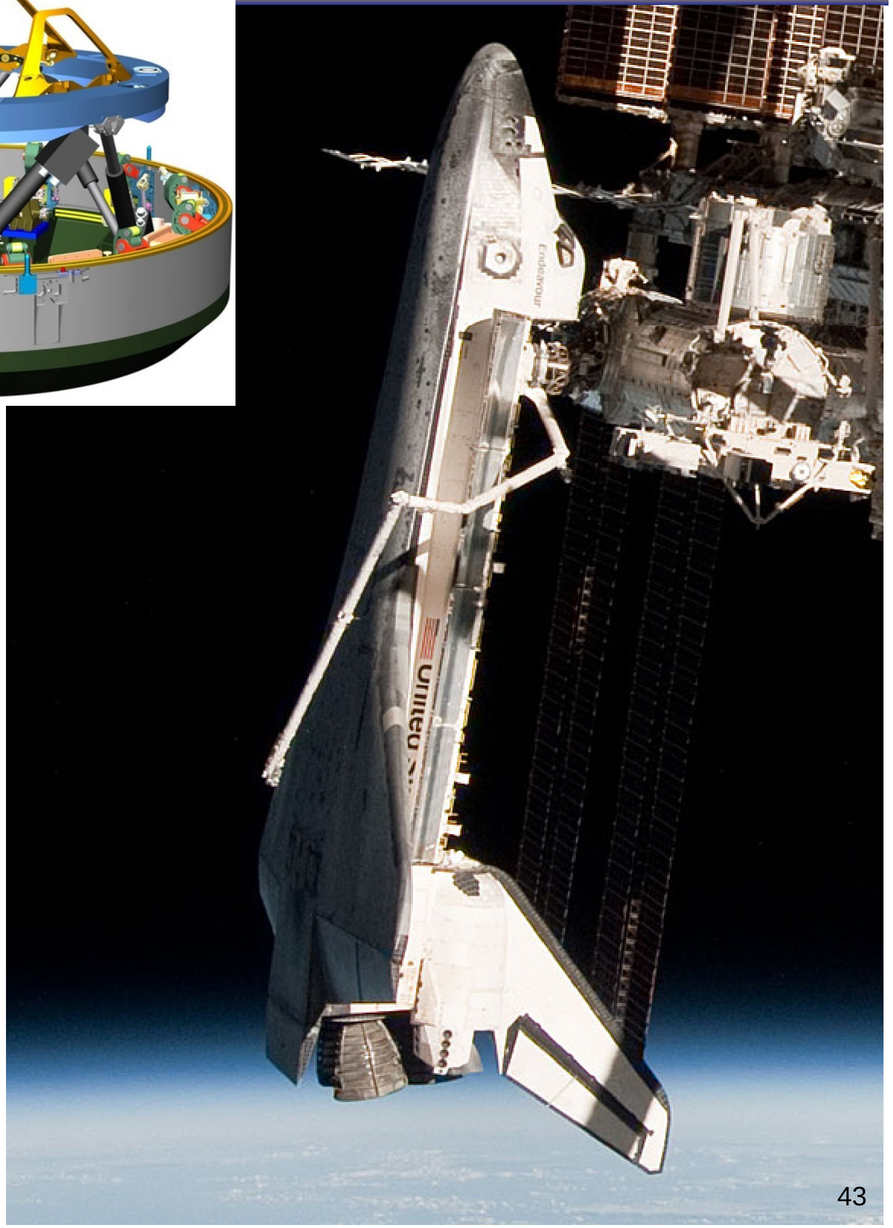
NAV Computer

Reboot (~15s)

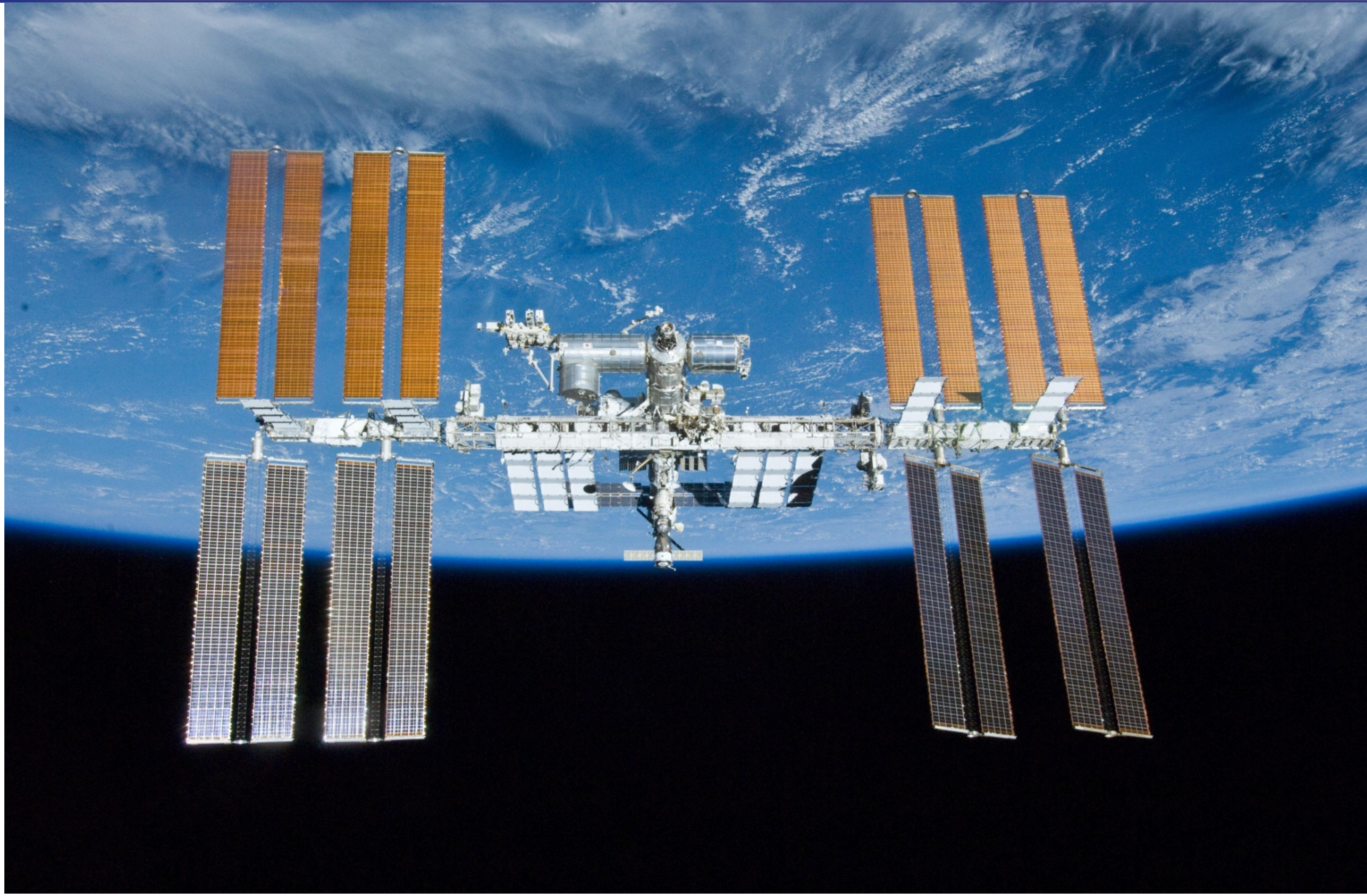
Close Call

Ex 7: ISS/VV Rendezvous/Docking iLIDS





Ex 8: ISS / Plasma Charging Langmuir Probes/PCU



Ex9: (SS) Launch/Landing

Outline

- I: Introduction
  - NASA (S/C Problems ~ Work Experiences/Examples)
- EMI/EMC Problem/Solution
- **Compliance Checks ~ Limits**
  - II: Test (MIL-STD) ~$$$
    - Radiation/Conduction (Wireless/Wired)
    - Emissions/Immunity (Susceptibility/Vulnerability)
  - III: Analysis/Design ~20 dB Penalty!
    - Radiation ~ TX/RX Antennas (Intentional/Unintentional)
    - THE Unique "Radiation Integrals" ~ Greens Function(Weight/Sum)
      - Analytical (Exact/Asymptotic) Antenna Answer (Solution: >100y Old)
      - Numerical (CEM) M&S ~ Canonical(V&V) / Hi-Fi Models
        - MoM (Source: Based on Solution to ME) OATS
        - FDM/FEM/TLM/etc (Field: Based on ME +BC) A/C

Outline

- **Test ~ US/Russian**
- **Test Procedures**
- **Test Types**
- **Test Setups**
  - **Frequency Bands**
  - **Polarizations**
  - **Positions**
- **Test Limits**
- **Test Results (Example/Typical)**

II: Test ~ Procedures

- **NASA/JSC EMI/EMC E3 Lab**
  - **Tests/Analyses: RE/RS&CE/CS /Etc.**
    - **Preliminary Meeting(s) ~ ISS/SS Space-Flight H/W Customers : Industry/MIL/GOV/NASA**
    - **Test Readiness Review (TRR)**
      - **Test Plan (Tests/Modes/Failure Criteria)**
      - **Quality/Safety/(Hazard Analysis)**
    - **TRR Board (Approval)**
    - **Scheduling (Thermal-VAC/Vib/Acoustics/EMI)**
    - **Testing (E3/Chambers) ~ NO Pass! (Filtering/Shielding)**
      - **ISS/SS Requirements (1m:Intensity/Frequency/Mod/Dwell/Etc)** **Antenna Bands/Pols/Positions**
      - **Failure [Chamber Cal ~ Reference Background (Noise Level)]** **(10 kHz – 20 GHz)**
      - **RE (4 Hours/Mode)**
      - **RS (40 Hours/Mode) ~ Full-Sweep/Discrete-Samples(EMV)**
    - **Data Package (Plots/Print-Outs/Pics)**
    - **Test Report (Results/Observations/Conclusions/Recommendations) EMV/Wavers!(COTS)**

II: Tests

- **System/Component Level**
  - **Space Flight HW**
    - **Thermal/Vac**
    - **Acoustics**
    - **Vib**
    - **EMI**
      - **External ~ Full A/C (Large/Tapered)**
        - **Antenna Interference**
        - **Antenna Placement**
        - **RCS/Tracking**
        - **Comm Links (Earth/ISS/SS/VV)**
      - **Internal ~ Semi A/C (Small/Rectangular)**
        - **Emissions**
        - **Immunity**

MIL-STD Tests

- **Radiated/Conducted (Emissions/Immunity)**

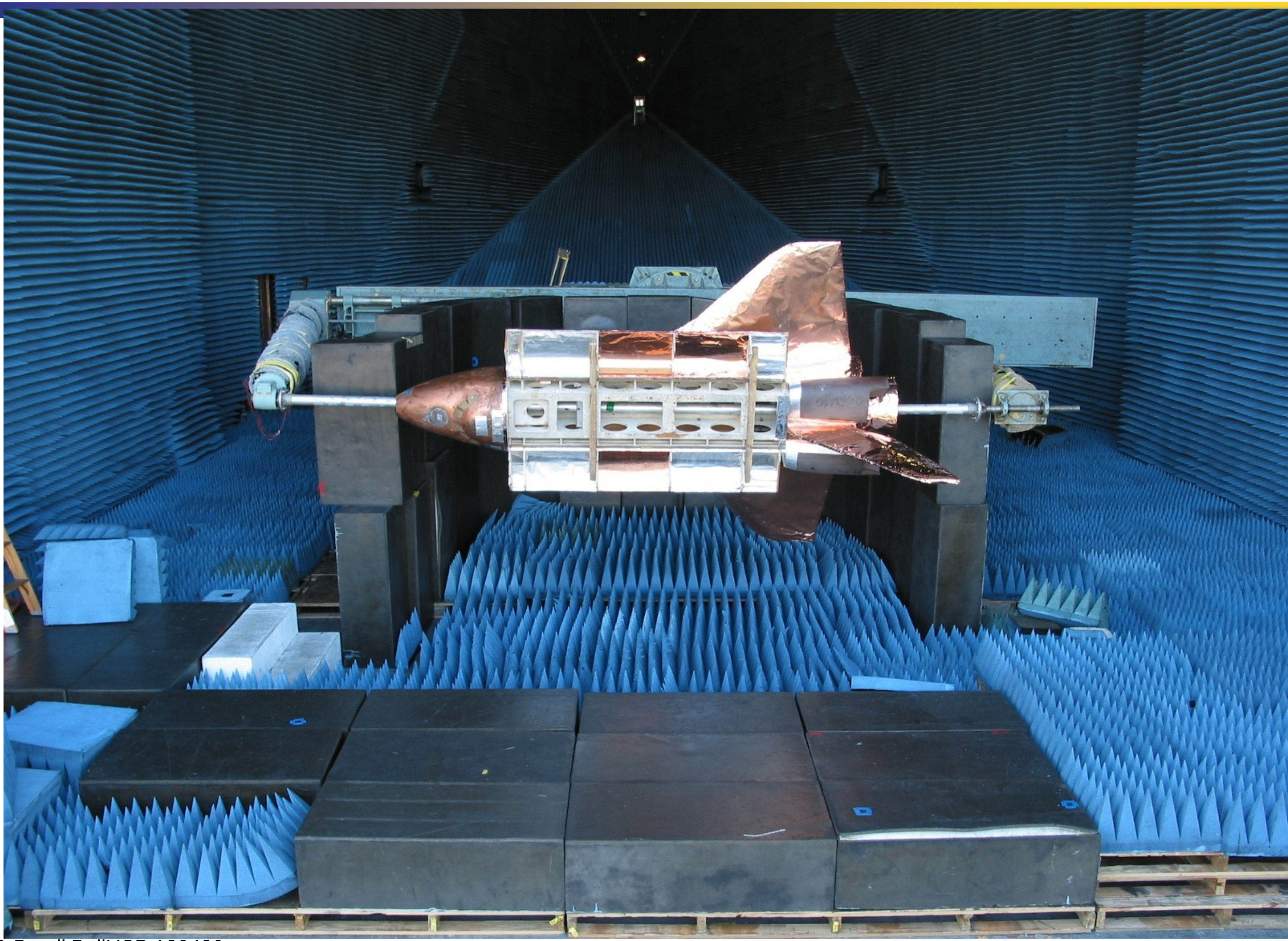
EMI Test	Description
CE01	30 Hz – 15 kHz Power Leads
CE03	15 kHz – 50 MHz Power Leads
CE07	DC Power Leads Spikes Time Domain
RE02	14 kHz – 10 GHz 13.5 – 15.5 GHz Electric Field
CS01	30 Hz – 50 kHz Power Leads
CS02	50 kHz – 50 MHz Power Leads
CS06	Spikes Power Leads
RS03	14 kHz – 20 GHz, Electric Field

EMI Test Schedule
US Segment

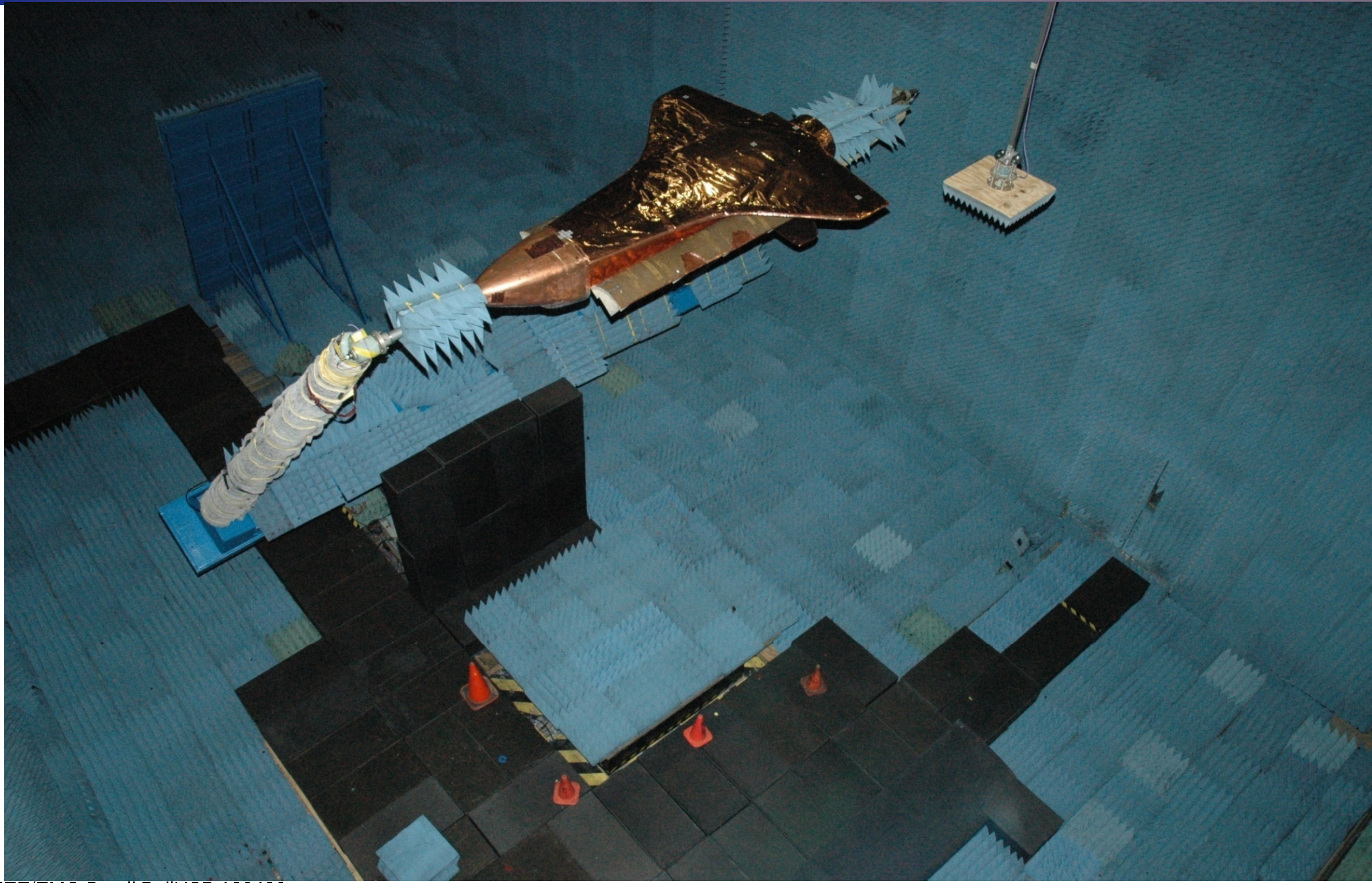
EMI Test	Description
CE Low Frequency	20 Hz – 10 kHz Power Leads
CE RF	10 kHz – 100 MHz Power Leads
RE	10 kHz – 1 GHz Electric Field
CS Low Frequency	20 Hz – 10 kHz Power Leads
CS RF	10 kHz – 100 MHz Power Leads
RS	14 kHz – 20 GHz, Electric Field

EMI Test Schedule
Russian Segment

Ex 1: SS / Cargo Bay Open

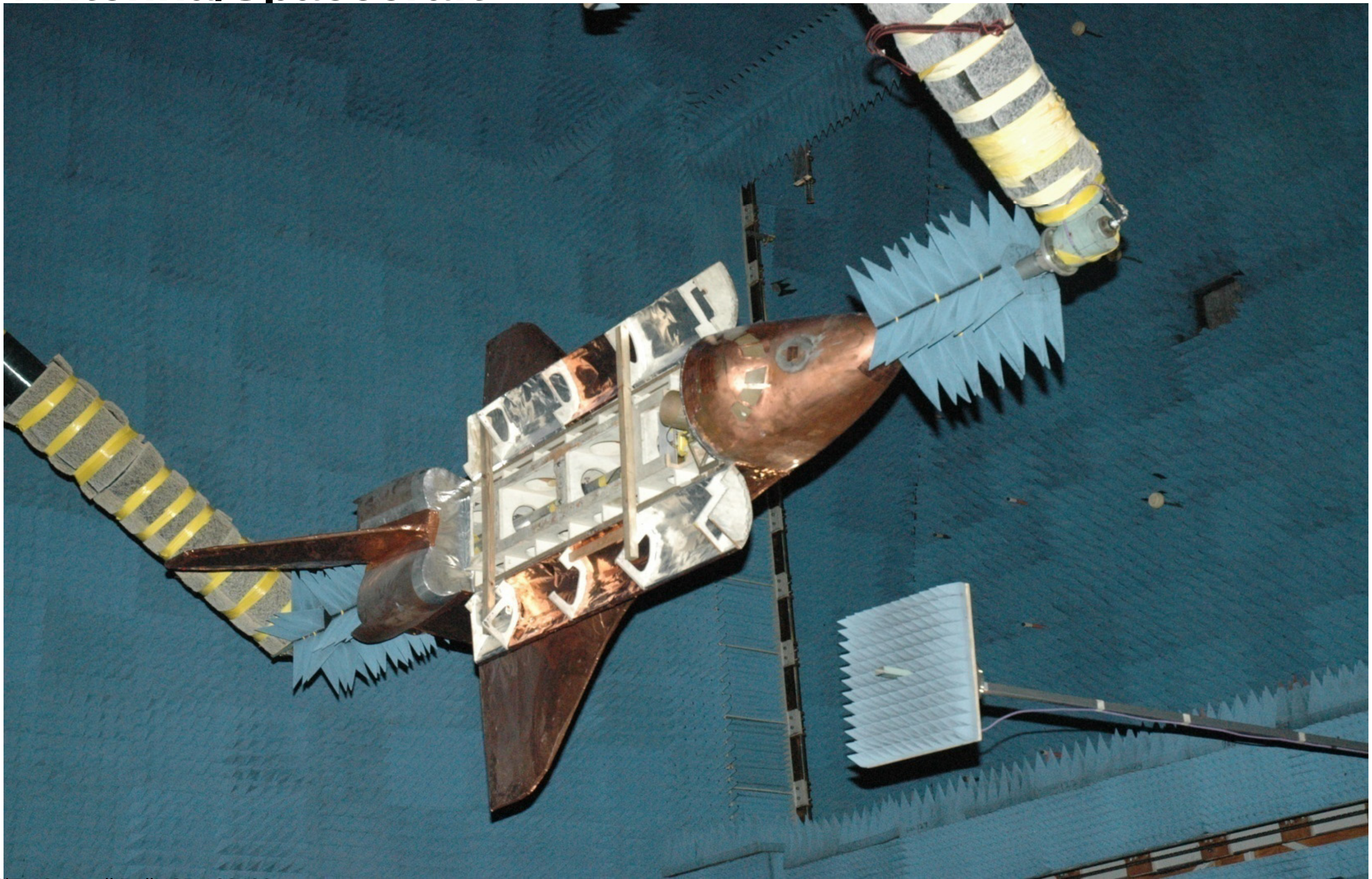


SS / Antenna Positioning

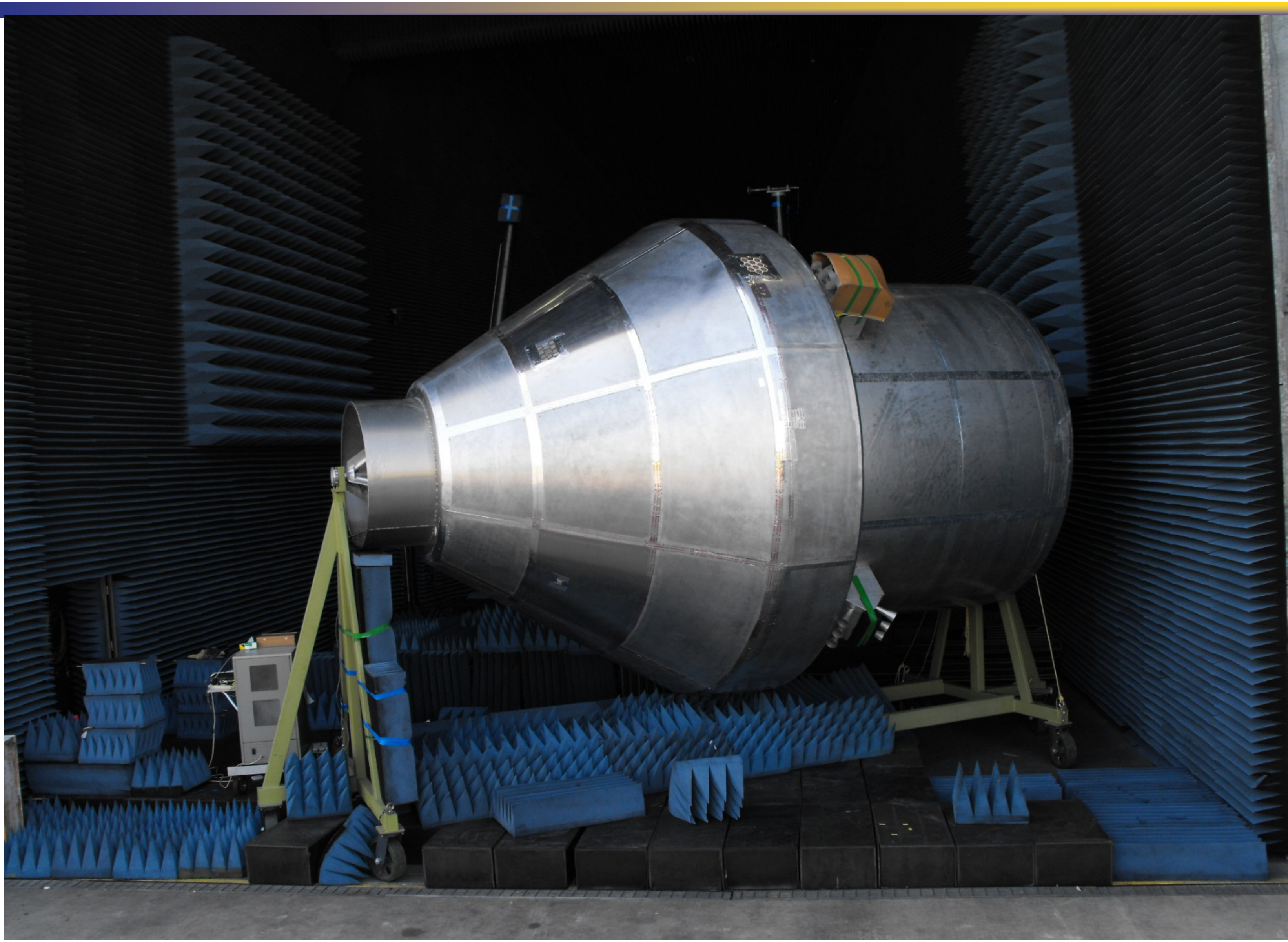


SS / Antenna Interference

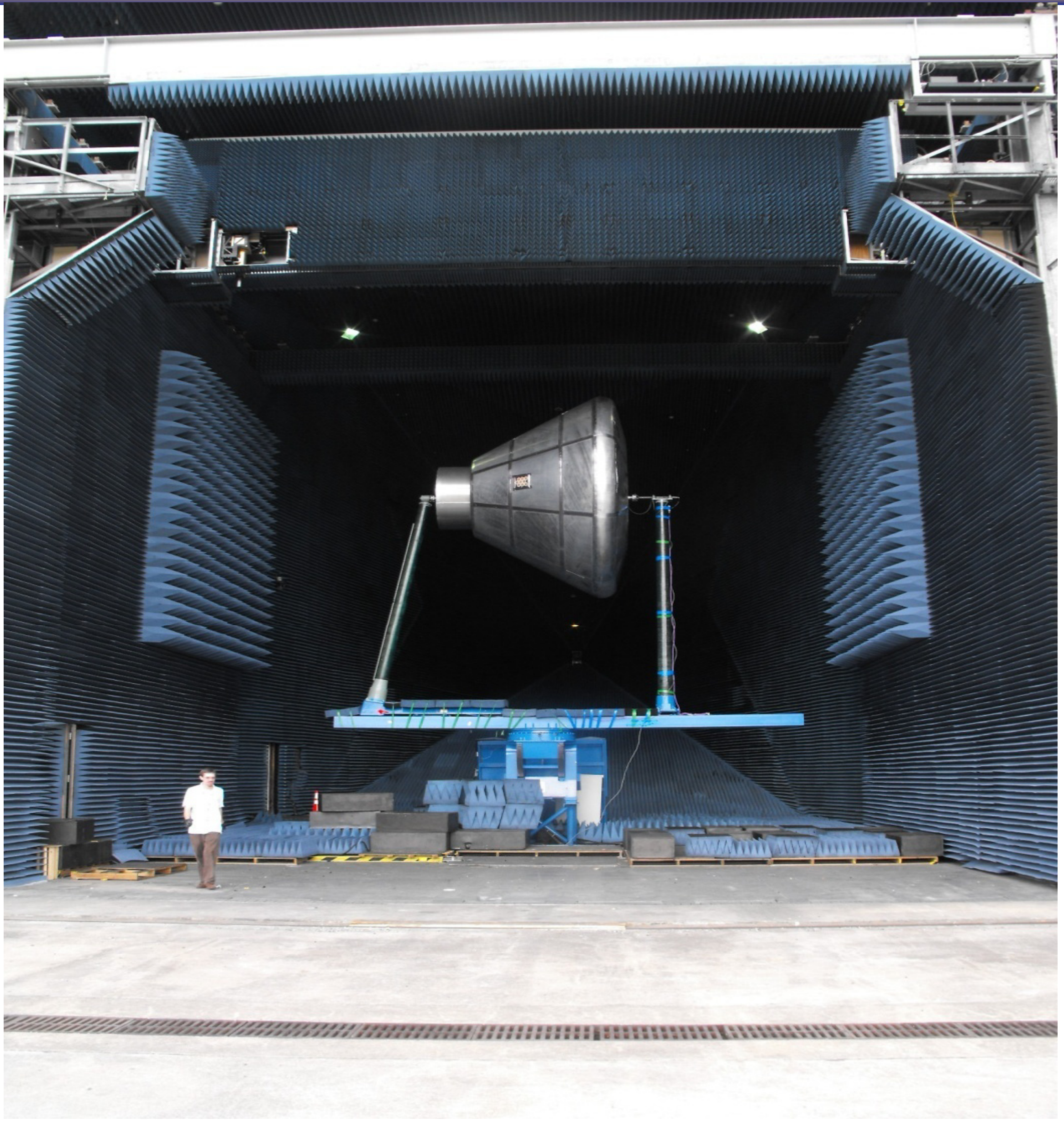
- **Antenna/Spacecraft**



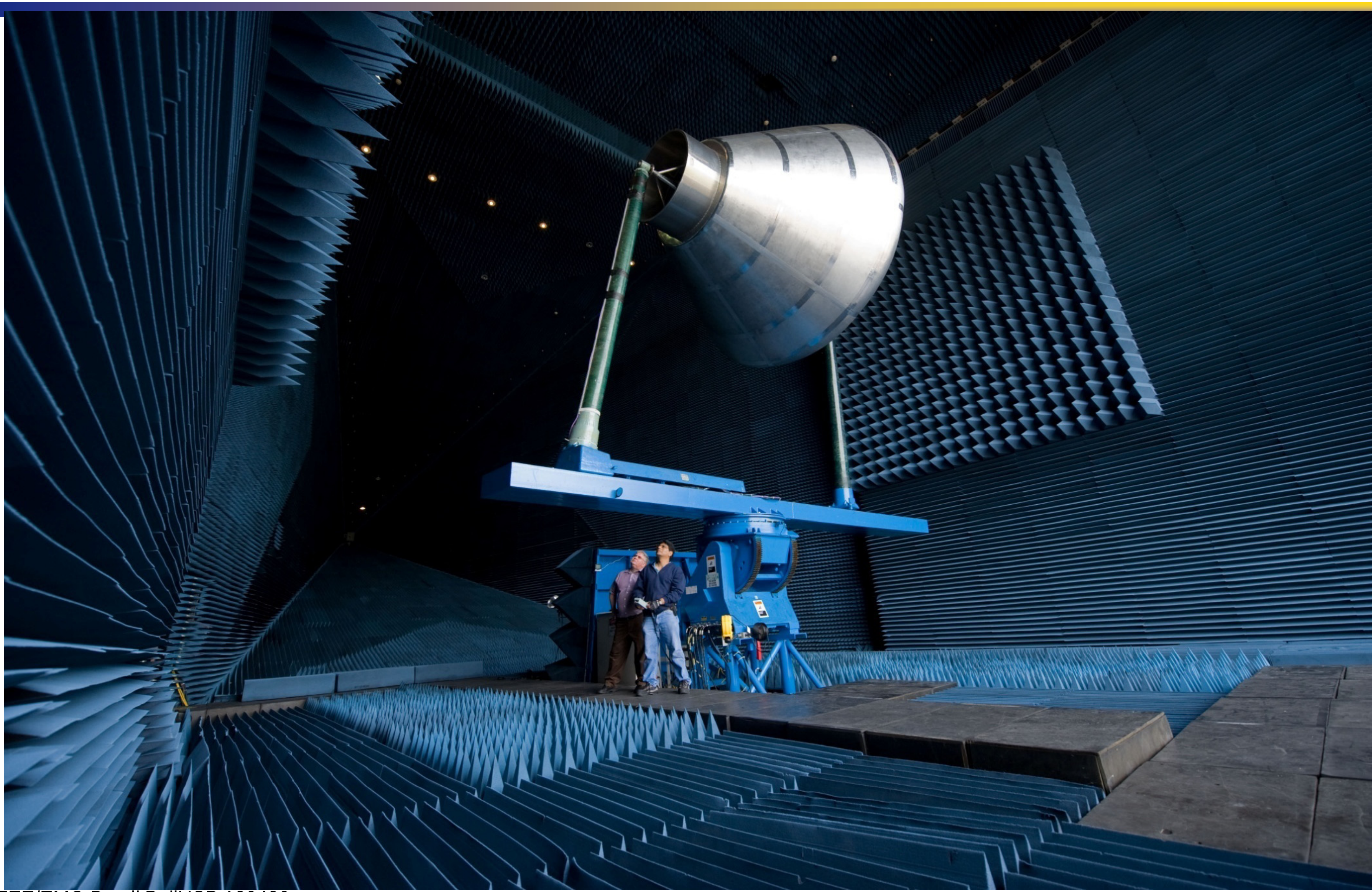
Ex 2: Orion / Prototype (CM/SM) Array Coupling



Orion / Prototype (CM) (OATS)

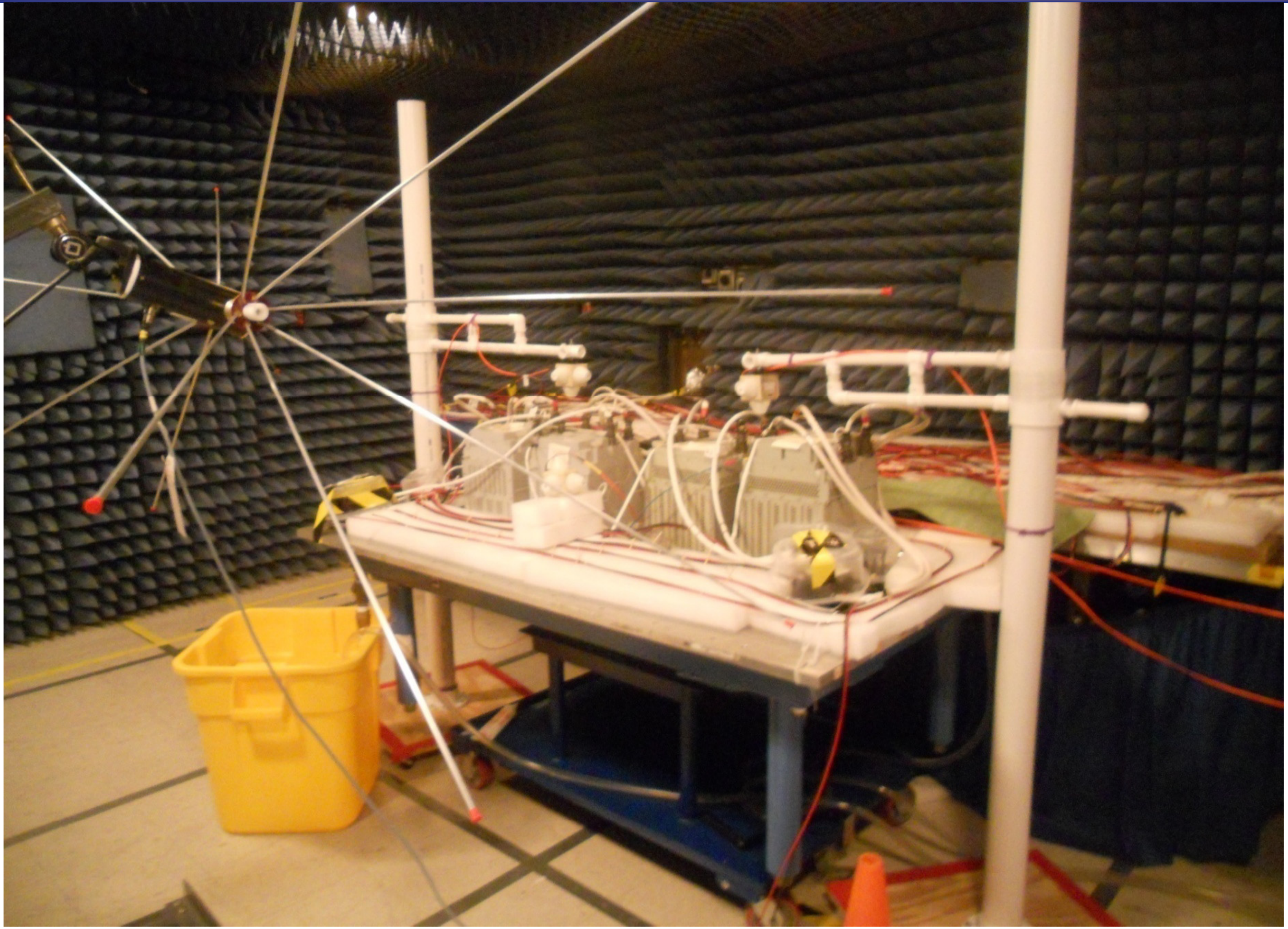


Orion / Prototype (CM) (A/C)



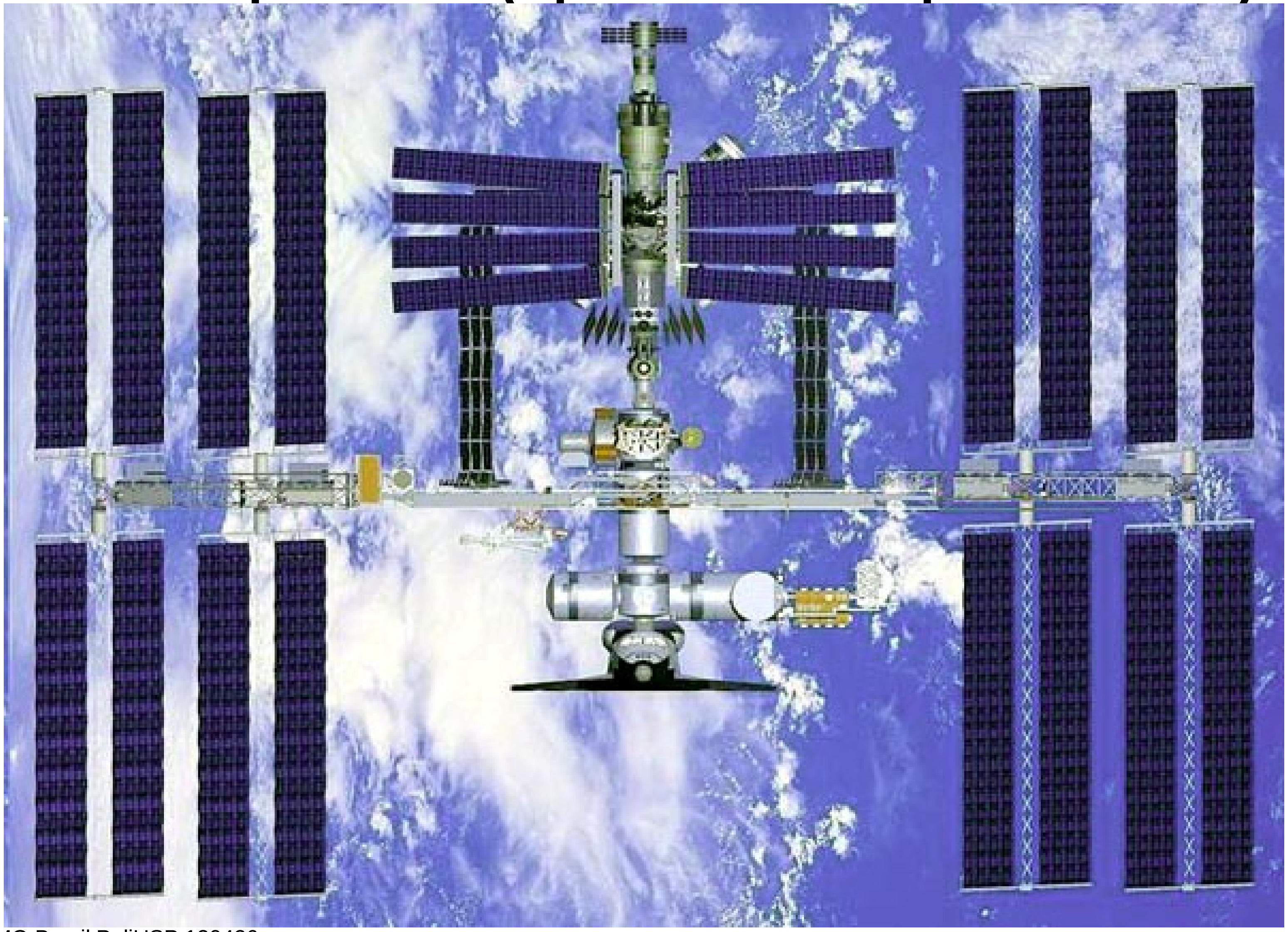
Ex 3: ISS / EVA (Spacewalk)

Ex 4: CPAS RS103 (SS)
(Solar Array DC2AC Converters)



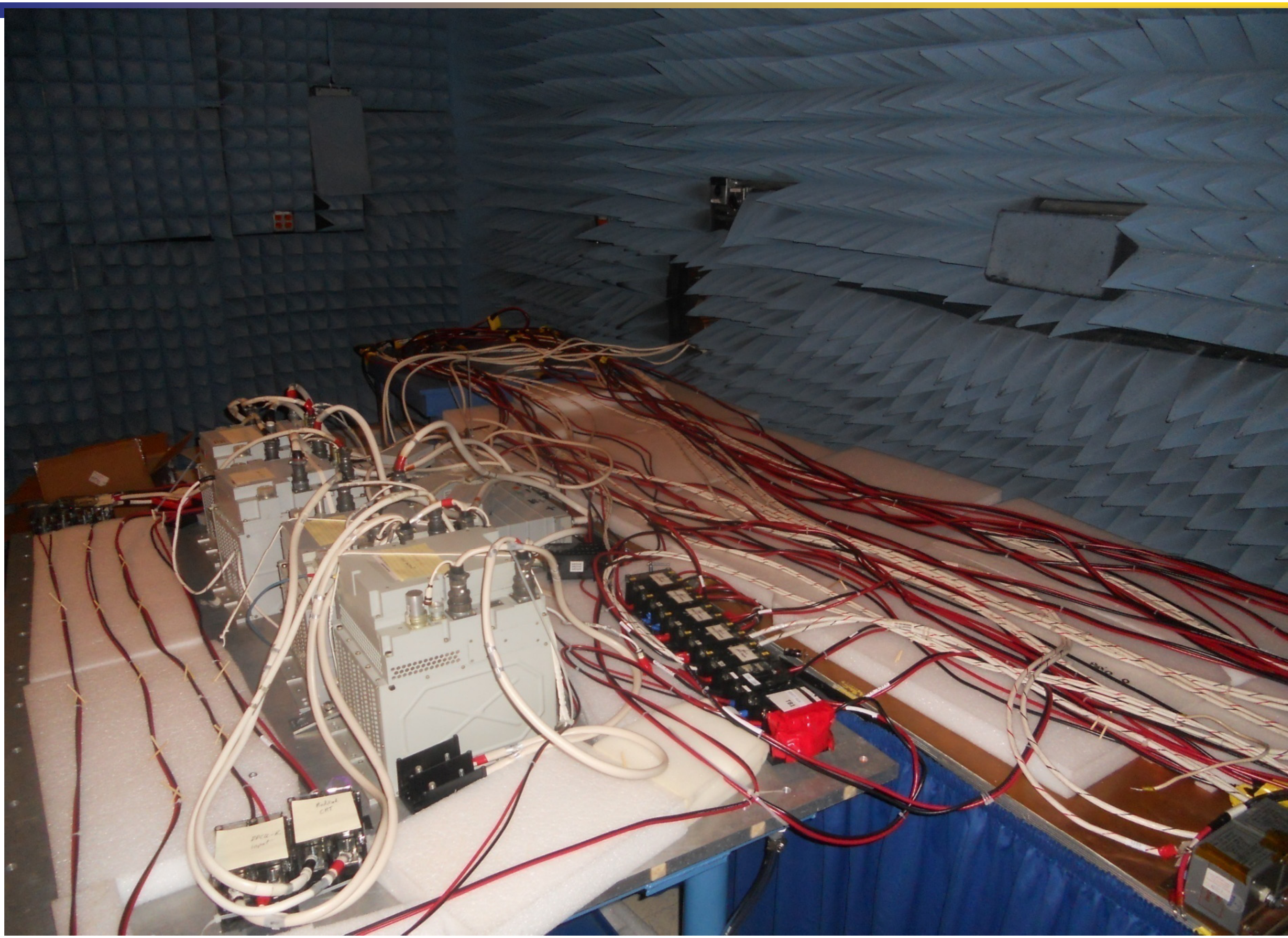
ISS
(Solar Arrays)

- **Antenna/Spacecraft (Space Shuttle/Space Station)**

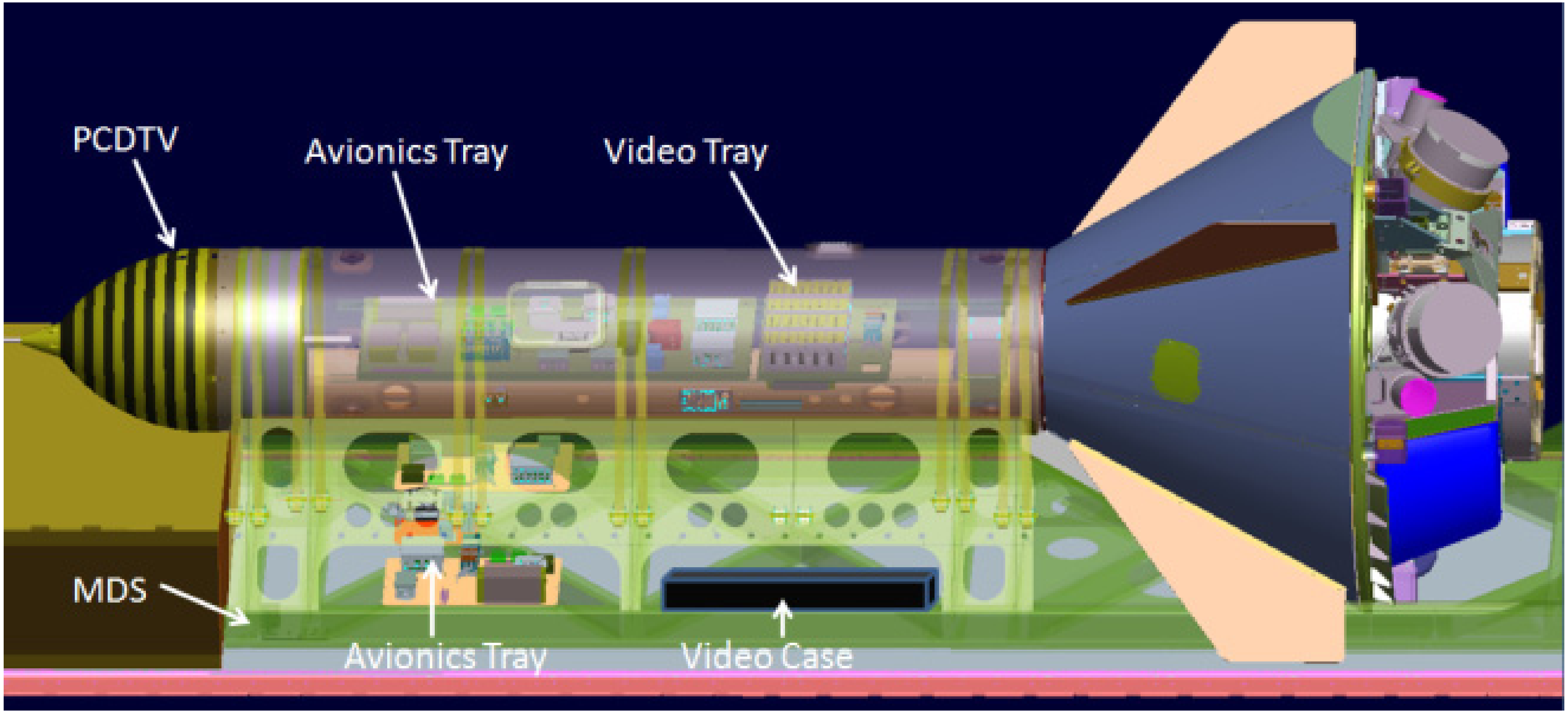


CPAS RS103 (ISS)
(Solar Array DC2AC Converters)

CPAS RS103 (ISS) (Solar Array DC2AC Converters)



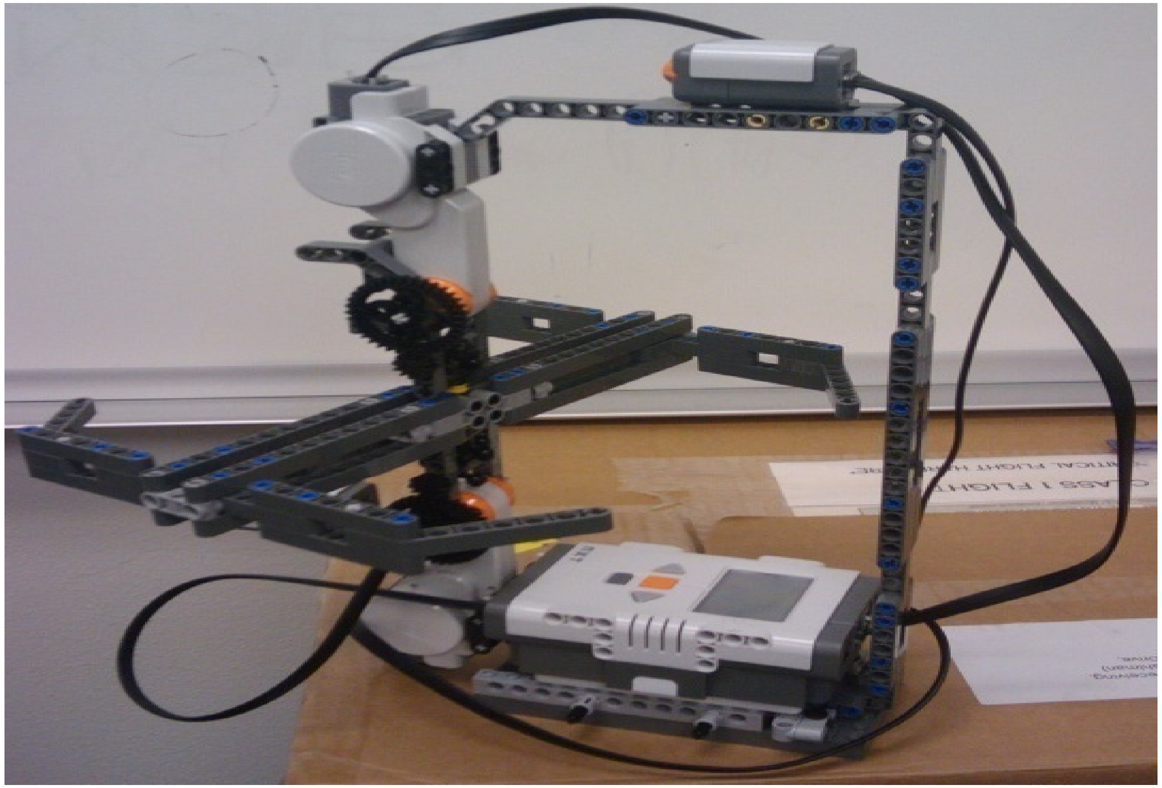
Ex 5: CPAS

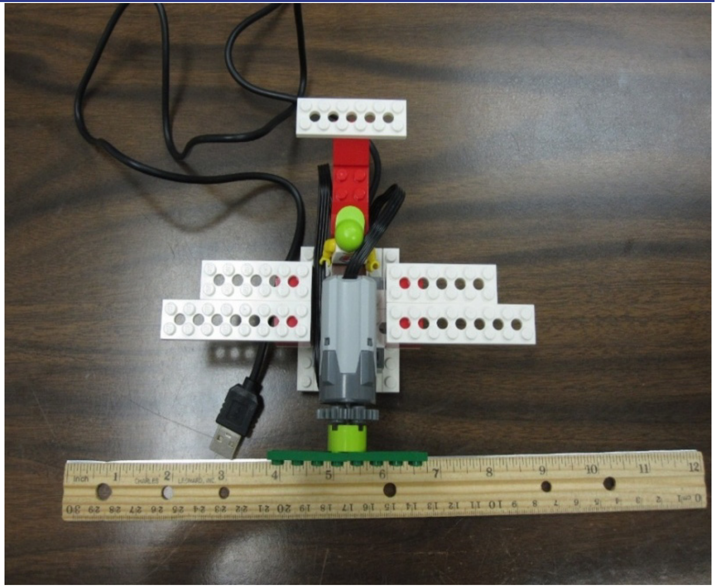

PCDTV
Avionics Tray
Video Tray
MDS
Avionics Tray
Video Case

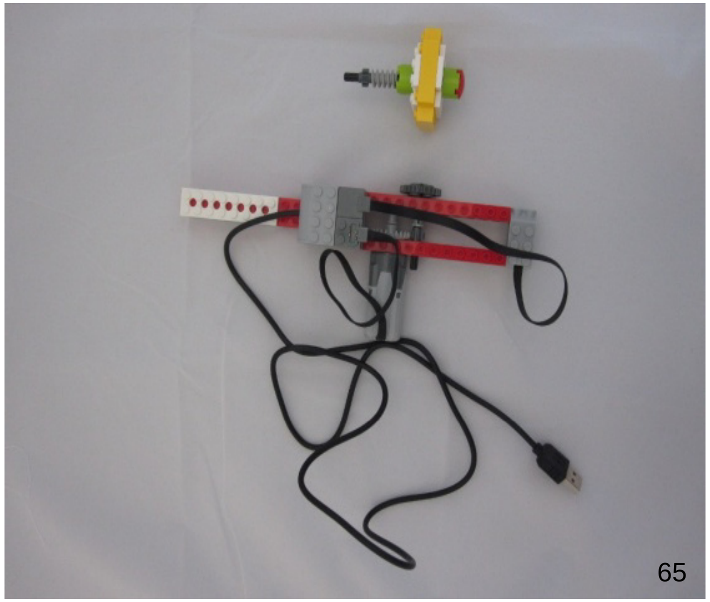
CPAS Prototype (C130 Drop Test)

YPG Drop Site

Ex 6: LEGO (Education Setup)



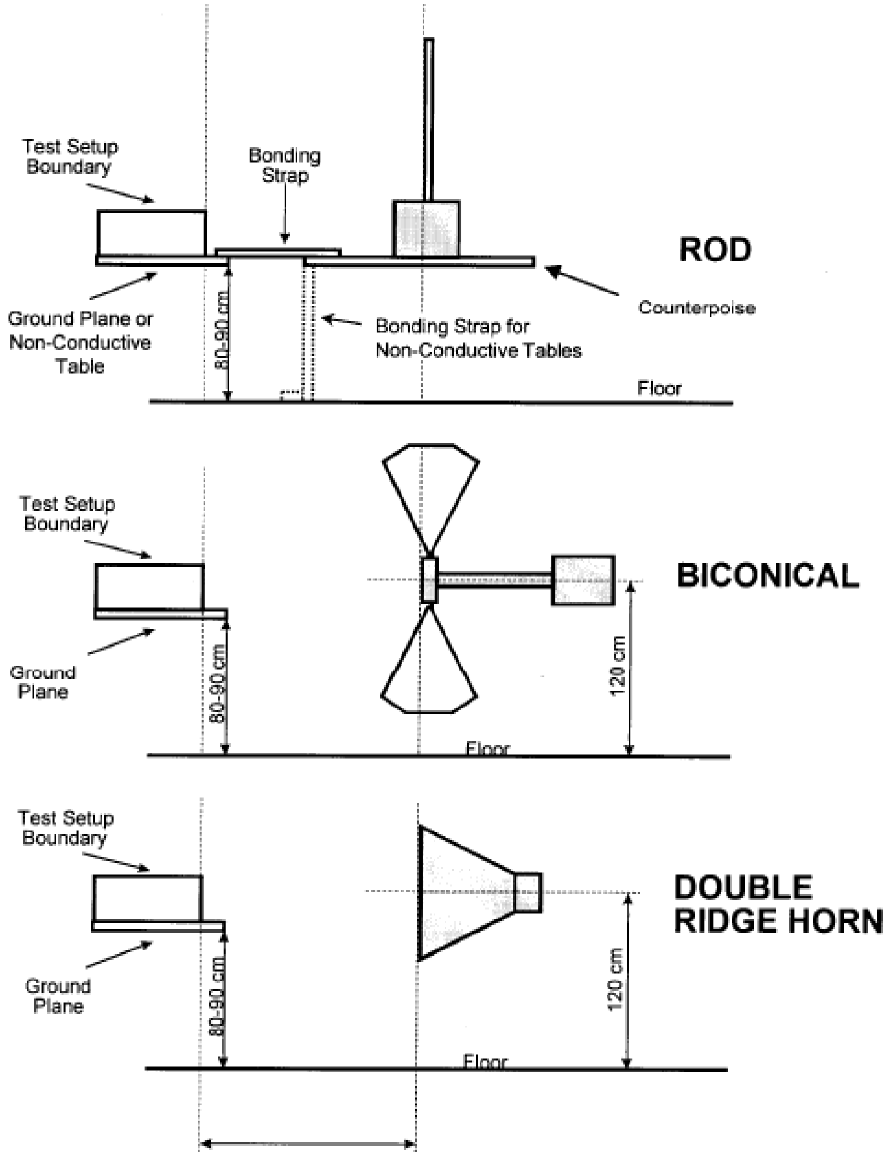




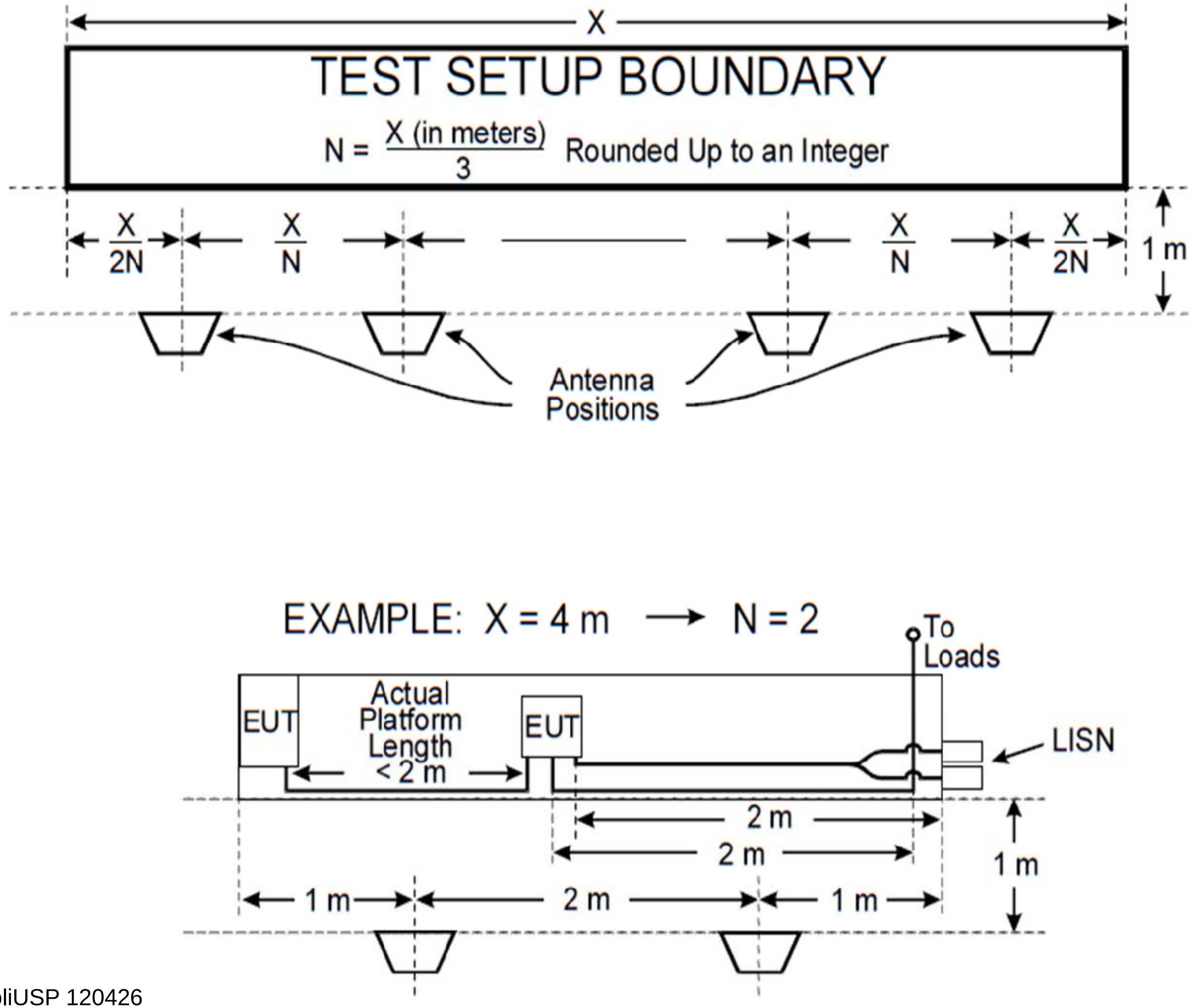
II: Tests ~ Radiation (RE/RS)

- **Emissions**
  - **MIL-STD 461 (RE02)**
- **Immunity**
  - **MIL-STD 461 (RS03)**

II: Tests ~ RE02 Setup (ISS) (Frequency Bands)

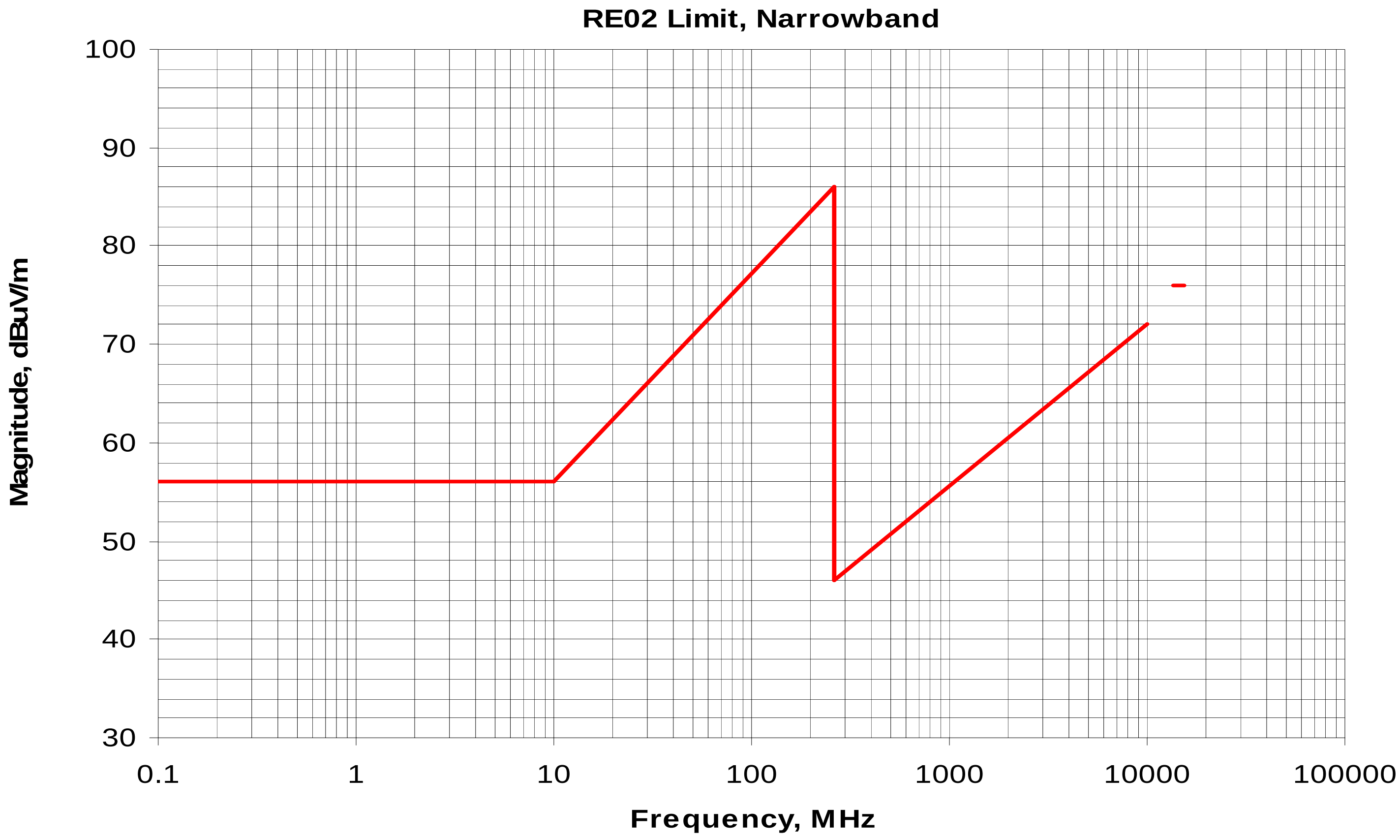


II: Tests ~ RE02 Setup (ISS) (Positions)



II: Tests ~ RE02/ISS (Limit)

- **14 kHz – 15.5 GHz**



II: Tests ~ RE/Ambients

TPS WL1021037
Page 132 of 176

Test Date: 05/24/2010 Test Time: 7:28 pm - 7:50 pm

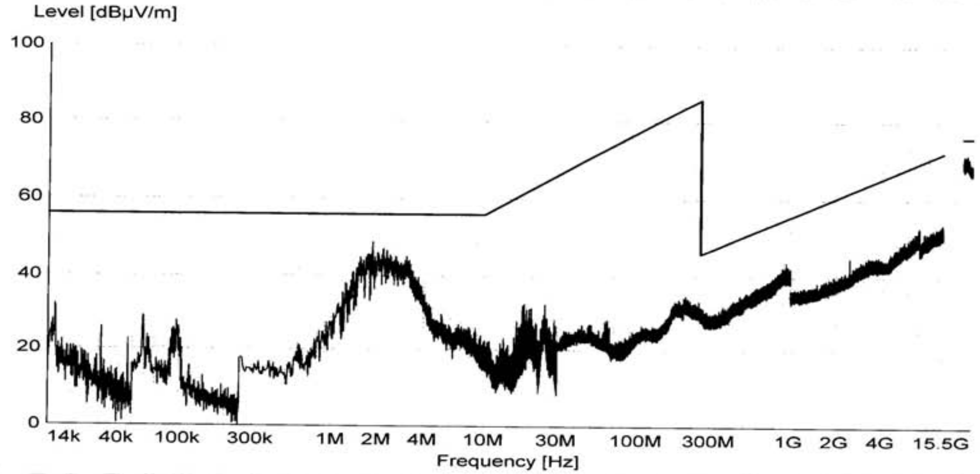
Sec:11.4 Steps 8-9 (RE02) Ambient Data (Met the requir.)

EUT NAME:	ROBONAUT 2 (EUT POSITION SERVO)
TEST CLASSIFICATION:	Certification
TP.NO: TPS.NO:	EV5-10-EMC-009P WL1021037
TEST SITE:	JSC B14A Rm. 1000
OPERATOR:	Cynthia Hightower, Charles Brooks
TEST SPECIFICATION:	Radiation Emissions Space Station Spec. SSP57000 Frequency Range 14 kHz - 10 GHz 13.5 - 15.5 GHz 120Vdc 10 amps fused ~ 5.9 amps meas

SCAN TABLE: "SSP30237 RE02"

Short Description: SSP30237 RE02

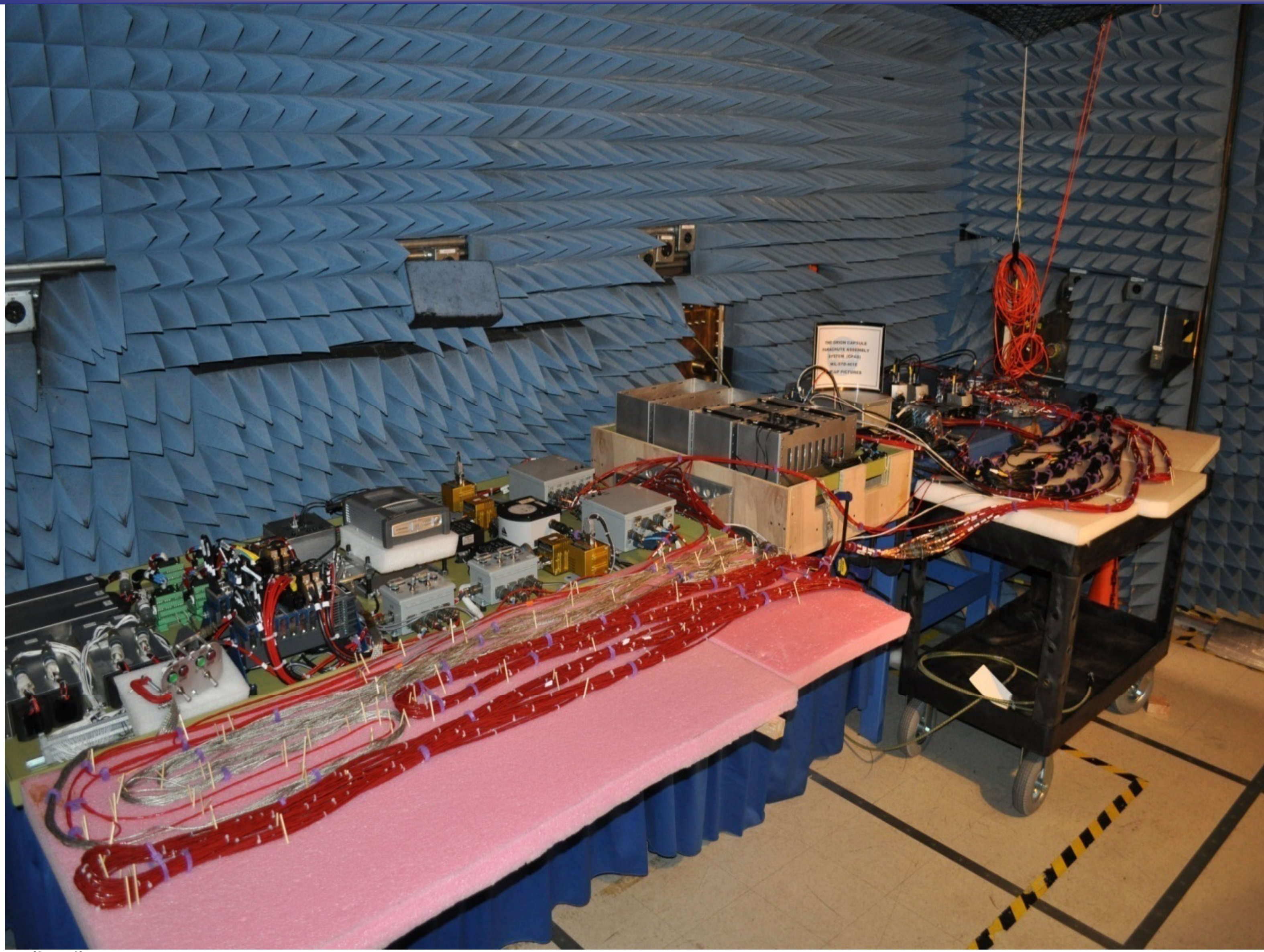
Start Frequency	Stop Frequency	Step Width	Detector	Meas. Time	IF Bandw.	Transducer
14.0 kHz	50.0 kHz	100.0 Hz	MaxPeak	10.0 ms	200 Hz	SAS-200/550-1 686
50.0 kHz	250.0 kHz	500.0 Hz	MaxPeak	10.0 ms	1 kHz	SAS-200/550-1 686
250.0 kHz	30.0 MHz	5.0 kHz	MaxPeak	5.0 ms	10 kHz	SAS-200/550-1 686
30.0 MHz	200.0 MHz	50.0 kHz	MaxPeak	5.0 ms	100 kHz	3104C 4708 4714
200.0 MHz	1.0 GHz	50.0 kHz	MaxPeak	5.0 ms	100 kHz	93490-1 1109 1110
1.0 GHz	10.0 GHz	500.0 kHz	MaxPeak	5.0 ms	1 MHz	3115 S/N 6059
13.5 GHz	15.5 GHz	5.0 MHz	MaxPeak	5.0 ms	10 MHz	3115 S/N 6059



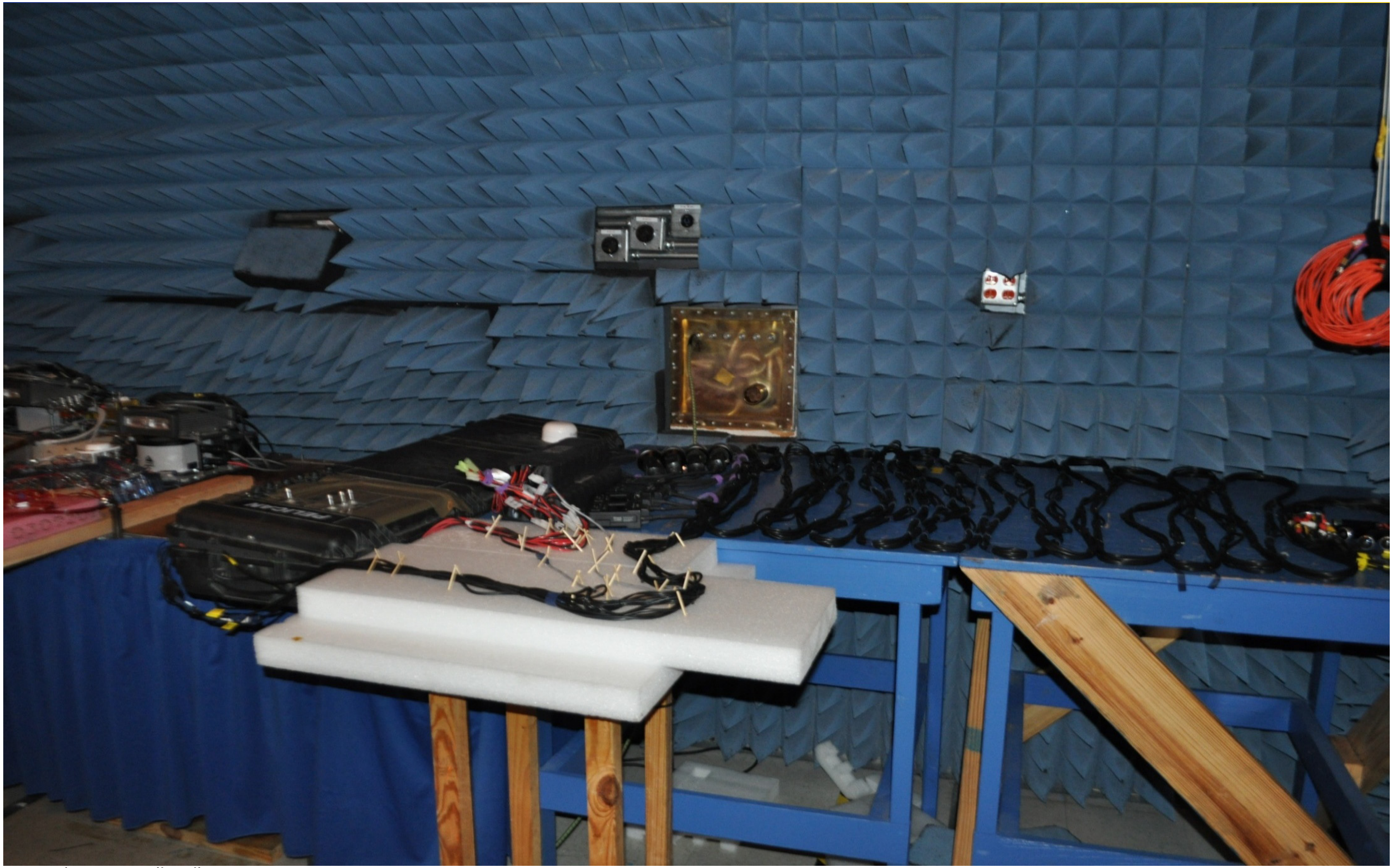
MES 14-30 AMB w/GSE
MES 30/200 H AMB w/GSE
MES 30/200 V AMB w/GSE
MES 200/1 AMB w/GSE
MES 1-15.5 H/P AMB w/GSE
MES 1-15.5 V/P AMB w/GSE
LIM SSP30237 RE02 SSP 30237 RE02

Page 1/1 5/26/2010 11:11AM **ORIGINAL**

Ex 1: CPAS RE102 (SS)
(Setup)



CPAS RE102 (SS)
(Setup)

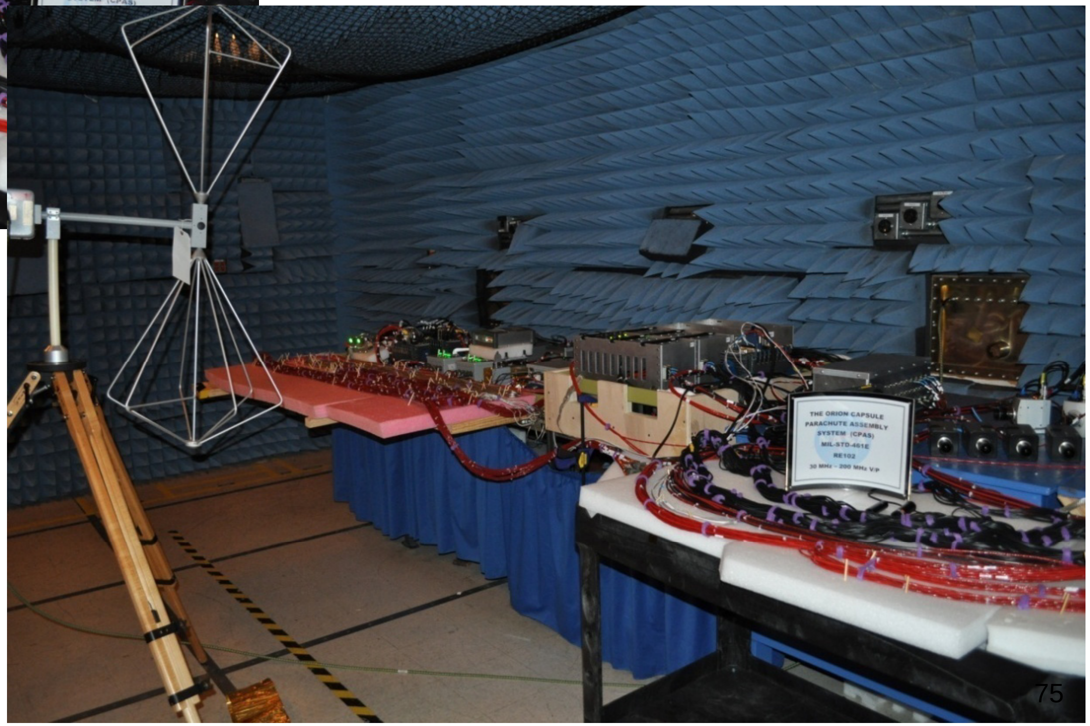


II: Tests ~ CPAS RE102 (SS)

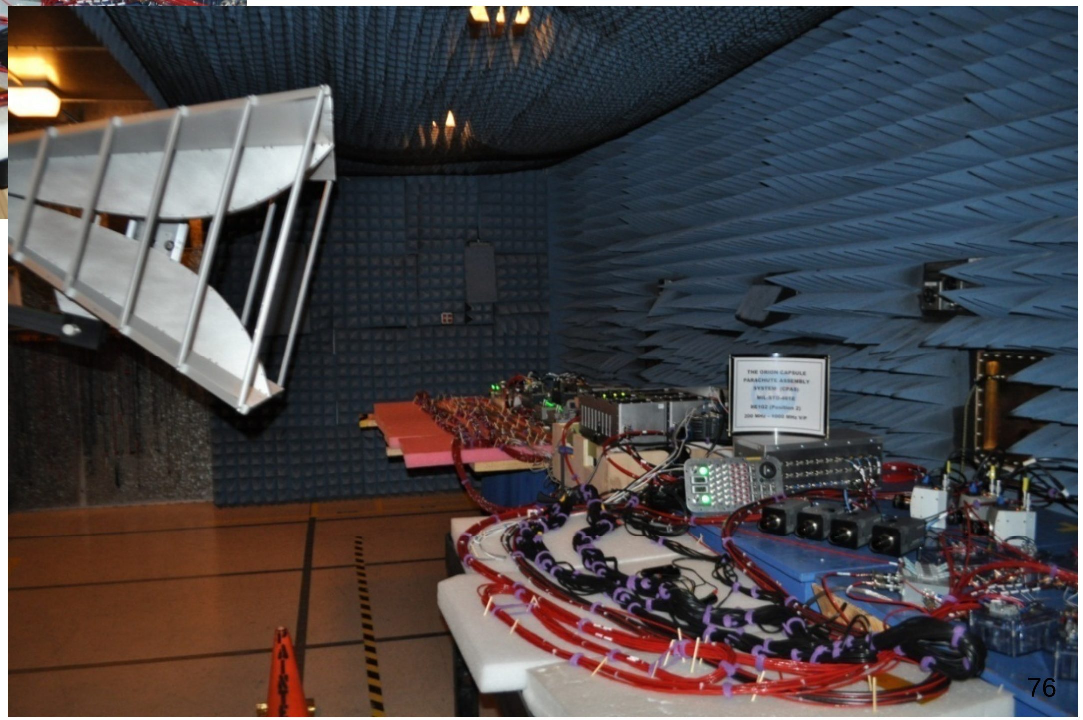
- **2-30 MHz (VP)**
- **30-200 MHz (HP/VP)**
- **200-1000 MHz (HP/VP)**
- **1-18 GHz (HP/VP)**

CPAS RE102 (SS) (2–30 MHz)

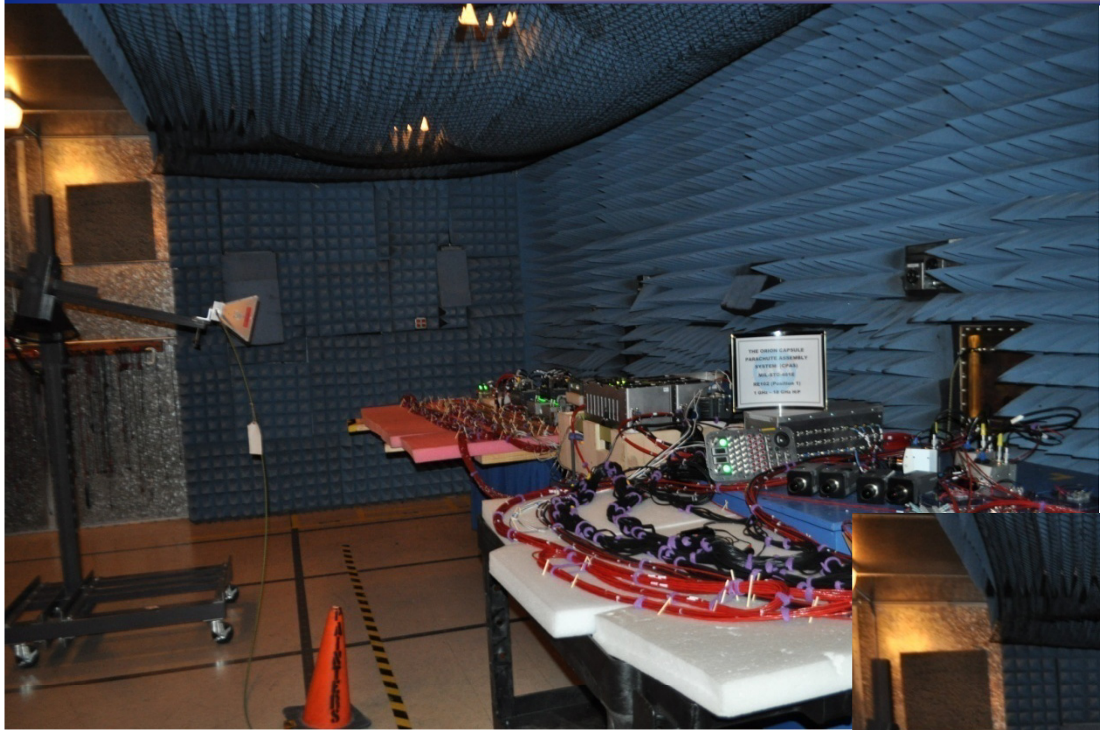
CPAS RE102 (SS) (30-200 MHz)

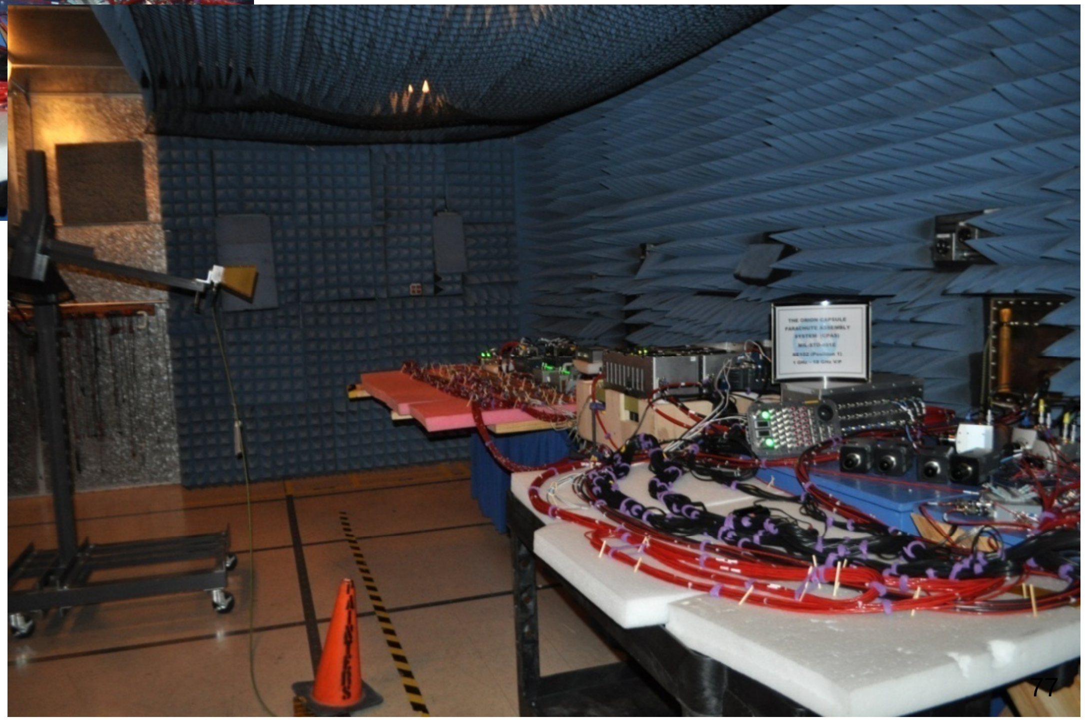


CPAS RE102 (SS)
(200-1000 MHz)



CPAS RE102 (SS)
(1-18 GHz)





Tests ~ RE102 Limit (SS) (BB Failures w/o Shielding)

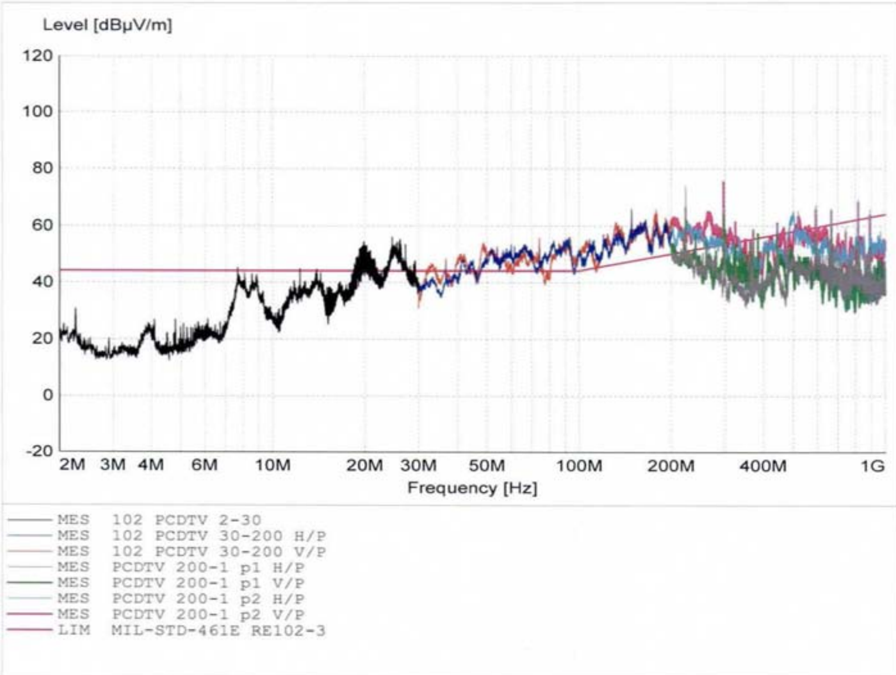
TEST DATE:05/19/2011 TEST TIME: 2:30 pm - 4:44 pm

The Orion Capsule Parachute Assembly System (CPAS)

TEST CLASSIFICATION:	Safety of Flight	Battery Operated
TP.NO: W.O.NO:	EV5-11-EMC-007P	EMCE0-11-011
TEST SITE:	JSC B14 Rm. 1000	
OPERATOR:	Cynthia Hightower	
TEST SPECIFICATION:	Radiated Emission MIL-STD-461E Freq. Range 2 MHz - 1GHz	
Graph Colors:	1. Black 2-30MHz 2. Blue 30-200MHz H/P 3.Red 30-200MHz V/P	
Graph Colors:	4. Grey 200-1GHz H/P p1 5. Green 200-1GHz V/P p1	
Graph Colors:	6.Lt Blue 200-1GHz H/P p2 7. Violet 200-1GHz V/P p2	

SCAN TABLE: "MIL-STD-461E RE102"

Start Frequency	Stop Frequency	Step Width	Detector	Meas. Time	IF Bandw.	Transducer
10.0 kHz	150.0 kHz	500.0 Hz	MaxPeak	15.0 ms	1 kHz	SAS-200/550-1 686
150.0 kHz	30.0 MHz	5.0 kHz	MaxPeak	15.0 ms	10 kHz	SAS-200/550-1 686
30.0 MHz	200.0 MHz	50.0 kHz	MaxPeak	15.0 ms	100 kHz	3104C 4708 4714
200.0 MHz	1.0 GHz	50.0 kHz	MaxPeak	15.0 ms	100 kHz	3106 S/N 2824
1.0 GHz	18.0 GHz	500.0 kHz	MaxPeak	15.0 ms	1 MHz	3115 S/N 6059



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Tests ~ RE102 Limit (SS) (NB Failures w/o Shielding)

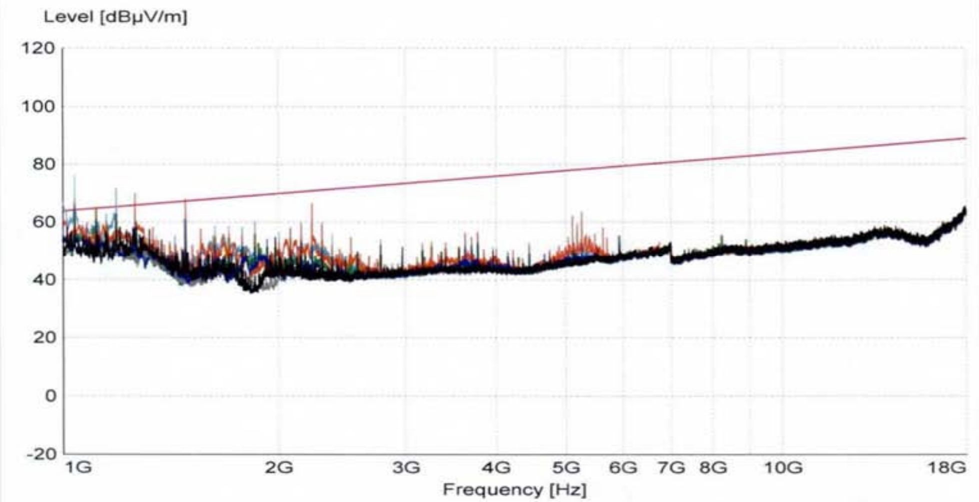
TEST DATE:05/20/2011 TEST TIME: 8:06 am - 10:23 am

The Orion Capsule Parachute Assembly System (CPAS)

TEST CLASSIFICATION:	Safety of Flight	Battery Operated
TP.NO: W.O.NO:	EV5-11-EMC-007P	EMCE0-11-011
TEST SITE:	JSC B14 Rm. 1000	
OPERATOR:	Cynthia Hightower	
TEST SPECIFICATION:	Radiated Emission MIL-STD-461E	Freq. Range 1 - 18GHz
Graph Colors:	1.Black 1-18GHz H/P p1	2. Blue 1-18GHz H/P p2
Graph Colors:	3:Red 1-18GHz H/P p3	4. Grey 1-18GHz V/P p1
Graph Colors:	5.Green 1-18GHz V/P p2	6.Lt Blue 1-18GHz V/P p3

SCAN TABLE: "MIL-STD-461E RE102"

Start Frequency	Stop Frequency	Step Width	Detector	Meas. Time	IF Bandw.	Transducer
10.0 kHz	150.0 kHz	500.0 Hz	MaxPeak	15.0 ms	1 kHz	SAS-200/550-1 686
150.0 kHz	30.0 MHz	5.0 kHz	MaxPeak	15.0 ms	10 kHz	SAS-200/550-1 686
30.0 MHz	200.0 MHz	50.0 kHz	MaxPeak	15.0 ms	100 kHz	3104C 4708 4714
200.0 MHz	1.0 GHz	50.0 kHz	MaxPeak	15.0 ms	100 kHz	3106 S/N 2824
1.0 GHz	18.0 GHz	500.0 kHz	MaxPeak	15.0 ms	1 MHz	3115 S/N 6059



MES PCDTV 1-18 p1 H/P
MES PCDTV 1-18 p2 H/P
MES PCDTV 1-18 p3 H/P
MES PCDTV 1-18 p1 V/P
MES PCDTV 1-18 p2 V/P
MES PCDTV 1-18 p3 V/P
LIM MIL-STD-461E RE102-3

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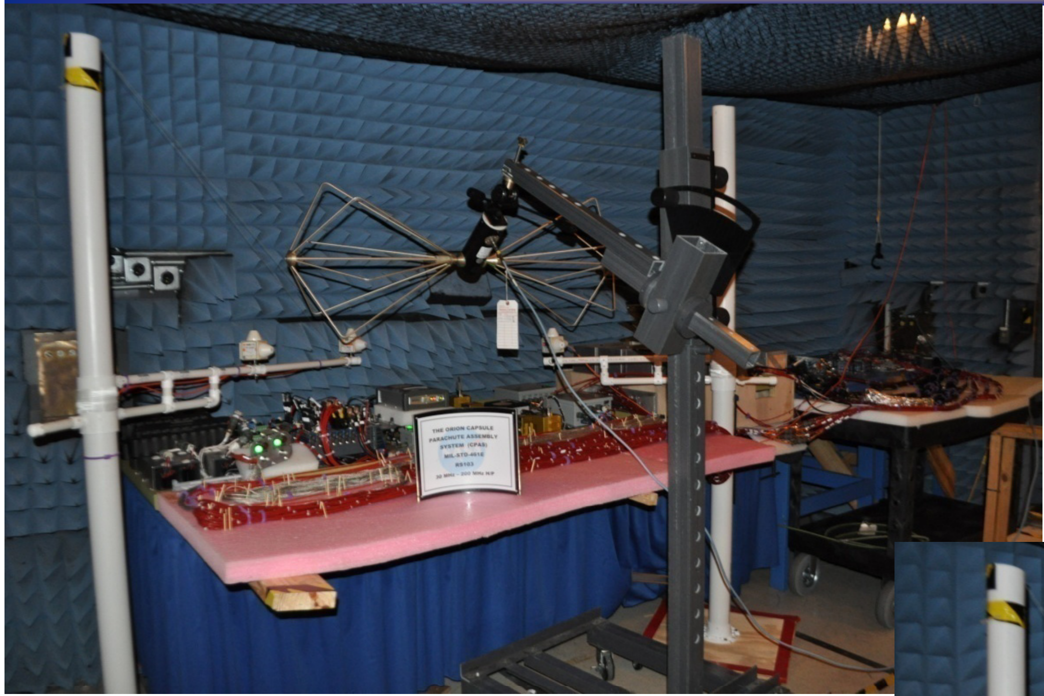
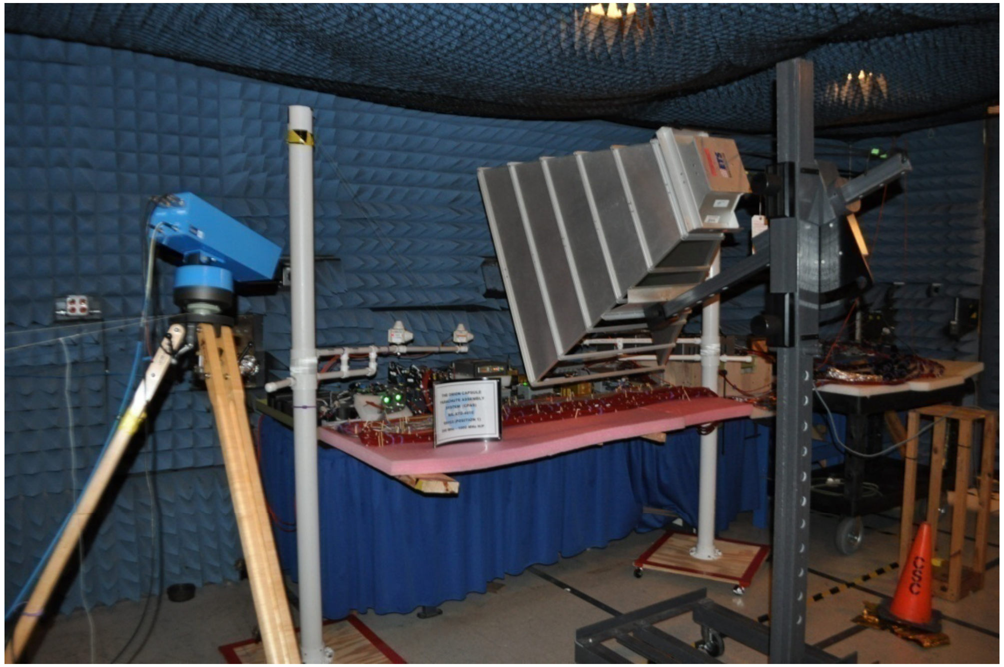
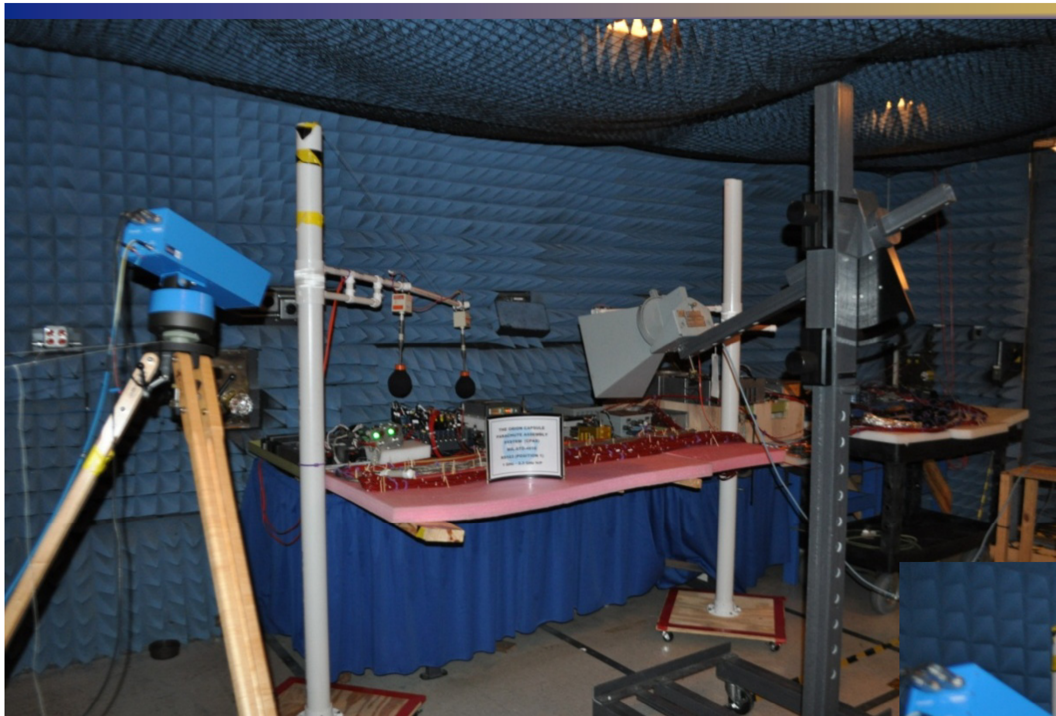
CPAS RS103 (SS)
(30-200 MHz)



CPAS RS103 (SS) (200-1000 MHz)



CPAS RS103 (SS)
(1-20 GHz)



II: CPAS RS103 (SS) (HP/Position#1)

Johnson Space Center
Electromagnetic Interference (EMI) Test Facility

Component: The Orion Capsule Parachute Assembly System (CPAS) RS103 POSITION 1

Horizontal Polarization

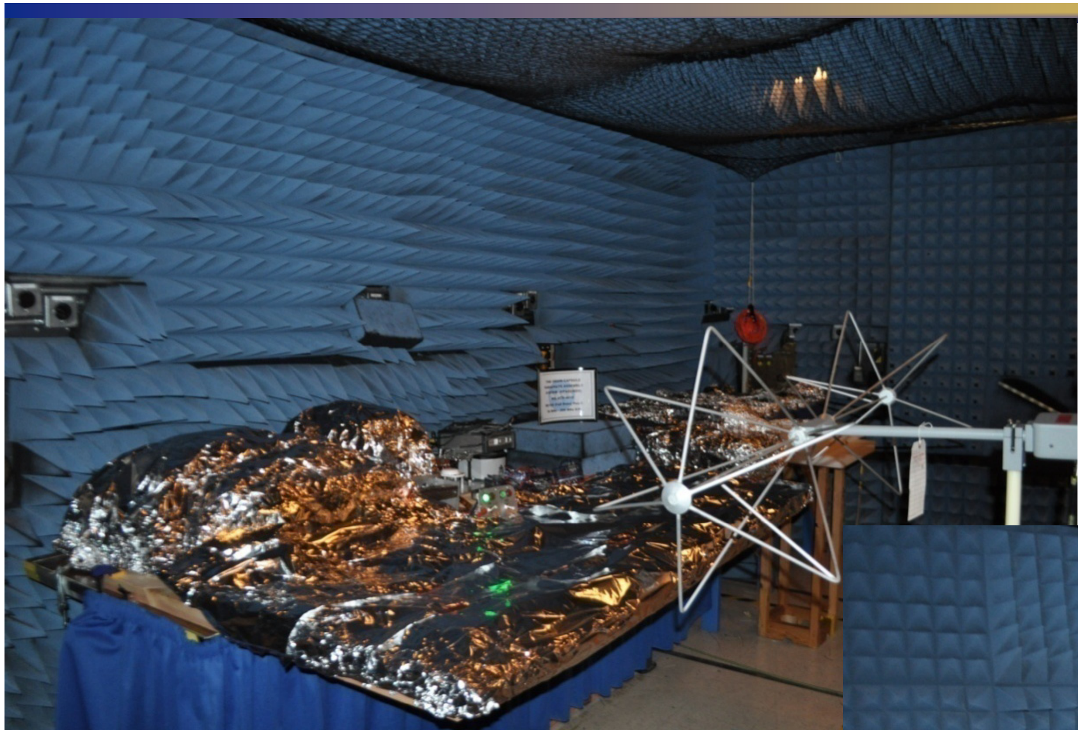
FREQUENCY (MHz)	MIL-STD-461E Limit (V/m)	Injected Test Signal			Remarks	Test Sample Response
		Probe #1 Level (V/m)	Probe #2 Level (V/m)	Probe #3 Level (V/m)		
30.000	200.00	16.00	107.80	200.50	(CPAS) Pass, Maintain RF V/m Level @ Limit	Not Susceptible
40.000	200.00	11.07	100.20	200.00	(CPAS) Pass, Maintain RF V/m Level @ Limit	
50.000	200.00	16.02	115.20	200.50	(CPAS) Pass, Maintain RF V/m Level @ Limit	
60.000	200.00	12.39	104.20	200.80	(CPAS) Pass, Maintain RF V/m Level @ Limit	
70.000	200.00	24.06	97.10	200.90	(CPAS) Pass, Maintain RF V/m Level @ Limit	
80.000	200.00	40.60	98.90	200.50	(CPAS) Pass, Maintain RF V/m Level @ Limit	
90.000	200.00	55.90	150.90	200.70	(CPAS) Pass, Maintain RF V/m Level @ Limit	
93.900	200.00	47.00	112.00	174.00	(CPAS) Pass, Max Obtainable Level	
95.000	200.00	46.70	109.00	174.30	(CPAS) Pass, Max Obtainable Level	
99.500	200.00	64.70	129.50	200.90	(CPAS) Pass, Maintain RF V/m Level @ Limit	
100.000	200.00	63.70	128.00	200.10	(CPAS) Pass, Maintain RF V/m Level @ Limit	
110.000	200.00	91.30	69.00	111.50	(CPAS) Pass, Max Obtainable Level	
120.000	200.00	120.00	107.00	133.60	(CPAS) Pass, Max Obtainable Level	
141.000	200.00	132.20	110.00	175.00	(CPAS) Pass, Max Obtainable Level	
145.000	200.00	132.40	102.00	166.00	(CPAS) Pass, Max Obtainable Level	
150.000	200.00	147.80	110.00	185.80	(CPAS) Pass, Max Obtainable Level	
153.000	200.00	152.80	109.90	193.40	(CPAS) Pass, Max Obtainable Level	
157.000	200.00	145.70	113.10	178.60	(CPAS) Pass, Max Obtainable Level	
163.600	200.00	176.10	132.10	200.10	(CPAS) Pass, Maintain RF V/m Level @ Limit	
165.000	200.00	170.00	127.70	191.10	(CPAS) Pass, Max Obtainable Level	
170.000	200.00	164.70	134.20	200.00	(CPAS) Pass, Maintain RF V/m Level @ Limit	Not Susceptible
180.400	200.00	195.00	108.10	200.30	(CPAS) Pass, Maintain RF V/m Level @ Limit	
185.100	200.00	181.00	95.10	200.10	(CPAS) Pass, Maintain RF V/m Level @ Limit	
190.000	200.00	191.50	84.40	200.50	(CPAS) Pass, Maintain RF V/m Level @ Limit	
200.000	200.00	186.30	84.40	200.80	(CPAS) Pass, Maintain RF V/m Level @ Limit	
300.000	200.00	200.10	164.20	191.00	(CPAS) Pass, Maintain RF V/m Level @ Limit	
400.000	200.00	200.00	131.40	150.30	(CPAS) Pass, Maintain RF V/m Level @ Limit	
500.000	200.00	200.50	135.60	151.80	(CPAS) Pass, Maintain RF V/m Level @ Limit	
600.000	200.00	200.30	130.00	197.20	(CPAS) Pass, Maintain RF V/m Level @ Limit	
700.000	200.00	150.40	184.90	200.50	(CPAS) Pass, From 700MHz -992MHz Primary/Secondary-SD/Activity LED Lights Flashed ON&OFF	
992.000	200.00	200.00	173.50	71.60	(CPAS) Pass, From 700MHz -992MHz Primary/Secondary-SD/Activity LED Lights Flashed ON&OFF	

II: Tests ~ CPAS (NOT Space Flight Qualified)

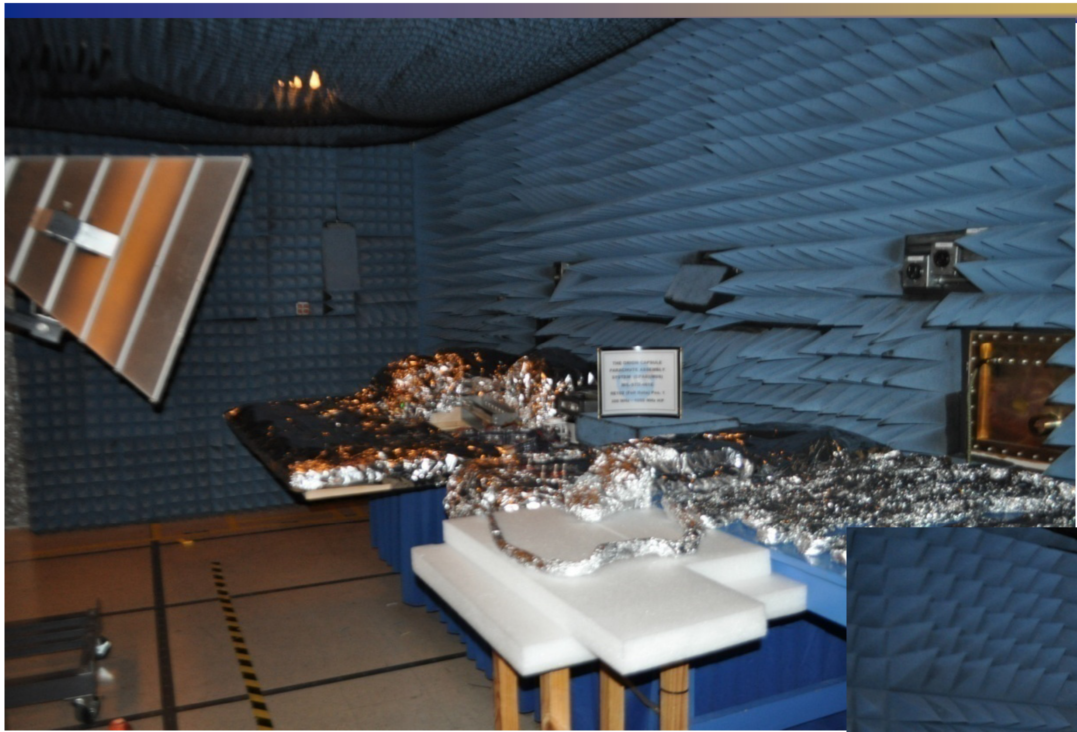
- **Faraday Cages**
- **Shielding**

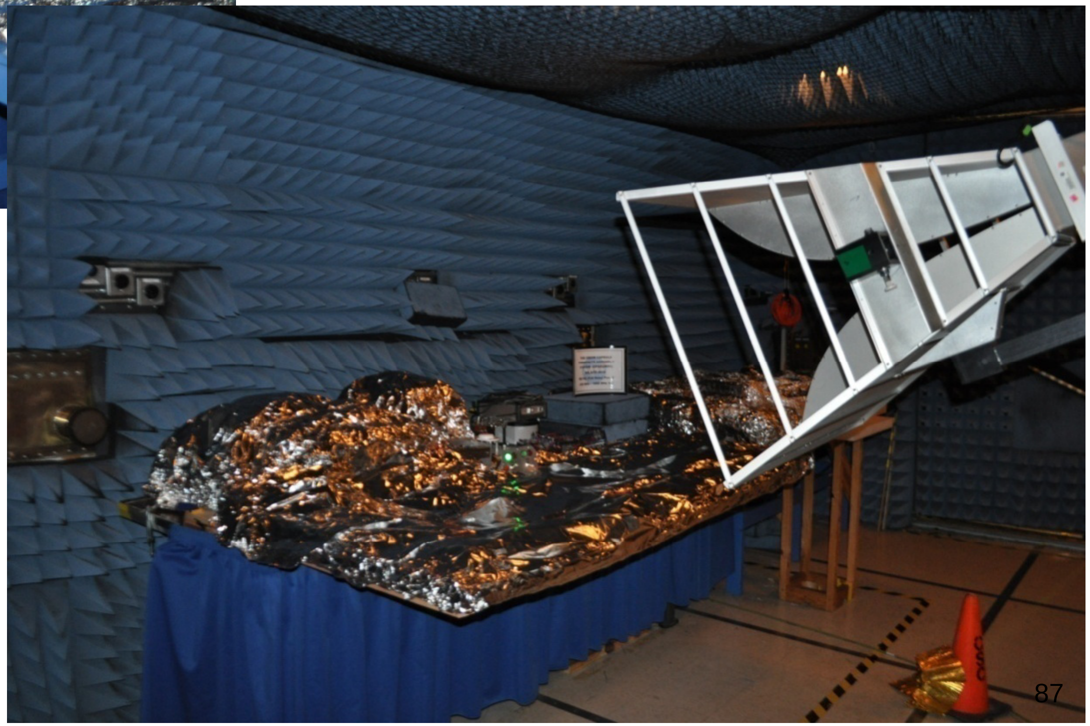
Cable/Component Shielding

CPAS RE102 (SS) (30-200 MHz)



CPAS RE102 (SS)
(200-1000 MHz)





CPAS RE102 (SS)
(1-18 GHz)

RE102 Limit (SS)
(NB Failure w/ Shielding)

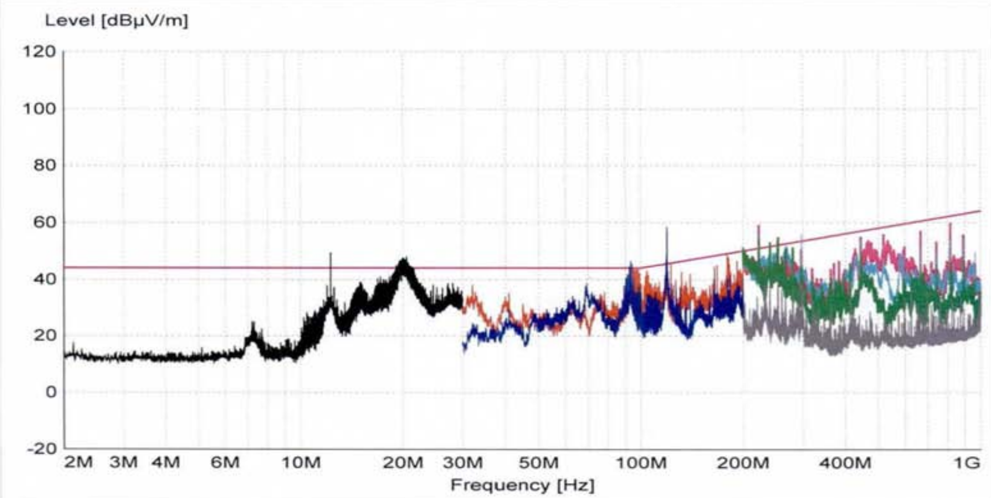
TEST DATE:06/3-4/2011   CPAS Completely Foiled

The Orion Capsule Parachute Assembly System (CPAS)

TEST CLASSIFICATION: Safety of Flight   Battery Operated
TP.NO: W.O.NO: EV5-11-EMC-007P   EMCEO-11-011
TEST SITE: JSC B14 Rm. 1000
OPERATOR: Cynthia Hightower
TEST SPECIFICATION: Radiated Emission MIL-STD-461E   Freq. Range 2 MHz - 1GHz
Graph Colors: 1. Black 2-30MHz   2. Blue 30-200MHz H/P   3.Red 30-200MHz V/P
Graph Colors: 4. Grey   200-1GHz H/P p1   5. Green 200-1GHz V/P p1
Graph Colors: 6.Lt Blue   200-1GHz H/P p2   7. Violet 200-1GHz V/P p2

SCAN TABLE: "MIL-STD-461E RE102"

Start Frequency	Stop Frequency	Step Width	Detector	Meas. Time	IF Bandw.	Transducer
10.0 kHz	150.0 kHz	500.0 Hz	MaxPeak	15.0 ms	1 kHz	SAS-200/550-1 686
150.0 kHz	30.0 MHz	5.0 kHz	MaxPeak	15.0 ms	10 kHz	SAS-200/550-1 686
30.0 MHz	200.0 MHz	50.0 kHz	MaxPeak	15.0 ms	100 kHz	3104C 4708 4714
200.0 MHz	1.0 GHz	50.0 kHz	MaxPeak	15.0 ms	100 kHz	3106 S/N 2824
1.0 GHz	18.0 GHz	500.0 kHz	MaxPeak	15.0 ms	1 MHz	3115 S/N 6059



MES Full sys.foil 2-30
MES Full sys len cv H/P
MES Full sys. len cv V/P
MES Full sys.200-1 H/P1
MES Full sys.200-1 V/P1
MES Full sys.200-1 H/P2
MES Full sys.200-1 V/P2
LIM MIL-STD-461E RE102-3

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II: RE102 Limit (SS) (Pass w/ Shielding)

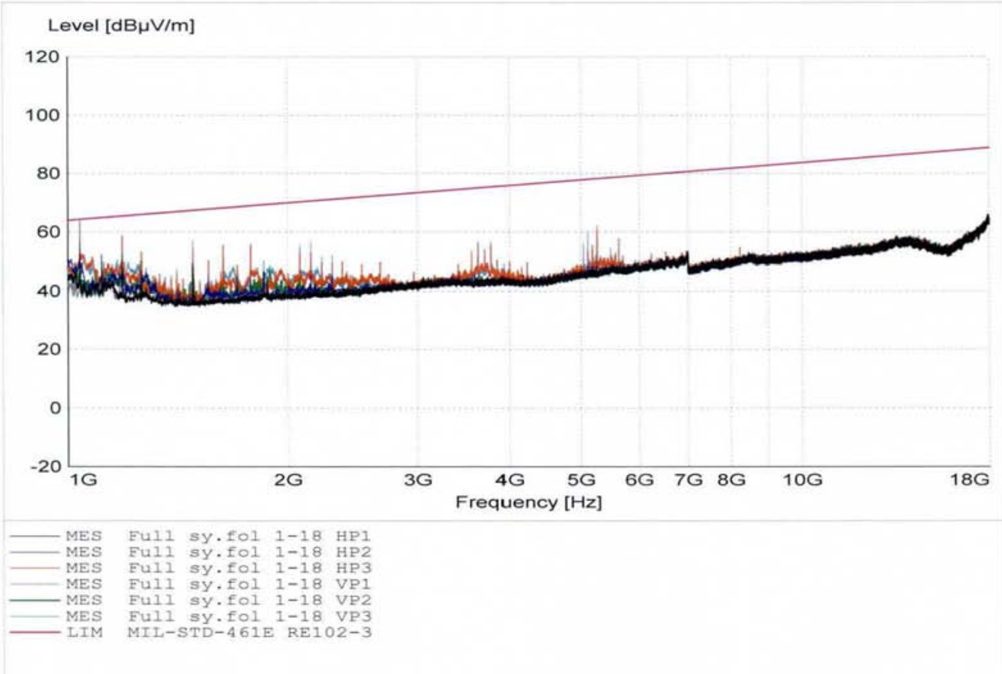
TEST DATE:06/04/2011 CPAS Completely Foiled

The Orion Capsule Parachute Assembly System (CPAS)

TEST CLASSIFICATION:	Safety of Flight	Battery Operated		
TP.NO: W.O.NO:	EV5-11-EMC-007P	EMCEO-11-011		
TEST SITE:	JSC B14 Rm. 1000			
OPERATOR:	Cynthia Hightower			
TEST SPECIFICATION:	Radiated Emission MIL-STD-461E		Freq. Range 1 - 18GHz	
Graph Colors:	1.Black	1-18GHz H/P p1	2. Blue	1-18GHz H/P p2
Graph Colors:	3:Red	1-18GHz H/P p3	4. Grey	1-18GHz V/P p1
Graph Colors:	5.Green	1-18GHz V/P p2	6.Lt Blue	1-18GHz V/P p3

SCAN TABLE: "MIL-STD-461E RE102"

Start Frequency	Stop Frequency	Step Width	Detector	Meas. Time	IF Bandw.	Transducer
10.0 kHz	150.0 kHz	500.0 Hz	MaxPeak	15.0 ms	1 kHz	SAS-200/550-1 686
150.0 kHz	30.0 MHz	5.0 kHz	MaxPeak	15.0 ms	10 kHz	SAS-200/550-1 686
30.0 MHz	200.0 MHz	50.0 kHz	MaxPeak	15.0 ms	100 kHz	3104C 4708 4714
200.0 MHz	1.0 GHz	50.0 kHz	MaxPeak	15.0 ms	100 kHz	3106 S/N 2824
1.0 GHz	18.0 GHz	500.0 kHz	MaxPeak	15.0 ms	1 MHz	3115 S/N 6059



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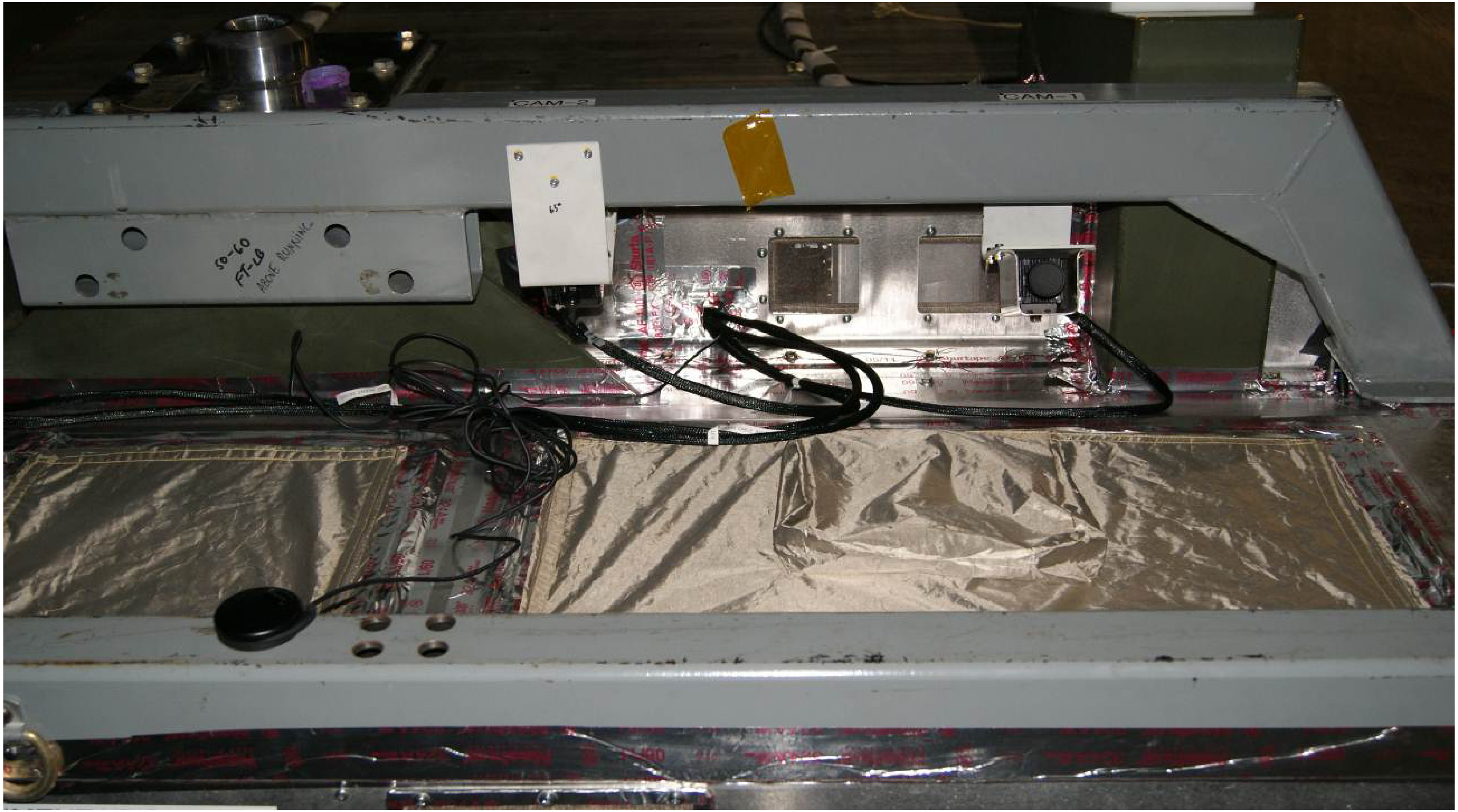
Faraday Cage (YPG) (Metal/Cloth/Mesh)

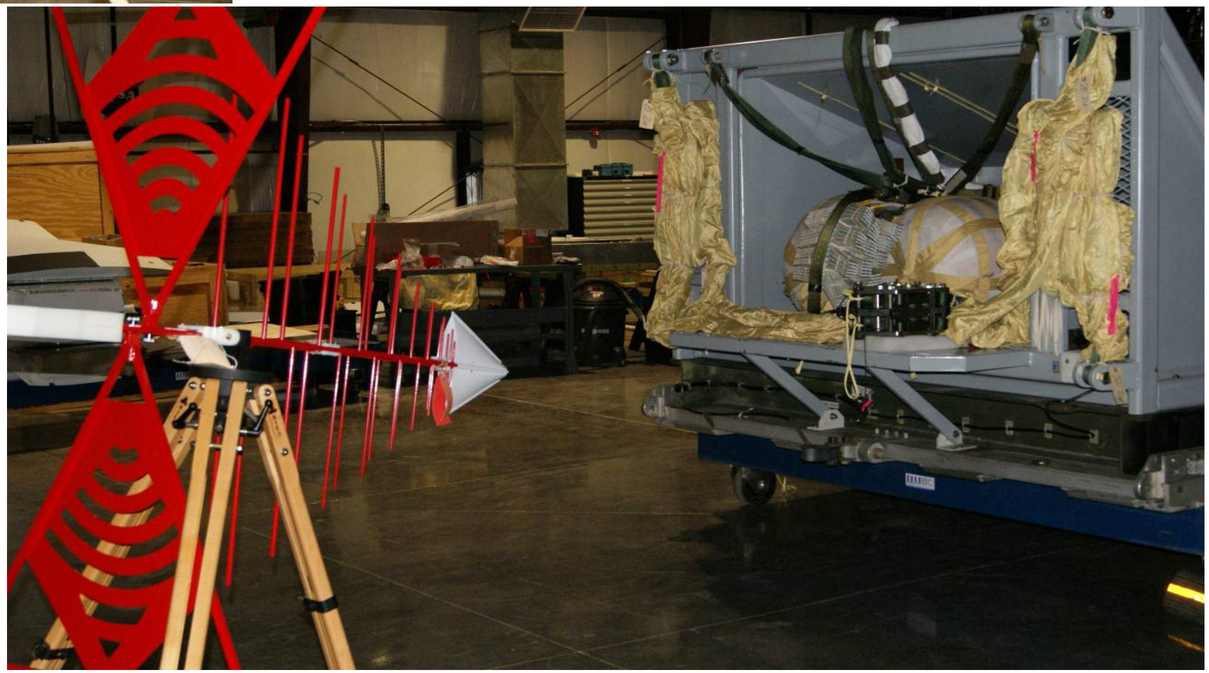
Integration (YPG)



II: Tests ~ CPAS RE102/RS103 (SS)

- **14 kHz - 30 MHz (VP)**
- **30-200 MHz (HP/VP)**
- **200-1000 MHz (HP/VP)**
- **1-20 GHz (HP/VP)**

CPAS RE102/RS103 (SS) (Pyros/Mortars)



CPAS RE102/RS103 (SS)

Weigh/CoG (YPG)

MIL STD 464 (YPG/FF/Integrated-System)

MIL STD 464
(YPG/FF/Integrated-System)

II: Test ~ CPAS (C-17)

Outline

- I: Introduction
  - NASA (S/C Problems ~ Work Experiences/Examples)
- EMI/EMC Problem/Solution
- **Compliance Checks ~ Limits**
  - II: Test (MIL-STD) ~$$$
    - Radiation/Conduction (Wireless/Wired)
    - Emissions/Immunity (Susceptibility/Vulnerability)
  - III: Analysis/Design ~20 dB Penalty!
    - Radiation ~ TX/RX Antennas (Intentional/Unintentional)
    - THE Unique "Radiation Integrals" ~ Greens Function(Weight/Sum)
      - Analytical (Exact/Asymptotic) Antenna Answer (Solution: >100y Old)
      - Numerical (CEM) M&S ~ Canonical(V&V) / Hi-Fi Models
        - MoM (Source: Based on Solution to ME) OATS
        - FDM/FEM/TLM/etc (Field: Based on ME +BC) A/C

III: Analysis/Design (Radiation)

- **Emissions**
  - **MIL-STD 461 (RE02)**
- **Immunity**
  - **MIL-STD 461 (RS03)**

Math Review
Linear (V/C)PDEs (Point Relations)

- **Solutions (2 Types)** $L_{PDE}\overline{F} = \overline{S}$
  - **Particular (Forced) "Integral" Solution (S≠0)**
    - **ONE/UNIQUE Solution!** $\overline{F}_p$
    - **Ex: THE Answer for ALL Antennas (Helmholtz/Maxwell)**
  - **Complementary/Homogeneous (Natural/BV) Solution (S=0)**
    - **INFINITE Solutions (Modes)**
    - **BCs (Select Mode ~ EVs/EFs)** $\overline{F}_c$
    - **Ex: TL/WG/Cavity Scattering/Coupling**
  - **General Solution**
    - **Sum** $\overline{F}_g = \overline{F}_p + \overline{F}_c$
      - **Particular Solution**
      - **Complimentary Solution**
    - **Ex: Coaxial/WG Feed (Horn)**

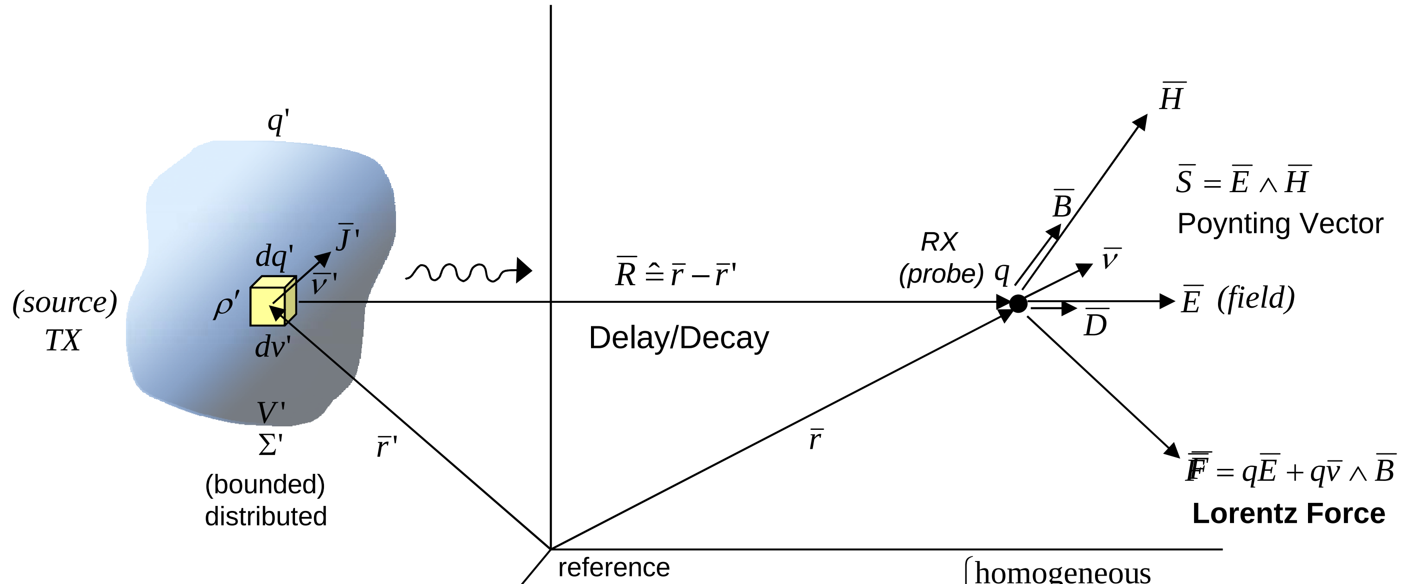
III: Analysis/Design (Method)

- **Radiation(RE/RS)=(TX/RX)/Antennas**
- **"THE" UNIQUE Antenna Answer ~ Electric/Magnetic (History!)**
  (6)Coupled->(2)Uncoupled
  - **Particular (Integral) Solution (ME/CoC/CR ~ HE/WE)**
    GE Green's Function (Unit/Point)
  - **THE (2) UNIQUE Electric/Magnetic Formulas (Helmholtz/Maxwell)**
- **Exact Solution – (2)"Radiation Integrals" (Fields/Potentials)**
- **Approximation – (1) FF Schelkunoff "Radiation Vector" ~ Ohm's Law**
- ***Example! (Engineers)***
- ***Derivation! (Physicists)***
- **Applications (RE/RS)=(TX/RX)~ Emissions/Immunity**
- **Compliance ~ Tests/Measurements (V&V)**

Solution
PDEs (Point Relations)

- Solve (Introduce)
  - Green's Function (Exact/Approximate)
    - Unit/Point Source (Hertzian Dipole)
    - Free Space (Lossless Example)
  - Source Distribution (<u>Current</u>)
  - Weight(Source)/Sum(Field)
    - Sum (Discrete) ~ "Real World"
    - Integrate (Continuum) ~ "Average"
      - Radiation Integrals

III: Analysis/Design (Basic Antenna)



charge~current
- **static**
  - **stationary (E)**
  - **steady (M)**
- **dynamic (EM)**

$(\mu_r, \varepsilon_r, \sigma)$ - simple (constant) $\begin{cases} \text{homogeneous} \\ \text{isotropic} \\ \text{linear} \\ \text{non-dispersive} \end{cases}$

(material)

$$\begin{cases} vacuum \sim SC \\ air \sim AF \\ salt - water \sim Navy \\ sand \sim Army \end{cases}$$

$$dq' = \begin{cases} \rho_v' dv' \\ \rho_s' da' \\ \rho_\ell' d\ell' \end{cases} \Leftrightarrow q' = \int_? dq' = \begin{cases} \int_{v'} \rho_v' dv' \\ \int_{s'} \rho_s' da' \\ \int_{c'} \rho_\ell' d\ell' \end{cases}$$

$$\bar{J}' = \rho' \bar{v}'$$

Radiation Integrals (Summary Sheet) ~ 2 problems!

Potentials

$$\Phi = \frac{1}{\varepsilon}\int_{v'} G\rho' dv'$$

$$\overline{A} = \mu\int_{v'} G\overline{J}' dv' \approx \mu G_o \overline{N}$$

$$\nabla \bullet \overline{J} = -j\omega\rho \quad \leftrightarrow \quad \rho = -\frac{1}{j\omega}\overline{\nabla}\bullet\overline{J}$$

$$\nabla \bullet \overline{A} = +\frac{k^2}{j\omega}\Phi \quad \leftrightarrow \quad \Phi = +\frac{j\omega}{k^2}\overline{\nabla}\bullet\overline{A}$$

$$k = \omega\sqrt{\mu\varepsilon}$$

$$Z = \sqrt{\frac{\mu}{\varepsilon}} = \frac{1}{Y}$$

Lorentz Gauge

where

$$\overline{N} \equiv \int_{v'} \overline{J}' e^{+jk\hat{r}\bullet\bar{r}'} dv'$$

Schelkunoff (Bell Labs) Radiation Vector

Fields

$$\overline{H} = \frac{\overline{\nabla}\wedge\overline{A}}{\mu} = \int_{v'} \overline{\nabla} G \wedge \overline{J}' dv \approx -jkG_o \hat{r}\times\overline{N}$$

$$\overline{E} = \begin{cases} -\overline{\nabla}\Phi - j\omega\overline{A} = -\dfrac{1}{\varepsilon}\displaystyle\int_{v'}(\overline{\nabla}G)\rho' dv' - j\omega\mu\int_{v'} G\overline{J}' dv' \\ -j\omega(\overline{\overline{I}} + \dfrac{\overline{\nabla}\,\overline{\nabla}}{k^2})\bullet\overline{A} = -j\omega\mu\displaystyle\int_{v'}\overline{\overline{G}}\bullet\overline{J}' dv' \end{cases} \approx +j\underbrace{\omega\mu}_{kZ} G_o \hat{r}\wedge(\hat{r}\wedge\overline{N})$$

$$\overline{\overline{G}} \equiv (\overline{\overline{I}} + \frac{\overline{\nabla}\,\overline{\nabla}}{k^2})G$$

$$G \equiv \frac{1}{4\pi}\frac{e^{-jkR}}{R}$$

$$\overline{\nabla}G = -\hat{R}\frac{1+jkR}{R}G$$

$$\overline{E} = \frac{\overline{\nabla}\wedge\overline{H}}{j\underbrace{\omega\varepsilon}_{kY}} \approx -Z\hat{r}\wedge\overline{H} \leftrightarrow \overline{H} = -\frac{\overline{\nabla}\wedge\overline{E}}{j\underbrace{\omega\mu}_{kZ}} \approx +\frac{\hat{r}\wedge\overline{E}}{Z}$$

Ohm's Law

$$G_o \equiv \frac{1}{4\pi}\frac{e^{-jkr}}{r}$$

Math Review: Design/Analysis (2 Part Problem)

- **Preliminary**
  - **Find Source/Field Relationships (Particular Solution)**
  - **Analysis/Synthesis(Design)**

- **(Analysis)**
- →
- **Source ←→ Field**
- ←
- **(Synthesis)**
- **(Design)**

III: Design/Analysis (2 Part Problem)

- **Part I (Graduate)**
  - **Solve for Currents on Antenna**
    - **Find Current ~ Knowing Field??? ~ ON Antenna**
    - **Numerical <u>Synthesis</u> (Design)**
      - **BC: Tangential E=0**
      - **BC: Normal B=0**
- **Part II (Undergraduate)**
  - **Solve for Fields Radiated by Antenna**
    - **Find Fields ~ Knowing Currents (or Guess!!!)**
    - **Numerical <u>Analysis</u>**

Integral Equations

$$\int_{-h}^{+h} dx' Z_\ell(x,x') I(x') = V(x)$$

1D Integral Equations

EFIE/Dirichlet BC

MFIE/Neumann BC

$$Z_\ell(x,x') = \frac{Z(x,x')}{\ell} = K(x,x')$$

$$\Delta x = \frac{\ell}{N} = \frac{2h}{N}$$

N small sub-elements centered on $x_m (m \in [1,N])$

1: Constrain observations to discrete samples at x_m

$$\int_{-h}^{+h} dx' Z_\ell(x_m,x') I(x') = V(x_m)$$

Field Computation by Moment Methods

Harrington (Mautz)

2: Assume I(x)=$I(x_n)$ Constant (for each interval n) “Stair-Step”

$$\Delta x \sum_{1}^{N} Z_\ell(x_m,x_n) I(x_n) = V(x_m) \quad m \in [1,N]$$

Singularity at (m=n)

$$\leftrightarrow$$

$$\sum_{n=1}^{n=N} Z(x_m,x_n) I(x_n) = V(x_m)$$

$$\Rightarrow$$

$$I(x_m) = \sum_{n=1}^{n=N} Z^{-1}(x_m,x_n) V(x_n)$$

Greens Function : Geometry

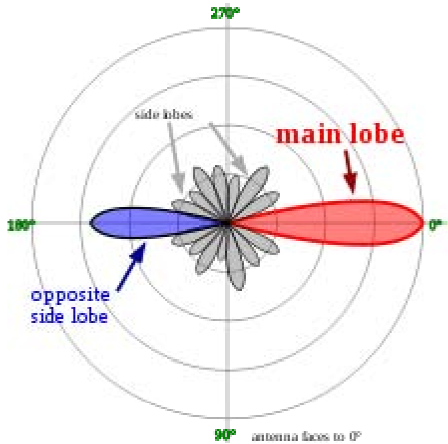
Pulse Basis Functions

Delta-Function Testing

(NEC)

Radiation Pattern

– **3D Samples**



Properties/Characteristics

- **Radiation Fields (Vectors)**
  - **Electric/Magnetic (Field Intensity / Flux Density)**
- **Radiation Parameters (Scalars)**
  - **Antenna Pattern (Picture/Polar-Plot)**
    - **Gain/Directivity (Efficiency) ~ Effective Length/Area**
    - **Structure**
      - **Beam Width (Solid Angle)**
      - **Lobes/Nulls ~ Levels/Depths**
        - **Main/Side/Back**
    - **Polarization (Elliptical ~ Circular/Linear)**
  - **Impedance/Reflections**
    - **(V/I)SWR**
    - **Matching**
    - **Bandwidth**

Conclusions

- **Radiation (Antennas)**
  - **Theory/Applications**
    - **Analysis/Design**
      - **Formulas (2 Radiation Integrals)**
        - **Exact/Approximate (MoM CEM Code)**
  - **Measurements**
    - **Test Techniques**
      - **Facility**
      - **Setup**
      - **Equipment**
        - **DUT**
        - **GSE**
    - **Test Limits**
      - **NASA / MIL STDs**

Appendix

- **Derivations**

Derivation
"Maxwell" (plus Conservation/Constitutive) Equations

$$\overline{\nabla}\times\overline{E} = -j\omega\overline{B} + 0$$
$$\overline{\nabla}\times\overline{H} = +j\omega\overline{D} + \overline{J}_t = +j\omega\overline{D} + \overline{J}_c + \overline{J}_a$$

FL
AL

and

$$\overline{\nabla}\cdot\overline{D} = \rho_t = \rho_a$$
$$\overline{\nabla}\cdot\overline{B} = 0$$

G(E)L (Relaxation)
G(M)L

$$\overline{\nabla}\bullet\overline{J}_a = -j\omega\rho_a \leftrightarrow \rho_a = -\frac{\overline{\nabla}\bullet\overline{J}_a}{j\omega}$$

(CoC)

$$\overline{D} = \varepsilon\overline{E}$$
$$\overline{B} = \mu\overline{H}$$
$$-----$$
$$J_c = \sigma\overline{E}$$

$$\left\{\begin{matrix} P/C/PE \\ M/L/KE \\ \\ R/Loss \end{matrix}\right\}$$

(CR)

Derivation

Governing Equations

combine

$$\overline{\nabla}\times\overline{E} = -j\omega\mu\overline{H} + 0 = -Z_\ell\overline{H} + 0$$
$$\overline{\nabla}\times\overline{H} = +(j\omega\varepsilon+\sigma)\overline{E} + \overline{J}_a = +j\omega\varepsilon_c\overline{E} + \overline{J}_a = +Y_\ell\overline{E} + \overline{J}_a$$

(GE)

where

$$Z_\ell \equiv j\omega\mu$$
$$Y_\ell \equiv j\omega\varepsilon + \sigma = j\omega\varepsilon_c$$

(per-unit length) impedance/admittance

and

$$\varepsilon_c \equiv \varepsilon + \frac{\sigma}{j\omega} = \varepsilon(1-jp) \equiv \varepsilon' - j\varepsilon''$$
$$p \equiv \frac{\sigma}{\omega\varepsilon} \equiv \tan\delta$$

(complex) permittivity (loss tangent)

p=0 (PEI)

p=∞ (PEC)

$$\overline{\nabla}\bullet\overline{J}_a = -j\omega\rho_a \leftrightarrow \rho_a = -\frac{\overline{\nabla}\bullet\overline{J}_a}{j\omega}$$

(CoC)

$$\overline{D} = \varepsilon\overline{E}$$
$$\overline{B} = \mu\overline{H}$$
$$-----$$
$$J_c = \sigma\overline{E}$$

(CR)

Derivation
Helmholtz (Wave) Equations

$$\Delta^2\overline{E} = +\frac{1}{\varepsilon}\overline{\nabla}\rho_a + j\omega\mu\vec{J}_a \rightarrow j\omega\mu[\overline{\overline{I}} - \frac{1}{\gamma^2}\overline{\nabla}\overline{\nabla}]\bullet\overline{J}_a$$
$$\Delta^2\overline{H} = -\overline{\nabla}\times\vec{J}_a$$

(fields)

or

$$\Delta^2\Phi = -\frac{\rho_a}{\varepsilon}$$
$$\Delta^2\overline{A} = -\mu\overline{J}_a$$

$$\xrightarrow{statics} \nabla^2\Phi = -\frac{\rho_a}{\varepsilon} \xrightarrow{sourceless} 0$$

(potentials)

Poisson/Laplace

if

$$\nabla\bullet\overline{A} = -j\omega\mu\varepsilon_c\Phi = -\frac{\gamma^2}{j\omega}\Phi \leftrightarrow \Phi = -\frac{j\omega}{\gamma_i^2}\overline{\nabla}\bullet\overline{A}$$

(Lorentz Gauge)

and

$$\overline{H} = +\frac{\nabla\times\overline{A}}{\mu} \rightarrow -\frac{1}{j\omega\mu}\overline{\nabla}\times\overline{E}$$
$$\overline{E} = -\overline{\nabla}\Phi - j\omega\overline{A} \rightarrow -j\omega[\overline{\overline{I}} - \frac{\overline{\nabla}\overline{\nabla}}{\gamma^2}]\bullet\overline{A} \rightarrow \frac{1}{j\omega\varepsilon_c}\overline{\nabla}\times\overline{H} \quad (\overline{J}_a = 0)$$

where

$$\Delta^2 \equiv \nabla^2 - \gamma^2$$

D'Alembertian/Laplacian

and

$$\gamma^2 \equiv Z_\ell Y_\ell = (j\omega\mu)(j\omega\varepsilon_c) = -\omega^2\mu\varepsilon_c \xrightarrow{\sigma=0} -\omega^2\mu\varepsilon \equiv -k^2$$

$$k^2 \equiv +\omega^2\mu\varepsilon$$

Derivation: Heuristic

- Poisson's Equations (ES/MS):

$$\nabla^2\Phi = -\frac{\rho}{\varepsilon}$$
$$\nabla^2\overline{A} = -\mu\overline{J}$$

$$\Phi = \frac{1}{\varepsilon}\int_{v'} G\rho' dv' \leftrightarrow$$
$$\overline{A} = \mu\int_{v'} G\overline{J}' dv'$$

$$G = \frac{1}{4\pi r}$$

- Outward (TW): $e^{-j\overline{k}\cdot\overline{r}}$

- Helmholtz (Wave) Equations:

$$\Delta^2\Phi = (\nabla^2 + k^2)\Phi = -\frac{\rho}{\varepsilon}$$
$$\Delta^2\overline{A} = (\nabla^2 + k^2)\overline{A} = -\mu\overline{J}$$

$\leftrightarrow$

$$\Phi = \frac{1}{\varepsilon}\int_{v'} G\rho' dv'$$
$$\overline{A} = \mu\int_{v'} G\overline{J}' dv'$$

$$G = \frac{e^{-j\overline{k}\cdot\overline{r}}}{4\pi r}$$

- Off-Axis:

$$G = \frac{e^{-j\overline{k}\cdot\overline{R}}}{4\pi R}$$

$$G(\overline{R}) = G(\overline{r}\,|\,\overline{r}')$$

Derivation: Heuristic

- Poisson's Equations (ES/MS):

$$\nabla^2\Phi = -\frac{\rho}{\varepsilon}$$
$$\nabla^2\overline{A} = -\mu\overline{J}$$

- Unit/Point Charge (Origin): $\rho' = 1\delta(x')\delta(y')\delta(z')$

- Gauss' (Electric) Law: $\nabla\cdot\overline{D} = \rho \Leftrightarrow \oint_{\Sigma}\overline{\mathrm{D}}\cdot\underbrace{d\overline{a}}_{\hat{n}da_n} = \int_V \rho dv \Leftrightarrow \oint_{\Sigma}\mathrm{D_n da_n} = q_t \rightarrow \mathrm{D_{no}}A_n = q_t$

$$\mathrm{D_r}A_{sphere} = 1$$
$$D_r(4\pi r^2) = 1$$
$$D_r = \frac{1}{4\pi r^2} = \varepsilon E_r$$
$$E_r = \frac{1}{4\pi\varepsilon r^2} = -\nabla_r\Phi\Big|_{unit/point} = -\partial_r\Phi\Big|_{unit/point}$$

$$\Phi_{unit/point} = -\int_{\infty}^{r} E_{r'}dr' = -\frac{1}{\varepsilon}\frac{1}{4\pi}\underbrace{\int_{\infty}^{r}\frac{1}{r'^2}dr'}_{\underbrace{-\frac{1}{r'}\Big|_{\infty}^{r}}_{-\frac{1}{r}+\frac{1}{\infty}}} = +\frac{1}{\varepsilon}\left(\frac{1}{4\pi r}\right) = G^{\Phi} = +\frac{1}{\varepsilon}G$$

$$\mathrm{G} = \frac{1}{4\pi r}$$

Derivation: Heuristic

- Superposition: Weighted/Sum Green's Function

$$\Phi_{unit/point} = +\frac{1}{\varepsilon} G$$

$$d\Phi_{point} = +\frac{dq'}{\varepsilon} G$$

$$\Phi = \int_{?} d\Phi_{point} = +\frac{1}{\varepsilon}\int_{?} G dq' = \begin{cases} \frac{1}{\varepsilon}\int_{v'} G\rho_v' dv' \\ \frac{1}{\varepsilon}\int_{s'} G\rho_s' da' \\ \frac{1}{\varepsilon}\int_{c'} G\rho_\ell' d\ell' \end{cases} \quad Duality \rightarrow \quad \overline{A} = \begin{cases} \mu\int_{v'} G\overline{J}_v' dv' \\ \mu\int_{s'} G\overline{J}_s' da' \\ \mu\int_{c'} G\overline{J}_\ell' d\ell' \end{cases}$$

$$\nabla^2\Phi = -\frac{\rho}{\varepsilon}$$
$$\nabla^2\overline{A} = -\mu\overline{J}$$

$$\Phi = \frac{1}{\varepsilon}\int_{v'} G\rho' dv'$$
$$\overline{A} = \mu\int_{v'} G\overline{J}' dv'$$

Derivation: Heuristic

$$\overline{E} = \begin{cases} -\overline{\nabla}\Phi - j\omega\overline{A} = -\begin{Bmatrix} \overline{\nabla}\left(\frac{1}{\varepsilon}\int_{v'} G\rho' dv'\right) \\ \frac{1}{\varepsilon}\int_{v'} (\overline{\nabla}G)\rho' dv' \end{Bmatrix} - j\omega\left(\mu\int_{v'} G\overline{J}' dv'\right) \\ -j\omega\left(\overline{\overline{I}} + \frac{\overline{\nabla}\,\overline{\nabla}}{k^2}\right)\bullet\overline{A} = -\begin{Bmatrix} j\omega\left(\overline{\overline{I}} + \frac{\overline{\nabla}\,\overline{\nabla}}{k^2}\right)\bullet\left(\mu\int_{v'} G\overline{J}' dv'\right) \\ j\omega\mu\int_{v'} \underbrace{\left[\left(\overline{\overline{I}} + \frac{\overline{\nabla}\,\overline{\nabla}}{k^2}\right)G\right]}_{\overline{\overline{G}}}\bullet\overline{J}' dv' \end{Bmatrix} = -j\omega\mu\int_{v'} \overline{\overline{G}}\bullet\overline{J}' dv' \end{cases}$$

$$\overline{H} = +\frac{\overline{\nabla}\wedge\overline{A}}{\mu} = +\begin{Bmatrix} \dfrac{\overline{\nabla}\wedge\left(\mu\int_{v'} G\overline{J}' dv'\right)}{\mu} \\ \int_{v'} (\overline{\nabla}G)\wedge\overline{J}' dv' \end{Bmatrix}$$

$$\nabla\bullet\overline{A} = +\frac{k^2}{j\omega}\Phi \leftrightarrow \Phi = +\frac{j\omega}{k^2}\overline{\nabla}\bullet\overline{A}$$

Lorentz Gauge

$$\Phi = \frac{1}{\varepsilon}\int_{v'} G\rho' dv'$$

$$\overline{A} = \mu\int_{v'} G\overline{J}' dv'$$

Radiation (Parameters)

Radiated (Radial) Power Density/Intensity

note (RMS power density)

$$\overline{S}_c \equiv \frac{\overline{E}\times\overline{H}^*}{2} = \frac{\overline{E}}{\sqrt{2}}\times\frac{\overline{H}^*}{\sqrt{2}} \equiv \overline{E}_{RMS}\times\overline{H}^*_{RMS}$$ (complex) Poynting Vector $\left(\frac{VA}{m^2}\right)$

far-field

$$\overline{S}_c\Big|_{r=r_o} \equiv \frac{1}{2}\overline{E}\times\overline{H}^*\Big|_{r=r_o} \approx \hat{r}S_{cr}(\vartheta,\phi) = \hat{r}\frac{U(\vartheta,\phi)}{r_o^2} = \hat{r}\frac{U_{\max}u(\vartheta,\phi)}{r_o^2}$$ $$r_o \geq r_{FF} \cong 2\frac{D^2}{\lambda}$$

where

$$U(\vartheta,\phi) = r_o^2 S_{cr}(\vartheta,\phi)$$ intensity $\left(\frac{VA}{sr}\right)$

and

$$u(\theta,\phi) \equiv \frac{U(\vartheta,\phi)}{U_{\max}}$$ (normalized) intensity

note

$$0 \leq |u(\vartheta,\phi)| \leq 1$$

max (boresight???)

$$U_{\max} \equiv \max[U(\vartheta,\phi)] = U(\vartheta,\phi)\Big|_{\vartheta=\vartheta_{\max},\phi=\phi_{\max}} = U(\vartheta_{\max},\phi_{\max})$$ (maximum) intensity

Radiation (Parameters) cont.

radiated power

$$P_{rad} \equiv \oint_{\Sigma} \bar{S}_c \bullet d\bar{a} \approx \begin{cases} \oint_{A_{sphere}} S_{cr} da_r \\ \oint_{\Omega_{sphere}} U d\Omega \end{cases} \rightarrow \frac{1}{2}\left|I_o\right|^2 R_{rad}$$

(complex) radiated power (out)

where

$$R_{rad} \equiv \frac{2P_{rad}}{\left|I_o\right|^2}$$

radiation resistance

note

$$d\Omega \equiv \frac{da_r}{r^2} \equiv \sin\vartheta d\vartheta d\phi$$

solid angle

∴

$$S_{cr}^{ave} \equiv \left\langle S_{cr} \right\rangle_{A_{sphere}} = \frac{\oint_{A_{sphere}} S_{cr} da_r}{\oint_{A_{sphere}} da_r} = \frac{\oint_{A_{sphere}} S_{cr} da_r}{4\pi r^2} = \frac{P_{rad}}{4\pi r^2}$$

$$U^{ave} \equiv \left\langle U \right\rangle_{\Omega_{sphere}} = \frac{\oint_{\Omega_{sphere}} U d\Omega}{\oint_{\Omega_{sphere}} d\Omega} = \frac{\oint_{\Omega_{sphere}} U d\Omega}{4\pi} = \frac{P_{rad}}{4\pi}$$

(average) power density/intensity

directivity/gain

$$D(\vartheta,\phi) \equiv \frac{S_{cr}(\vartheta,\phi)}{S_{cr}^{ave}} = \frac{U(\vartheta,\phi)}{U^{ave}} = \frac{U(\vartheta,\phi)}{\frac{P_{rad}}{4\pi}} = \frac{U(\vartheta,\phi)}{\frac{P_{out}}{4\pi}}$$

$$G(\vartheta,\phi) \equiv \frac{U(\vartheta,\phi)}{\frac{P_{in}}{4\pi}} \to \underbrace{\frac{P_{out}}{P_{in}}}_{\xi_t} \frac{U(\vartheta,\phi)}{\frac{P_{out}}{4\pi}} = \xi_t D(\vartheta,\phi)$$

directivity/gain

where

$$\xi_t \equiv \frac{P_{out}}{P_{in}} \le 1$$

(total) antenna efficiency

max

$$D_{\max} \equiv \max[D(\vartheta,\phi)] = D(\vartheta,\phi)\Big|_{\vartheta=\vartheta_{\max},\phi=\phi_{\max}} = D(\vartheta_{\max},\phi_{\max})$$

$$G_{\max} \equiv \max[G(\vartheta,\phi)] = G(\vartheta,\varphi)\Big|_{\theta=\theta_{\max},\phi=\phi_{\max}} = G(\vartheta_{\max},\phi_{\max})$$

(maximum) directivity/gain

note

$$D_{\max} \equiv \max\left[\frac{U(\vartheta,\phi)}{U^{ave}}\right] = \frac{\max[U(\vartheta,\phi)]}{U^{ave}} = \frac{U_{\max}}{U^{ave}}$$

Example: Hertzian Dipole

- Given: $\bar{J}' = \hat{z} I_o \delta(x')\delta(y') \qquad (-\Delta h \le z' \le +\Delta h)$
- Find: $\approx E_{r\vartheta\varphi}$ and $\approx H_{r\vartheta\varphi}$
- Solution: $k_o = \omega\sqrt{\mu_o \varepsilon_o}$

$$Z_o = \sqrt{\frac{\mu_o}{\varepsilon_o}} = 377 \cong 120\pi$$

$$\bar{N} \equiv \int_{v'} \bar{J}' e^{+jk\hat{r}\bullet\bar{r}'} dv' \rightarrow \int_{-\Delta h}^{+\Delta h} \hat{z} I_o e^{+jk_o \overbrace{\hat{r}\bullet\hat{z}}^{\cos\vartheta} z'} dz' = \hat{z} I_o \underbrace{\int_{-\Delta h}^{+\Delta h} \underbrace{e^{+jk_o \overbrace{z'\cos\vartheta}^{\cong o}}}_{\cong 1} dz'}_{\underbrace{2\Delta h}_{\Delta\ell}} = \hat{z} \overbrace{I_o \Delta\ell}^{p_o} = \hat{z} p_o$$

$$\bar{H} \approx -jkG_o \hat{r} \times \bar{N} \rightarrow -jk_o G_o \overbrace{\hat{r} \times \hat{z}}^{-\hat{\varphi}\sin\vartheta} p_o = +\hat{\varphi} j p_o k_o G_o \sin\vartheta$$

$$H_\varphi \approx +jp_o k_o G_o \sin\vartheta$$

$$E_\vartheta \approx Z_o H_\varphi = +jp_o Z_o k_o G_o \sin\vartheta$$

Example: Hertzian Dipole

$$\overline{S}_c \approx \frac{\overline{E} \wedge \overline{H}^*}{2} \rightarrow \hat{r}\frac{\overbrace{E_\vartheta}^{Z_o H_\varphi} H_\varphi^*}{2} \approx \hat{r}\frac{Z_o|H_\varphi|^2}{2} \approx \hat{r}\frac{Z_o\left|j\overbrace{p_o}^{I_o\Delta\ell} k_o \overbrace{G_o}^{\frac{e^{-jk_o r}}{4\pi r}} \sin\vartheta\right|^2}{2}$$

$$\approx \hat{r}\frac{1}{r^2}\underbrace{[\frac{1}{2}|I_o|^2 Z_o \Delta\ell^2 \frac{k_o^2}{16\pi^2}\sin^2\vartheta]}_{U} \approx \hat{r}\frac{U}{r^2}$$

$$P_{\substack{rad\\(out)}} \approx \int_{S_\infty} \overbrace{S_{cr}}^{\frac{U}{r^2}} \overbrace{da_r}^{r^2 d\Omega} \approx \int_{\Omega_\infty} U \overbrace{d\Omega}^{\sin\vartheta d\vartheta d\varphi} \approx \int_o^{2\pi}\int_0^{\pi} \frac{1}{2}|I_o|^2 Z_o\Delta\ell^2 \frac{k_o^2}{16\pi^2}\sin^3\vartheta d\vartheta d\varphi$$

$$\approx \frac{1}{2}|I_o|^2 Z_o \Delta\ell^2 \frac{k_o^2}{16\pi^2}\underbrace{(\int_0^{\pi}\sin^3\vartheta d\vartheta)}_{\frac{4}{3}}\underbrace{(\int_0^{2\pi} d\varphi)}_{2\pi} \approx \frac{1}{2}|I_o|^2 \overbrace{Z_o}^{120\pi}\Delta\ell^2\frac{k_o^2}{6\pi} \approx \frac{1}{2}|I_o|^2[\underbrace{20(k_o\Delta\ell)^2}_{R_{rad}}]$$

$$R_{rad} \approx 20(\overbrace{k_o}^{\frac{2\pi}{\lambda}}\Delta\ell)^2 \approx 80\pi^2(\overbrace{\frac{\Delta\ell}{\lambda}}^{\Delta\ell_\lambda})^2 \approx 80\pi^2\Delta\ell_\lambda^2$$

Example: Hertzian Dipole

$$S_{cr}^{ave} = \frac{P_{rad}}{4\pi r^2} \rightarrow \frac{\frac{1}{2}|I_o|^2 20(k_o\Delta\ell)^2}{4\pi r^2}$$

$$D \approx \frac{S_{cr}}{S_{cr}^{ave}} \approx \frac{\frac{U}{r^2}}{\frac{P_{rad}}{4\pi r^2}} \approx 4\pi\frac{U}{P_{rad}} \rightarrow 4\pi\frac{\frac{1}{2}|I_o|^2 \overbrace{Z_o}^{120\pi} \Delta\ell^2 \frac{k_o^2}{16\pi^2}\sin^2\vartheta}{\frac{1}{2}|I_o|^2 20 k_o^2 \Delta\ell^2} \approx \frac{3}{2}\sin^2\vartheta$$

$$D_{\max} = D\big|_{\vartheta=90^o} \approx \frac{3}{2}$$

$$D_{\max}^{dB} = 10\log_{10} D_{\max} \rightarrow 10\log_{10}\frac{3}{2} = 1.76\,dB$$

$$\sin^2\vartheta_{HPBW} = \frac{1}{2}$$

$$\vartheta_{HPBW} = \sin^{-1}\frac{1}{\sqrt{2}} = 45^o$$

$$\theta_{HPBW} = 2\vartheta_{HPBW} = 90^o$$

Radiation Integrals

Potentials

$$\Phi = \frac{1}{\varepsilon}\int_{v'} G\rho' dv'$$

$$\overline{A} = \mu\int_{v'} G\overline{J}' dv' \approx \mu G_o \overline{N}$$

$$\nabla \bullet \overline{A} = +\frac{k^2}{j\omega}\Phi \leftrightarrow \Phi = +\frac{j\omega}{k^2}\overline{\nabla} \bullet \overline{A}$$ Lorentz Gauge

where

$$\overline{N} \equiv \int_{v'} \overline{J}' e^{+jk\hat{r}\bullet\overline{r}'} dv'$$ Schelkunoff (Bell Labs) Radiation Vector

Fields

$$\overline{E} = \begin{cases} -\overline{\nabla}\Phi - j\omega\overline{A} = -\frac{1}{\varepsilon}\int_{v'}(\overline{\nabla}G)\rho' dv' - j\omega\mu\int_{v'} G\overline{J}' dv' \\ -j\omega(\overline{\overline{I}} + \frac{\overline{\nabla}\,\overline{\nabla}}{k^2}) \bullet \overline{A} = -j\omega\mu\int_{v'} \underbrace{\left[(\overline{\overline{I}} + \frac{\overline{\nabla}\,\overline{\nabla}}{k^2})G\right]}_{\overline{\overline{G}}} \bullet \overline{J}' dv' = -j\omega\mu\int_{v'} \overline{\overline{G}} \bullet \overline{J}' dv' \approx +j\omega\mu G_o \hat{r} \wedge (\hat{r} \wedge \overline{N}) \end{cases}$$

$$\overline{H} \approx +\frac{\hat{r} \wedge \overline{E}}{Z} \leftrightarrow E \approx -Z\hat{r} \wedge \overline{H}$$ Ohm's Law

Backup Slides

Backup Slides

Backup Slides

Backup Slides

EMC Antennas: A survey of theory and types

Dr. Vince Rodriguez

Antenna Product Manager

ETS-LINDGREN™
An ESCO Technologies Company

Outline I

- Radiation pattern
  - What is it
  - E and H plane
  - Far and near field
  - Omnidirectional/Directional
  - Isotropic
  - Main, side and back lobes.
  - Half power and 3dB beamwidth

Outline II

- Half Power Beamwidth
  - Biconicals
  - LPDA
  - Hybrid Antennas
  - DRGH Antennas
  - Caveats
  - Conclusion

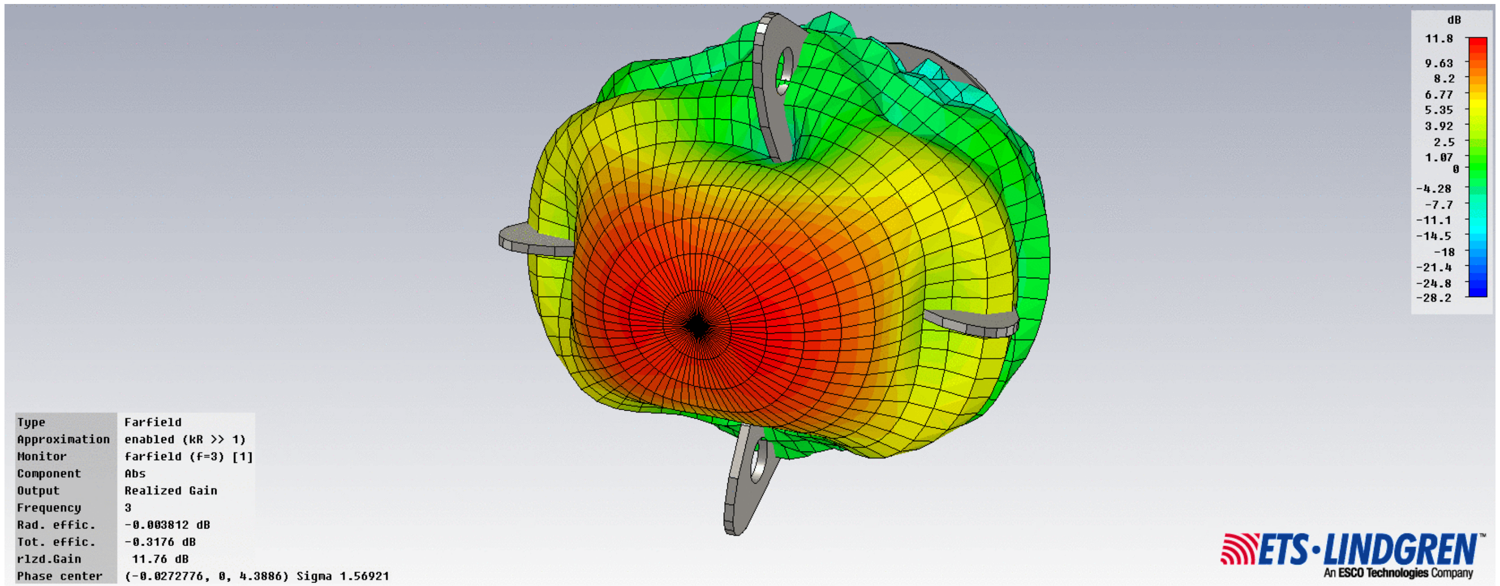
Radiation Pattern

Book definition

"a 3D plot that displays the strength of the radiated fields or power density as a function of direction"

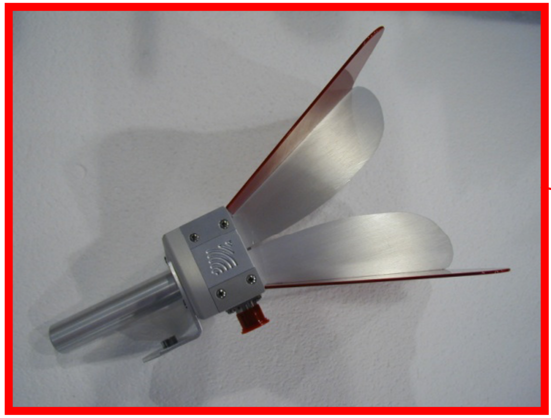
Radiation Pattern

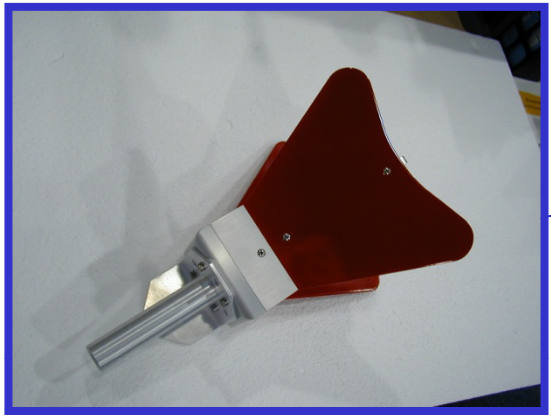
The radiation is then a representation of how much Electromagnetic energy is concentrated in each direction around the antenna

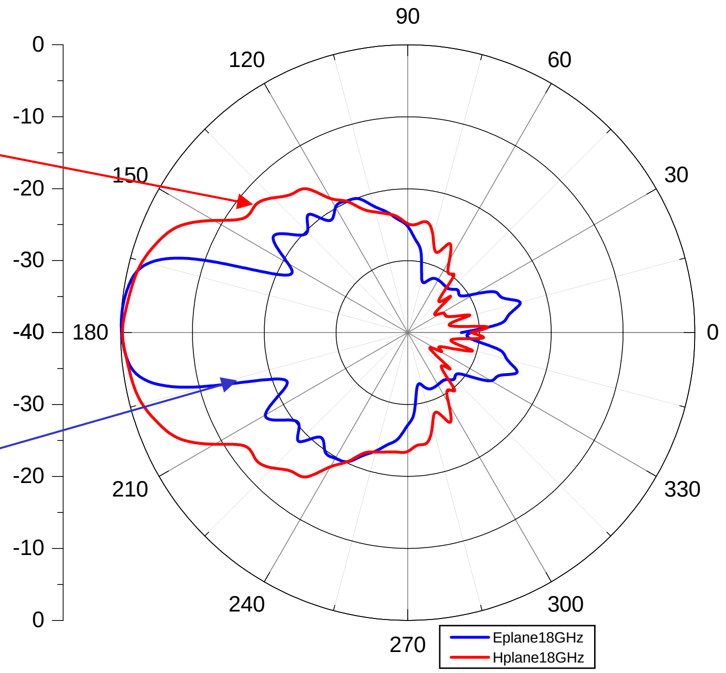


Radiation Pattern

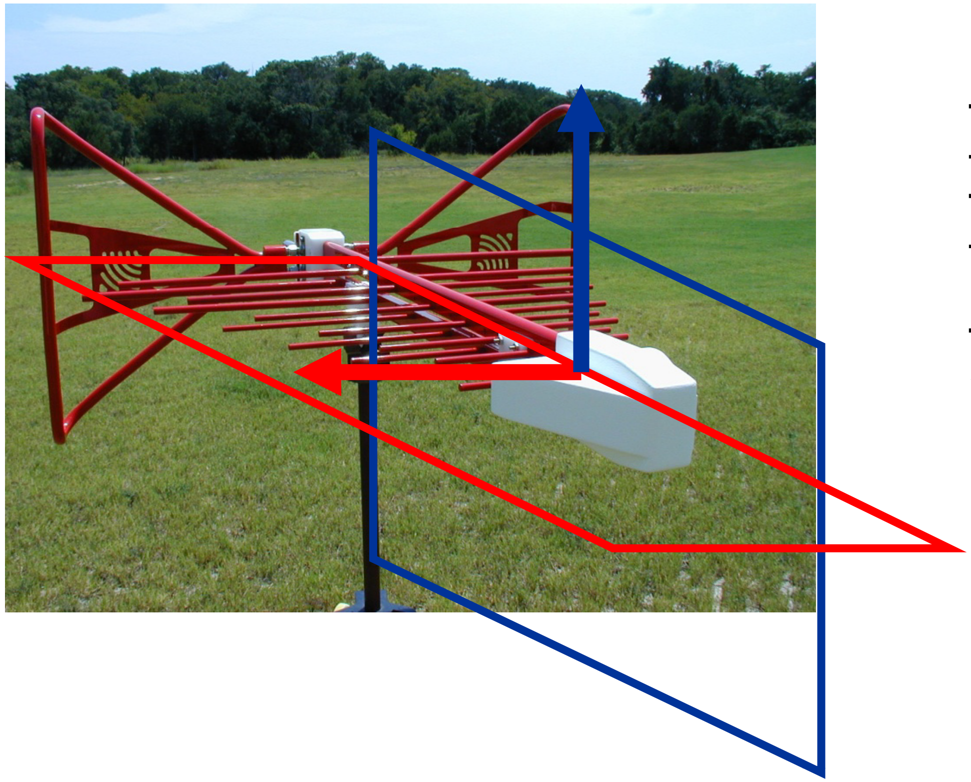
Because of the difficulty of plotting a 3D plot usually the patterns are shown as E and H planes







Radiation Pattern: E and H Plane



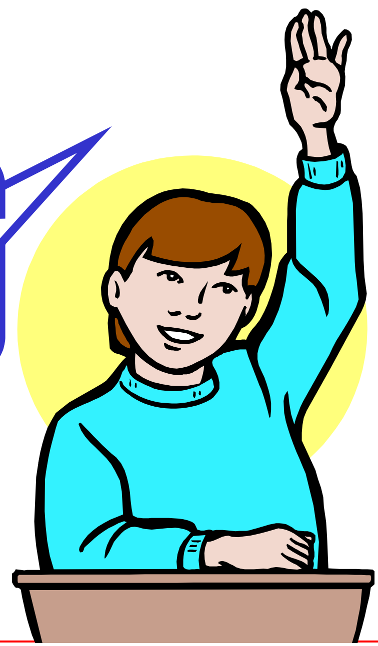
The E plane is the plane that is parallel to the Electric field
The H plane is the plane that is parallel to the Magnetic field

The Electric and Magnetic fields are perpendicular to each other

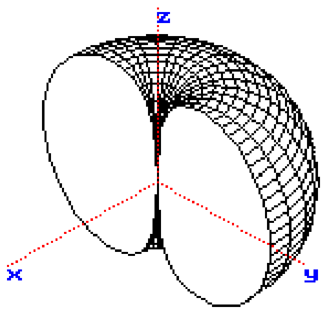
Radiation Pattern: Omnidirectional and Directional

OMNI = Latin for Every or All

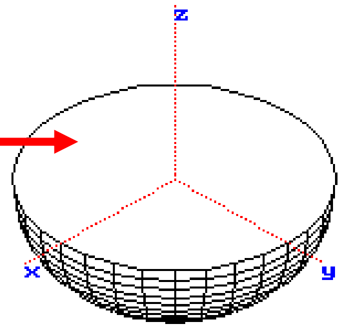
So, Omnidirectional radiates in “every” direction?



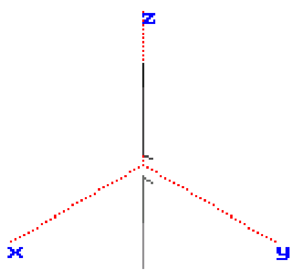
Radiation Pattern: Omnidirectional and Directional

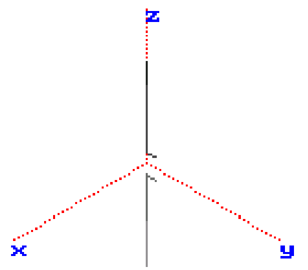


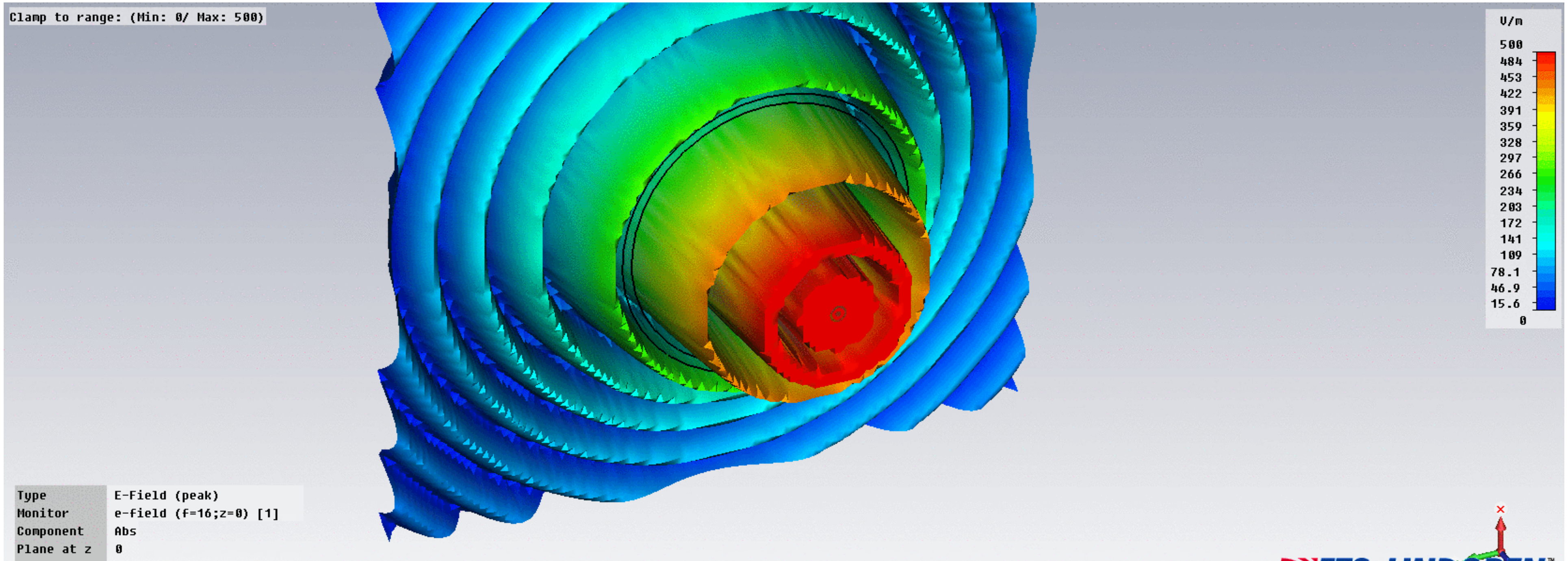
Omni directional on the H plane. It radiates equally on all directions on this plane



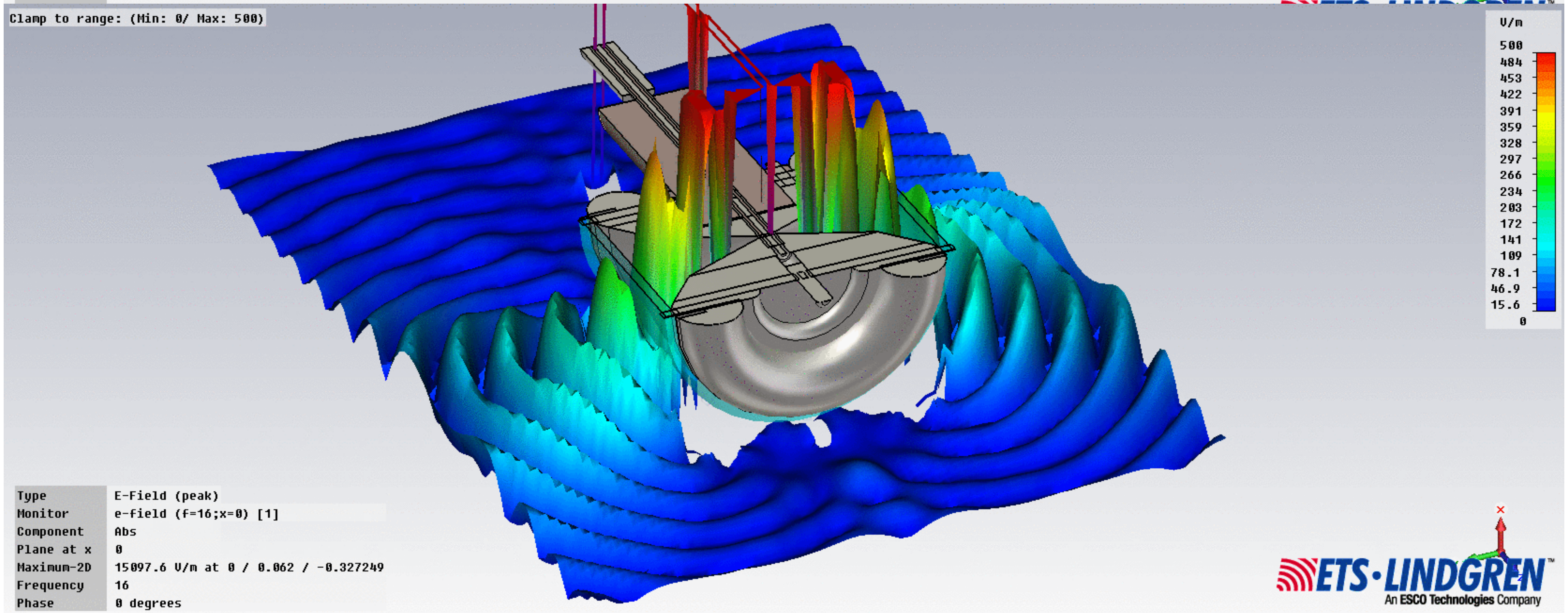
But not on this plane







Clamp to range: (Min: 0/ Max: 500)
V/m
500
484
453
422
391
359
328
297
266
234
203
172
141
109
78.1
46.9
15.6
0
Type
E-Field (peak)
Monitor
e-field (f=16;z=0) [1]
Component
Abs
Plane at z
0



Clamp to range: (Min: 0/ Max: 500)
V/m
500
484
453
422
391
359
328
297
266
234
203
172
141
109
78.1
46.9
15.6
0
Type
E-Field (peak)
Monitor
e-field (f=16;x=0) [1]
Component
Abs
Plane at x
0
Maximum-2D
15097.6 V/m at 0 / 0.062 / -0.327249
Frequency
16
Phase
0 degrees
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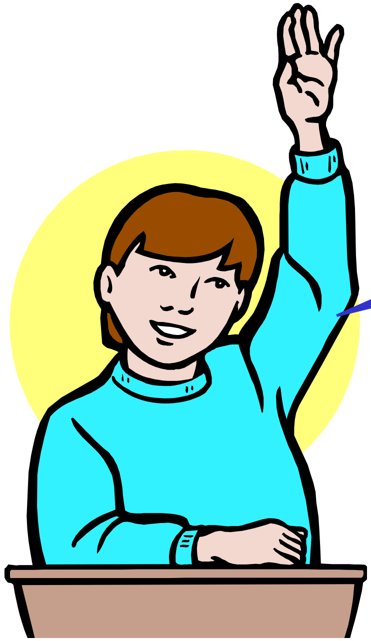
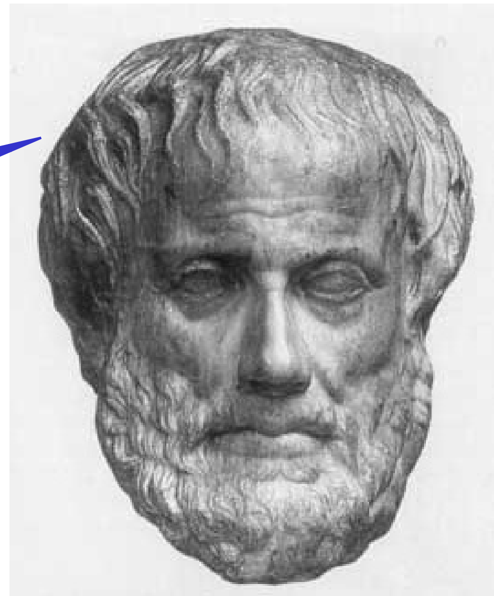
Radiation Pattern: Omnidirectional and Directional



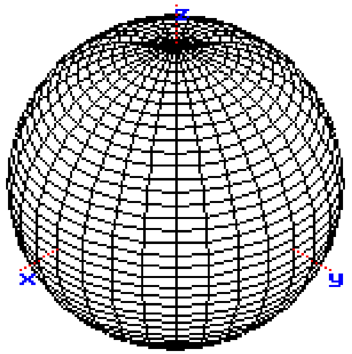
Can you radiate equally on all directions

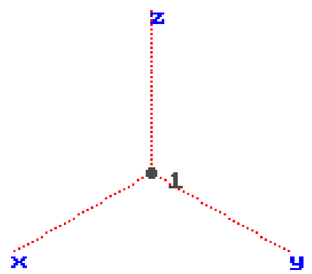
Isotropic, Greek, isos meaning same, tropos meaning direction,



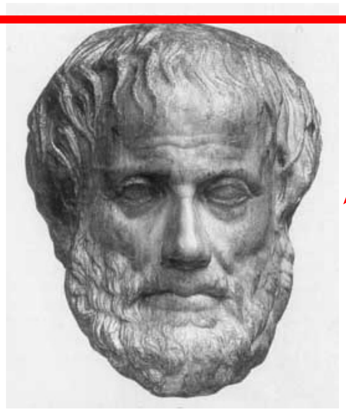
Aristotle

Radiation Pattern: Omnidirectional and Directional





There is no such thing in real life. An isotropic radiator is a mathematical concept, an idea that belongs in the world of ideas like my professor, Plato, would say.
It is however use as a comparison to determine the Directive Gain of a real antenna

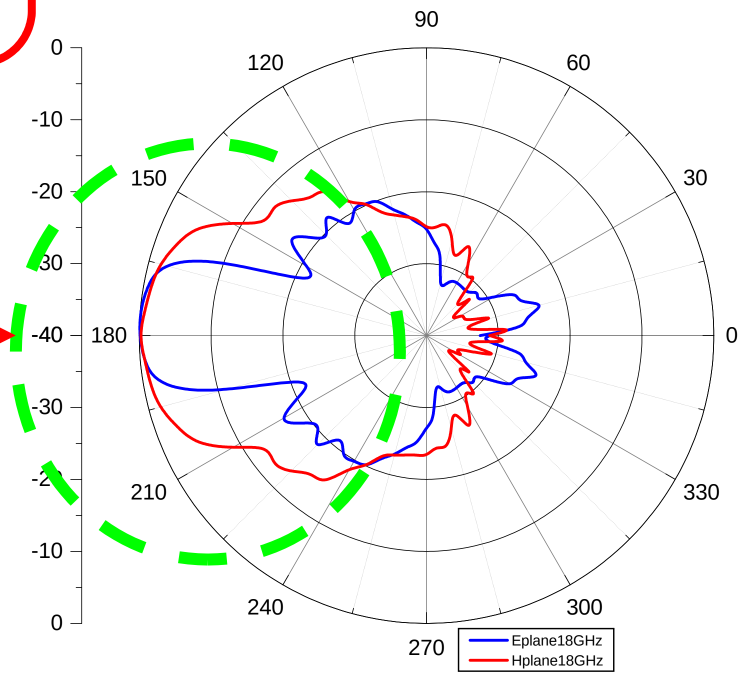


Aristotle

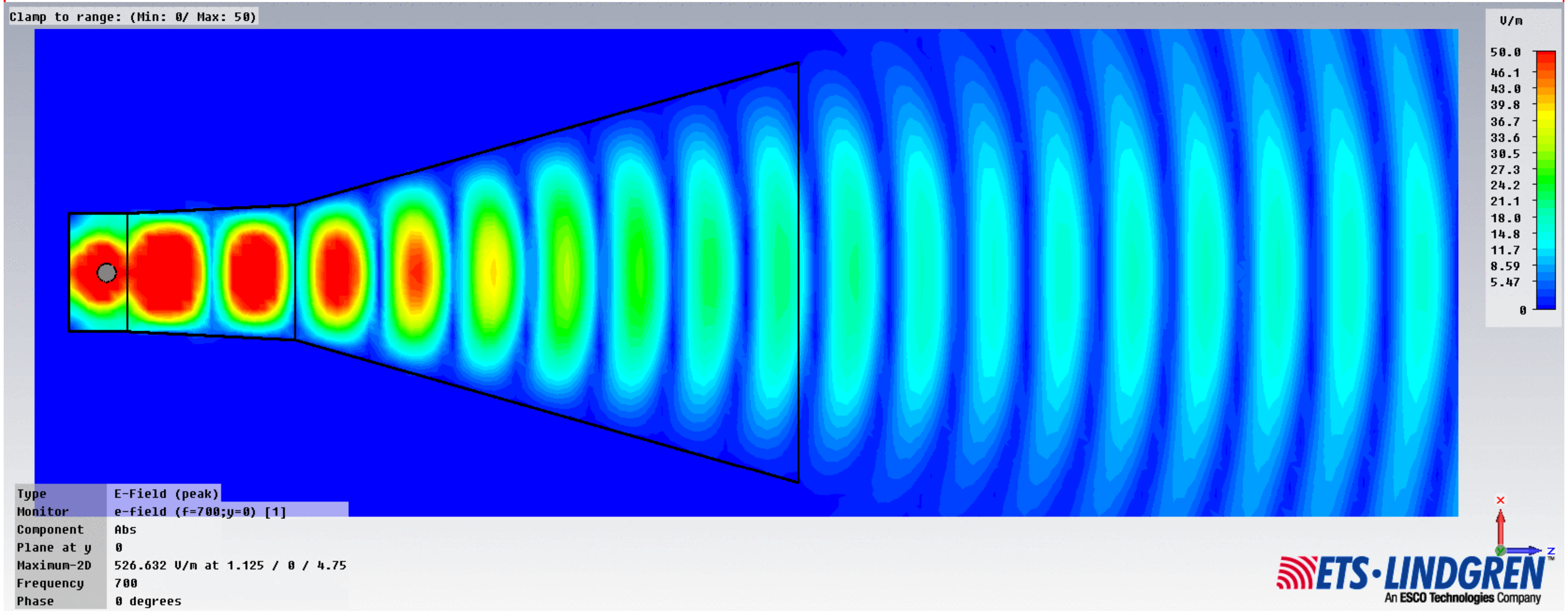
Omnidirectional and Directional

Directional?, well that is plain English, The antenna radiates mainly in one direction. Lets look again at a horn antenna

Radiation is mainly in this direction



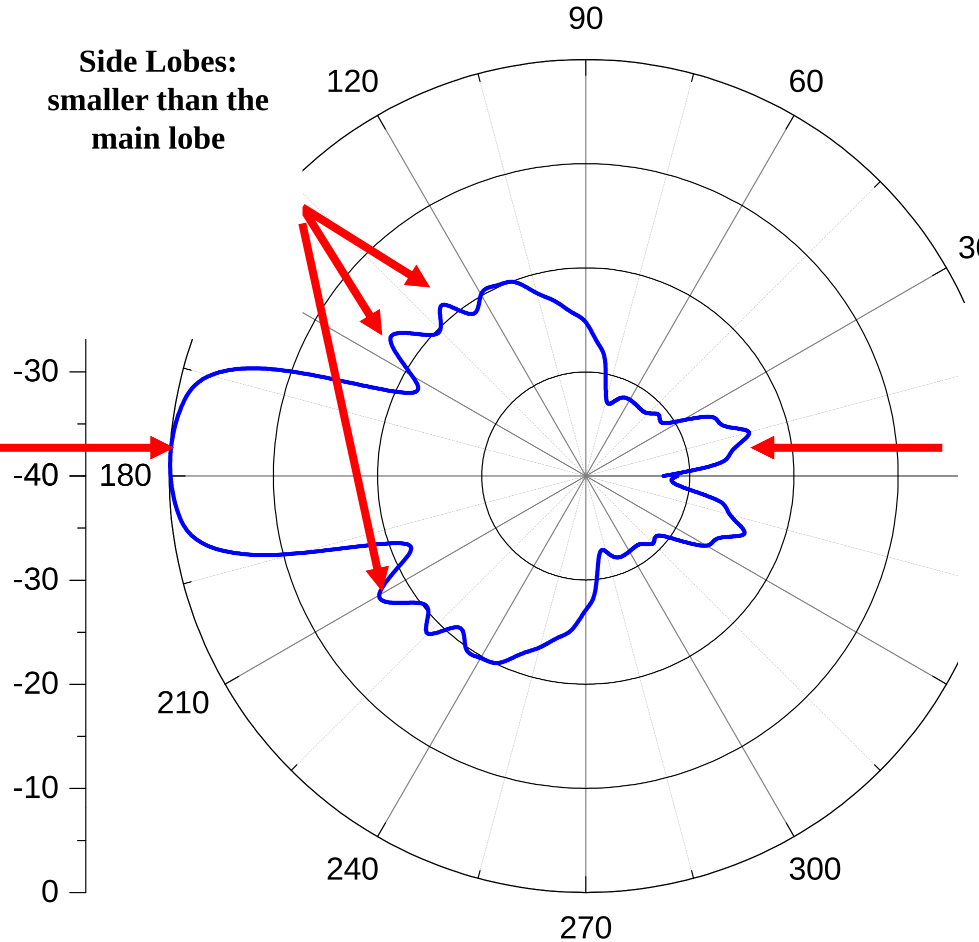
Directional



Radiation Pattern: Main, Side and Back

Side Lobes: smaller than the main lobe

Main Lobe: Is the strongest in level.



Is a side lobe that happens to be on the opposite direction than the main lobe

Radiation Pattern: Half Power Beamwidth

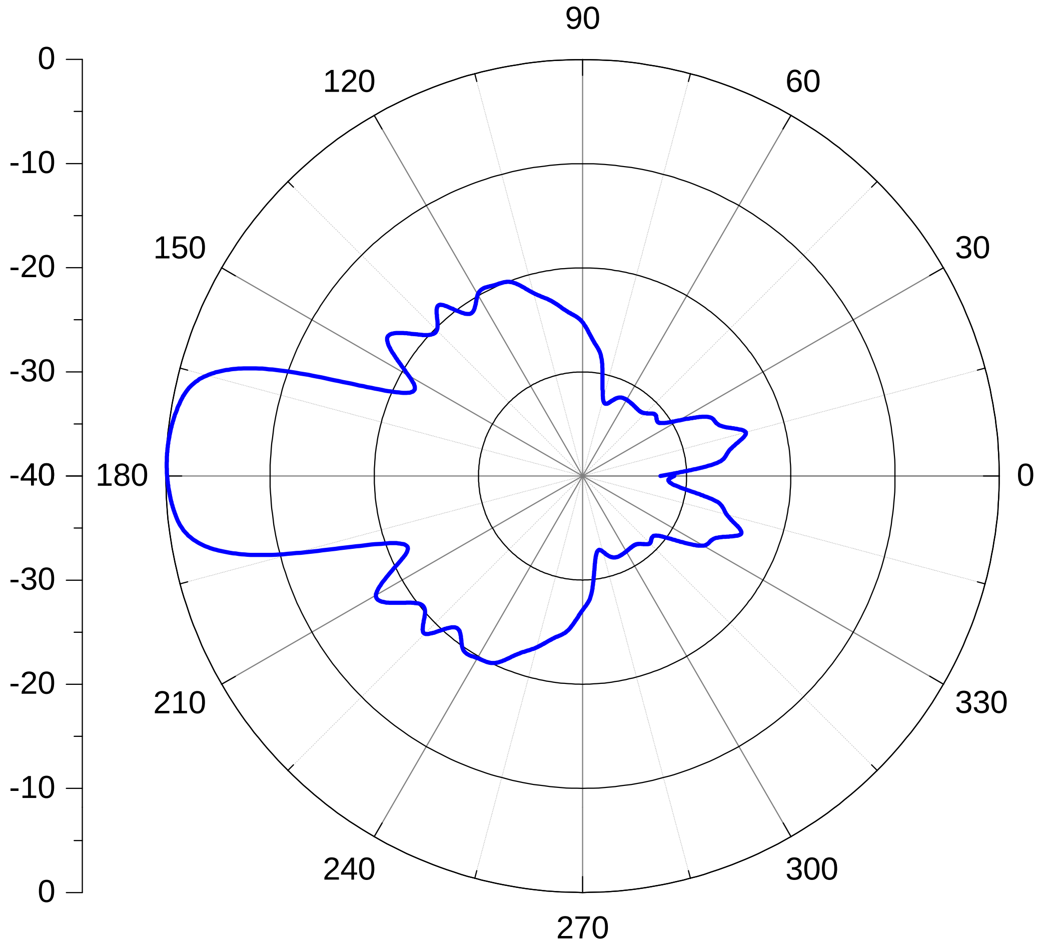
Half power

Half = $\frac{1}{2} = 0.5$

In decibels

-3dB= half power

$$10 \times \log_{10}\left(\frac{1}{2}\right) = -3.02 \approx -3dB$$



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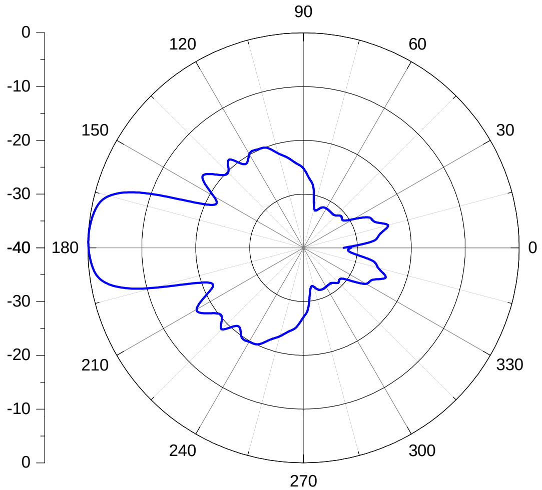
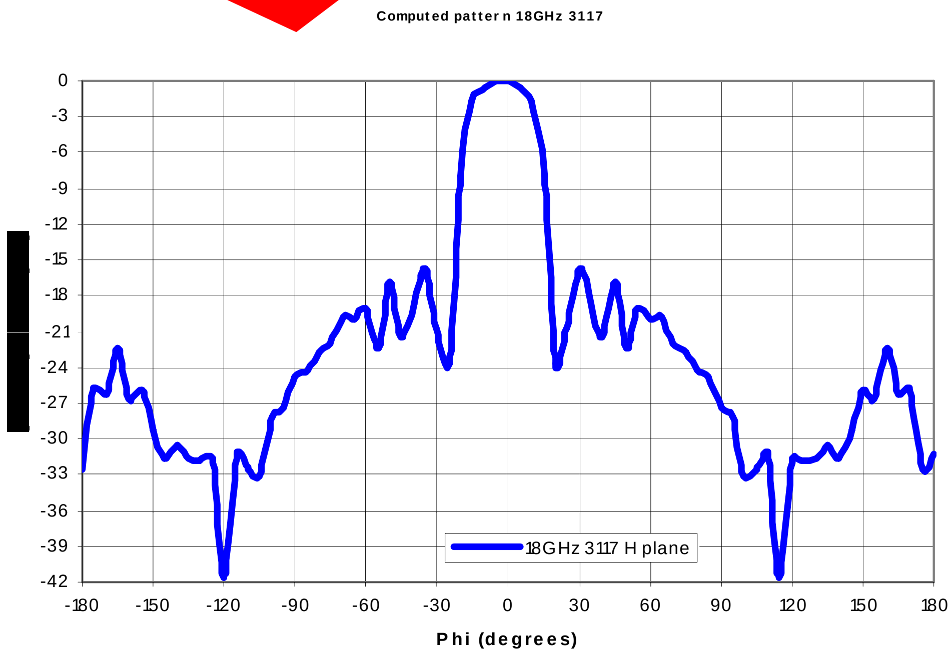
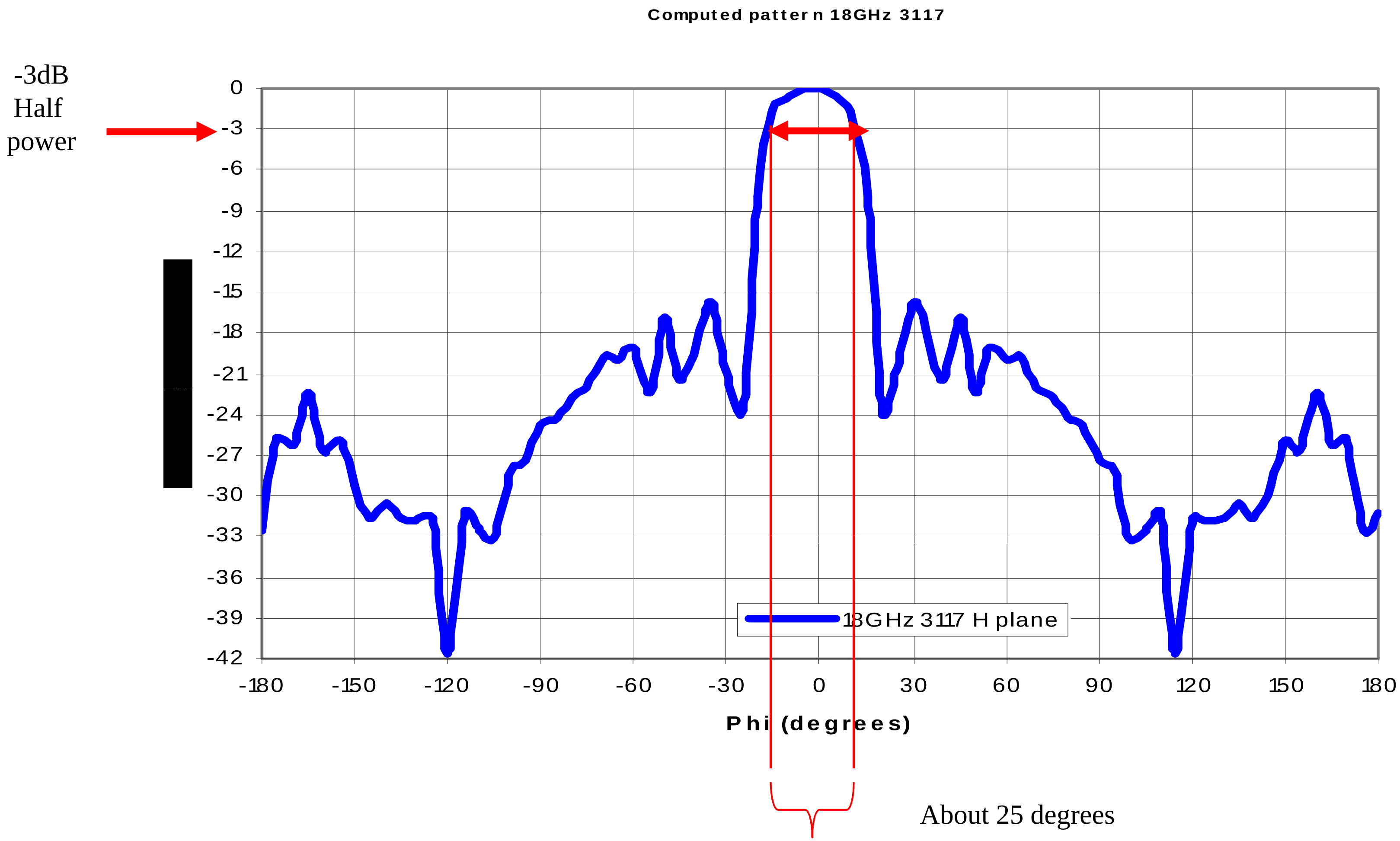
Radiation Pattern: Half Power Beamwidth

Let's represent the pattern in Cartesian coordinates, for clarity





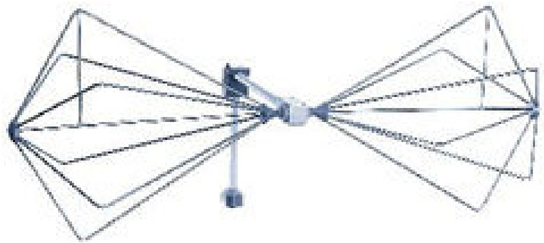
Radiation Pattern: Half Power Beamwidth



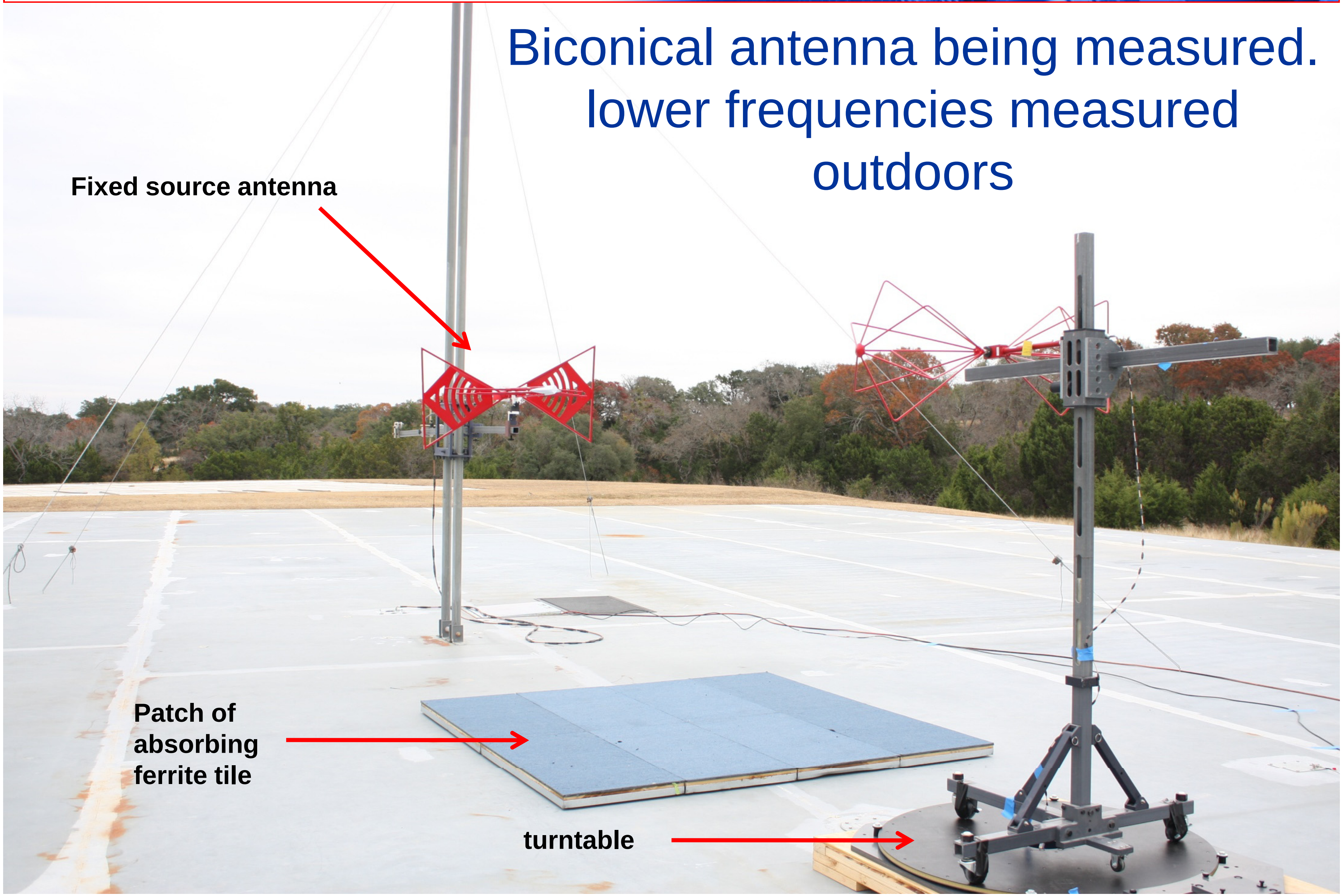
PATTERN MEASUREMENT OF TYPICAL EMC ANTENNAS

Biconical

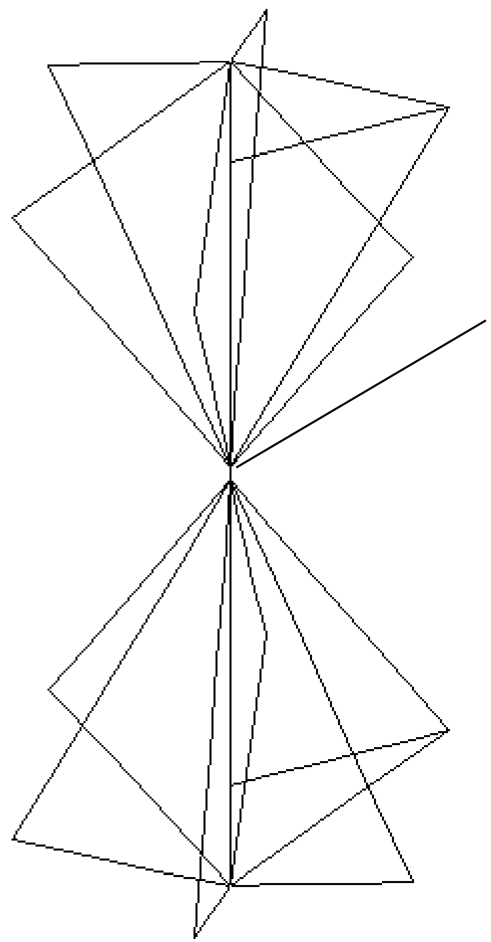
- Workhorse of the EMC antennas for low frequency
- Electrically Small so high VSWR
- Balun determines the frequency range
- Broad banded and omnidirectional

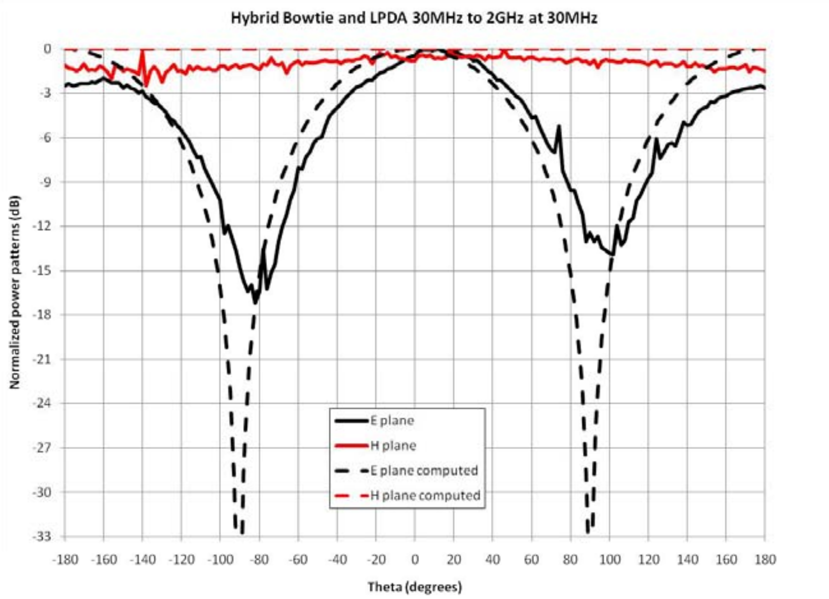


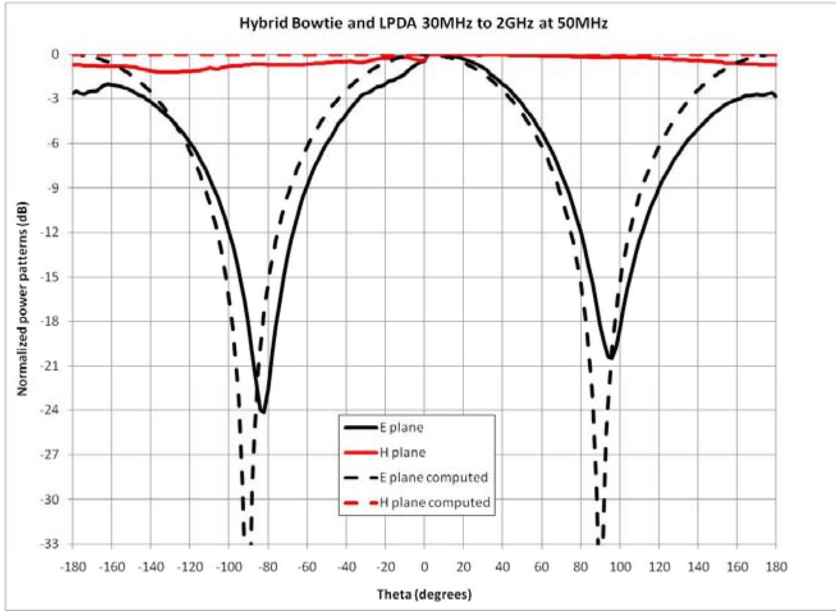
Biconical antenna being measured. lower frequencies measured outdoors

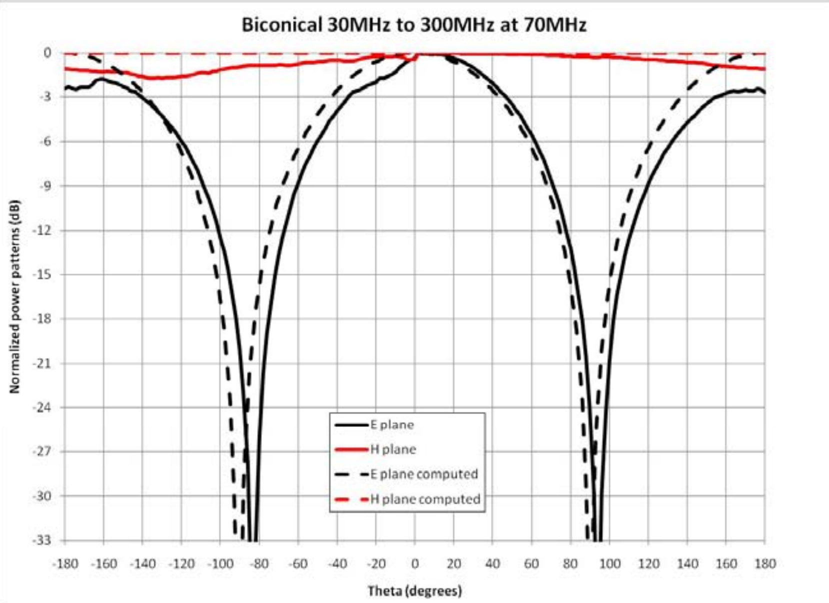


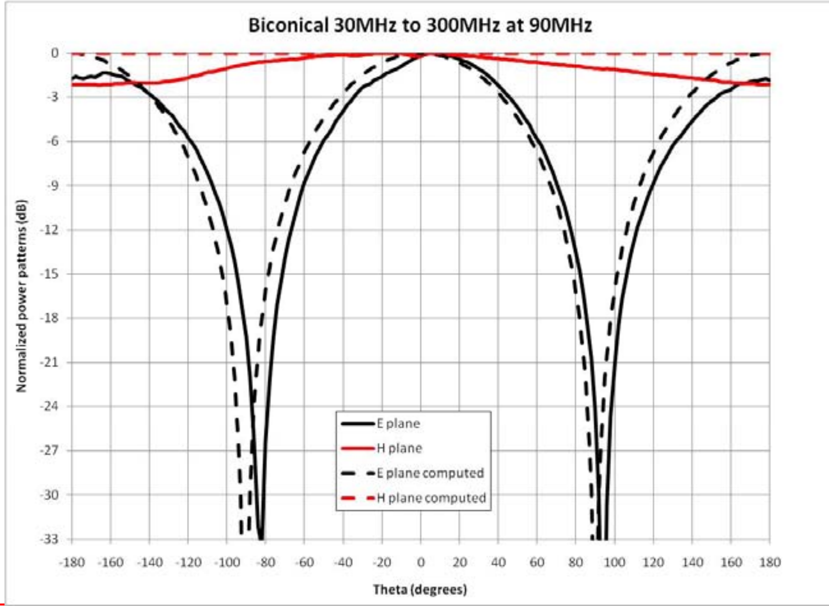
Simplified model of the typical 30MHz to 300MHz biconical antenna.

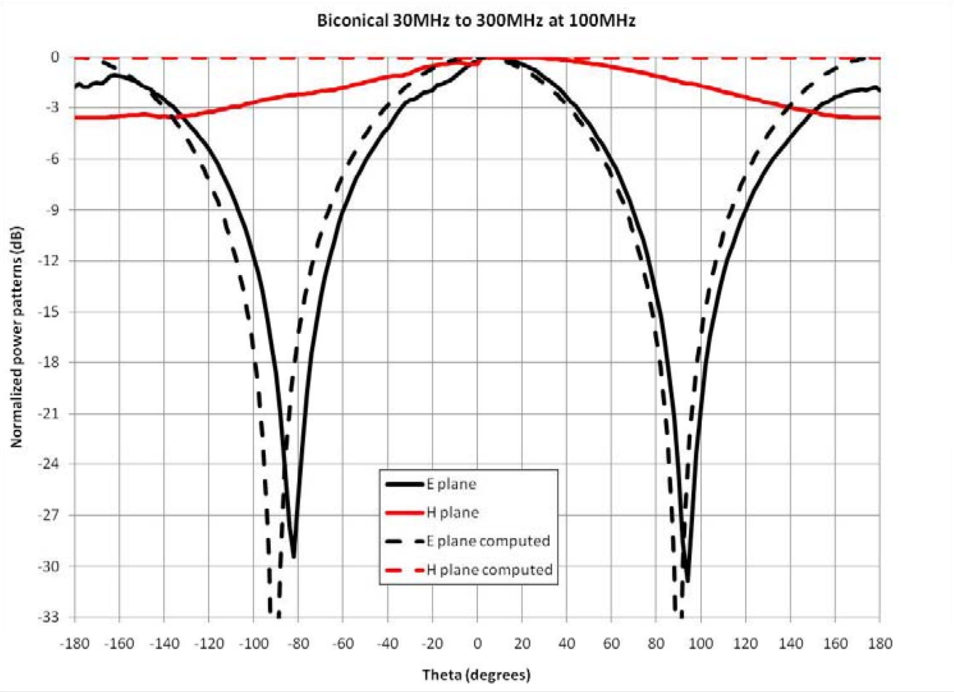


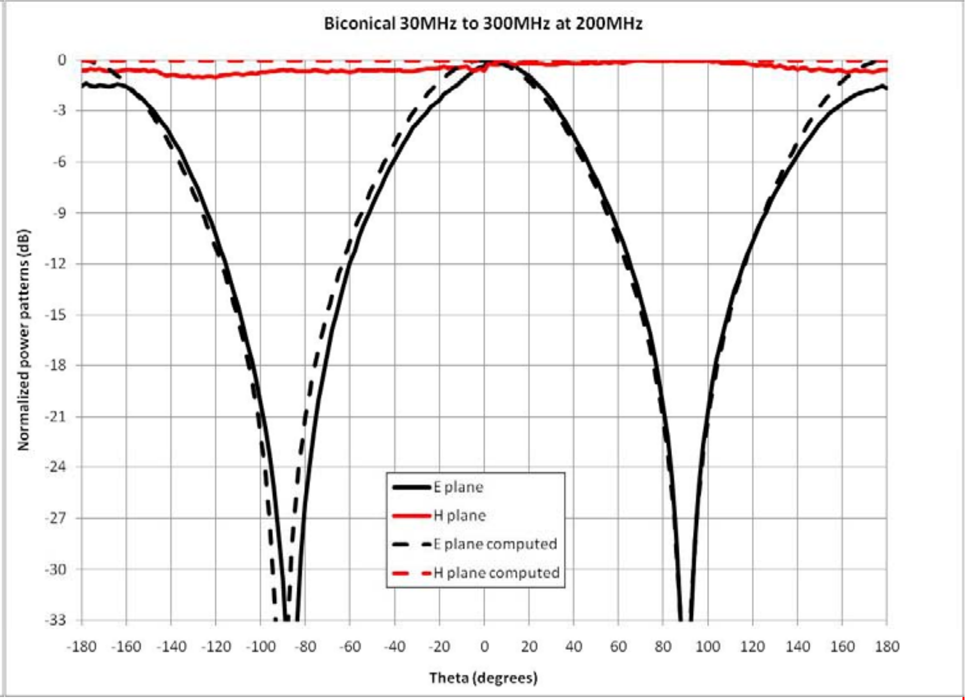

Hybrid Bowtie and LPDA 30MHz to 2GHz at 30MHz
Normalized power patterns (dB)
0
-3
-6
-9
-12
-15
-18
-21
-24
-27
-30
-33
-180 -160 -140 -120 -100 -80 -60 -40 -20 0 20 40 60 80 100 120 140 160 180
Theta (degrees)
E plane
H plane
E plane computed
H plane computed

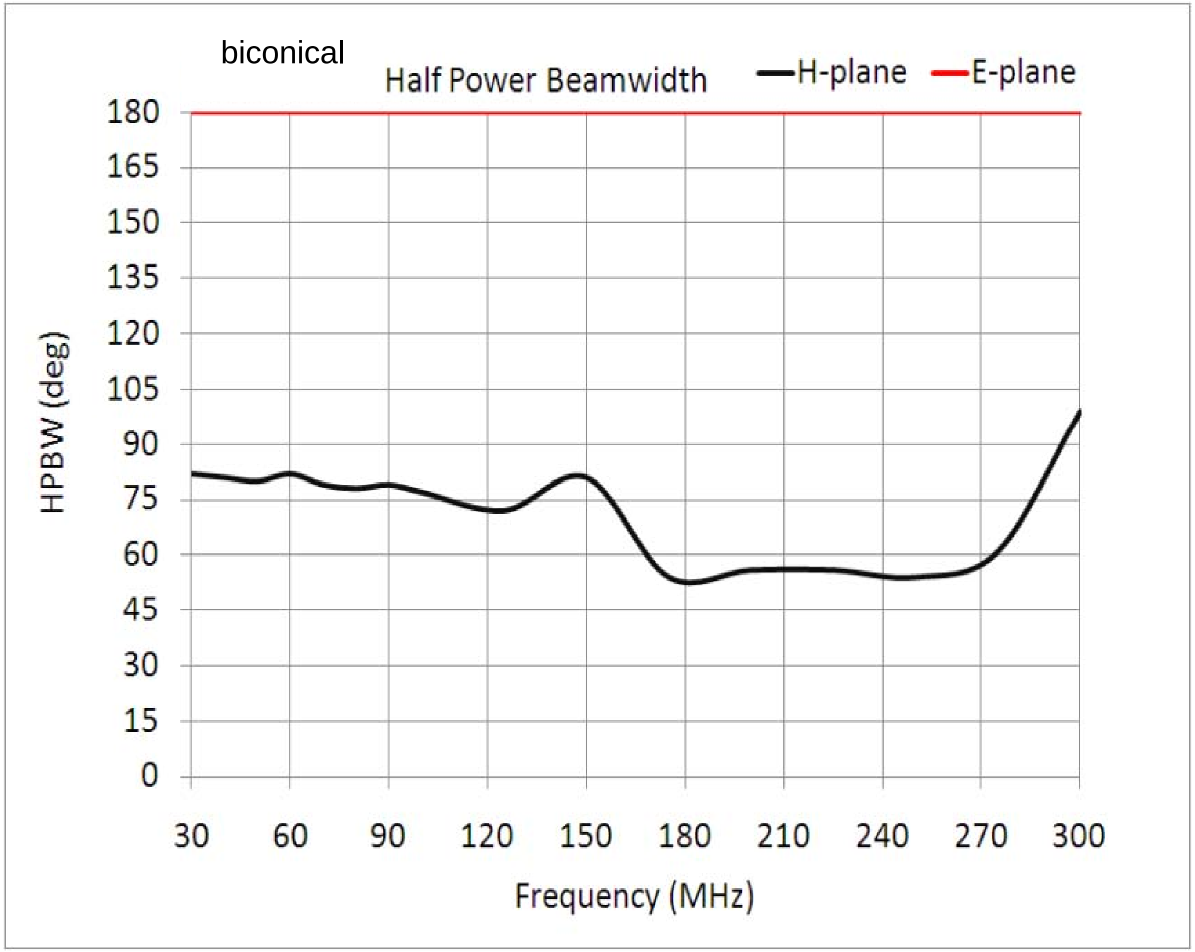

Hybrid Bowtie and LPDA 30MHz to 2GHz at 50MHz
Normalized power patterns (dB)
0
-3
-6
-9
-12
-15
-18
-21
-24
-27
-30
-33
-180 -160 -140 -120 -100 -80 -60 -40 -20 0 20 40 60 80 100 120 140 160 180
Theta (degrees)
E plane
H plane
E plane computed
H plane computed


Biconical 30MHz to 300MHz at 70MHz
Normalized power patterns (dB)
0
-3
-6
-9
-12
-15
-18
-21
-24
-27
-30
-33
-180 -160 -140 -120 -100 -80 -60 -40 -20 0 20 40 60 80 100 120 140 160 180
Theta (degrees)
E plane
H plane
E plane computed
H plane computed


Biconical 30MHz to 300MHz at 90MHz
Normalized power patterns (dB)
0
-3
-6
-9
-12
-15
-18
-21
-24
-27
-30
-33
-180 -160 -140 -120 -100 -80 -60 -40 -20 0 20 40 60 80 100 120 140 160 180
Theta (degrees)
E plane
H plane
E plane computed
H plane computed

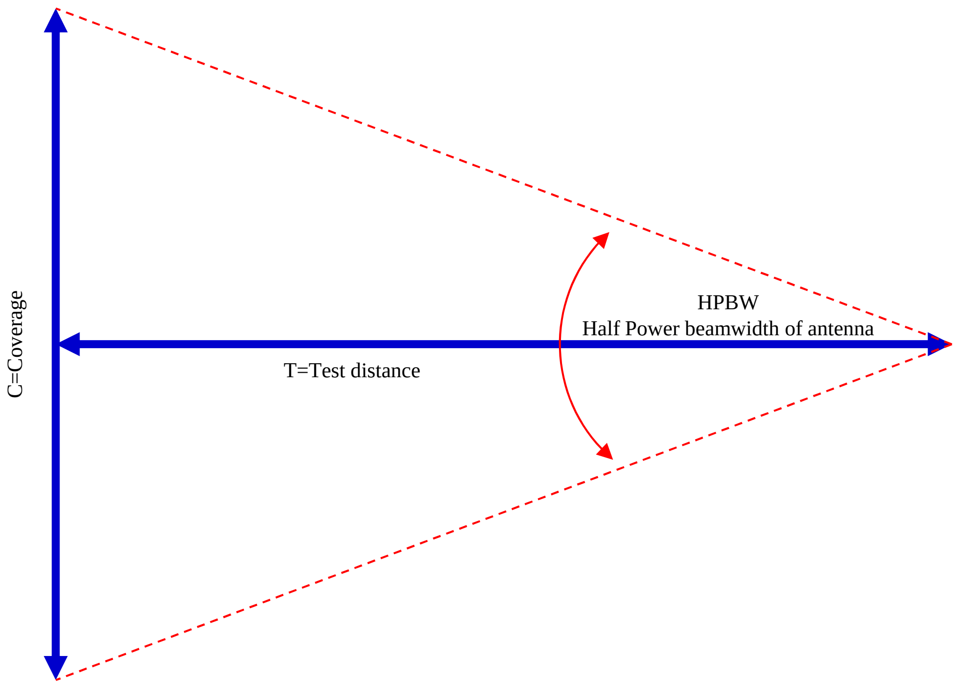

Biconical 30MHz to 300MHz at 100MHz
Normalized power patterns (dB)
Theta (degrees)
E plane
H plane
E plane computed
H plane computed


Biconical 30MHz to 300MHz at 200MHz
Normalized power patterns (dB)
Theta (degrees)
E plane
H plane
E plane computed
H plane computed

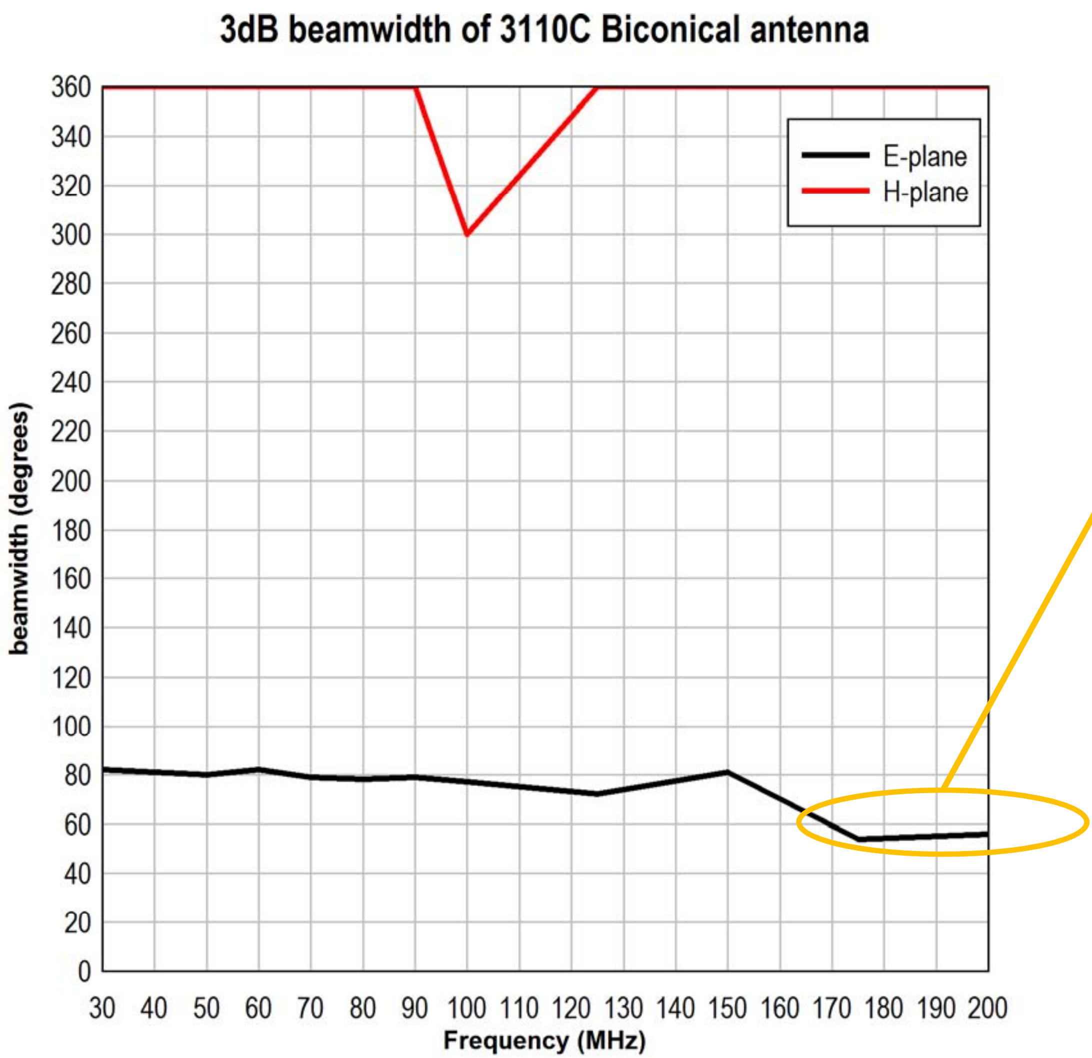

biconical
Half Power Beamwidth
H-plane
E-plane
180
165
150
135
120
105
90
75
60
45
30
15
0
HPBW (deg)
30
60
90
120
150
180
210
240
270
300
Frequency (MHz)

Coverage

$$C=2T \times \tan(HPBW/2)$$



Typical Biconical coverage



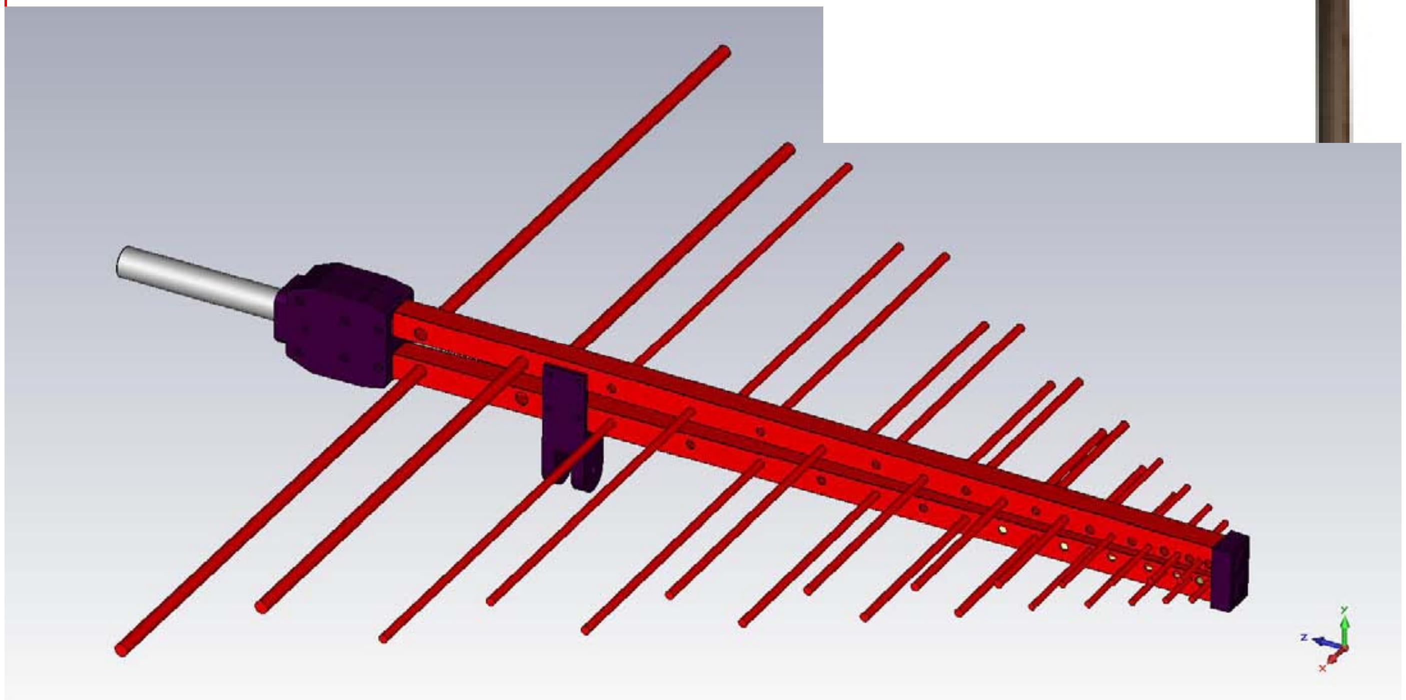
Worst case 55 degrees on E plane
Hence:
3m test distance
3.12m coverage
10m test distance
10.4m coverage

Logarithmic Periodic Dipole Array

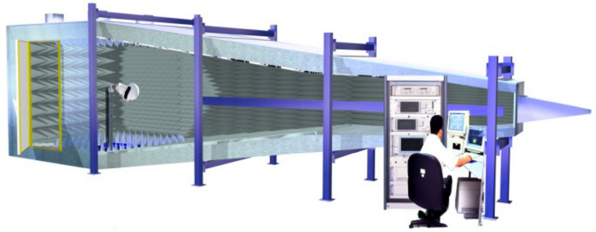
- Log P. Log Per. LPDA, etc
- Efficient antennas
- In order not to make them extremely long usually gain is capped at 6dBi
- Some units can handle high power
- Usually used between 200MHz and 2GHz
- Broad banded and directional

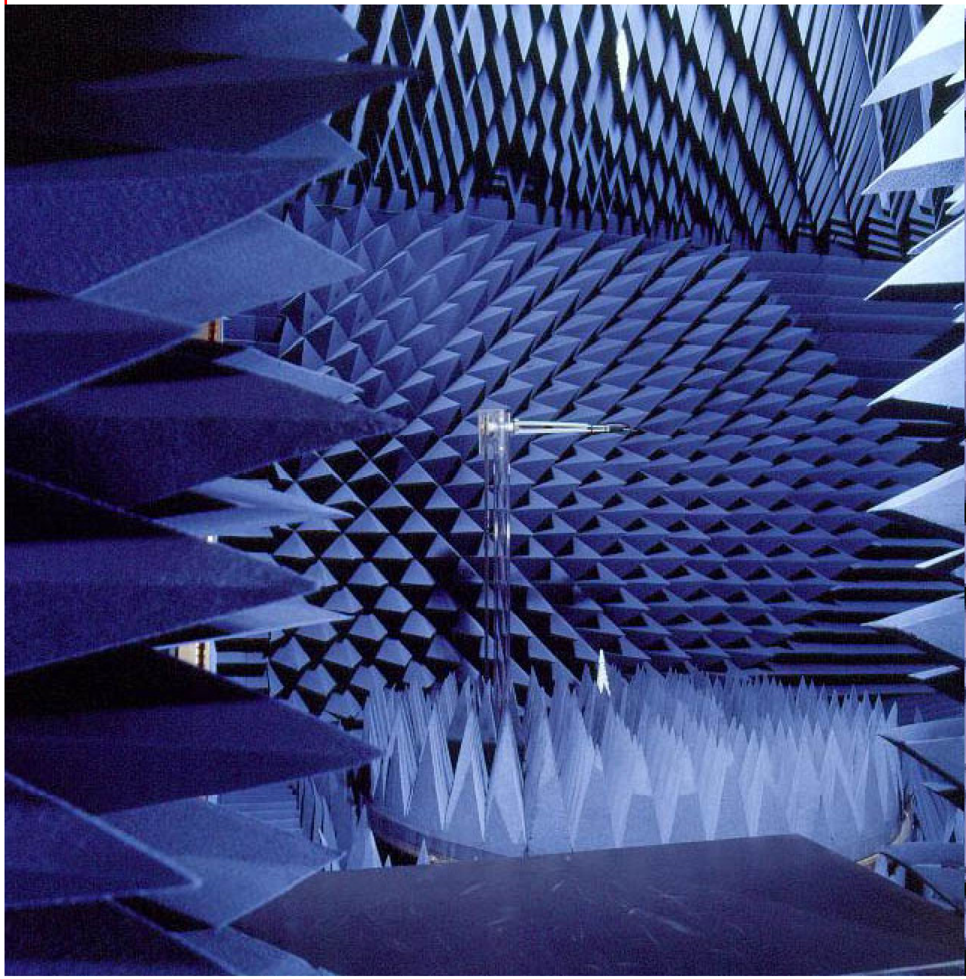
80MHz to 2GHz LPDA on the OATS

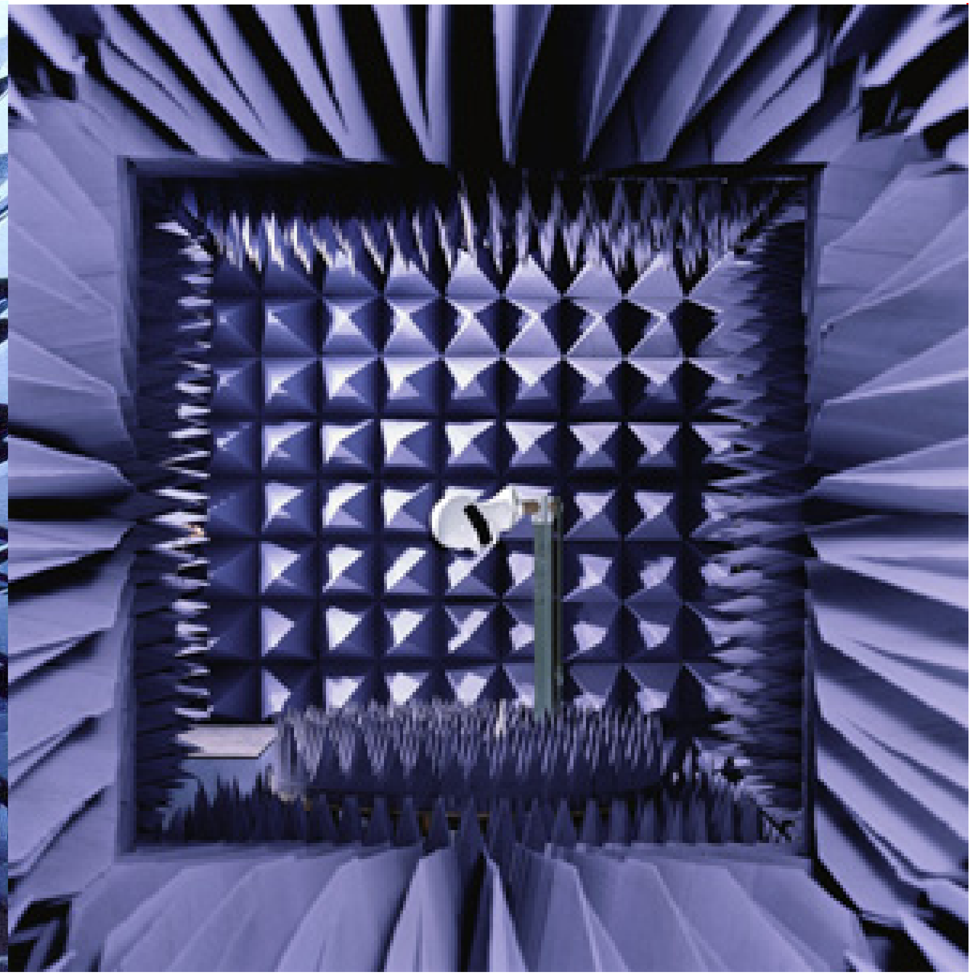
Numerical Model and Picture of the 200MHz to 2GHz log Periodic This one was measured in the taper anechoic antenna pattern measurement chamber

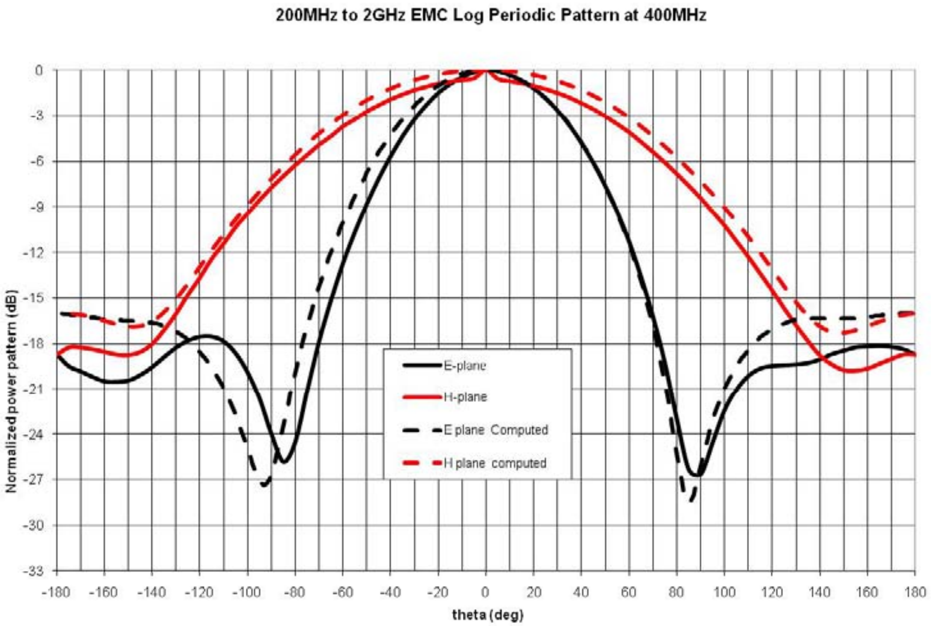


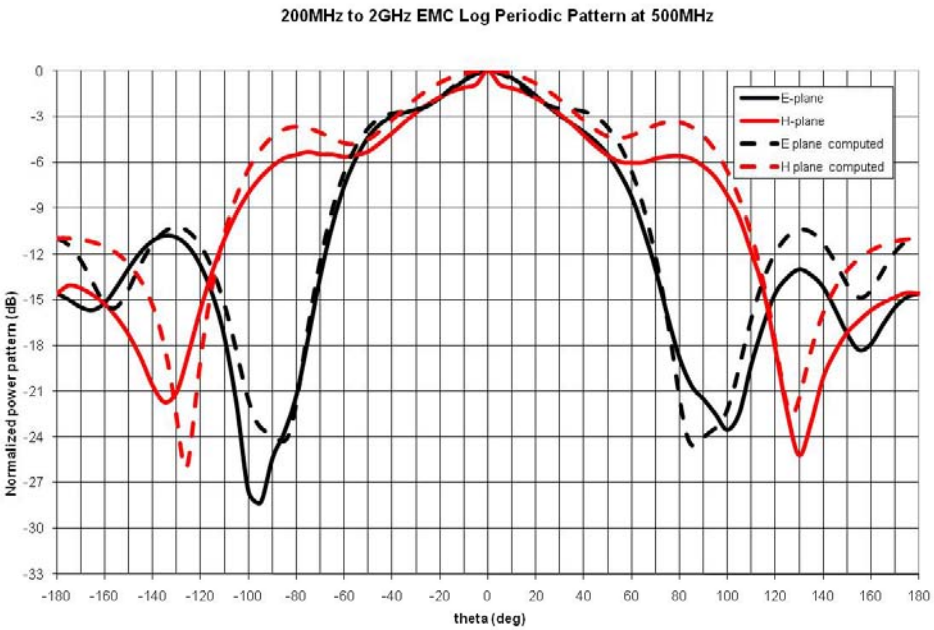
The Taper anechoic chamber has a range of 400MHz to 18GHz it was used from 400MHz to 2GHz

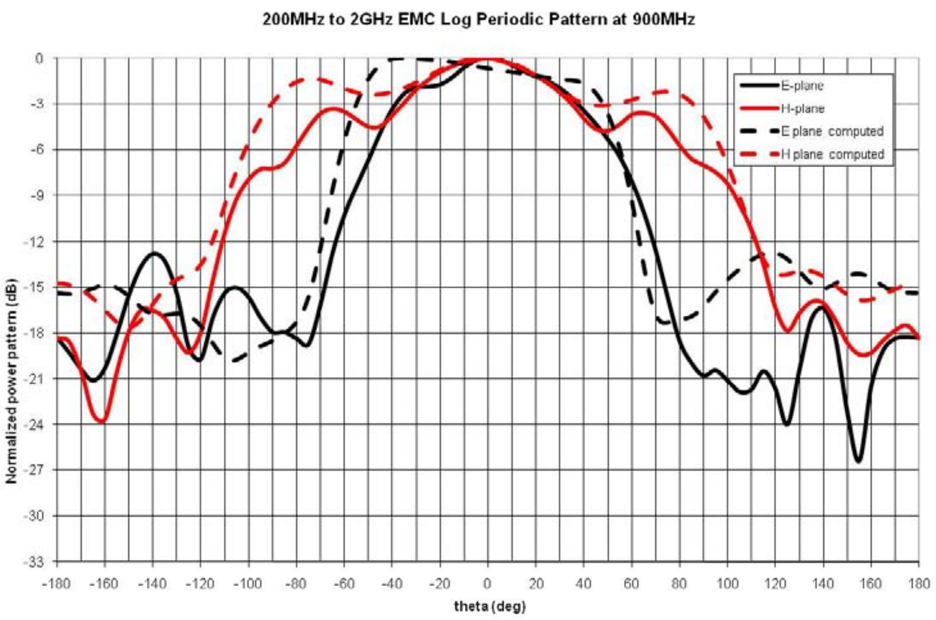


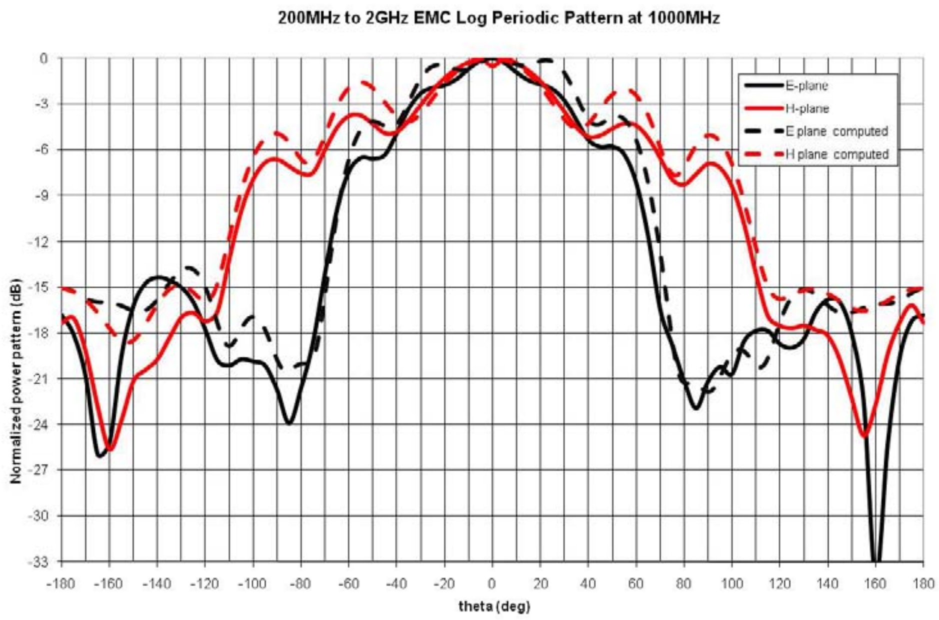


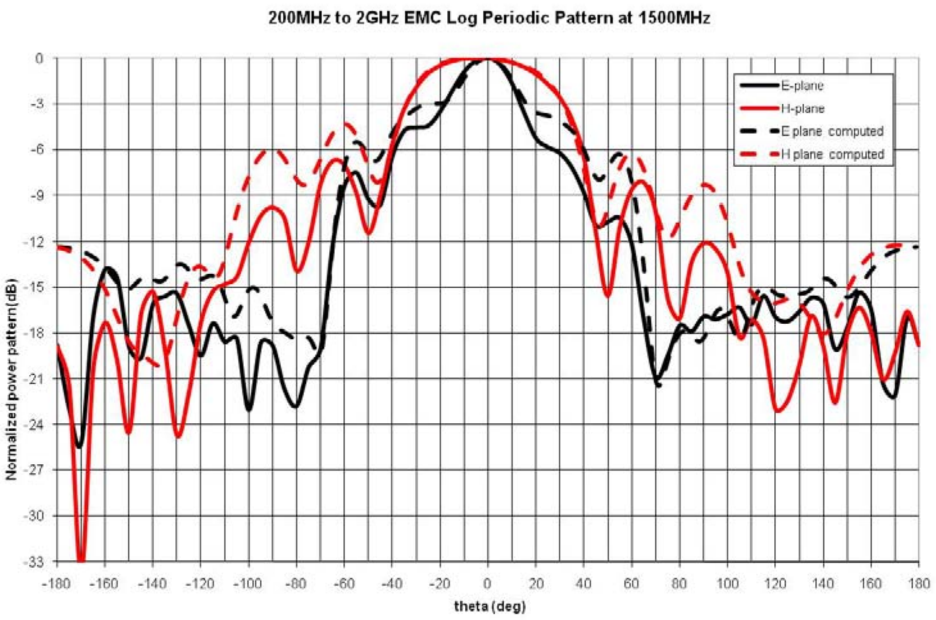


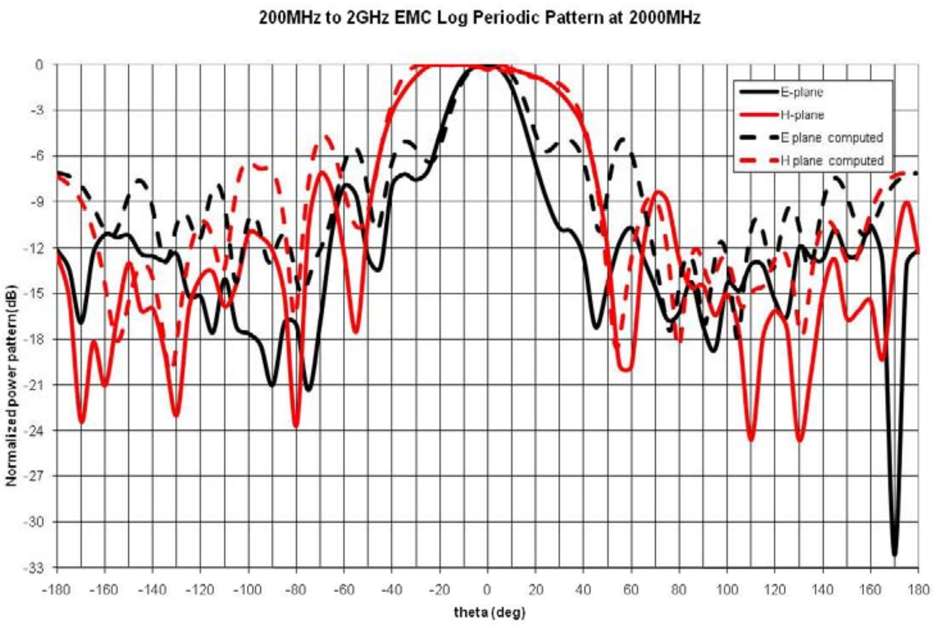

200MHz to 2GHz EMC Log Periodic Pattern at 400MHz
Normalized power pattern (dB)
theta (deg)
E-plane
H-plane
E plane Computed
H plane computed


200MHz to 2GHz EMC Log Periodic Pattern at 500MHz
Normalized power pattern (dB)
theta (deg)
E-plane
H-plane
E plane computed
H plane computed


200MHz to 2GHz EMC Log Periodic Pattern at 900MHz
E-plane
H-plane
E plane computed
H plane computed
Normalized power pattern (dB)
theta (deg)


200MHz to 2GHz EMC Log Periodic Pattern at 1000MHz
E-plane
H-plane
E plane computed
H plane computed
Normalized power pattern (dB)
theta (deg)


200MHz to 2GHz EMC Log Periodic Pattern at 1500MHz
E-plane
H-plane
E plane computed
H plane computed
Normalized power pattern(dB)
theta (deg)


200MHz to 2GHz EMC Log Periodic Pattern at 2000MHz
E-plane
H-plane
E plane computed
H plane computed
Normalized power pattern(dB)
theta (deg)

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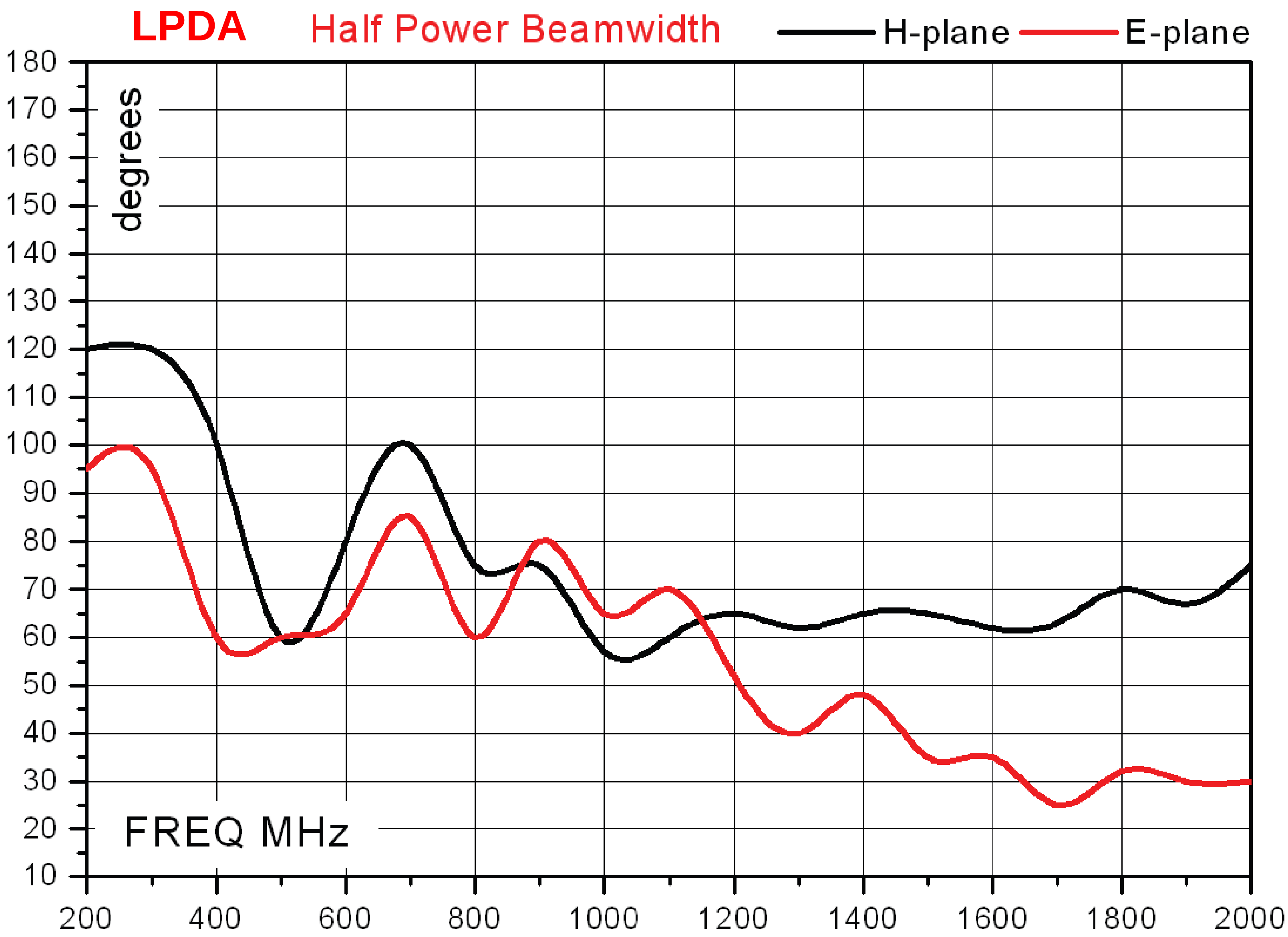
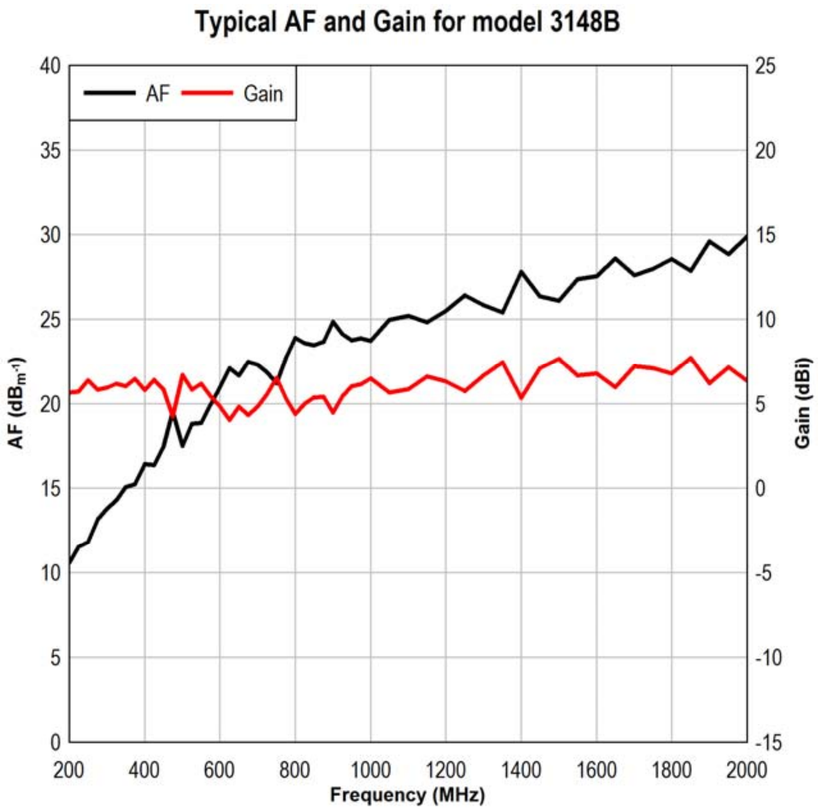


Typical LPDA 200MHz to 1000MHz



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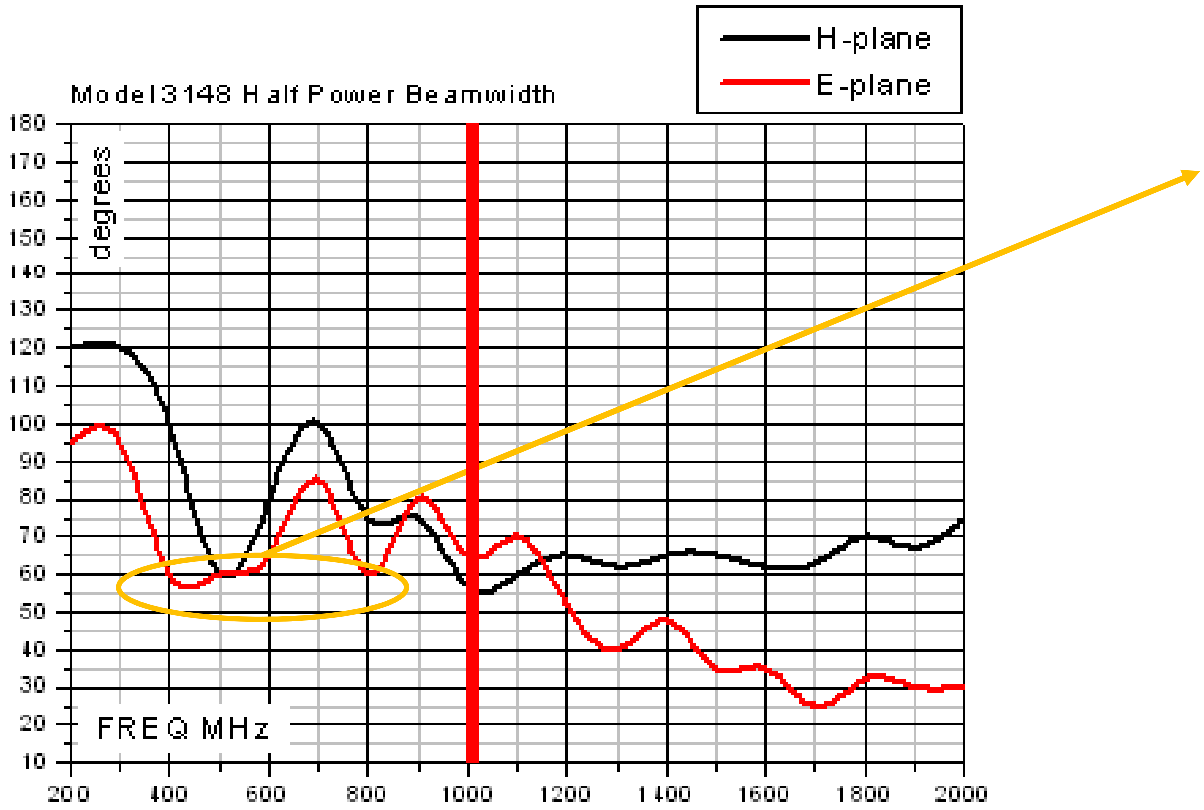
3148B coverage

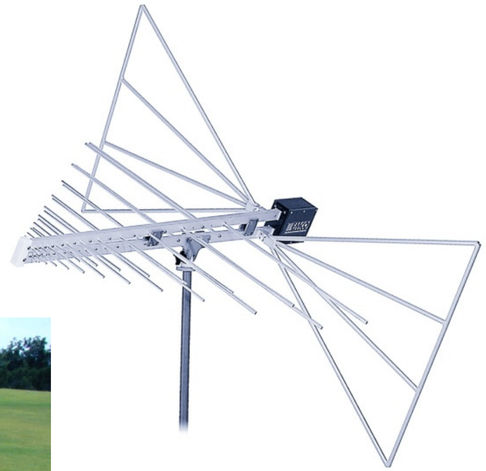


Worst case 56 degrees on E plane
Hence:
3m test distance
3.19m coverage
10m test distance
10.63m coverage

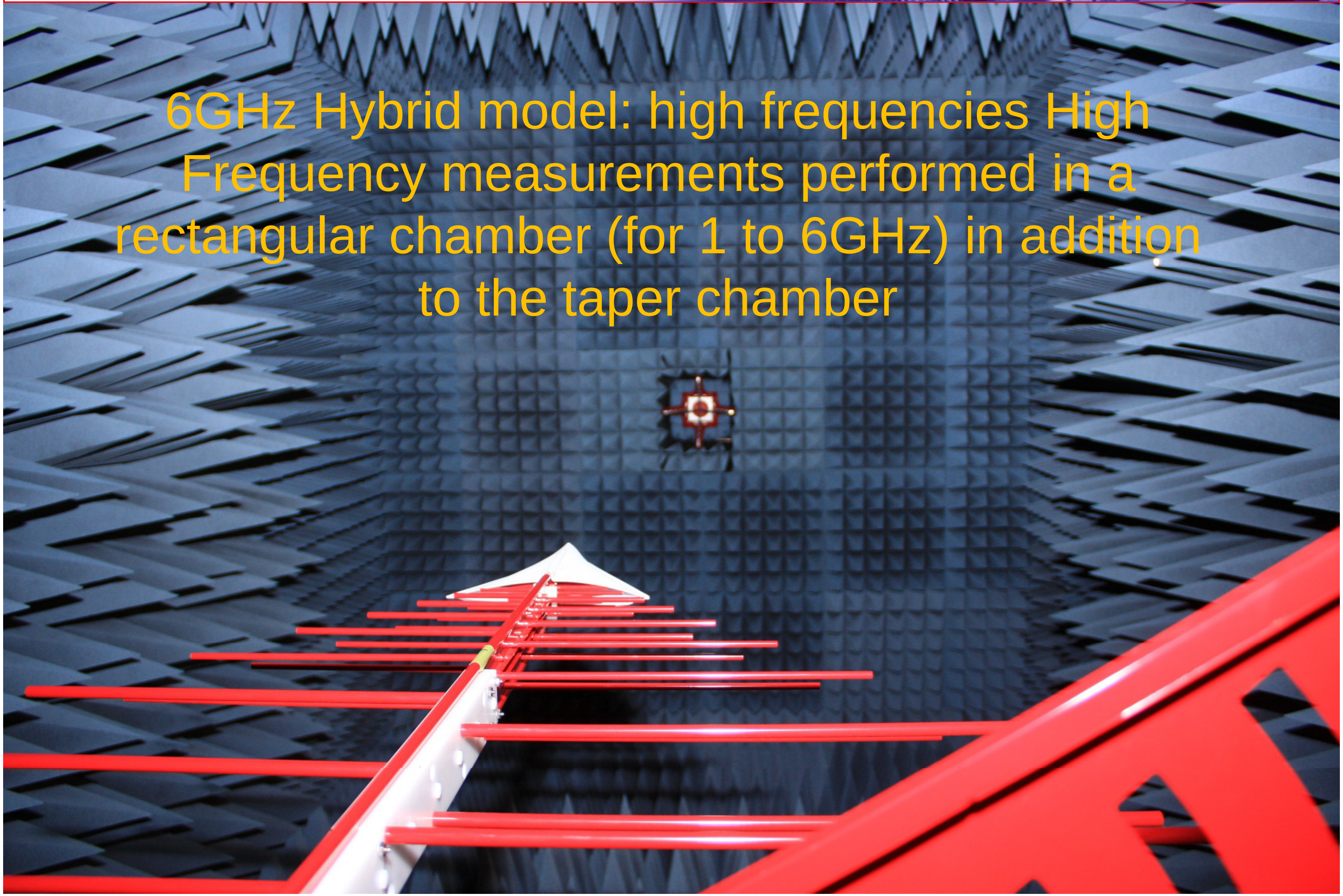
Notice that we do not use above 1GHz

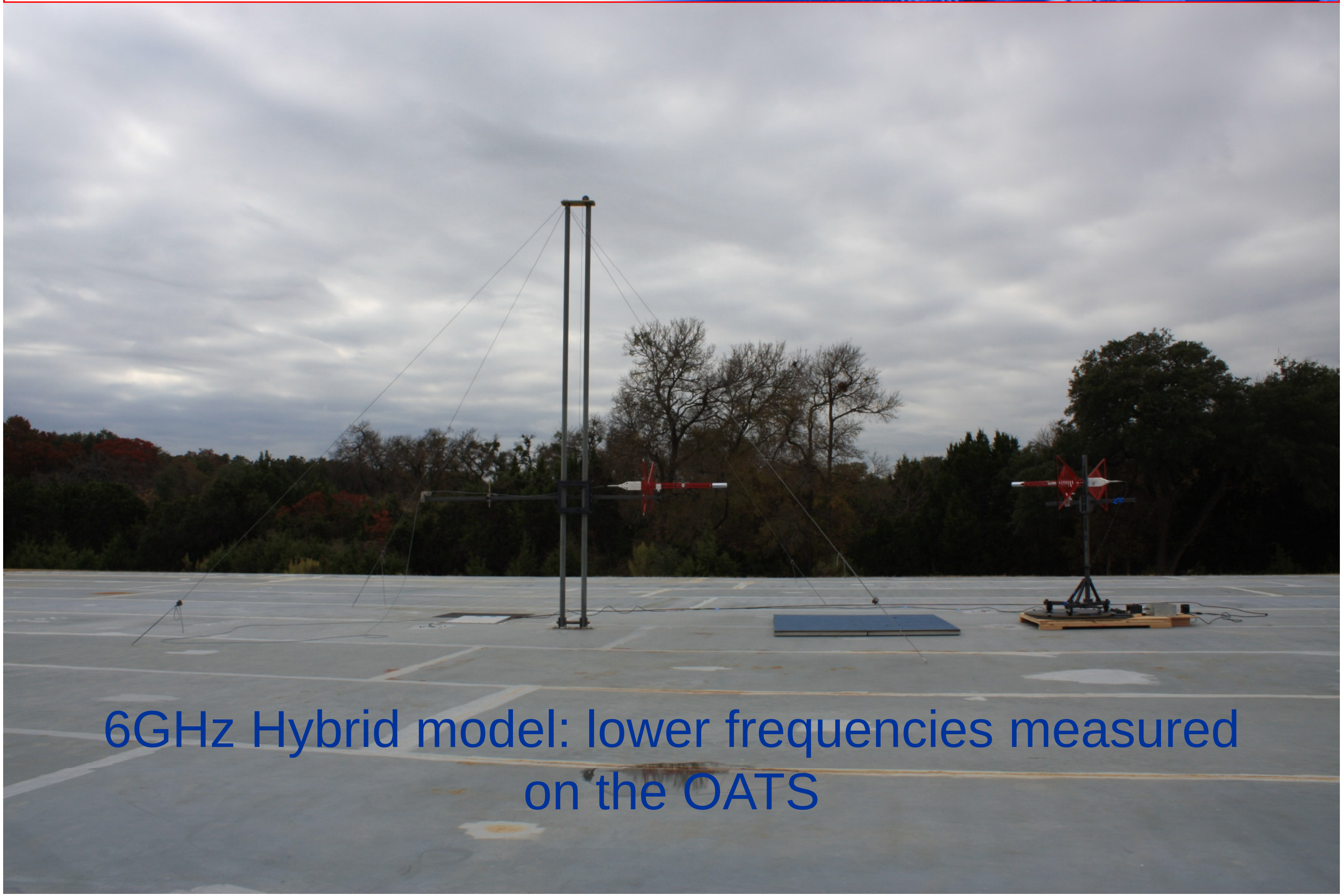
Biconical/Bowtie Log Periodic Hybrid

- Extremely broadband antennas mixing the advantages of the biconicals (electrically small) and LPDA (high gain and broadband)
- Some standards do not approve
- Incredible broadband one single antenna covering from 30MHz to 6GHz



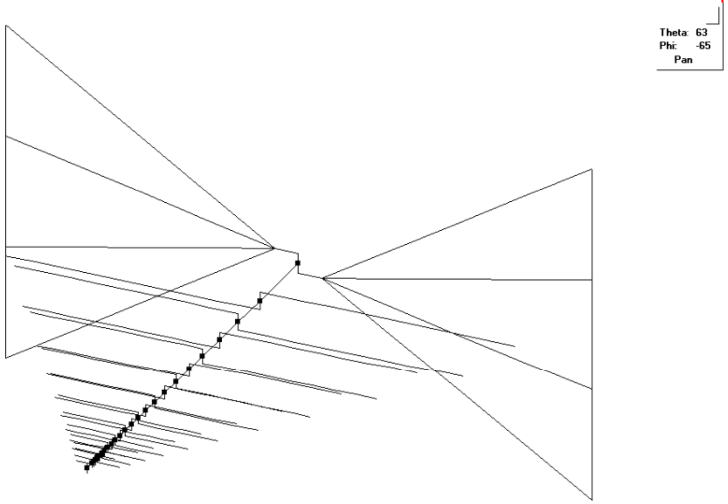
6GHz Hybrid model: high frequencies High Frequency measurements performed in a rectangular chamber (for 1 to 6GHz) in addition to the taper chamber

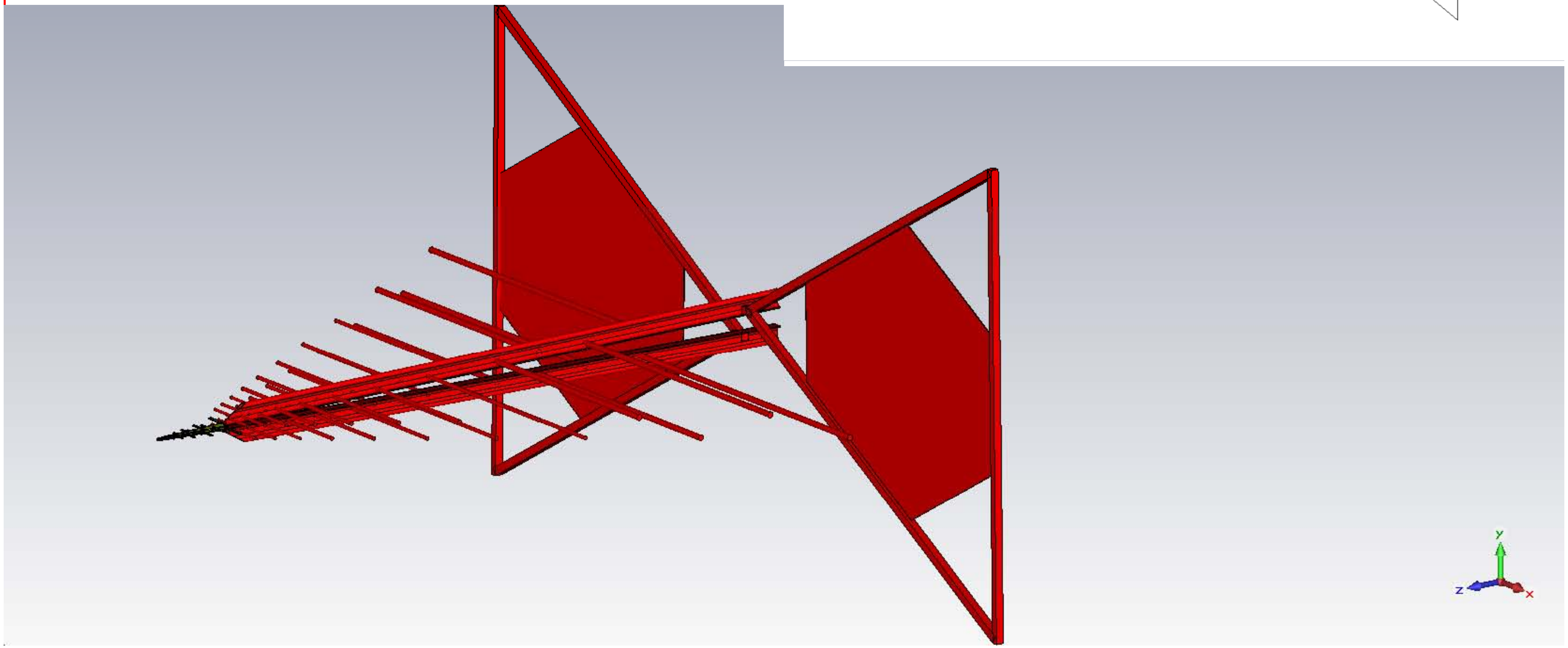


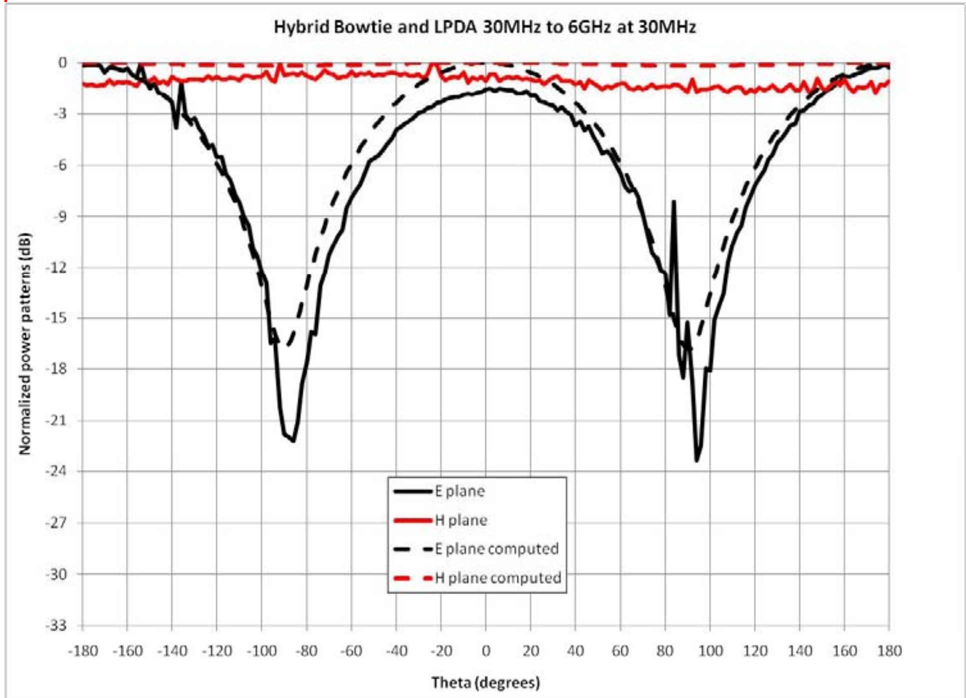


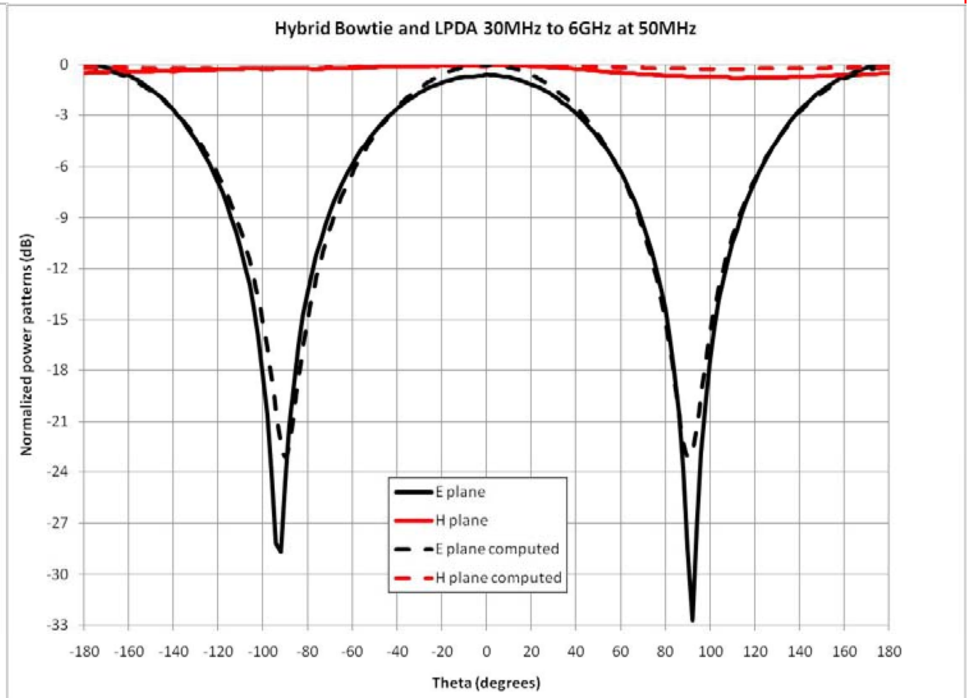
6GHz Hybrid model: lower frequencies measured on the OATS

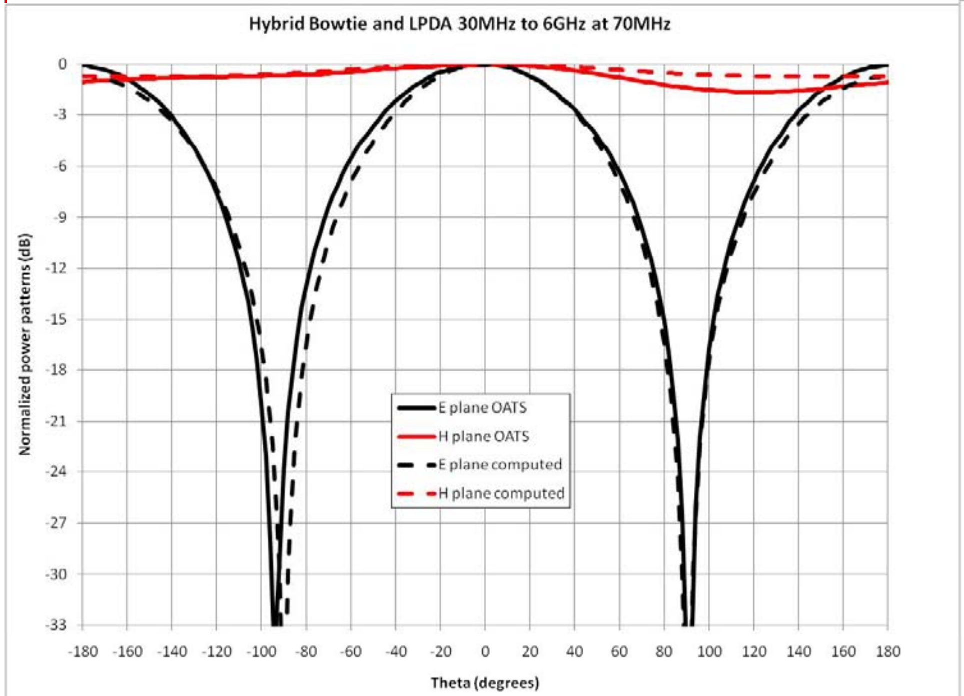
Numerical Model for NEC and a commercial package for the 30MHz to 6GHz Hybrid antenna

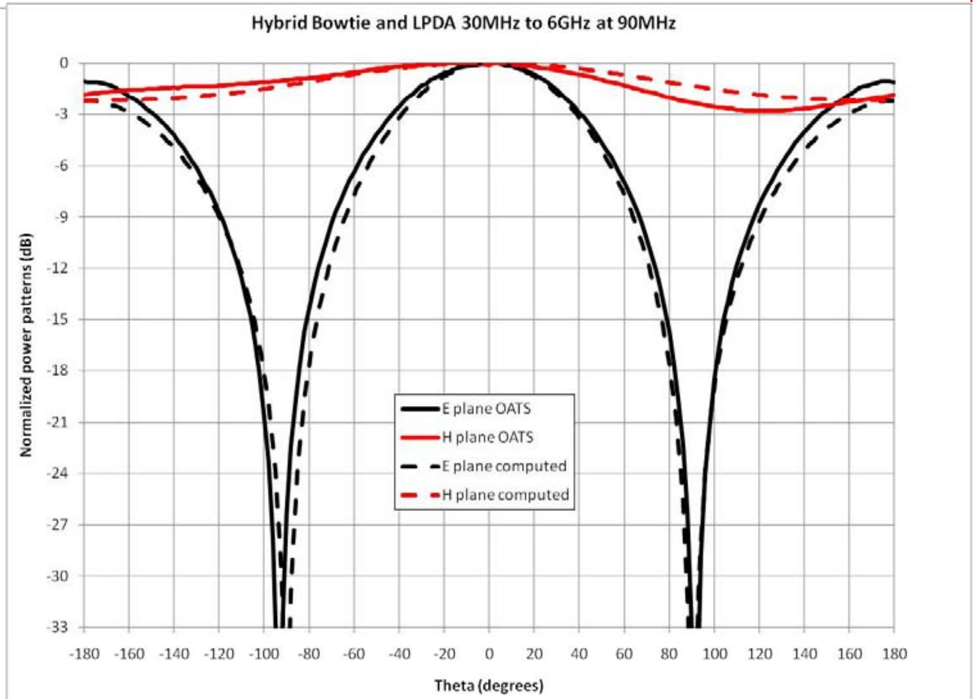


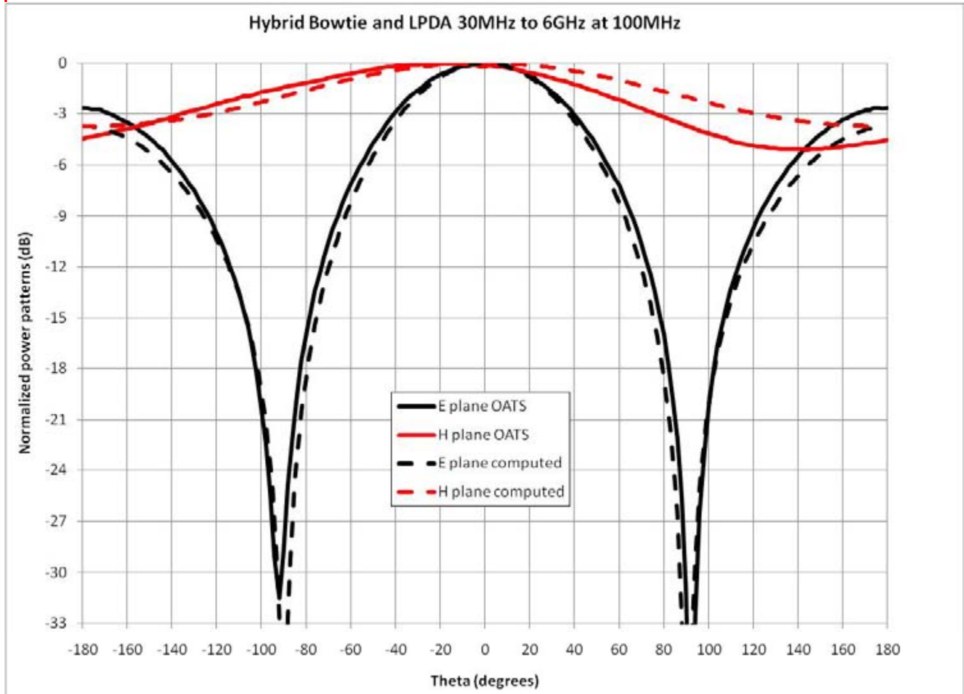


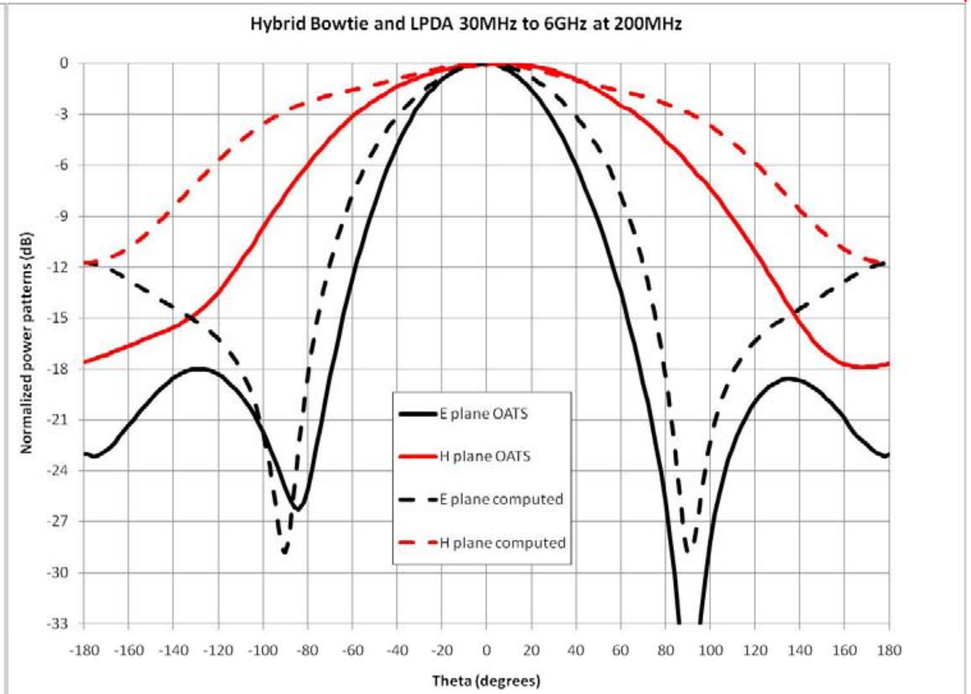

Hybrid Bowtie and LPDA 30MHz to 6GHz at 30MHz
Normalized power patterns (dB)
Theta (degrees)
E plane
H plane
E plane computed
H plane computed

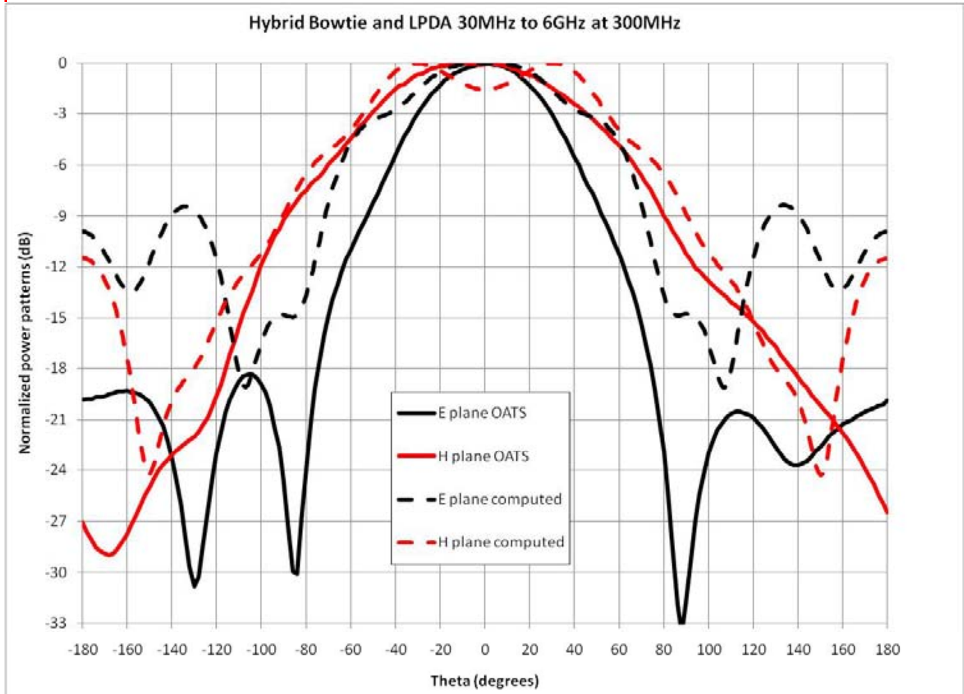

Hybrid Bowtie and LPDA 30MHz to 6GHz at 50MHz
Normalized power patterns (dB)
Theta (degrees)
E plane
H plane
E plane computed
H plane computed

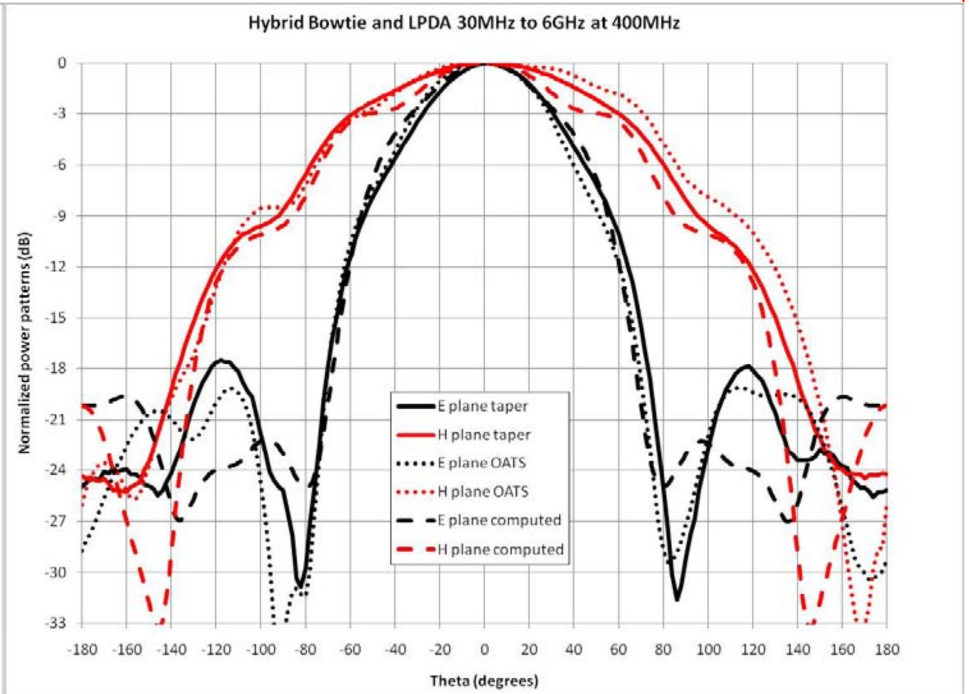

Hybrid Bowtie and LPDA 30MHz to 6GHz at 70MHz
Normalized power patterns (dB)
Theta (degrees)
E plane OATS
H plane OATS
E plane computed
H plane computed

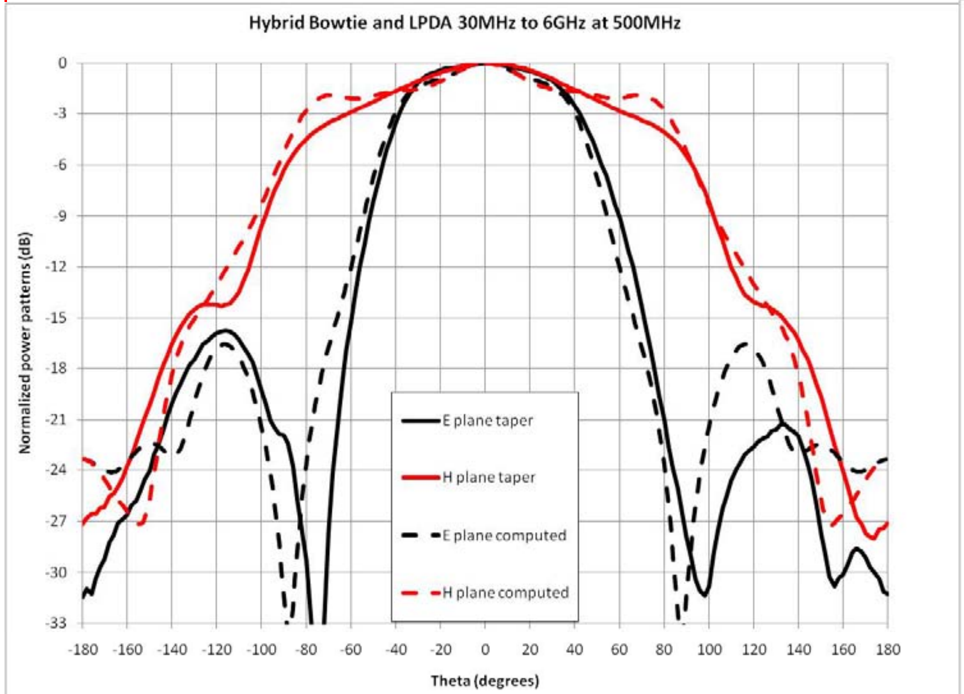

Hybrid Bowtie and LPDA 30MHz to 6GHz at 90MHz
Normalized power patterns (dB)
Theta (degrees)
E plane OATS
H plane OATS
E plane computed
H plane computed

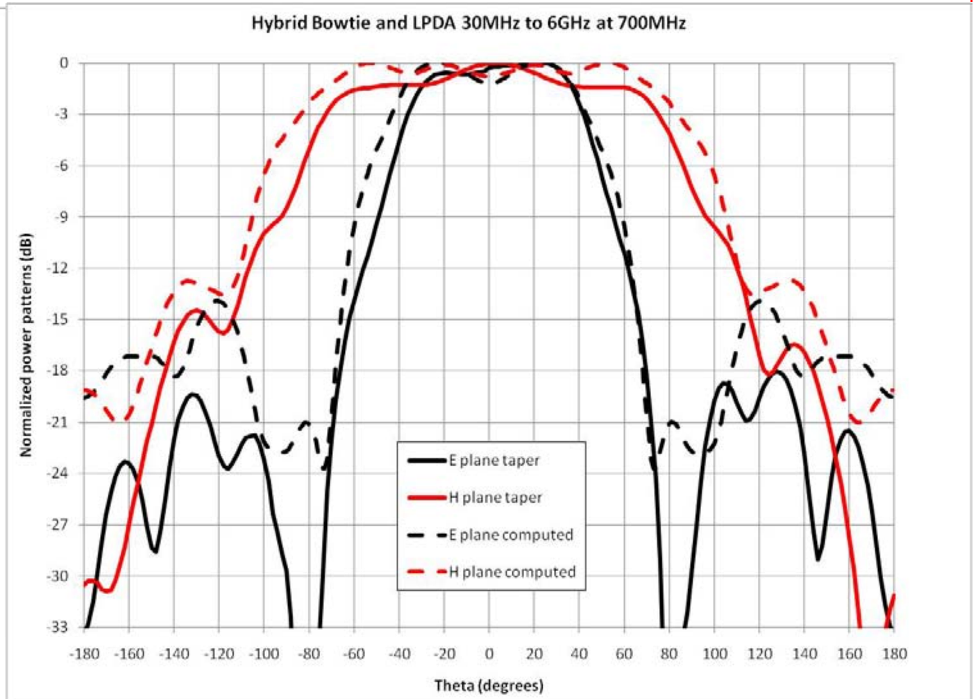

Hybrid Bowtie and LPDA 30MHz to 6GHz at 100MHz
Normalized power patterns (dB)
Theta (degrees)
E plane OATS
H plane OATS
E plane computed
H plane computed

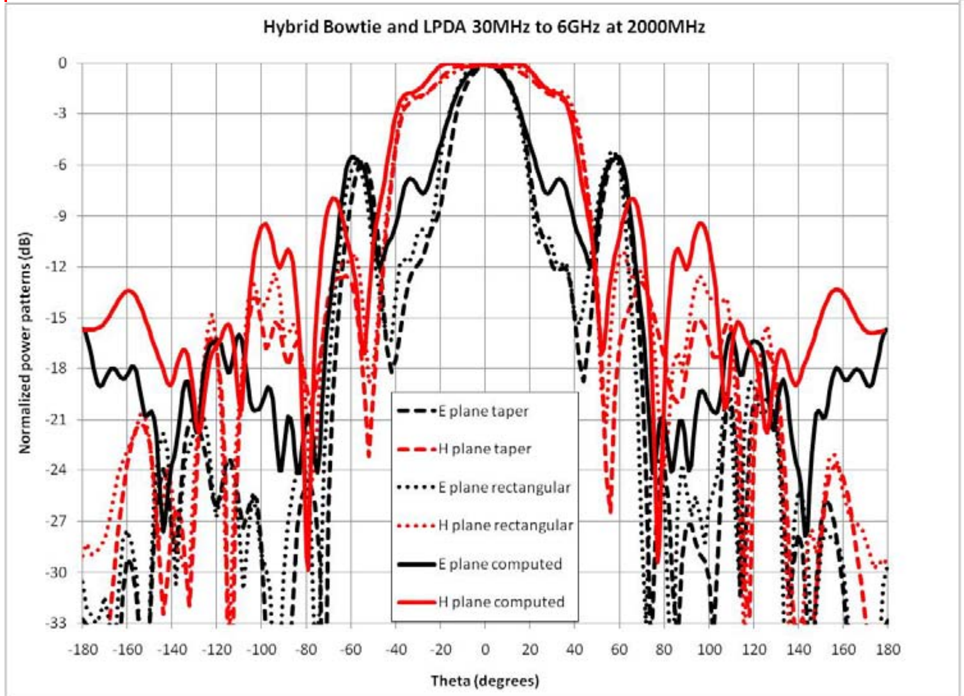

Hybrid Bowtie and LPDA 30MHz to 6GHz at 200MHz
Normalized power patterns (dB)
Theta (degrees)
E plane OATS
H plane OATS
E plane computed
H plane computed

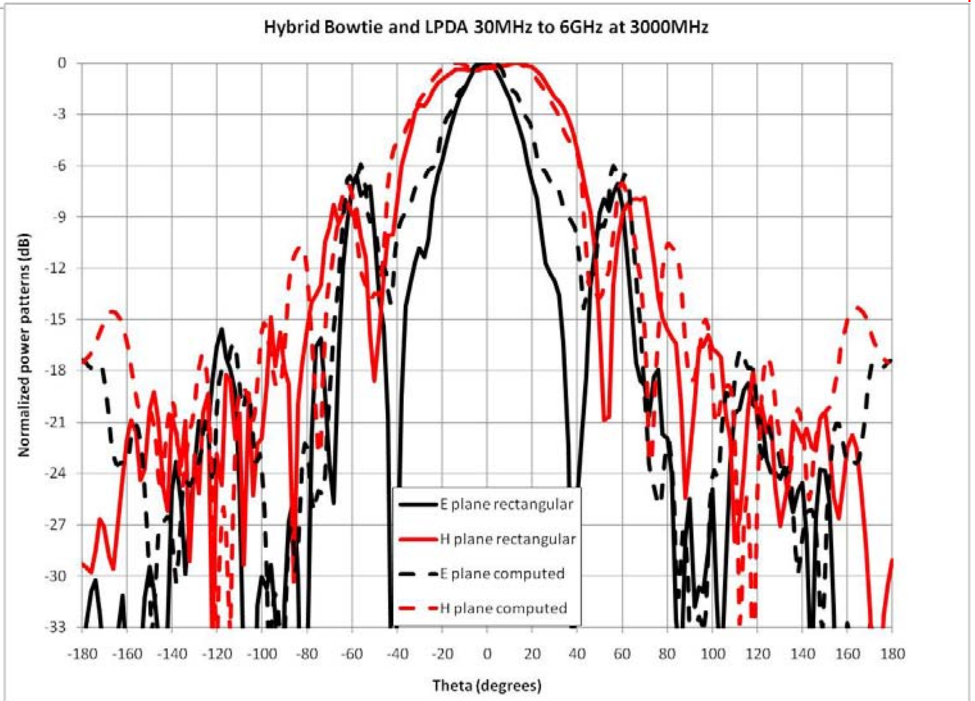

Hybrid Bowtie and LPDA 30MHz to 6GHz at 300MHz
Normalized power patterns (dB)
Theta (degrees)
E plane OATS
H plane OATS
E plane computed
H plane computed

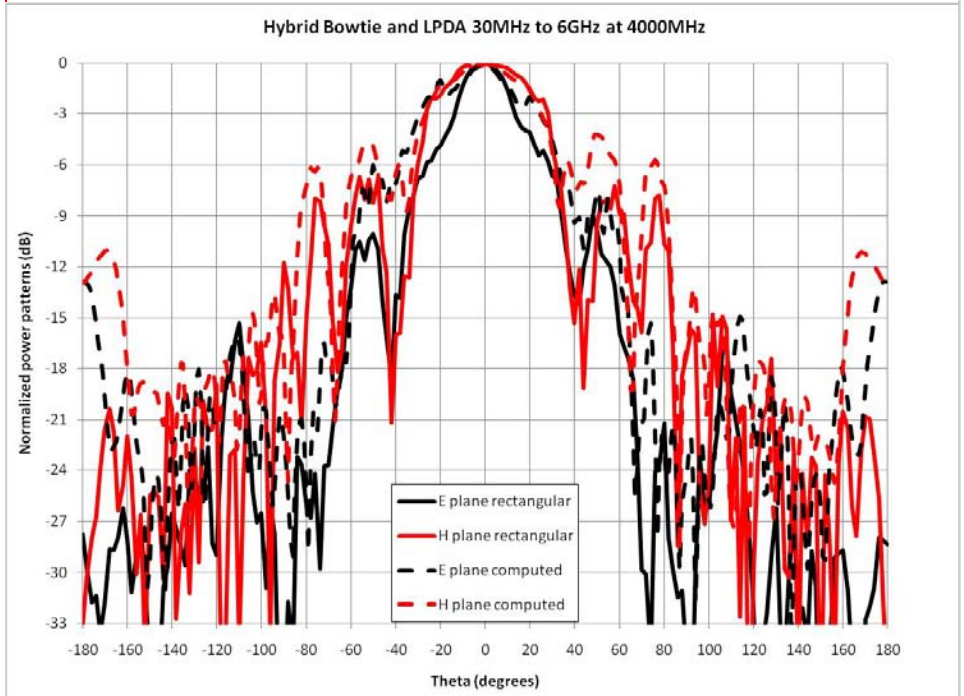

Hybrid Bowtie and LPDA 30MHz to 6GHz at 400MHz
Normalized power patterns (dB)
Theta (degrees)
E plane taper
H plane taper
E plane OATS
H plane OATS
E plane computed
H plane computed

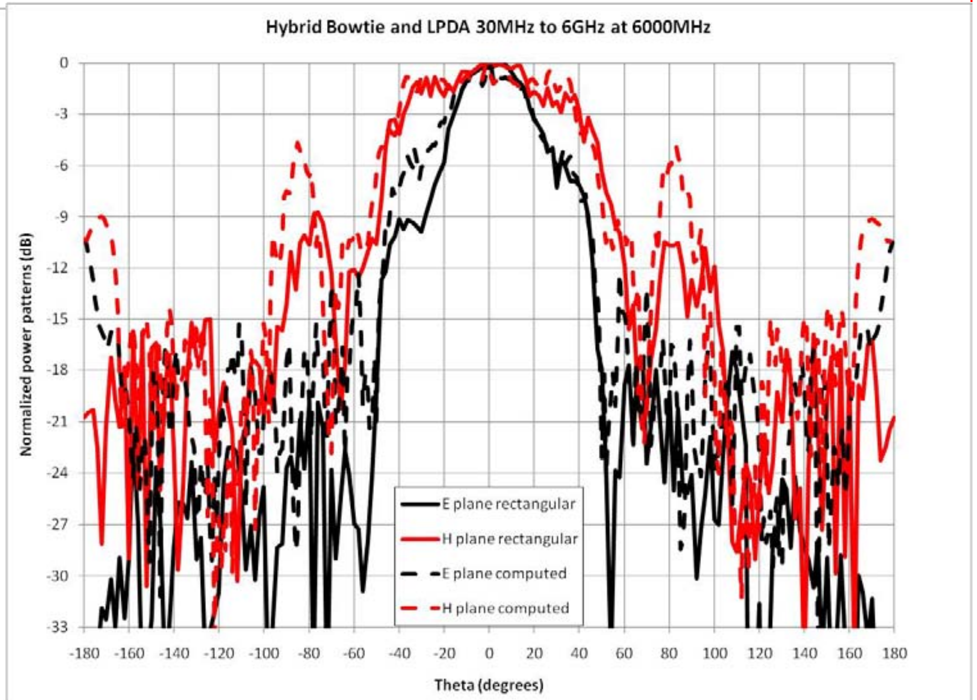

Hybrid Bowtie and LPDA 30MHz to 6GHz at 500MHz
Normalized power patterns (dB)
0
-3
-6
-9
-12
-15
-18
-21
-24
-27
-30
-33
-180 -160 -140 -120 -100 -80 -60 -40 -20 0 20 40 60 80 100 120 140 160 180
Theta (degrees)
E plane taper
H plane taper
E plane computed
H plane computed

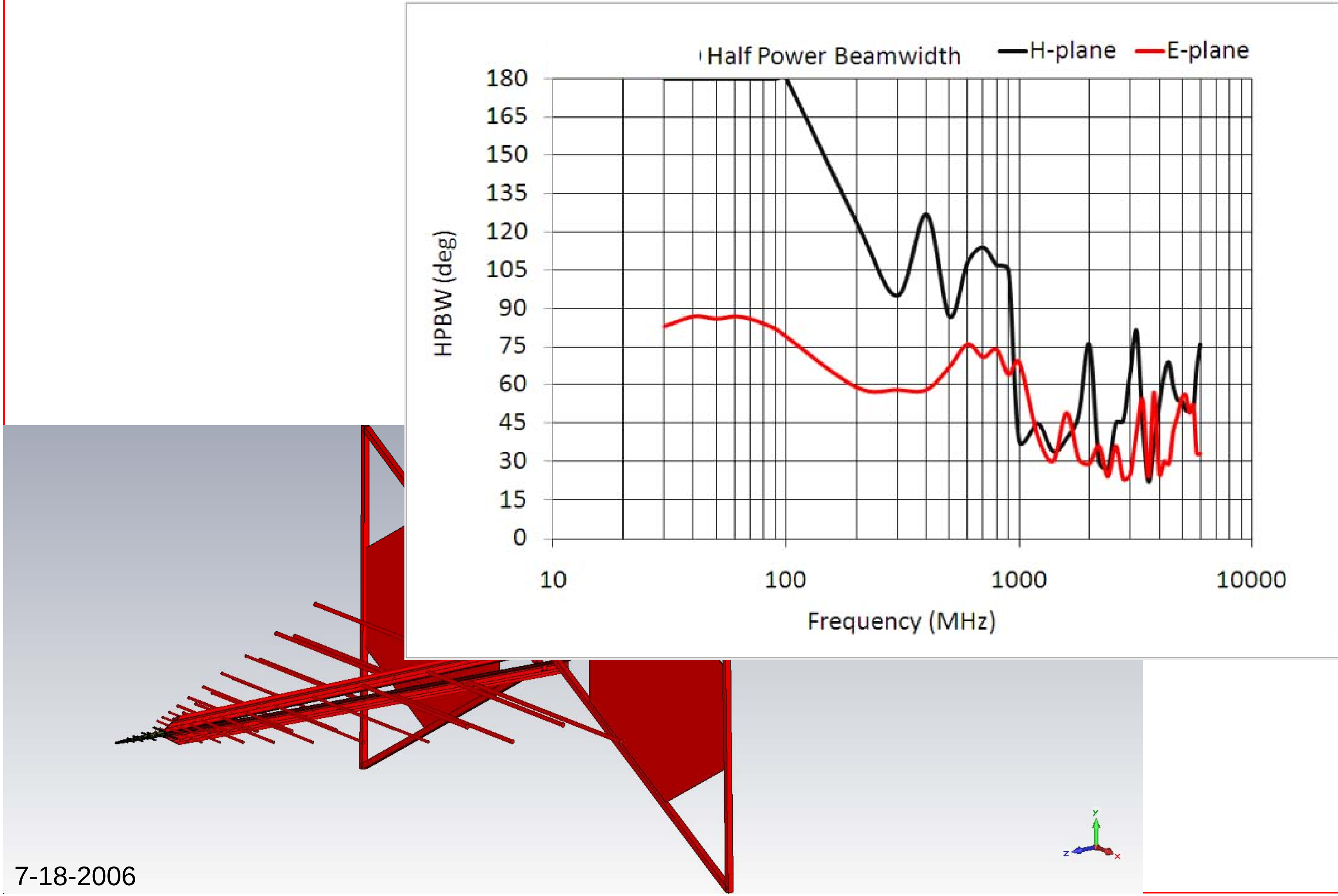

Hybrid Bowtie and LPDA 30MHz to 6GHz at 700MHz
Normalized power patterns (dB)
0
-3
-6
-9
-12
-15
-18
-21
-24
-27
-30
-33
-180 -160 -140 -120 -100 -80 -60 -40 -20 0 20 40 60 80 100 120 140 160 180
Theta (degrees)
E plane taper
H plane taper
E plane computed
H plane computed


Hybrid Bowtie and LPDA 30MHz to 6GHz at 2000MHz
Normalized power patterns (dB)
Theta (degrees)
E plane taper
H plane taper
E plane rectangular
H plane rectangular
E plane computed
H plane computed

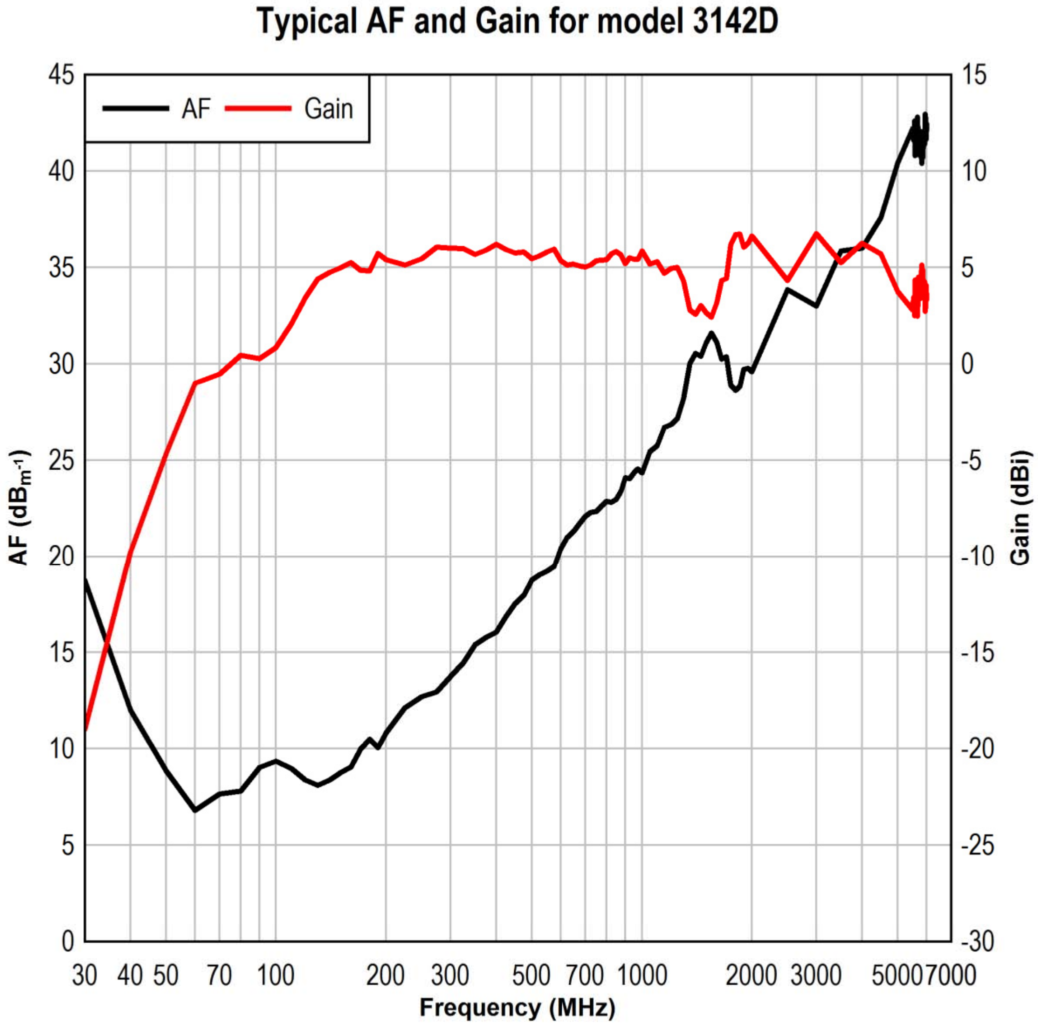

Hybrid Bowtie and LPDA 30MHz to 6GHz at 3000MHz
Normalized power patterns (dB)
Theta (degrees)
E plane rectangular
H plane rectangular
E plane computed
H plane computed


Hybrid Bowtie and LPDA 30MHz to 6GHz at 4000MHz
Normalized power patterns (dB)
Theta (degrees)
E plane rectangular
H plane rectangular
E plane computed
H plane computed

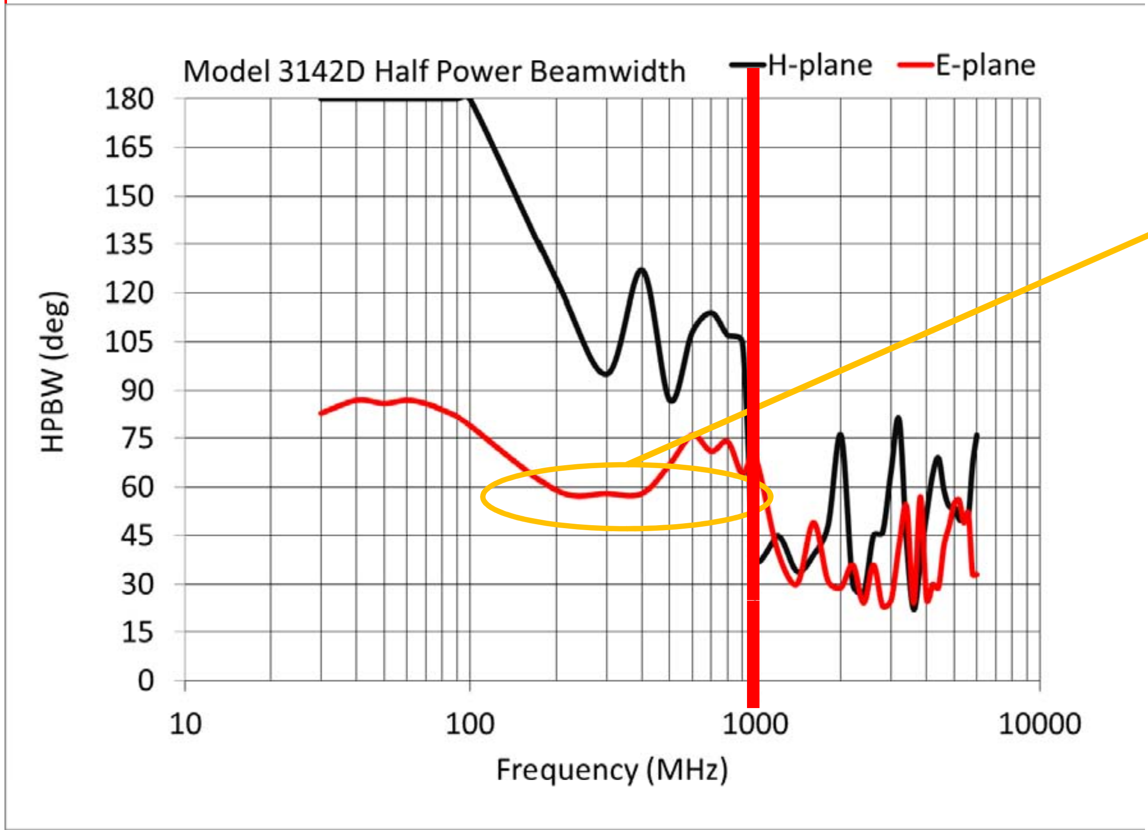

Hybrid Bowtie and LPDA 30MHz to 6GHz at 6000MHz
Normalized power patterns (dB)
Theta (degrees)
E plane rectangular
H plane rectangular
E plane computed
H plane computed


Half Power Beamwidth
H-plane
E-plane
HPBW (deg)
180
165
150
135
120
105
90
75
60
45
30
15
0
10
100
1000
10000
Frequency (MHz)

Typical Hybrid Antenna 30MHz-6GHz



Hybrid antenna coverage

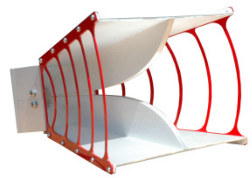


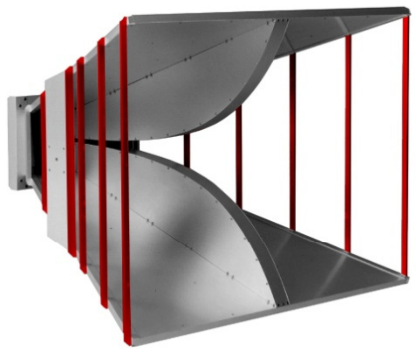
Worst case 58 degrees on E plane
Hence:
3m test distance
3.32m coverage
10m test distance
11.09m coverage

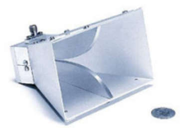
Above 1GHz worst case is 25 degrees on E plane and H plane
Hence
1.33m coverage at 3m
4.43m coverage at 10m

Dual Ridge Guide Horns

- Extremely broadband antennas with higher gain than any other broadband antennas 8 to 10dB
- Can have pattern issues at the upper band
- Recently, pattern problems have been solved.
- Ideal for immunity, but also can be used for emissions



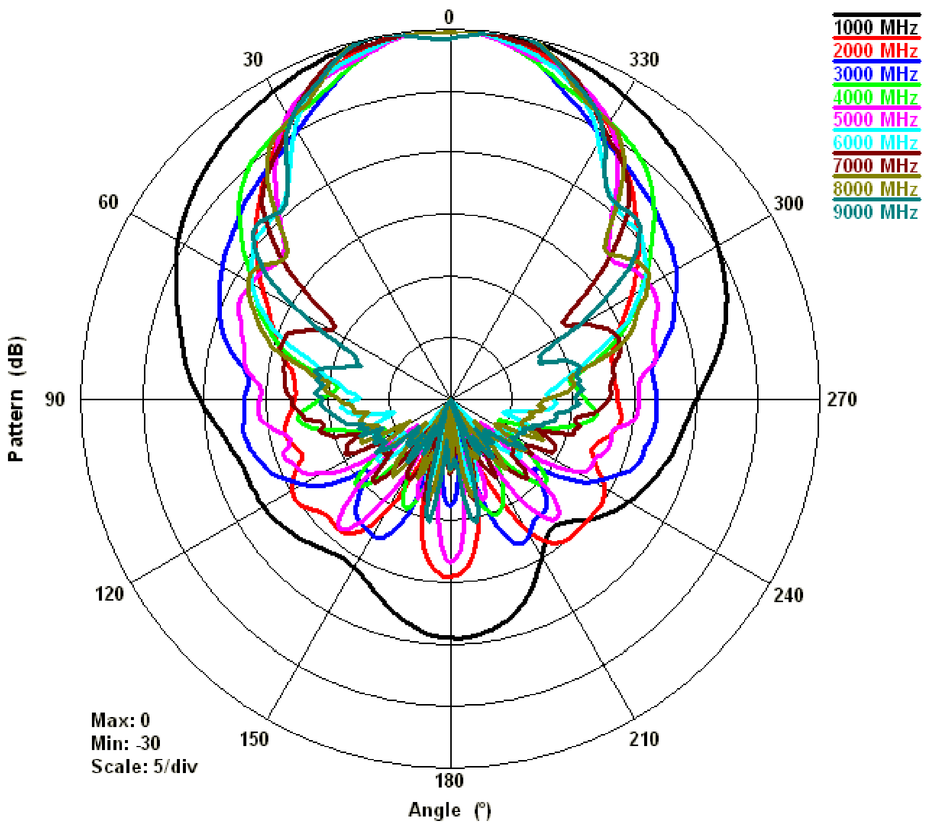


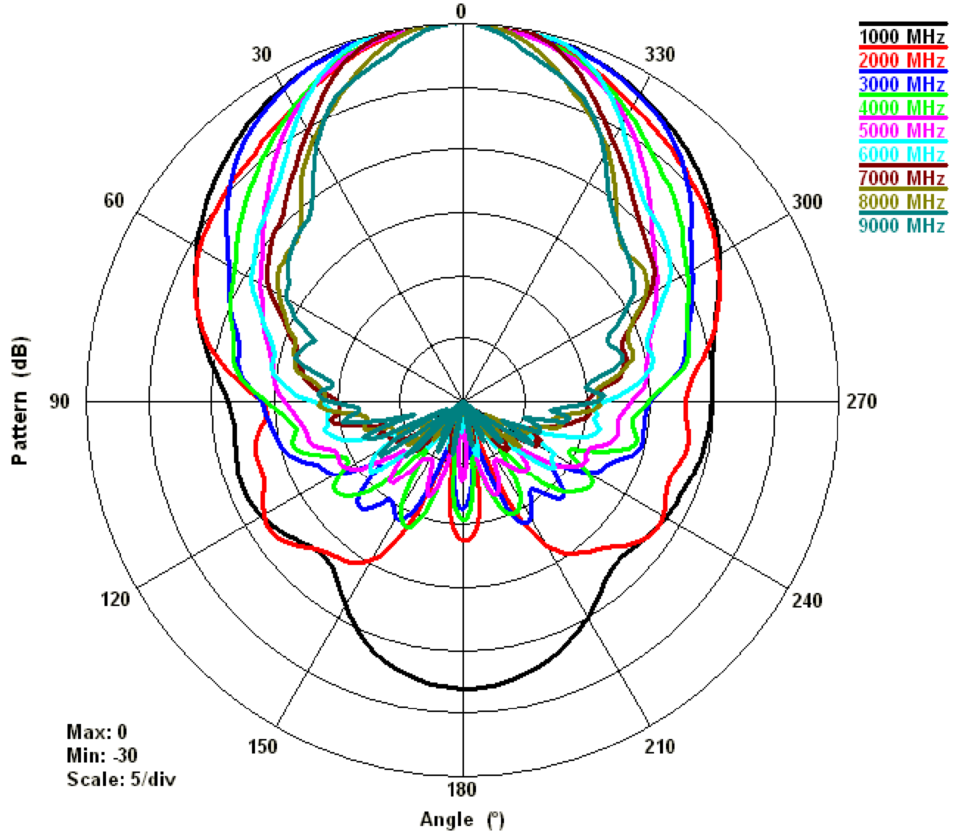


Discussed frequently in the literature

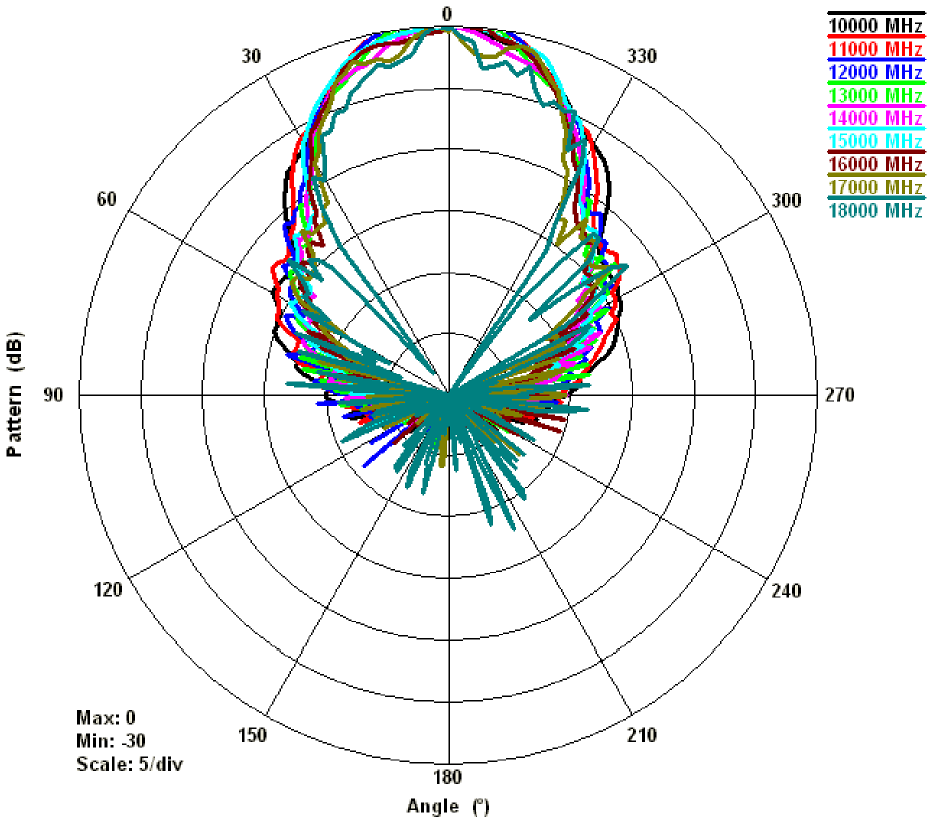
- C. Bruns, P. Leuchtmann, and R. Vahldieck "Analysis of a 1-18GHz Broadband Double-Ridge Antenna," *IEEE Transactions of Electromagnetic Compatibility*, Vol 45, No. 1, pp.55-60, February 2003
- V. Rodriguez "New Broadband EMC double-ridge guide horn antenna" *RF Design.* May 2004, pp. 44-50.
- V. Rodriguez, "A new broadband Double Ridge guide Horn with improved Radiation Pattern for Electromagnetic Compatibility Testing",*16th international Zurich symposium on Electromagnetic compatibility*, Zurich, Switzerland, February 2005.
- V. Rodriguez "Improvements to Broadband Dual Ridge Waveguide Horn Antennas" *2009 IEEE International Symposium on Antennas and Propagation and USNC/URSI National Radio Science Meeting.* Charleston SC June 1-5 2009.
- V. Rodriguez "Recent Improvements to Dual Ridge Horn Antennas: The 200MHz to 2GHz and 18GHz to 40GHz Models" *2009 IEEE International Symposium on EMC*. Austin, TX Aug 17-21 2009

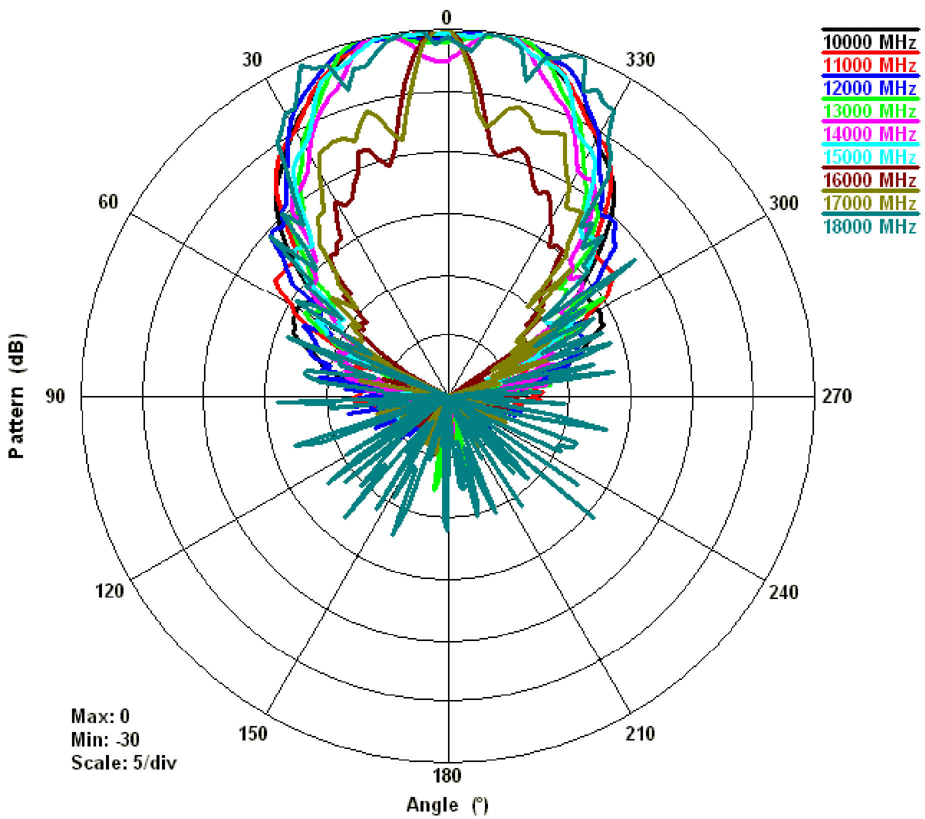
1 to 18GHz models
E plane





1 to 18GHz models
E plane





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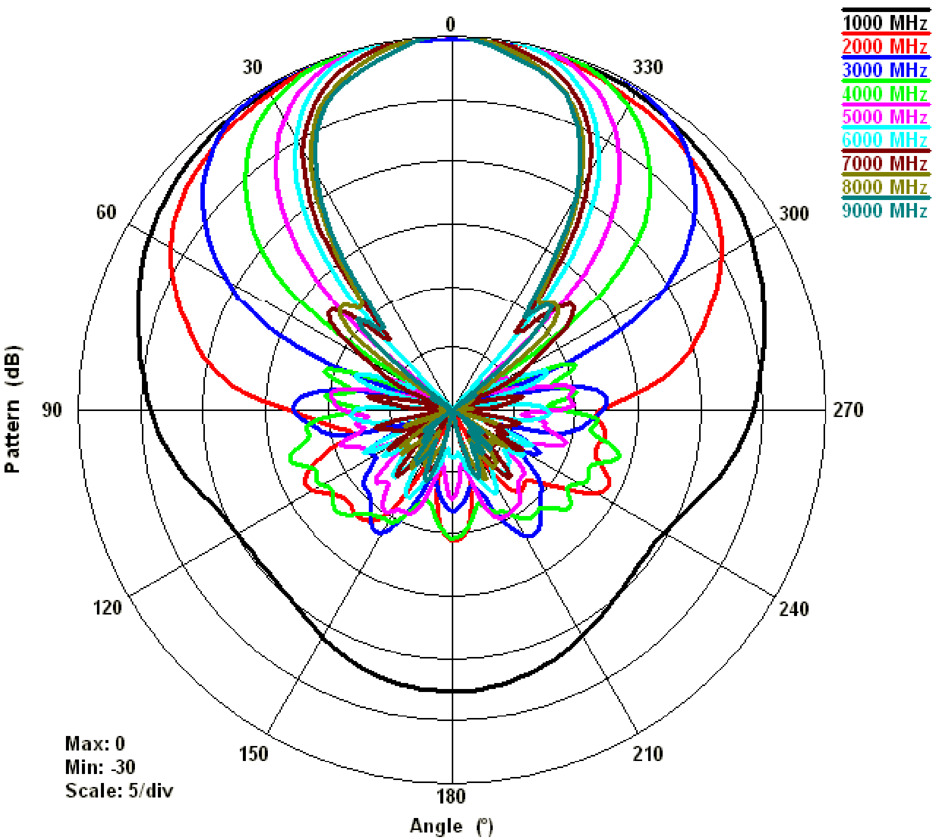
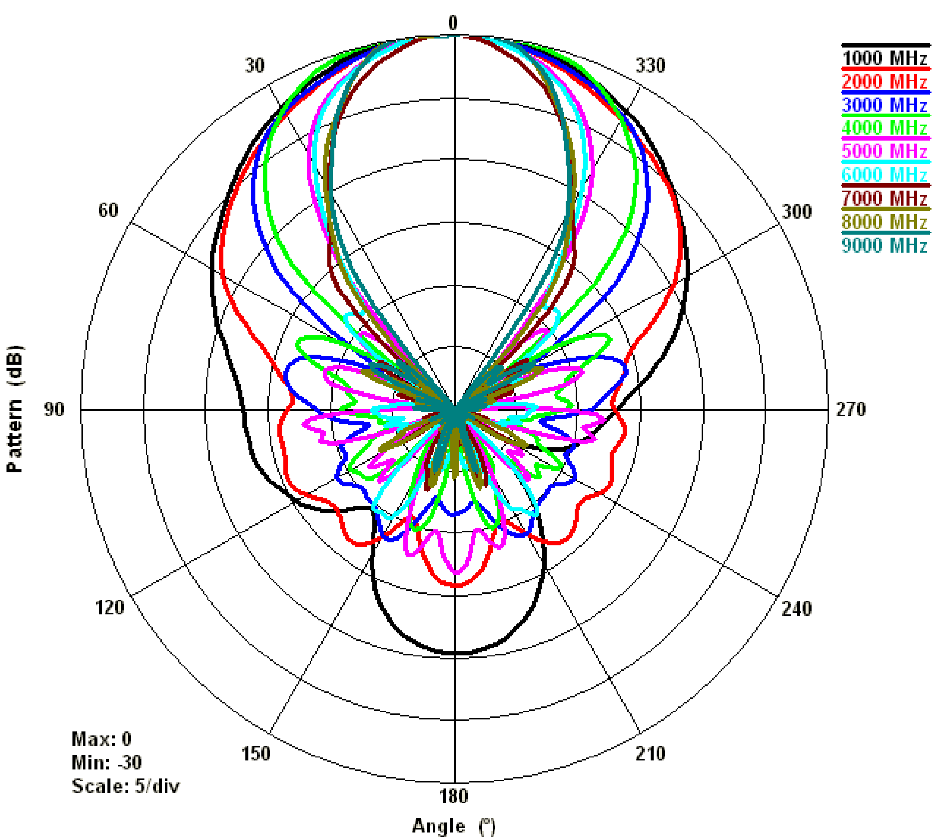
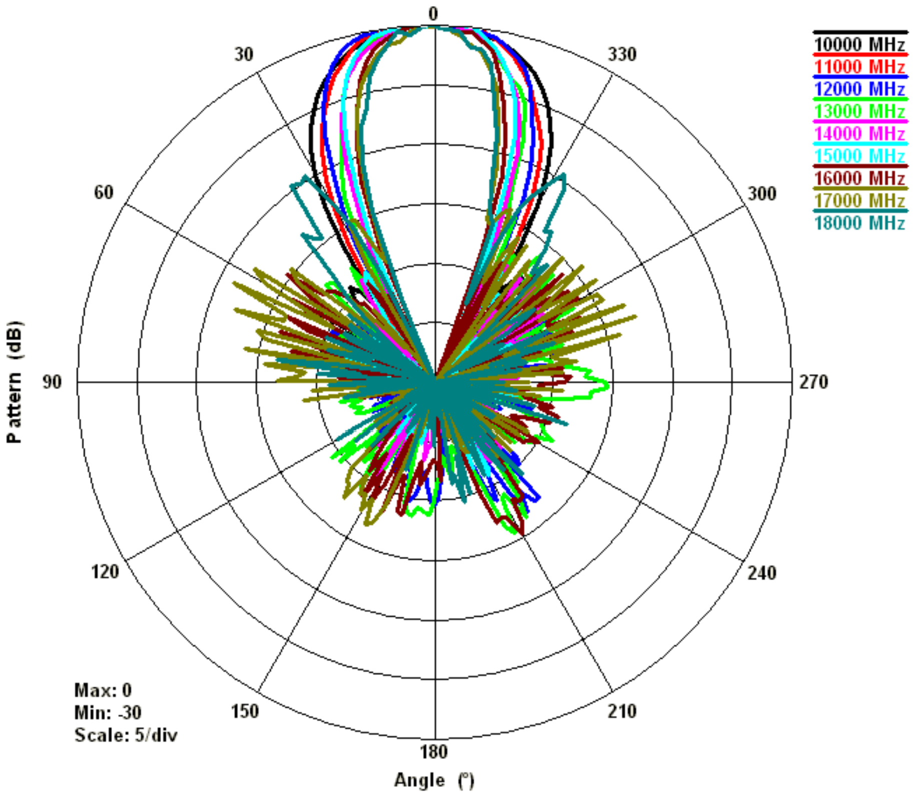
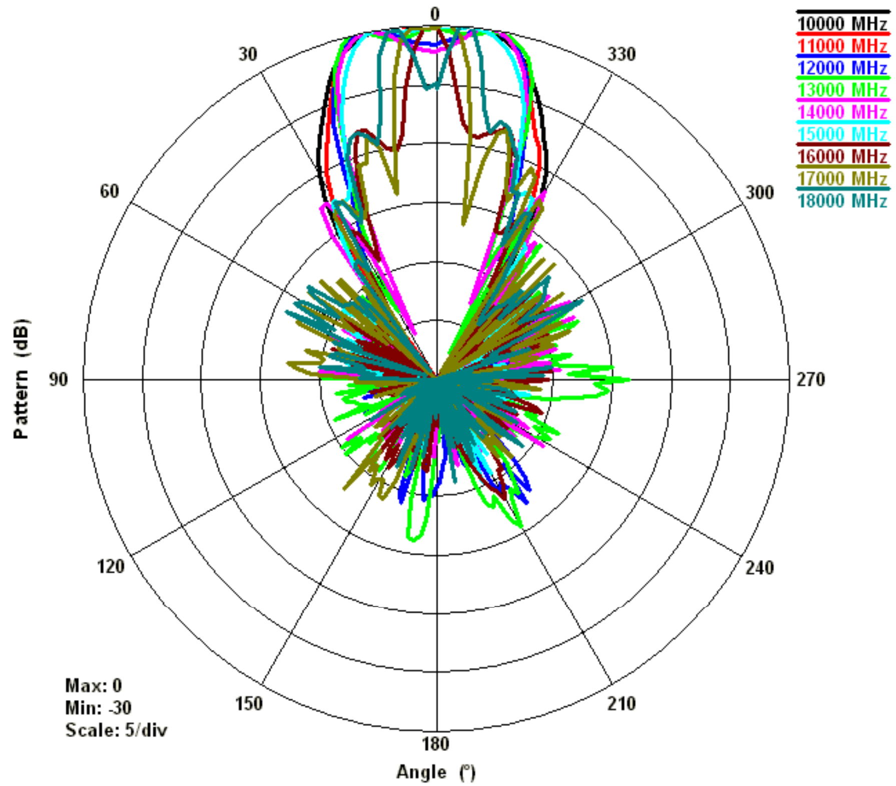
1 to 18GHz models
H plane





1 to 18GHz models
H plane



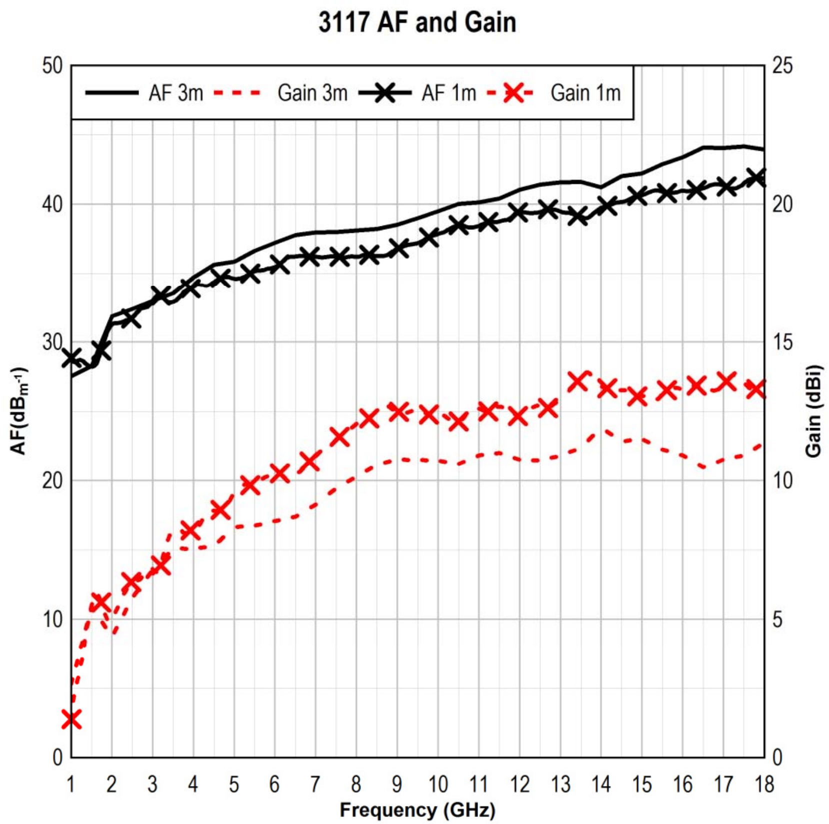


Ridge horns 1GHz to 18GHz

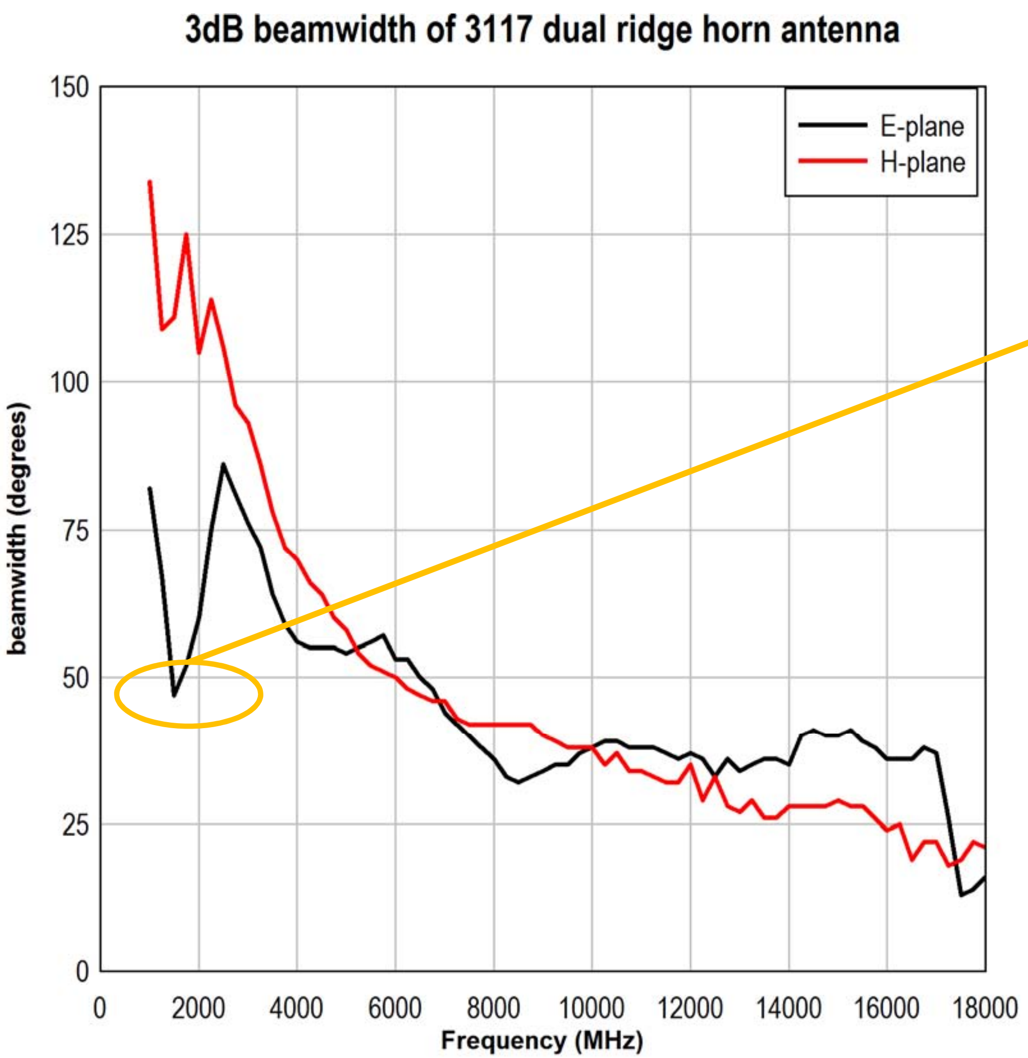
Dual Ridge Horns.
Above 3117 (although currently not in the CISPR 12 limits there are limits for 1GHz to 2GHz in the European norm)

Stinger and tripod mounts are available

Low VSWR and great coverage



3117 coverage



Worst case 48 degrees on E plane up to 6GHz
Hence:
3m test distance
2.67m coverage
10m test distance
8.9m coverage

Notice that we do not use above 6GHz as there are no known limits at those high frequencies

As with all antennas the beam narrows as the frequency increases and the gain does as well.

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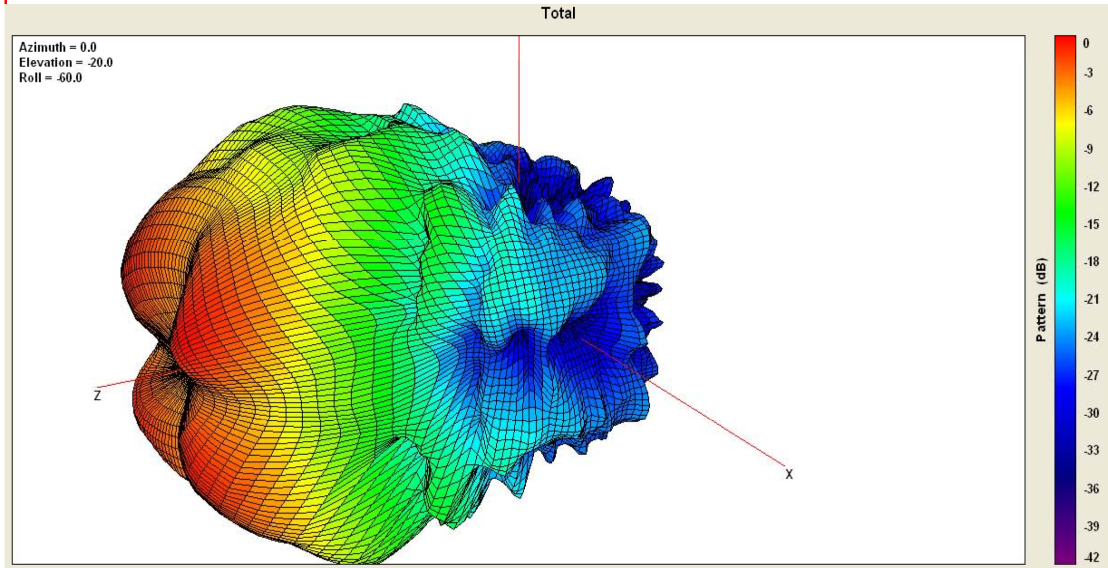
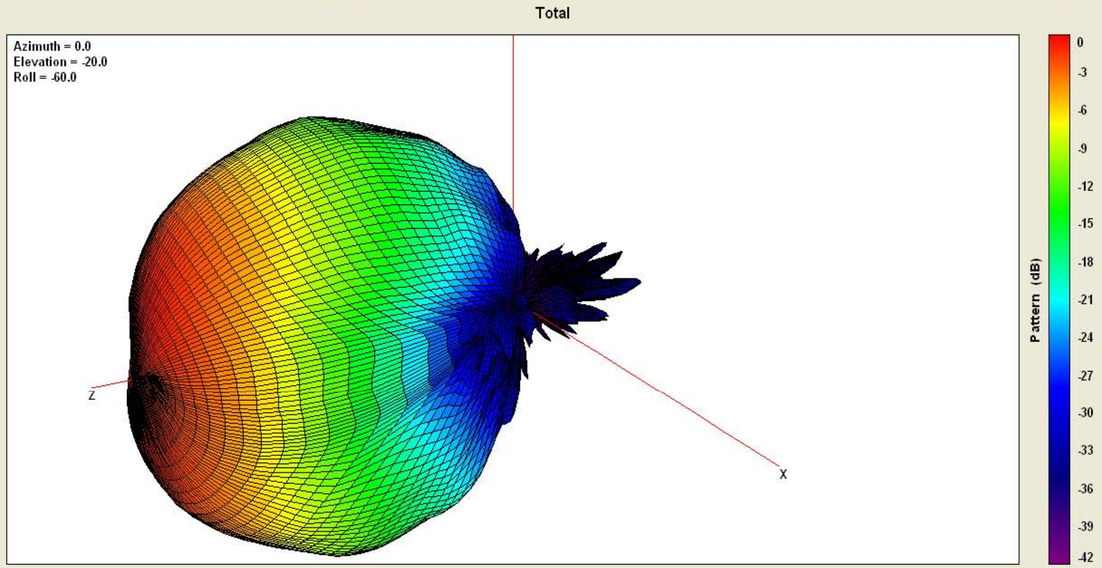
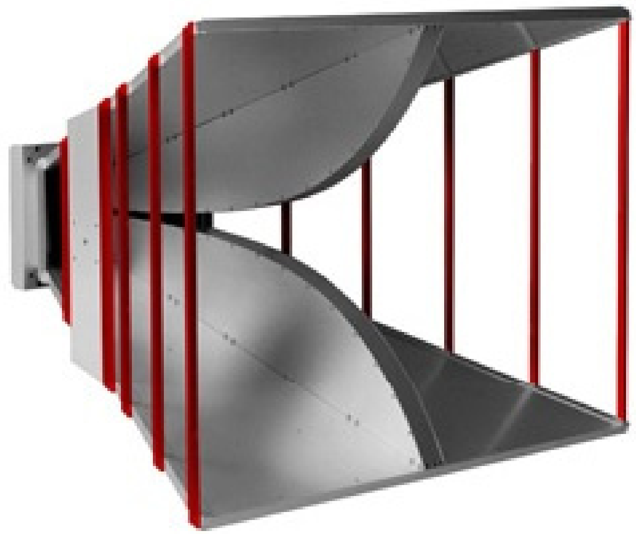
200MHz to 2000MHz model at 2GHz

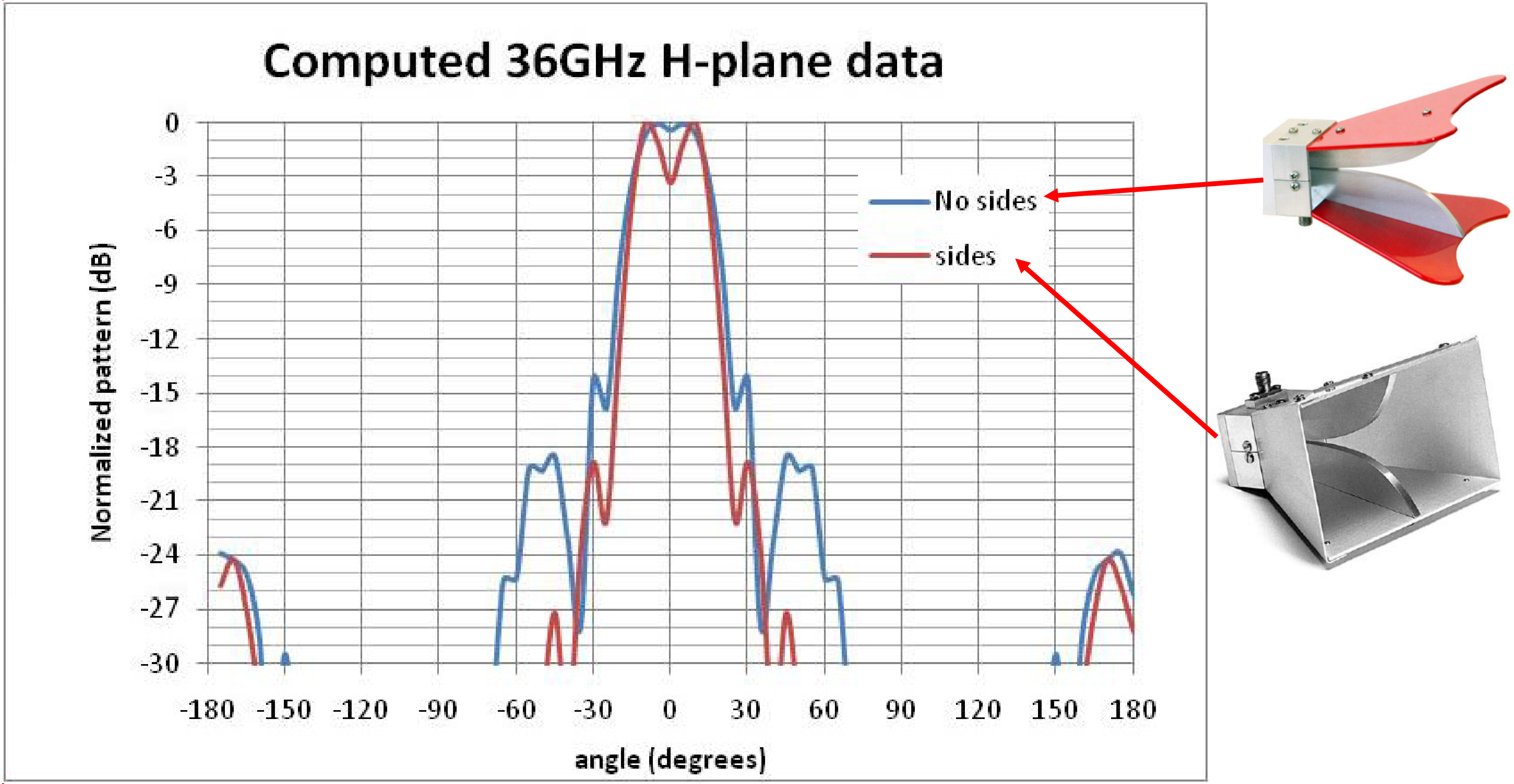




The common design for the 200-2000MHz design has a pattern that splits into four beams.
Improved designs introduced 3 years ago avoid this problem by improving the feed cavity.
The boresight gain increases by 6dB gain



18 to 40GHz designs.

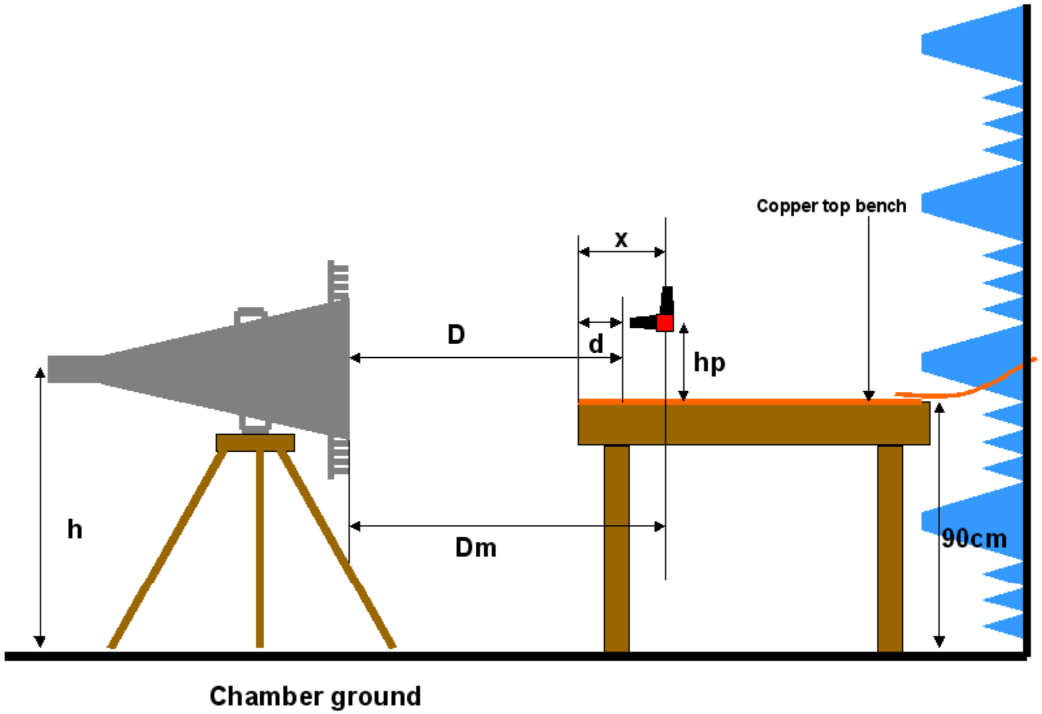


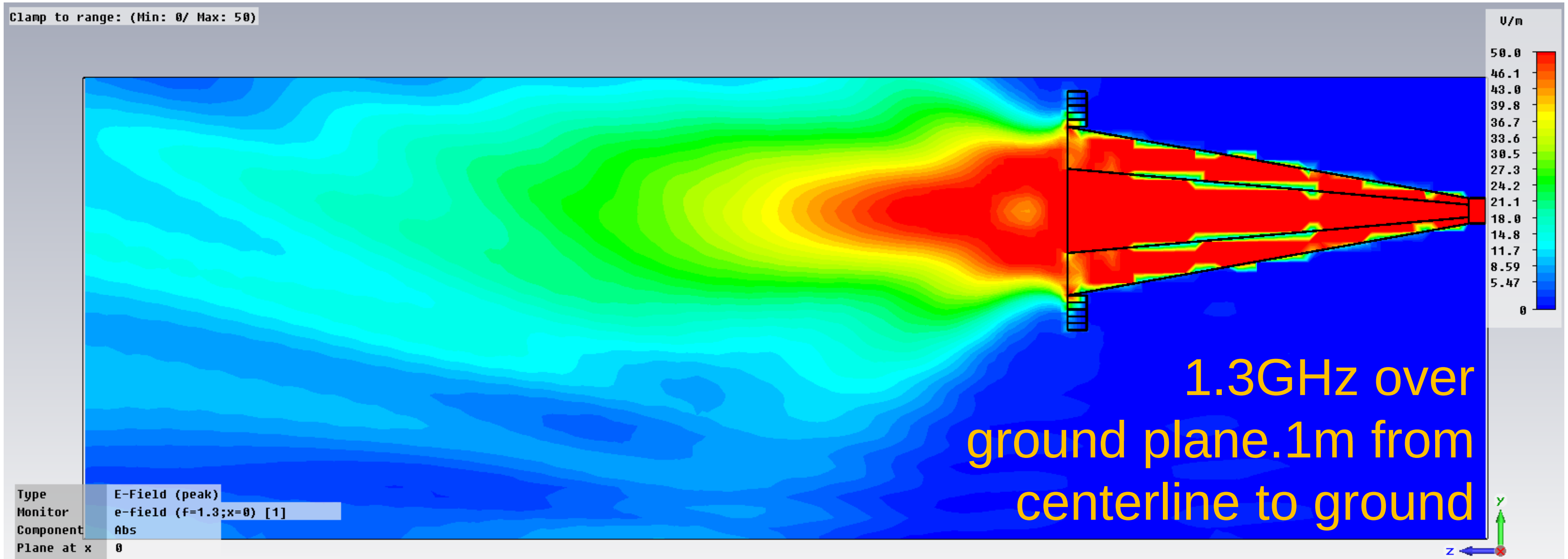
Regarding pattern Information

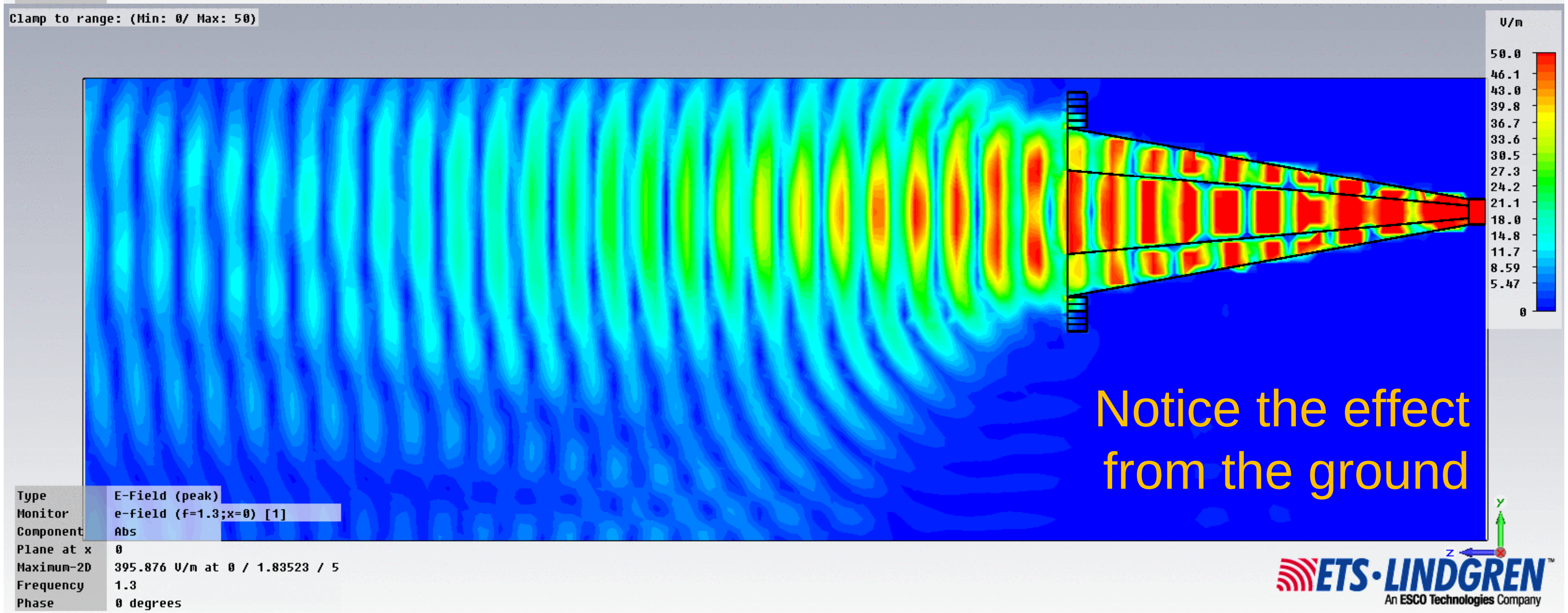
- Pattern Data is Free Space and Far Field
- Sometimes neither condition is met in an EMC test layout
- Use as guidelines

There is no far field, there is no free space

As the field is incident onto the metallic top bench both polarizations are affected very differently.







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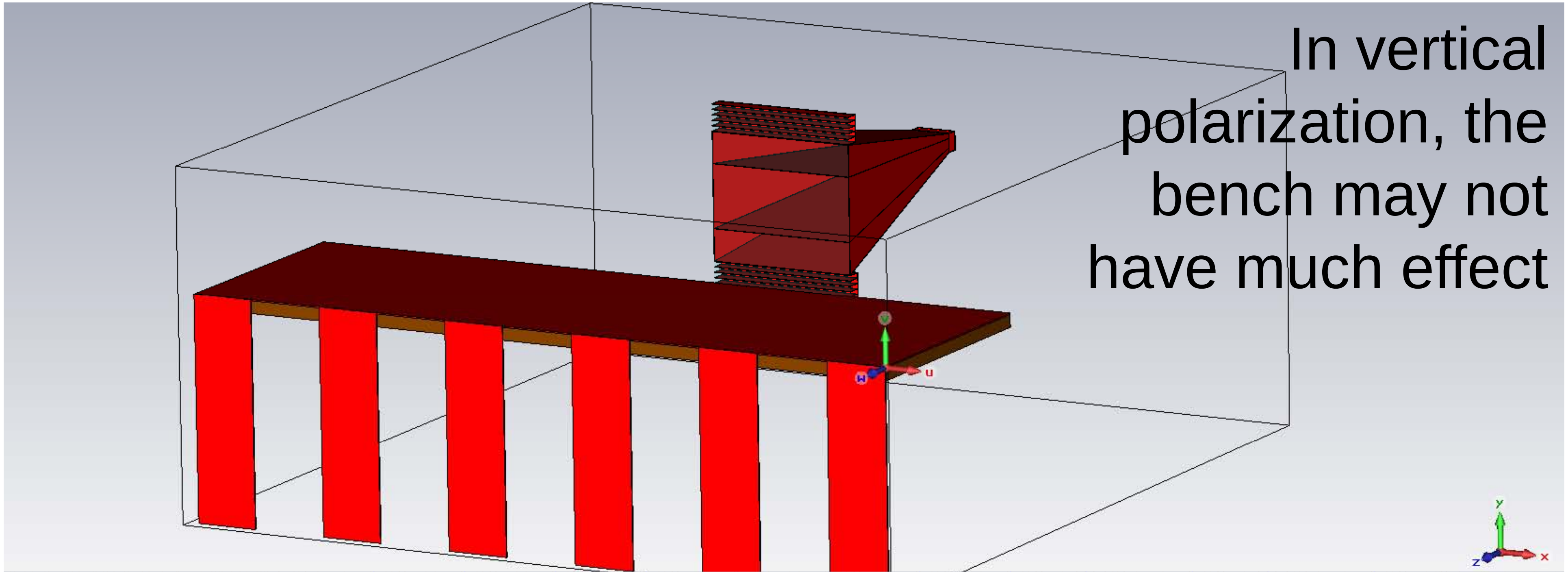
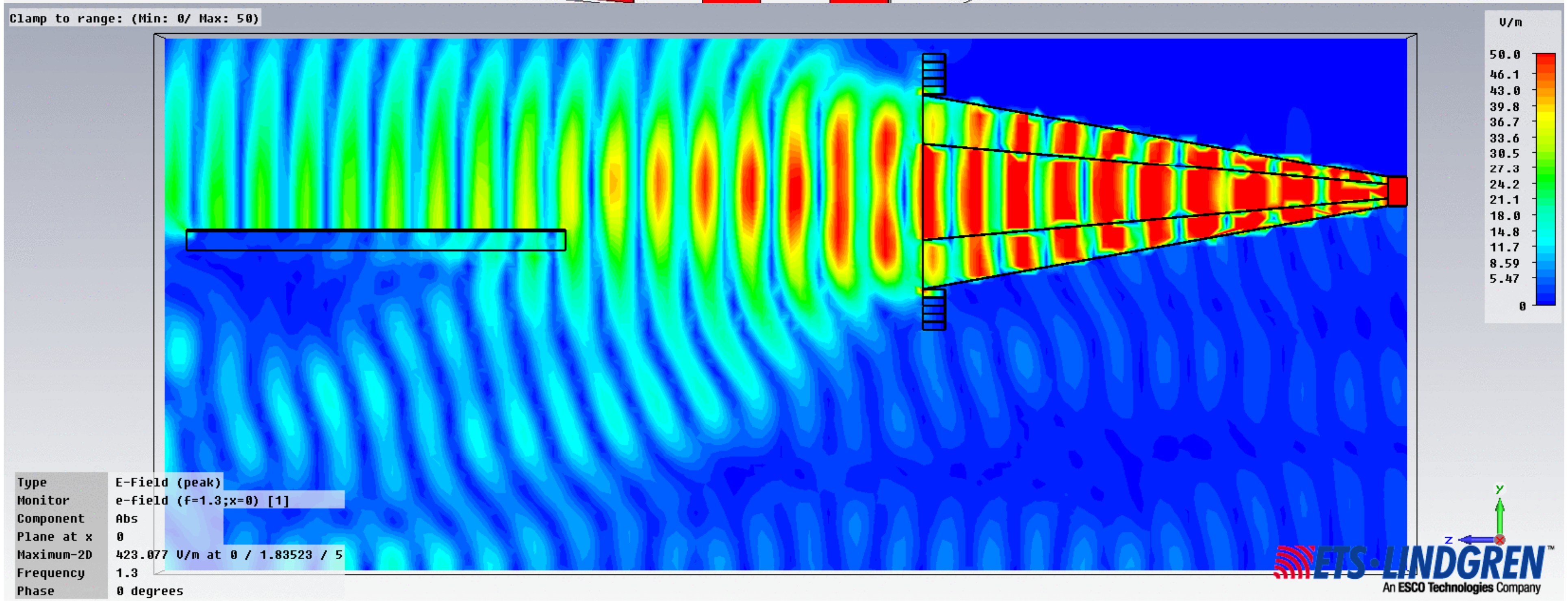
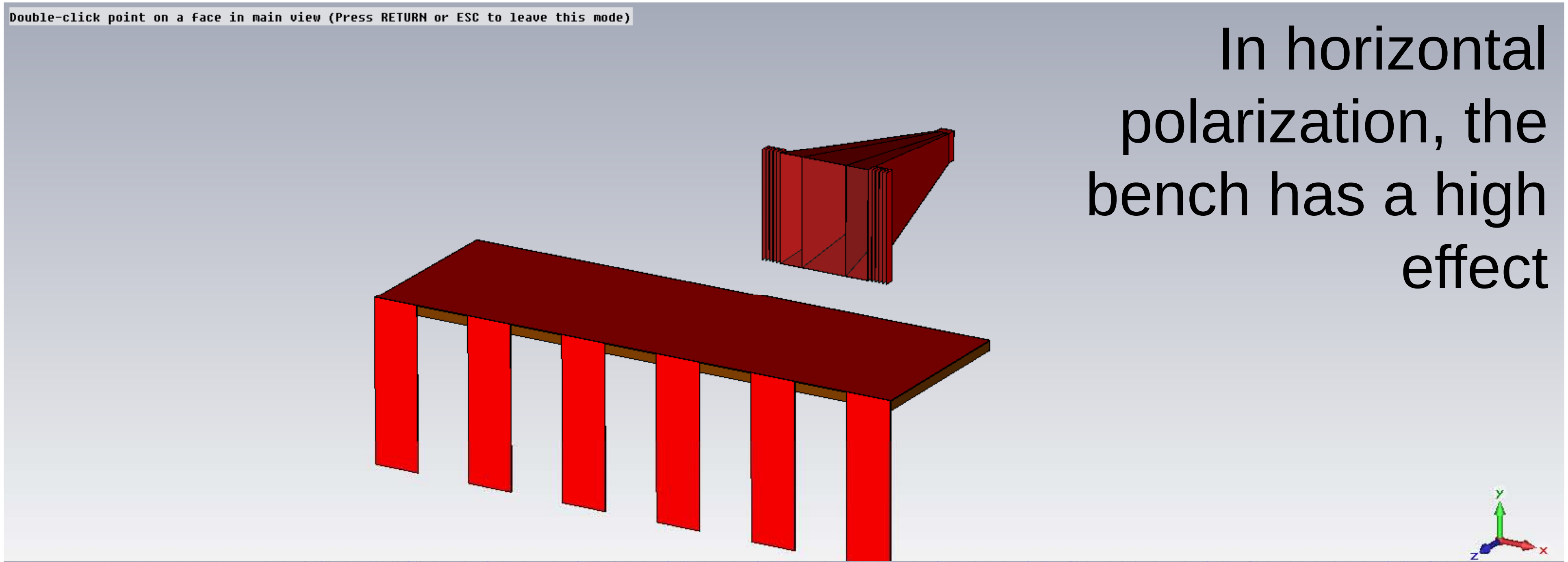
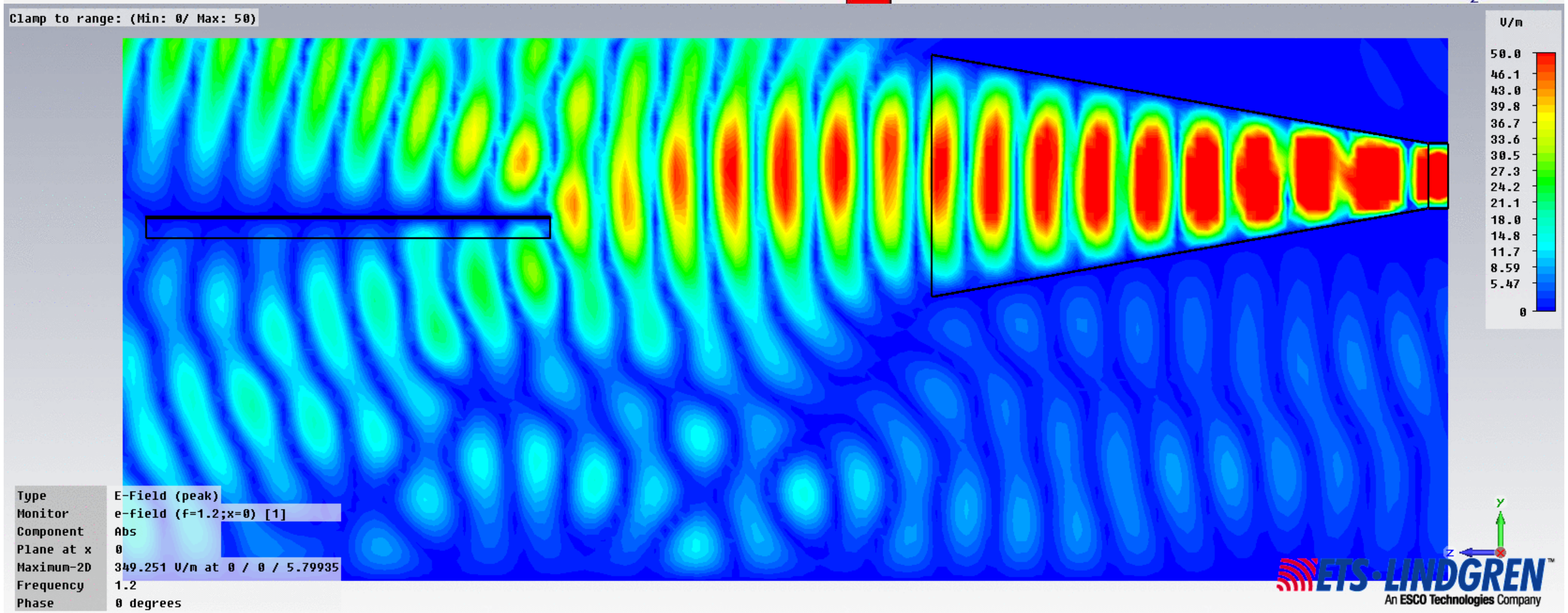
In vertical polarization, the bench may not have much effect

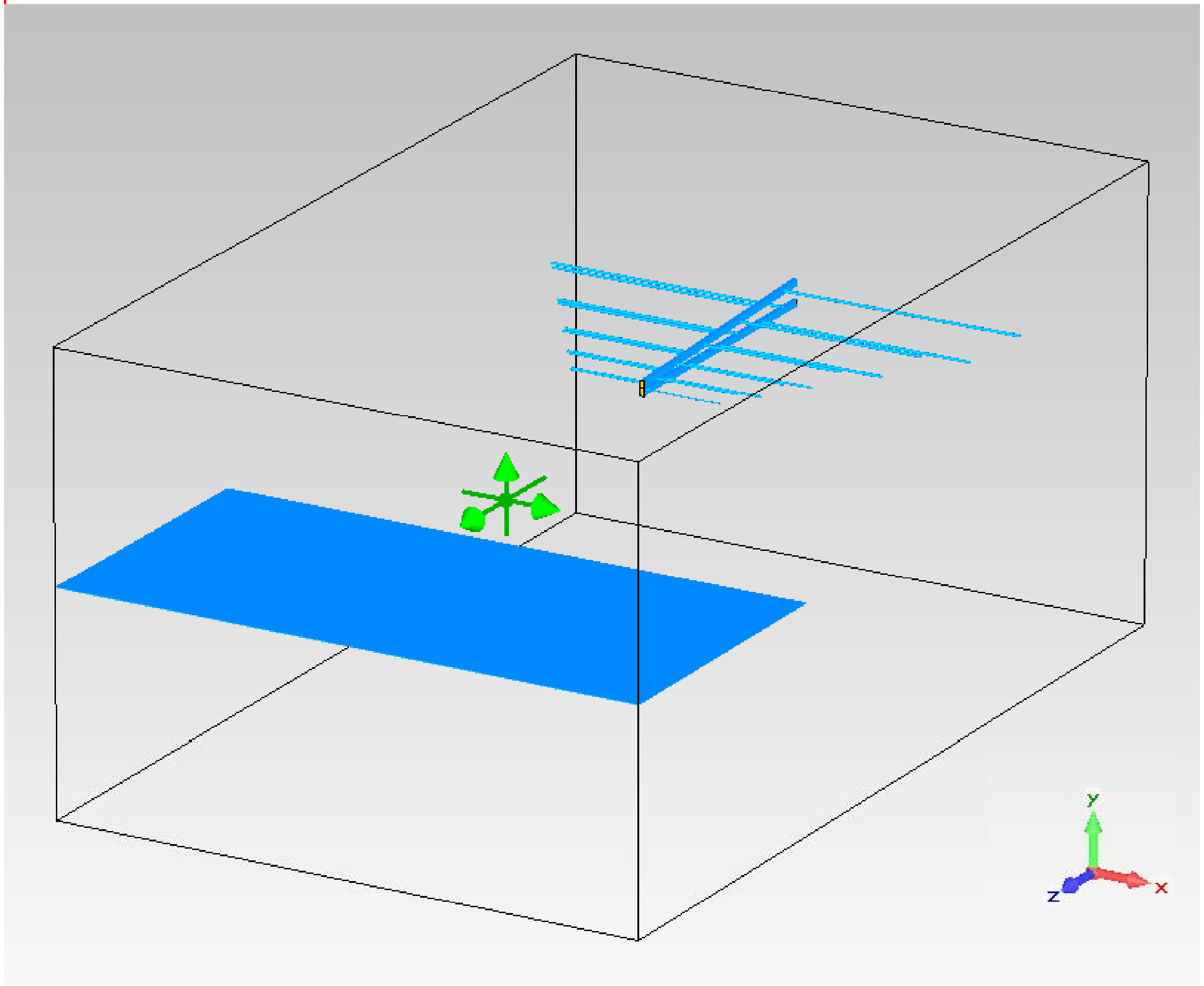




In horizontal polarization, the bench has a high effect

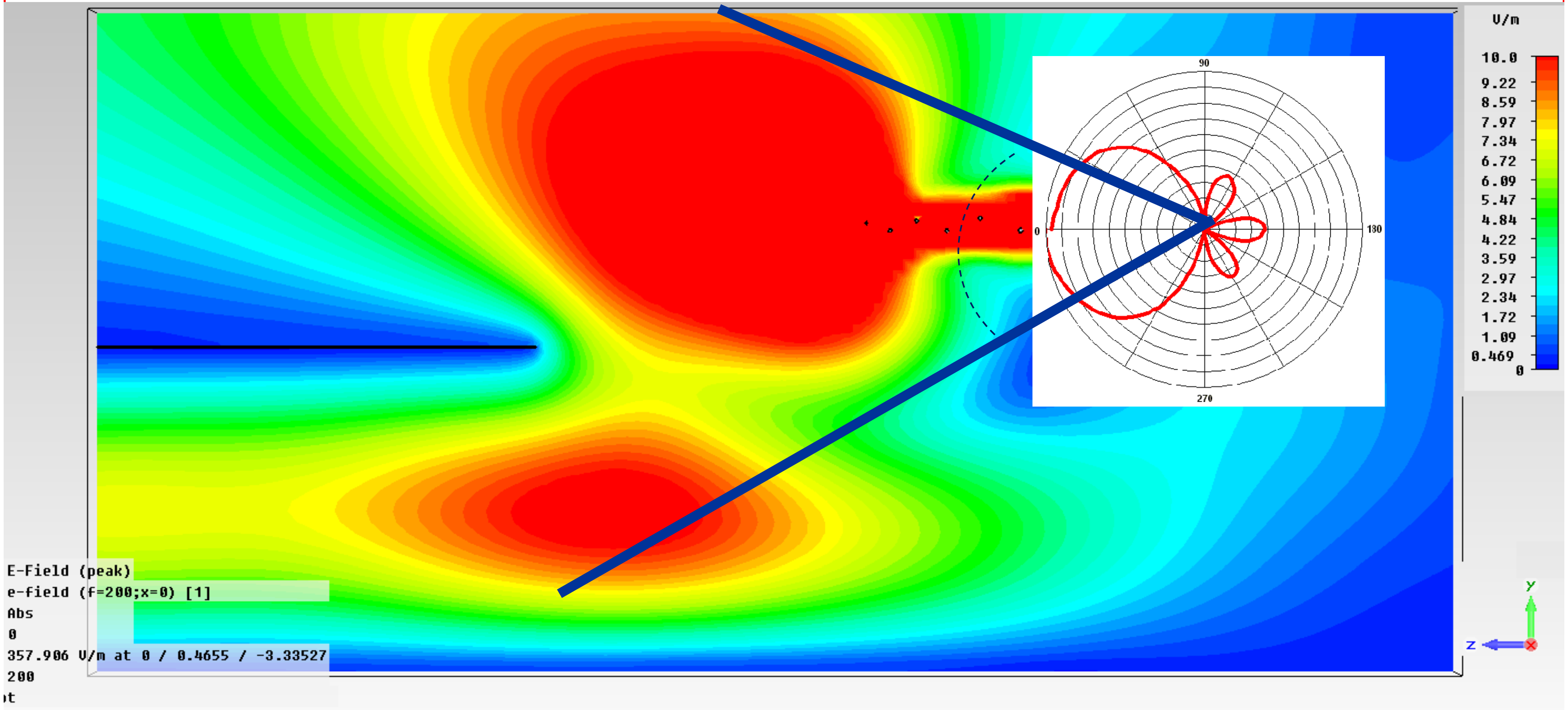






This effect is present even at low frequencies. Let us consider a Log periodic operating in the 200MHz range

The bench splits the beam and the half power beamwidth at 200MHz does not longer have any meaning



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Conclusions

- A brief introduction to antenna patterns has been given
- Analysis of measured and computed data has been introduced for the most common EMC antennas
- Biconical, LPDA, Hybrid antennas have been shown

Conclusions

- A survey of Dual Ridge Horn antenna patterns has been shown
- DRHA have been previously described in the literature
- Limitations of the pattern knowledge have been show through simulations.

Combining EMC and Signal Integrity for Effective PCB Design

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IBM

Sao Paulo, Brazil

26 April 2012

IEEE

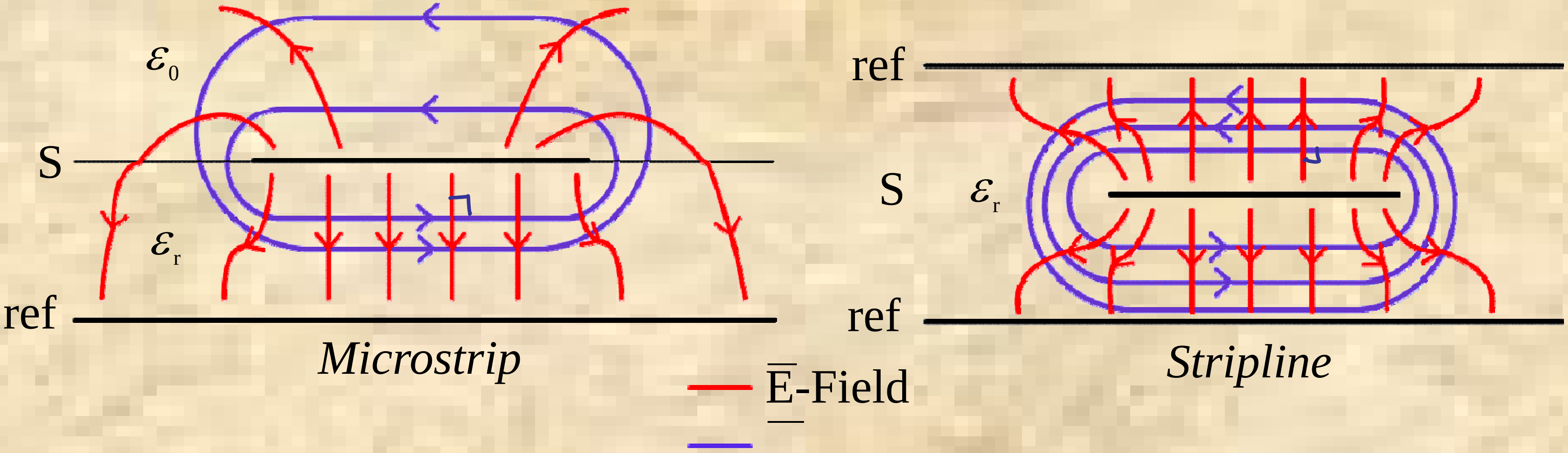
Electromagnetic Design

- Good Signal Integrity and good EMC design is not mutually exclusive!
  - Good SI design usually improves EMC!
  - Issues occur because of scale
    - SI – 10% crosstalk is worrisome
      - For a one volt intentional signal → 100 mV is a concern
    - EMC – emissions from unshielded cables
      - Radiated emissions level reached with ~ 1 mV common mode noise on unshielded cable (above 1 GHz)

Overview

- Traditional SI Tools
- Improved SI helps EMC
- Improved EMC helps SI

Traditional SI Tools Assume TEM Waves



- Transverse Electromagnetic (TEM) waves have the electric- and magnetic-field lines perpendicular, and **E** x **H** is in the direction of propagation.
- Stripline supports a <u>pure</u> TEM wave, but microstrip is only <u>quasi</u>-TEM.

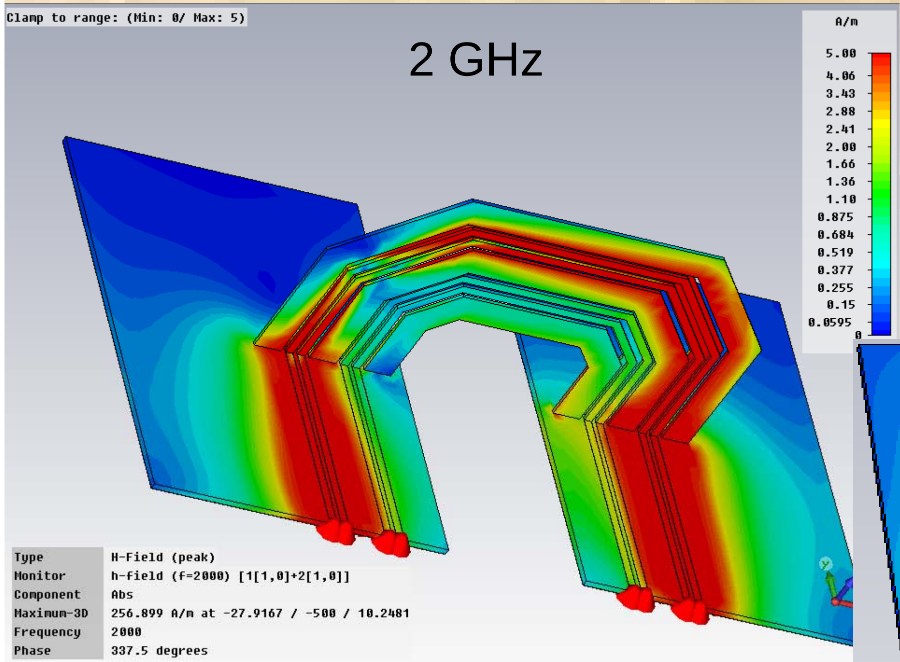
Traditional SI Tools are Valid When….

- The E & H fields create a TEM (quasi TEM) wave
- Object is small compared to wavelength
  – Usually true for cross section of microstrip and strip line
  – NOT TRUE
    - Multi Gb/s signal lines in board-to-board & board-to-cable connectors
    - Via structures in Printed Circuit Boards (PCB)

Differential Signaling Fixes Everything -- ***FALSE***

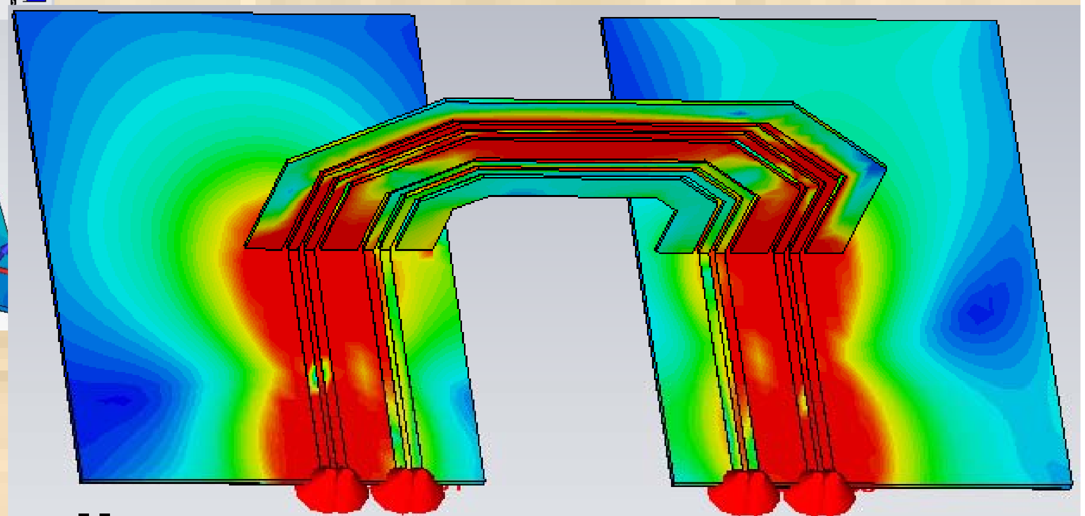
- Differential signaling ***does*** help SI
  - Often not truly differential, but rather single ended complementary
- Common mode noise on differential signal lines is a big issue for EMC
- Differential to common mode conversion occurs with any asymmetry
  - BOTH EMC and SI effects

Surface Currents in Typical High Speed Differential Connector



Driven Common Mode

7 GHz



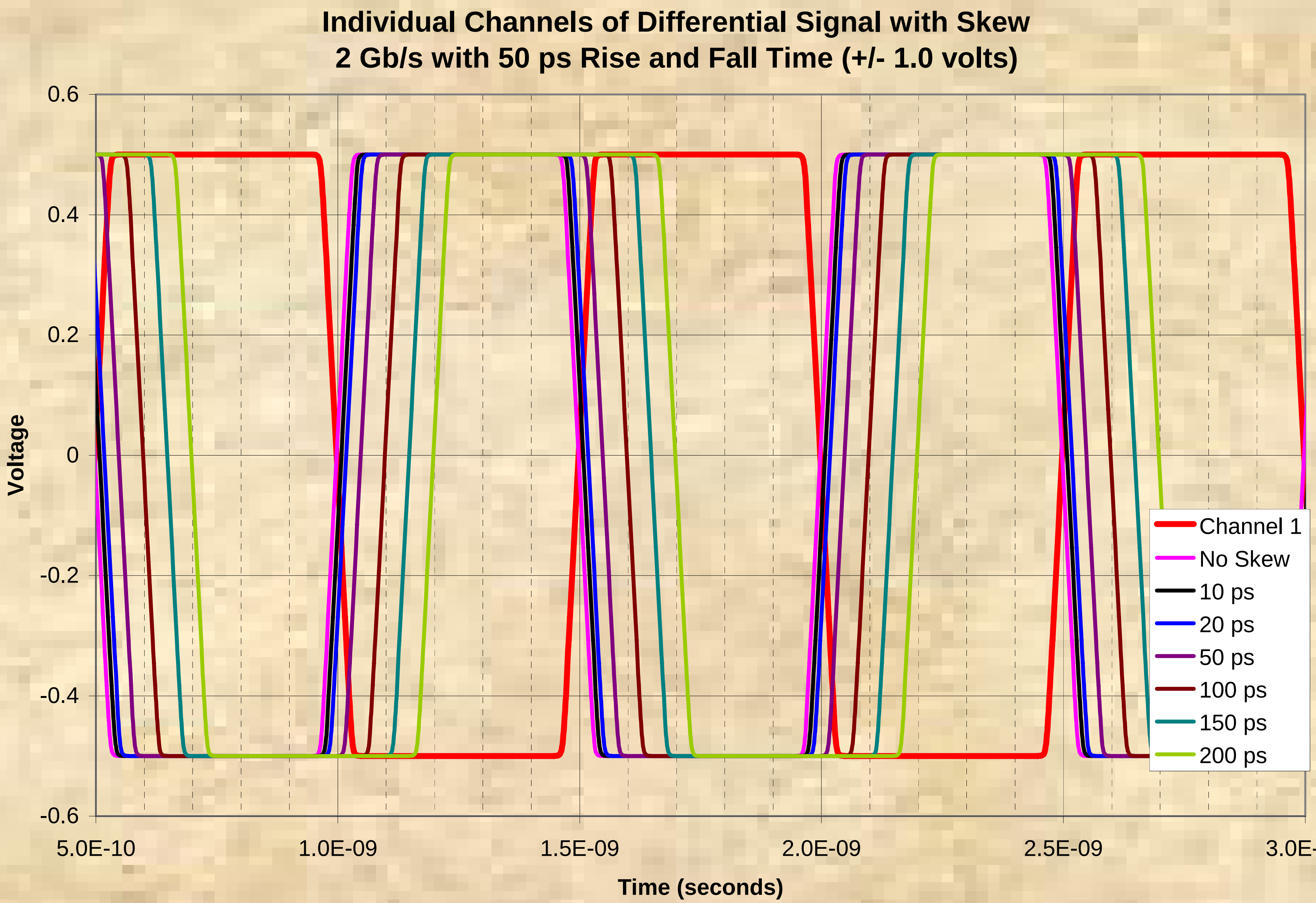
Not electrically small!

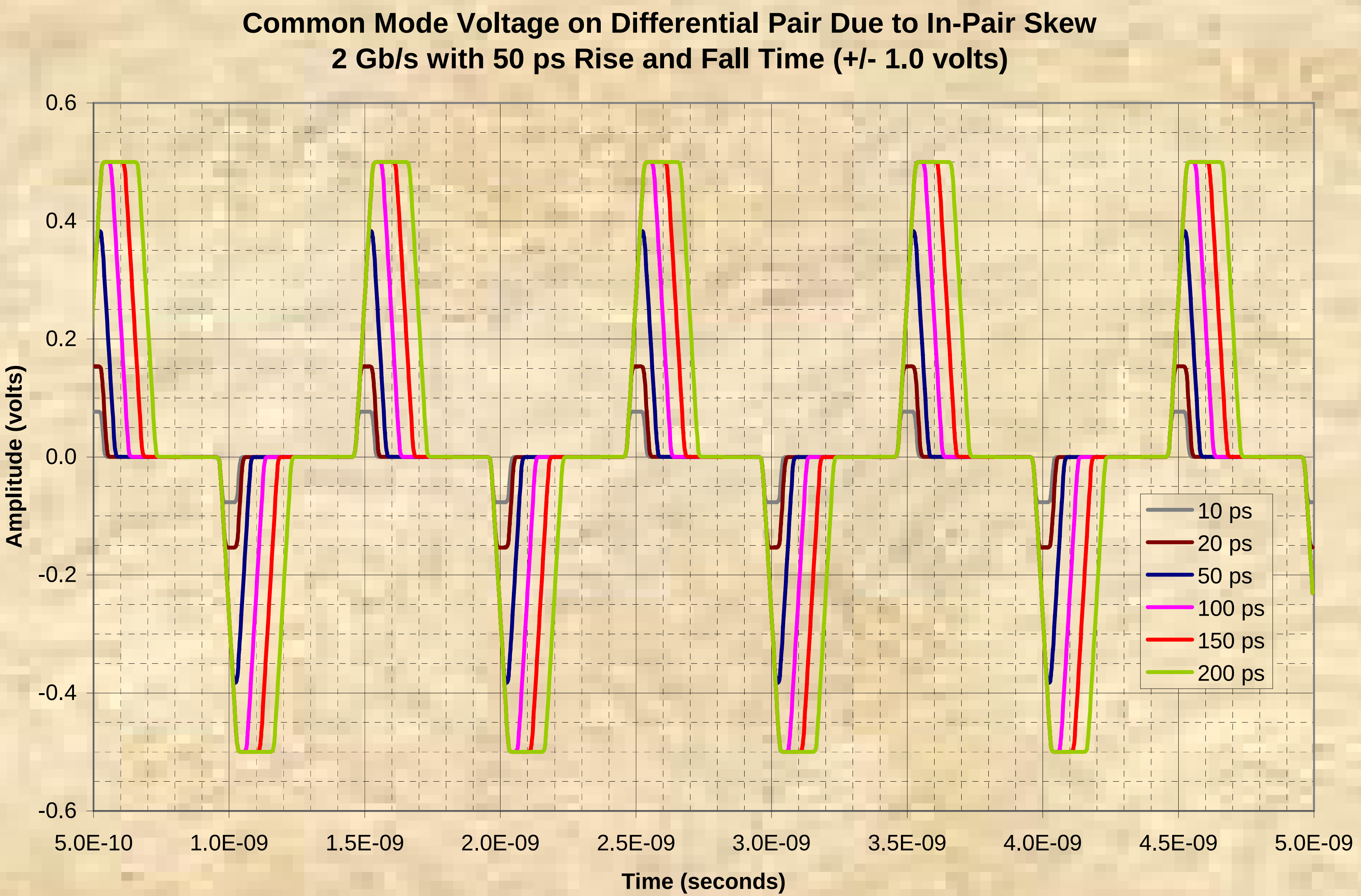
Common Mode Creation on Differential Signal Lines

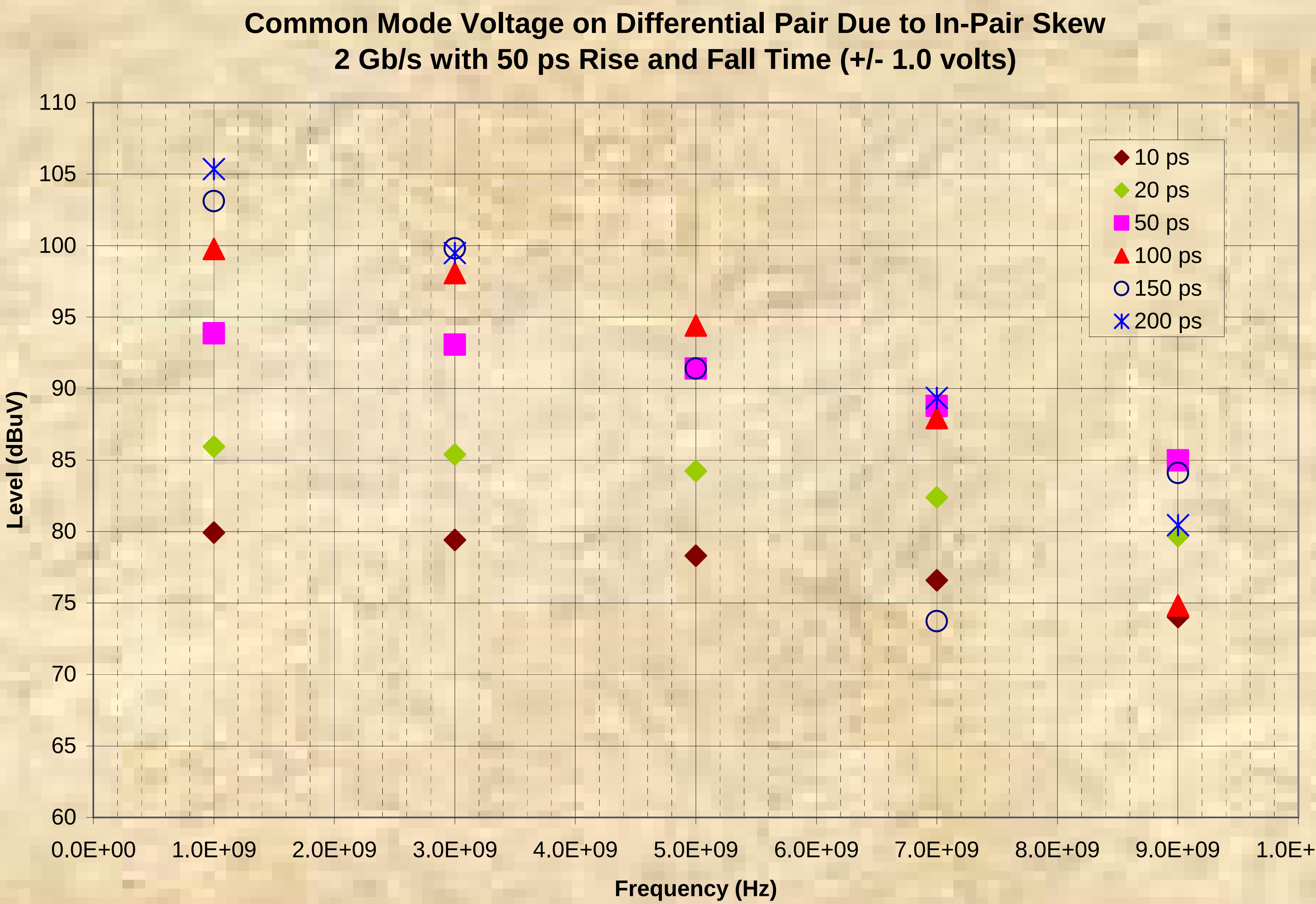
- Asymmetry
  - In-pair skew
  - Too close to edge of reference plane
  - ‘Ground’ Via asymmetry
  - Amplitude asymmetry
  - Rise/fall time mismatch

Common Mode Noise Due to Skew

- Small amounts of skew create significant common mode nose
- As little as 1% of bit width for skew can have significant EMI effects
- As little as 10% of bit width skew creates CM signal of equivalent amplitude as initial signals

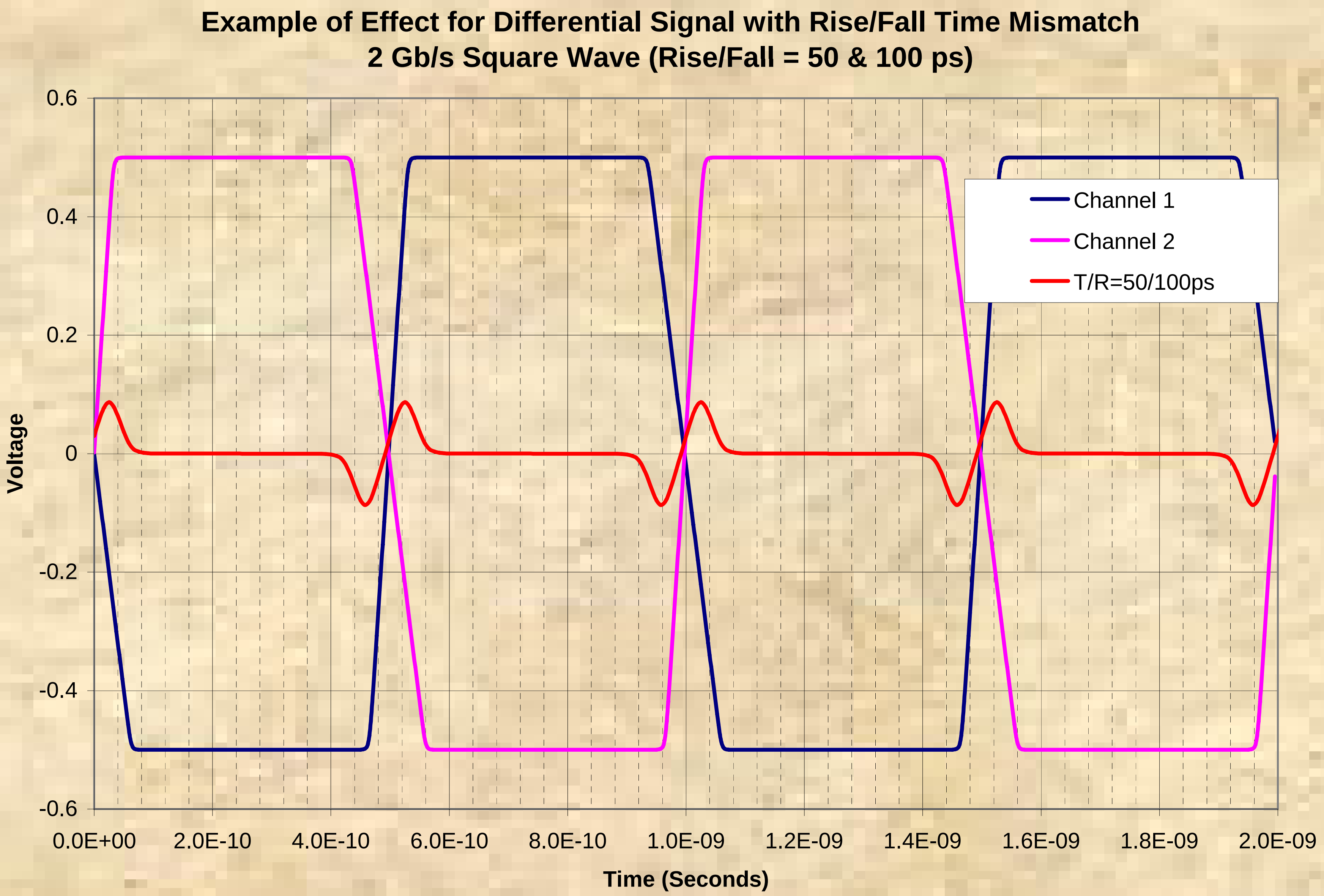

Individual Channels of Differential Signal with Skew
2 Gb/s with 50 ps Rise and Fall Time (+/- 1.0 volts)
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
Voltage
5.0E-10
1.0E-09
1.5E-09
2.0E-09
2.5E-09
3.0E-09
Time (seconds)
Channel 1
No Skew
10 ps
20 ps
50 ps
100 ps
150 ps
200 ps

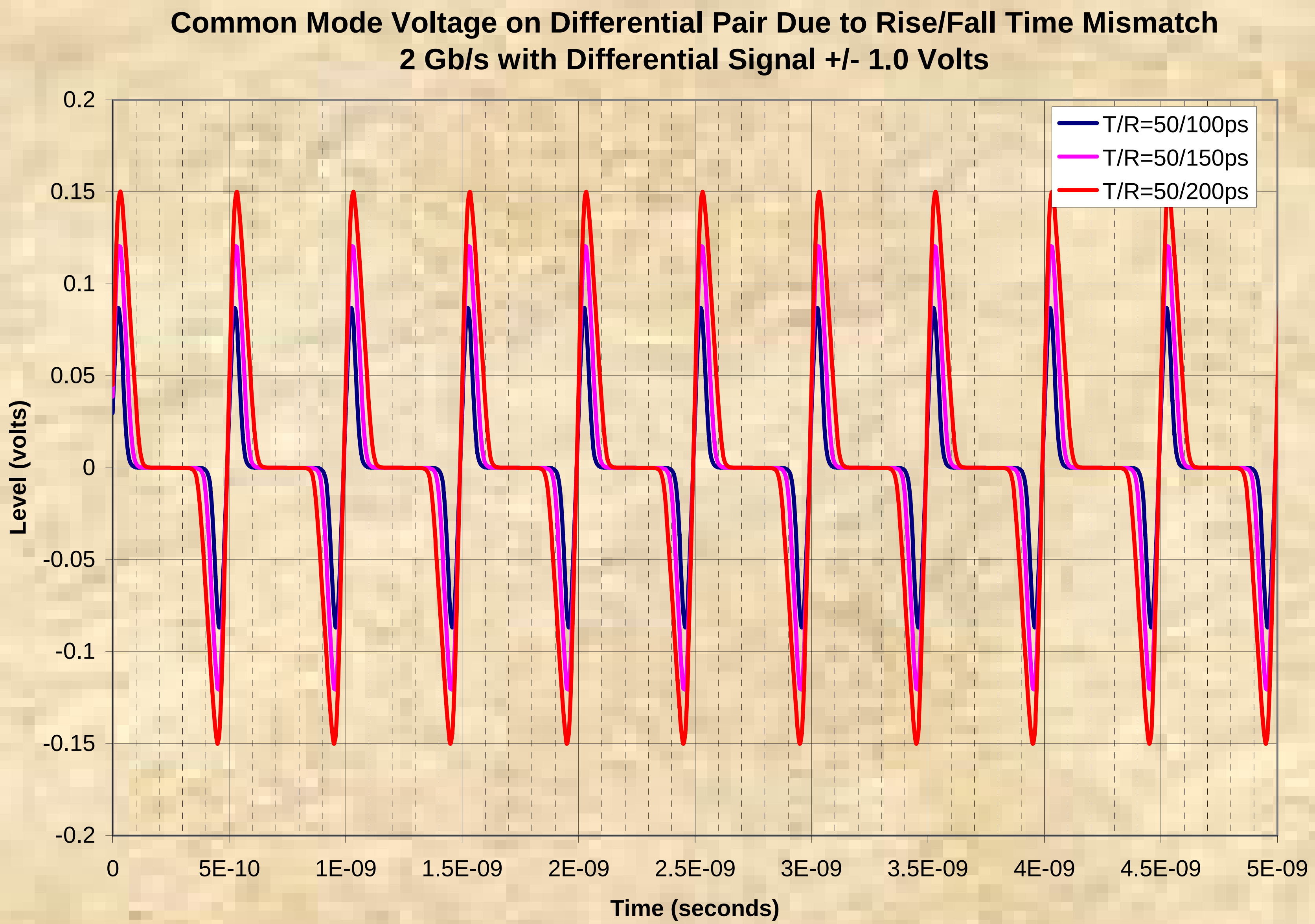

Common Mode Voltage on Differential Pair Due to In-Pair Skew
2 Gb/s with 50 ps Rise and Fall Time (+/- 1.0 volts)
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
Amplitude (volts)
5.0E-10
1.0E-09
1.5E-09
2.0E-09
2.5E-09
3.0E-09
3.5E-09
4.0E-09
4.5E-09
5.0E-09
Time (seconds)
10 ps
20 ps
50 ps
100 ps
150 ps
200 ps


Common Mode Voltage on Differential Pair Due to In-Pair Skew
2 Gb/s with 50 ps Rise and Fall Time (+/- 1.0 volts)
Level (dBuV)
110
105
100
95
90
85
80
75
70
65
60
0.0E+00
1.0E+09
2.0E+09
3.0E+09
4.0E+09
5.0E+09
6.0E+09
7.0E+09
8.0E+09
9.0E+09
1.0E+10
Frequency (Hz)
10 ps
20 ps
50 ps
100 ps
150 ps
200 ps

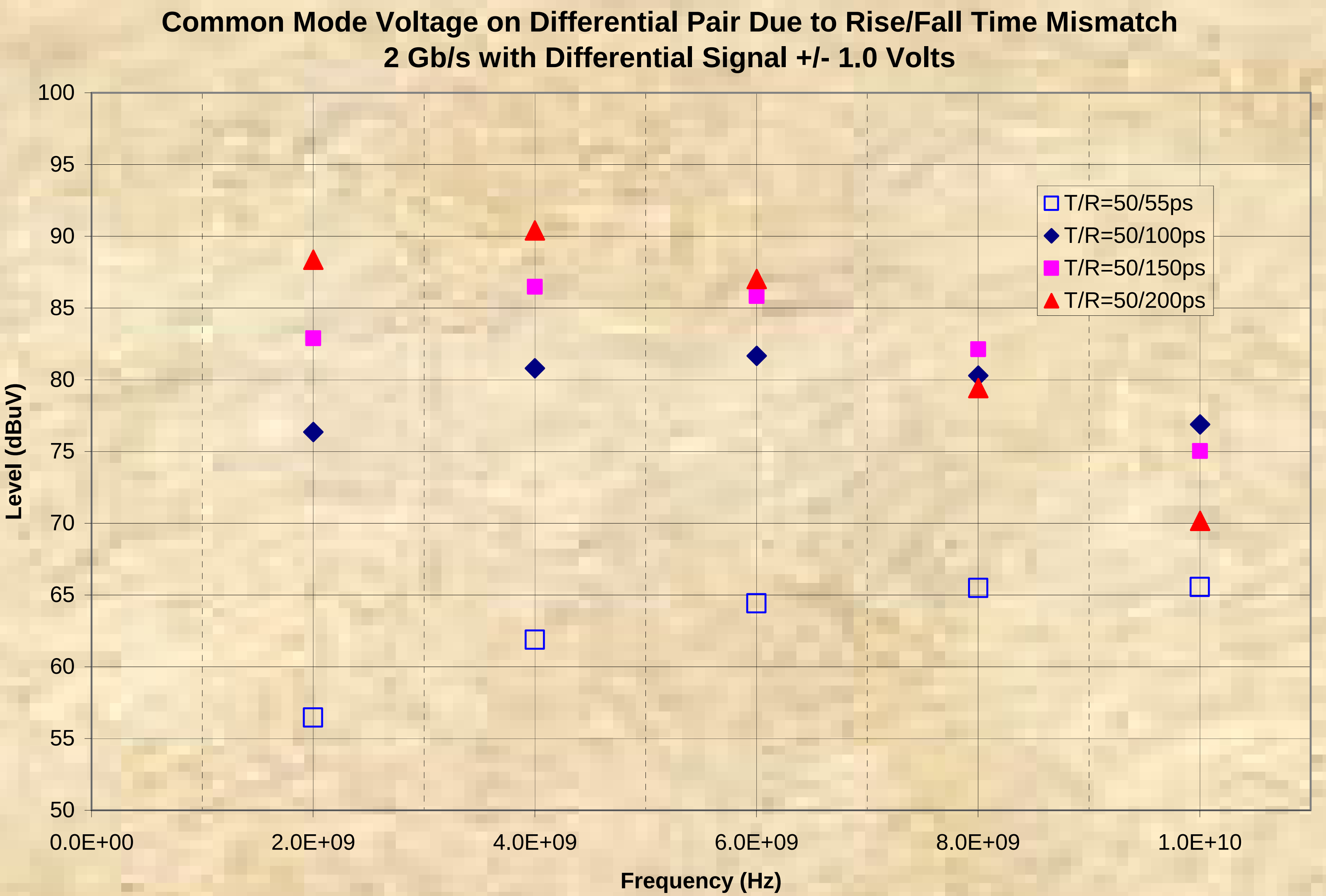
Common Mode from Rise/Fall Time Mismatch

- Small amounts of mismatch create significant CM noise
- Not as significant as skew, but harder to control!


Example of Effect for Differential Signal with Rise/Fall Time Mismatch
2 Gb/s Square Wave (Rise/Fall = 50 & 100 ps)
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
Voltage
0.0E+00
2.0E-10
4.0E-10
6.0E-10
8.0E-10
1.0E-09
1.2E-09
1.4E-09
1.6E-09
1.8E-09
2.0E-09
Time (Seconds)
Channel 1
Channel 2
T/R=50/100ps

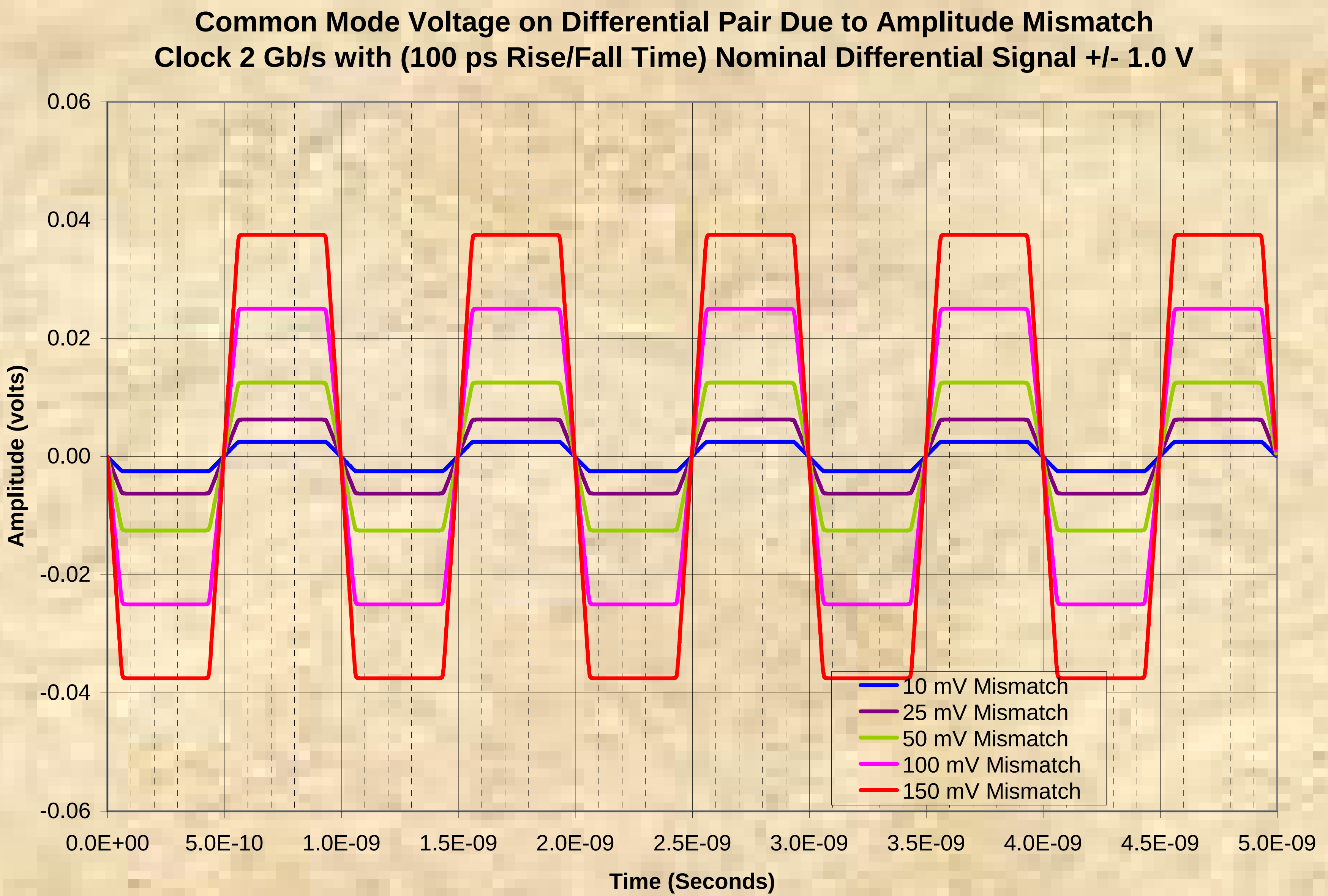


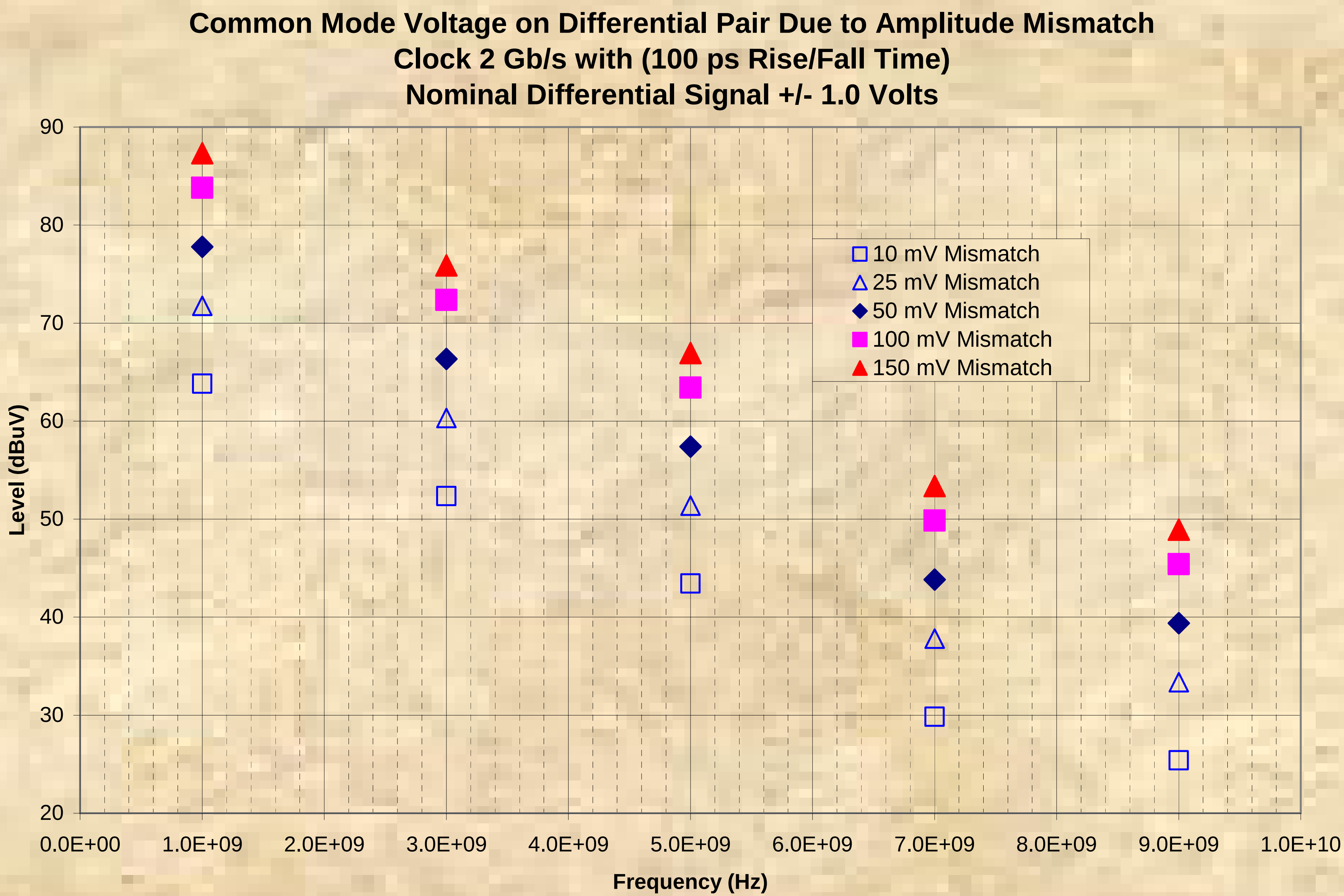
Common Mode Voltage on Differential Pair Due to Rise/Fall Time Mismatch
2 Gb/s with Differential Signal +/- 1.0 Volts
T/R=50/100ps
T/R=50/150ps
T/R=50/200ps
Level (volts)
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
0
5E-10
1E-09
1.5E-09
2E-09
2.5E-09
3E-09
3.5E-09
4E-09
4.5E-09
5E-09
Time (seconds)


Common Mode Voltage on Differential Pair Due to Rise/Fall Time Mismatch
2 Gb/s with Differential Signal +/- 1.0 Volts
Level (dBuV)
Frequency (Hz)
100
95
90
85
80
75
70
65
60
55
50
0.0E+00
2.0E+09
4.0E+09
6.0E+09
8.0E+09
1.0E+10
T/R=50/55ps
T/R=50/100ps
T/R=50/150ps
T/R=50/200ps

Common Mode from Amplitude Mismatch

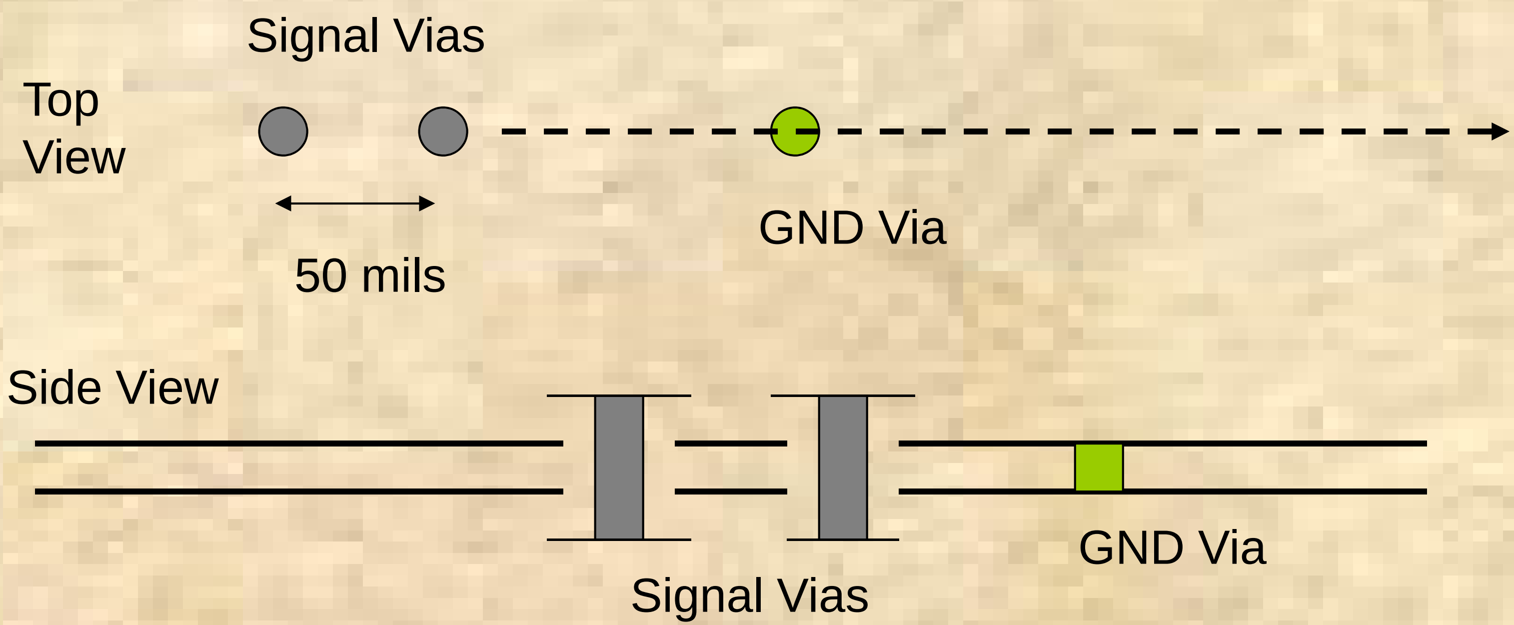
- Small amounts of mismatch create significant CM noise
- Harmonics are additive with other sources of CM noise

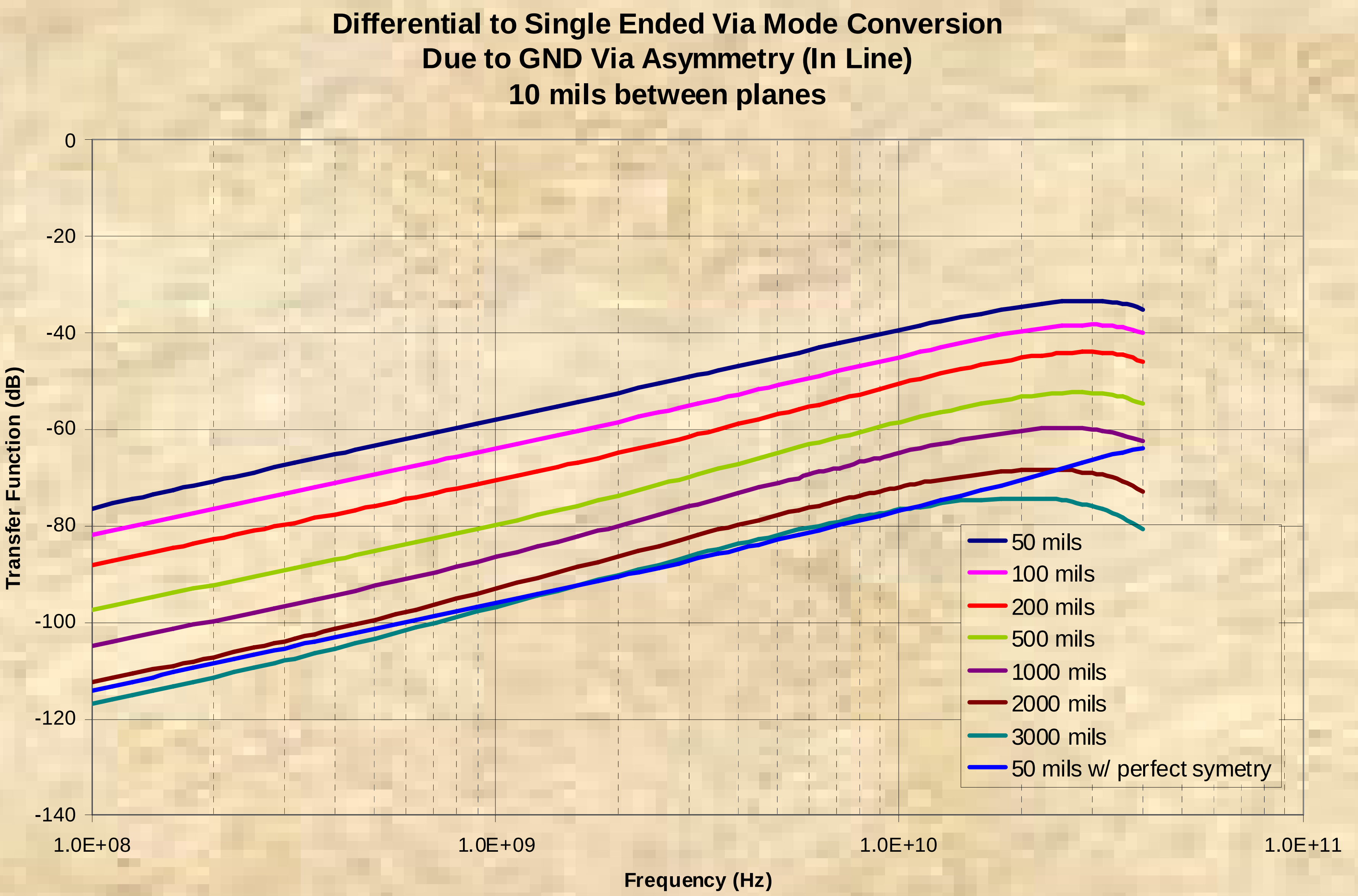

Common Mode Voltage on Differential Pair Due to Amplitude Mismatch
Clock 2 Gb/s with (100 ps Rise/Fall Time) Nominal Differential Signal +/- 1.0 V
0.06
0.04
0.02
0.00
-0.02
-0.04
-0.06
Amplitude (volts)
0.0E+00
5.0E-10
1.0E-09
1.5E-09
2.0E-09
2.5E-09
3.0E-09
3.5E-09
4.0E-09
4.5E-09
5.0E-09
Time (Seconds)
10 mV Mismatch
25 mV Mismatch
50 mV Mismatch
100 mV Mismatch
150 mV Mismatch


Common Mode Voltage on Differential Pair Due to Amplitude Mismatch
Clock 2 Gb/s with (100 ps Rise/Fall Time)
Nominal Differential Signal +/- 1.0 Volts
Level (dBuV)
90
80
70
60
50
40
30
20
0.0E+00
1.0E+09
2.0E+09
3.0E+09
4.0E+09
5.0E+09
6.0E+09
7.0E+09
8.0E+09
9.0E+09
1.0E+10
Frequency (Hz)
10 mV Mismatch
25 mV Mismatch
50 mV Mismatch
100 mV Mismatch
150 mV Mismatch

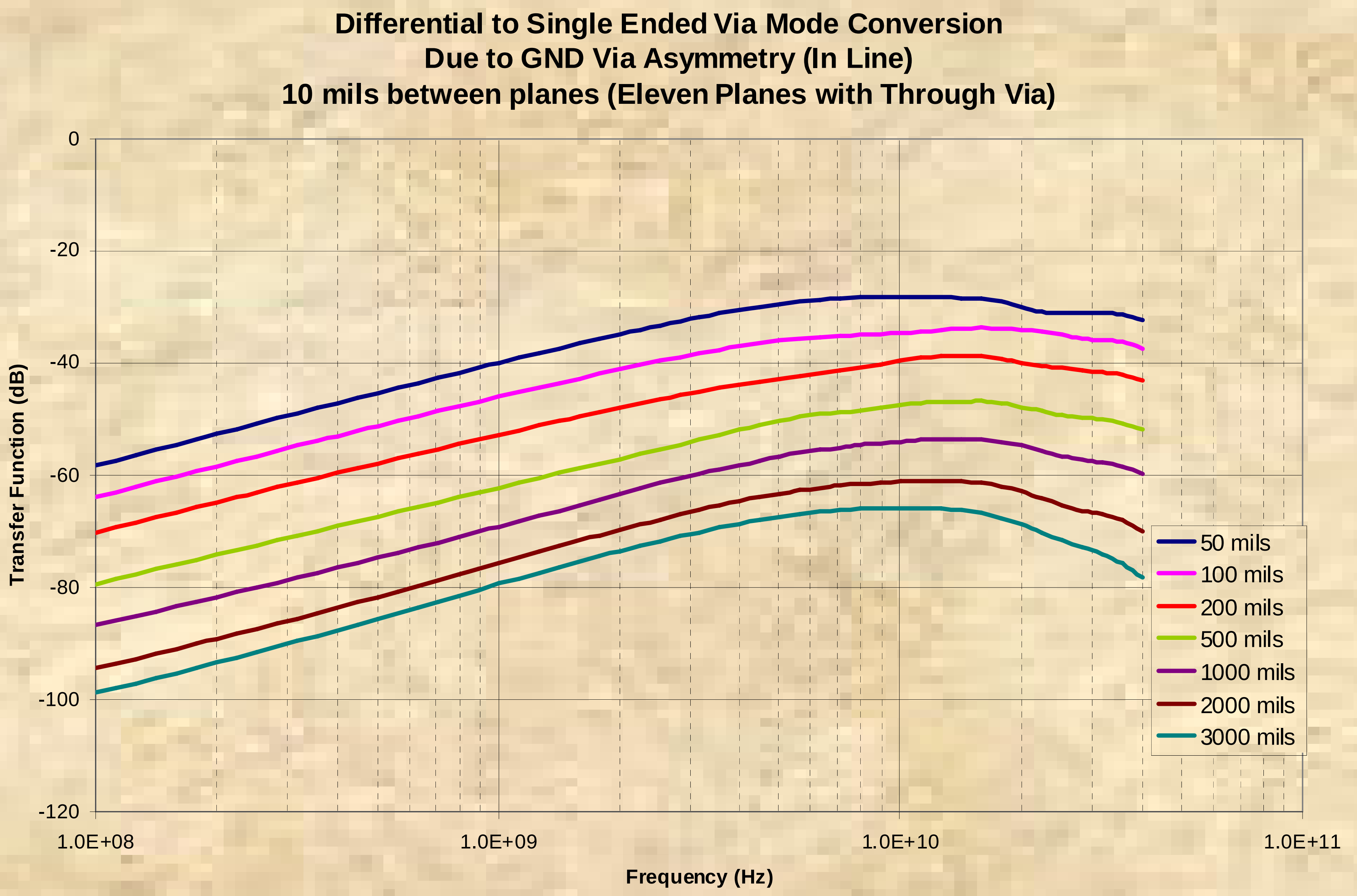
Common Mode from Via Asymmetry

- Significant CM created!

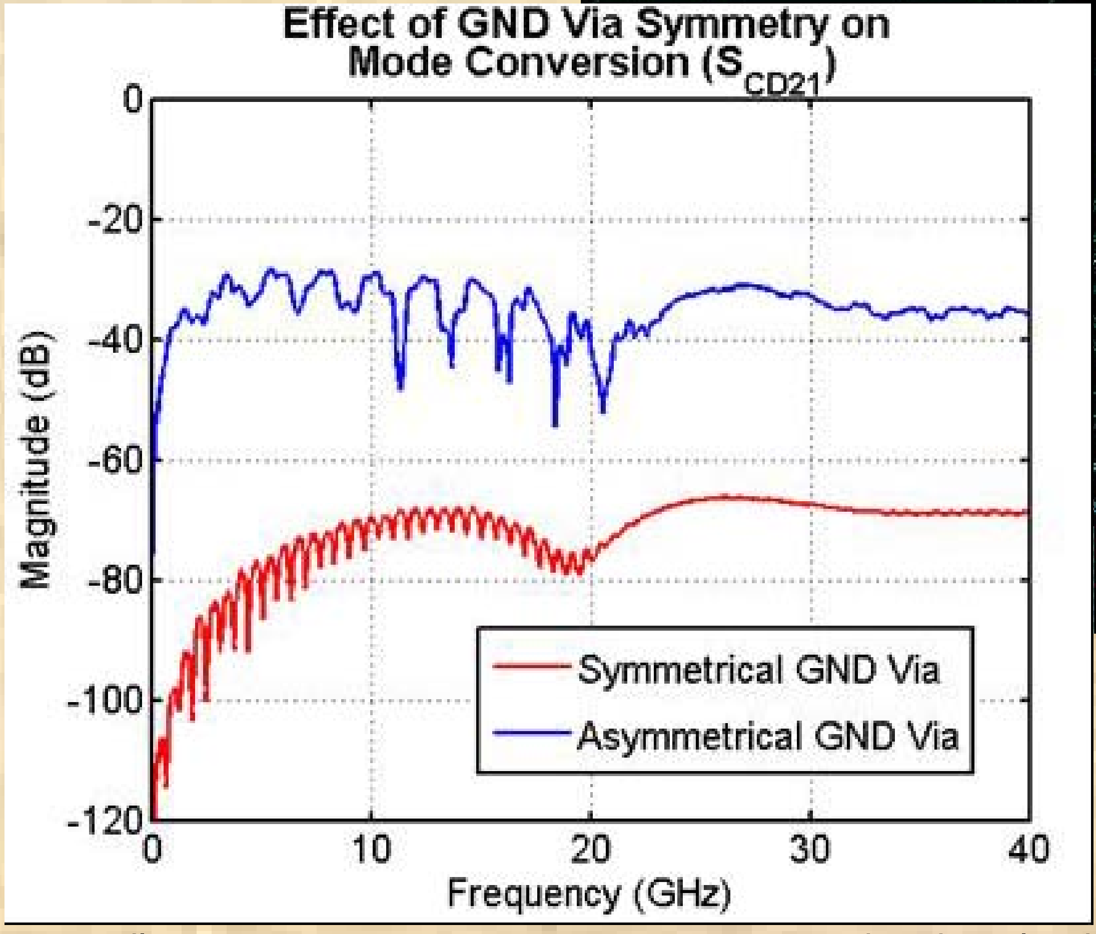


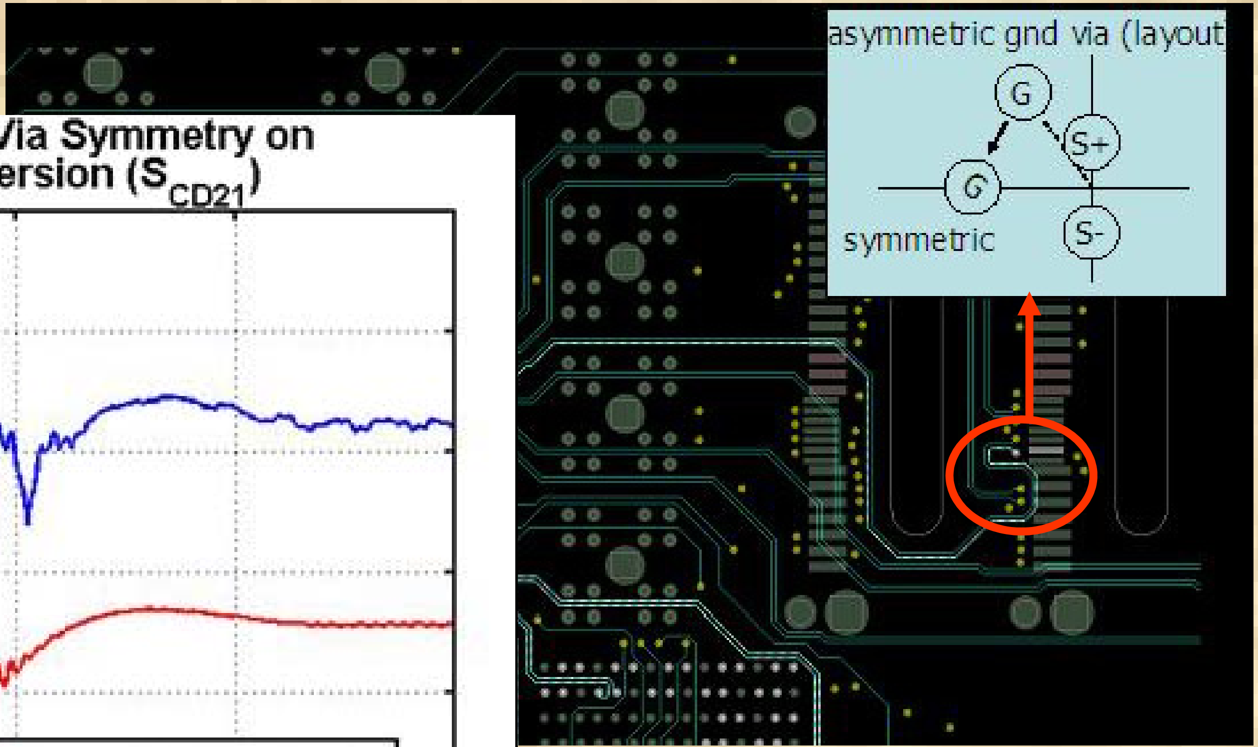


Differential to Single Ended Via Mode Conversion
Due to GND Via Asymmetry (In Line)
10 mils between planes
Transfer Function (dB)
0
-20
-40
-60
-80
-100
-120
-140
1.0E+08
1.0E+09
1.0E+10
1.0E+11
Frequency (Hz)
50 mils
100 mils
200 mils
500 mils
1000 mils
2000 mils
3000 mils
50 mils w/ perfect symetry

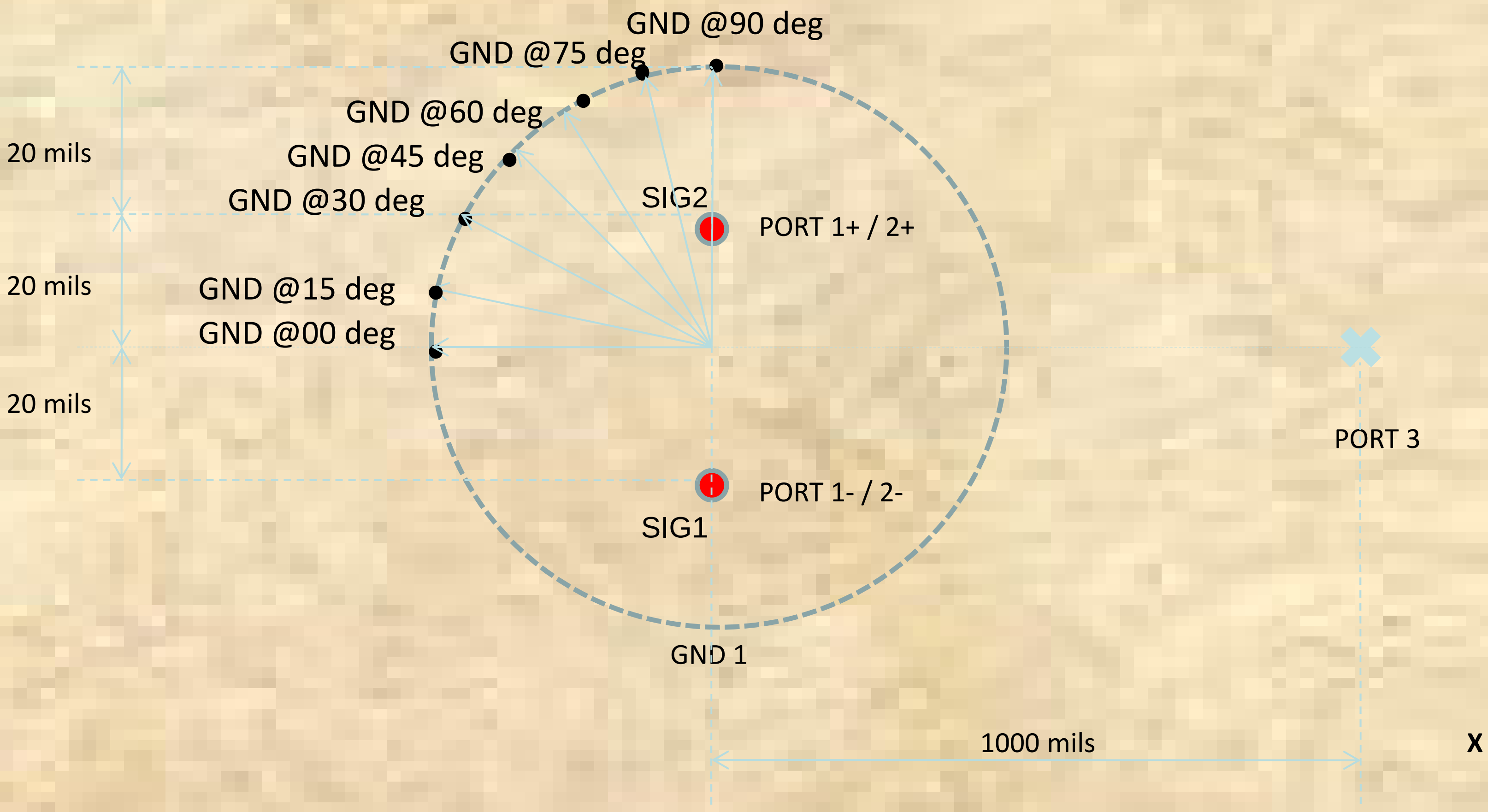

Differential to Single Ended Via Mode Conversion
Due to GND Via Asymmetry (In Line)
10 mils between planes (Eleven Planes with Through Via)
Transfer Function (dB)
0
-20
-40
-60
-80
-100
-120
1.0E+08
1.0E+09
1.0E+10
1.0E+11
Frequency (Hz)
50 mils
100 mils
200 mils
500 mils
1000 mils
2000 mils
3000 mils

Via Symmetry Effect on Common Mode Conversion

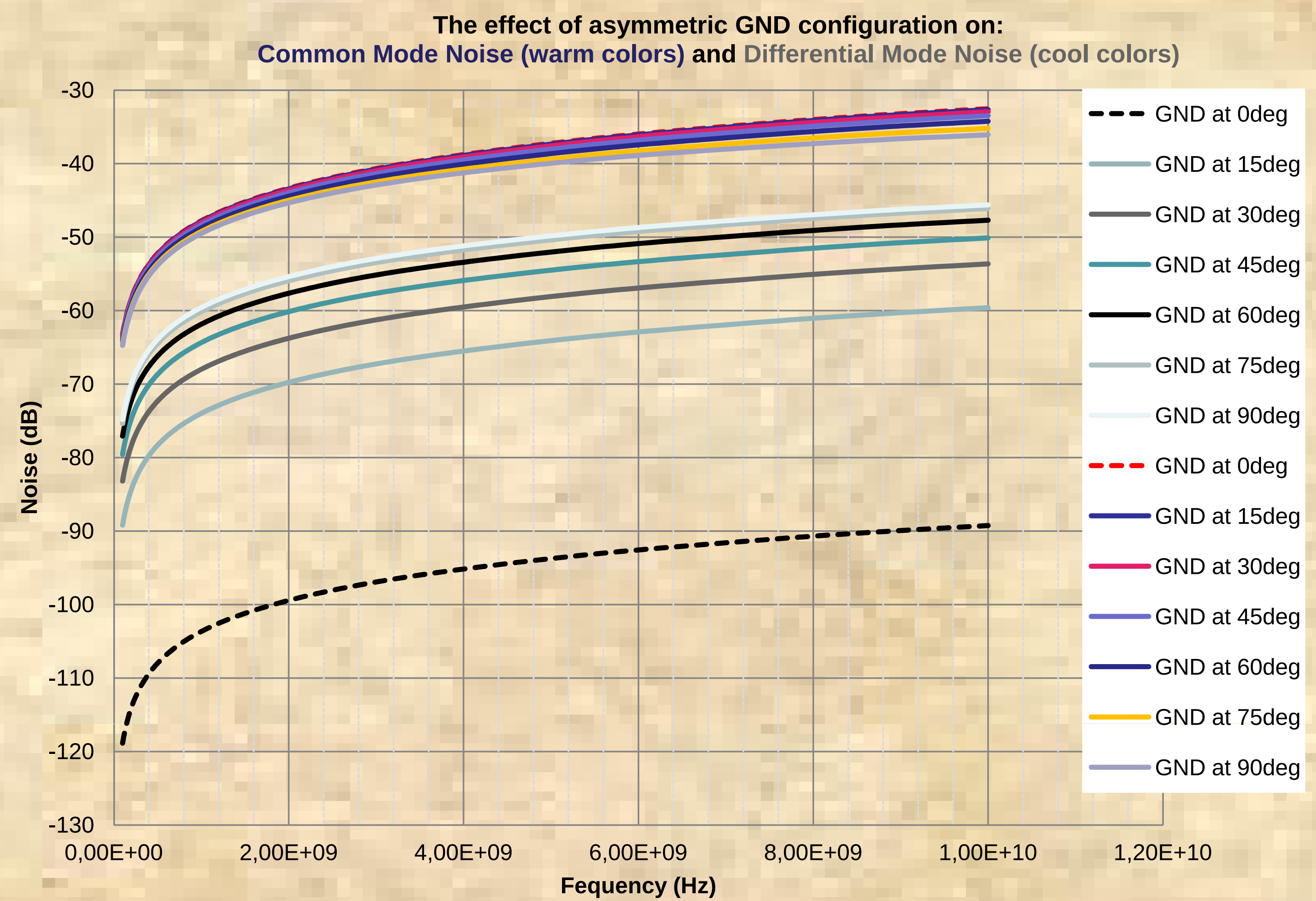




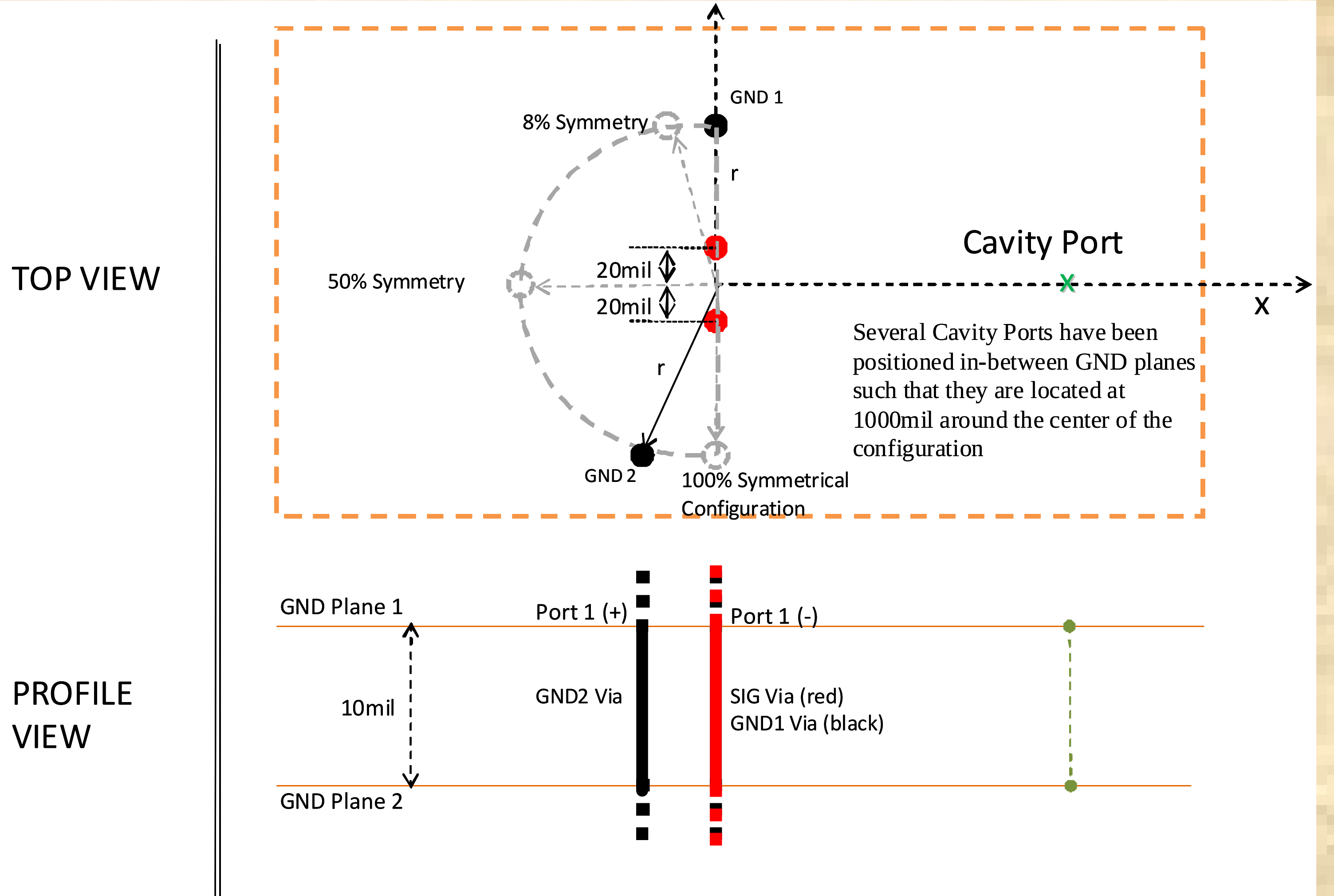
Top View of the Board:
Different GND configurations



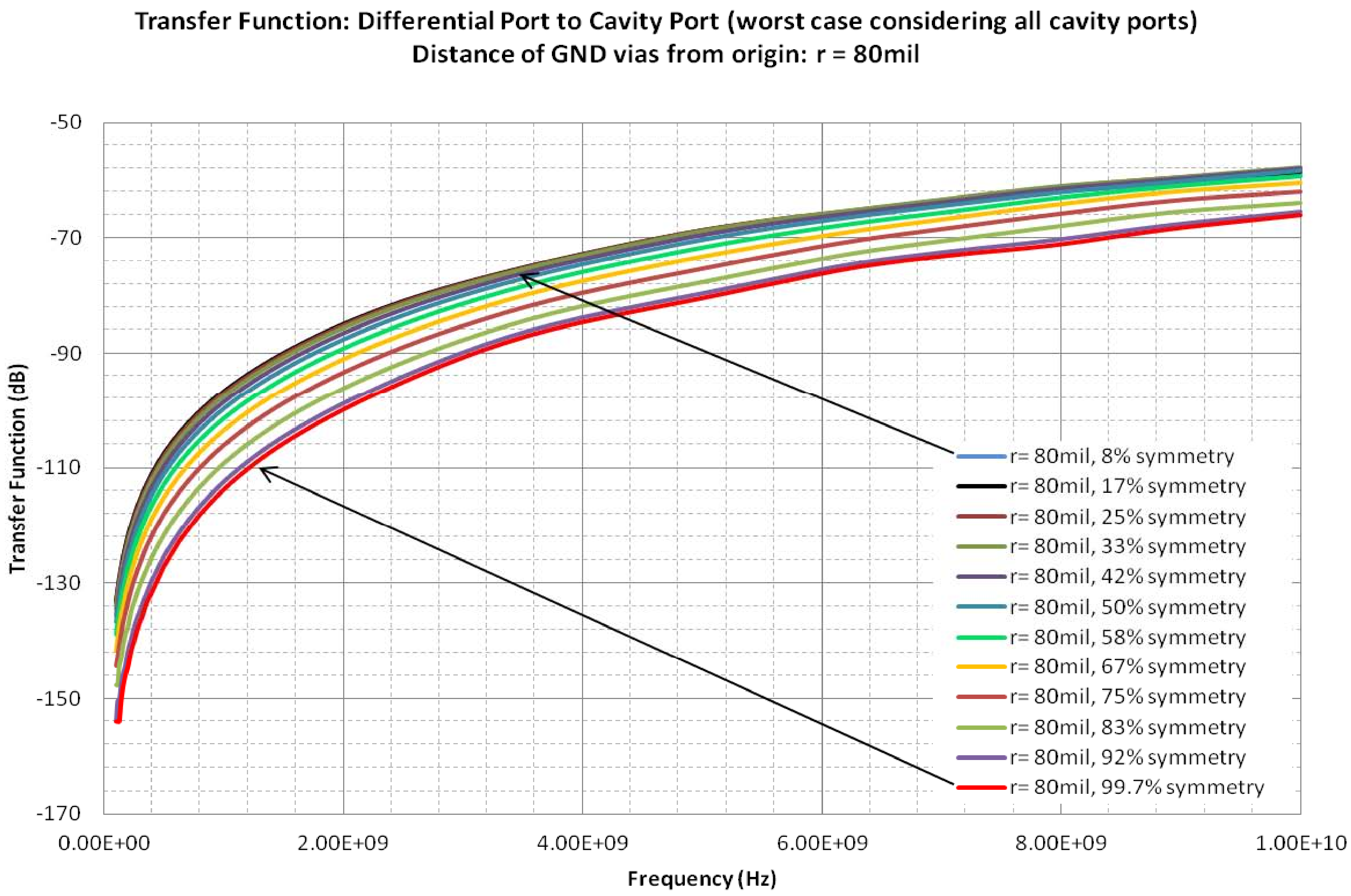
Asymmetric Ground Via Effects
Via to Noise Between Planes



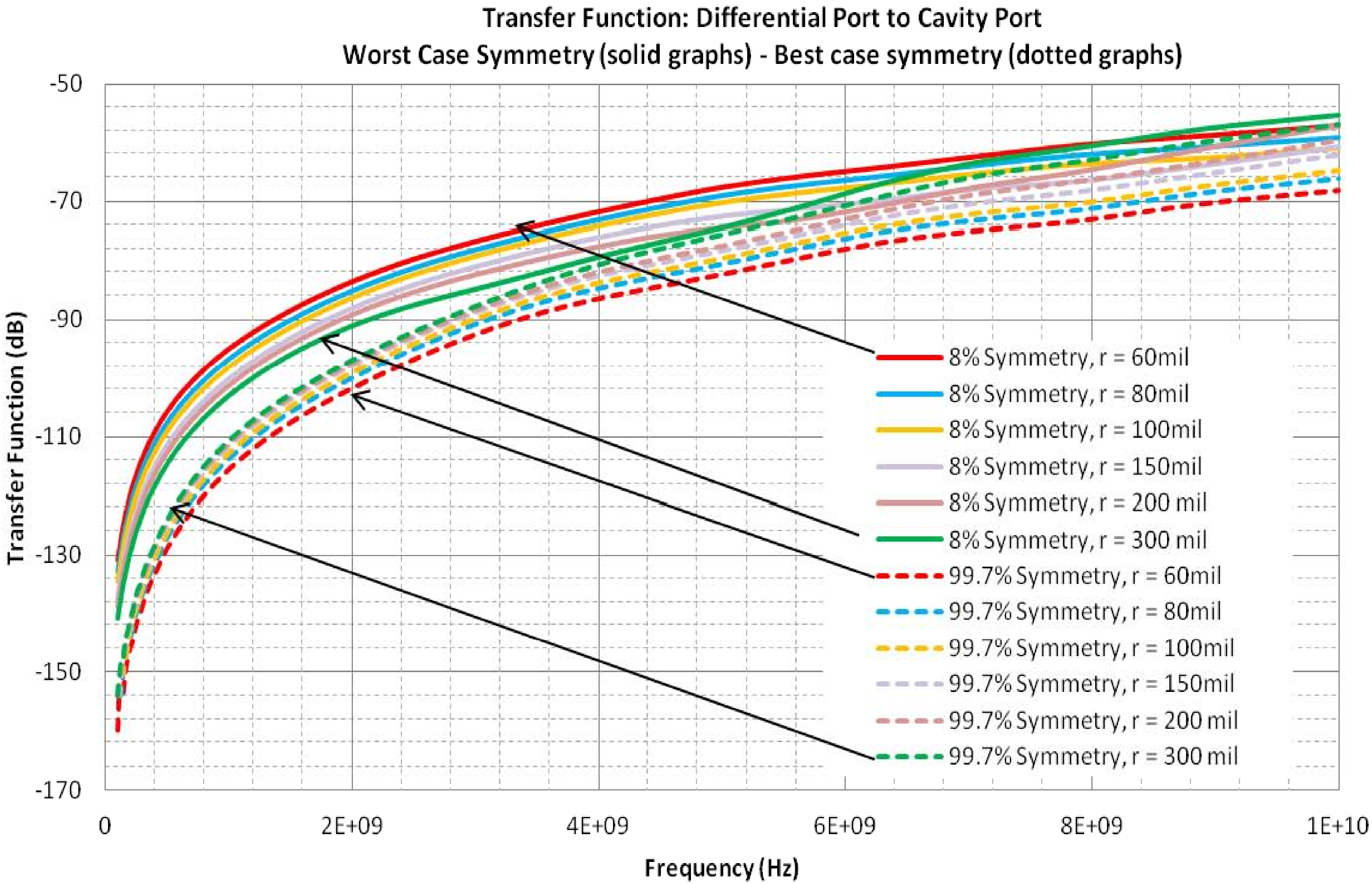
Asymmetry with Two GND Vias

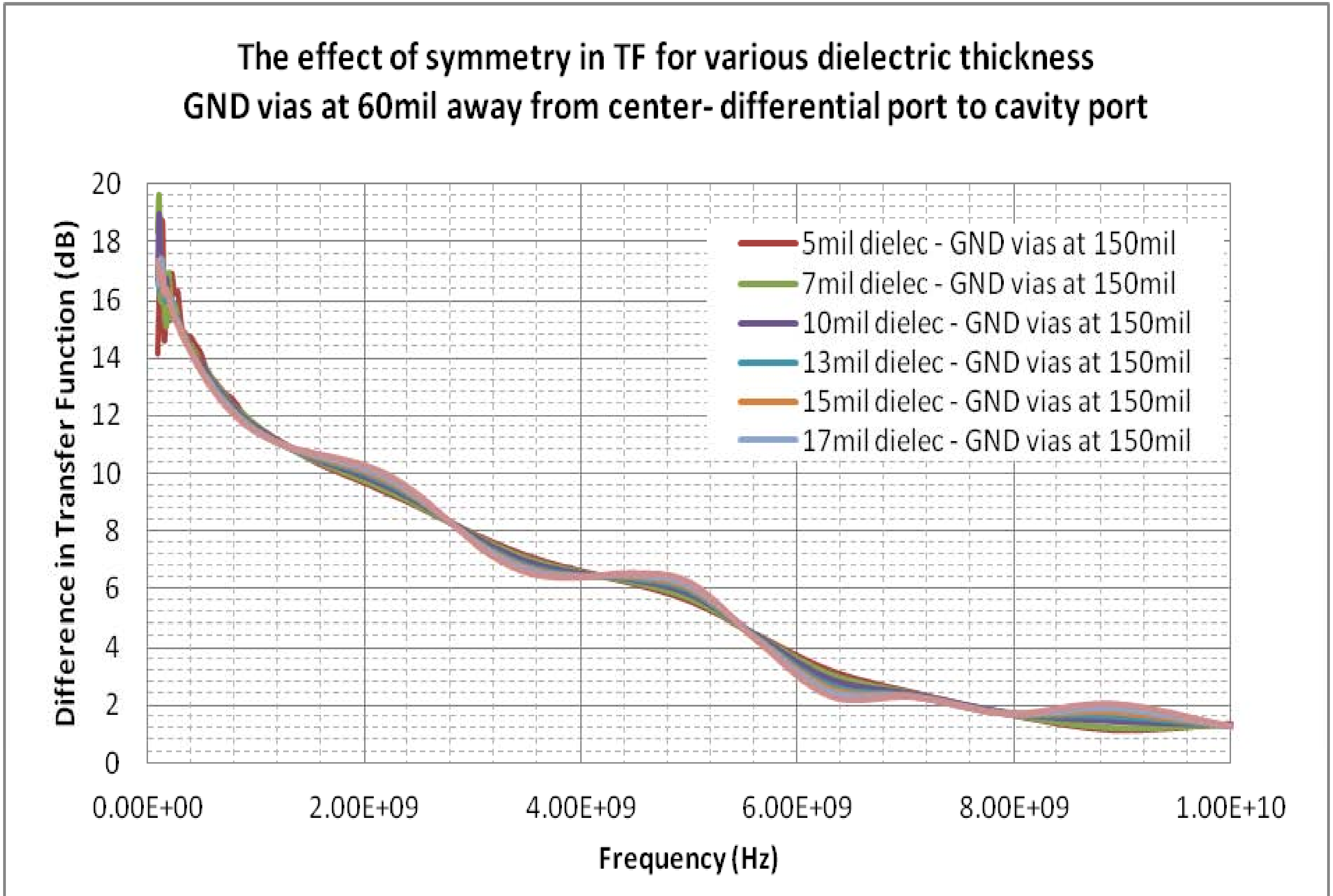


Dielectric Constant, Metal Thickness: 4.3, 1mil
Antipad, Pad, Via Drill Diameter: 35 mil, 20mil, 12 mil

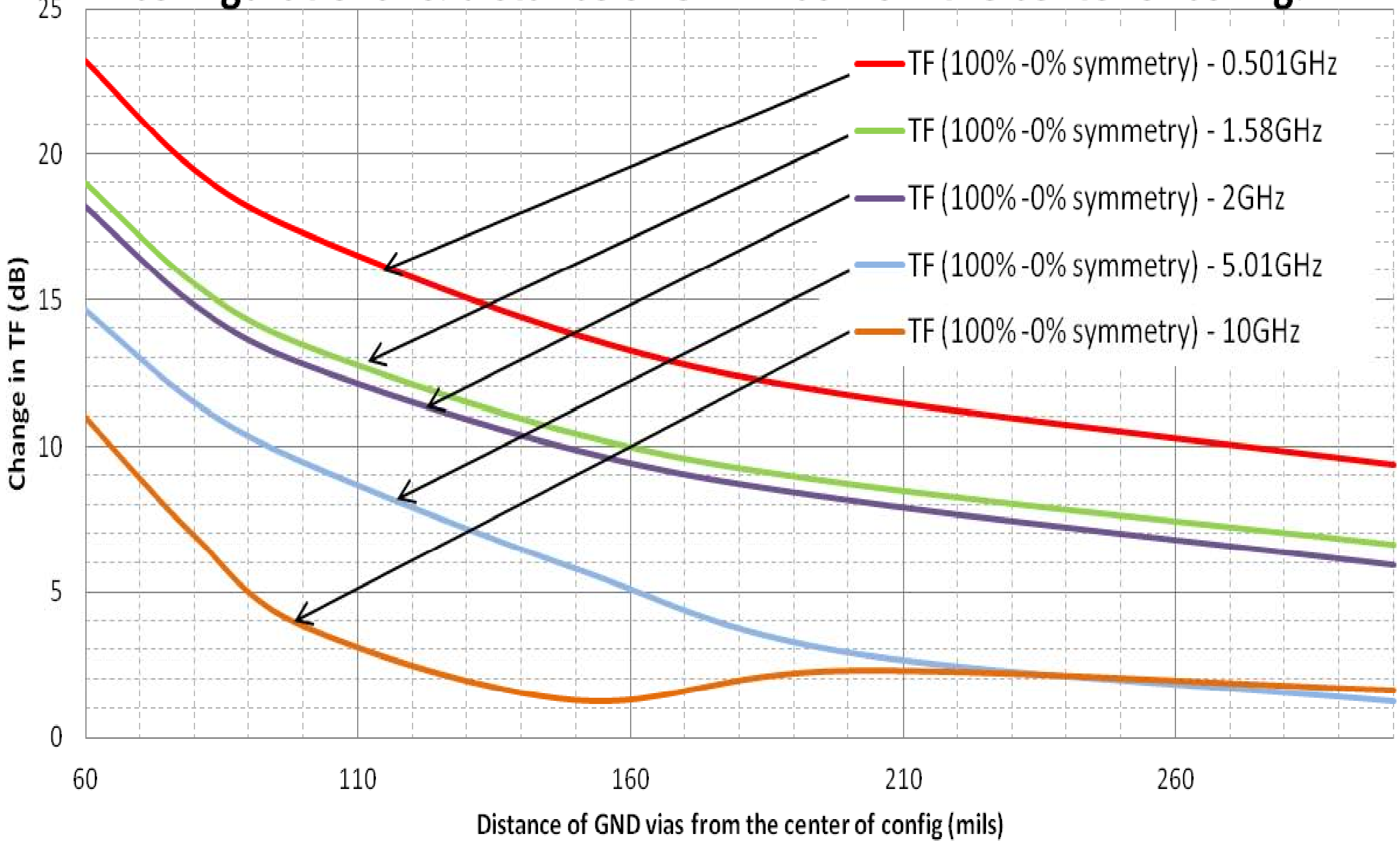


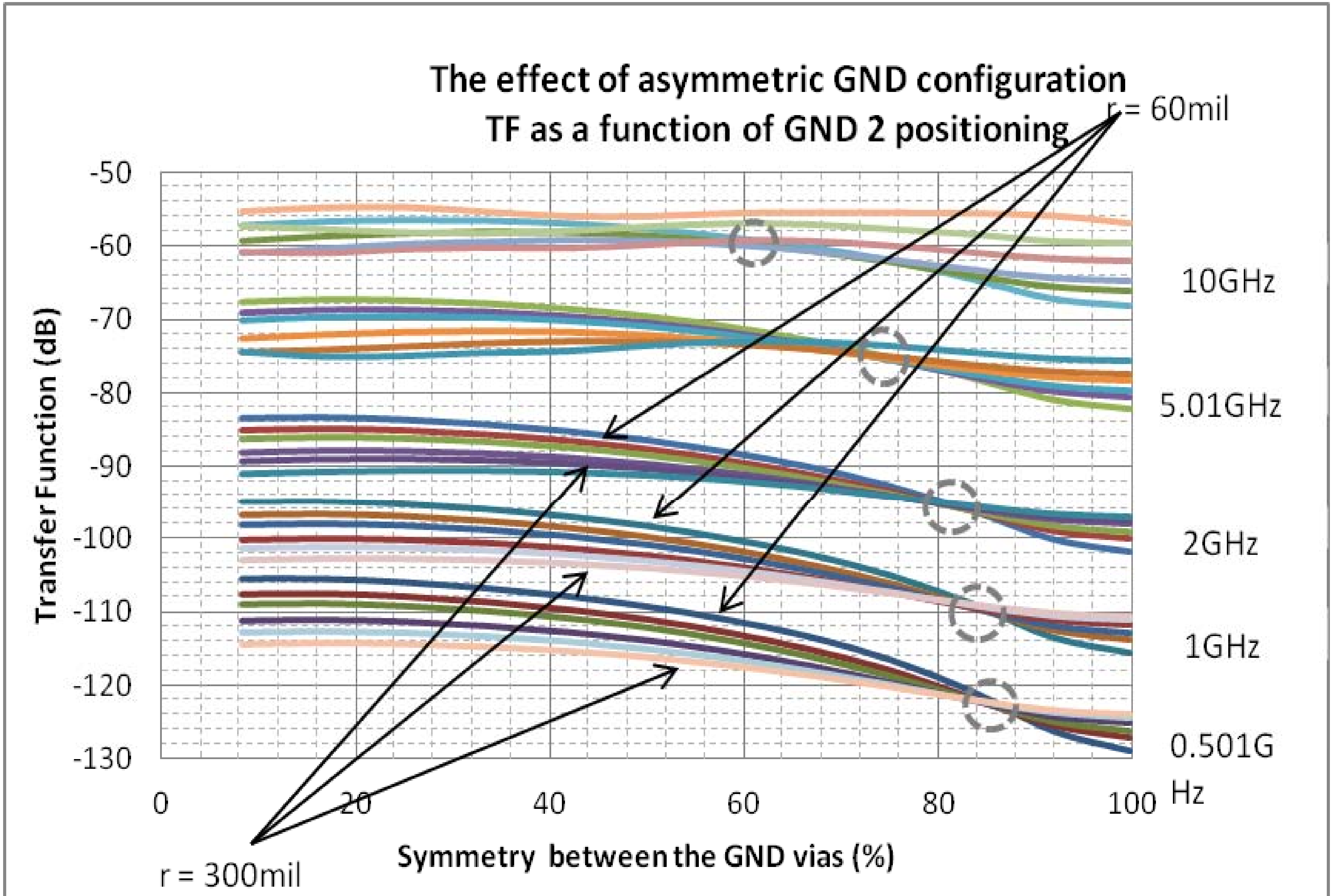
Transfer Function: Differential Port to Cavity Port (worst case considering all cavity ports)
Distance of GND vias from origin: r = 80mil
Transfer Function (dB)
-50
-70
-90
-110
-130
-150
-170
0.00E+00
2.00E+09
4.00E+09
6.00E+09
8.00E+09
1.00E+10
Frequency (Hz)
r= 80mil, 8% symmetry
r= 80mil, 17% symmetry
r= 80mil, 25% symmetry
r= 80mil, 33% symmetry
r= 80mil, 42% symmetry
r= 80mil, 50% symmetry
r= 80mil, 58% symmetry
r= 80mil, 67% symmetry
r= 80mil, 75% symmetry
r= 80mil, 83% symmetry
r= 80mil, 92% symmetry
r= 80mil, 99.7% symmetry

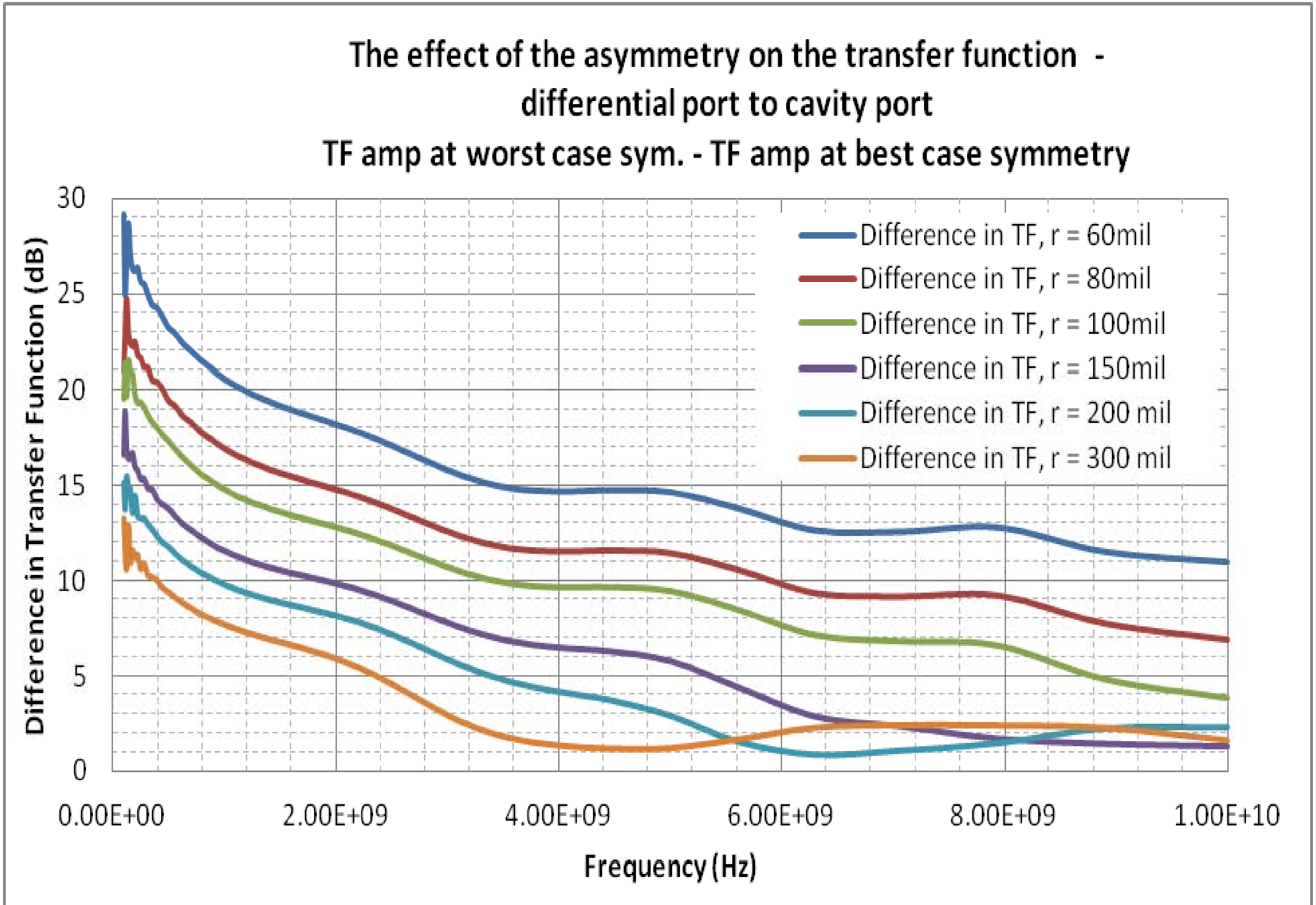

Transfer Function: Differential Port to Cavity Port
Worst Case Symmetry (solid graphs) - Best case symmetry (dotted graphs)
Transfer Function (dB)
-50
-70
-90
-110
-130
-150
-170
0
2E+09
4E+09
6E+09
8E+09
1E+10
Frequency (Hz)
8% Symmetry, r = 60mil
8% Symmetry, r = 80mil
8% Symmetry, r = 100mil
8% Symmetry, r = 150mil
8% Symmetry, r = 200 mil
8% Symmetry, r = 300 mil
99.7% Symmetry, r = 60mil
99.7% Symmetry, r = 80mil
99.7% Symmetry, r = 100mil
99.7% Symmetry, r = 150mil
99.7% Symmetry, r = 200 mil
99.7% Symmetry, r = 300 mil


The effect of symmetry in TF for various dielectric thickness
GND vias at 60mil away from center- differential port to cavity port
Difference in Transfer Function (dB)
20
18
16
14
12
10
8
6
4
2
0
0.00E+00
2.00E+09
4.00E+09
6.00E+09
8.00E+09
1.00E+10
Frequency (Hz)
5mil dielec - GND vias at 150mil
7mil dielec - GND vias at 150mil
10mil dielec - GND vias at 150mil
13mil dielec - GND vias at 150mil
15mil dielec - GND vias at 150mil
17mil dielec - GND vias at 150mil

Change in TF while comparing symmetrical and asymmetrical configurations vs. distance of GND vias from the center of config.

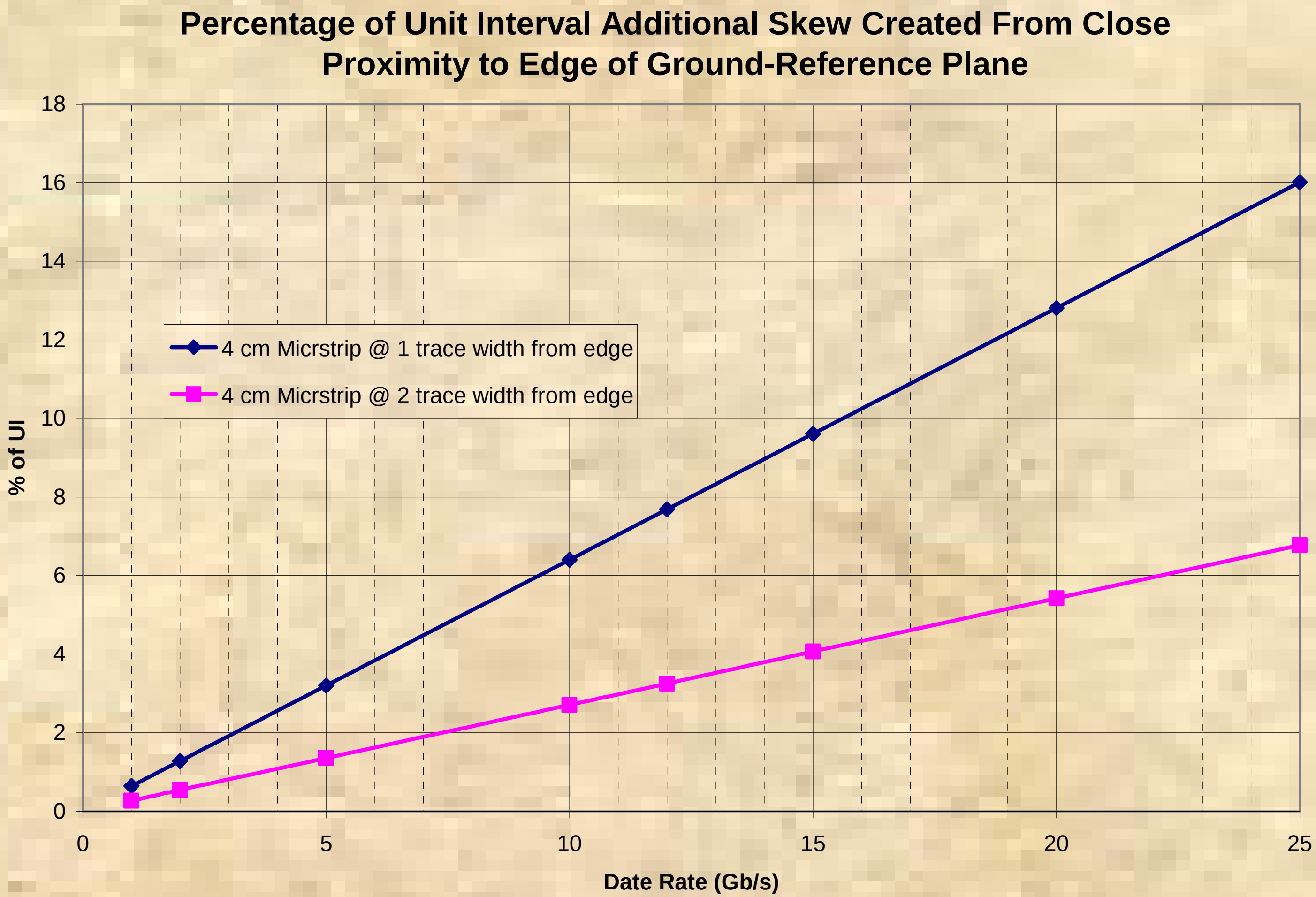



The effect of asymmetric GND configuration
TF as a function of GND 2 positioning
r = 60mil
-50
-60
-70
-80
-90
-100
-110
-120
-130
Transfer Function (dB)
10GHz
5.01GHz
2GHz
1GHz
0.501G
Hz
0
20
40
60
80
100
Symmetry between the GND vias (%)
r = 300mil



The effect of the asymmetry on the transfer function -
differential port to cavity port
TF amp at worst case sym. - TF amp at best case symmetry
Difference in TF, r = 60mil
Difference in TF, r = 80mil
Difference in TF, r = 100mil
Difference in TF, r = 150mil
Difference in TF, r = 200 mil
Difference in TF, r = 300 mil
Difference in Transfer Function (dB)
30
25
20
15
10
5
0
0.00E+00
2.00E+09
4.00E+09
6.00E+09
8.00E+09
1.00E+10
Frequency (Hz)

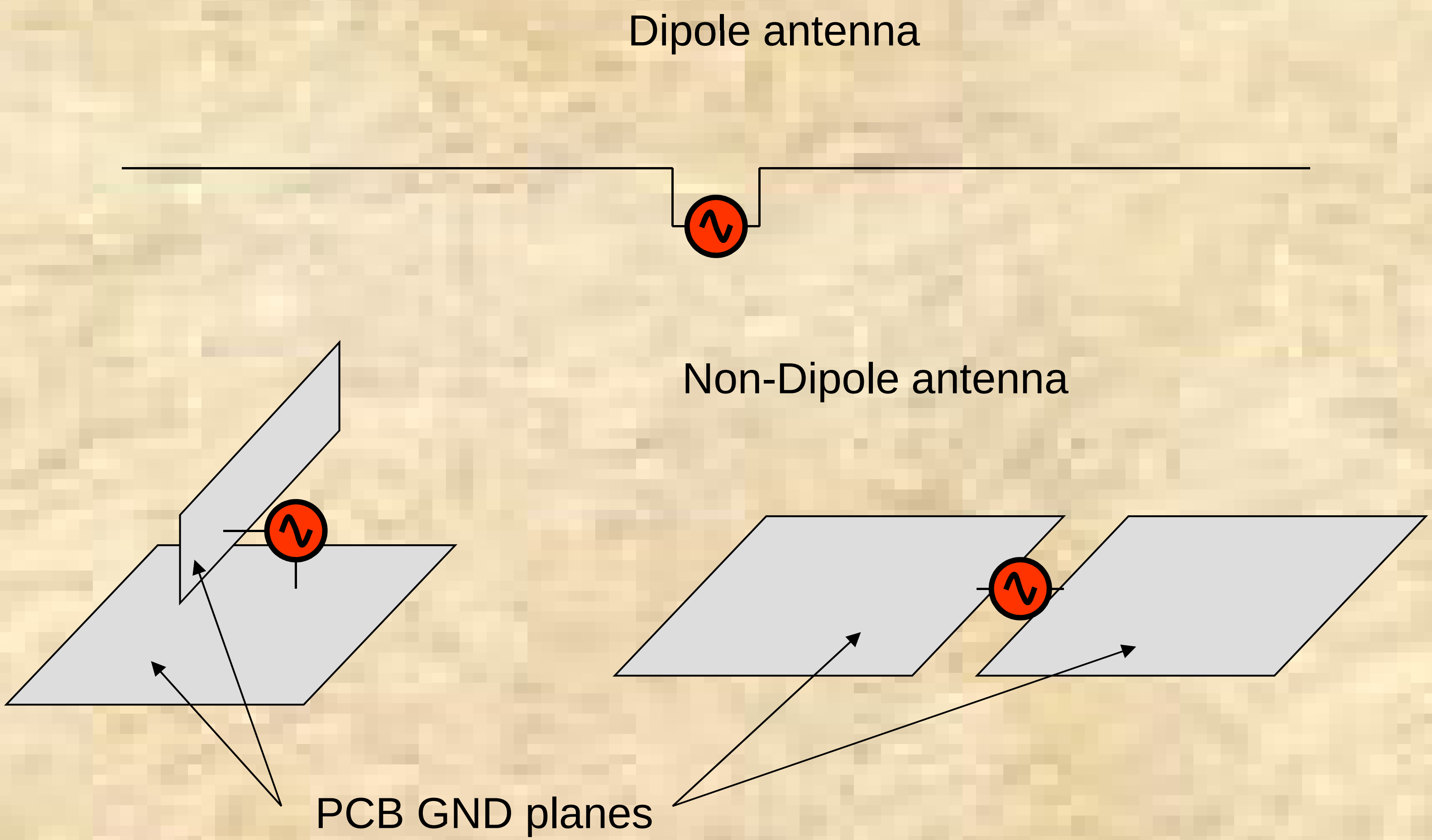
Trace Near Edge of Ground-Reference Plane



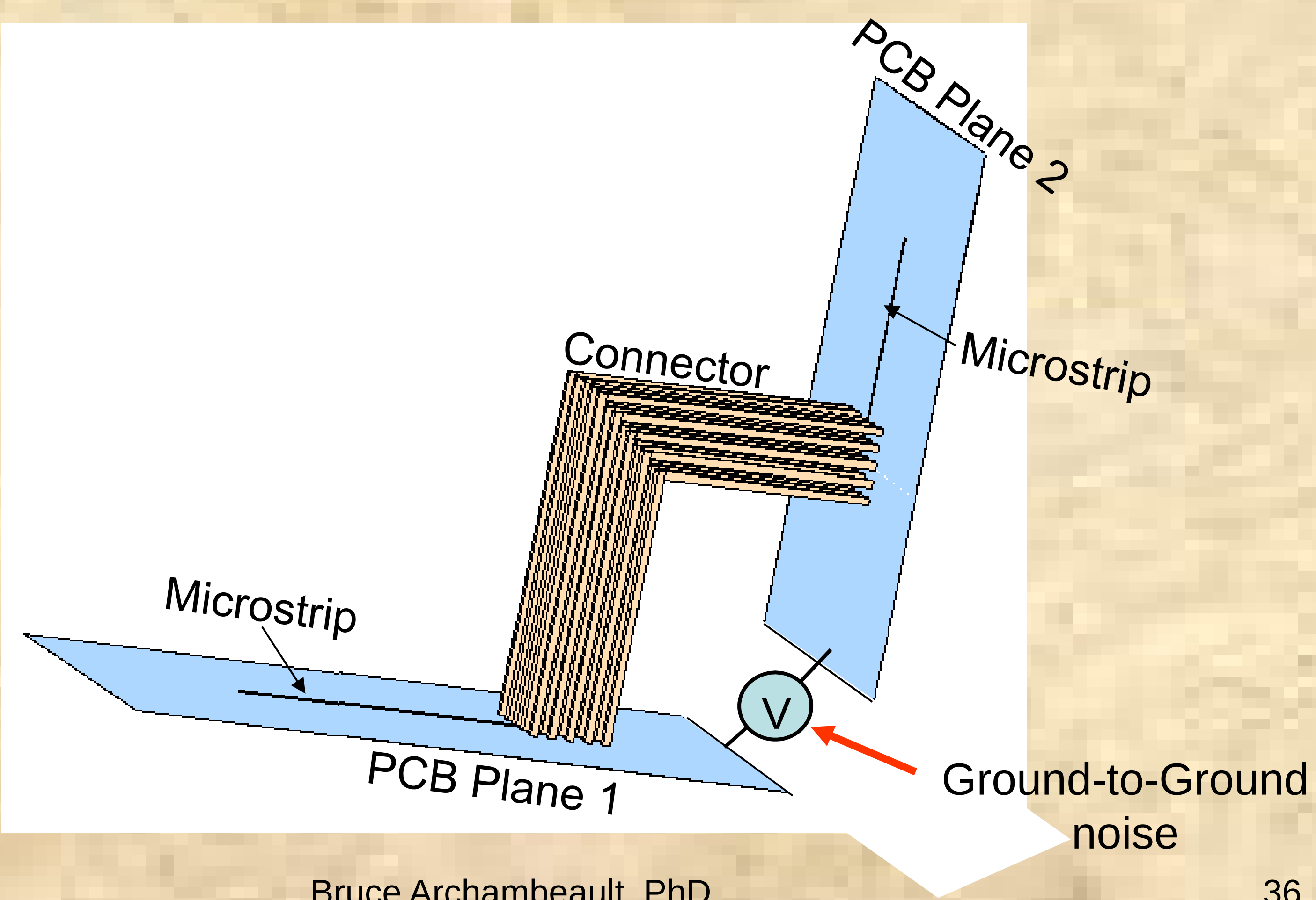
Common Mode is Impossible to Avoid

- Many other asymmetries can add to common mode noise creation
  - Dielectric weave effects
- For EMI, small amounts of CM noise is significant!
  - Above 1 GHz, 1 mV of CM noise is risky!
  - CM filters are required if cables not heavily shielded

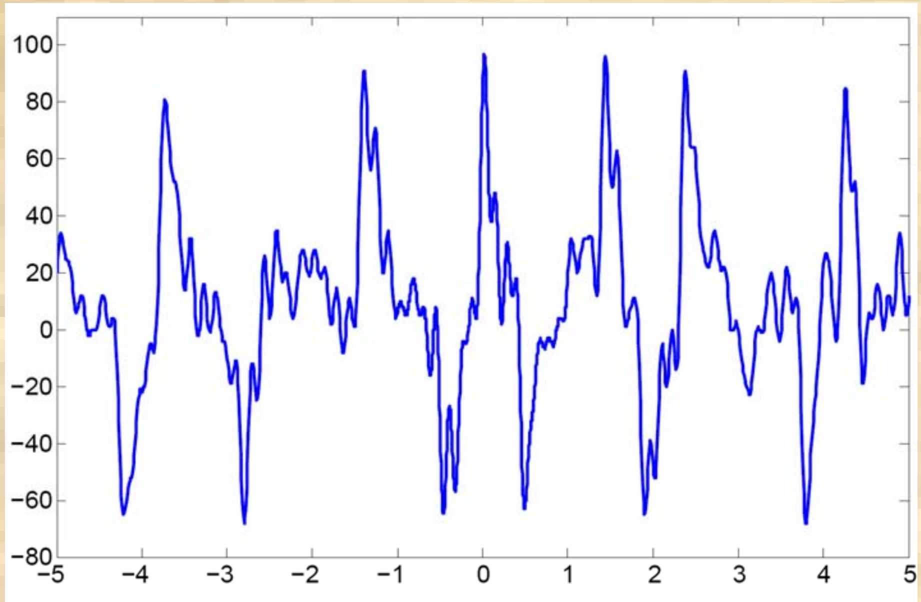
Antenna Structures



Board-to-Board Differential Pair Issues



Example Measured Differential Individual Signal-to-GND

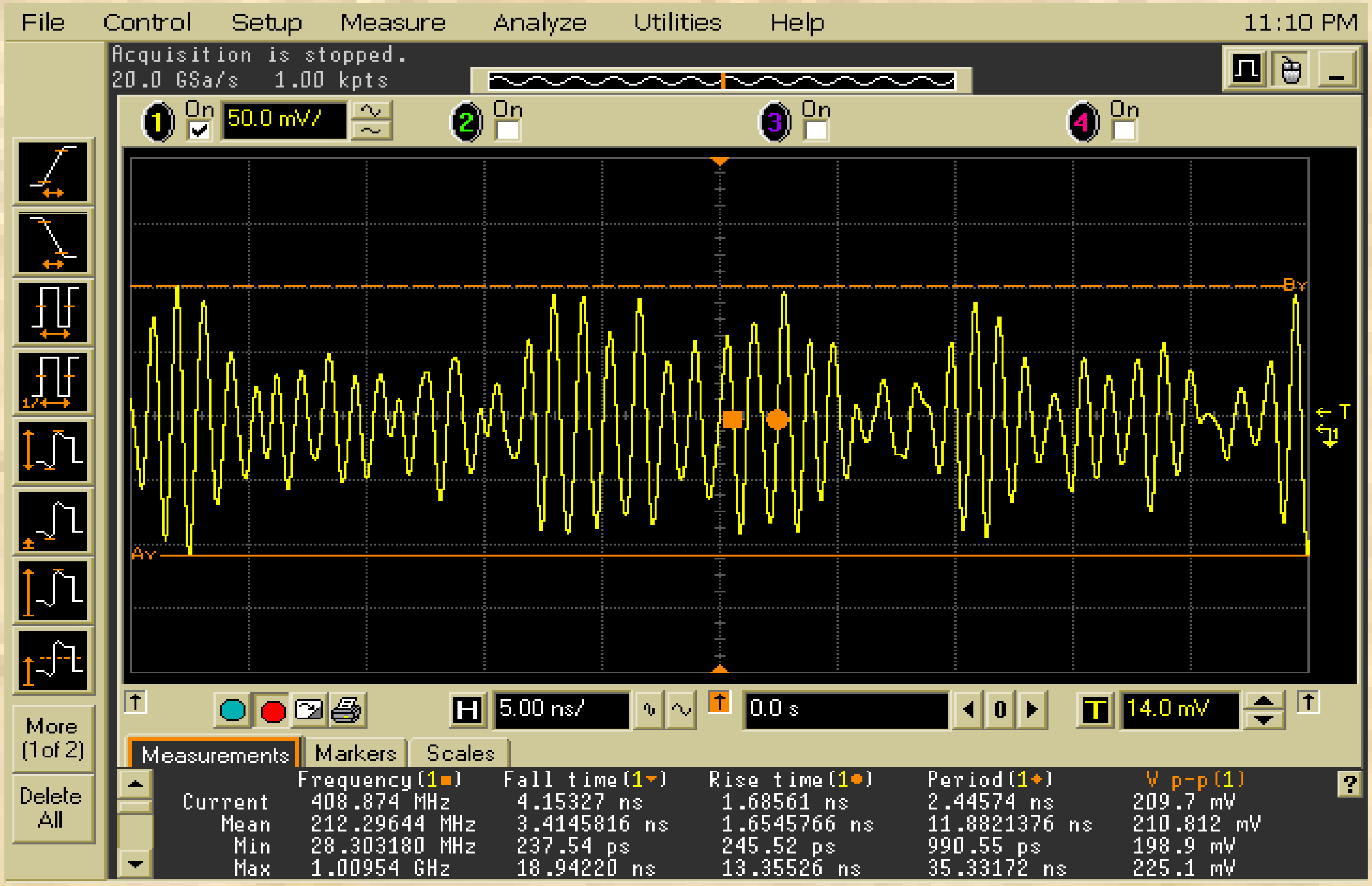


500 mV P-P (each)

Individual Differential Signals ADDED

Common Mode Noise 170 mV P-P

Measured GND-to-GND Voltage

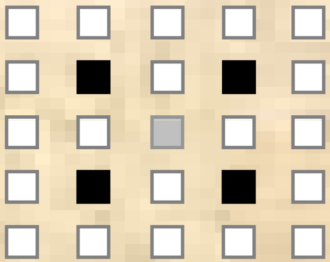


205 mV P-P

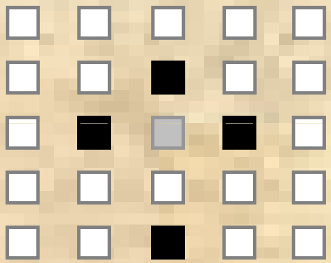
Pin Assignment Controls Inductance for CM signals

37.17 nH
(a)

25.21 nH
(b)



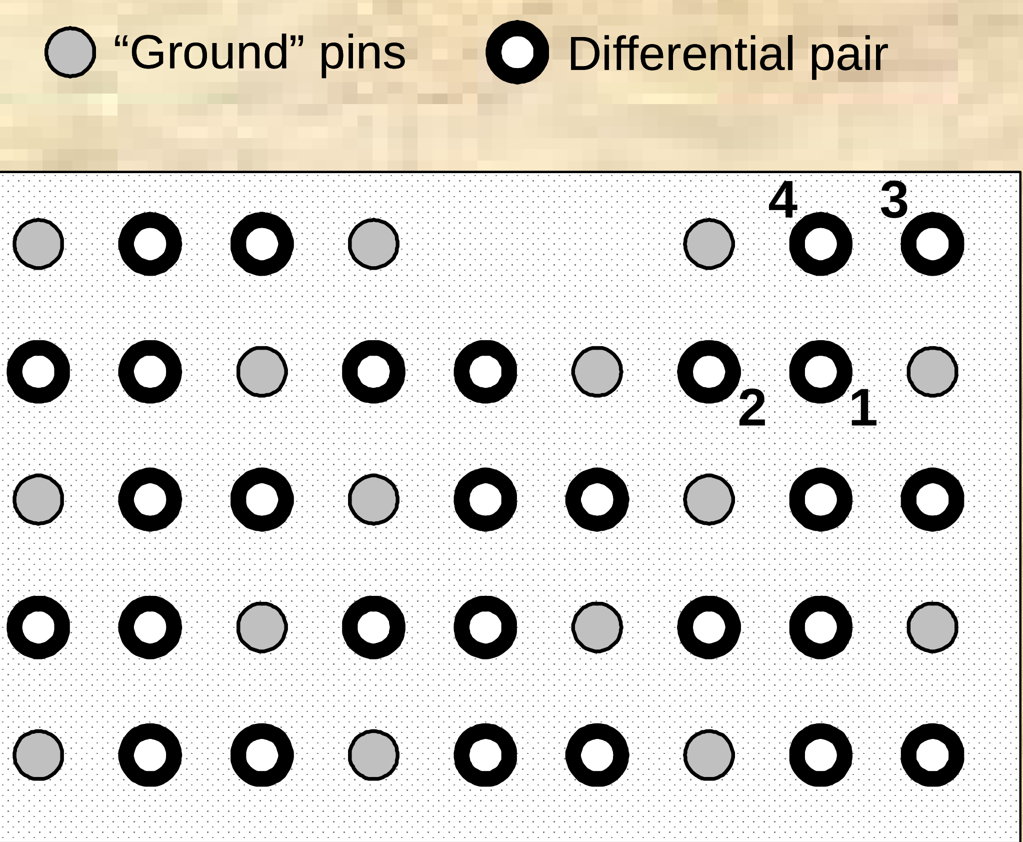
16.85 nH
(c)



20.97 nH
(d)

Signal Pin   Related Ground Pins

Different pins within Same Pair may have Different Loop Inductance for CM



pin 1 -- 26.6nH

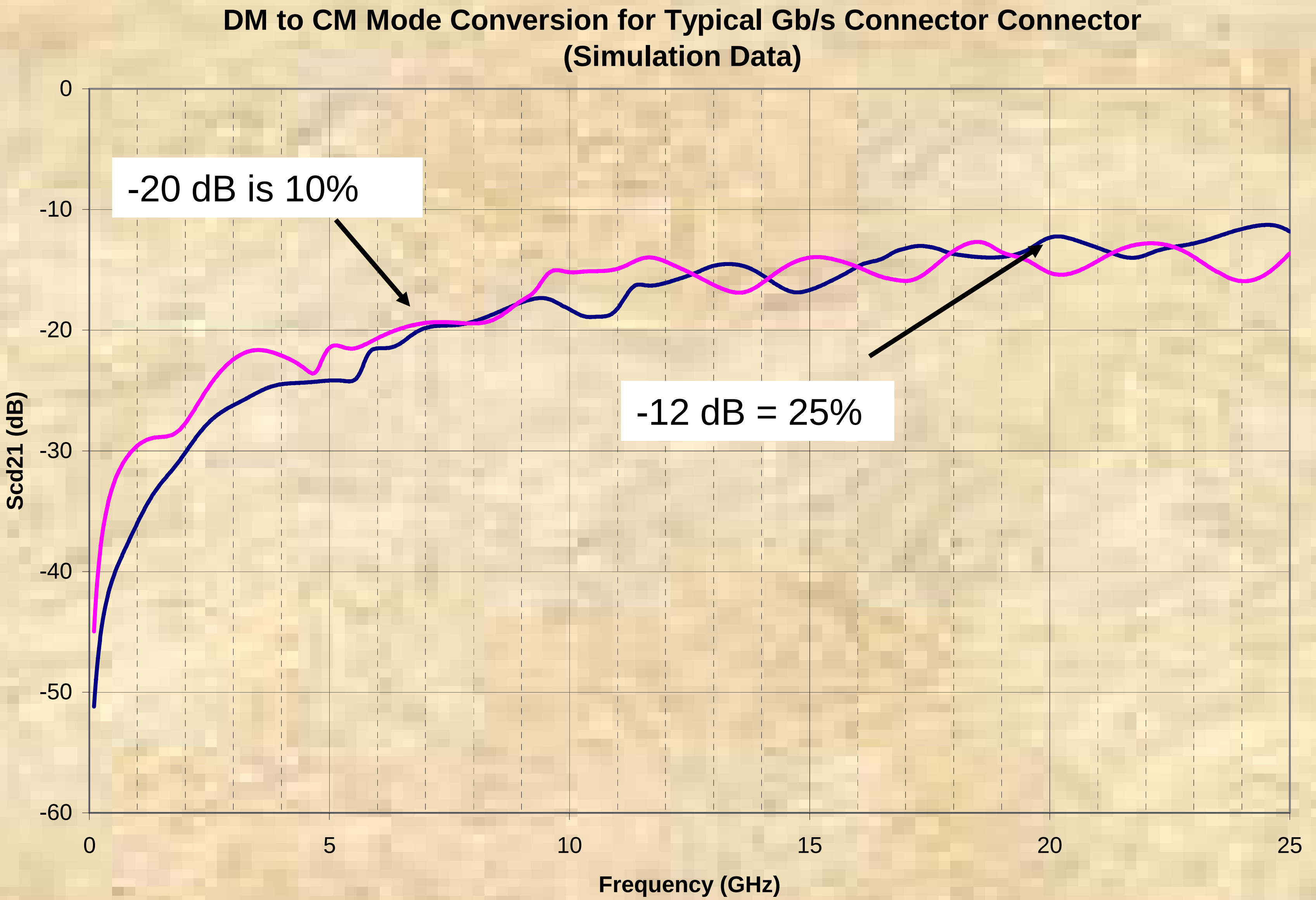
pin 2 -- 23.6nH

pin 3 -- 31.8nH

pin 4 -- 28.8nH

Immunity Concerns for SI Performance

- Mode Conversion
  - DM-to-CM = CM-to-DM
  - ESD and RF external noise couples to connectors etc as Common Mode
    - Differential IC receivers ignore common mode noise for good SI
  - If mode conversion occurs, some of the CM noise becomes DM!


DM to CM Mode Conversion for Typical Gb/s Connector Connector
(Simulation Data)
-20 dB is 10%
-12 dB = 25%
Scd21 (dB)
0
-10
-20
-30
-40
-50
-60
0
5
10
15
20
25
Frequency (GHz)

Cross Talk in Differential Connector Due to Mode Conversion?

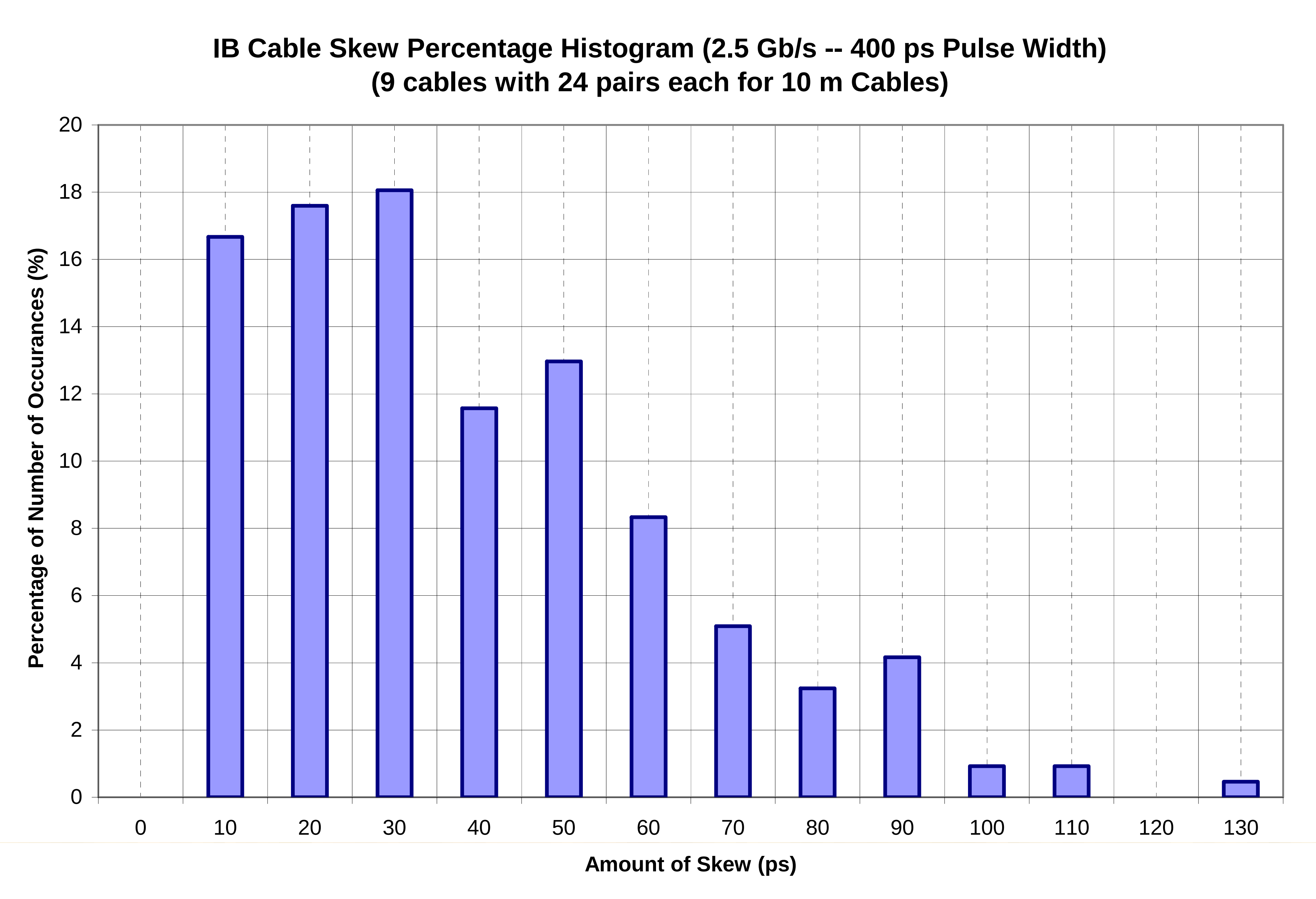
- Differential signal enters connector
  - Mode conversion creates common mode noise
  - Common mode cross talk to adjacent pair
  - Mode conversion on victim pair creates differential noise!
    - Not considered in most simulations!

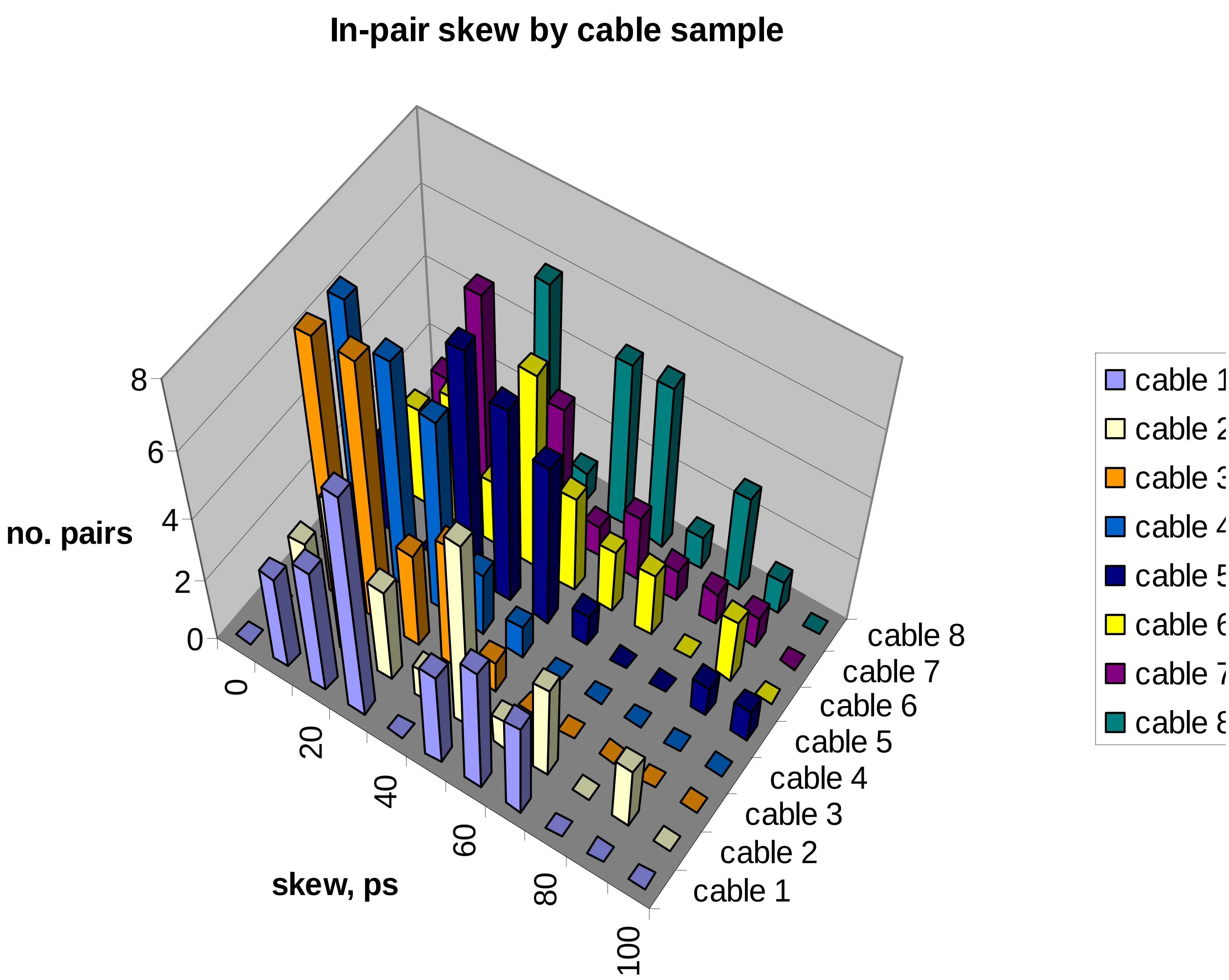
Differential Cable Measurements

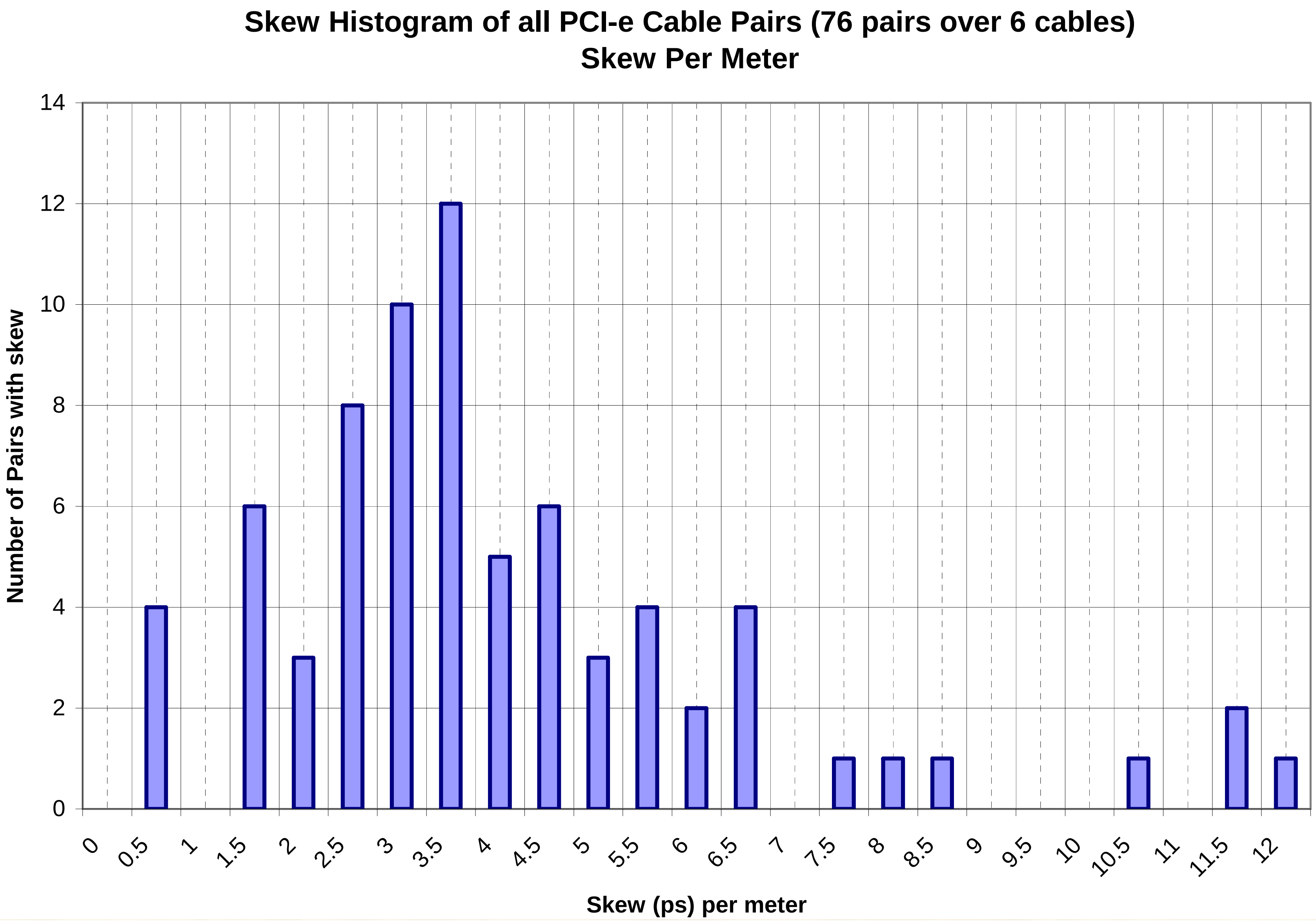
- Measured skew data from cables
  - Infiniband, SAS, PCIe, Cat 7 Ethernet
- Time domain measurements with pulse generator source
- S-parameter frequency domain measurements

Cable Skew Measurements

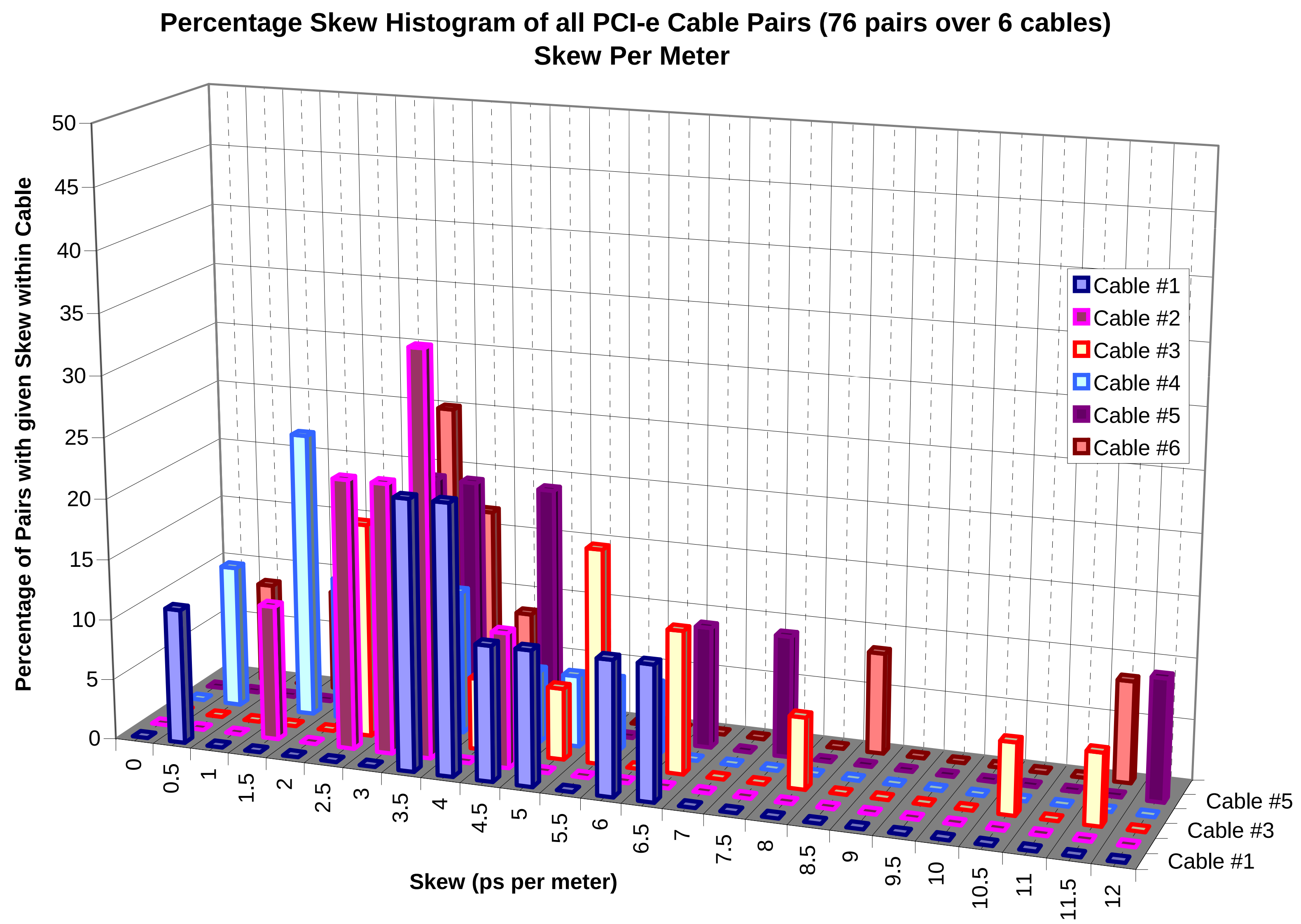
- Infiniband, SAS, PCIe, Cat 7 cables
- Multiple pairs within multiple cables
- Look for amount of skew and consistency


IB Cable Skew Percentage Histogram (2.5 Gb/s -- 400 ps Pulse Width)
(9 cables with 24 pairs each for 10 m Cables)
Percentage of Number of Occurances (%)
0
2
4
6
8
10
12
14
16
18
20
0
10
20
30
40
50
60
70
80
90
100
110
120
130
Amount of Skew (ps)

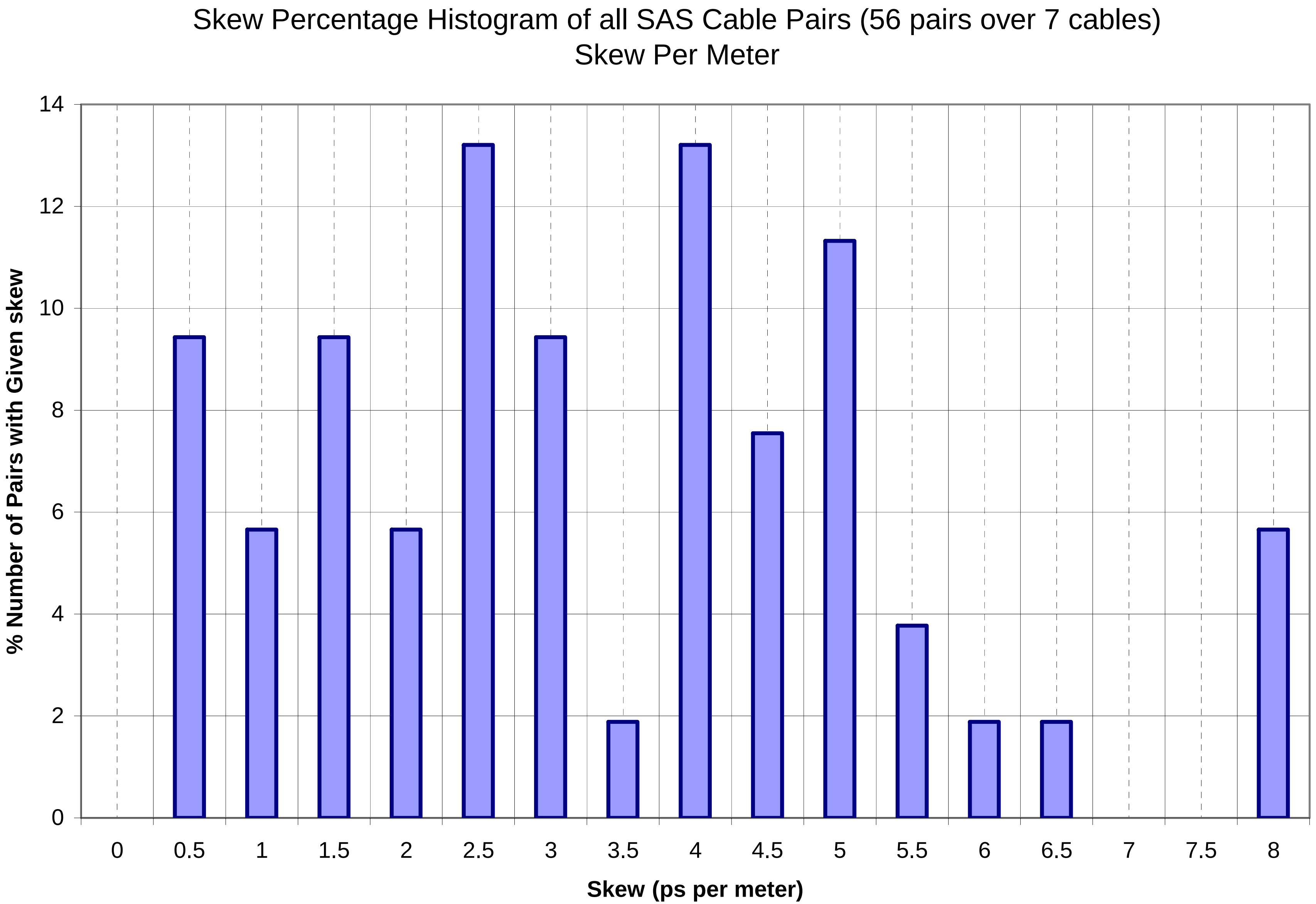

In-pair skew by cable sample
no. pairs
8
6
4
2
0
skew, ps
0
20
40
60
80
100
cable 8
cable 7
cable 6
cable 5
cable 4
cable 3
cable 2
cable 1

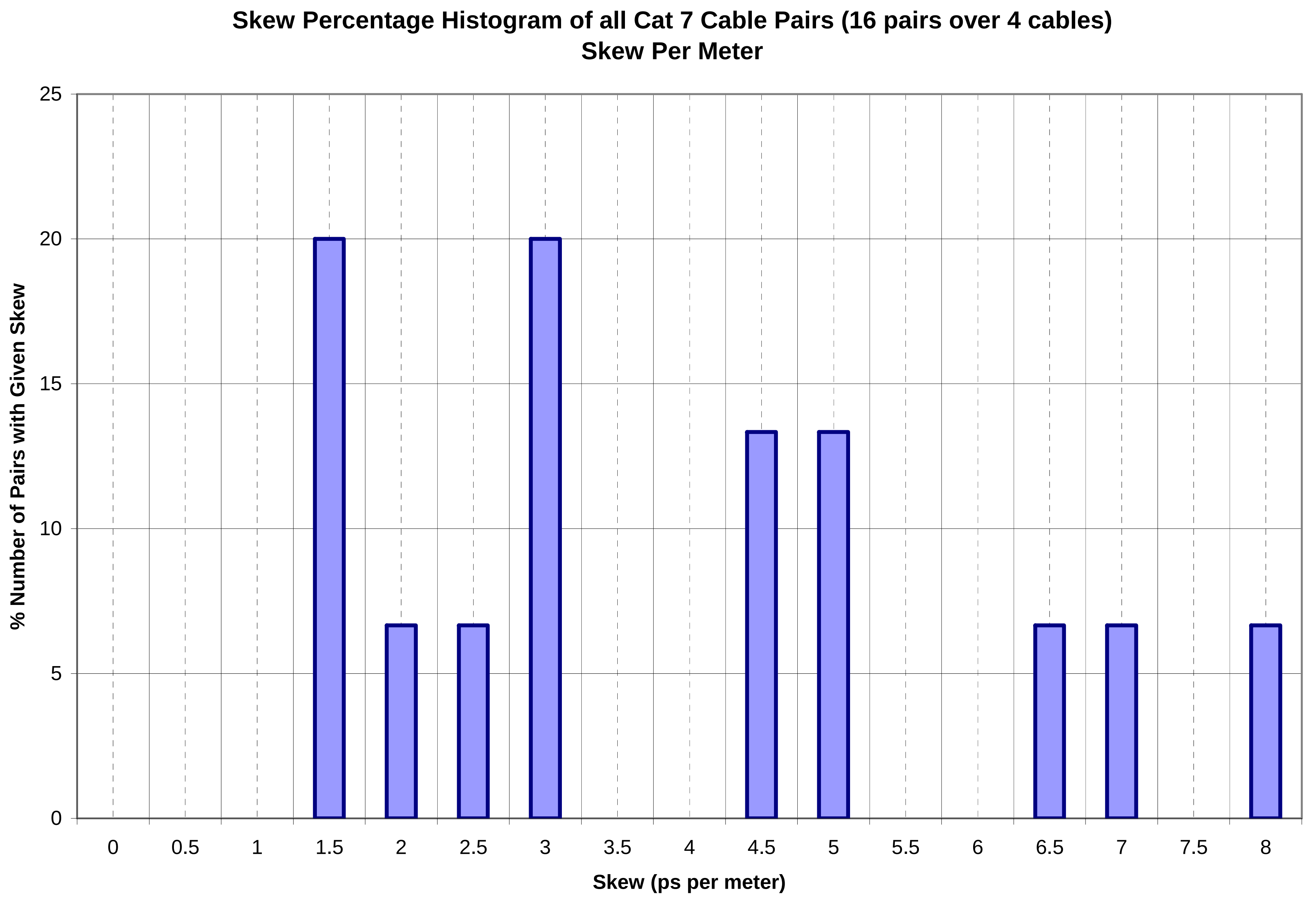


Skew Histogram of all PCI-e Cable Pairs (76 pairs over 6 cables)
Skew Per Meter
Number of Pairs with skew
0
2
4
6
8
10
12
14
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
7.5
8
8.5
9
9.5
10
10.5
11
11.5
12
Skew (ps) per meter



Percentage Skew Histogram of all PCI-e Cable Pairs (76 pairs over 6 cables)
Skew Per Meter
Percentage of Pairs with given Skew within Cable
50
45
40
35
30
25
20
15
10
5
0
Cable #1
Cable #2
Cable #3
Cable #4
Cable #5
Cable #6
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
7.5
8
8.5
9
9.5
10
10.5
11
11.5
12
Skew (ps per meter)
Cable #5
Cable #3
Cable #1


Skew Percentage Histogram of all SAS Cable Pairs (56 pairs over 7 cables)
Skew Per Meter
% Number of Pairs with Given skew
0
2
4
6
8
10
12
14
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
7.5
8
Skew (ps per meter)



Skew Percentage Histogram of all Cat 7 Cable Pairs (16 pairs over 4 cables)
Skew Per Meter
% Number of Pairs with Given Skew
0
5
10
15
20
25
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
7.5
8
Skew (ps per meter)

So-Called Differential Cables

- Actually ***add*** to common mode signals with uncontrolled in-pair skew!
- Requires additional cable shielding
  - Bulk cable shield
  - Backshell connection to chassis
- Mode conversion limits and shielding effectiveness limits must be considered *together*

Pseudo-Differential Net Summary

- Small amounts of skew can cause significant common mode current
- Small amount of rise/fall time deviation can cause significant amount of common mode current
- Discontinuities (vias, crossing split planes, etc) and convert significant amount of differential current into common mode current

Summary

- TEM based SI tools are limited
- A little extra SI analysis for CM issues can have great impact on EMC and help SI immunity
- Differential signals ***WILL*** have common mode noise
  - Care is needed to minimize common mode noise
- Common mode noise causes EMC issues on external cables and between boards
- In-pair skew, rise/fall time mismatch, amplitude mismatch, and physical channel asymmetry cause common mode noise
  - GND via asymmetry
  - Trace close to edge of ground-reference plane
  - Dielectric weave effects

Using Equivalent Emission Sources to Evaluate Component System Interactions

Escola Politécnica da Universidade de São Paulo

Comissão Nacional de Energia Nuclear
Instituto de Pesquisas Energéticas e Nucleares

Carlos A. F. Sartori (sartori@pea.usp.br; sartori@ipen.br)

Introduction

- EMC Design (Conceptual Studies & Other Project Phases)

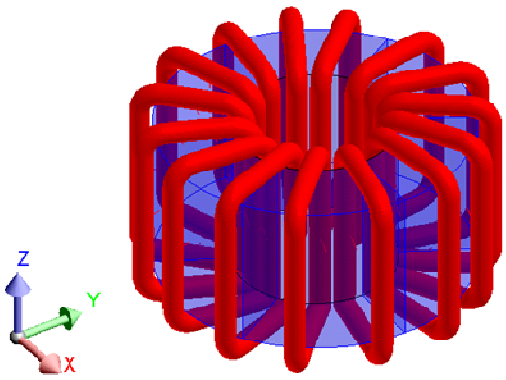
  EM Environment & System Interactions (EMI Prediction)
  Trial and Error Approach (Analytical & Experimental)
  Reliable Methods and Software Availabilities
  Powerful Software & Constraints

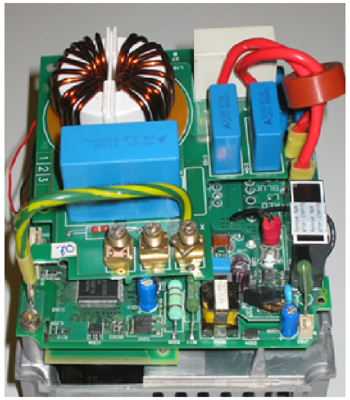
- Prediction of Electromagnetic Interference (Constraints)

  Complex Systems & Accuracies (Cables, Accessories, Equipments configurations…)
  Geometrical Configurations (Positioning, Routings, Scalar Factor, etc.)
  Electrical Parameters (Different Media, Frequency range, etc.)

  Memory & Time consuming
  High Development Costs & Reliability, etc.
  Malfunctions …

Introduction
Systems Representations & EMI Prediction





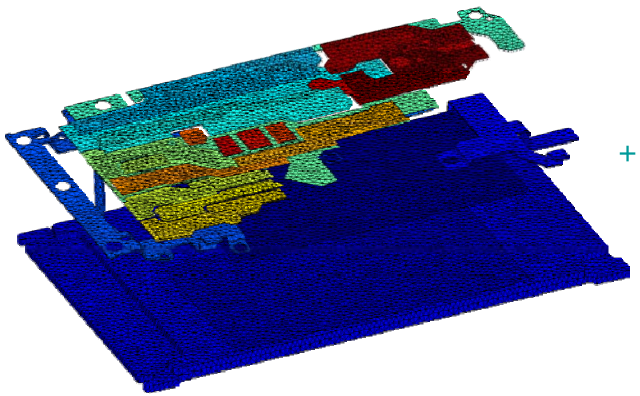
Inductor and the associated Variable Speed Drive
JMO (B. Vincent et al.)

Introduction

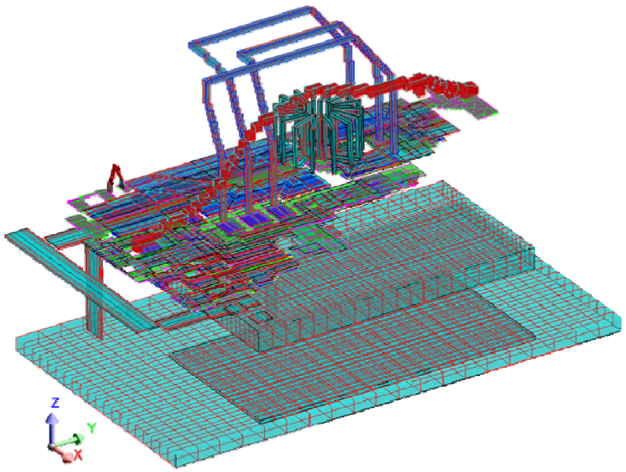
Systems Representations & EMI Prediction

30cm

=



+



Method of Moments

PEEC (InCa3D®)

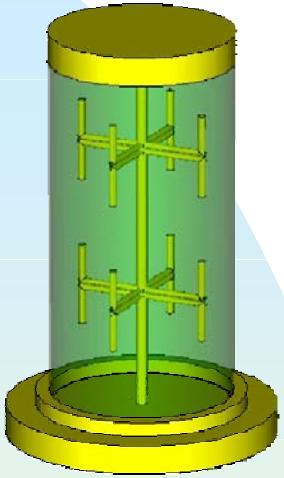
Protection Relay Model - Illustration of Arrange Complexity (V. Ardon et al.)

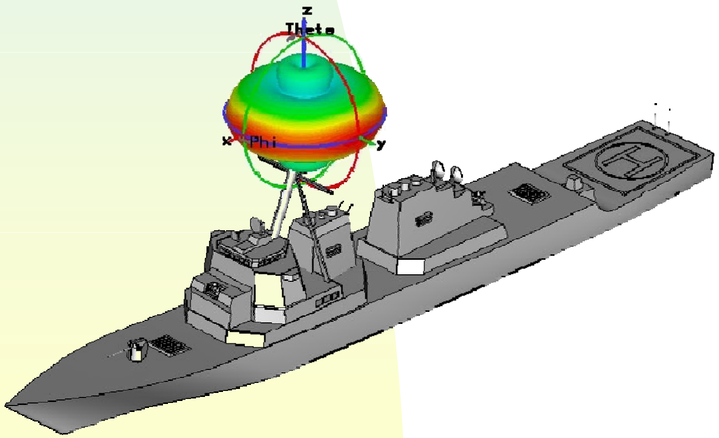
Introduction

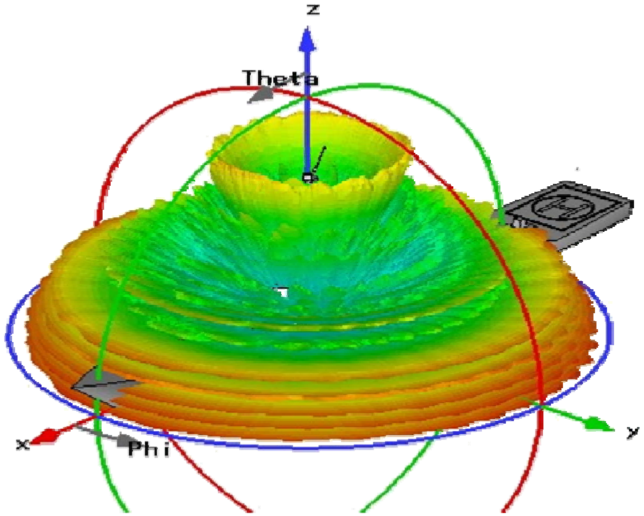
Systems Representations & EMI Prediction

Results: Complex Far Field Behavior & Vessel Structure
Naval Antenna 1.1 GHz

Illustration: Antenna & Destroyer Dimensions







Software (CST)

Introduction
Systems Representations & EMI Prediction

- Aims & Objectives

EM Environmental & Coupling Evaluation (EMI Prediction)

Robust & **Accurate** Approach
Light Tool & **Fast** EMC Design

Hybrid Approach (Numerical & Experimental) & *Proposed Method Base: Emission Source Modeling* (*Conducted & Radiation Sources*)
Software Environmental Integration
Numerical Method Integration

Outline

- Introduction
- Methodology (Proposed Method)
  - General Aspects
  - The Theoretical & Experimental Approach
  - Experimental Setup (Sensor Configuration)
- Applications & Results
- Conclusions

Methodology Description – General Aspects

- **Identification & Characterization of Radiated Emission Sources** (Black Box): (Systems, Components, Equipment) - Numerical & **Experimental** (Available Data)
- **Equivalent Source Model** Determination: Analytical & Numerical Approach
- **Integration in EMF Software**
- Evaluation of the EM Environment (**EMF Calculation** & Site Characteristics) Cavities, components, equipment & system layout; etc.
- **Coupling Evaluation** (Cables, equipments, components, etc.)

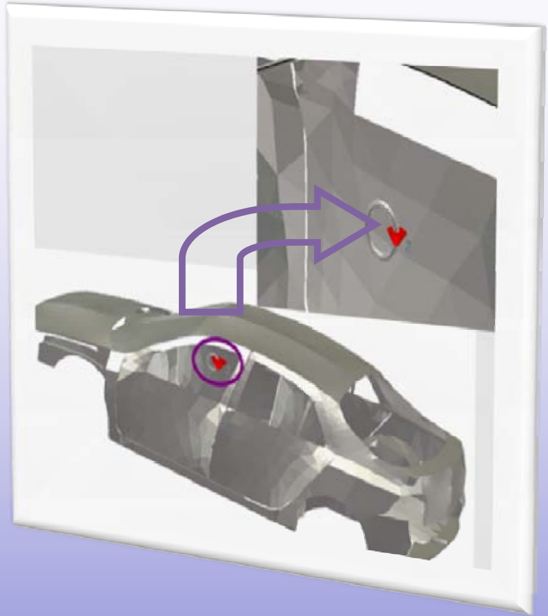
Fist Approach: FEM & Loop Antennas (9kHZ - 30MHz)

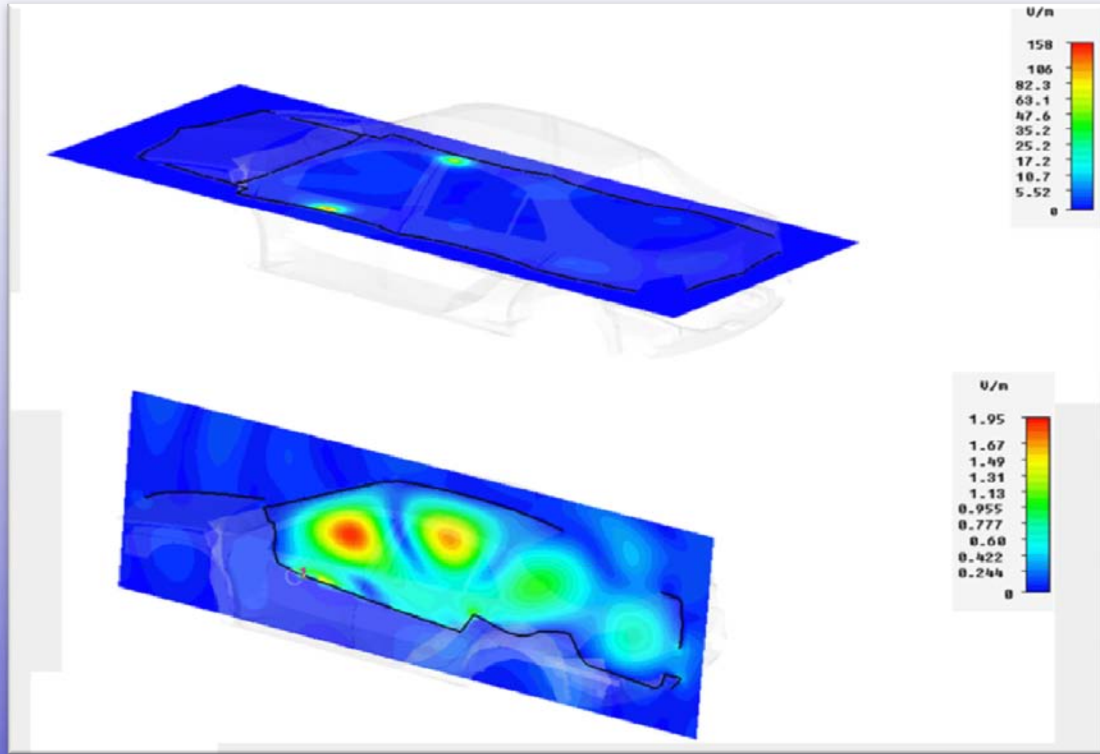
van Veen & Bergervöet 1986 (1997)

Current Approach: Magnetic Field

Illustrations of the Equivalent Source Methodology
On-Board Systems

Equivalent Source Methodology Illustration

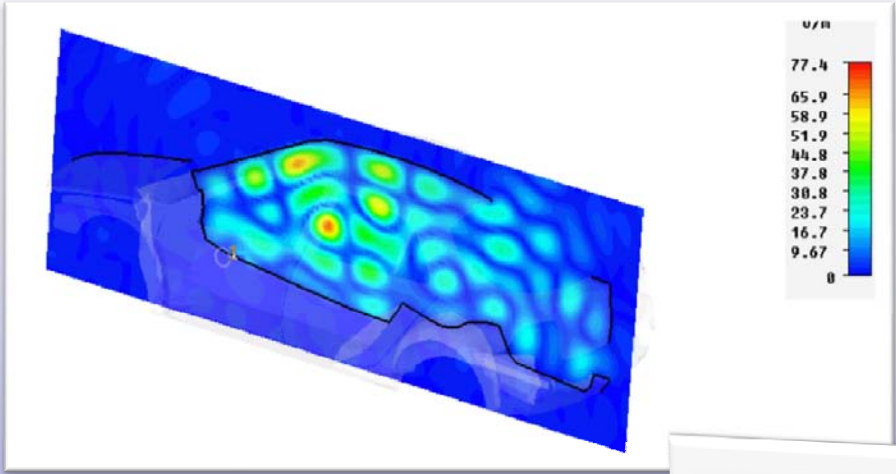


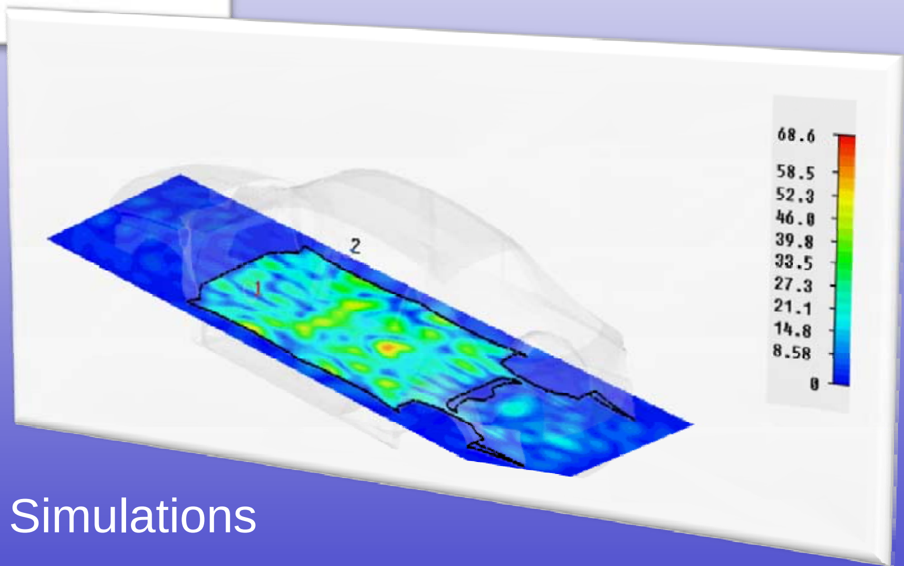


Equivalent Sources Applied in Simulations

Electric Field Distribution (5 MHz)

Equivalent Source Methodology Illustration



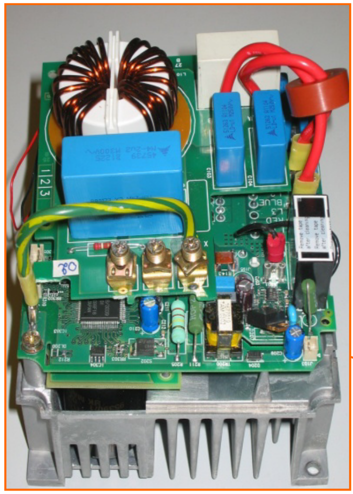


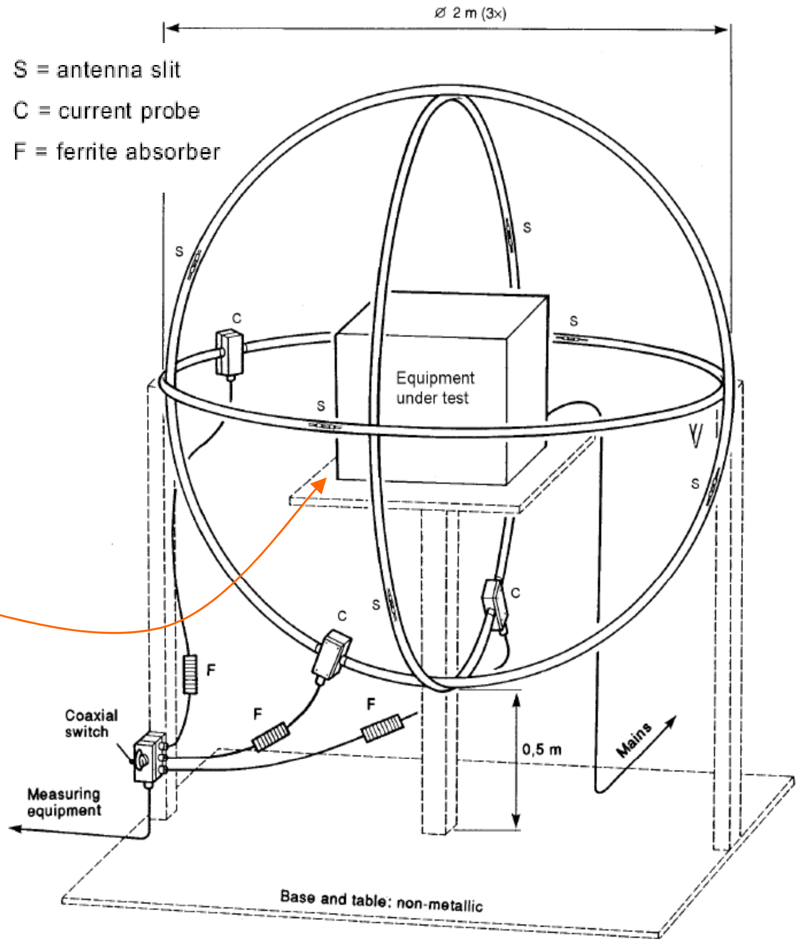
Equivalent Sources Applied in Simulations

Electric Field Distribution (800 MHz)

Methodology

General Aspects – First Step
Previous Research

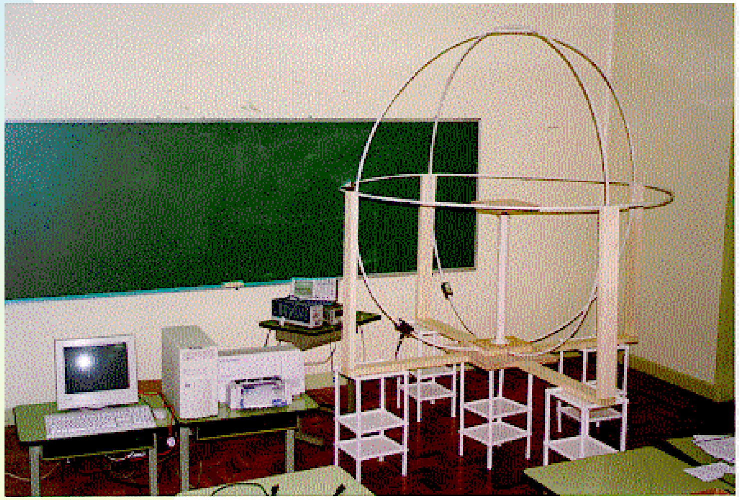


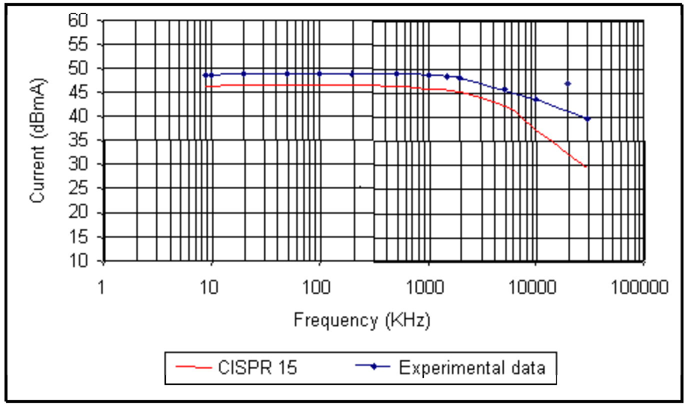


Methodology

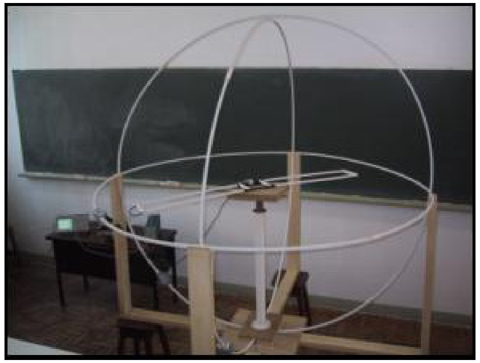
General Aspects
Previous Research van Veen & Bergervöet Antenna
(Undergraduate Student Programming Project)

Antenna Setup & Calibration





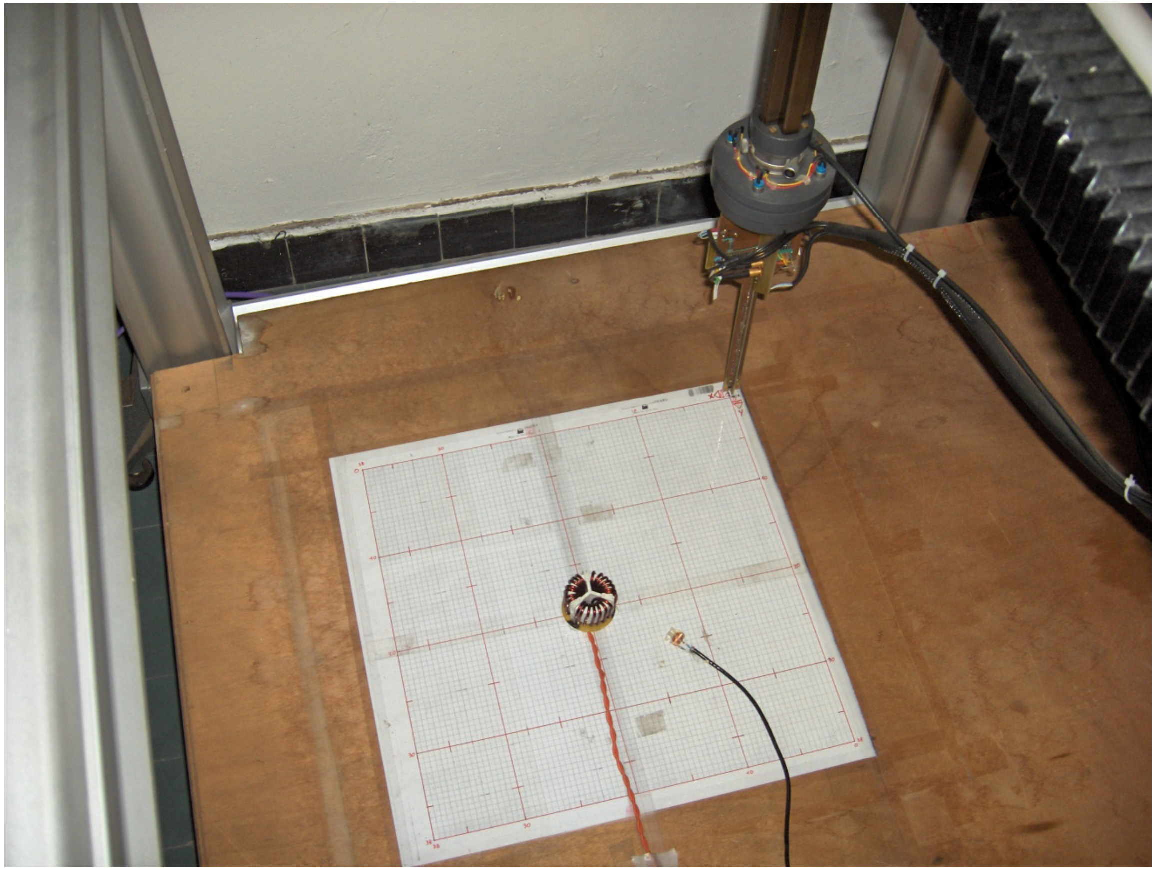
The antenna calibration curve



Frequency Range
Low signal Intensity
Inaccuracies (Dipole + *Octupole*)

Methodology

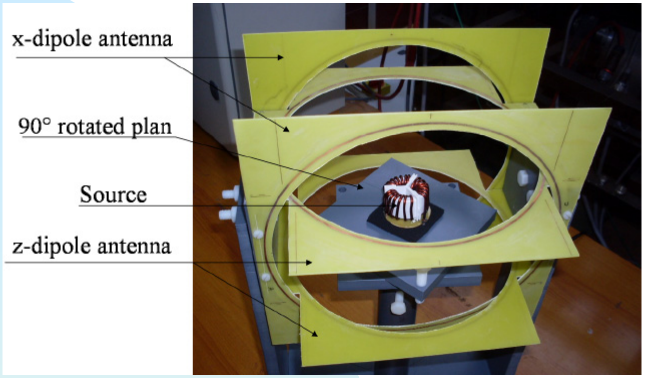
General Aspects
Previous Research: Scanning Method

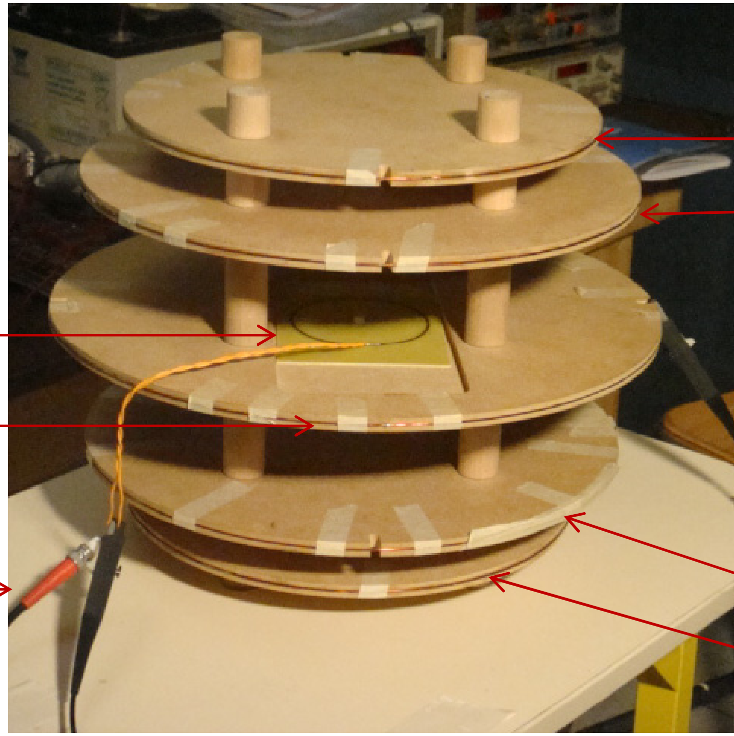


Laboratoire Ampère - ECL

Methodology

General Aspects
Current Research: “Spatial Filter” Method





Prototype Antennas

Equivalent Source Model & Coupling

MULTIPOLE EXPANSION METHOD

Near Field & Quasi-static Approximation
Magnetic Field Source Coefficients

Numerical or Experimental Approach

Numerical (Simple Sources)
Experimental (Complex Geometrical Sources)
Loop Antennas rather than Scanning Methods
Accuracies & Direct Method vs Inverse Problem

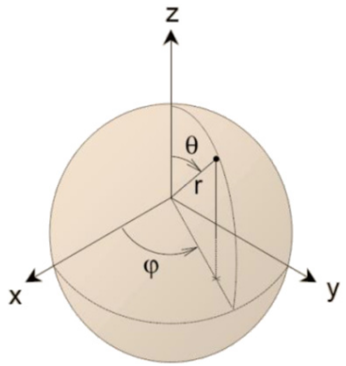
Source Coupling

Magnetic Field Source Coefficients

Theoretical Aspects

Multipole Expansion

- Theory of Multipole Expansion
  - 3D Outgoing Electromagnetic Field
  - Outside Sphere of Validation
  - Equivalent Source (inside)



$$E(r,\theta,\varphi) = \sum_{n=1}^{\infty} \sum_{m=-n}^{n} Q_{nm}^{TE} \mathbf{F}_{1nm}(r,\theta,\varphi) + Q_{nm}^{TM} \mathbf{F}_{2nm}(r,\theta,\varphi)$$

$$H(r,\theta,\varphi) = \frac{j}{\eta} \sum_{n=1}^{\infty} \sum_{m=-n}^{n} Q_{nm}^{TM} \mathbf{F}_{1nm}(r,\theta,\varphi) + Q_{nm}^{TE} \mathbf{F}_{2nm}(r,\theta,\varphi)$$

Theoretical Aspects

Multipole Expansion

$$E(r,\theta,\varphi) = \sum_{n=1}^{\infty} \sum_{m=-n}^{n} Q_{nm}^{TE} \mathbf{F}_{1nm}(r,\theta,\varphi) + Q_{nm}^{TM} \mathbf{F}_{2nm}(r,\theta,\varphi)$$

$$H(r,\theta,\varphi) = \frac{j}{\eta} \sum_{n=1}^{\infty} \sum_{m=-n}^{n} Q_{nm}^{TM} \mathbf{F}_{1nm}(r,\theta,\varphi) + Q_{nm}^{TE} \mathbf{F}_{2nm}(r,\theta,\varphi)$$

$\eta = \sqrt{(\mu/\varepsilon)}$: Intrinsic Impedance

Q_{nm} : Magnetic and Electric coefficients

F_{1nm} and F_{2nm} are the vector spherical harmonics

n is the degree and m is the azimuthal order

Theoretical Aspects

Multipole Expansion

- Near Field & Magnetic Field ($E \sim 0$ & $Q^{TM} = 0$)
  - *Radial Component H_r*
  - Y_{nm} are the Normalized Spherical Harmonics

$$H_r = -\frac{1}{4\pi}\sum_{n=1}^{+\infty}\sum_{m=-n}^{n} Q_{nm}\frac{\partial}{\partial r}\left(\frac{1}{r^{n+1}}\right)Y_{nm}(\theta,\varphi)$$

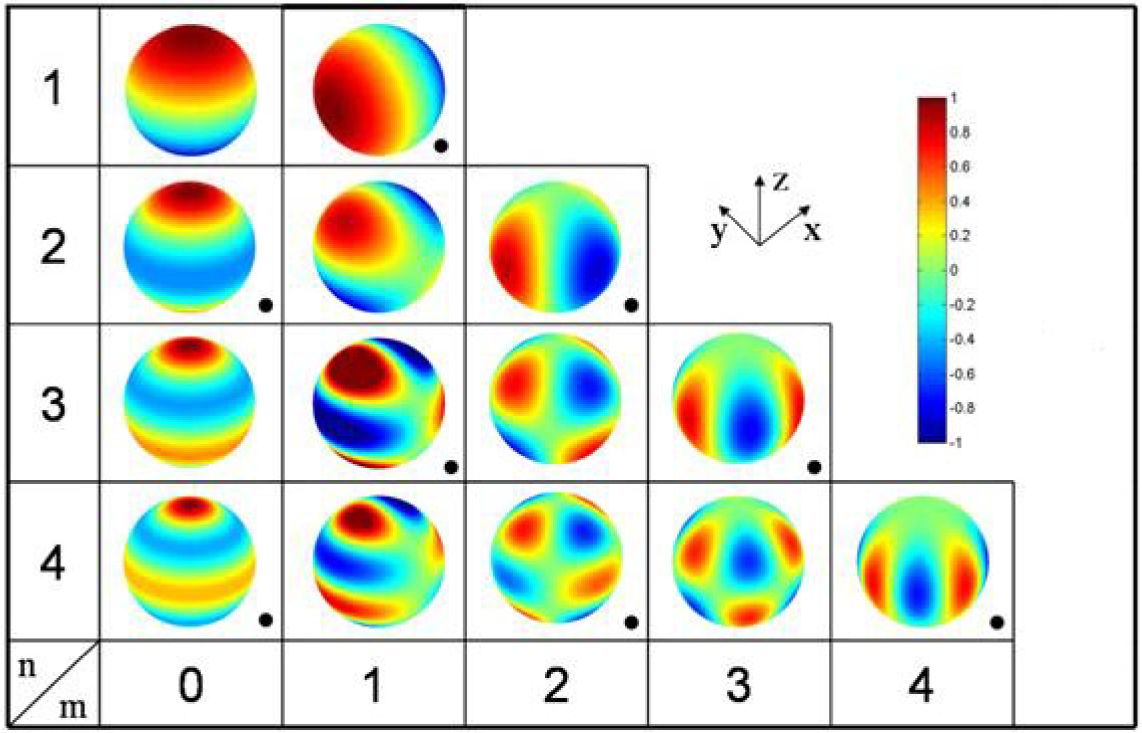
$$Y_{nm}(\theta,\varphi) = \sqrt{\frac{(2n+1)(n-m)!}{4\pi(n+m)!}}P_n^m(\cos\theta)e^{jm\varphi}$$

Remarks:
i) ($2n+1$) terms for each order n
ii) Order source (N_{max}) $\rightarrow$ $N_{max}(N_{max}+2)$ components
iii) ***Order n Terms decrise with $r^{-(n+1)}$***

Theoretical Aspects

Multipole Expansion & Spherical Harmonics

Spherical Harmonics (*n*<4, *m*>0)



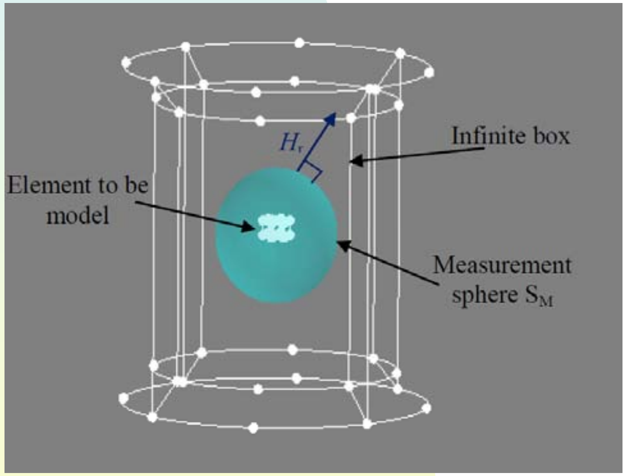
Theoretical Aspects

Multipole Identification

Numerical Approach & Multipole Identification

Calculation of the Radial Component H_r
Measured Sphere S_M (Radius r_0, with the Source)

Q $_{nm}$ Integrating on S_M & Orthogonal Property of Y_{nm}



Source Modeling Flux 2D®

$$Q_{nm} = 4\pi \frac{r_0^n}{(n+1)} \int_0^{2\pi} \int_0^{\pi} H_r(r_0, \theta, \varphi) Y_{nm}(\theta, \varphi) dS.$$

$$\iint_{S_M} Y_{nm} Y_{n'm'} dS = \begin{cases} r_0^2, & \text{if } (n,m) = (n',m') \\ 0, & \text{otherwise.} \end{cases}$$

n = N $_{max}$ → $2N_{max}$ points per axis

Equivalent Magnetic Source Concept

Experimental Approach

Real source: Complex

Sensor $S_{1,1}$

Sensor S_{10}

Sensor $S_{1,-1}$

n=1 : dipolar behavior

n=2 : quadripolar behavior

n≥3 : higher orders behavior

$$\vec{B} = \frac{1}{r^3}\left(s_{1,-1}\vec{B}_{1,-1} + s_{1,0}\vec{B}_{1,0} + s_{1,1}\vec{B}_{1,1}\right)$$

$$+\frac{1}{r^4}\left(s_{2,-2}\vec{B}_{2,-2} + s_{2,-1}\vec{B}_{2,-1} + s_{2,0}\vec{B}_{2,0} + s_{2,1}\vec{B}_{2,1} + s_{2,2}\vec{B}_{2,2}\right)$$

$$+\frac{1}{r^5}\left(s_{3,-3}\vec{B}_{3,-3} + s_{3,-2}\vec{B}_{3,-2} + s_{3,-1}\vec{B}_{3,-1} + s_{3,0}\vec{B}_{3,0} + s_{3,1}\vec{B}_{3,1} + s_{3,2}\vec{B}_{3,2} + s_{3,3}\vec{B}_{3,3}\right)$$

$$+\frac{1}{r^6}(\ldots) + \frac{1}{r^7}(\ldots) + \ldots$$

Equivalent Magnetic Source Concept

Experimental Approach

Real source: C

Sensor $S_{2,2}$

Sensor $S_{2,1}$

Sensor S_{20}

Sensor $S_{2,-1}$

Sensor $S_{2,-2}$

n=1 : dipolar behavior

n=2 : quadripolar behavior

n≥3 : higher orders behavior

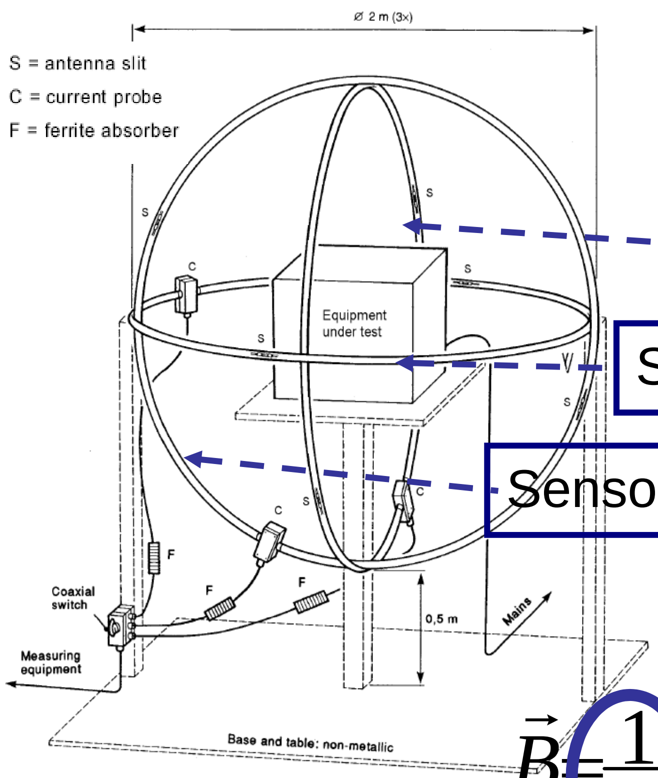
$$\vec{B} = \frac{1}{r^3}\left(s_{1,-1}\vec{B}_{1,-1} + s_{1,0}\vec{B}_{1,0} + s_{1,1}\vec{B}_{1,1}\right)$$

$$+\frac{1}{r^4}\left(s_{2,-2}\vec{B}_{2,-2} + s_{2,-1}\vec{B}_{2,-1} + s_{2,0}\vec{B}_{2,0} + s_{2,1}\vec{B}_{2,1} + s_{2,2}\vec{B}_{2,2}\right)$$

$$+\frac{1}{r^5}\left(s_{3,-3}\vec{B}_{3,-3} + s_{3,-2}\vec{B}_{3,-2} + s_{3,-1}\vec{B}_{3,-1} + s_{3,0}\vec{B}_{3,0} + s_{3,1}\vec{B}_{3,1} + s_{3,2}\vec{B}_{3,2} + s_{3,3}\vec{B}_{3,3}\right)$$

$$+\frac{1}{r^6}(\ldots) + \frac{1}{r^7}(\ldots) + \ldots$$

The Standard Antenna



Sensor $S_{1,1}$ → $s_{1,1} + \varepsilon_{1,1}(n\geq 3)$

Sensor S_{10} → $s_{1,0} + \varepsilon_{1,0}(n\geq 3)$

Sensor $S_{1,-1}$ → $s_{1,-1} + \varepsilon_{1,-1}(n\geq 3)$

$$\vec{B} = \frac{1}{r^3}\left(s_{1,-1}\vec{B}_{1,-1} + s_{1,0}\vec{B}_{1,0} + s_{1,1}\vec{B}_{1,1}\right)$$

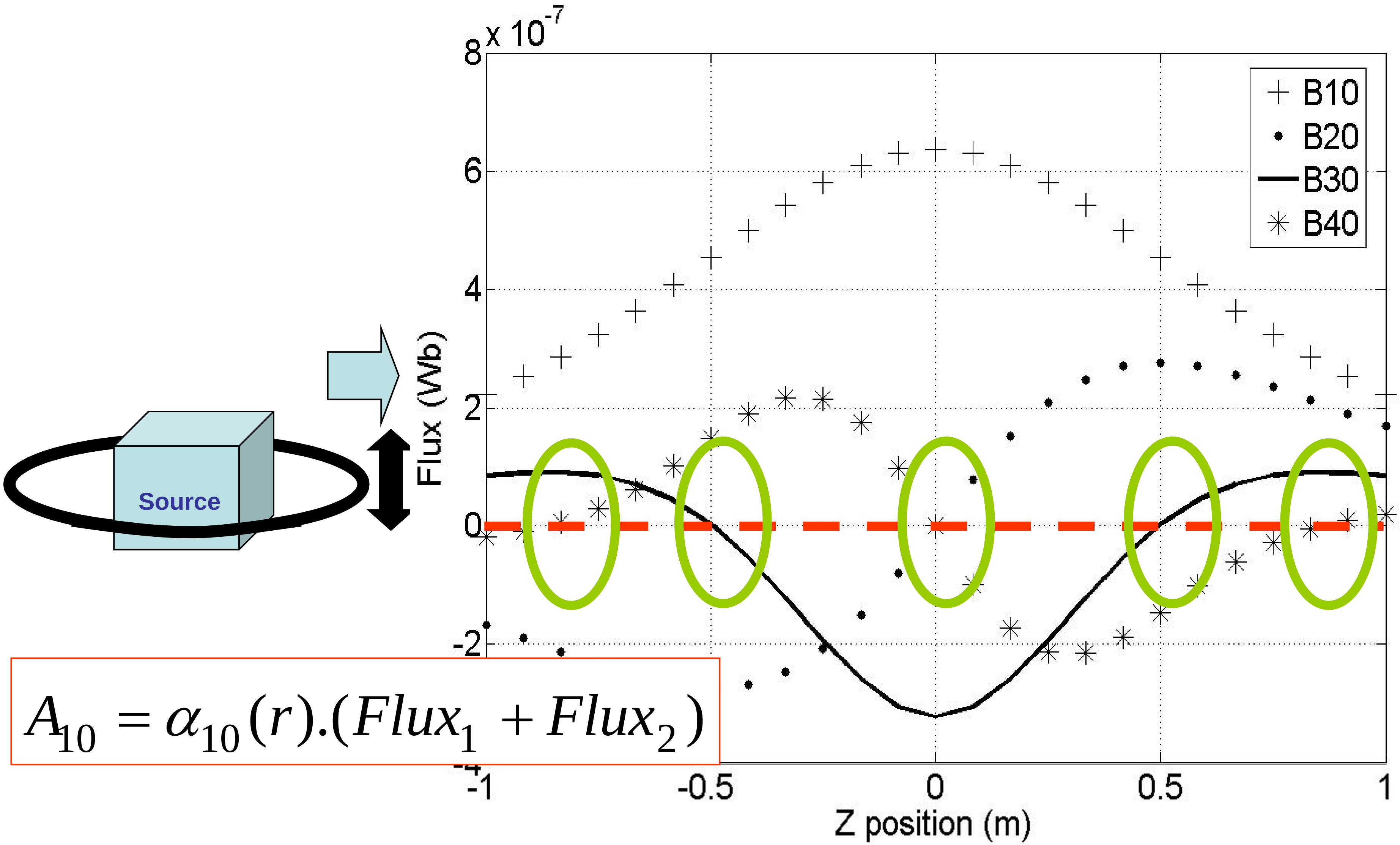
$$+\frac{1}{r^4}\left(s_{2,-2}\vec{B}_{2,-2} + s_{2,-1}\vec{B}_{2,-1} + s_{2,0}\vec{B}_{2,0} + s_{2,1}\vec{B}_{2,1} + s_{2,2}\vec{B}_{2,2}\right)$$

$$+\frac{1}{r^5}\left(s_{3,-3}\vec{B}_{3,-3} + s_{3,-2}\vec{B}_{3,-2} + s_{3,-1}\vec{B}_{3,-1} + s_{3,0}\vec{B}_{3,0} + s_{3,1}\vec{B}_{3,1} + s_{3,2}\vec{B}_{3,2} + s_{3,3}\vec{B}_{3,3}\right)$$

$$+\frac{1}{r^6}(\ldots) + \frac{1}{r^7}(\ldots) + \ldots$$

Sensor Evaluation

Z Axis



$$A_{10} = \alpha_{10}(r).(Flux_1 + Flux_2)$$

Experimental Approach

Experimental Approach & Multipole Identification

Spatial Filter Antenna (Q_{10} & Q_{20}) ~ 100 MHz
Second Order & z-direction (m=0)

$$Q_{10} = \frac{10^8 r_M}{32\pi}(\varphi_{10_1} + \varphi_{10_2}),$$

$$Q_{20} = \frac{6125 * 10^4 r_M^2}{3\pi\sqrt{21}}(\varphi_{20_1} - \varphi_{20_2});$$

$$\varphi_{10\_i} = \mathrm{AF}_{10} i_{10\_i};$$

$$\varphi_{20\_i} = \mathrm{AF}_{20} i_{20\_i}.$$

Measured Current (Loop n) I_{MES} & Multiple Source Current I_{DUT}

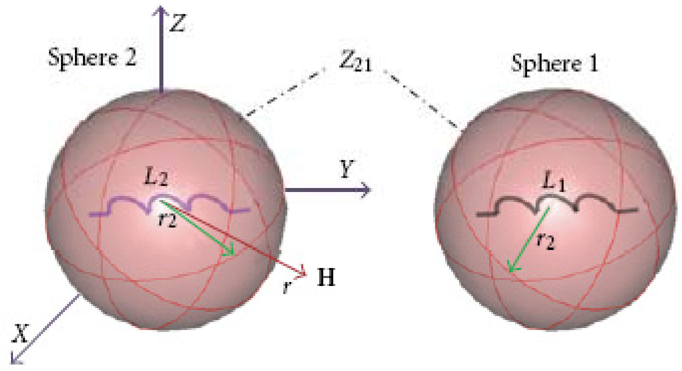
Decoupling Process

$$i_{\mathrm{MES}}^{(n)} = i_{\mathrm{DUT}}^{(n)} - \sum_{\substack{k=1 \\ k \neq n}}^{5} \frac{j\omega M_{kn} i_{\mathrm{MES}}^{(k)}}{r_n + j\omega L_n};$$

Theoretical Approach

Equivalent Source Coupling

Mutual Impedance & Mutual Inductance Computation
No intersection of Validation Spheres & Multipole Coefficients
Same Reference System



$$Z_{12} = \frac{1}{i_1 i_2} \frac{1}{k^2} \sqrt{\frac{\varepsilon_0}{\mu_0}} \sum_{n=1}^{N_{\max}} \sum_{m=-n}^{n} (-1)^m (Q_{1n,-m} * Q_{2n,m})$$

$$M_{12} = \frac{1}{j\omega i_1 i_2} \frac{1}{k^2} \sqrt{\frac{\varepsilon_0}{\mu_0}} \sum_{n=1}^{N_{\max}} \sum_{m=-n}^{n} (-1)^m (Q_{1n,-m} * Q_{2n,m})$$

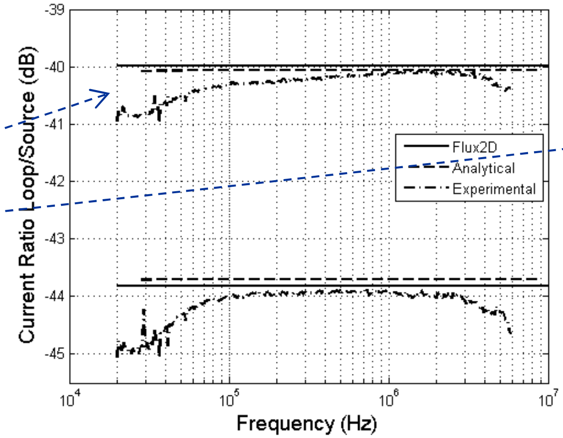
Outline

- Introduction
- Methodology (Proposed Method)
  - General Description
  - The Theoretical & Experimental Approach
  - Experimental Setup (Sensor Configuration)
- Applications & Results
- Summary

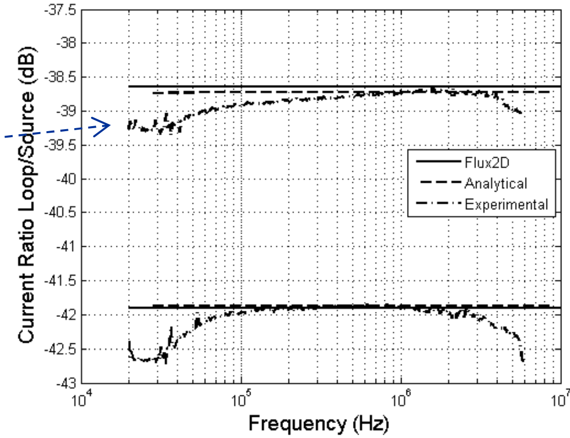
Application and Results

Mutipole Identification & Source Coupling Results (20KHz-10MHz)

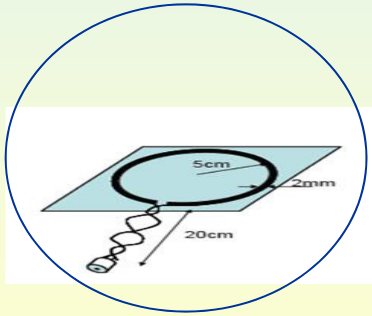
Decoupled Current
Δ= -4dB (37%)

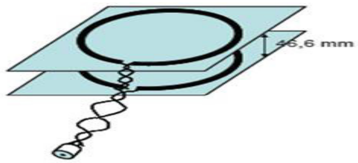


Dipole dB current ratio, sensor $Q_{10\text{-}1}$



Dipole dB current ratio, sensor $Q_{20\text{-}1}$





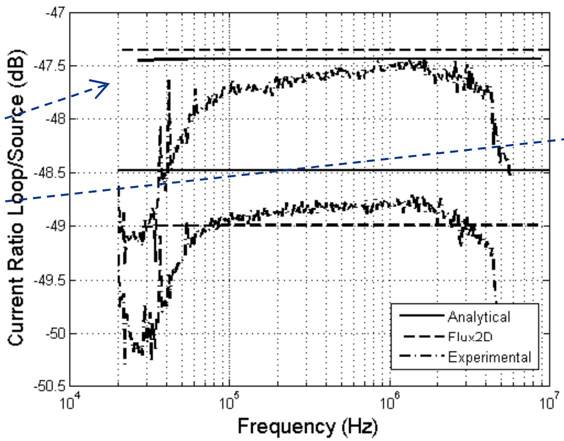
Dipolo and Quadrupole (Validation Sources)

$$\text{Dipole: } Q_{10} = \pi r^2 i;\; Q_{20} = 0,$$
$$\text{Quadrupole: } Q_{10} = 0;\; Q_{20} = \pi r^2 h_0 i.$$

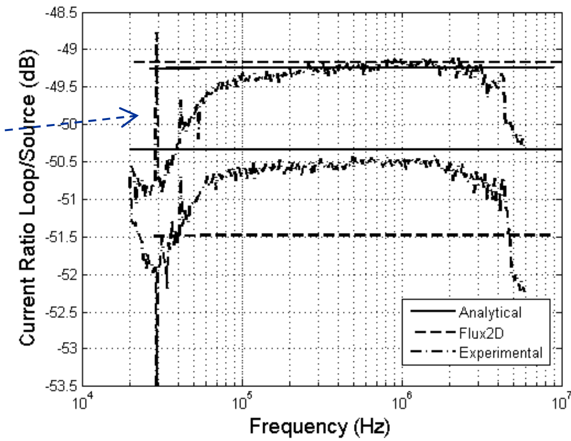
Application and Results

Mutipole Identification & Source Coupling Results (20KHz-10MHz)

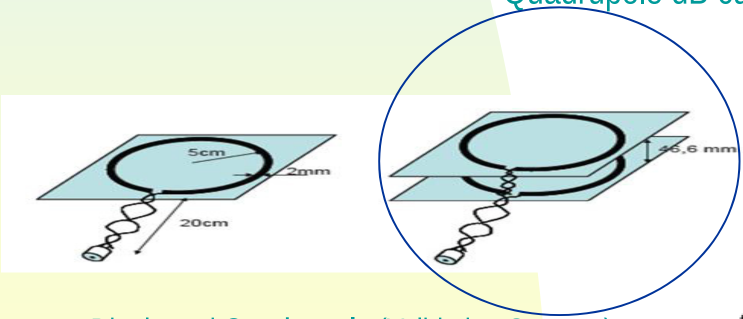
Decoupled Current
Δ= -3.5dB (33%)



Quadrupole dB current ratio, sensor Q_{10-1}



Quadrupole dB current ratio, sensor Q_{20-1}



Dipolo and Quadrupole (Validation Sources)

$$\text{Dipole: } Q_{10} = \pi r^2 i;\ \ Q_{20} = 0,$$

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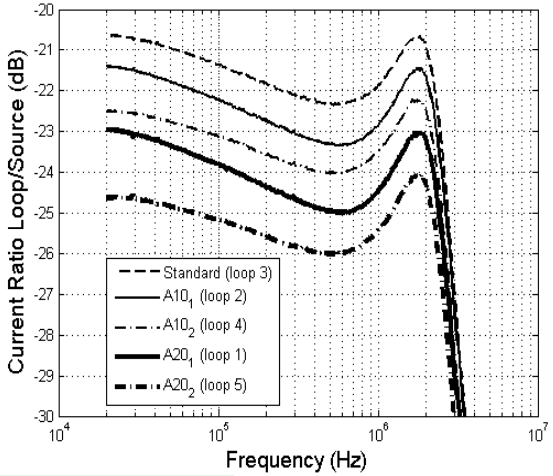
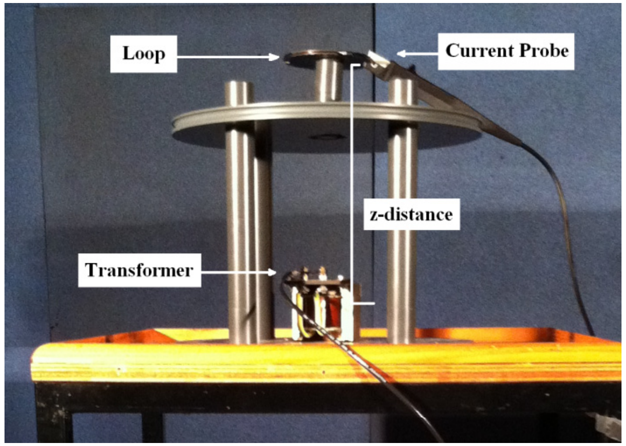
Application and Results

Mutipole Identification & Source Coupling Results (20KHz-10MHz)



Transformer dB current ratio for all sensors



Mutual Impedance measurement Setup
220V/20A Transformer & Loop

TABLE I: Components of the multipole Expansion (200kHz)

Component	Q_{10} (m·Am^2)	Q_{20} (m·Am^3)	Error (%)
Dipole	7.3	0	7.6 (Q_{10})
Quadrupole	0	0.63	20 (Q_{20})
Transformer	66.5	0.82	-

TABLE II: Comparison between mutual inductances

Height (cm)	Measured (nH)	Estimated (nH)	Error (%)
29.3	3.65	3.17	13
35.8	1.98	1.92	3

Summary

Proposed Method

Equivalent emission sources

Enables the Evaluation of Coupling Components etc.

Method Steps

First: *Equivalent Sources Identification*

Spherical Multipole Expansion & Numerical or Experimental Approach

Second: *Coupling Computation* (Equivalent Source & Mutual Inductance)

Other kind of Multipole Expansions,

Tracks or cables & Cylindrical Multipolar Expansion

(Coupling between track etc.)

Characteristic: *Potentially helpful when used together with Other Software or Numerical Method*

Example: Circuit Simulators (Eq. Source vs Full Model Configuration)

Gain of Memory Space & Processing Time

ACKNOWLEDGEMENTS: Capes-Cofecub (0568/09) EPUSP & ECL; CNPq (PQ 308587 2008-1); IPEN/CNEN-SP & CTMSP

ELECTRIC POWER RESEARCH INSTITUTE

Overview and Updates on Related EMC Standards Activities

for Nuclear Power Plants

Philip F. Keebler

Sr. Research Engineer, EPRI

IEEE EMC Society: Emerging Technologies in EMC

April 27, 2012

POLI USP

Escola Politécnica - University of São Paulo

São Paulo, Brazil

Contents

- 1. Facts: Qualifying Digital I&C Equipment (DICE) for EMC
- 2. What happens before EMC qualification?
  - The Manufacturer
  - The Utility
  - The EMC Test House
- 3. EPRI's role in standards
- 4. EMC testing standards & NRC publications
- 5. IEC 62003 & including risk assessment in EMC qualification testing
- 6. ANSI C63 activities for NPPs

Facts about Qualifying I&C Equipment for EMC

Understanding the facts leads to a more thorough understanding about why qualification sometimes "breaks down" and how standards should be developed.

- Why?
  - Hopefully, we learn from our mistakes instead of repeating them.
  - Analysis of what "went wrong" helps us to determine what to change to improve the process.
  - Determining what "went wrong" can help us to identify how improving the process can reduce costs.

Facts about Qualifying I&C Equipment for EMC

- Why (cont'd)?
  - Much of what we do in qualification is very technical (i.e.)
    - How to set up a test
    - How to run a test
    - What we should observe during a test
    - How do we determine equipment failure
    - How to interpret and report the data
  - How does "break down" of the qualification process impact other parts of the modification project?
  - "Break down" of part of the EMC qualification process most always adds cost to other parts of the whole qualification process.

What happens before EMC qualification?
The Manufacturer

- Little, if any, pre-qualification done by manufacturer
  - Most manufacturers have no or limited EMC test equipment
  - Those that do have equipment have limitations in how to use it
  - Lab space/set up is usually limited (e.g., not the right ground planes, etc.)
  - Not all DICE error modes defined (i.e., this is what EMC test engineers need to know to determine “what is” an equipment failure and “what is not”

What happens before EMC qualification?
The Manufacturer

- The minimal amount of EMC qualification testing will be requested by the manufacturer
  - Because most manufacturers don't understand what EMC is and the value of proper testing, many select the minimal number of tests.
  - What are the risks?
    - Critical tests will be omitted
    - Not all failure modes will be observed
    - Test data will be incomplete
    - Higher risk of plant shutdown
  - But, the cost of EMC testing is cheaper!

What happens before EMC qualification?

The Utility

- The utility requests that EMC qualification be done following the requirements of EPRI TR-102323 (R3)
  - Utility requests one set of tests in the EPRI guidance, but manufacturer disagrees and wants to do something different
  - Which revision should really be followed?
    - R1 or R3
    - NRC reviewed and endorsed R1
    - But, R3 is the latest
  - Manufacturer gets the EMC test house involved and they make a different recommendation

What happens before EMC qualification?
The Utility

- The utility requests that EMC qualification be done following the requirements of EPRI TR-102323 (R3)
  - Deciding on test specification adds costs and delays schedule
  - Utility hires consultant to make recommendation
  - Inconsistent purchase specifications across utilities

The Midnight Run

- What's the last thing an I&C engineer wants to hear when a new piece of I&C equipment must be installed to replace one that has failed and cannot be repaired?
  - That the new equipment was not tested according to the utility (EMC) qualification specs.

A Statement from an I&C Engineer
2010

- "A few years ago [utility] revised its procedure used to evaluate digital components that are installed in its power plants. The procedure requires the design engineer to evaluate the affects of EMI on new components being installed in the plant. Our biggest concern at [NPP] is when you have to evaluate new equipment that does not meet the EPRI TR-102323 guide or a different test is performed by the manufacturer to satisfy acceptance criteria. How do you know if the equipment is still acceptable to install in the plant?"

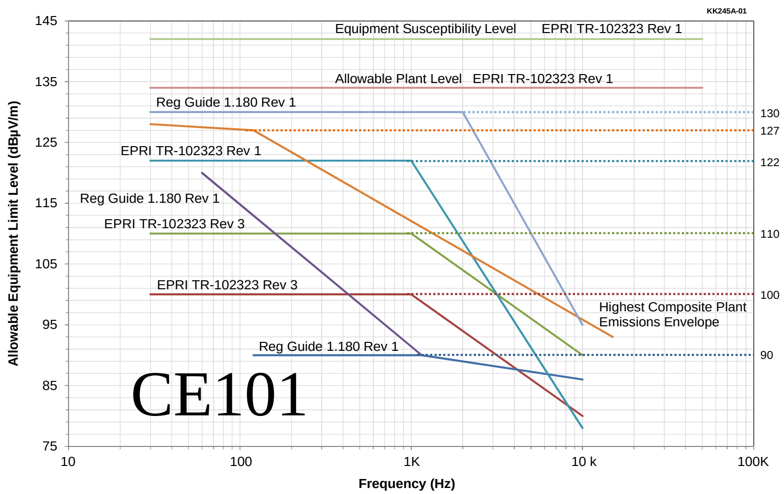
What happens before EMC qualification?
The EMC Test House

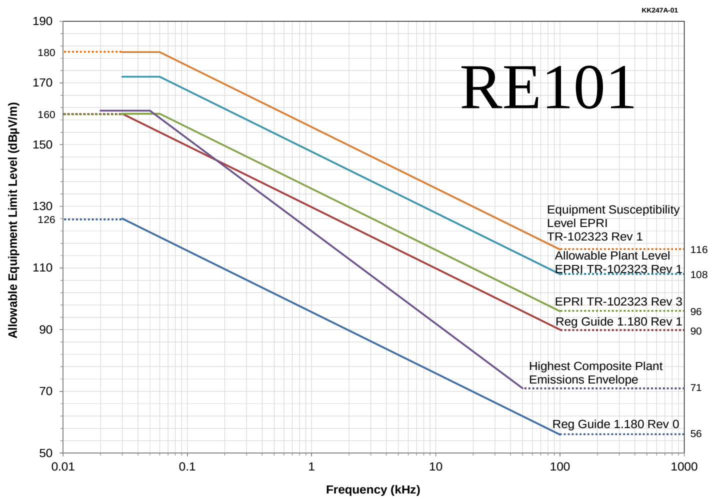
- The aim of the EMC test house is to properly address EMC performance
  - Tests are typically done with their “scope” – lab accreditation is done based on “scope”: Can labs carry out the tests in their “scope” according to the requirements defined by their accreditation body (ACLASS, A2LA, NIST)
  - EPRI research in 2010 identified no labs that included EPRI TR-102323 in their accreditation “scope”
  - One lab now includes EPRI-102323 (R3) in their “scope” per their last accreditation review

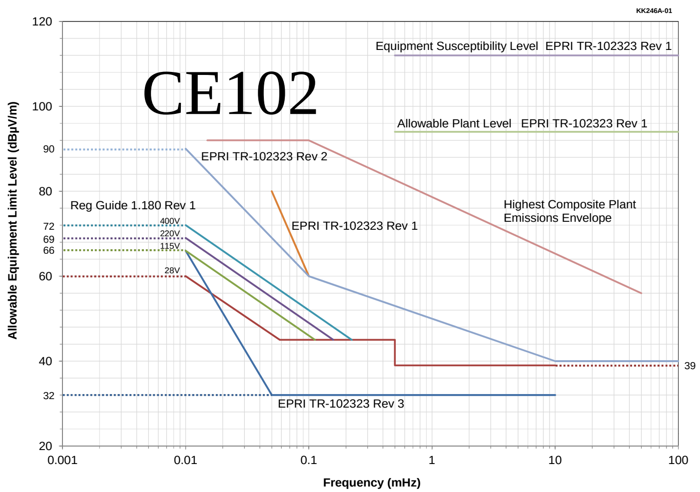
What happens before EMC qualification?
The EMC Test House

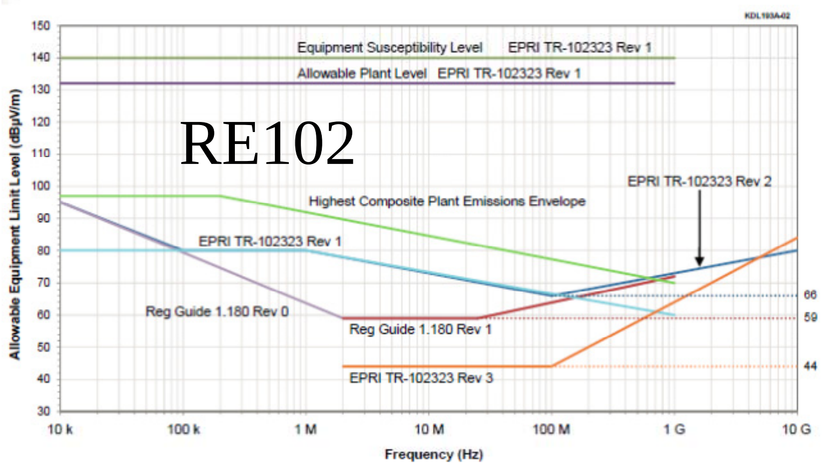
- The aim of the EMC test house is to properly determine EMC performance of the DUT
  - Test methods and procedures, and test limits are defined by industry standards
  - Test methods defined by their “scope” are commonly applied as regular business by the test house – use of MIL-STDs and IEC standards not a problem here
  - Limits defined in *Test Limit Standards* are developed based on the historical electromagnetic environment (EME) where DUT is known to “live”
  - Too much “freedom” in applying limits presents unnecessary confusion in defining test methods

How confusing can it be?









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How is the picture looking so far?

And Longer…

Manufacturer	Utility	EMC Test House
Limited test equip.	Conflicting test sets	Tests defined by stds.
Limited experience	Which EPRI revision	Work follows "scope"
Limited lab space	Test house tries to help	Limits defined by EME
Incomplete failure list	Deciding on test set	Too many limit options
Recognizing value	Consultant steps in	
Higher risks	Inconsistent purch. spec.	
Cheaper testing		

EPRI's role in standards

- EPRI research is designed to positively impact industry by influencing standards development
  - EPRI does not write standards
  - EPRI research helps to develop new standards and influence existing standards
    - Lab & field test data help to define new trends in the electromagnetic environment
  - EPRI TR-102323 is not a standard
  - Manufacturers and test houses cannot purchase EPRI documents from standards bodies or standards retailers
  - EPRI documents are not public until they are 5 years old
  - By the time they are publically available, they are close to being out of date

EMC Testing Standards

New & Enhanced Standards are Paving the Way for US EMC-Specific Standards for NPPs

- MIL-STD-461/462: designed for military program controlling both susceptibility and emissions
- IEC 61000: emissions & immunity tests designed for commercial equipment
- ANSI/IEEE C63.12, C63.15 and C62.45 (Susceptibility type tests)
- Each one of the family of standards above has been updated several times over the period between 1994 & 2012 → EPRI TR-102323 must be frequently updated

Better Approach: Industry provides an EMC testing standard that follows an updated path each time a core testing standard (ANSI or IEC) is updated

This approach is being carried out in a current EPRI I&C project on EMC for Nuclear Digital I&C Equipment.

NRC Publications on EMC

What do they say about the importance of EMC and the development of new EMC standards?

NRC NUREG History on EMC

NUREG	YEAR	TITLE
CR-5904	4-1994	Functional Issues and Environmental Qualification of Digital Protection Systems of Advanced Light-Water Nuclear Reactors
CR-5941	4-1994	Technical Basis for Evaluating Electromagnetic and Radio-Frequency Interference in Safety-Related I&C Systems
CR-6406	9-1996	Environmental Testing of an Experimental Digital Safety Channel
CR-6436	11-1996	Survey of Ambient Electromagnetic and Radio-Frequency Interference Levels in Nuclear Power Plants
CR-6431	12-1997	Recommended Electromagnetic Operating Envelopes for Safety-Related I&C Systems in Nuclear Power Plants
CR-6579	1-1998	Digital I&C Systems in Nuclear Power Plants: Risk Screening of Environmental Stressors and a Comparison of Hardware Unavailability with an Existing Analog System
CR-5609	8-2003	Electromagnetic Compatibility Testing for Conducted Susceptibility Along Interconnecting Signal Lines
CR-6782	8-2003	Comparison of U.S. Military and International Electromagnetic Compatibility Guidance
CR-6479	2009	Technical Basis for Environmental Qualification of Microprocessor-Based Safety-Related Equipment in Nuclear Power Plants
RG 1.180	2000 & 2003	Guidelines for Evaluating Electromagnetic and Radio-Frequency Interference in Safety-Related Instrumentation & Control Systems

From NUREG/CR-6406 (1996)…

- Reported EMI/RFI to be the most severe environmental stressor on an experimental digital safety channel. Other stressors included temperature, humidity and smoke.
- System interfaces were identified to be most vulnerable elements of the design.
- Commercially components exhibited greater susceptibility to conducted EMI.
- ***Are these outcomes similar to those determined by the EMC community for other critical plant environments?***
- ***With increasing reliance on software, how must the error handling be evaluated as part of EMC testing?***

NUREG/CR-6479 (2009)

TITLE

Technical Basis for Environmental Qualification of Microprocessor-Based Safety-Related Equipment in Nuclear Power Plants

(NUREG/CR-6479, ORNL/TM-13264)

This 2009 document, includes several comments that are important for EMC conformity assurance in nuclear power plants.

NUREG/CR-6479 (2009) – EMC Comment 1

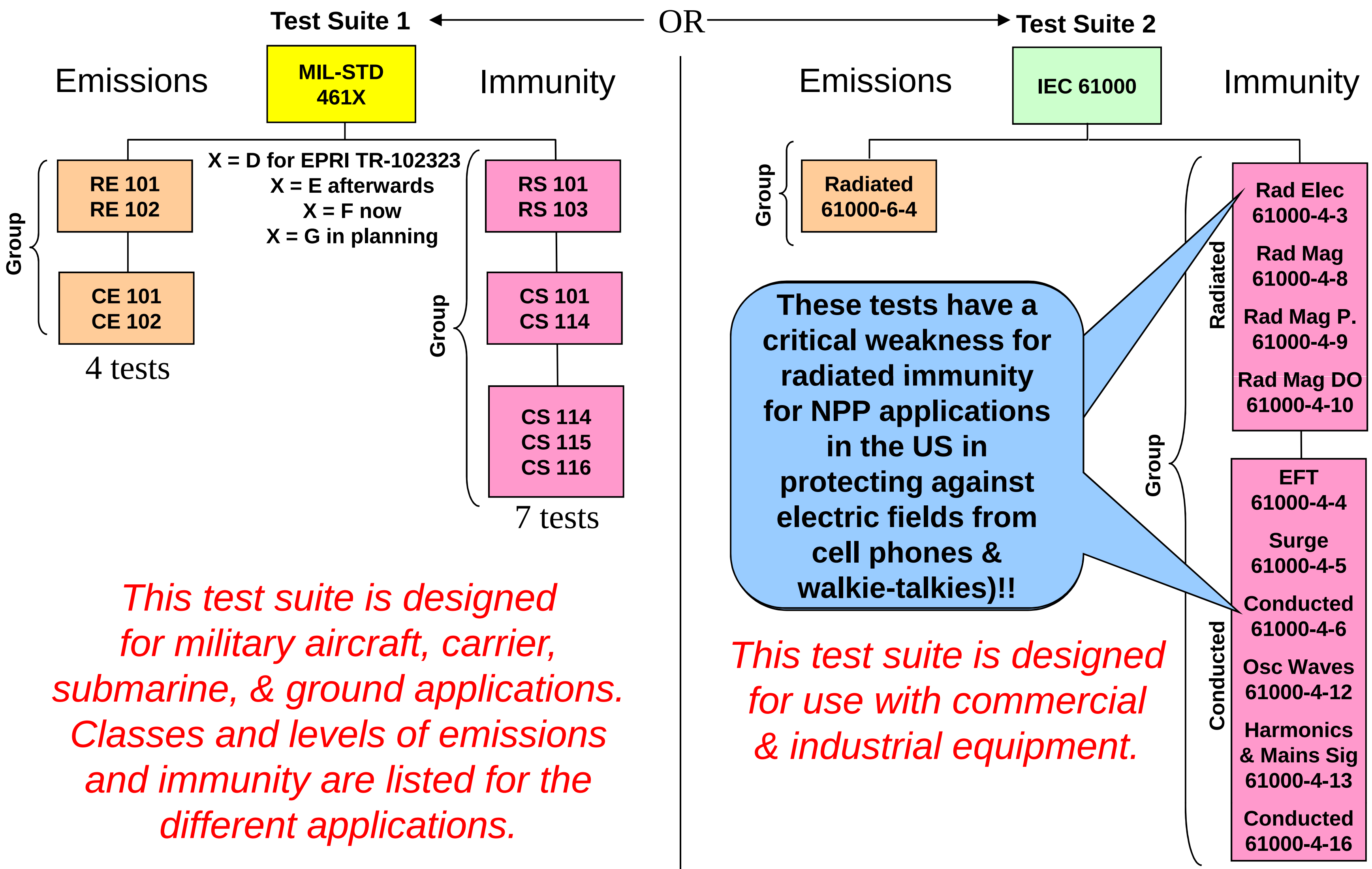
- “There is a need for electromagnetic compatibility standard(s) for the nuclear power plant environment.” The information provided in the following reports can be used as the basis for electromagnetic compatibility of I&C systems in nuclear power plants:
    - NUREG/CR-6431, "Recommended Electromagnetic Operating Envelopes for Safety-Related I&C in Nuclear Power Plants"
    - NUREG/CR-5941, "Technical Basis for Evaluating Electromagnetic and Radio-Frequency Interference in Safety-Related I&C Systems"
    - NUREG/CR-6436, "Survey of Ambient Electromagnetic and Radio-Frequency Interference Levels in Nuclear Power Plants"

NUREG/CR-6479 (2009) – EMC Comment 2

- “The nuclear industry should adopt a new philosophy of qualification, in which the assurance that safety-related equipment will perform properly is "**built-in**" as well as being "**tested-in**”.”

NUREG 1.180-2003 or EPRI TR-102323

Pick a Test Suite or Group



This test suite is designed for military aircraft, carrier, submarine, & ground applications. Classes and levels of emissions and immunity are listed for the different applications.

This test suite is designed for use with commercial & industrial equipment.

Too Many Disagreements between Two EMC Test Approaches for Nuclear I&C Equipment

Differences between EPRI TR-102323 Rev. 3 & NUREG 1.180-R1 (2003)

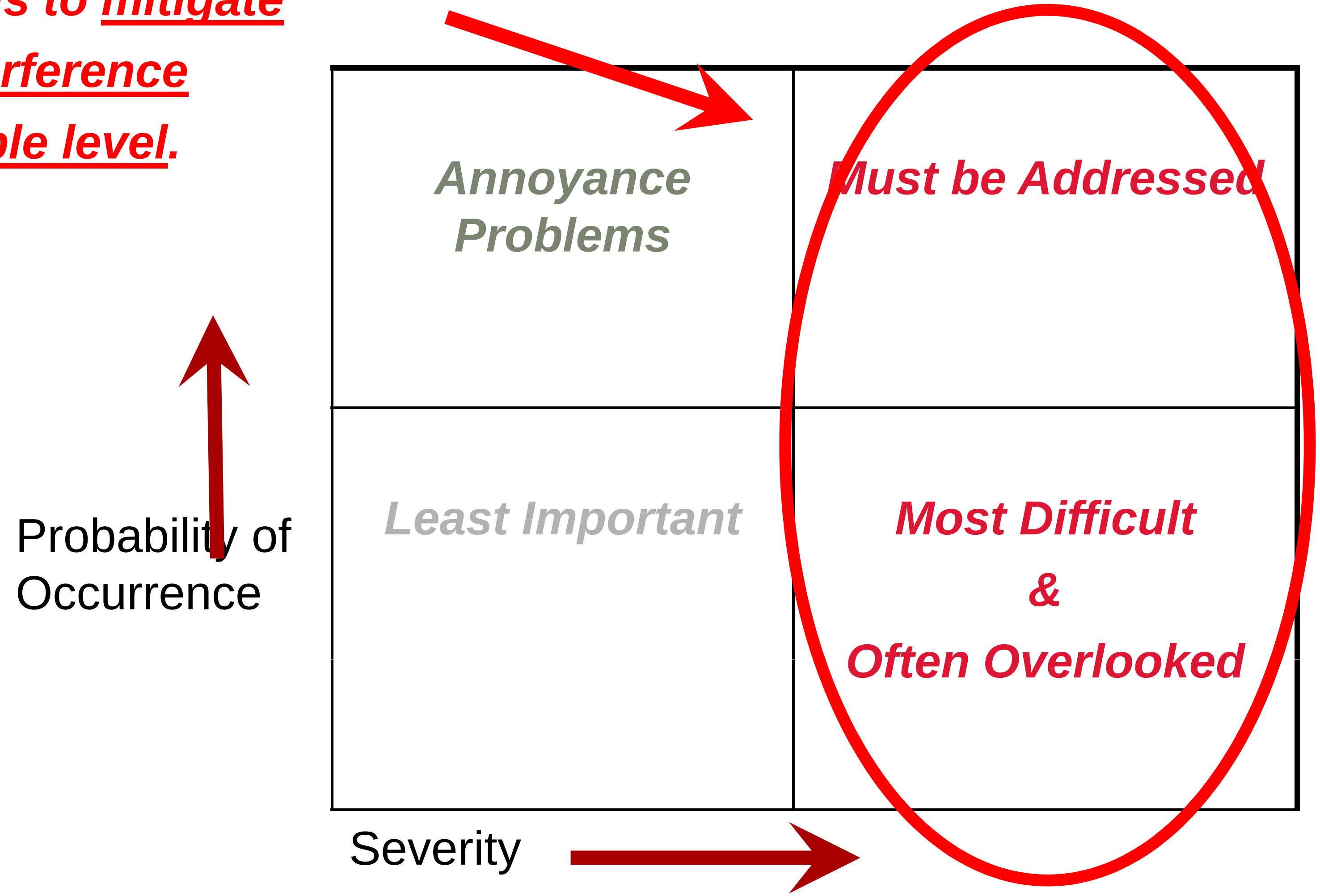
Test	Does this test in EPRI TR-102323 Rev. 3 (2004) agree with the tests in NRC NUREG 1.180-R1 (2003)?
RE101	Agree
RE102	Disagree (minor)
CE101	Disagree (significant)
CE102	Disagree (minor)
RS101	Disagree (significant)
RS102	Agree
CS101	Disagree (significant)
CS114	Disagree (significant)
CS115	Electrically-Fast Transients: Disagree (significant)
CS116	Voltage Surge (Combination Wave): Disagree (minor)

New IEC EMC Testing Standard

Bringing risk assessment into the “equation”

Goal of EMC Requirements

The goal of nuclear plant EMC requirements is to <u>mitigate the risk of interference to an acceptable level</u>.



New IEC EMC Testing Standards

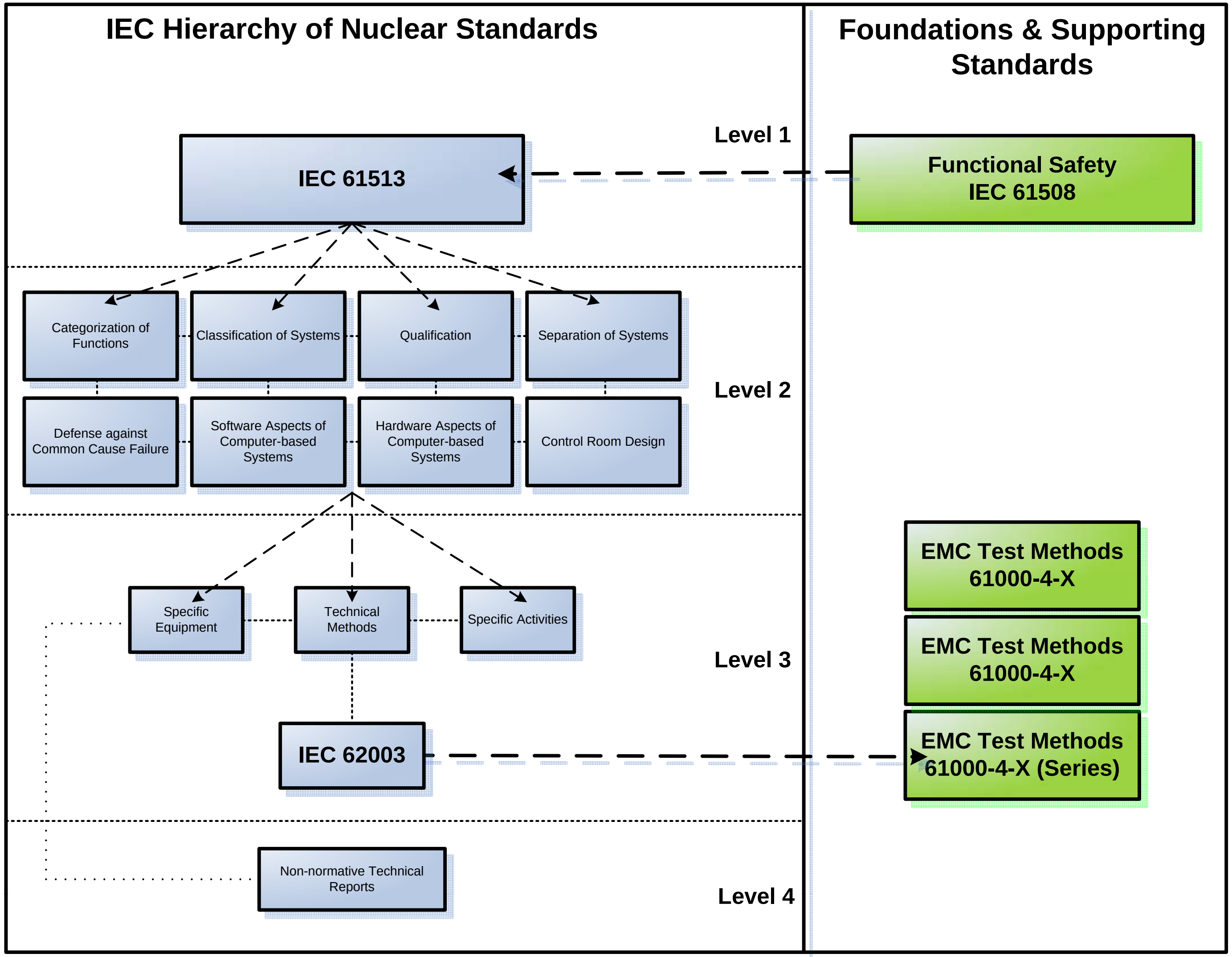
- **In 2009, IEC 62003: 2009-03 was issued:**

  Nuclear power plants
  – Instrumentation and control important to safety: Requirements for electromagnetic compatibility testing

- **It establishes limits and testing requirements using the IEC series of EMC standards.**

- **However, it used a functional safety approach based on the IEC 61508 series of standards.**

Structure of IEC 62003



EMC Requirements in IEC 62003

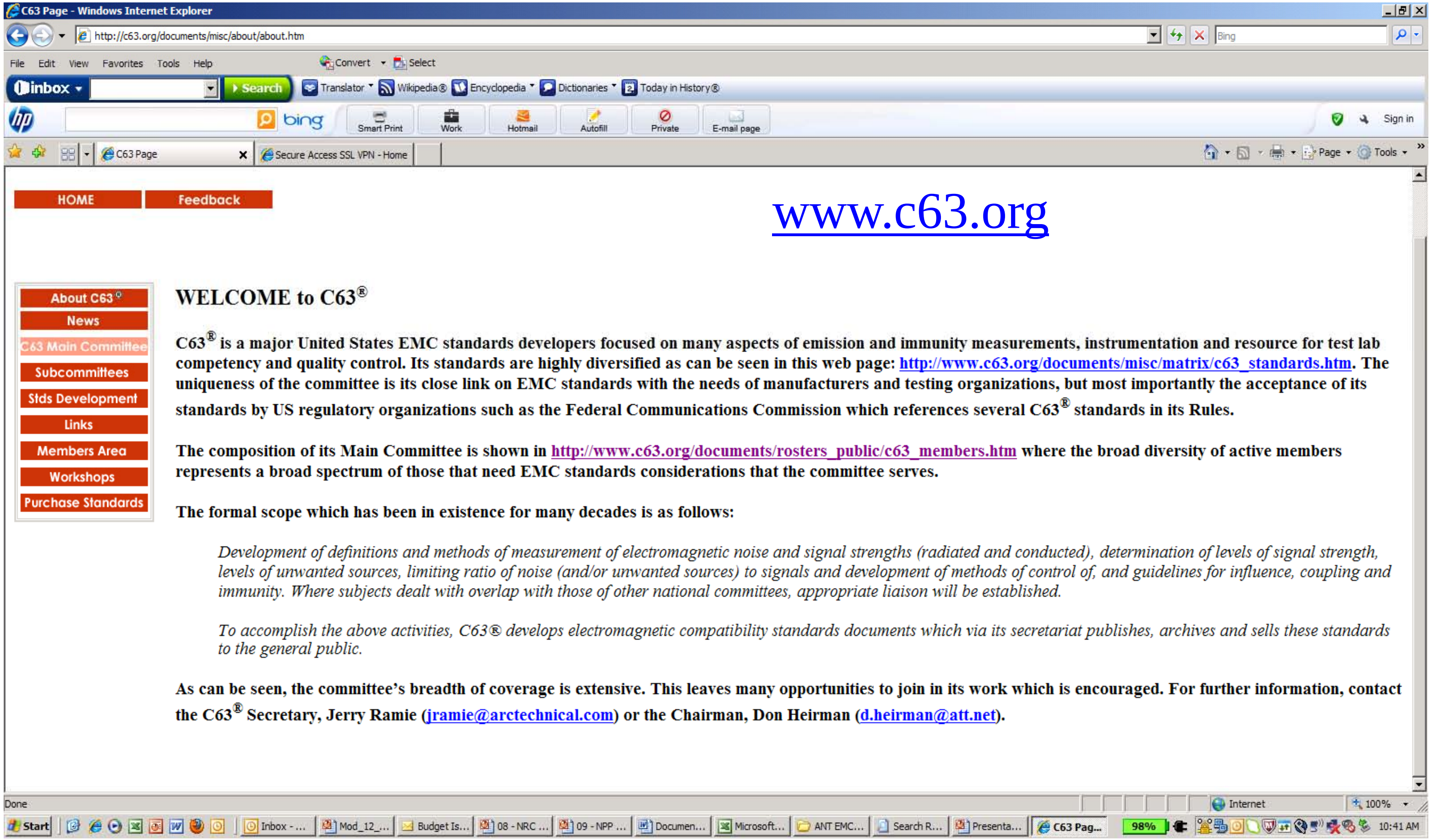
#	Test Requirement	Test Standard
1	Surge disturbances of large energy	IEC 61000-4-5
2	Voltage dips, short interruptions, voltage variations	IEC 61000-4-11
3	Electrical fast transients/bursts	IEC 61000-4-4
4	Electrostatic discharges	IEC 61000-4-2
5	Radio-frequency electromagnetic field, radiated	IEC 61000-4-3
6	Power frequency magnetic field	IEC 61000-4-8
7	Pulse magnetic field	IEC 61000-4-9
8	Conducted disturbances, induced by radio-frequency field	IEC 61000-4-6
9	Oscillatory damped disturbances	IEC 61000-4-12
10	Fluctuations of power supply voltage	IEC 61000-4-14
11	Conducted common mode disturbances in the range of 0 Hz to 150 Hz	IEC 61000-4-16
12	Variations of power frequency in supply systems	IEC 61000-4-28
13	Harmonics and inter-harmonics distortion of power supply waveform	IEC 61000-4-13
14	Damped oscillatory magnetic field	IEC 61000-4-10

Environment Types in IEC 62003

IEC 62003: 2009-03 identified four types of environments and created different requirements based on the installation environment.

	Severity of electromagnetic environment of equipment location			
	Light EME	Middle EME	Harsh EME	Severe EME
Immunity Level	I	II	III	IV

US Accredited Standards Committee on EMC – C63®



WELCOME to C63®

C63® is a major United States EMC standards developers focused on many aspects of emission and immunity measurements, instrumentation and resource for test lab competency and quality control. Its standards are highly diversified as can be seen in this web page: http://www.c63.org/documents/misc/matrix/c63_standards.htm. The uniqueness of the committee is its close link on EMC standards with the needs of manufacturers and testing organizations, but most importantly the acceptance of its standards by US regulatory organizations such as the Federal Communications Commission which references several C63® standards in its Rules.

The composition of its Main Committee is shown in http://www.c63.org/documents/rosters_public/c63_members.htm where the broad diversity of active members represents a broad spectrum of those that need EMC standards considerations that the committee serves.

The formal scope which has been in existence for many decades is as follows:

> *Development of definitions and methods of measurement of electromagnetic noise and signal strengths (radiated and conducted), determination of levels of signal strength, levels of unwanted sources, limiting ratio of noise (and/or unwanted sources) to signals and development of methods of control of, and guidelines for influence, coupling and immunity. Where subjects dealt with overlap with those of other national committees, appropriate liaison will be established.*
>
> *To accomplish the above activities, C63® develops electromagnetic compatibility standards documents which via its secretariat publishes, archives and sells these standards to the general public.*

As can be seen, the committee's breadth of coverage is extensive. This leaves many opportunities to join in its work which is encouraged. For further information, contact the C63® Secretary, Jerry Ramie (jramie@arctechnical.com) or the Chairman, Don Heirman (d.heirman@att.net).

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Status of C63 Standards

Status of C63® Standards
Date: May 18, 2011

Contact the Subcommittee or Working Group Chair for each standard for additional information or questions

Project / Standard #	Brief Title	Sub-committee Contact	Working Group Chair contact	Project Scope (PINS[1])	Status
C63.2-2009 Learn more	EM Noise & Field Strength Instrumentation	SC 1	None	No active PINS	Current. No plans for further maintenance at this time.
C63.4-2009 Learn more	Emission measurements	SC 1	Heirman, Don	C63.4 PINS	Current. Maintenance is underway.
C63.5-2006 Learn more	Antenna Calibration	SC 1	Camell, Dennis	C63.5 PINS	Current. Maintenance is underway.
C63.6-1996 Learn more	Computation Errors in OATS Measurements – Guide	None	None	No active PINS	Admin withdrawn. No plans for future maintenance.
C63.7-2005 Learn more	OATS, Construction of	SC 1	Heirman, Don	No active PINS	Current. No plans for further maintenance at this time.
C63.8-draft Learn more	Calibration of EMC Test Equipment – Guide	SC 6	Kuczynski, Victor	C63.8 PINS	New standard. Draft is being written.
C63.9-2008 Learn more	Office equipment immunity	SC 5	* Berger, Stephen	No active PINS	Current. No plans for further maintenance at this time.
C63.10-2009 Learn more	Unlicensed Transmitter measurements	SC 1	Wall, Art	C63.10 PINS	Current. Maintenance is underway.
C63.11-draft Learn more	Inter-lab Comparison of EMC Testing	SC 6	Kuczynski, Victor	C63.11 PINS	New project. Draft is being written.
C63.12-1999 (R2007) Learn more	EMC Limit Setting	C63 Main Committee	Showers, Ralph Hare, Ed	No active PINS	Published 15 Aug 2007 . Was reaffirmation of C63.12-1999.
C63.13 1991 Learn more	EMI Power Line Filters	None	None	No active PINS	Administratively withdrawn. No plans for future maintenance.
C63.14-2009 Learn more	Definitions	SC 2	Shellman, Marcus	C63.14 PINS	Current. Revisions continuous as needed.
C63.15-2010 Learn more	Immunity Measurement & Instrumentation	SC 5	None	No active PINS	Current; no plans for further maintenance at this time.
C63.16-1993 Learn mored	ESD Test Methodology	SC 5	Heirman, Don	No active PINS	Administratively withdrawn Standard is under study by Subcommittee 5.
C63.17-2006 Learn more	Unlicensed Personal Communications Service (PCS) Devices	SC 7	* Berger, Stephen	PINS being proposed at Oct 2010 meeting	Current. Working Group is evaluating to determine if further maintenance is needed

Status of C63 Standards

C63.11-draft Learn more	Inter-lab Comparison of EMC Testing	SC 6	Kuczynski, Victor	C63.11 PINS	New project. Draft is being written.
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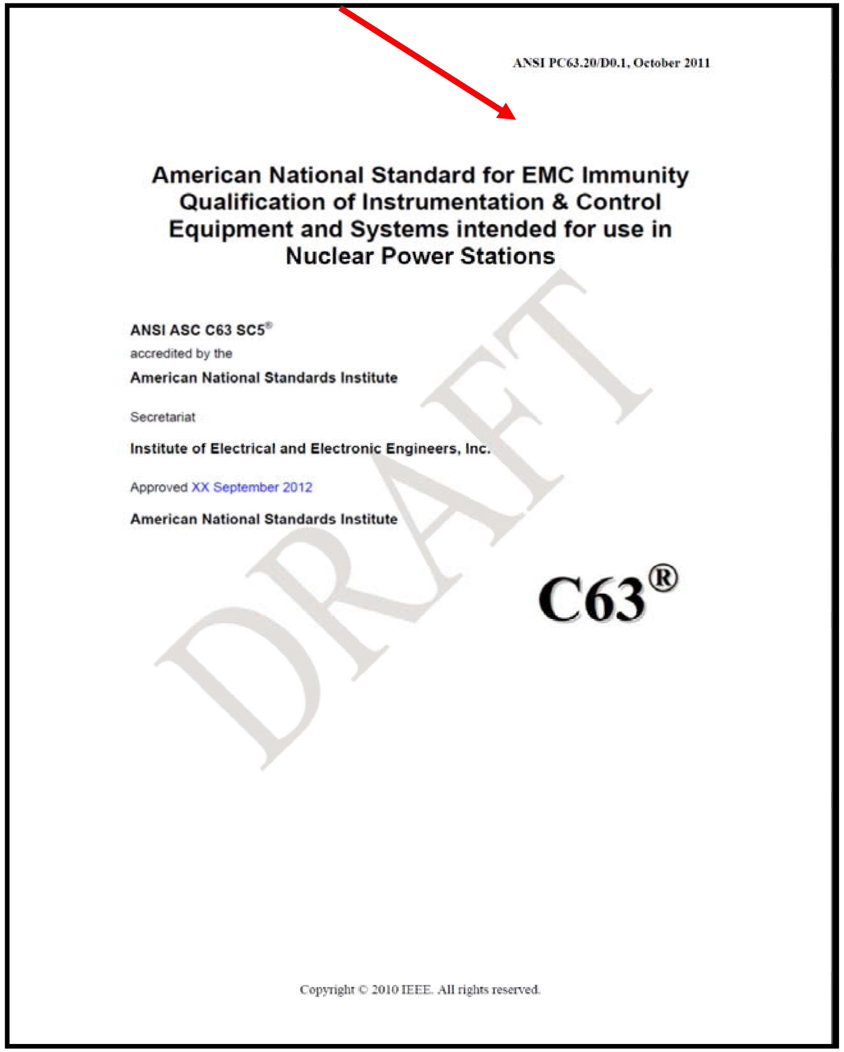
C63.17-2006 Learn more	Unlicensed Personal Communications Service (PCS) Devices	SC 7	* Berger, Stephen	PINS being proposed at Oct 2010 meeting.	Current. Working Group is evaluating to determine if further maintenance is needed.
C63.18-1997 Learn more	On-Site Medical Immunity testing	SC 8	Silberberg, Jeffrey L	C63.18 PINS	Administratively withdrawn. Maintenance is underway. The standard is in the comment-resolution phase of a recirculation ballot.
C63.19-2006 Learn more	EMC for Hearing Aids,	SC 8	Berger, Stephen	C63.19 PINS	WG is working on extending frequency range and other improvements. The standard is in recirculation ballot.
C63.20-draft Learn more	Nuclear Power Plant Immunity	SC 5	Berger, Stephen	C63.20 PINS	New project (April 2010). Working group being formed.
C63.22-2004 Learn more	Guide for Automated EMI Measurements	SC 1	* Schaefer, Werner	No active PINS	Current. No plans for further maintenance at this time..
C63.23-draft Learn more	Measurement Uncertainty	SC 1	DeLisi, Bob	C63.23 PINS	New standard. Draft being written.
C63.24-draft Learn more	On-Site Generic Immunity testing	SC 5	Berger, Stephen	C63.24 PINS	New standard. Draft being written.
C63.25-draft Learn more	Test Site validation time domain	SC 1	Camell, Dennis	C63.25 PINS	New standard. Draft being written.
C63.26-draft Learn more	Licensed transmitter measurements	SC 1	Wall, Art	C63.26 PINS	New standard. Draft being written.

* = No active Working Group. Former Working Group Chair is still a participant with C63®, so he is listed.
**=No active Working Group. The Chair of the Subcommittee responsible for the standards is listed.

PC63.20: EMC Immunity Qualification of I&C Equipment & Systems Intended for use in Nuclear Power Stations

- Scope
  - This standard provides test methods and limits for assuring the EMC immunity of instrumentation and control (I&C) systems used in nuclear power plants.



ANSI PC63.20/D0.1, October 2011

American National Standard for EMC Immunity Qualification of Instrumentation & Control Equipment and Systems intended for use in Nuclear Power Stations

ANSI ASC C63 SC5®

accredited by the

American National Standards Institute

Secretariat

Institute of Electrical and Electronic Engineers, Inc.

Approved XX September 2012

American National Standards Institute

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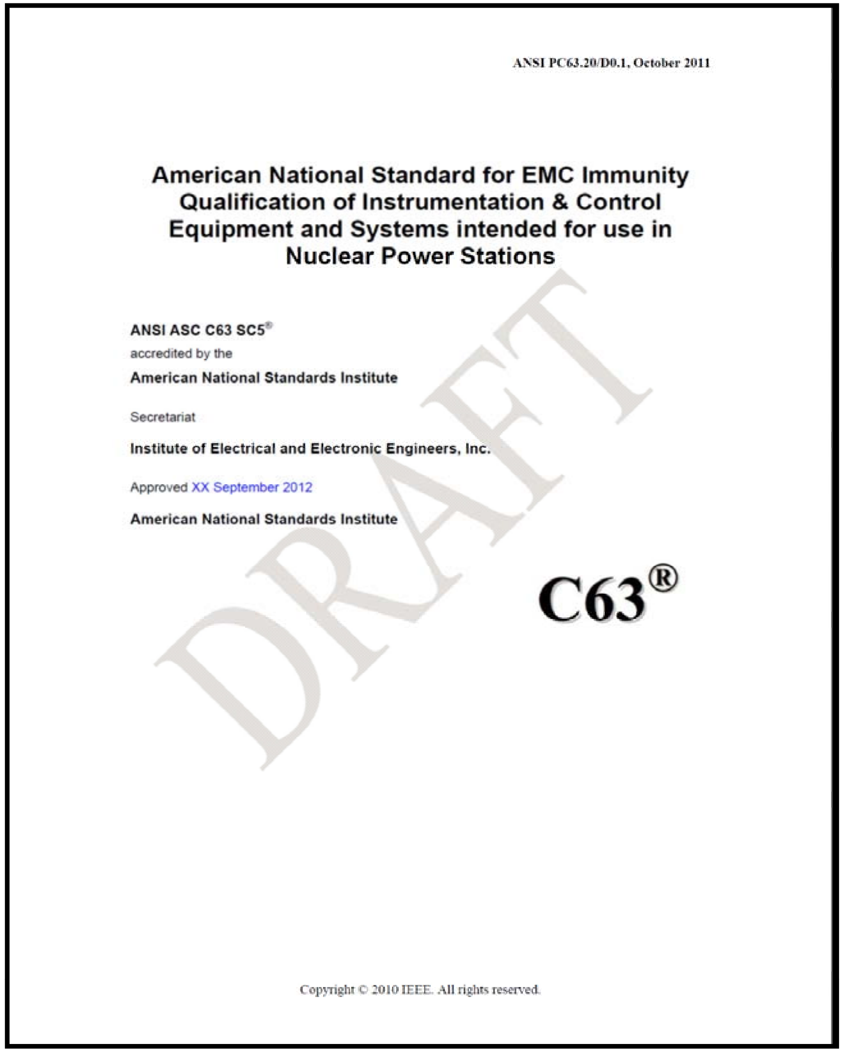
PC63.20: EMC Immunity Qualification of I&C Equipment & Systems Intended for use in Nuclear Power Stations

- Purpose
  - This standard provides test methods and limits for evaluation of the EMC immunity of I&C systems used in nuclear power plants. The purpose of the document is to provide the required tests and parameters so that I&C will operate properly in the electromagnetic environments anticipated in these plants.


ANSI PC63.20/D0.1, October 2011

American National Standard for EMC Immunity Qualification of Instrumentation & Control Equipment and Systems intended for use in Nuclear Power Stations

ANSI ASC C63 SC5®

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Secretariat

Institute of Electrical and Electronic Engineers, Inc.

Approved XX September 2012

American National Standards Institute

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DRAFT

PC63.20: EMC Immunity I&C Equipment

Working Group

C63.20 (Nuclear Power Plant Immunity) Working Group Roster

Name	Role within C63.20 WG	Affiliation
Berger, Stephen	Chair	TEM Consulting
Keebler, Phil	Vice Chair	EPRI
Vacant	Secretary	--
Kuczynski, Victor	Member	Vican Electronics
TBD	Observer	US Nuclear Regulatory Commission
Zimmerman, Dave	Member	Spectrum EMC

WG Members are Needed

- EPRI is in the process of recruiting a number of I&C engineers from NPP utilities, and design (some with EMC experience) engineers from I&C manufacturers
- If interested in membership, please contact:
  - Stephen Berger at stephen.berger@ieee.org
  - Philip Keebler at pkeebler@epri.com

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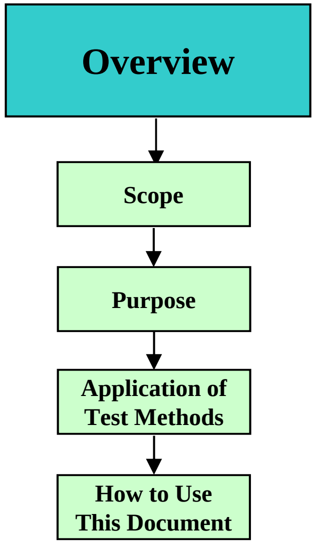
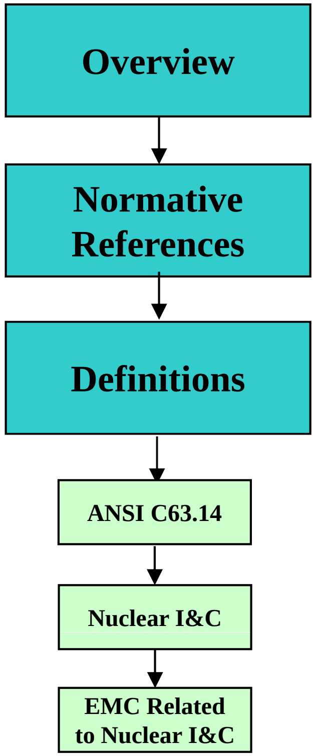
PC63.20: EMC Immunity I&C Equipment

Structure (Initial Draft)



PC63.20: EMC Immunity I&C Equipment

Structure (Initial Draft)



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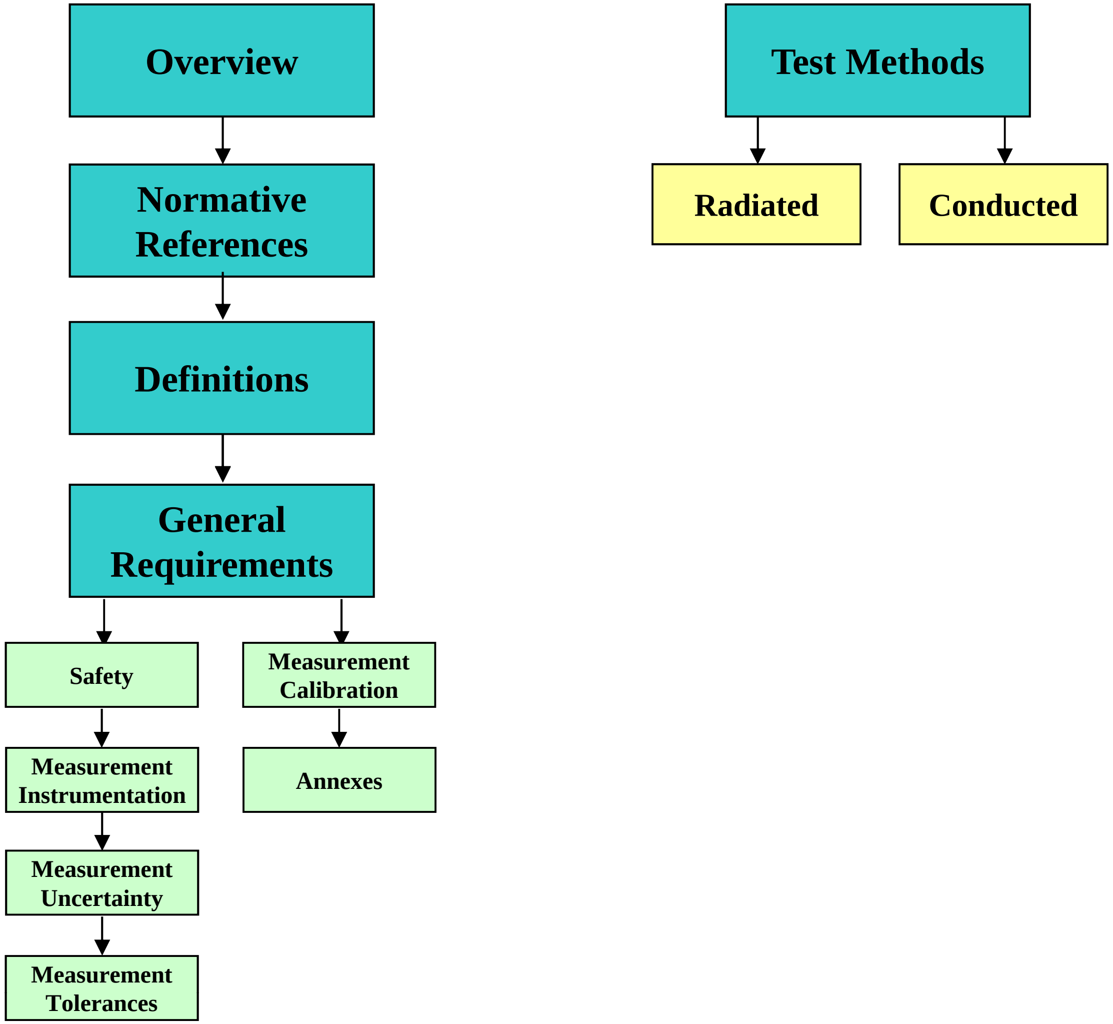
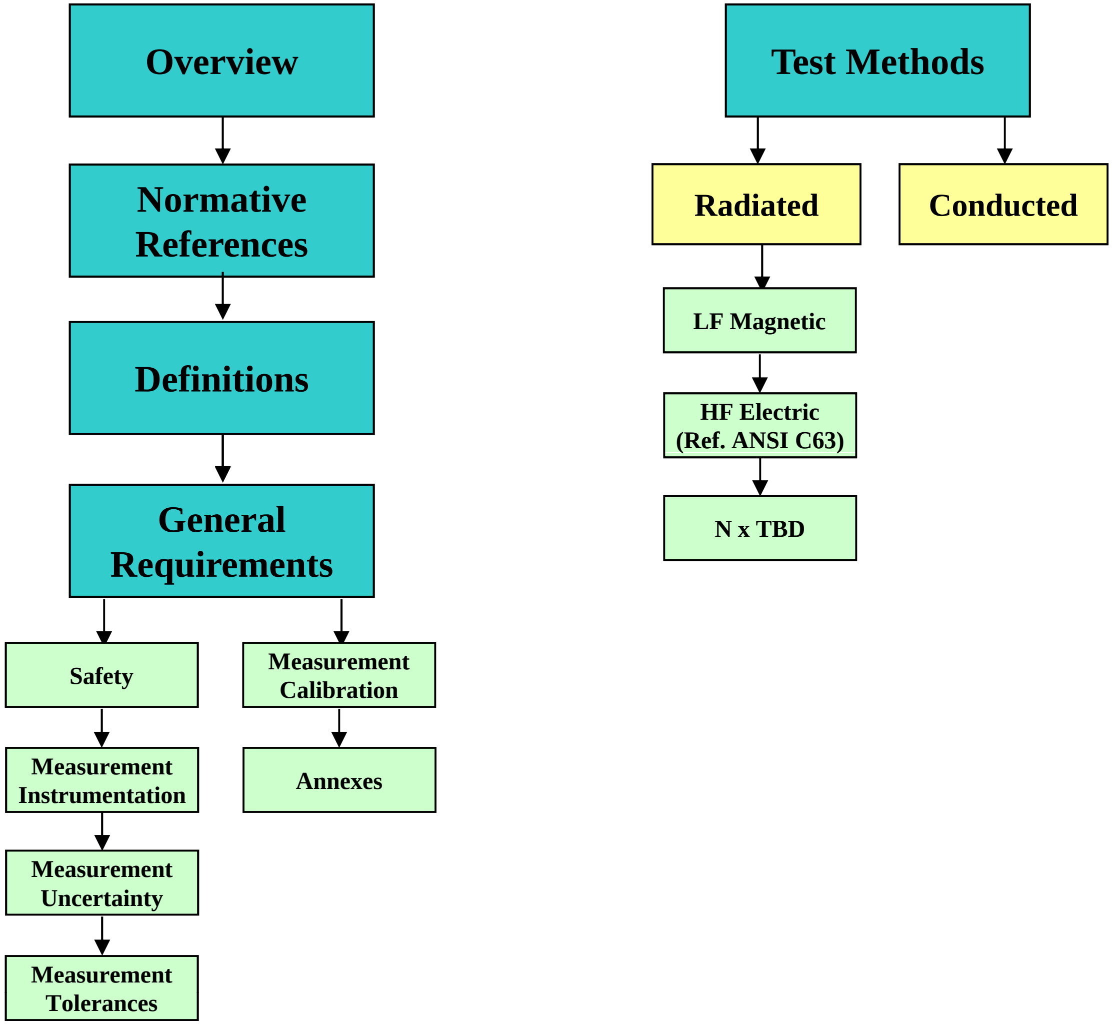
PC63.20: EMC Immunity I&C Equipment

Structure (Initial Draft)



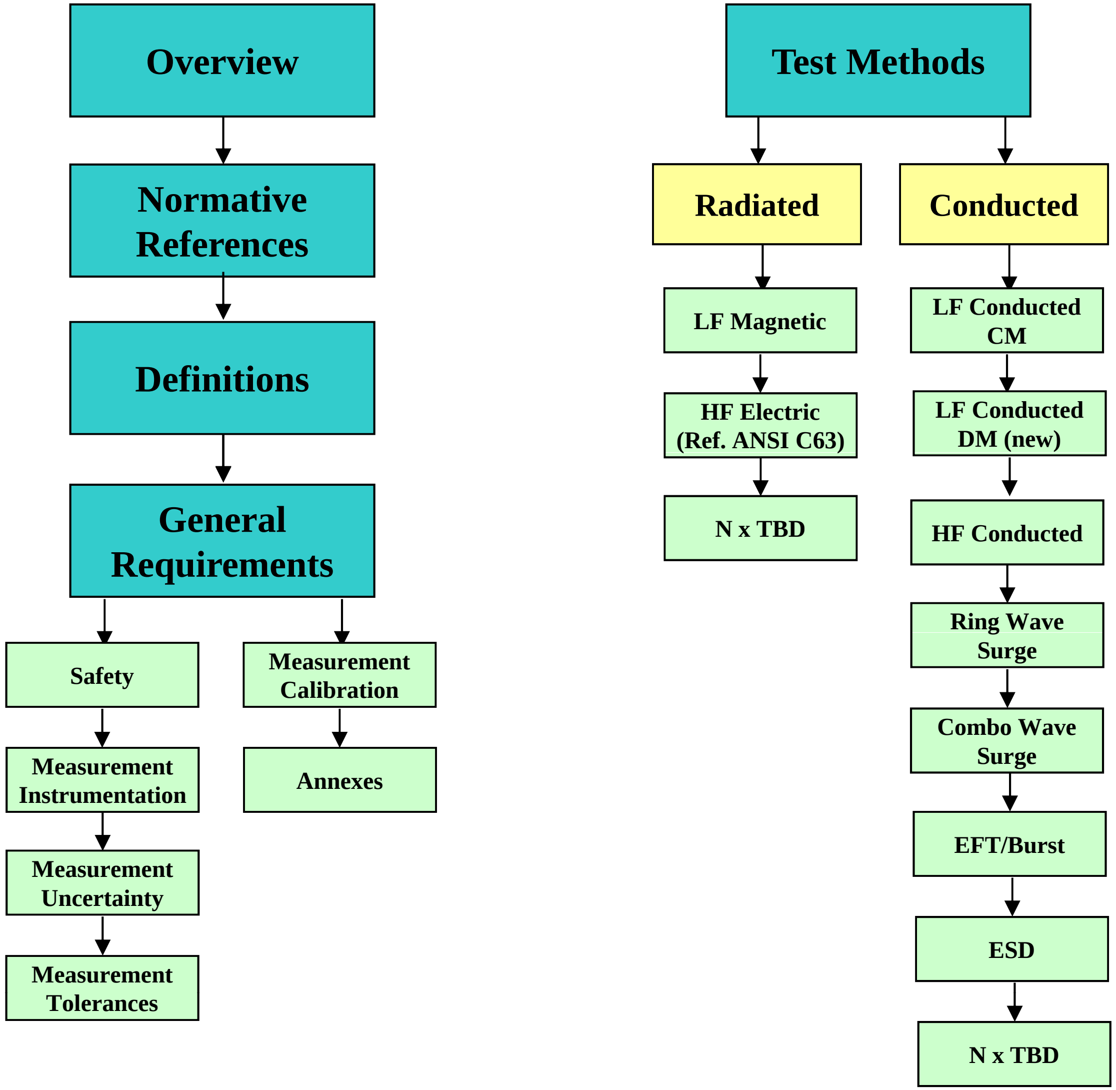
PC63.20: EMC Immunity I&C Equipment

Structure (Initial Draft)



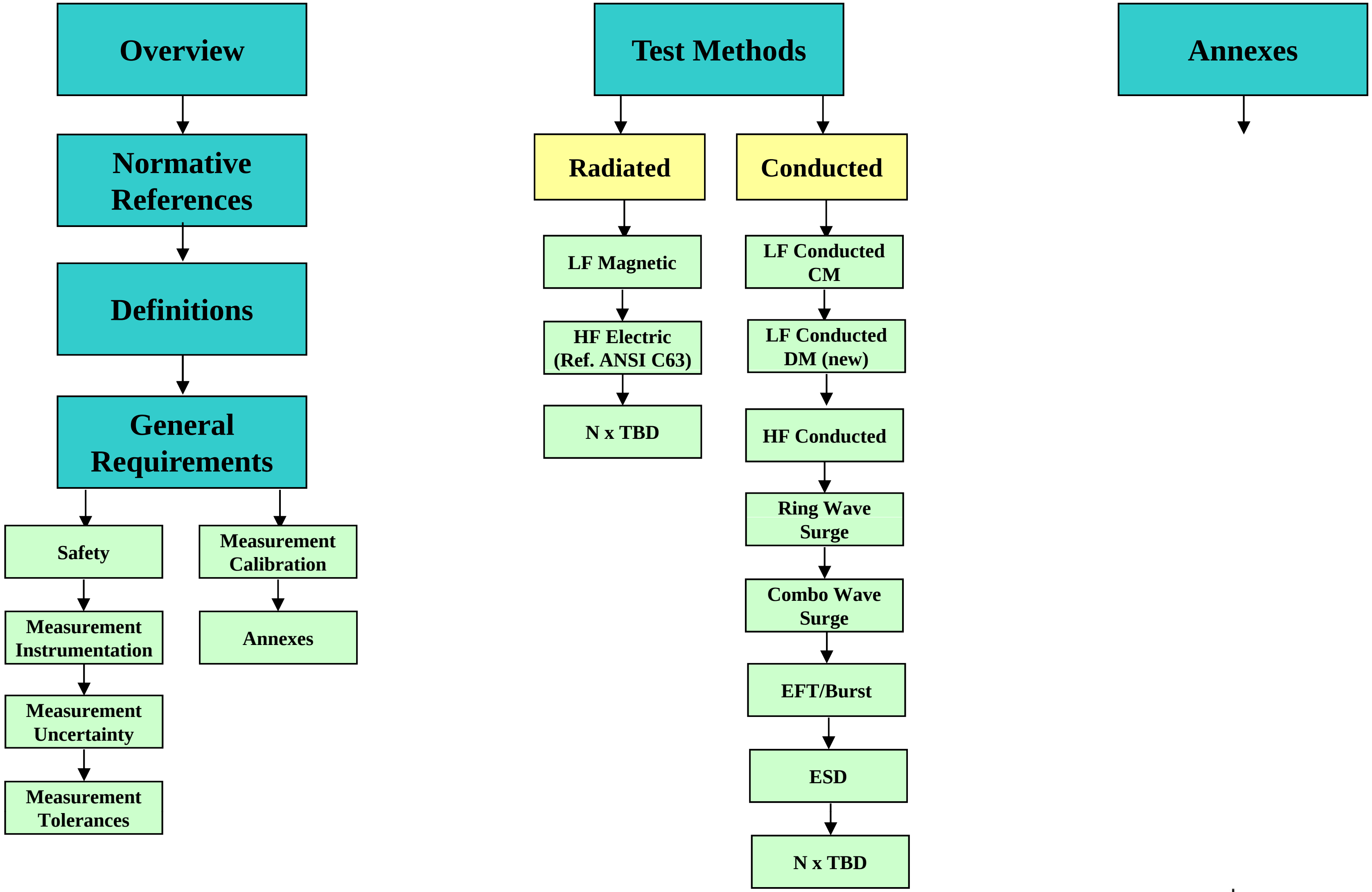
PC63.20: EMC Immunity I&C Equipment

Structure (Initial Draft)



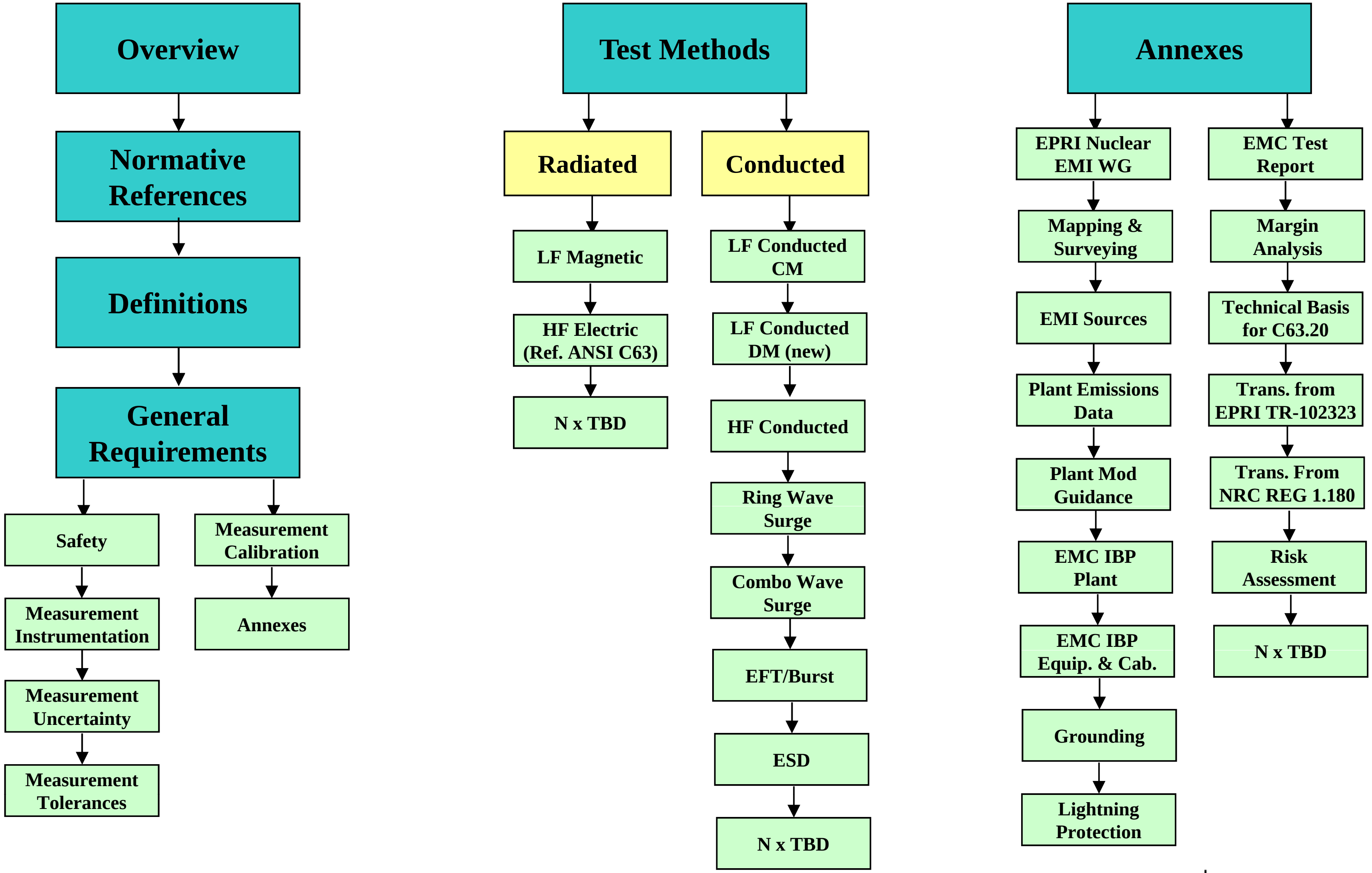
PC63.20: EMC Immunity I&C Equipment

Structure (Initial Draft)

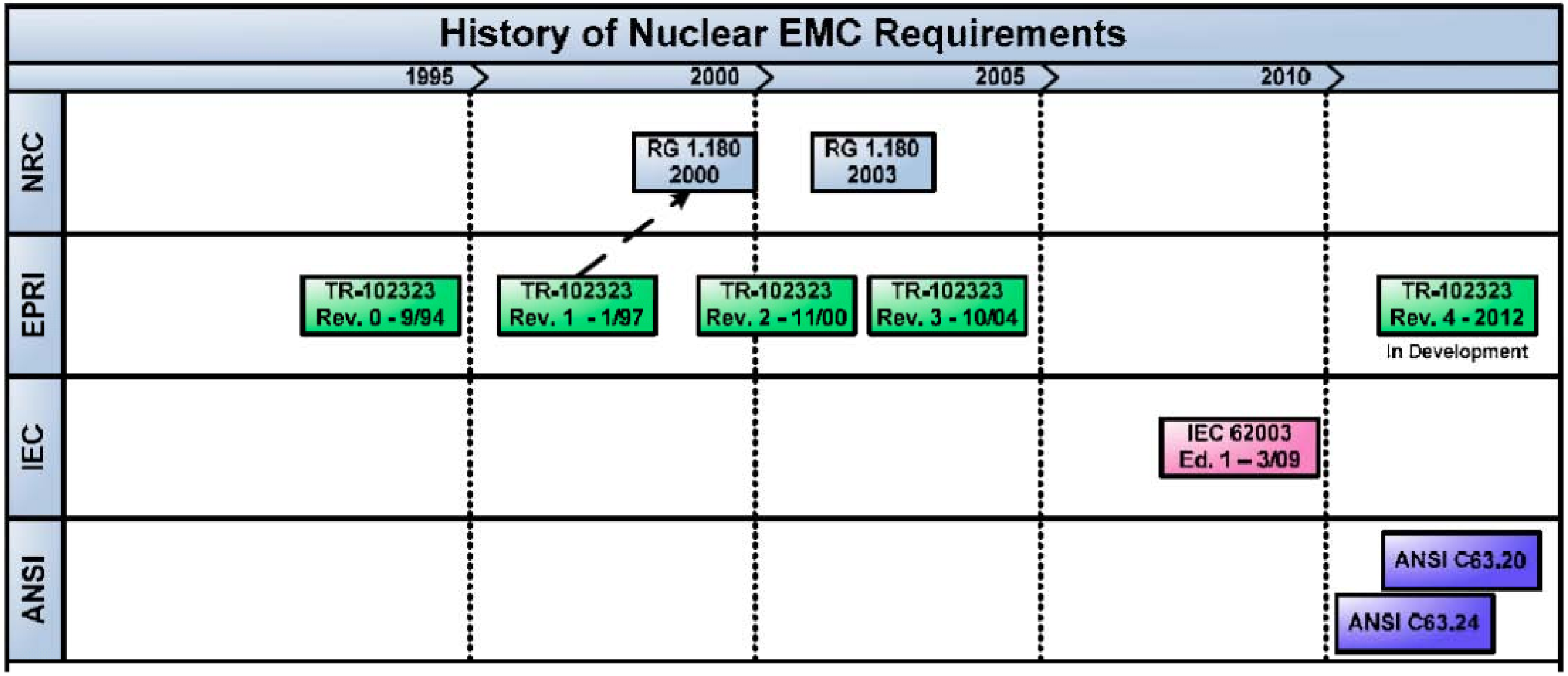


PC63.20: EMC Immunity I&C Equipment

Structure (Initial Draft)

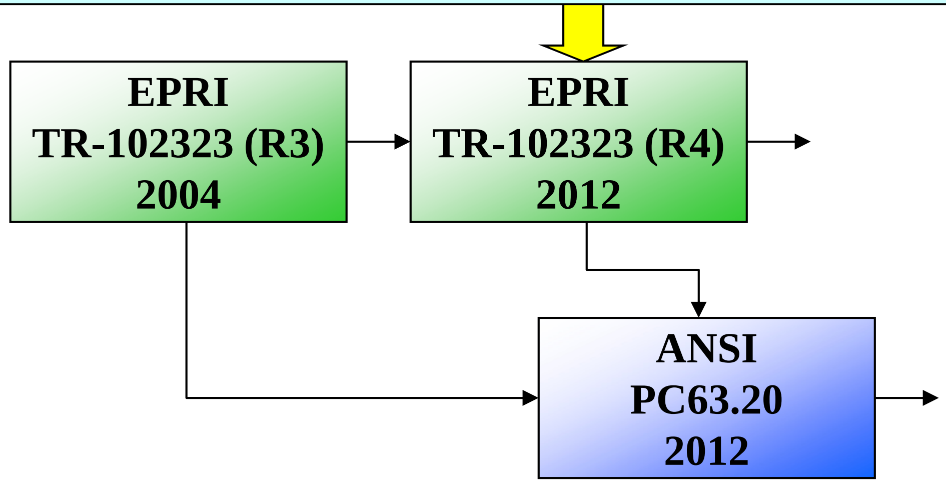


Chronology of Nuclear EMC References



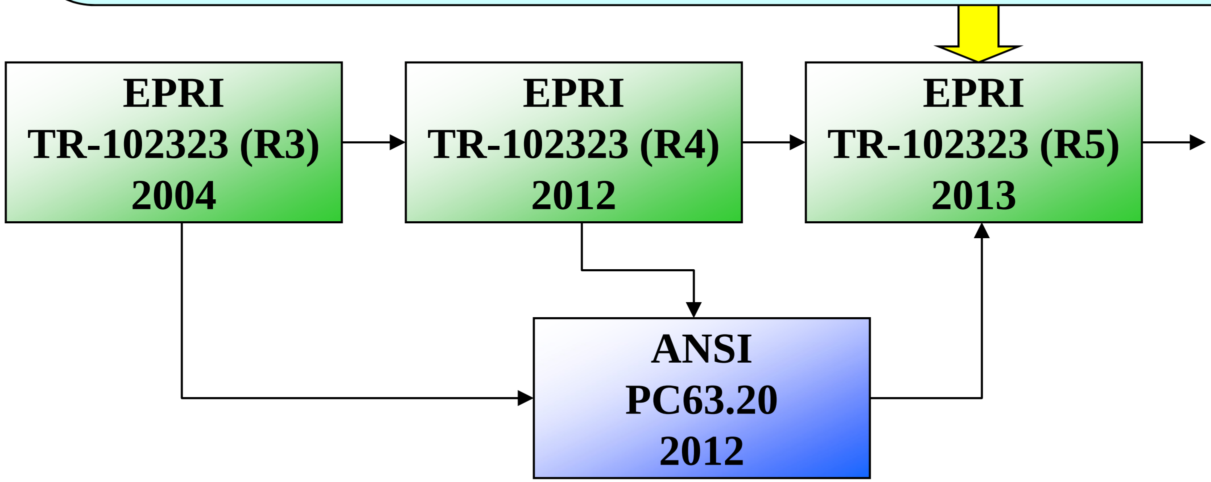
EPRI TR-102323 (Rev. 4) & PC63.20

- EPRI Rev. 4 & C63.20 are being developed in parallel.
- Rev. 4 will present the Value Proposition for C63.20.
- Rev. 4 will also discuss how its tests map to the tests defined in C63.20.



C63.20 & EPRI TR-102323 (Rev. 5)

- EPRI Rev. 4 & C63.20 are being developed in parallel.
- Rev. 4 will present the Value Proposition for C63.20.
- Rev. 4 will also discuss how its tests map to the tests defined in C63.20.
- Rev. 5 will present new guidance on & case histories from using C63.20.



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Address in Updated EMC Guidance?

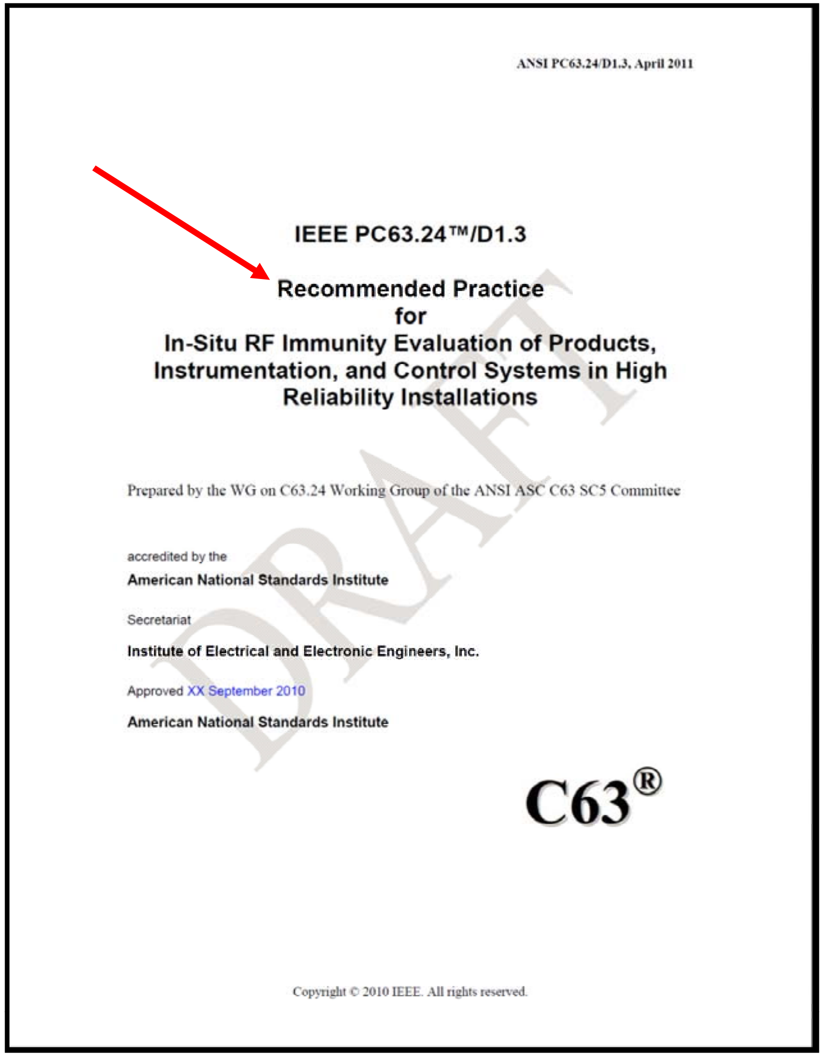
- Different categories of equipment emission and immunity levels
  - Similar to various surge and EFT levels
  - i.e. Power Generation Equipment, AC
    - 120 Vac single phase < 2kW
    - 120 Vac >2kW; <40 kW
    - 240 Vac
    - 480 Vac
- Harmonize the various EMC standards to make it more uniform
  - Eliminate selecting standards based on pass/fail
  - Should meet the intent of the EMC testing

Additional Considerations

- Emissions only test the effects on Input Power
  - Emissions on I/O may not be captured on radiated emission tests
  - Output power of Inverters are not required to be tested
- Transients cannot be captured by EMC testing
  - CE07 test removed from Mil-Std 461
  - Spectrum Analyzer does not capture transients
- Update the plant levels based upon the existing electromagnetic environment

PC63.24: On-Site RF Immunity Evaluation of Products & I&C Systems in High Reliability Installations

- Scope
  - This recommended practice provides an in-situ EMC immunity qualification test for products, instrumentation, and control systems in their installed environment.
  - This recommended practice does not address in-band RF interference or coexistence where the fundamental frequency of an RF transmitter overlaps with frequencies used by another product or system such as a wireless network, monitoring or other wireless communications link.



ANSI PC63.24/D1.3, April 2011

IEEE PC63.24™/D1.3

Recommended Practice
for
In-Situ RF Immunity Evaluation of Products, Instrumentation, and Control Systems in High Reliability Installations

DRAFT

Prepared by the WG on C63.24 Working Group of the ANSI ASC C63 SC5 Committee

accredited by the
American National Standards Institute

Secretariat
Institute of Electrical and Electronic Engineers, Inc.

Approved XX September 2010
American National Standards Institute

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PC63.24: On-Site Immunity Testing - Generic

Working Group

C63.24 (On-Site Immunity Testing – Generic) Working Group Roster

Name	Role within C63.24 WG	Affiliation
Berger, Stephen	Chair	TEM Consulting
Keebler, Phil	Vice Chair	EPRI
Vacant	Secretary	--
Hodes, Harry	Member	ACME Testing
Hoolihan, Dan	Member	Hoolihan EMC Consulting
Kuczynski, Victor	Member	Vican Electronics
Silberberg, Jeffrey L	Member	FDA Center for Devices & Radiological Health
Zimmerman, Dave	Member	Spectrum EMC

WG Members are Needed

- EPRI is in the process of recruiting a number of I&C engineers from NPP utilities, wireless and design (some with EMC experience) engineers from I&C manufacturers
- If interested in membership, please contact:
  - Stephen Berger at stephen.berger@ieee.org
  - Philip Keebler at pkeebler@epri.com

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PC63.24: On-Site RF Immunity Evaluation of Products & I&C Systems in High Reliability Installations

- Purpose
  - There is a need to evaluate the in-situ RF immunity of products, instrumentation and control systems in large installations. This recommended practice heavily uses the work of ANSI C63.18, but with a more generic approach and incorporate new techniques which have become available. The standard will focus on installation environments that require a high level of confidence that these products and systems have a high level of EMC immunity. This recommended practice provides a generic method for evaluating the RF immunity of electronic products, instrumentation, and control systems, as and where installed or operated. A particular focus is on immunity to RF sources that may enter the environment, intentionally or unintentionally or be integrated into the operating environment. The characteristics of RF sources in the environment were used to establish the levels and test methods.

PC63.24: On-Site RF Immunity Evaluation of Products & I&C Systems in High Reliability Installations

- Purpose
  - The test protocol is designed to be performed:
    - a) in a way that is relatively rapid and practical;
    - b) to identify specific effects and thresholds (i.e., transmit power and distance) to provide the basic information needed to develop a mitigation action plan;
    - c) to generate test results that can be used in the formulation of policies and procedures for managing the use of RF transmitters within a facility.
  - A preferred method and several alternative RF sources and methods for ad hoc testing are outlined in this recommended practice to allow flexibility with regard to the time, personnel, and resources available to perform the testing. As a result, these different options provide different levels of accuracy and comprehensiveness. The most appropriate ad hoc test strategy will depend upon the needs and resources of the user of this recommended practice. This recommended practice also provides guidance for selection of the devices to be tested, operation of transmitters used as RF test sources, and assessment of test results.

PC63.24: On-Site RF Immunity Evaluation of Products & I&C Systems in High Reliability Installations

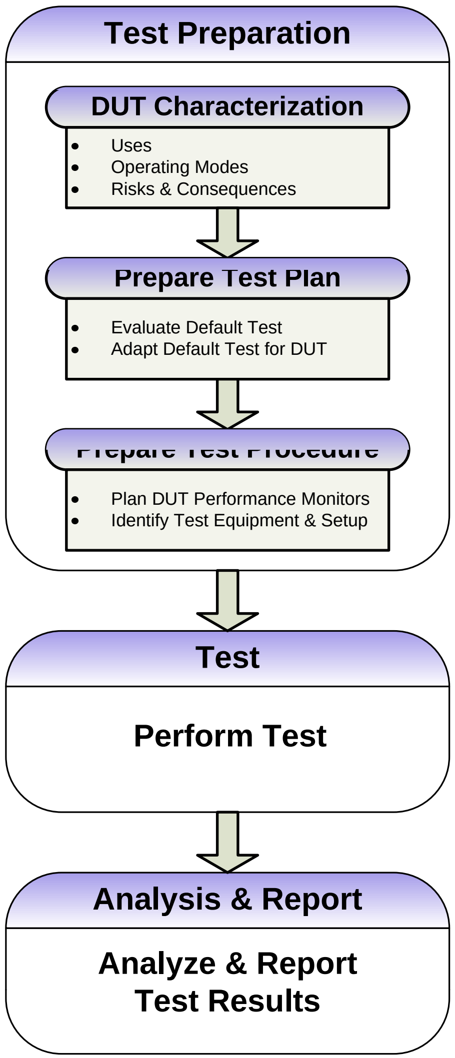
- Purpose
  - An important function of this recommended practice is to define a consistent test protocol to allow results to be obtained and compared within and across institutions. Staff and engineers have performed their own rudimentary (“ad hoc”) EMC testing using in-house methodology, RF transmitter sources and devices. As a result, comparison of the findings between organizations might not be appropriate. To facilitate comparison between organizations, it is important that the recommendations herein are followed, deviations are kept to a minimum, and the testing is performed as consistently as possible.

PC63.24: On-Site RF Immunity Evaluation of Products & I&C Systems in High Reliability Installations

- Purpose
  - Policies and procedures for mitigation of electromagnetic interference (EMI), including use or restriction of specific RF transmitters within specific areas, should be based on objective information, including that obtained by the use of this test method. With regard to purchase evaluation, confirming that devices conform to voluntary EMC standards can provide some information, although many RF transmitters are able to greatly exceed these immunity levels when nearby or in the very near field. This recommended practice can be used to supplement the information obtained by testing for conformance to voluntary EMC standards. A list of EMC standards and guidelines that contain radiated RF immunity requirements that are applicable to, or additional background information and further recommendations for mitigation of EMI facilities are presented in the annexes.

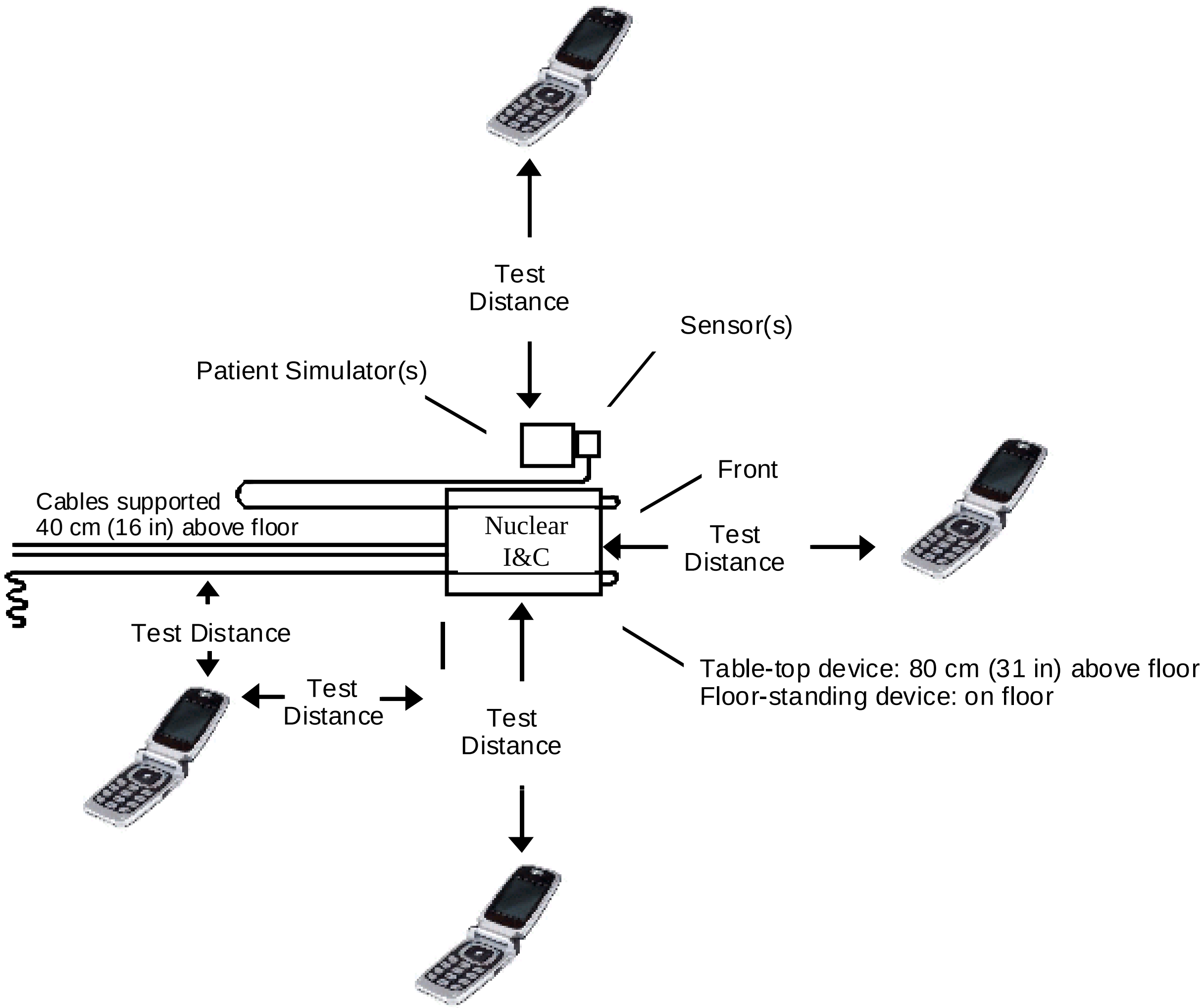
PC63.24: On-Site RF Immunity Evaluation

Test Process Overview



PC63.24: On-Site RF Immunity Evaluation

Test Process Overview



Why would one want to develop a US National Standard on EMC for US Nuclear Plants when most of the I&C equipment is manufactured internationally?

- The answer is that C63 is the secretariat for the US national committee to the IEC. C63 standards commonly form a core part of the US national position into the IEC. Hence, C63 standards focused on NPPs (e.g., C63.20 & C63.24) would be written based on US market needs but then be advanced to the IEC. Down the road, they should be included and subsumed into the IEC and the process tends to start over. Generally, different markets address their individual needs but all try and coordinate within the IEC. In this case, we plan to make sure C63.20 uses as much of the IEC work as we can and only add new material were we have compelling need.

Automotive EMC Testing: Full Vehicle and Component Testing

Dr. Vince Rodriguez, Ph.D.

Antenna Product Manager

ETS-Lindgren, Cedar Park, TX, USA

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EMC Testing per CISPR 12 and ISO 11451-2:

CISPR 12, ISO 11451-2 and Equivalent Standards

Outline

- CISPR 12 site and chamber requirements
- Antenna requirements for CISPR 12
- ISO 11451-1 and –2: Chamber requirements
- Recommended antennas and Amplifier Power

CISPR 12

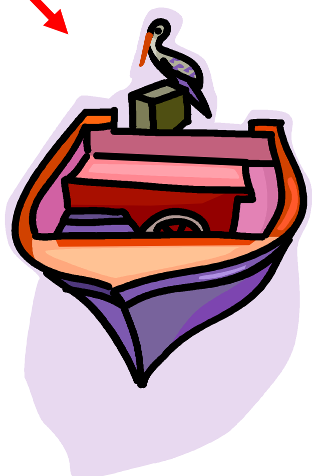
Vehicles, boats, and internal combustion engine driven devices –

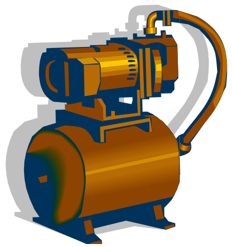
Radio disturbance characteristics –

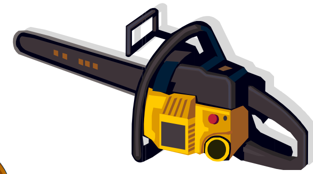
Limits and methods of measurement for the protection of receivers except those installed in the vehicle/boat/device itself or in adjacent vehicles/boats/devices

CISPR 12

Radio disturbance characteristics for the protection of receivers used from emissions from vehicles, boats, and on devices ...







CISPR 12

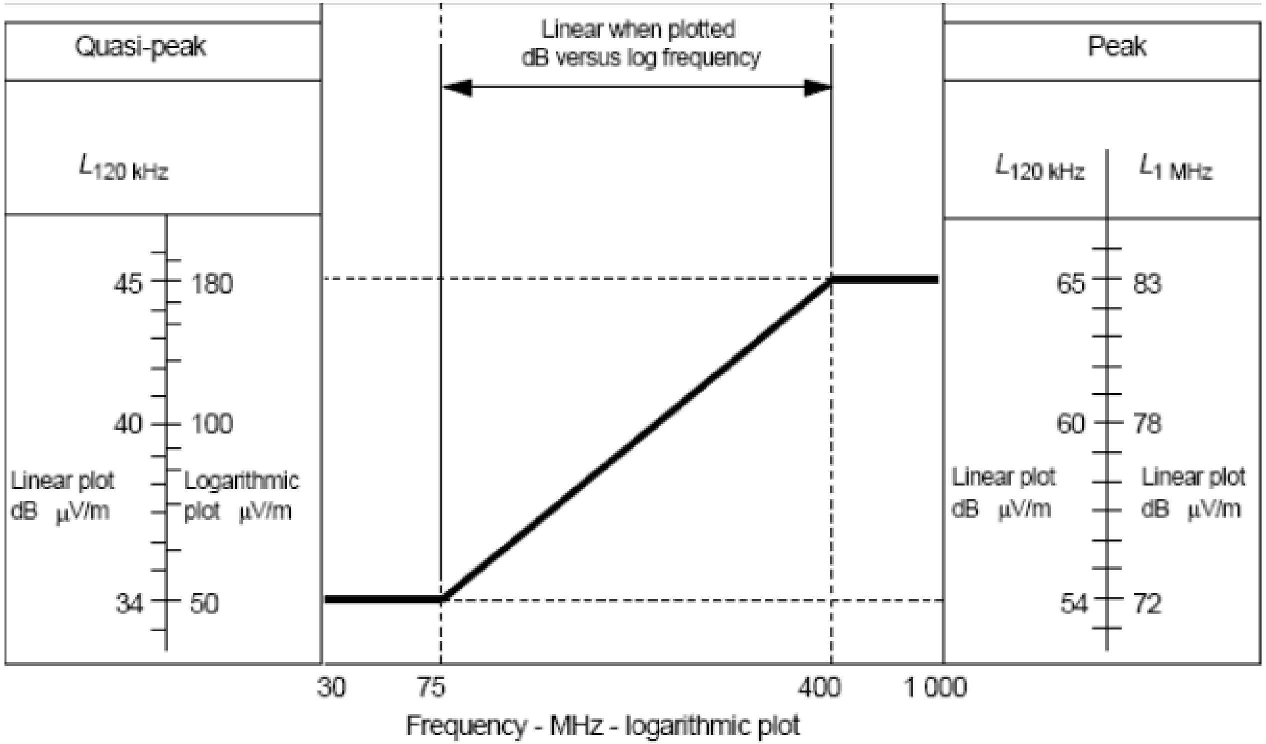
- So CISPR 12 deals with how much do electric and electronic systems affect outside receivers from emissions from systems aboard:
  - Automobiles powered by internal combustion engines or electric motors
  - Boats (up to 15m) powered by internal combustion engines or electric motors
  - Devices powered by internal combustion engines but not for the transport of people.(I.e. compressors, chainsaws, garden maintenance equipment, etc)

CISPR 12

- As with any other emissions standard we look at measurements at 10m (3m being allowed and limits being raised by 10dB)
- There are limits for Broadband noise and narrowband noise

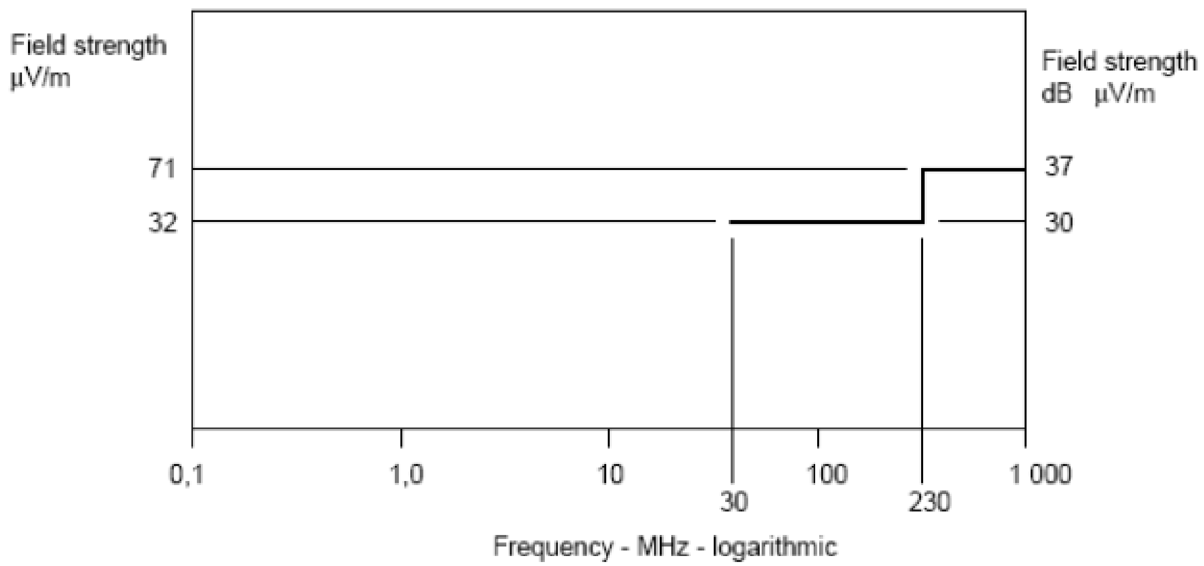
CISPR 12

- Limits for broadband emissions.
- Background noise should be 6dB below the limits (more on that later) and for 3m levels should be 10dB higher



CISPR 12

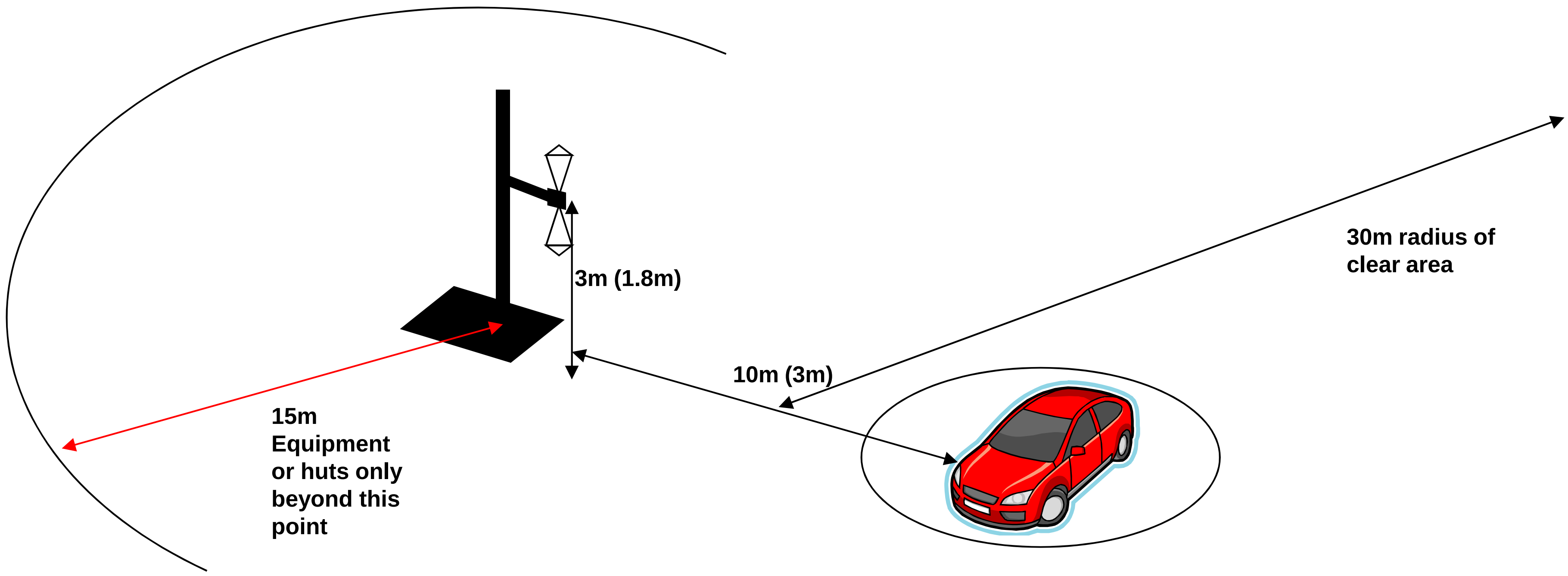
- Limits for narrow band emissions.
- Background noise should be 6dB below the limits (more on that later) and for 3m levels should be 10dB higher



CISPR 12

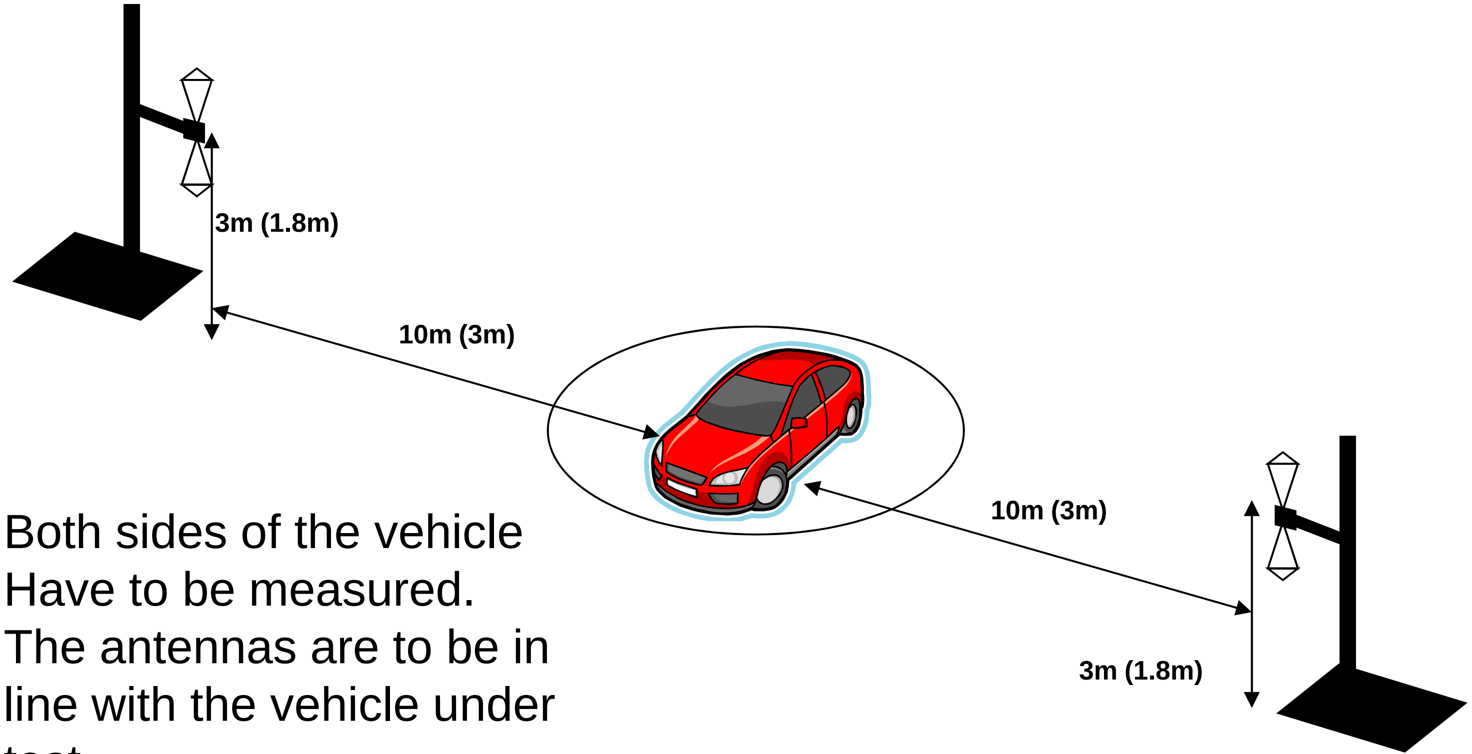
- Regarding the test site, the CISPR 12 Standard defines the oats as the recommended site.
- The OATS must follow the requisites stated in CISPR 16

OATS layout



3m (1.8m)
30m radius of
clear area
10m (3m)
15m
Equipment
or huts only
beyond this
point

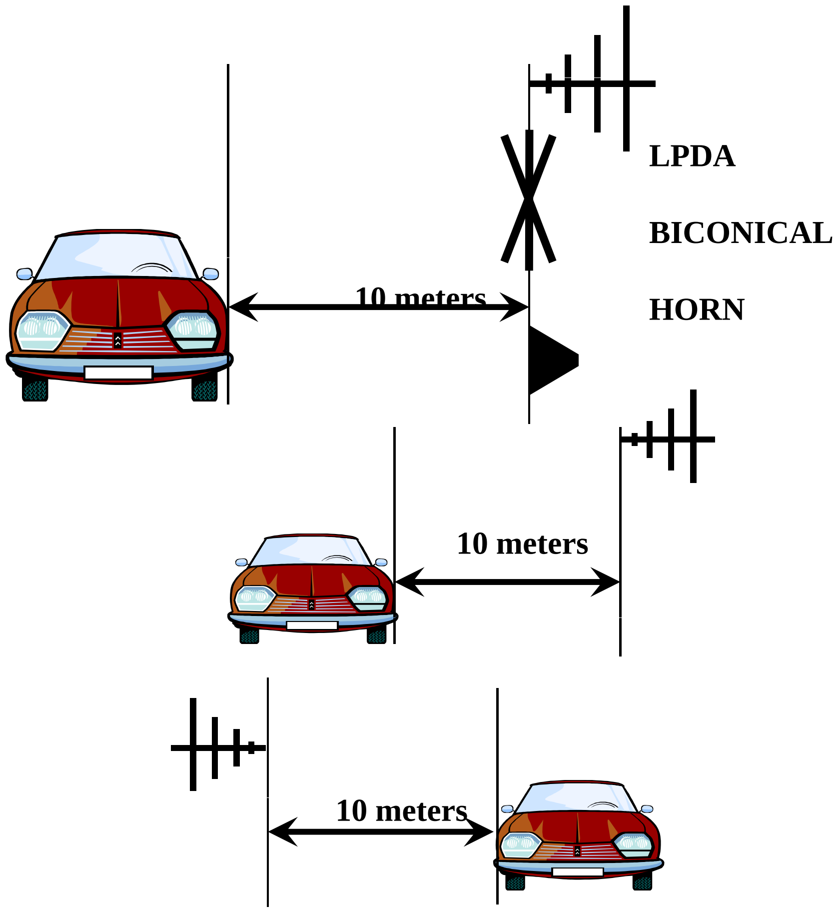
measurement layout



Both sides of the vehicle
Have to be measured.
The antennas are to be in
line with the vehicle under
test.

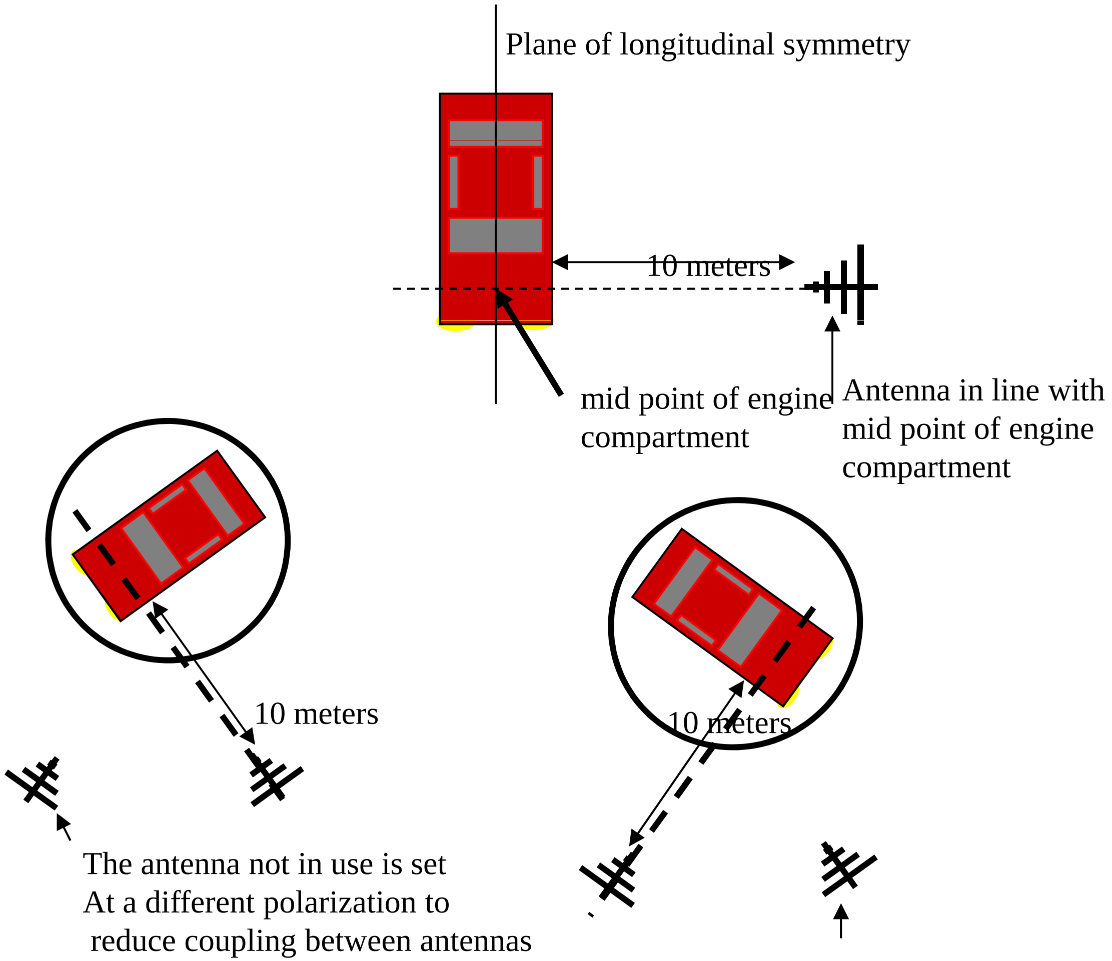
Measurement Layout

- The 10m emission testing locates the antenna 10m from the outer shell of the vehicle
- The antenna is not scan but located at 3m height. (For 3m testing the antenna is located at 1.8meters.
- Both sides of the vehicle and both polarizations are tested



Automotive Testing: A Short Introduction

- The antenna is to be in line with the middle point of the engine compartment.
- A two antenna position site and the addition of a turntable makes the test much easier
- There is no need to reposition the vehicle to test the other side.



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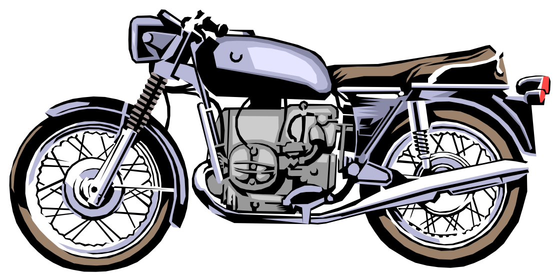
CISPR 12 EUT req.

- Internal combustion engine:
  - Engine Idle:
    - 2500RPM 1cyl
    - 1500RPM 2 or more cyl
- Electric Propulsion motors
  - Vehicle running:
    - 40km/h or max vehicle speed if less.

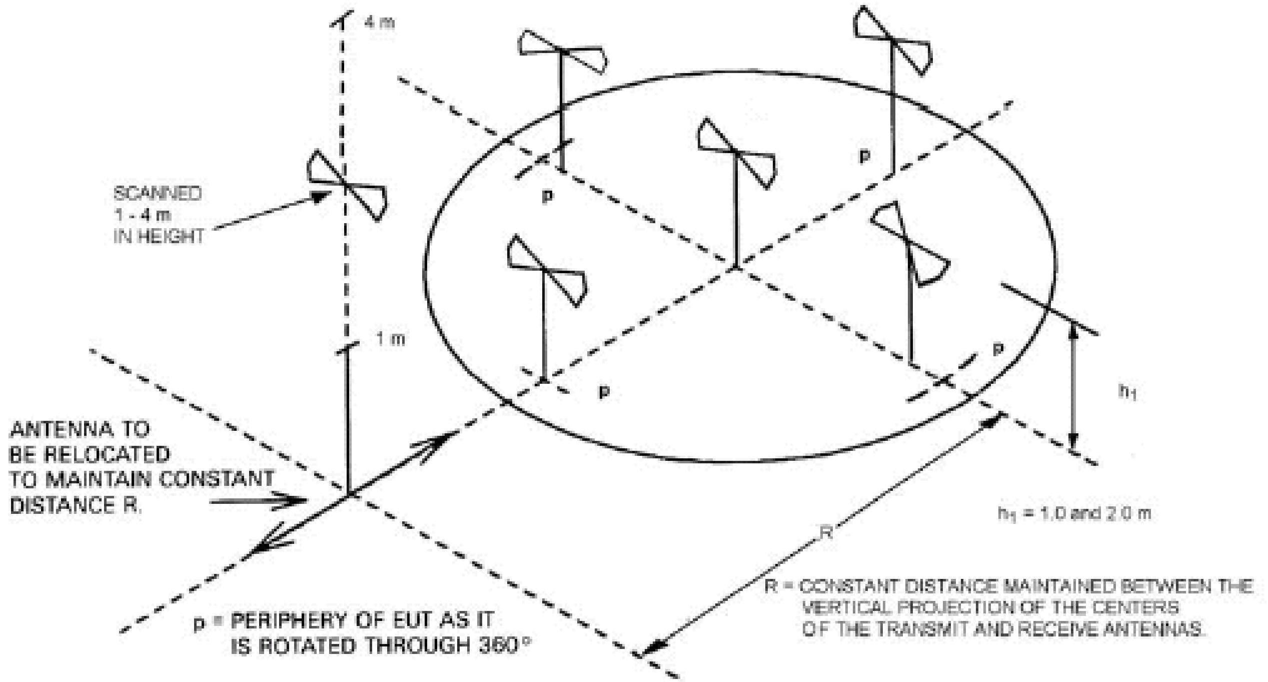


Alternative Sites

- Anechoic Chamber:
  - A shielded absorber lined enclosure can be used provided that correlation with OATS can be shown
  - In my view, doing the NSA measurement of the Chamber if the results fall within the limits of the CISPR 16 requirements the Chamber is good for CISPR 12 testing

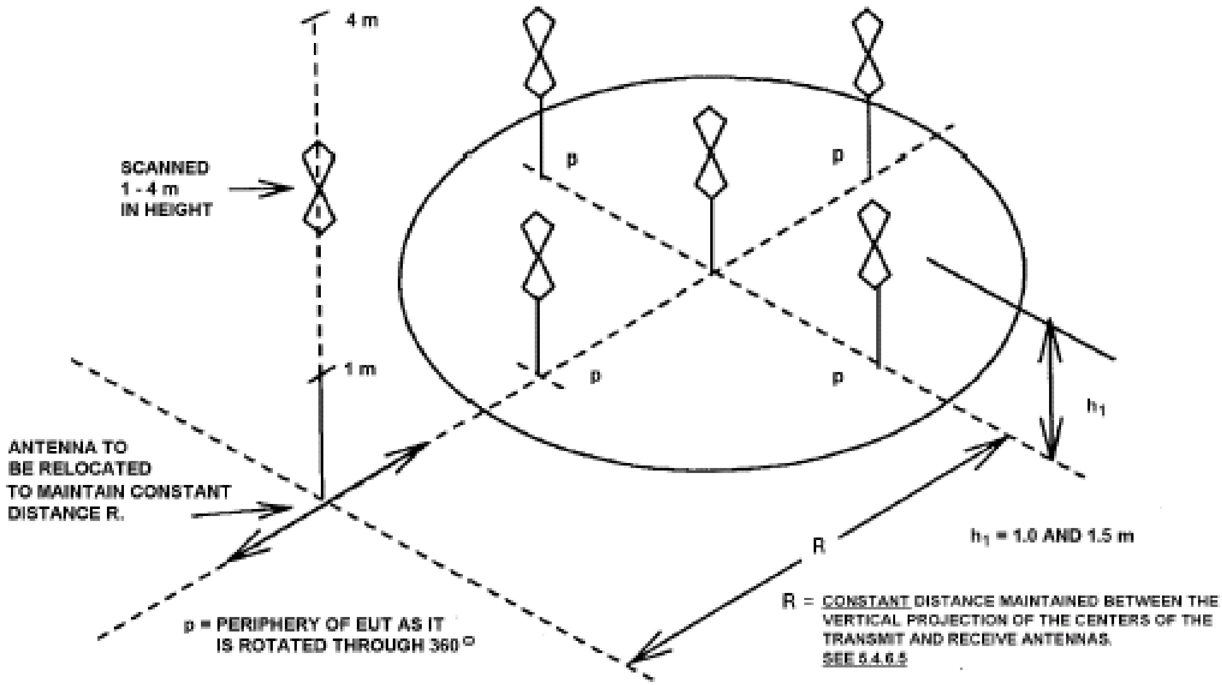
Site Quality Verification
(NSA – Normalized Site Attenuation)

- Horizontal Polarization



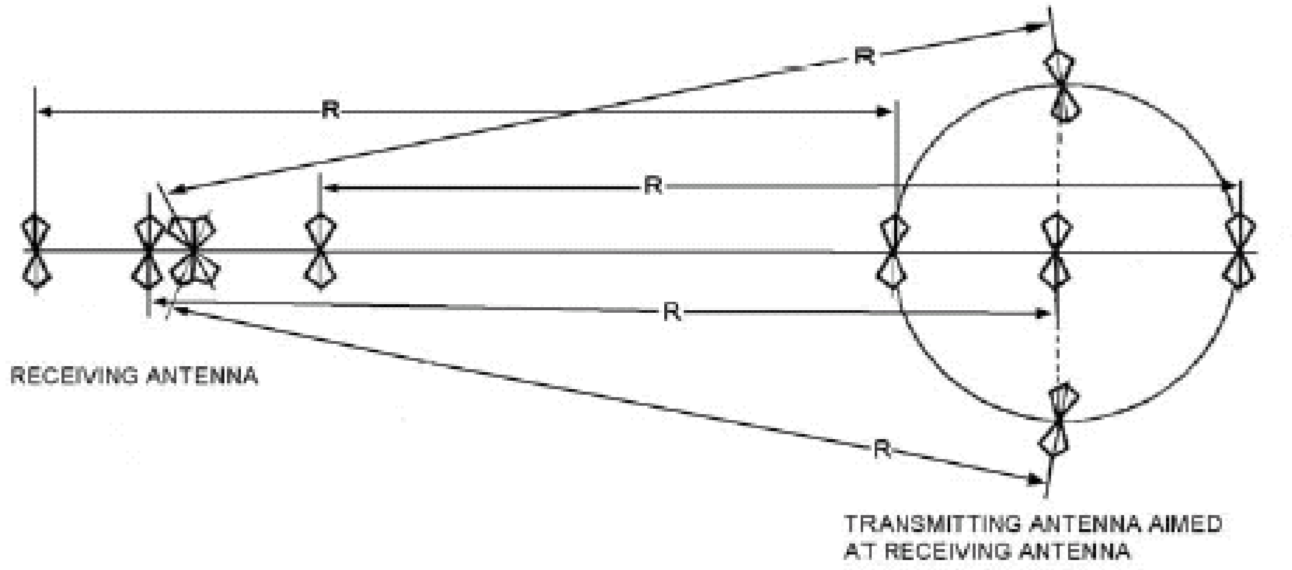
Site Quality Verification
(NSA – Normalized Site Attenuation)

- Vertical Polarization



Site Quality Verification
(NSA – Normalized Site Attenuation)

- Typical measurement positions.



CISPR 12 Absorber

Hybrid Absorber .

Electric and Magnetic Losses

Preferred technology for EMC Applications. foam has to have special formula for good matching with ferrite tile at the bottom. At High frequencies its performance is not as good as MW pyramid of equal size. Flat top causes undesired reflections at MW range. Between 1m and 1.5m in length

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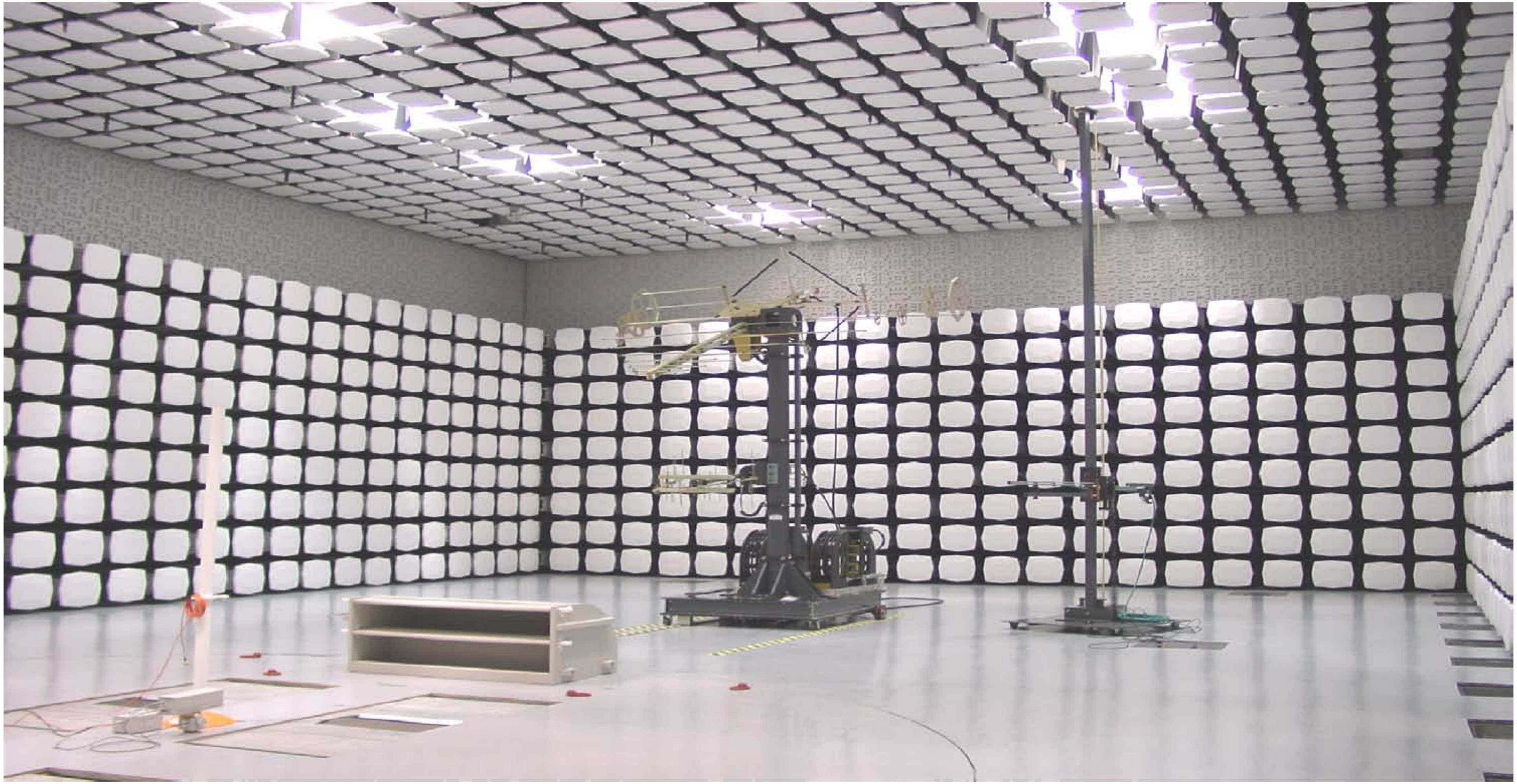

Honda R&D America Raymond, Ohio

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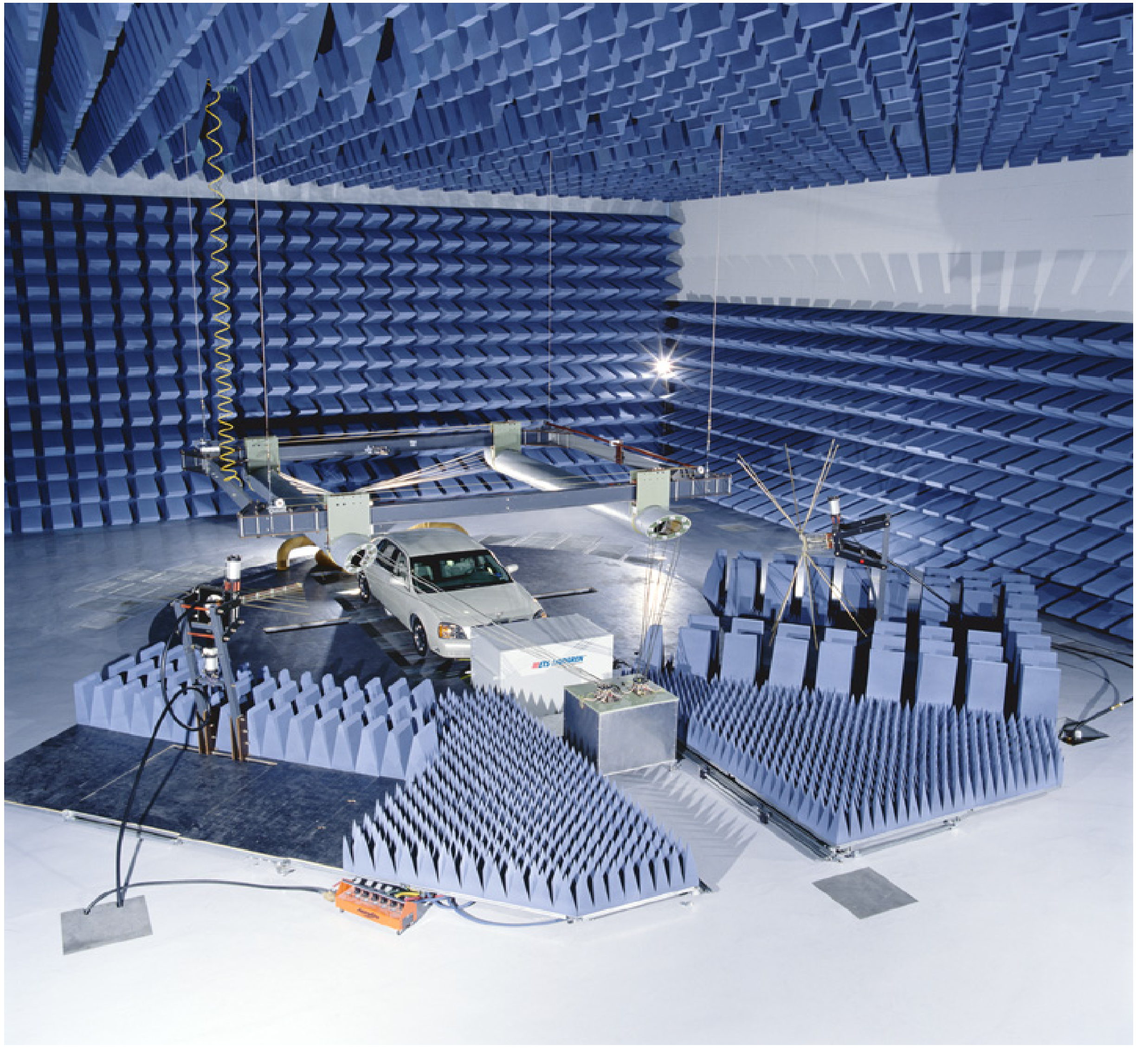

GM Proving Grounds Milford, Michigan

ETS·LINDGREN™
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Commercial EMC/Automotive EMC and Antenna/Satellite Chamber
at LIT/INPE São Jose dos Campos, SP, Brazil

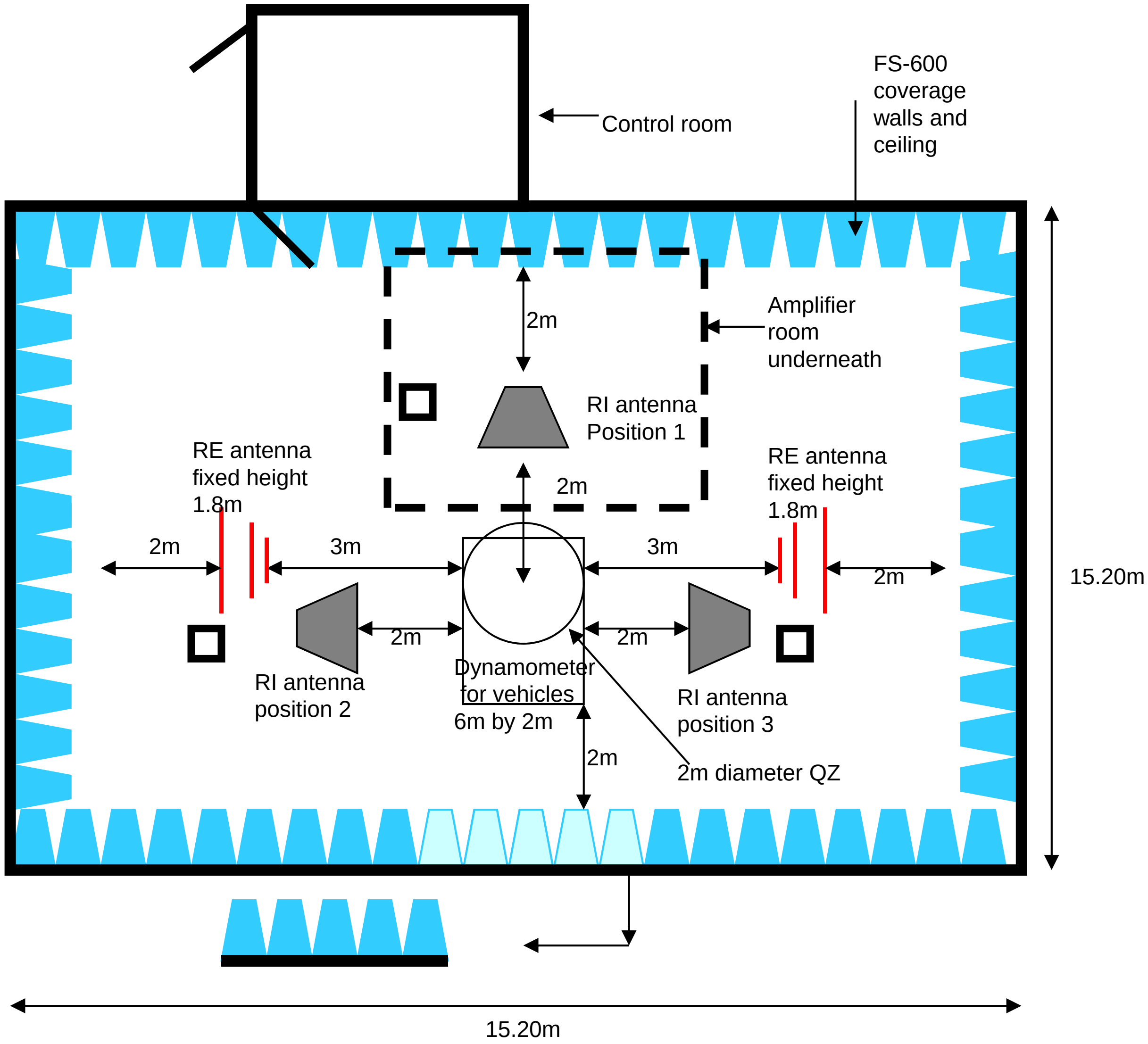
Typical EMC 10m range Chambers

model	Size Ft (m)	absorber	NSA	FU
FACT 10 –3.0 Std	59,30,22 (18,9.2,6.6)	PS-1250 all walls and ceiling, RI patch of PS 600	±4.0dB	0 to +6dB 75%
FACT 10 – 3.0 Std +	63,38,28 (19,11.5,8.5)	PS-1250 9 rows walls, ceiling, RI patch of PS 600	±3.5dB	0 to +6dB 75%
FACT 10 –3.0 premium	63,38,28 (19,11.5,8.5)	FS-1500 9 rows on walls, ceiling, RI patch FS-400	±3.0dB	0 to +6dB 75%
FACT 10 –4.0 Std	65,36,22 (20,11,6.6)	PS-1250 all walls and ceiling, RI patch of PS 600	±4.0dB	0 to +6dB 75%
FACT 10 – 4.0 Std +	65,40,28 (20, 12, 8.5)	PS-1250 9 rows walls, ceiling, RI patch of PS 600	±3.5dB	0 to +6dB 75%
FACT 10 –4.0 premium	65,40,28 (20,12,8.5)	FS-1500 9 rows on walls, ceiling, RI patch FS-400	±3.0dB	0 to +6dB 75%
FACT 10-6.0 Std +	71,43,28 (22,13,8.5)	PS-1250 9 rows walls, ceiling, RI patch of PS 600	±3.5dB	0 to +6dB 75%

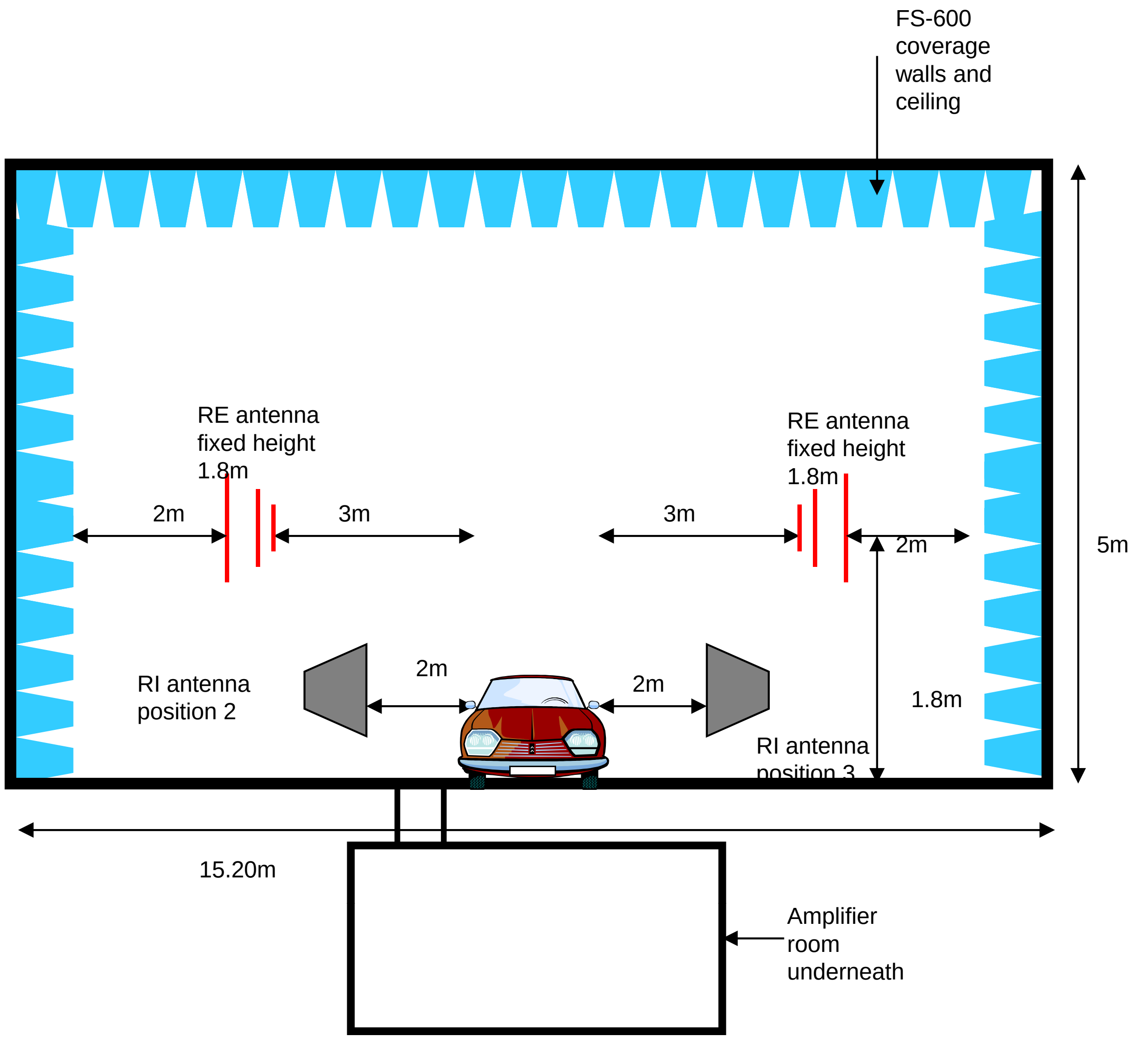
Special features for automotive

- Dynamometer Turn Table. Although for emissions the vehicle just needs to idle.
- Exhaust system
- Fire Protection systems
- QZ may be as large as 9m making chamber larger
- Chamber supported EH generators
- Large level entry door

Dynamometer no Turntable (3m testing)



Turntable no Dynamometer (3m testing)



CISPR12: Antennas

- **Antennas are a key requirement in CISPR 12. The standard bases its choice of antennas on the CISPR 16 Standard**

Frequency range	**Type**
30-300MHz	Biconical Model
200-2000MHz	Log periodic Model
1GHz-18 GHz	Dual ridge guide horn

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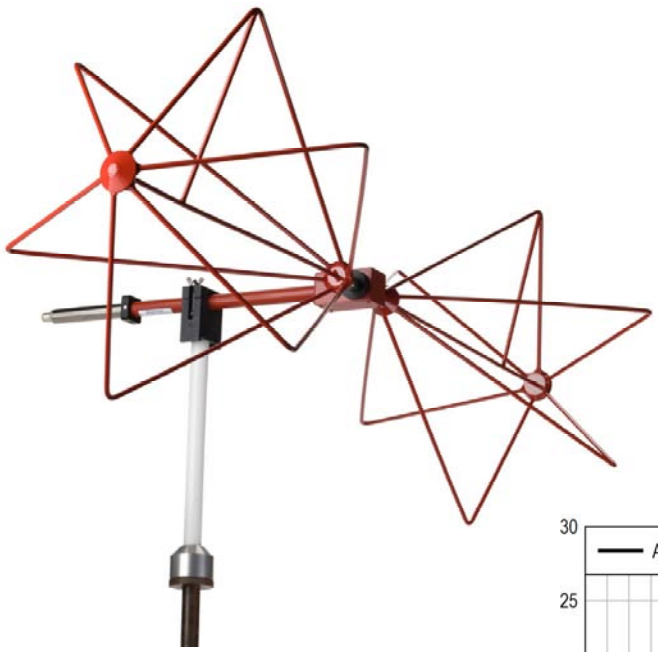
30MHz to 200MHz

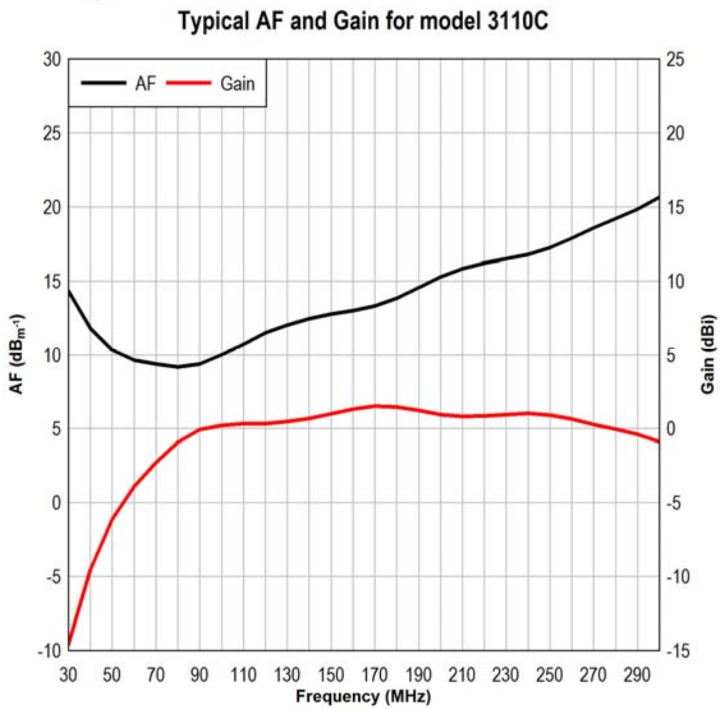
Biconical Antennas.

is recommended for emission testing from 30MHz to 200MHz.

It is calibrated at 1, 3 and 10m per SAE ARP 958 and ANSI C63.4

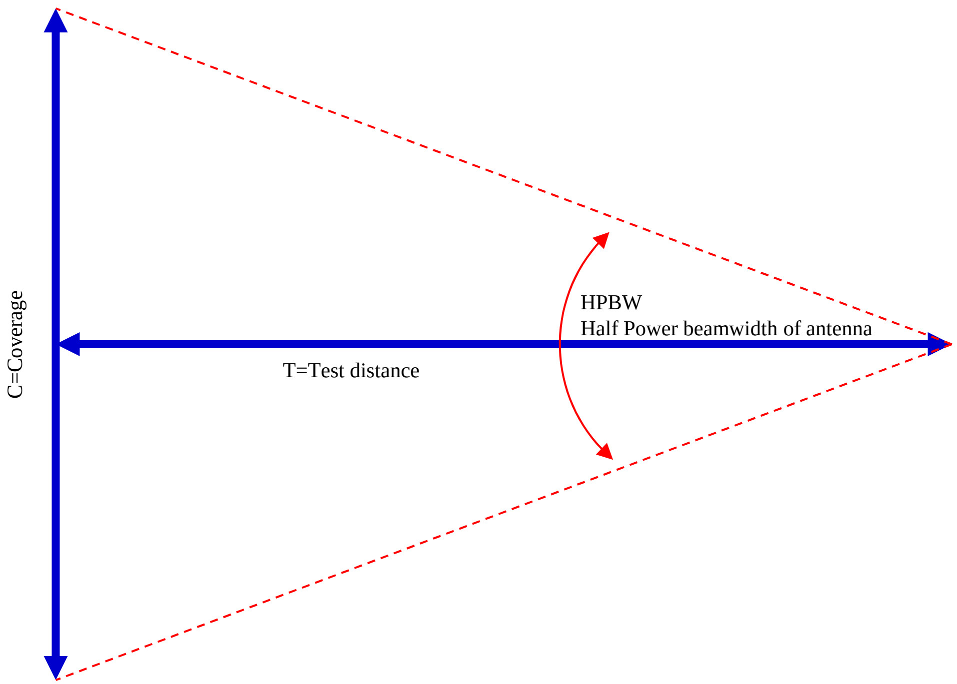
It includes all hardware for mounting the antenna using the rear mount (stinger) or a center or gravity mount.



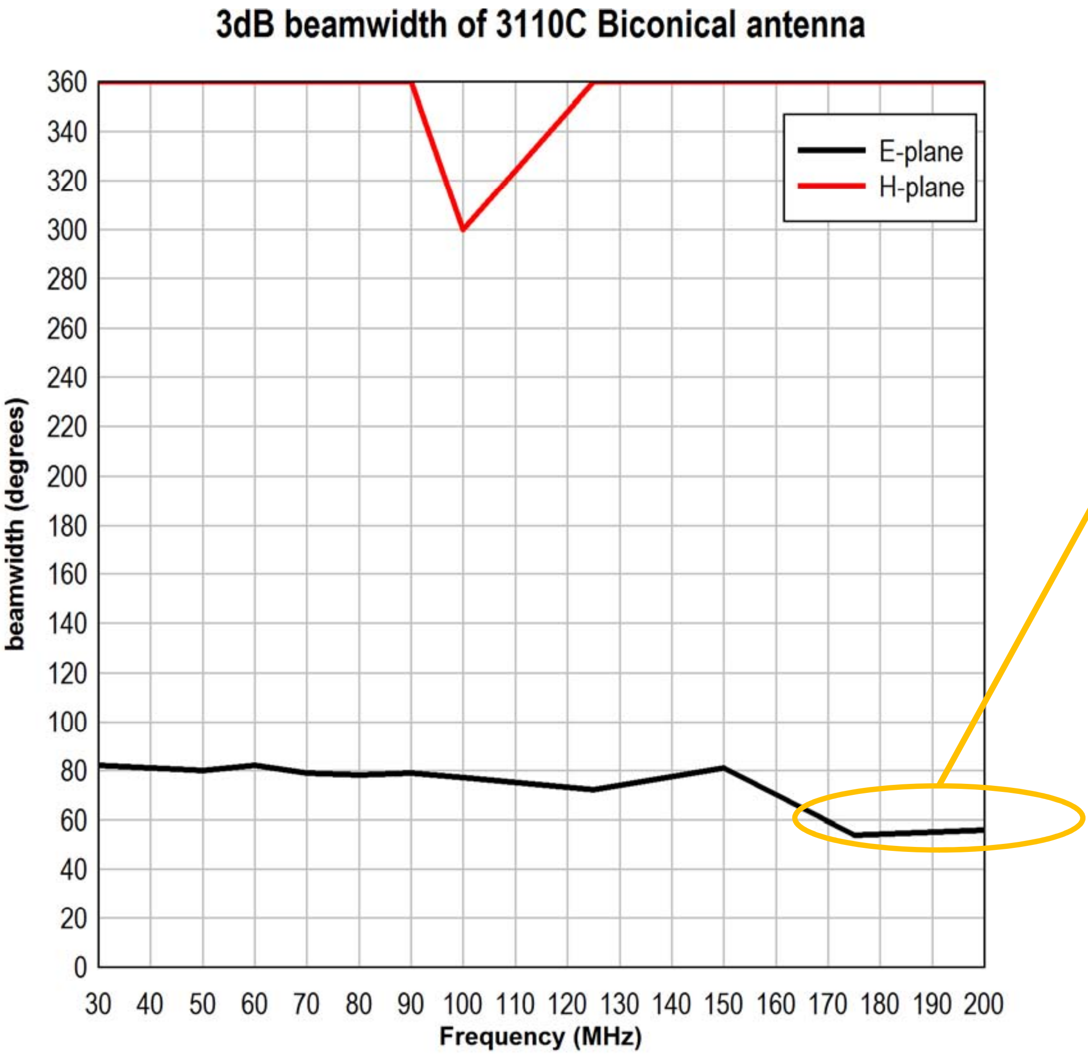


Coverage

C=2T x tan(HPBW/2)



Biconical coverage

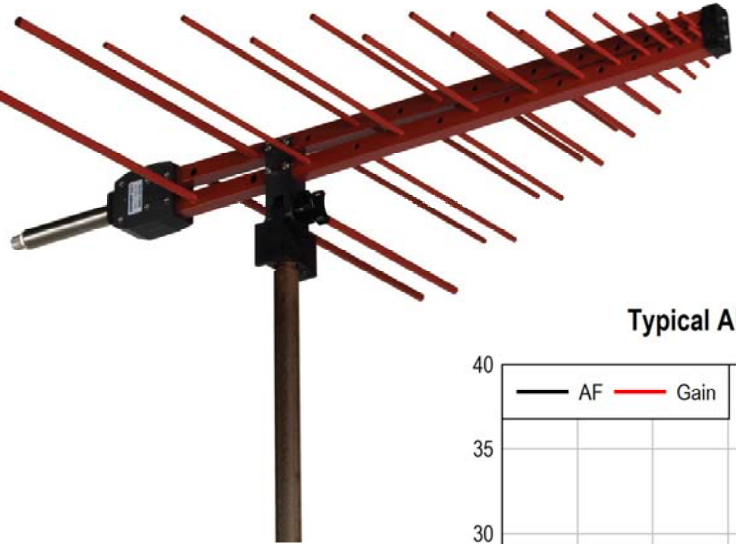


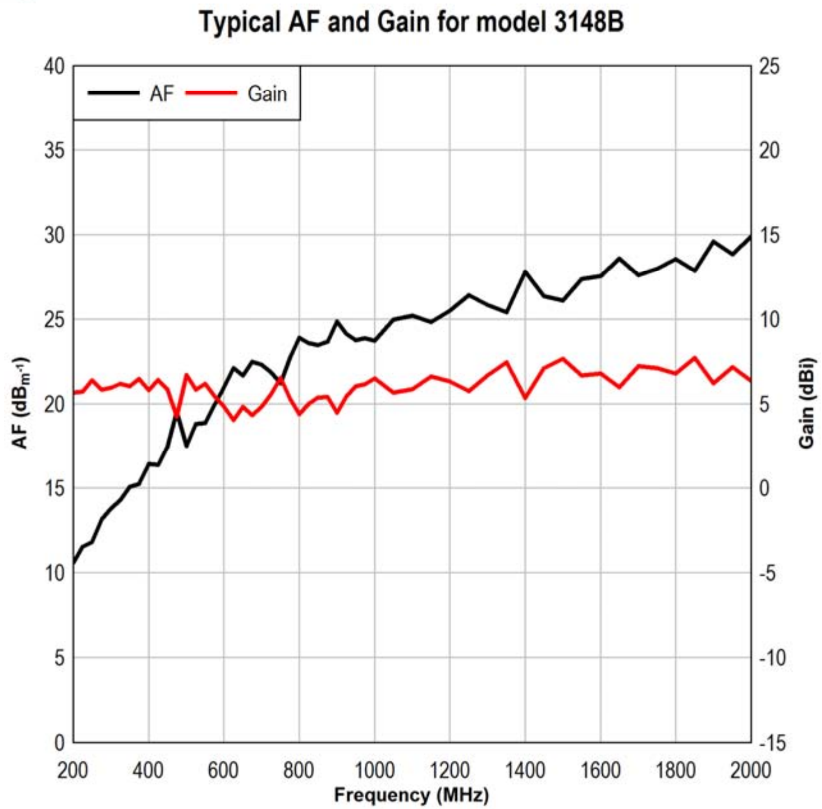
Worst case 55 degrees on E plane
Hence:
3m test distance
3.12m coverage
10m test distance
10.4m coverage

LPDA 200MHz to 1000MHz

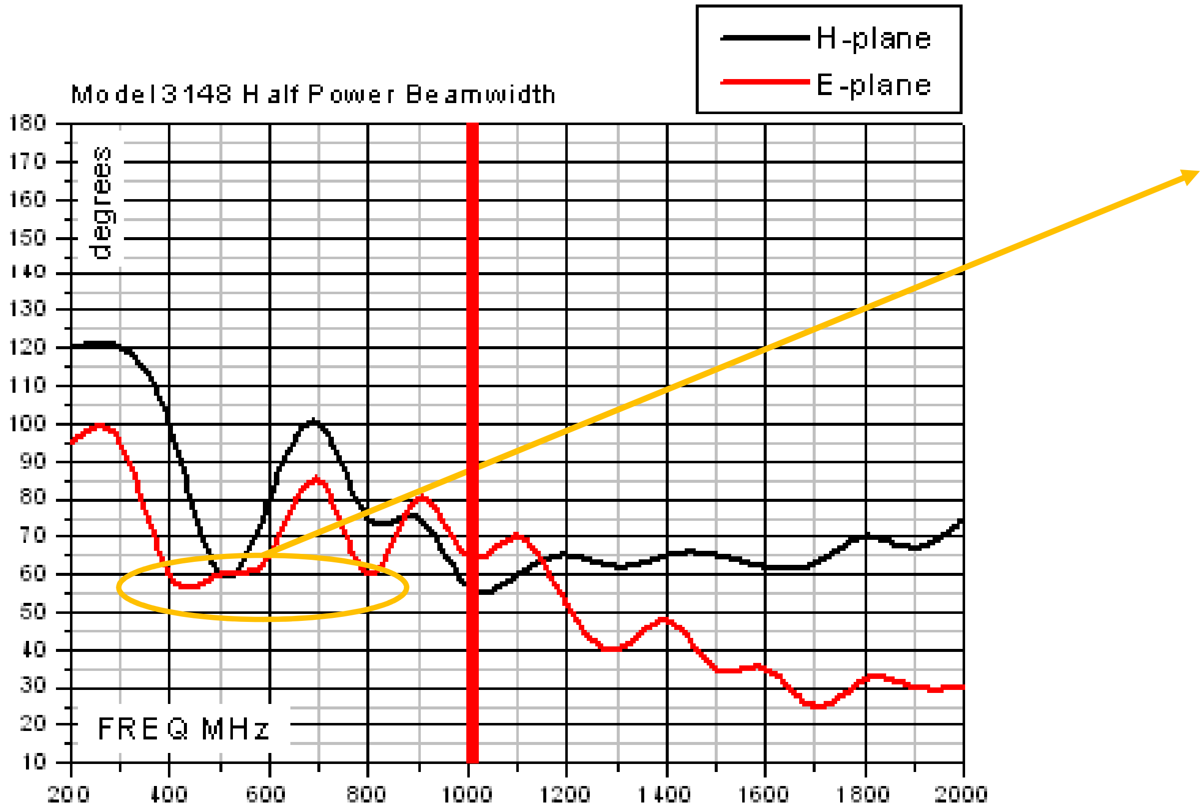
LPDA antenna:
Low VSWR constant gain

Flexible mounting:
Rear "stinger" mount and center of gravity mount.





LPDA coverage



Worst case 56 degrees on E plane
Hence:
3m test distance
3.19m coverage
10m test distance
10.63m coverage

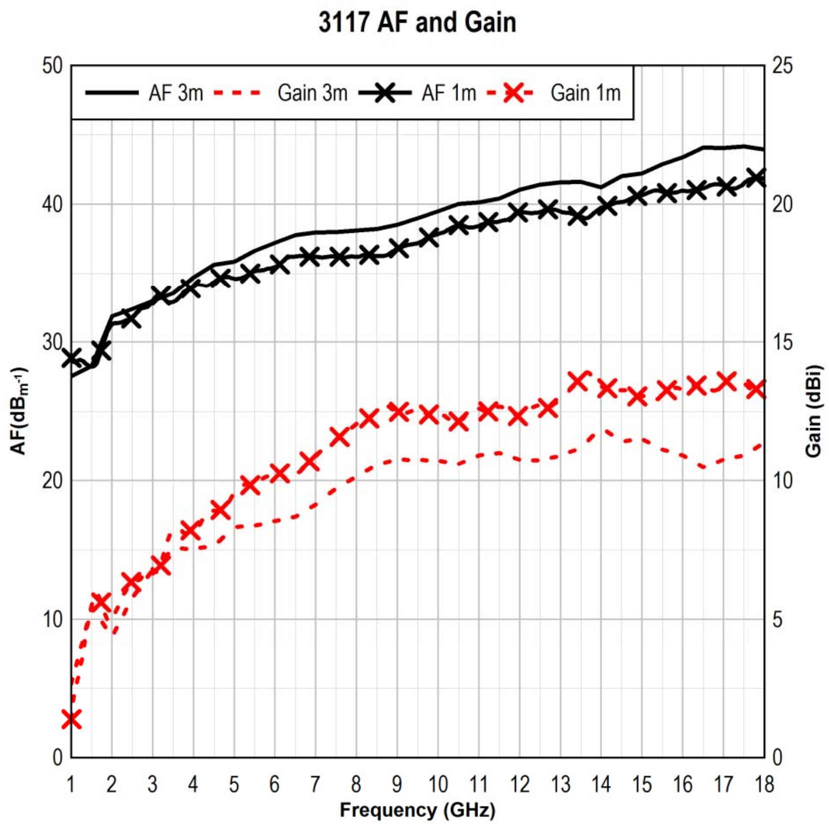
Notice that we do not use above 1GHz

Ridge horns 1GHz to 18GHz

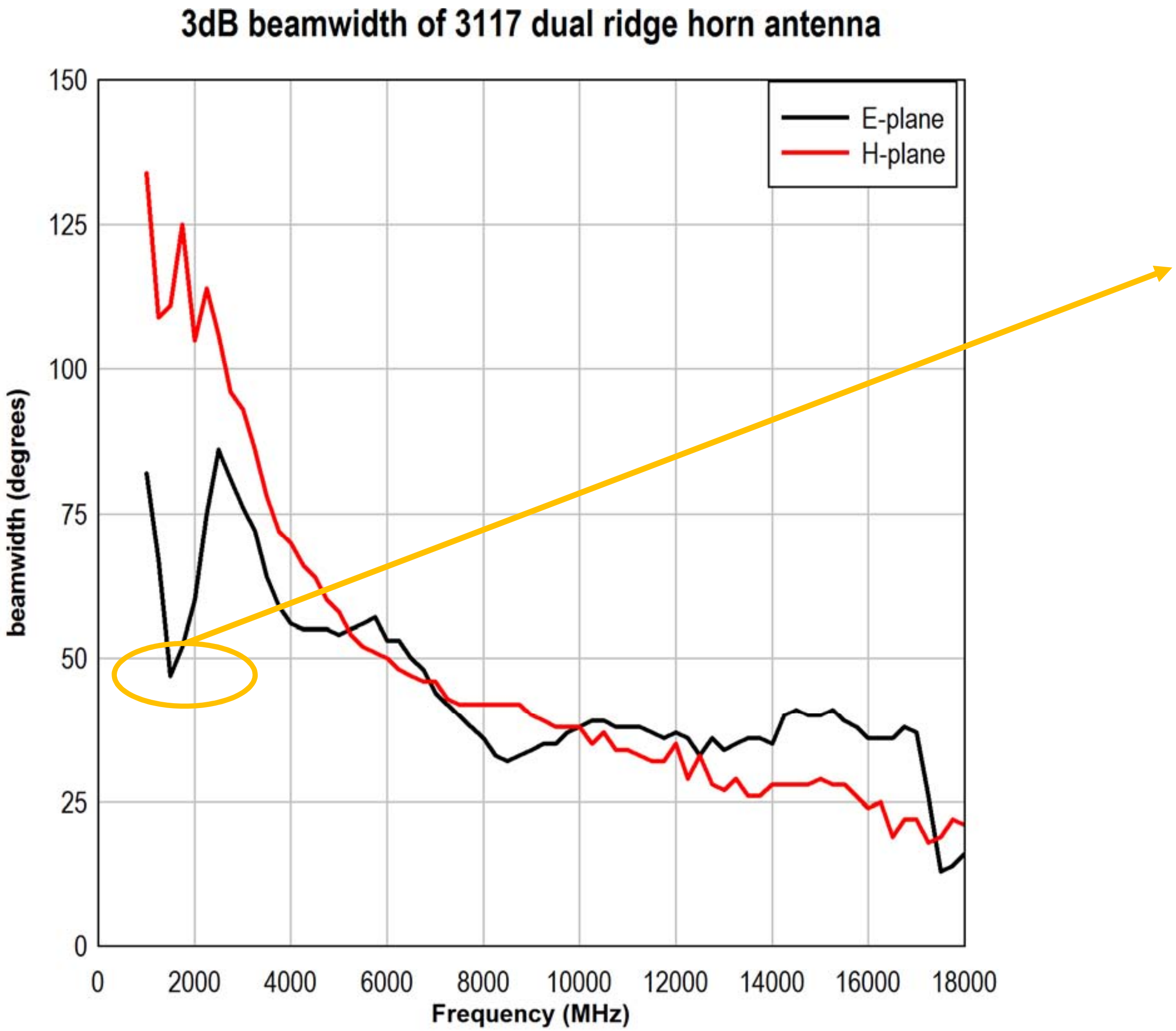
Dual Ridge Horns.
(although currently not in the CISPR 12 limits there are limits for 1GHz to 2GHz in the European norm)

Stinger and tripod mounts are available

Low VSWR and great coverage



DRHA coverage



Worst case 48 degrees on E plane up to 6GHz
Hence:
3m test distance
2.67m coverage
10m test distance
8.9m coverage

Notice that we do not use above 6GHz as there are no known limits at those high frequencies

As with all antennas the beam narrows as the frequency increases and the gain does as well.

Vehicle immunity

Automotive Immunity testing

The main Standards that this solution addresses are the following:

ISO 11451-2

SAE J551-11

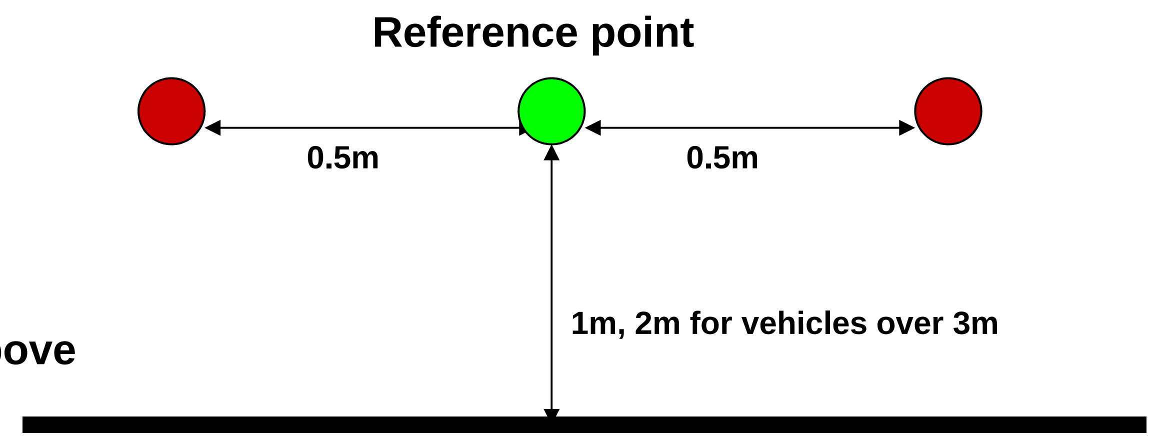
95/54 EC Annex VI

The SAE and the ISO are virtual copies of each other and they both require a highest severity level of 100V/m. ISO contemplates an additional level of severity to be agreed between the test house and the manufacturer..

Field uniformity requirements are (for SAE and ISO) that the field level be generated at a reference point located 1m above the ground on to which the vehicle rests (2m for vehicles higher than 3m) and at two points 75cm on either side of the reference point. At these points the field level should be within 3dB of the reference point level. For 95/54 EC the points are 50cm on either side and the highest level of severity is 24V/m with 80% AM modulation.

Automotive EMC Immunity

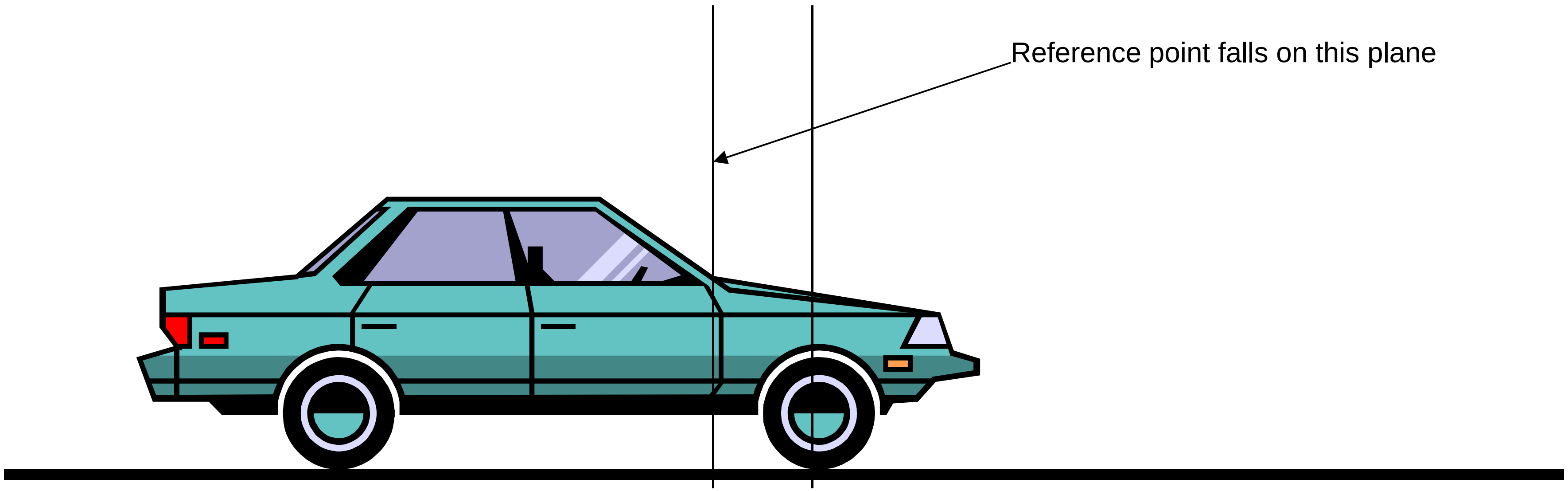
- 100V/m highest severity level (200v/m contemplated in the ISO standard
- Field Uniformity Requirements

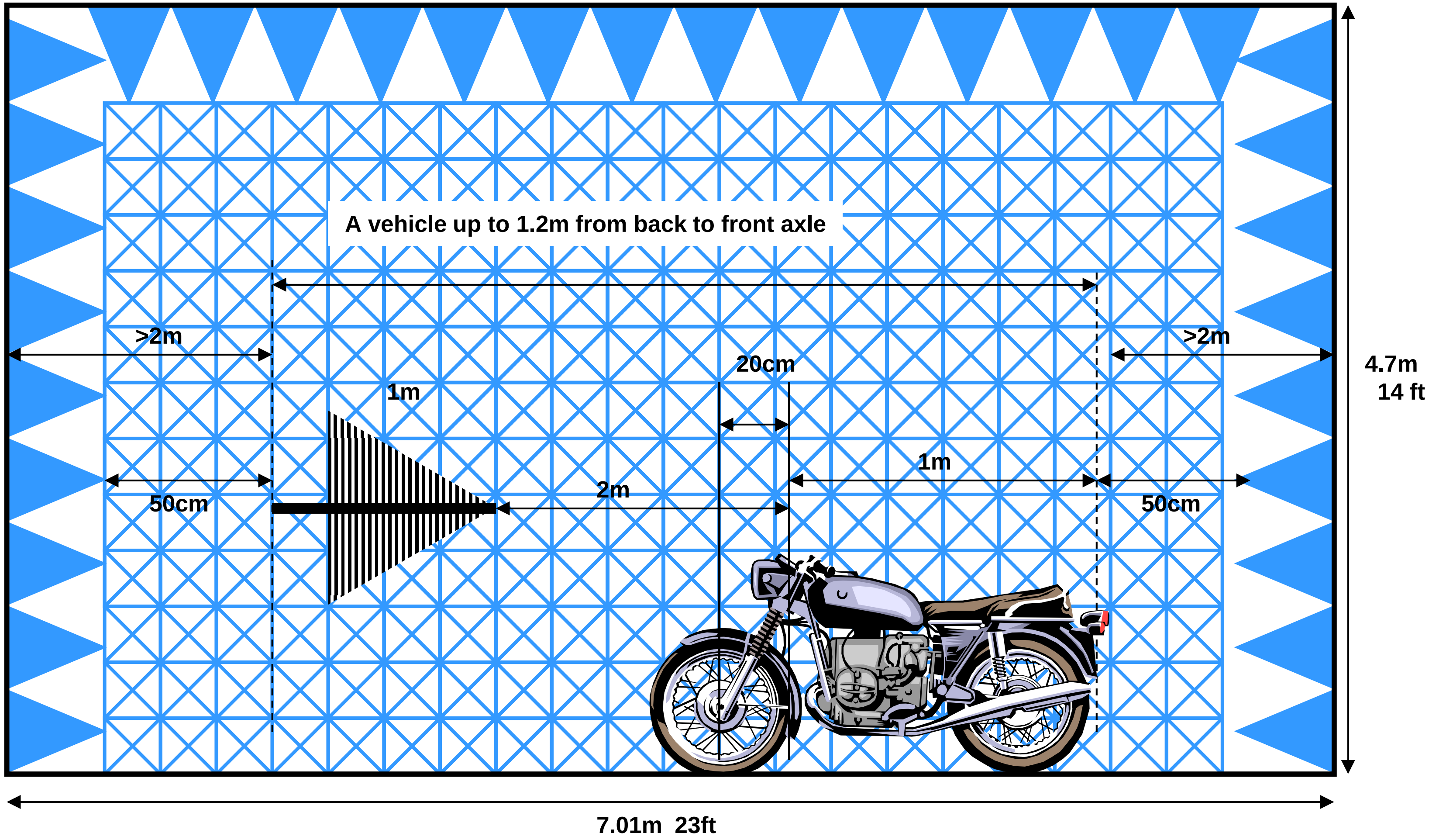


SAEJ551-11
ISO 11451-2
200MHz and above

Automotive EMC Immunity

The reference point position on the vehicle corresponds to the point where the windshield and the hood of the car meet. Or the front axel, which ever is farther away from the antenna.
For rear-engined vehicles the vehicle will be tested with the rear facing the antenna and the reference point at the rear axel.




A vehicle up to 1.2m from back to front axle
>2m
>2m
20cm
1m
1m
2m
50cm
50cm
4.7m
14 ft
7.01m 23ft

Recommended Antennas

- 100kHz to 30MHz Stripline/E-H generator
- 30MHz to 100MHz Biconical
- 100MHz to 1000MHz Dual Ridge Horn
- 1000MHz to 18000MHz Octave Gain horns

Stripline generator

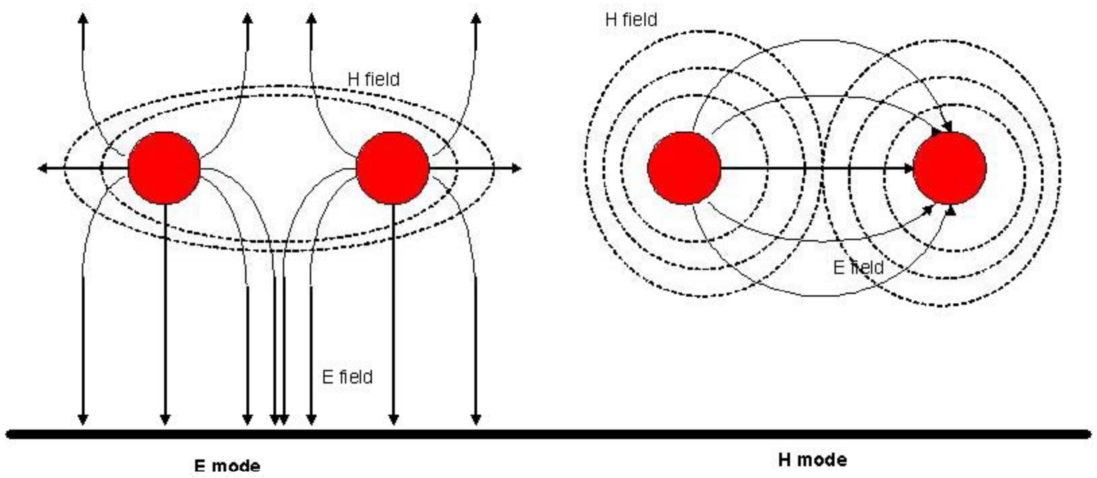
- Transverse Electromagnetic Mode Transmission lines.
- Field concentrated between elements and ground.
- At low frequencies chamber resonances can have an effect on its performance

E-H Field Generators

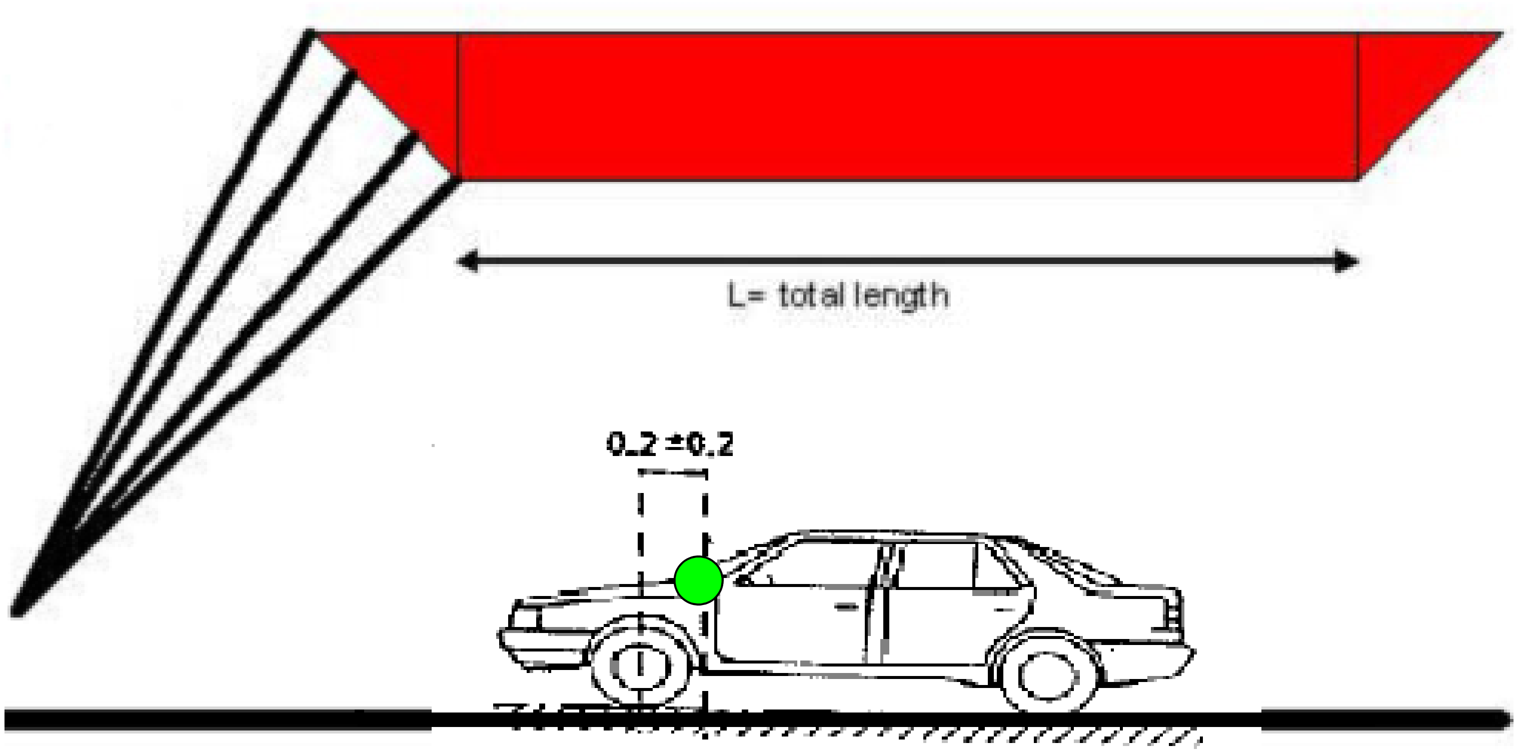
- Transverse Electromagnetic Mode Transmission lines.
- Field concentrated between elements and ground.
- No radiation into the chamber unless separation between the elements is more than ½ a wavelength

E-H Field Generators

- Two elements
- Both can be driven together against ground (E Mode)
- One can be driven against the other isolated from ground (H Mode)



E-H Field Generators

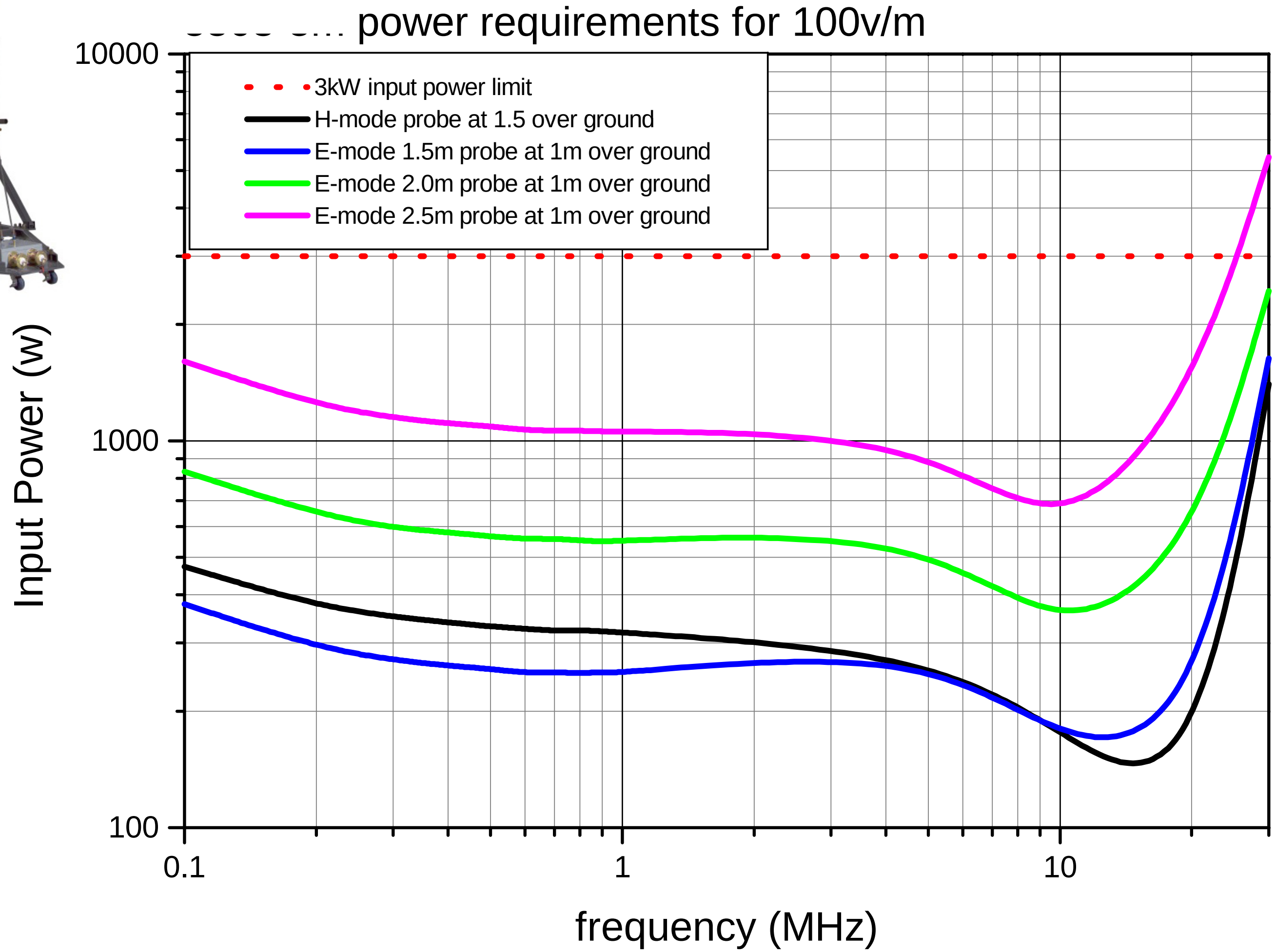


Self Supported Units: ideal for smaller vehicles

1. 5m element length.
2. 2.5m maximum element height.
3. 2m Maximum element separation for H mode.
4. Manual Operation
5. 3kW maximum input power.

Self supported units

with its limited input power (3kW) can only meet 100v/m requirements. Also it is manually operated and requires at least 4 people to set up. It is intended as a lower cost alternative for small vehicle testing



Automated chamber supported Units

1. **Variable element length (as customer required)**
2. **Variable pneumatic element separation for H mode.**
3. **Variable height motor driven**
4. **10kW maximum input power.**

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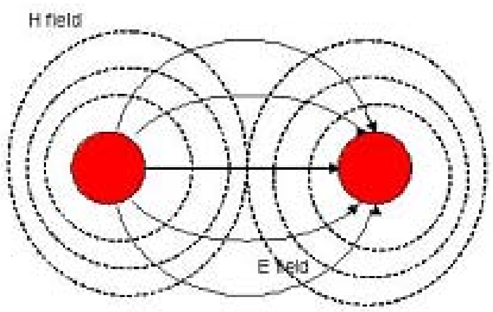
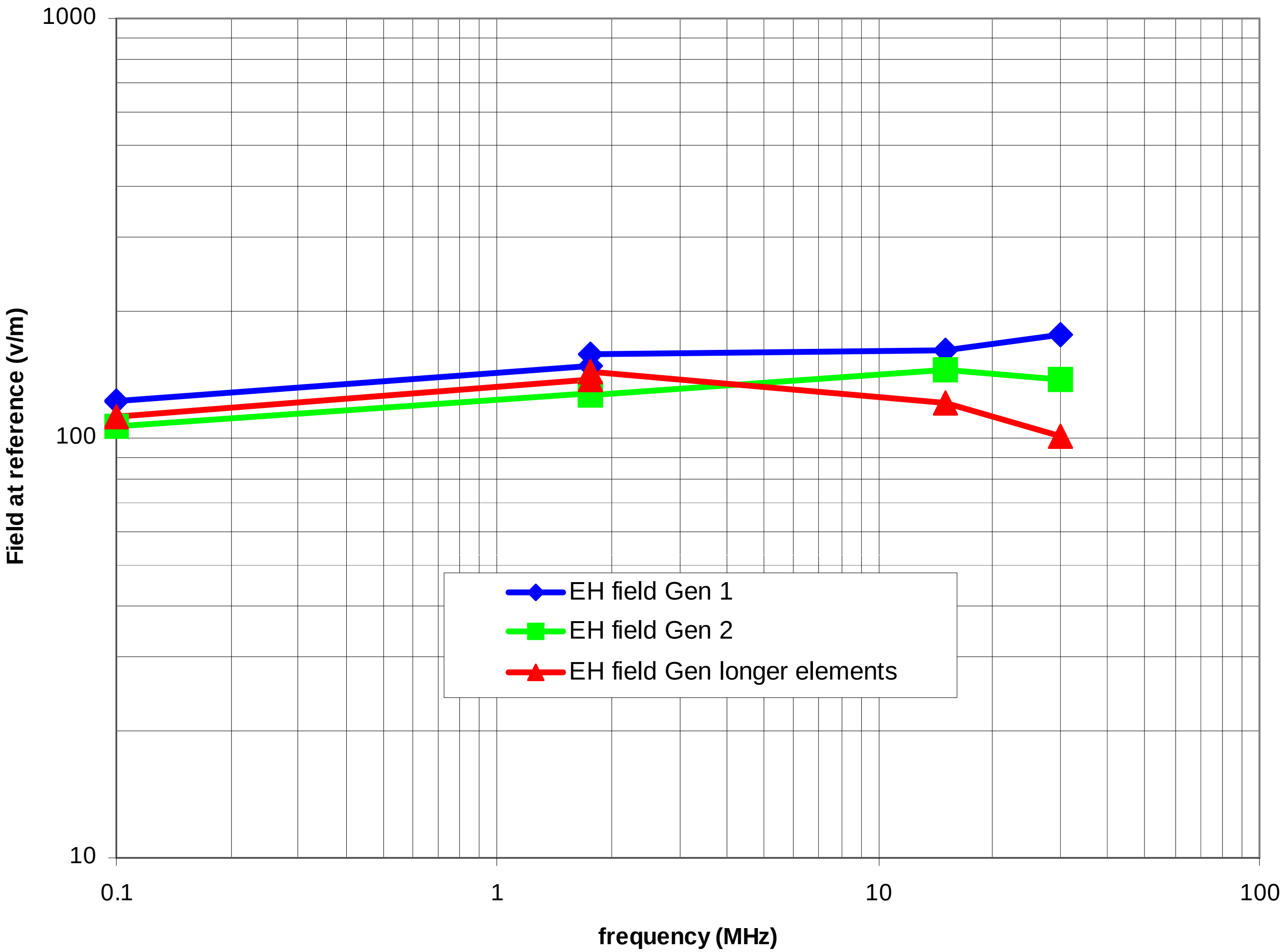
Chamber supported

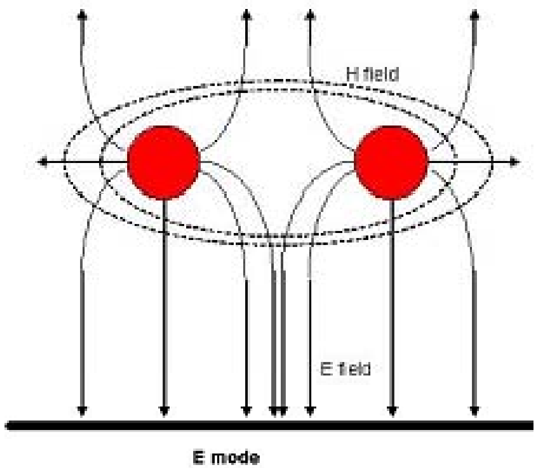


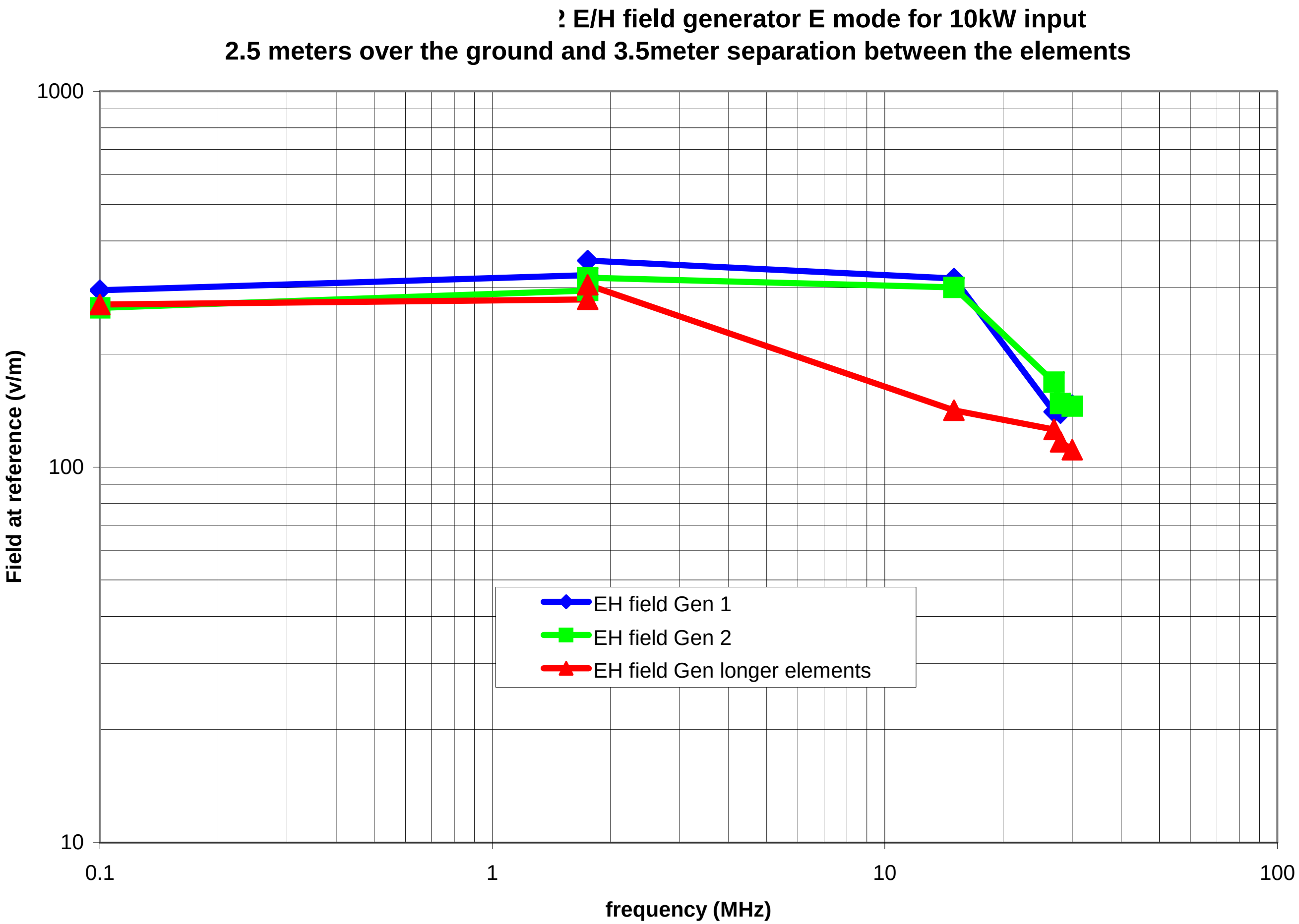
H mode

E/H field generator Horizontal polarization (H mode) for 10kW input.
2 meters over the ground and 3.5meter separation between the elements

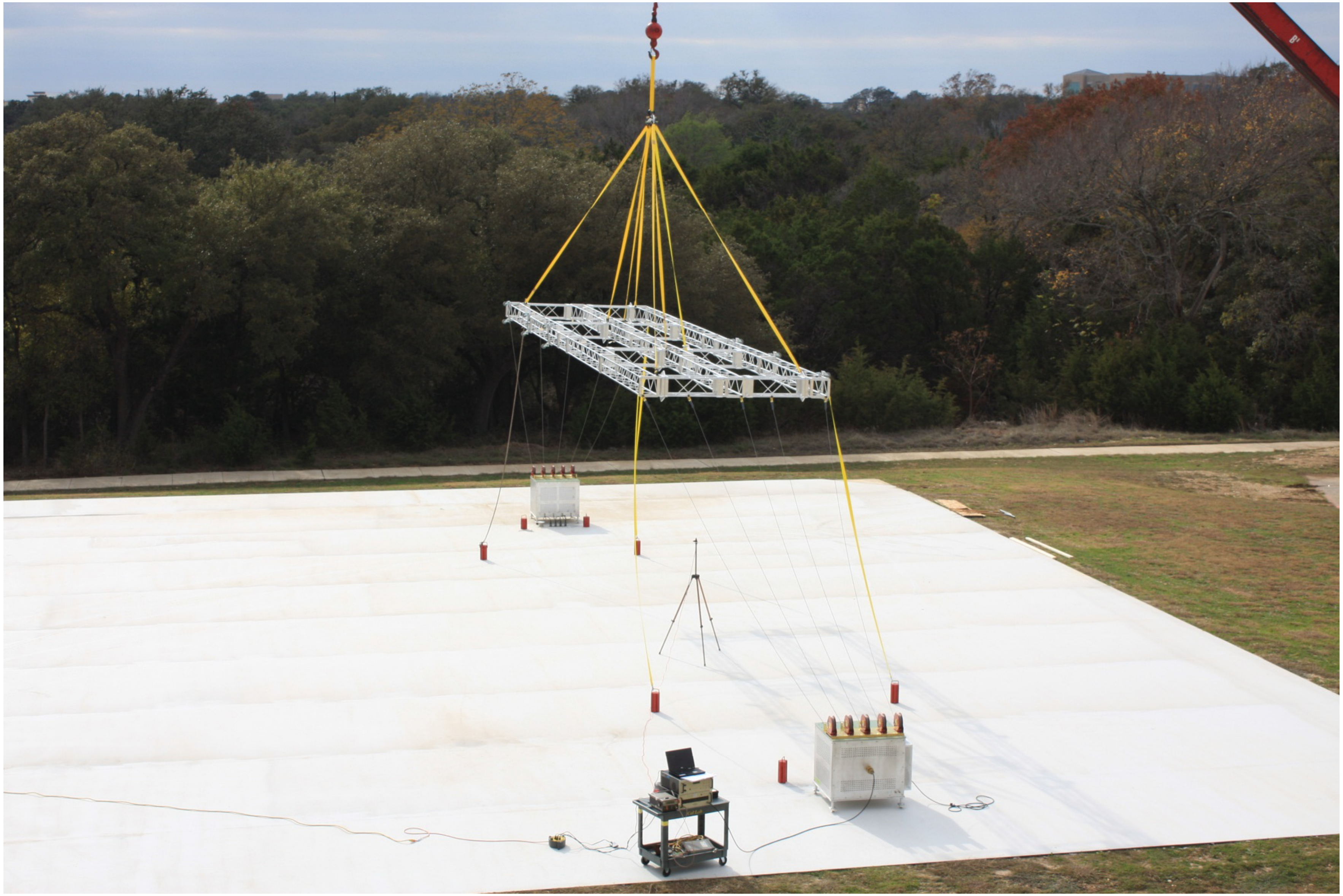


Chamber supported

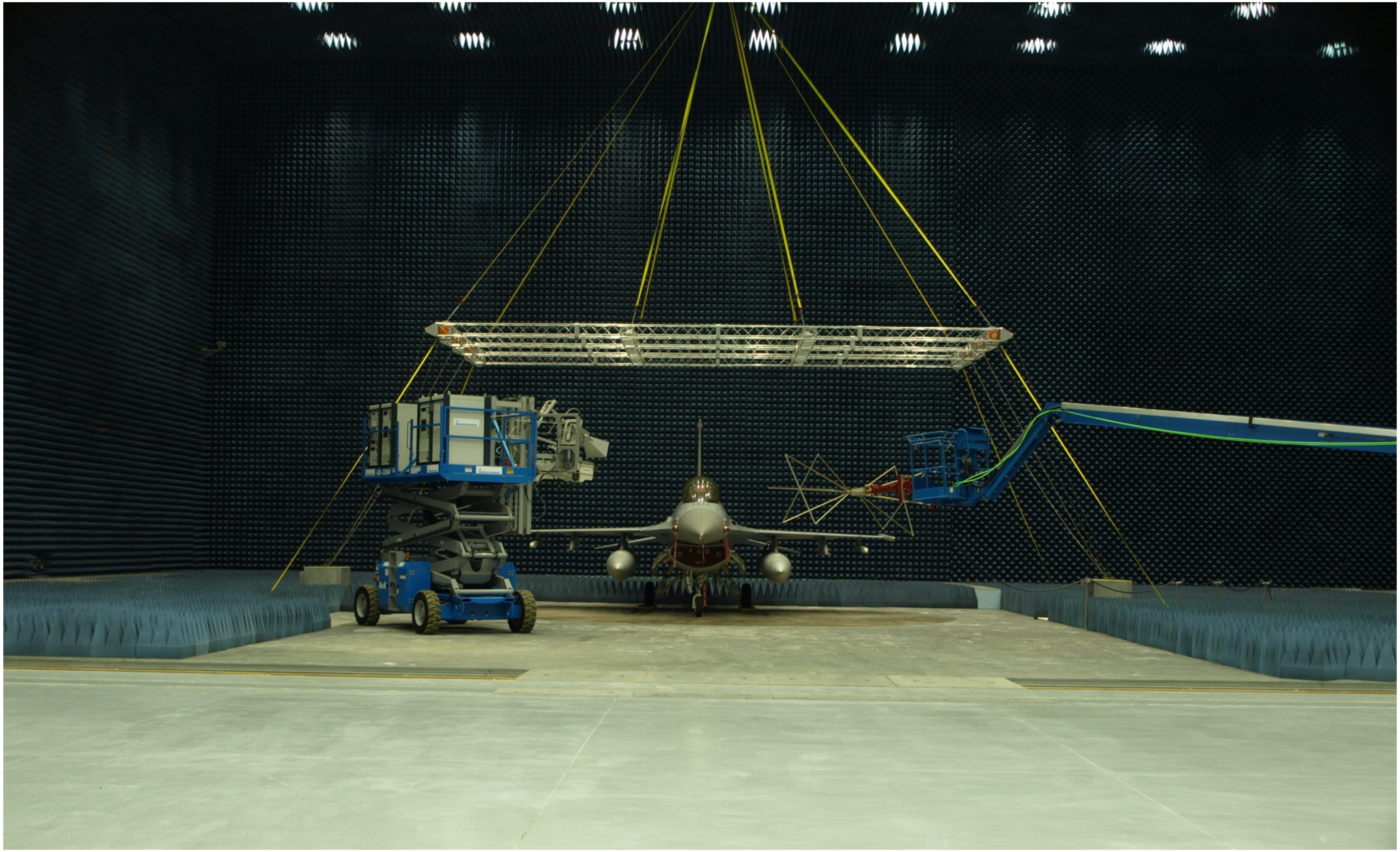




Stripline under factory test



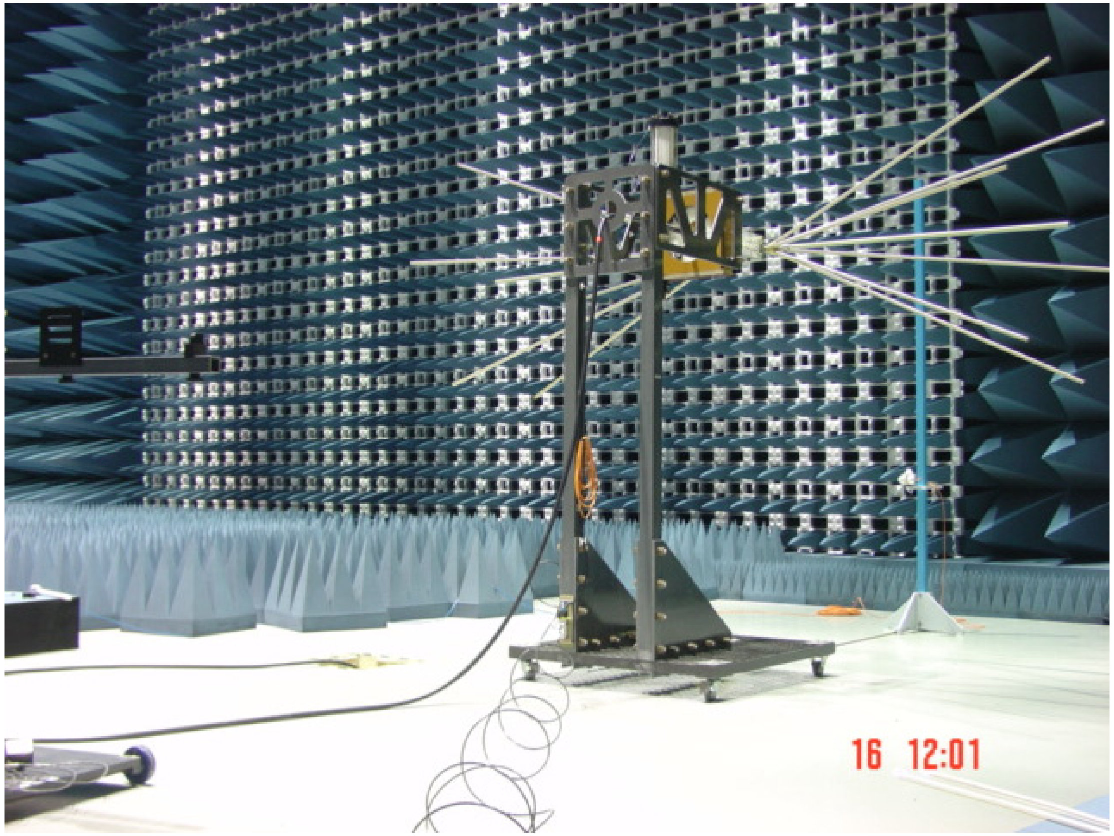
Stripline installed in chamber



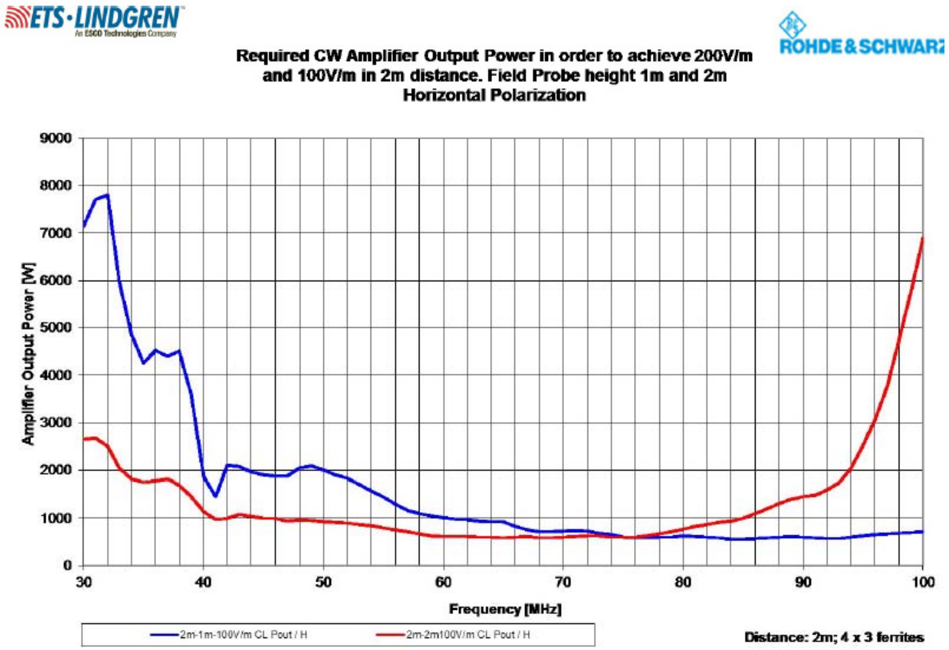
HP bicon (30MHz-100MHz)

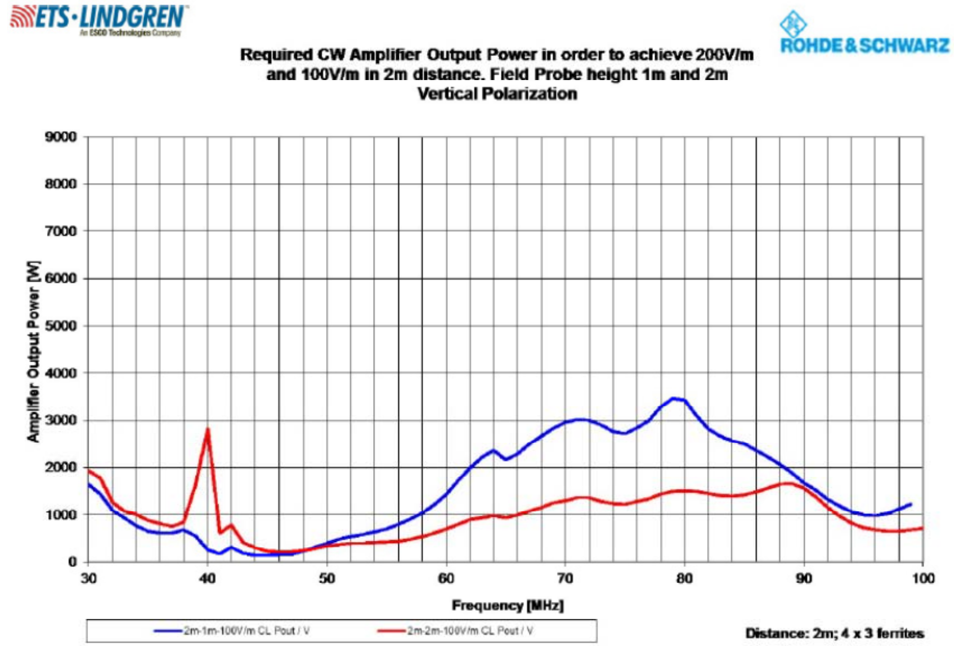
fixed height positioner with
pneumatic assisted polarization.

HP bicon at INPE chamber



HP bicon Data



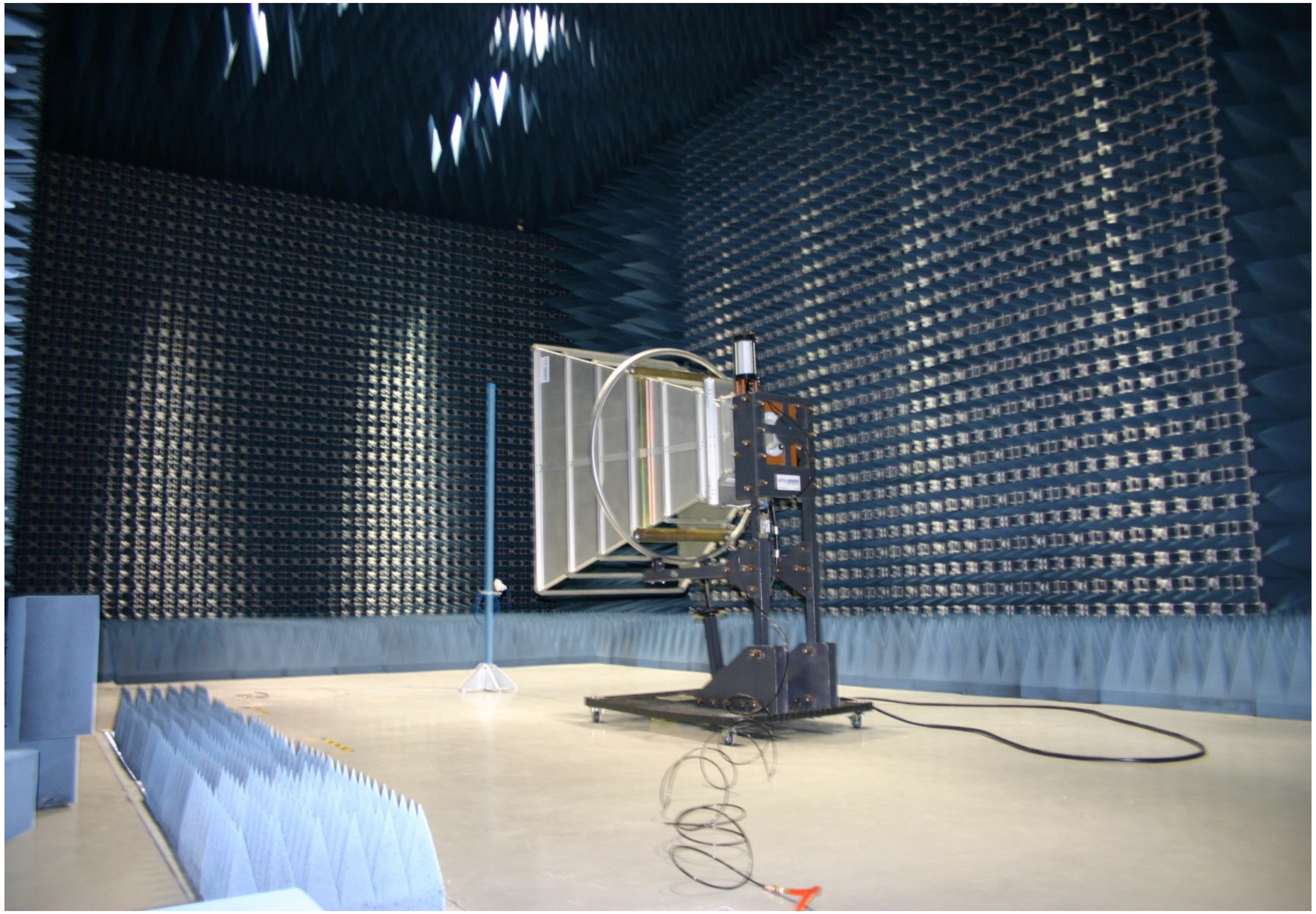


Red line is the probe 2m over ground
Blue line is the probe 1m over ground
Horizontal and Vertical polarizations are shown with the power for 100V/m

DRHA(100MHz-1000MHz)

fixed height positioner with pneumatic assisted polarization and manual boresight adjustment (±10 degrees)

DRHA in INPE chamber



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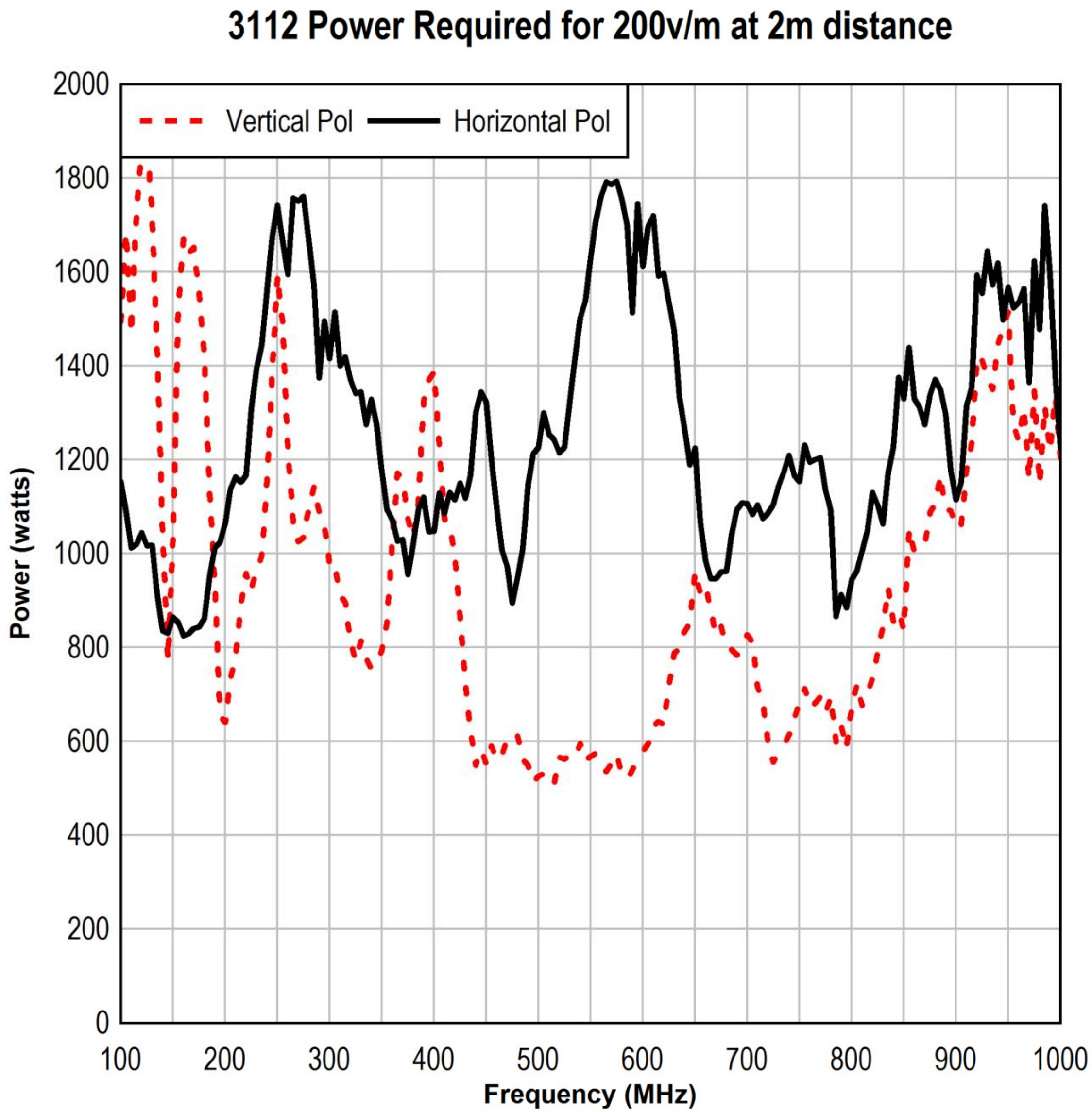
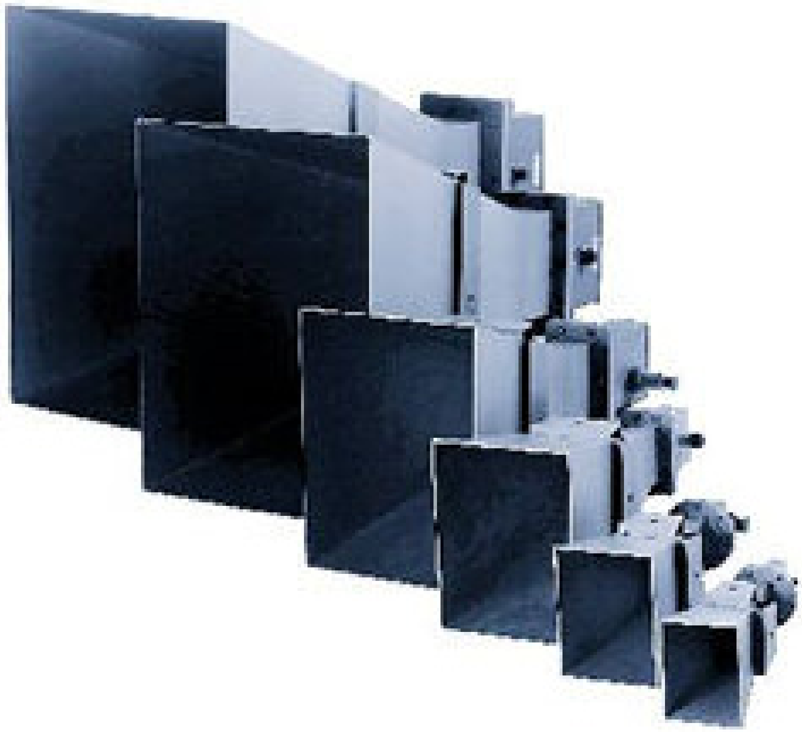
DRHA measured data



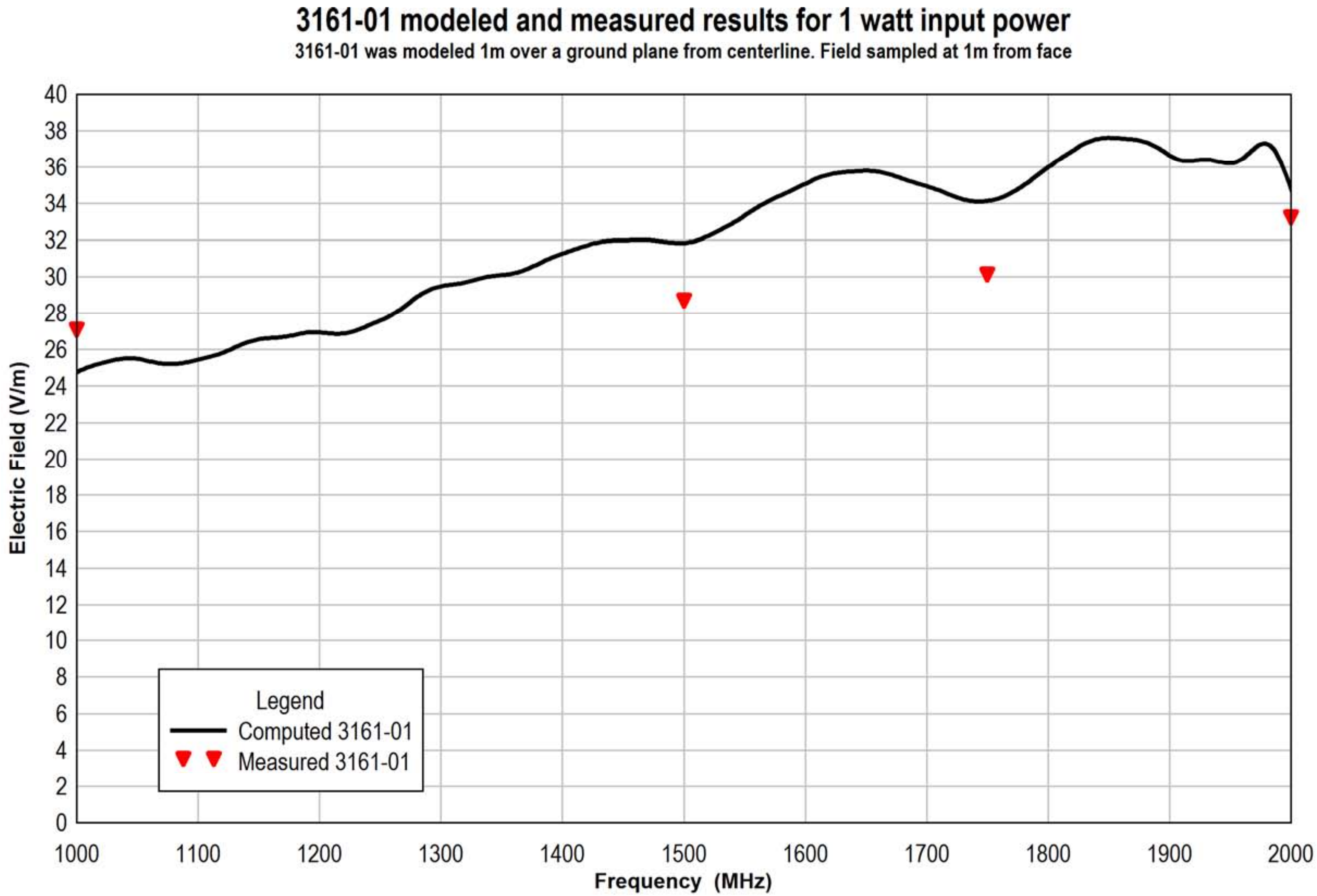
Above 1GHz (octave horns)



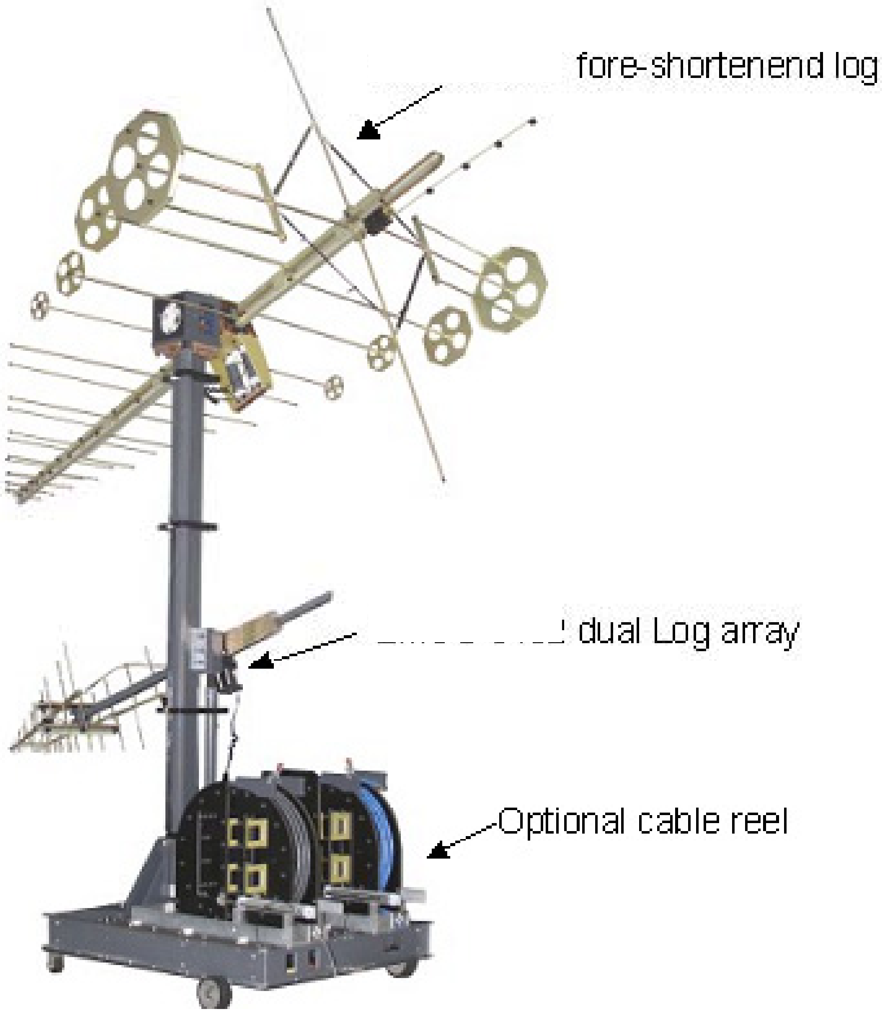
Gains of 15.5 to 17dBi

4 antennas to cover from 1 to 18GHz.

Typical data 1 to 2GHz Octave



Foreshortened logs



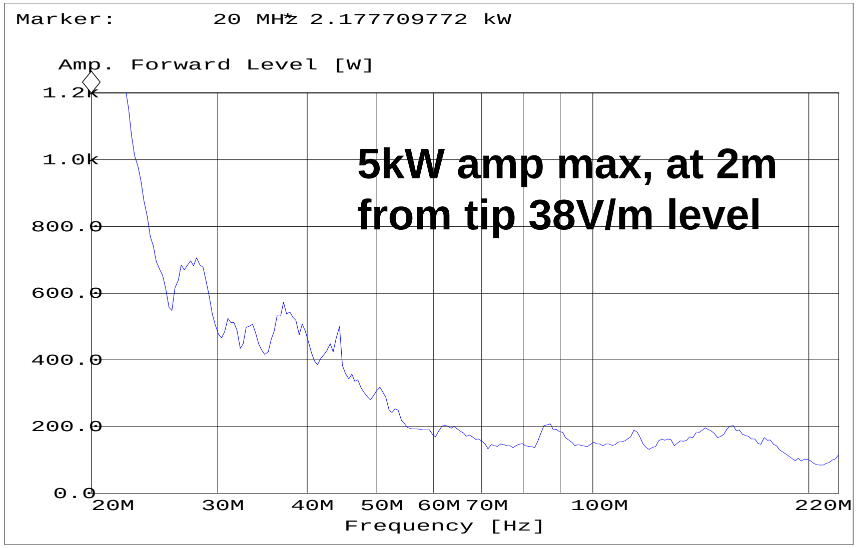
20 to 250MHz range of large Log P

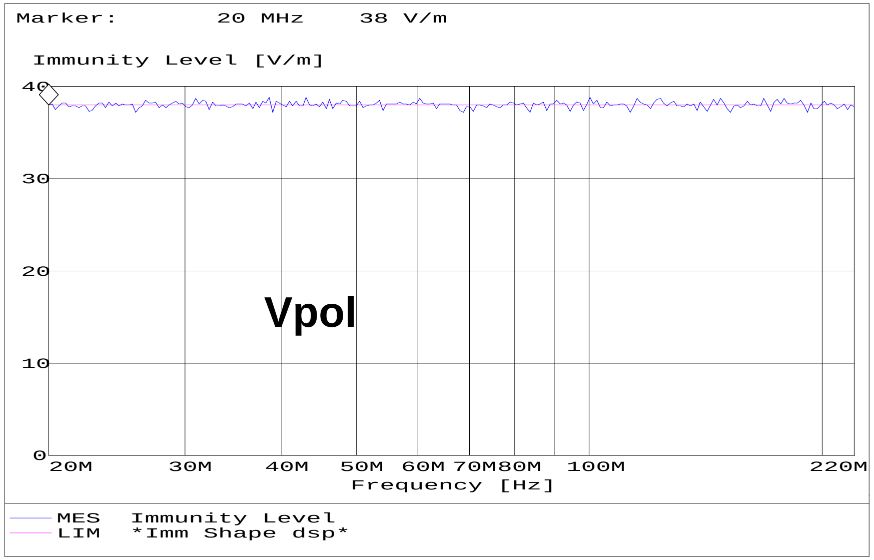
200MHz to 1GHz range for dual log.

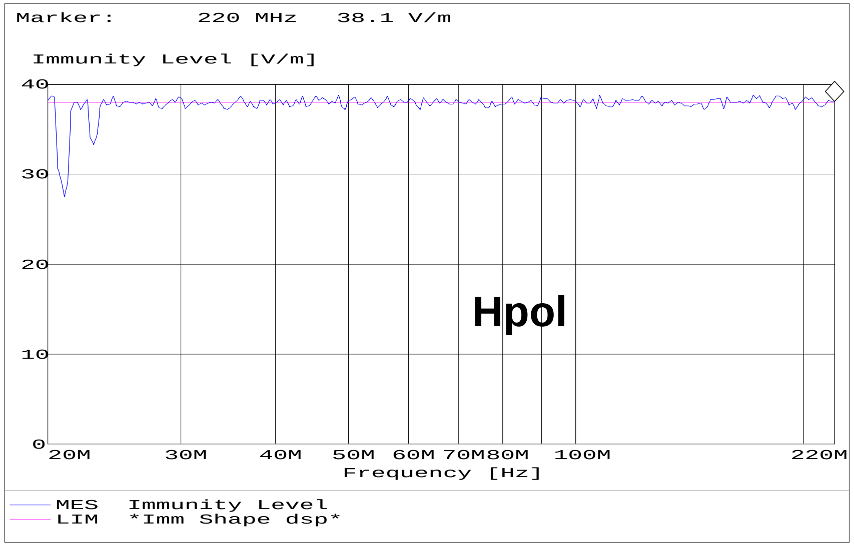
5kW max power.

This solution is ideal for 95/54/EC but wont be able to generate 100V/m over the entire range

Foreshortened logs







Data courtesy of ROHDE&SCHWARZ

Overview

Table II. Immunity antenna overview.

Frequency range	**power**	**type**	**Standard**
100kHz-30MHz	10kW	E/H field generator	ISO 11451-2 SAE J551-11 95/54 EC (20-30MHz)
30-100MHz	10kW	High power biconical	ISO 11451-2 SAE J551-11 95/54 EC
100-1000MHz	2kW	Dual ridge guide horn	ISO 11451-2 SAE J551-11 95/54 EC
1GHz-18 GHz	250-550W	Octave Horn	ISO 11451-2 SAE J551-11
20-200MHz	5kW	Fore shortened Log periodic antenna	95/54 EC 100 v/m above 40MHz
200-1000MHz	1kW	Dual array of Log periodic antennas	

Automotive Component EMC Testing:

CISPR 25, ISO 11452-2 and Equivalent Standards

Outline

- The Standards
- CISPR 25 chamber requirements
- Antenna requirements for CISPR 25
- ISO 11452-1 and –2: Chamber requirements
- Recommended antennas and Amplifier Power
- Conclusions

CISPR 25

Radio disturbance characteristics for the protection of receivers used on board vehicles,

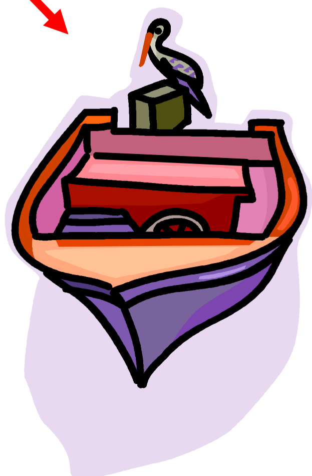
boats, and on devices –

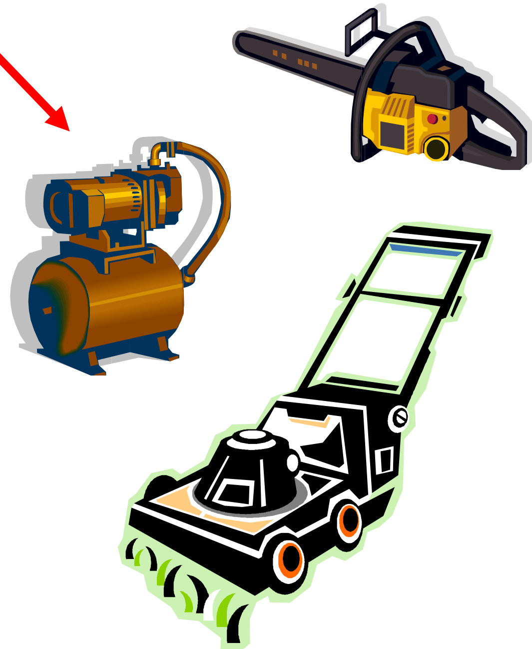
Limits and methods of measurement

ETS·LINDGREN™
An ESCO Technologies Company

CISPR 25

Radio disturbance characteristics for the protection of receivers used on board vehicles, boats, and on devices ...





CISPR 25

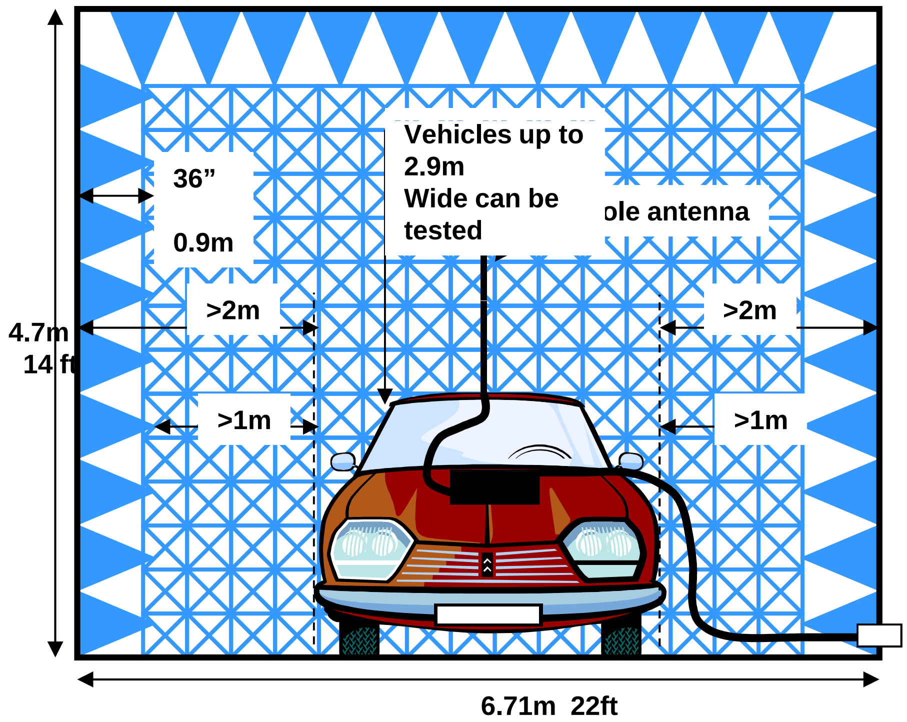
- So CISPR 25 deals with how much do electric and electronic systems affect receivers in:
  - Automobiles powered by internal combustion engines
  - Boats powered by internal combustion engines
  - Devices powered by internal combustion engines but not for the transport of people.(I.e. compressors, chainsaws, garden maintenance equipment, etc)

CISPR 25

- The standard has two parts, one deals with: Measurement of emissions received by an antenna on the same vehicle.
- The other with: Measurement of components and modules

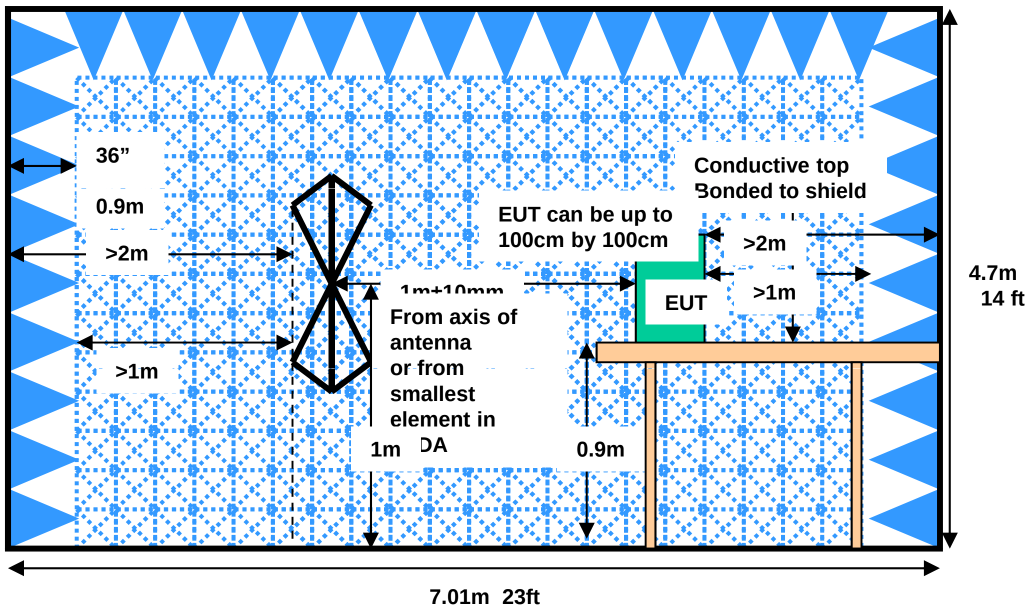
CISPR 25

- The 1st part is a "full-vehicle test", it has an equivalent on SAE J551/4



CISPR 25

- The second part is a component test it has an equivalent on SAE J1113/41



CISPR 25

This presentation deals with the component/sub-assembly testing part of the standard.

And more specifically with the anechoic facility required for the test per the standard

CISPR 25: Shielding

- The Standard States: The ambient electromagnetic noise levels shall be at least 6 dB below the limits specified in the test plan for each test to be performed. The shielding effectiveness of the shielded enclosure shall be sufficient to assure that the required ambient electromagnetic noise level requirement is met.
- The levels can be as low at 18 dB(μV/m). Hence isolation from the exterior is a must, a Shielded room is required per the standard

CISPR 25: Shielding

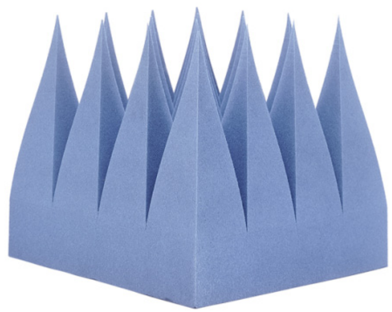
- While at low frequencies, no resonant behavior will appear inside the chamber, as the frequencies increase the resonant modes can exist that will cause measurement errors
- To avoid these errors the walls and ceiling of the chamber will be covered with absorber

CISPR 25: Absorber

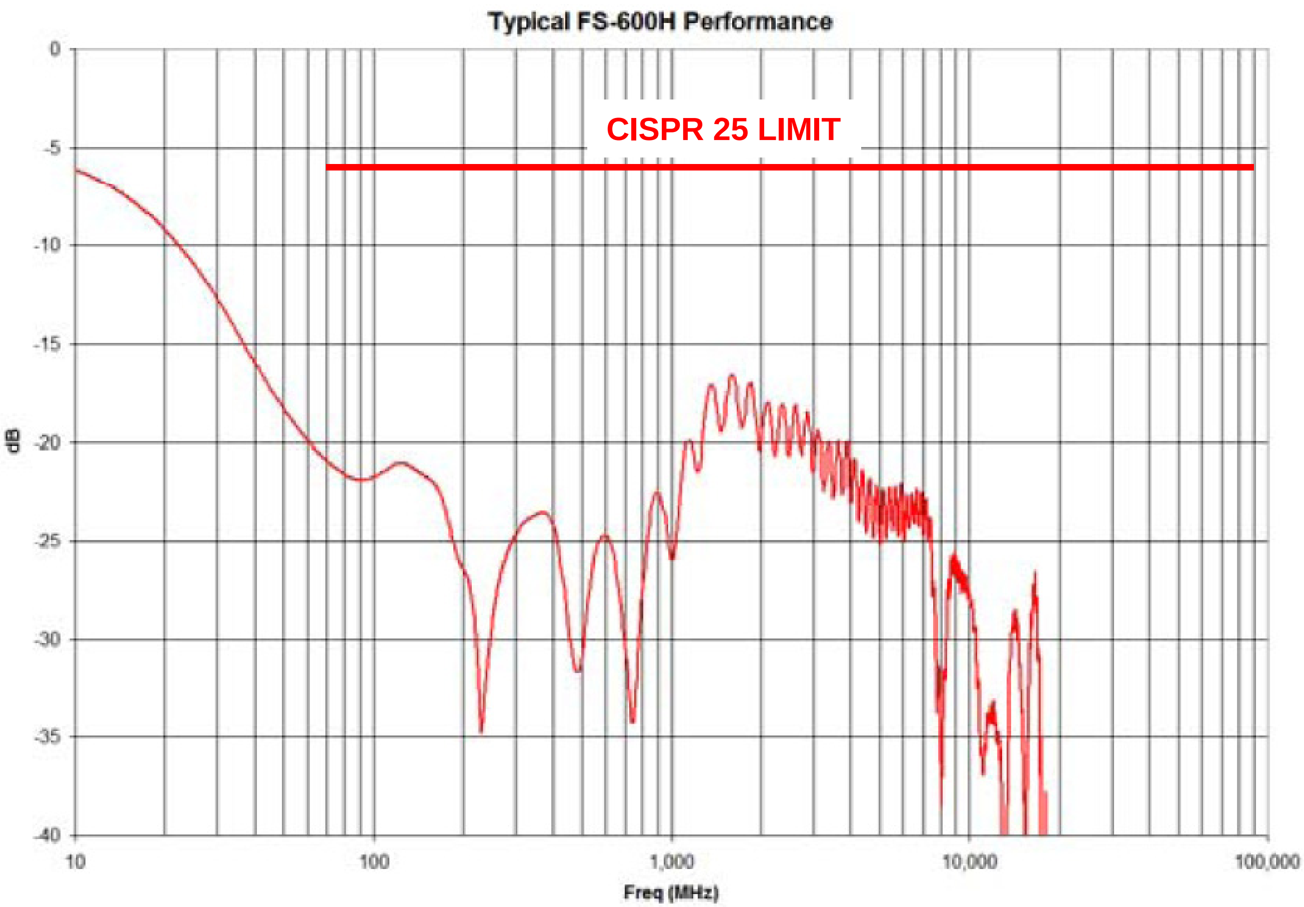
- CISPR 25 covers a frequency range of 150kHz to 2GHz (per the latest drafts)
- No absorber is known to provide absorption down at 150kHz range so the Standard requires –6dB of absorption from 70MHz and above.
- To achieve this there are two types of absorber technology that can be used

FS-600H Hybrid Ferrite and Polyurethane foam absorber

EHP-36PCL Polyurethane foam absorber



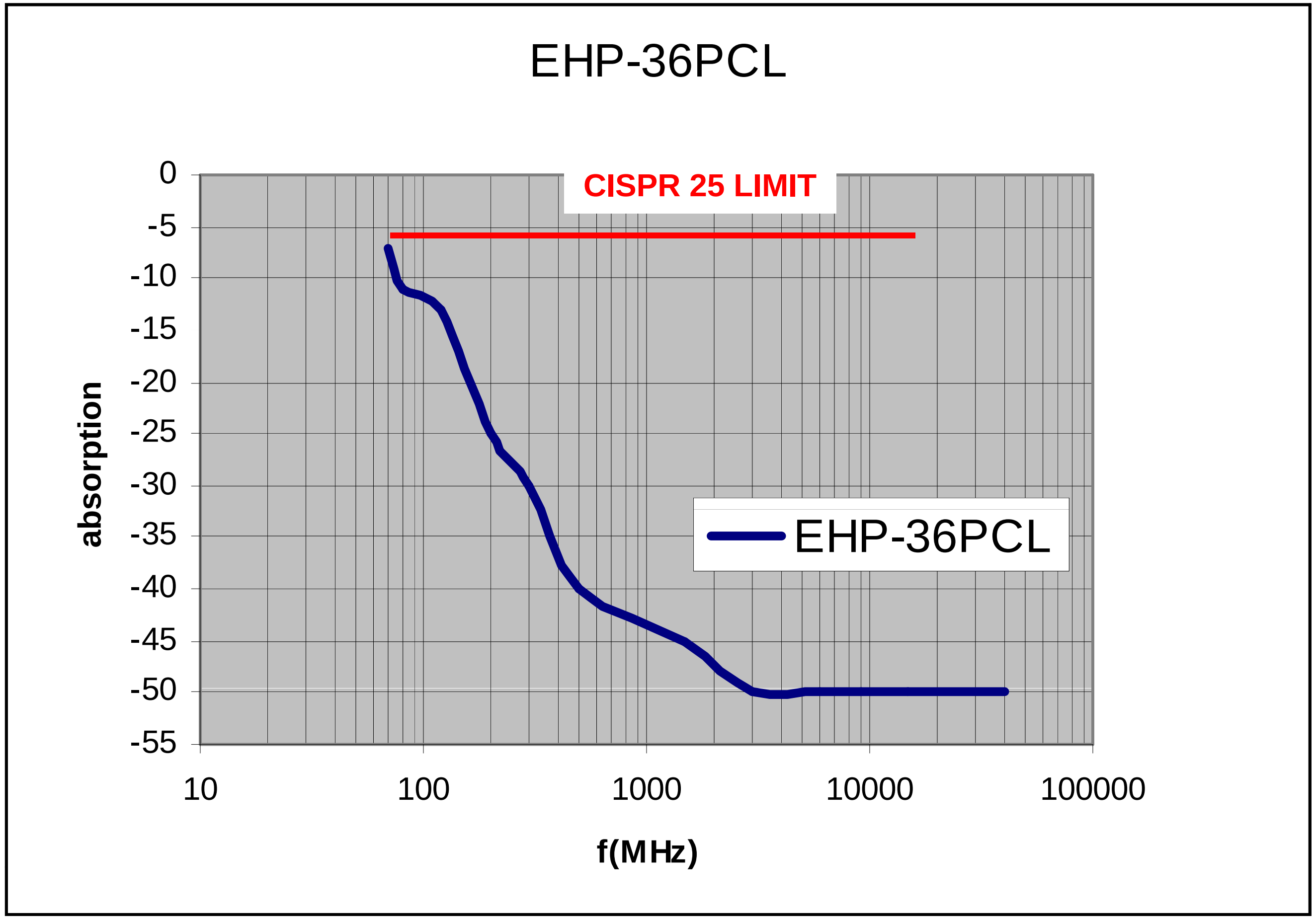
CISPR 25: Absorber



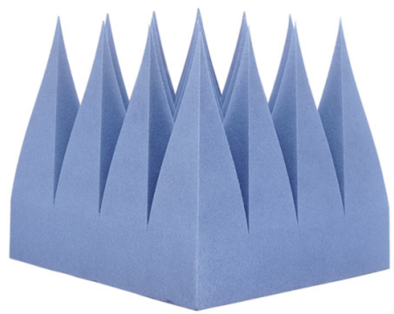
FS-600H
Hybrid Ferrite
and
Polyurethane
foam absorber

*From 30 MHz – 18 GHz**

CISPR 25: Absorber



EHP-36PCL Polyurethane foam absorber



CISPR 25: Absorber

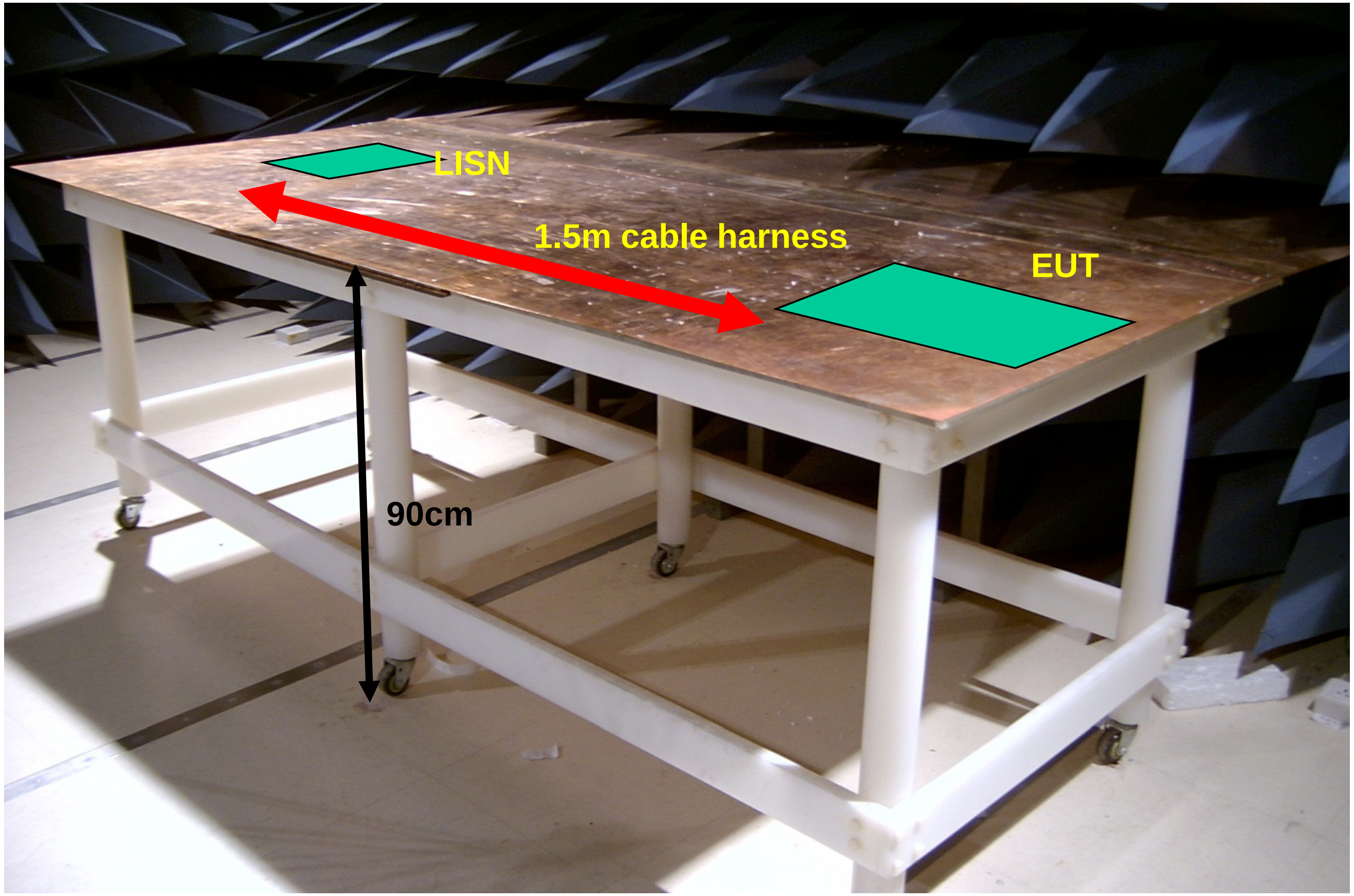
- EHP-36PCL
  - No ferrite so chamber does not require additional structure
  - Absorption really good above 1GHz
  - At 90cm still meets the requirements of the Standard.
  - Poor absorption at frequencies below 70MHz
  - Can not be fitted with reflective covers
- FS-600H
  - Shorter at 60cm of length
  - Absorption down to 20MHz (ideal if new draft requesting comparison with OATS is approved)
  - Reflective Covers provide better illumination in the chamber
  - A bit more costly with the ferrites

Sizing the Chamber

- There are several guidelines that re to be followed when sizing the chamber for CISPR 25. The main is to look at some of the dimensions required by the standard. Let’s Start with the Bench

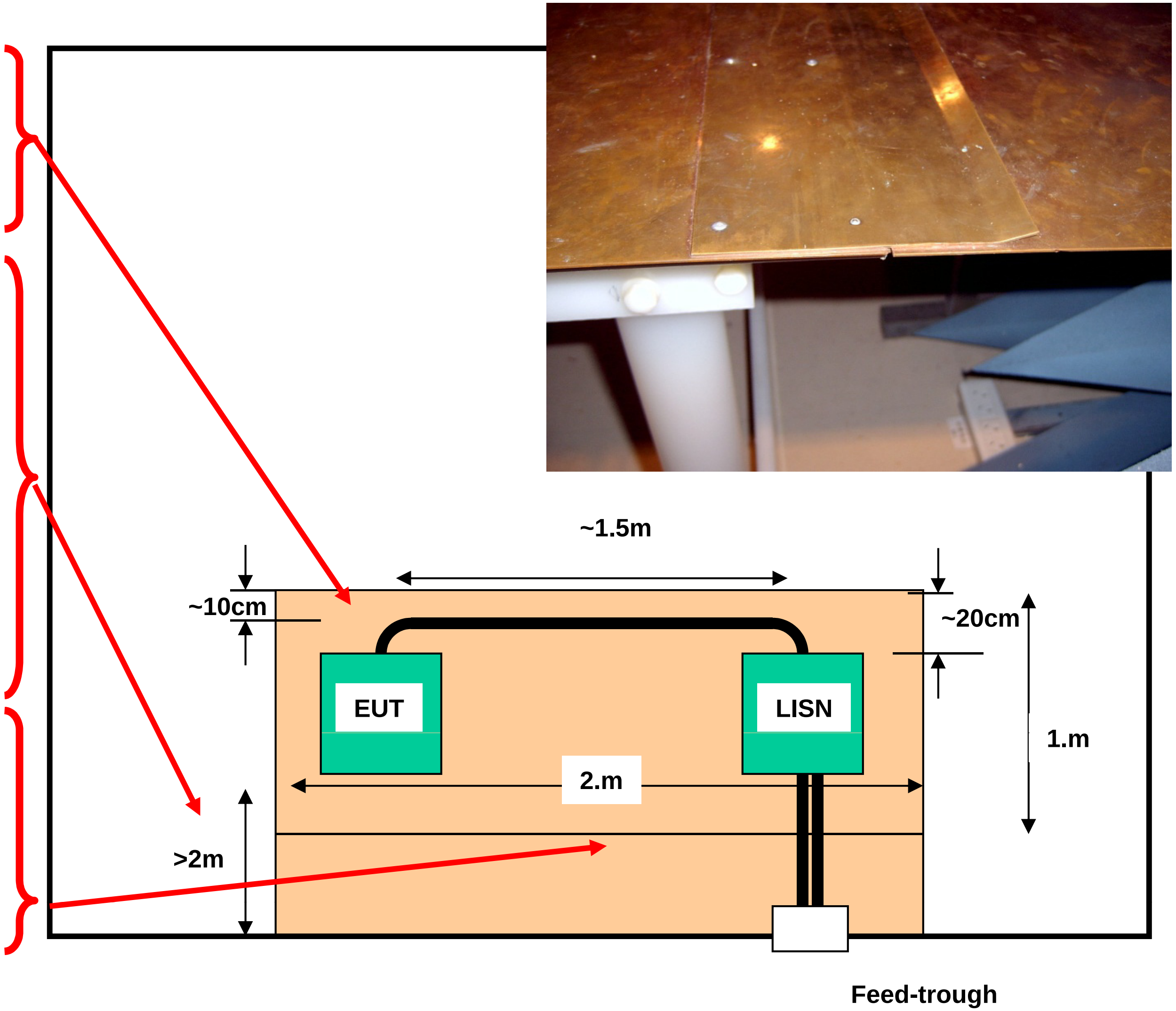
CISPR 25: the bench

- The bench is where the equipment under test (EUT) is placed
- A 1.5m cable harness feeds all necessary signals and power to the EUT
- Artificial Networks or LISN are also placed on the other end of the cable harness.



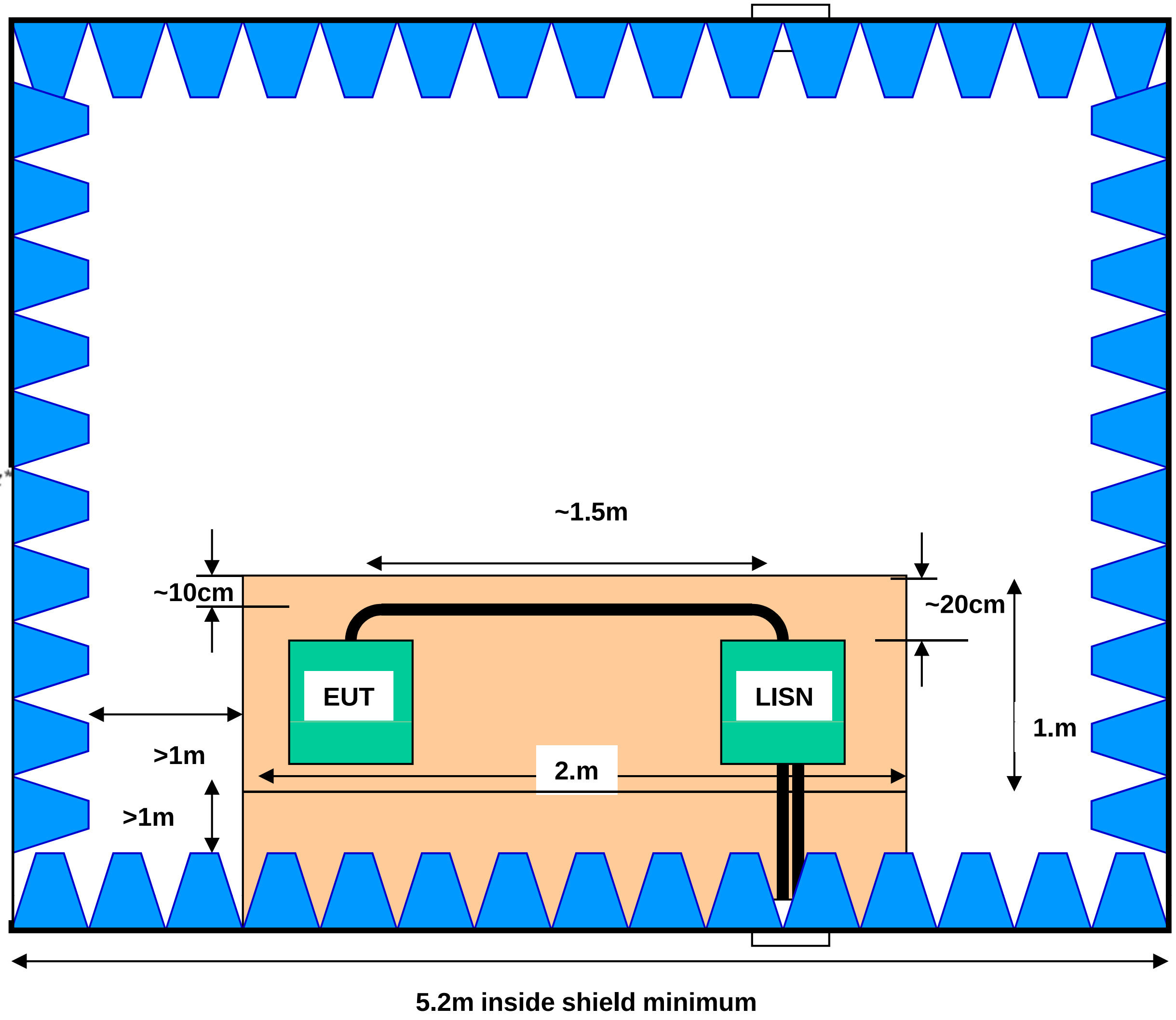
Chamber sizing

- A 2m by 1m bench will be sufficient to test most components, a larger bench can be used.
- The standard calls for 2m to the shield line, this requirement comes from the days before hybrid absorbers and usually the most stringent is the 1m distance from EUT to absorber tips.
- The bench must be grounded to the chamber shield (see picture)



Chamber sizing

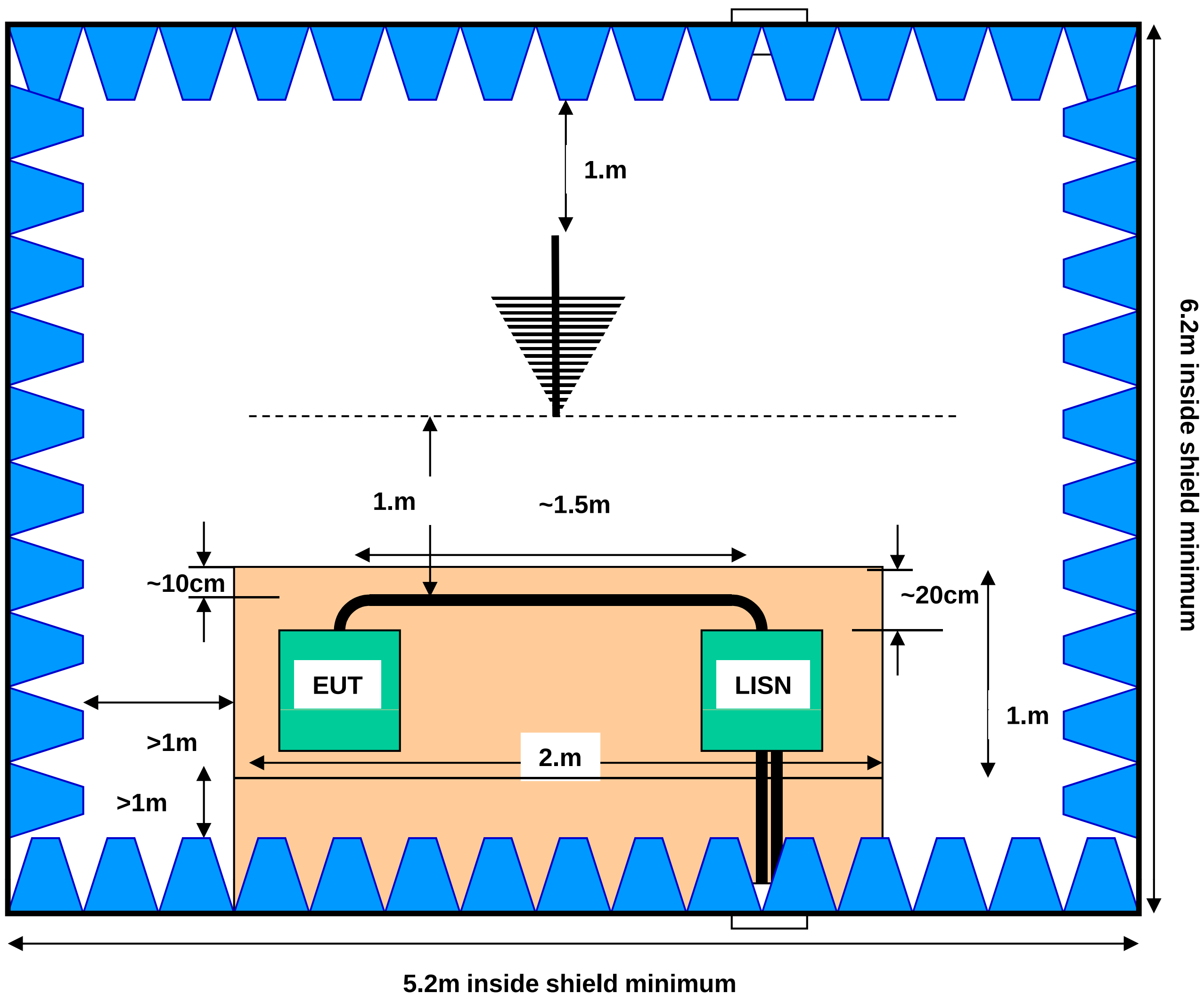
- The Absorber material covers all the walls of the chamber
- For the current exercise we will assume FS-600H being used



Chamber sizing

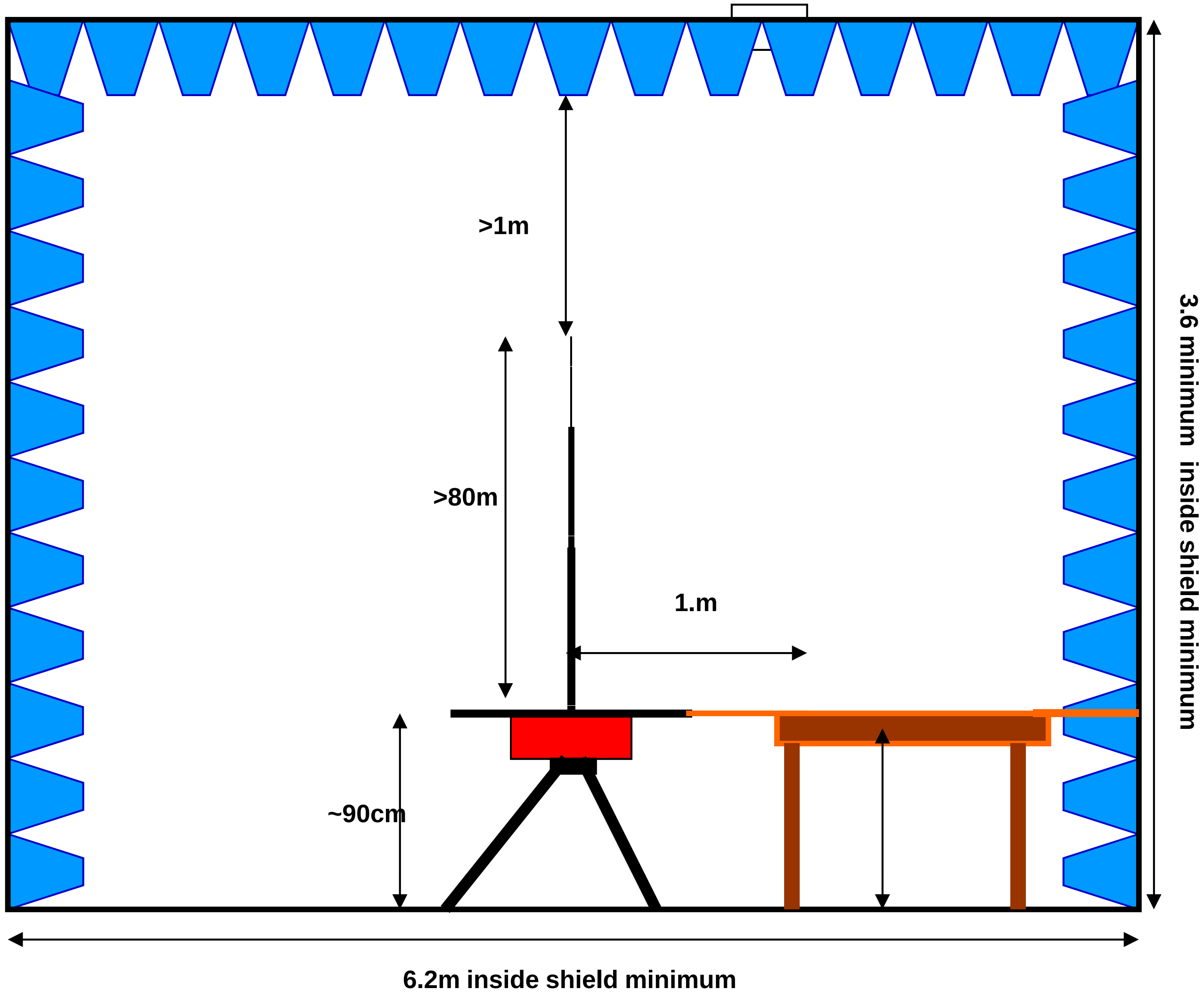
- The antenna is places at 1m from the cable harness.
- The 1m is measured from the tip of the antenna for Log P
- From the axis of the elements for biconical antennas
- From the axis of the monopole, for monopoles additionally the ground plane is connected to the metallic top of the bench

- The 1m rule to the tips of the absorber applies to the antenna elements.



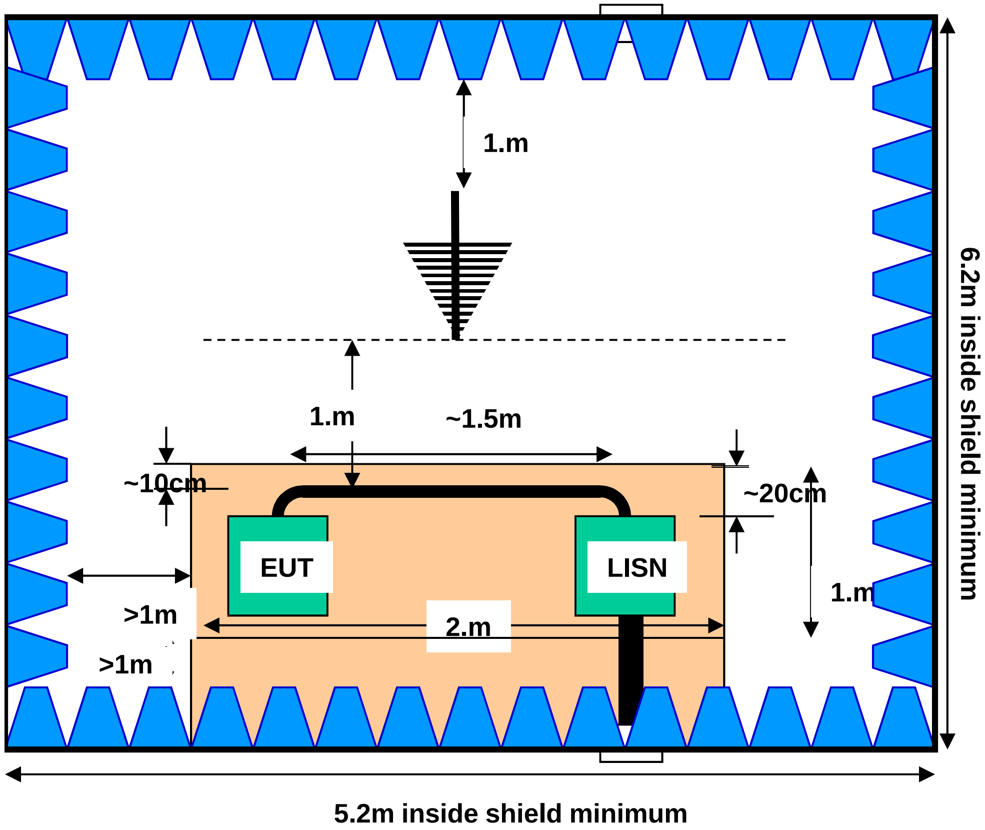
Chamber sizing

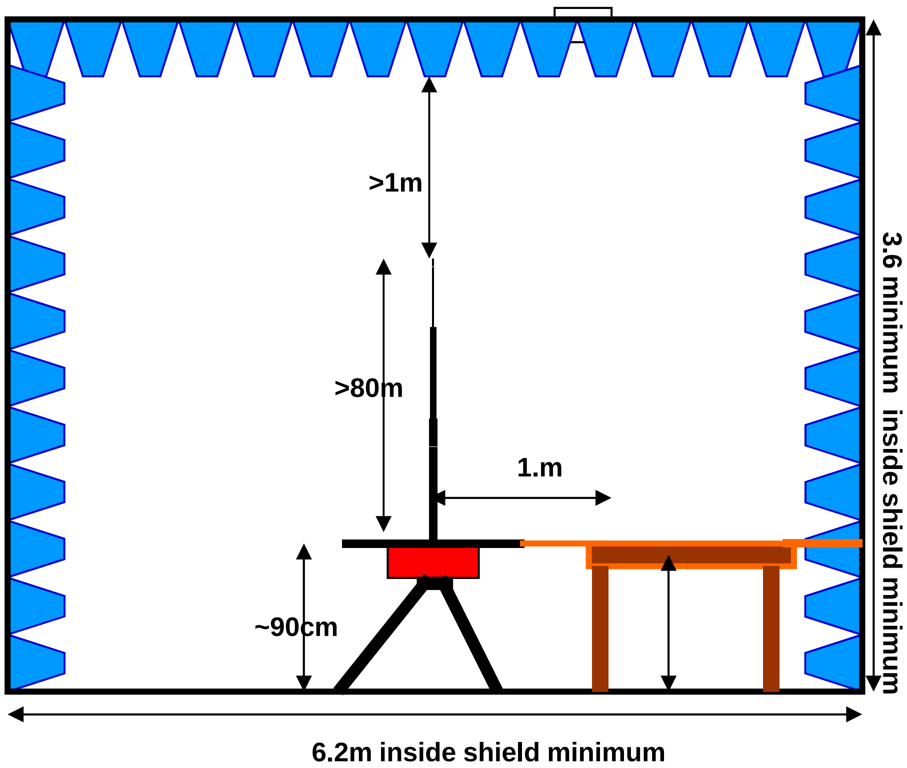
- The 80cm monopole is the longest element in the chamber.
- The 1m rule to the tips of the absorber applies to the antenna elements.
- This helps is sizing the height of the chamber.
- 3.6m is a minimum required, however it is recommended to have a higher chamber



Chamber size 6.2m by 5.2m by 4m

- **The reason for a larger chamber than the minimum is that it provides the user with more working space making the measurement process easier. In addition, the chamber for sized purely for CISPR25 based on that Standard. However, the same chamber can be used for ISO 11452-2 and all the other standards based on that one including the Ford and GM component standards**





ISO 11452-2

Road vehicles - Electrical disturbances by narrowband radiated electromagnetic energy - Component test methods - Part 2: Absorber-lined chamber

ISO 11452-2

- ISO 11452 deals with passenger cars and commercial vehicles regardless of the method of propulsion.
- Hence it applies to internal combustion engines and electric motors
- The chamber requirements offer many parallels to CISPR 25 requirements.

ISO 11452-2

- The frequency range that applies is 200MHz to 18GHz
- Generally high field levels are required for immunity
- Below 200MHz antennas are very large to be efficient hence it is better to use BCI (Bulk Current Injection) or TEM cells and Stripline as directed by ISO 11452-4, ISO 11452-3, and ISO 11452-5

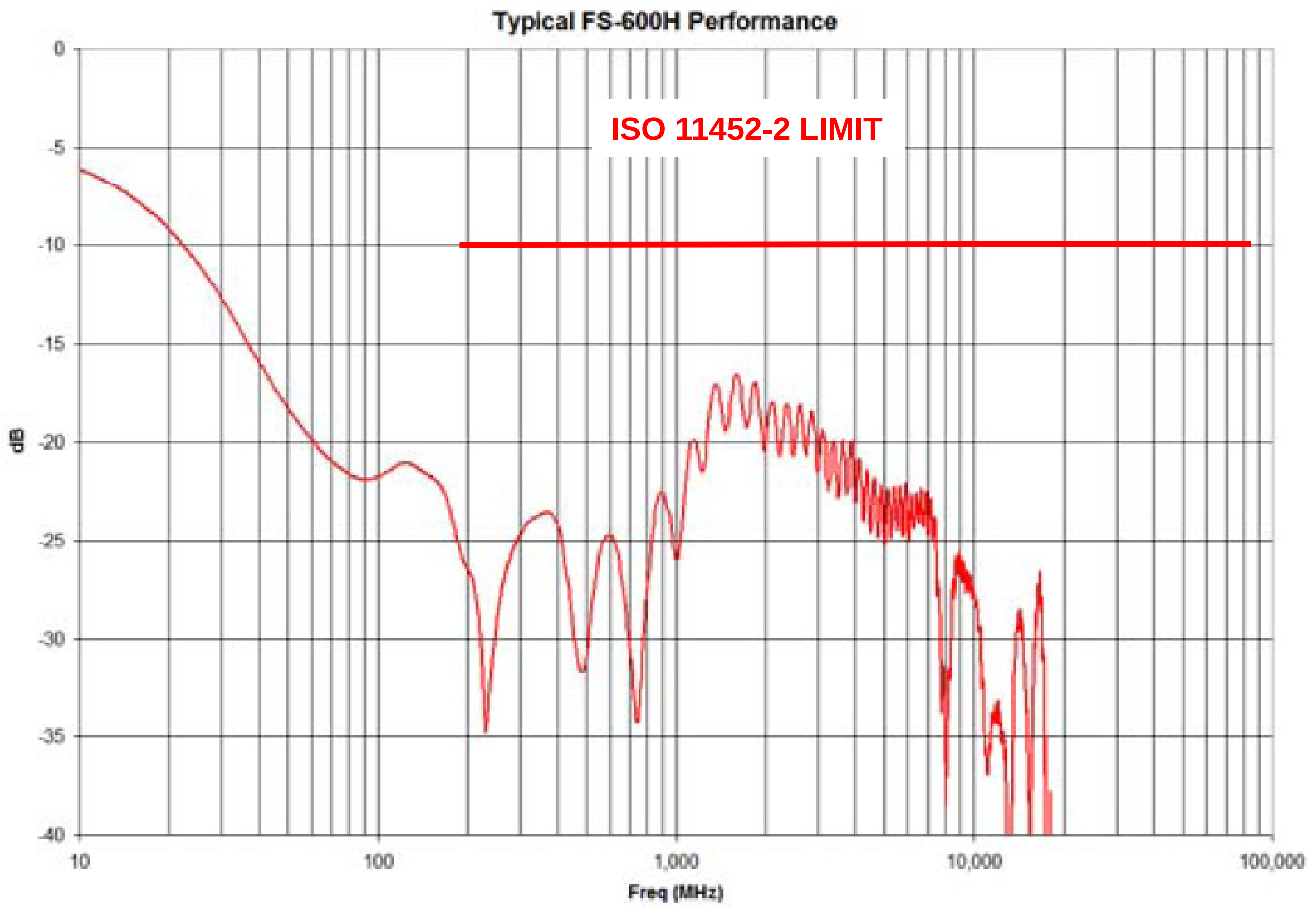
ISO 11452-2

- Field Level Requirements:
  - The test is to be conducted at:
    - Level I 25v/m
    - Level II 50v/m
    - Level III 75v/m
    - Level IV 100v/m
    - Level V (open to the users of the standard)

ISO 11452-2

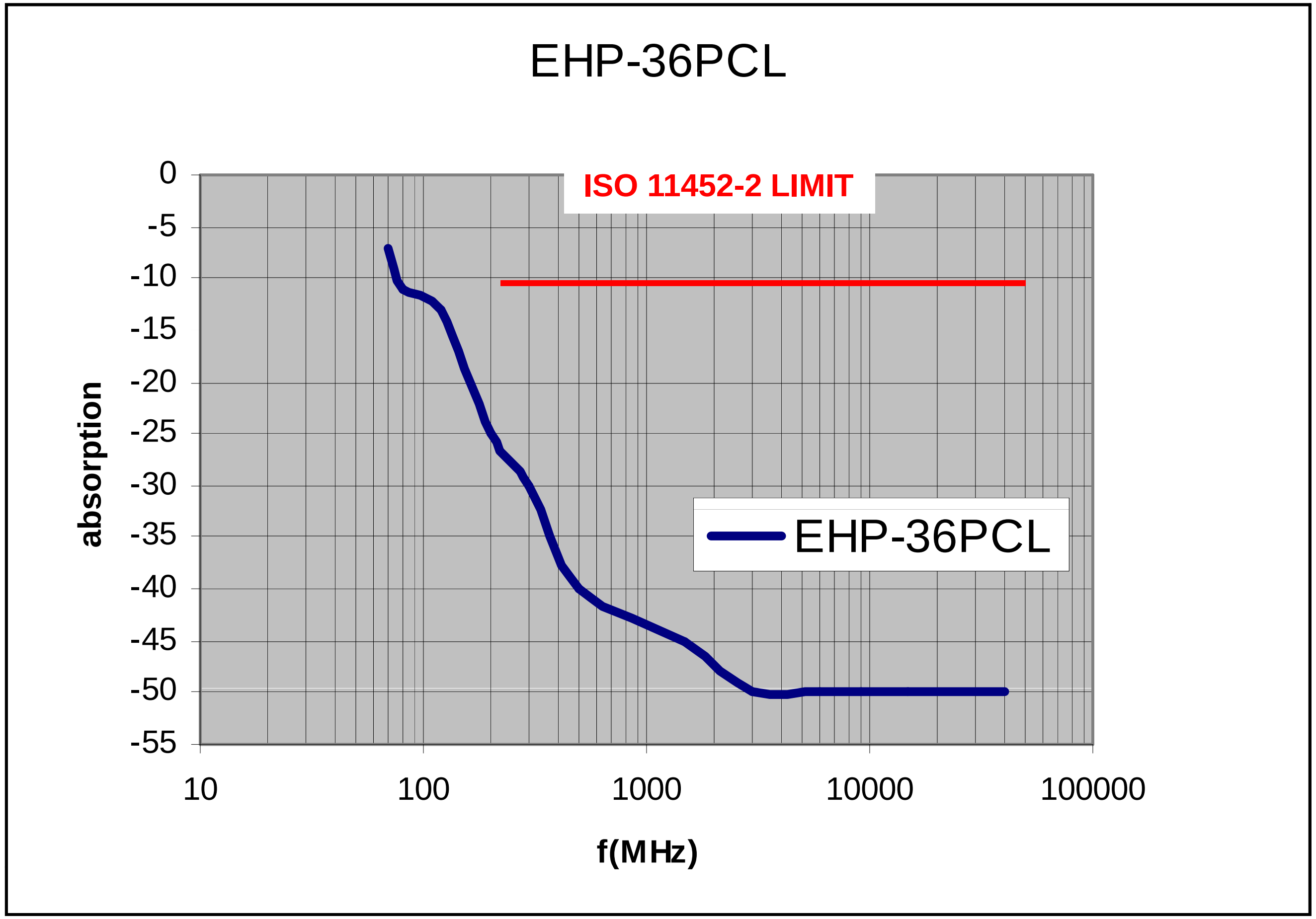
- Chamber Requirements:
  - The chamber is to be treated with RF absorber material such that the reflectivity in the area of the EUT is –10dB for the test range.
  - The chamber is to be treated in as many surfaces are needed (optionally excluding the floor).

ISO 11452-2: Absorber

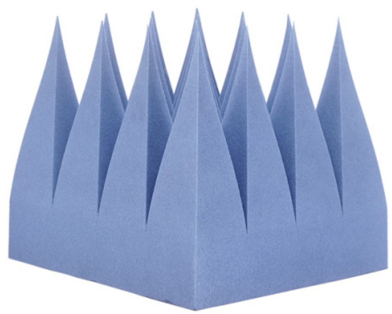


FS-600H
Hybrid Ferrite and Polyurethane foam absorber

CISPR 25: Absorber



EHP-36PCL
Polyurethane
foam absorber

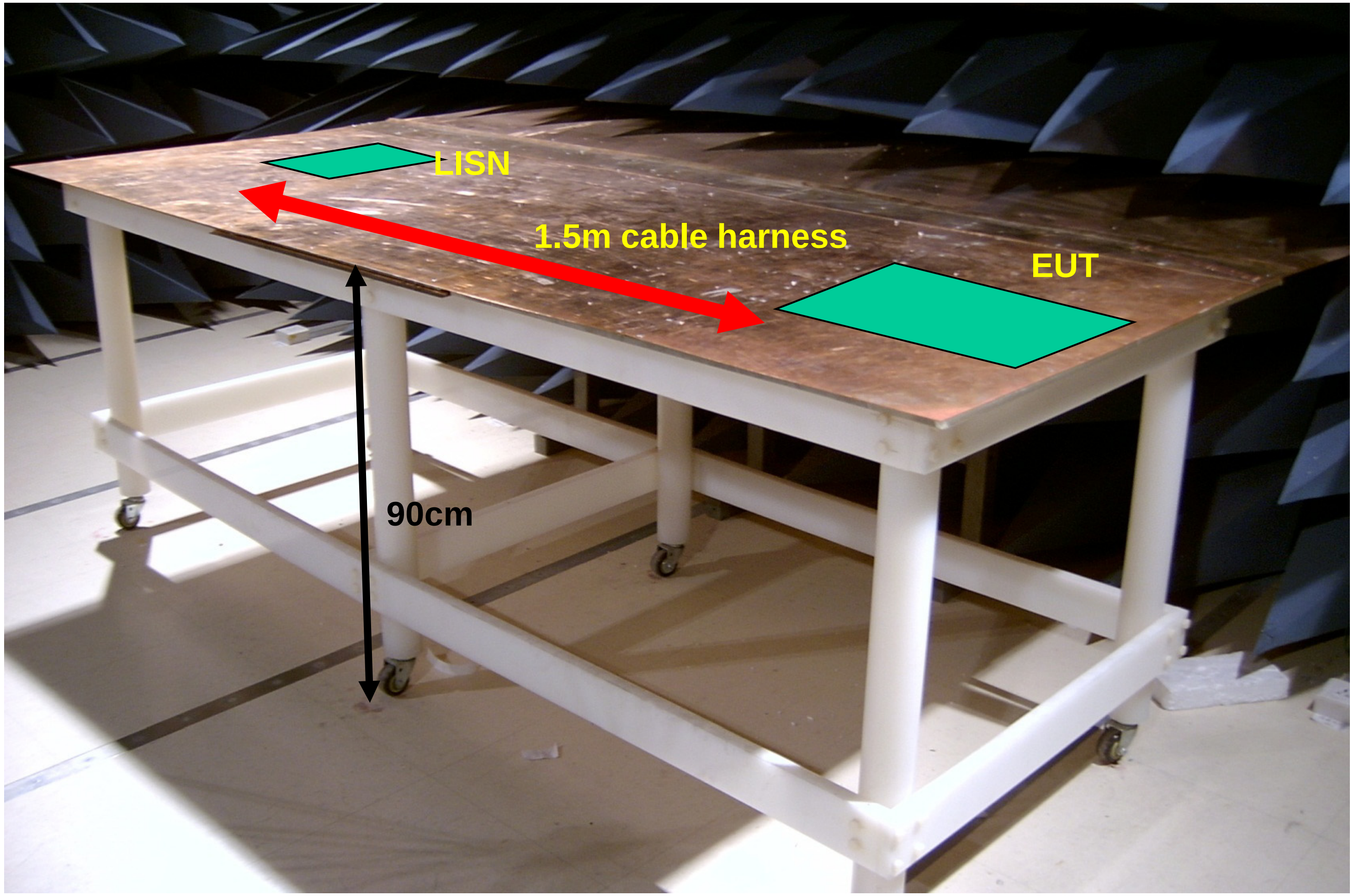


ISO 11452-2

- Chamber Requirements:
  - As it can be seen both of the suggested absorber types for CISPR 25 also meet the requirements for ISO 11452.
  - As before the FS-600H is recommended since better absorption is achieved at lower frequencies, creating a better environment is Stripline approaches are used.

ISO 11452-2: the bench

- **The bench is where the equipment under test (EUT) is placed**
- **A 1.5m cable harness feeds all necessary signals and power to the EUT**
- **Artificial Networks or LISN are also placed on the other end of the cable harness.**

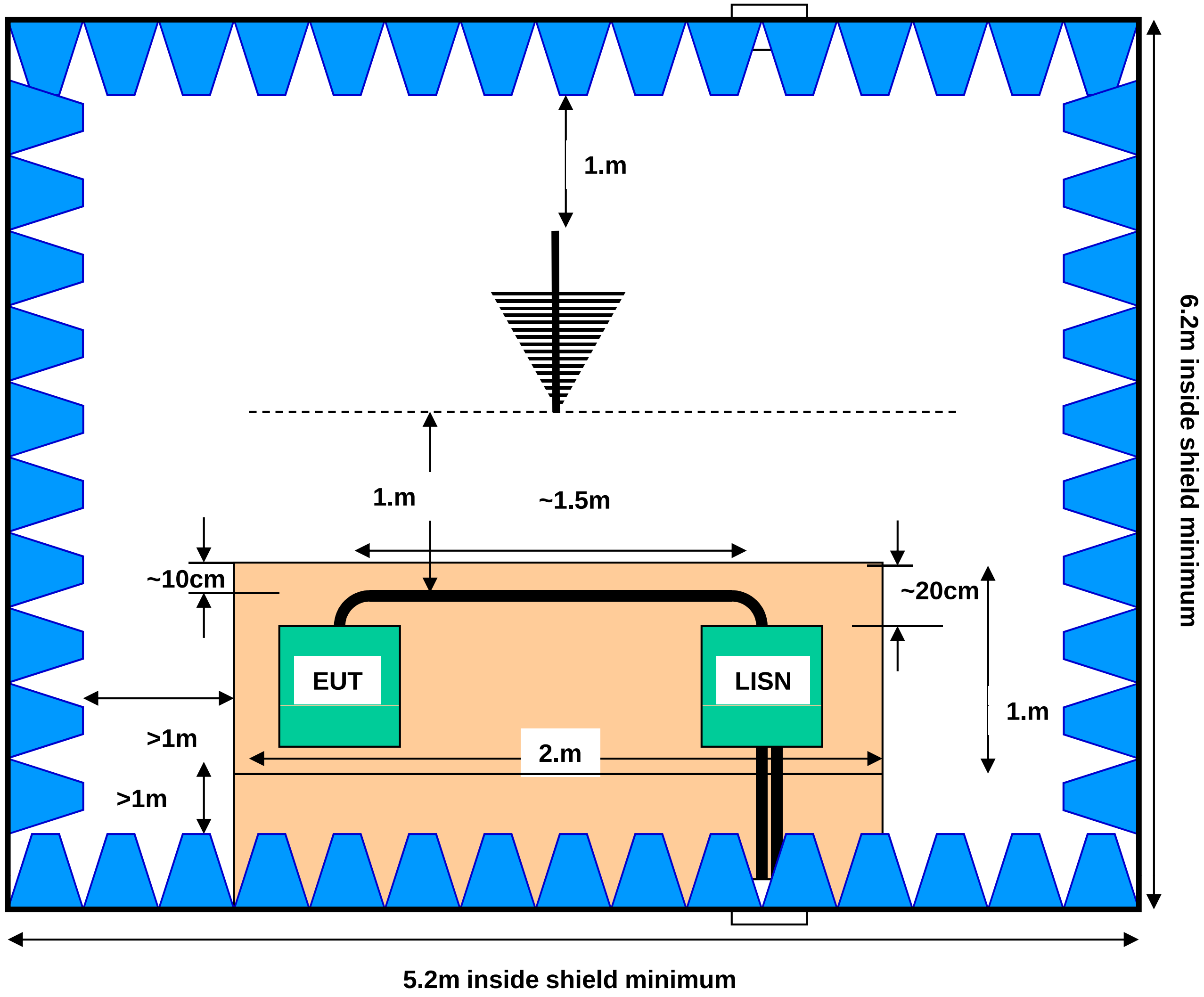


ISO 11452-2: the bench

- **The bench for ISO 11452-2 must be metallic topped.**
- **Ideally most users of the standard use the metallic topped bench since that way they use the same one that they uses for CISPR 25**
- **However:**
  - **For the Ford internal standard for the radar pulse 600v/m test in the 1.2 to 1.4 and 2.7 to 3.1 GHz the standard requests the metallic top to be removed.**
- **For Metallic top bench it should be grounded to the chamber in the same manner as in the CISPR 25 test.**

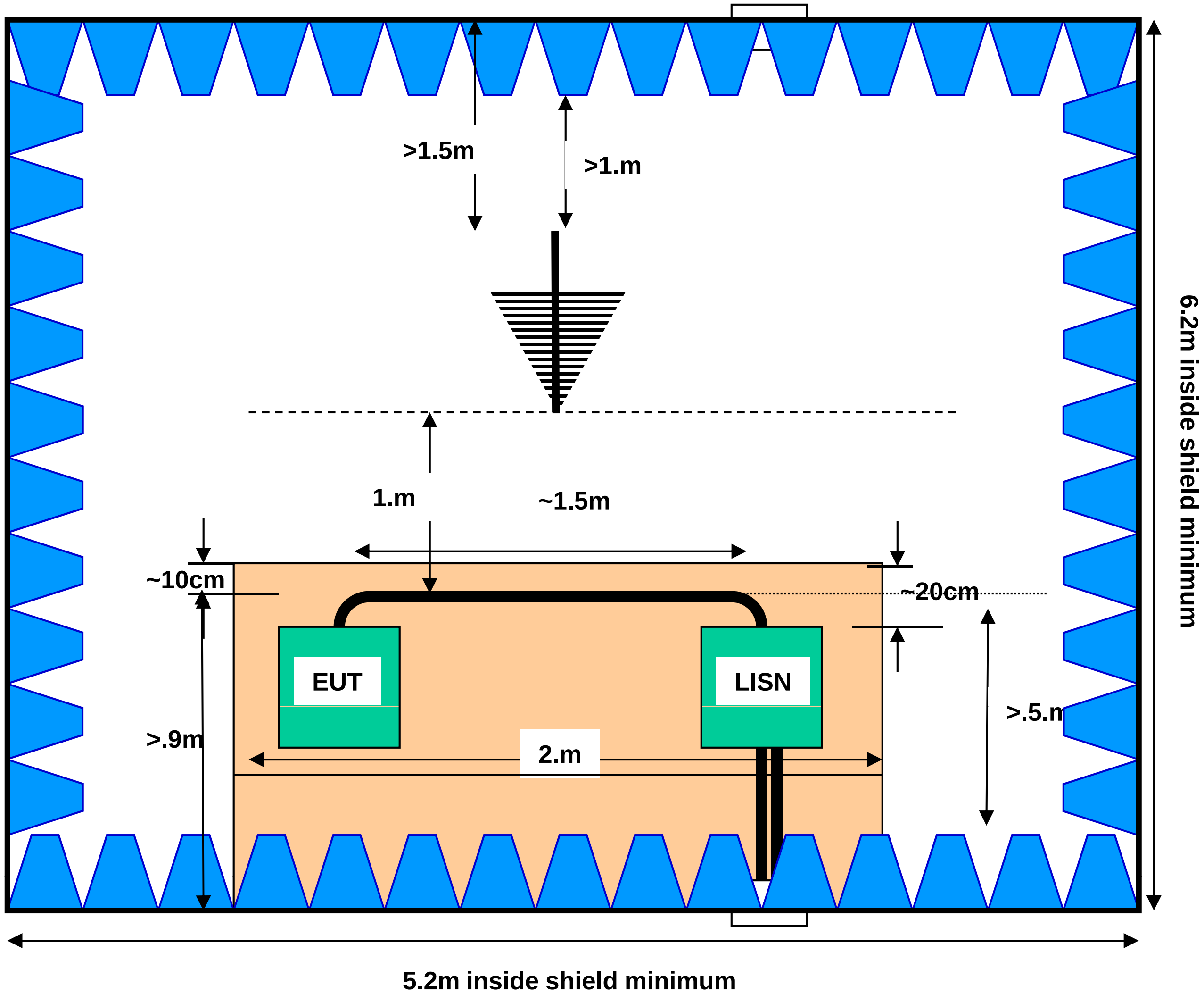
CISPR 25: Chamber layout

- Here is the layout for the CISPR 25 chamber.
- Let’s now look at the layout for the ISO 11452-2



ISO 11452-2: Chamber layout

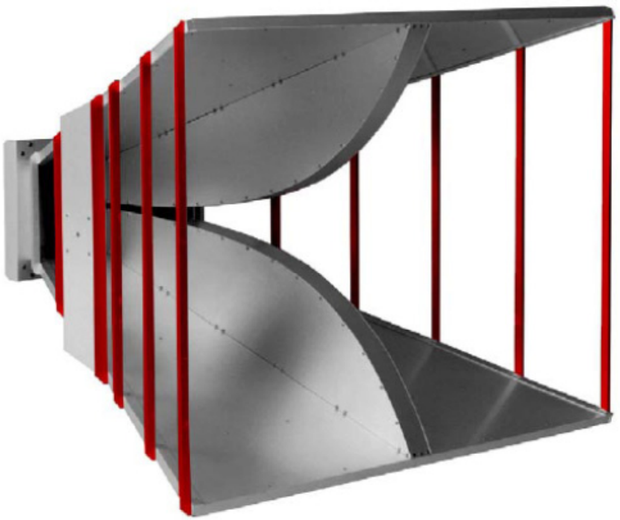
- **Here is the layout for the ISO 11452-2 chamber.**
- **The layout dimensions are very similar**
- **As is the test distance (1m)**
- **No antenna elements can be closer than 50cm from the edge of the bench**

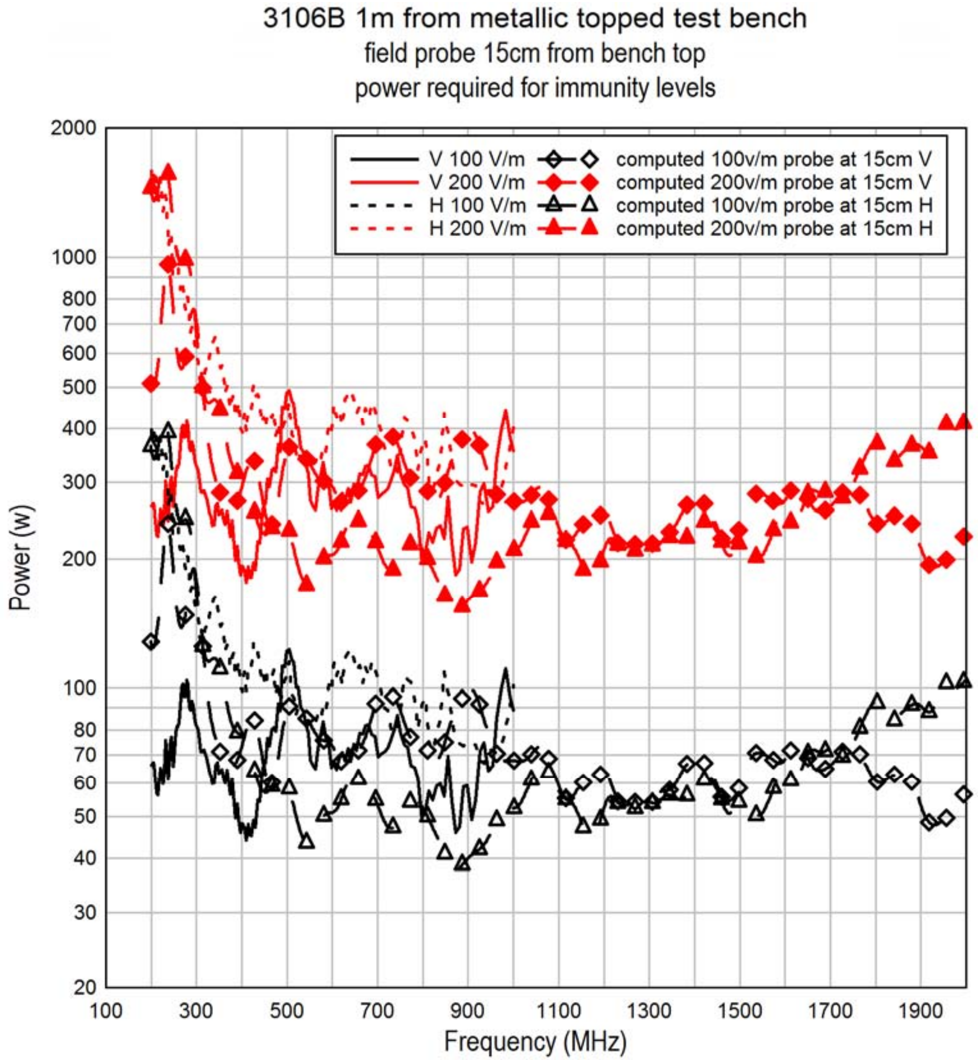


Antennas ISO 11452-2

- The ISO 11452-2 is an immunity Standard
- The ideal antennas will have high gain to reduce the amplifier size
- For the 200MHz to 2GHz range the ideal antenna is the Dual Ridge Horn such as the EMCO 3106B

200MHz and up





Antennas ISO 11452-2

- For frequencies above 2GHz octave Horns with a 15 to 16dBi gain are the recommended Choice.
- If radiated test is needed below 200MHz a high power biconical is the recommended choice, but BCI or TEM cells is a more amplifier efficient approach.

Conclusions

- **Hopefully you have gain knowledge on the chamber and antenna requirements for full vehicle testing**
- **These are expensive large facilities that only manufacturers could afford**
- **There may be a potential market for private EMC labs to set up full vehicle labs to take care of the increasing demand for full vehicle testing in Asia.**

Conclusion

- CISPR 25 and ISO 11452-2 are the most common and “international of the automotive component standards.
- Lots of other standard are based on them.
- They can share the same chamber design.
- The presented Designs could also be used for Mil Std 461F and RTCA DO 160.

Accredited EMC Labs in 2012

- Daniel D. Hoolihan
  - Hoolihan EMC Consulting
  - 32515 Nottingham Court – Box 367
  - Lindstrom, Minnesota 55045
  - 651-213-0966, FAX 651-213-0977
  - Cell Phone 651-269-3569
  - danhoolihanemc@aol.com

Accredited = Quality

- How do you determine the “Quality” of an EMC laboratory?
  - A lab that is accredited is a lab that is most likely to be a High-Quality EMC lab
  - Accreditation should be done by:
    - an independent and
    - recognized organization

Introduction

Lab Accreditation

- should give the user **confidence** in the capabilities of the lab

- helps **Qualify EMC labs** for a customer

- has become **increasingly important** over the last 25 years

Lab Accreditation Standard

- **ISO/IEC 17025**
  - **International Standards Organization (ISO)**
  - **International Electrotechnical Committee (IEC)**
- **International Standard**
  - **ISO and IEC are located in Geneva, Switzerland**
- "*General Requirements for the Competence of Testing and Calibration Laboratories*"
  - First Edition - Published 15 December 1999
  - **Second Edition - Published 15 May 2005**

Accreditation to 17025

- Accreditation to ISO/IEC 17025 is the goal
- It reinforces the concept of a Qualified EMC Laboratory – however:
  - people,
  - equipment and
  - procedures
  - can all change over time

Scope of Accreditation

- You must check the
- **SCOPE OF ACCREDITATION**
  - to assure that the lab is qualified for those specific EMC tests you want performed on your product
  - The scope of an EMC Lab can range from one test to hundreds of tests!

Advantages of Lab Accreditation

- In the USA, it allows a lab to **test and qualify products**
  - for a **Declaration of Conformity (DoC)**
  - under the **Federal Communications Commission (FCC) Rules**
  - A **Declaration of Conformity** covers devices such as Class B Personal Computers and Peripherals, Citizens Band receivers, TV interface devices, and Consumer Industrial, Scientific and Medical (ISM) equipment.

ISO/IEC 17025

- ISO/IEC 17025 superseded both:
  - ISO/IEC Guide 25 – old international standard
  - European Norm 45001 – Europe’s equivalent to Guide 25
- ISO/IEC 17025 has been adopted by many countries around the world

ISO/IEC 17025 - Contents

- Foreword
- Introduction
- 1- SCOPE
- 2 - NORMATIVE REFERENCES
- 3 - TERMS AND DEFINITIONS
- **4 - MANAGEMENT REQUIREMENTS**
- **5 - TECHNICAL REQUIREMENTS**

ISO/IEC 17025 - Contents

- ALSO INCLUDES TWO ANNEXES:
  - Annex A (Informative) - Nominal Cross Reference to ISO 9001:2000
  - Annex B (Informative) - Guidelines for Establishing Applications for Specific Fields
- And a Bibliography

ISO/IEC 17025 - Contents

- 17025 separates the Management Requirements (ISO 9001 Requirements) from the Technical Requirements
  - The Technical Requirements section is what differentiates ISO/IEC 17025 from ISO 9001
  - **If you comply with ISO/IEC 17025, you comply with ISO 9001 but not vice-versa**!

Clause 4 - Management Requirements

- 4.1 **Organization**
- 4.2 **Management System**
- 4.3 **Document Control**
- 4.4 **Review of Requests, Tenders, and Contracts**
- 4.5 **Subcontracting of Tests**
- 4.6 **Purchasing Services and Supplies**

Clause 4 - Management Requirements (continued)

- **4.7 Service to the Customer**
- **4.8 Complaints**
- **4.9 Control of Nonconforming Testing Work**
- **4.10 Improvement**
- **4.11 Corrective Action**
- **4.12 Preventive Action**
- **4.13 Control of Records**

Clause 4 - Management Requirements (continued)

- **4.14 Internal Audits**
- **4.15 Management Reviews**

ISO/IEC 17025
Clause 5 - Technical Requirements

- **5.1 General**
- **5.2 Personnel**
- **5.3 Accommodation and Environmental Conditions**
- **5.4 Test Methods and Method Validation**
- **5.5 Equipment**

ISO/IEC 17025
Clause 5 - Technical Requirements

- **5.6 Measurement Traceability**
- **5.7 Sampling**
- **5.8 Handling of Test Items**
- **5.9 Assuring the Quality of Test Results**
- **5.10 Reporting the Results**

Key Management Requirements

- Quality Policy Statement
- Quality Manual
  - Quality Procedures
- Record of Latest Internal Audit
- Minutes from Last Management Review
- Complaint Record with Corrective Actions

Key Technical Requirements

- EMC Test Equipment Calibrated by Accredited Calibration Labs with appropriate Scopes of Accreditation
- Personnel Training Records
- Test Procedures
- Test Methods

Key Technical Requirements

- Accommodations – Temperature and Humidity; Semi-Anechoic Chambers
- Test Facility Validation
  - (Radiated Facilities- Emission and Immunity)
- Test Report
  - Measurement Uncertainty Analysis

Common Non-Conformities

- Quality Manual not consistent with ISO/IEC 17025
- Missing or Incomplete Quality Procedures
- No Internal Audit within the previous 12 months
- Incomplete Management Review
- Purchase orders missing significant details for calibration of test equipment

Common Non-Conformities

- Technical Personnel Training Matrix incomplete or missing
- Test procedures that lack technical detail
- Test equipment not calibrated by an accredited calibration laboratory
- No periodic checks on the magnetic field ambient, the electric field ambient, and the conducted ambient on the power lines
- Test Setups that don’t comply with linear dimensions of international EMC standards

Examples of Common Non-Conformities

- 4.2.2 – The laboratory's management system policies related to quality, including a quality policy statement, shall be defined in a quality manual (however named). The overall objectives shall be established, and shall be reviewed during management review. The Quality Policy Statement shall be issued under the authority of top management. It shall include the following:
  - A) the laboratory management's commitment to good professional practice and to the quality of its testing in servicing its customers
  - B) the management's statement of the laboratory's standard of service
  - C) the purpose of the management system related to quality
  - D) a requirement that all personnel concerned with testing activities within the laboratory familiarize themselves with the quality documentation and implement the policies and procedures in their work
  - E) the laboratory management's commitment to comply with this handbook and to continually improve the effectiveness of the management system
- Many Quality Policy statements from testing labs miss some of the A) though E) requirements

Examples of Common Non-Conformities

- 4.3.1 – The laboratory shall establish and maintain procedures to control all documents that form part of its management system (internally generated or from external sources), such as regulations, standards, other normative documents, test methods, as well as drawings, software, specifications, instructions and manuals.
- Testing Laboratories are oftentimes missing procedures to control their documents

Examples of Common Non-Conformities

- 5.5.2 - Equipment and its software used for testing shall be capable of achieving the accuracy required and shall comply with specifications relevant to the tests concerned. Calibration programs shall be established for key quantities or values of the instruments where these properties have a significant effect on the results. Before being placed into service, equipment shall be calibrated or checked to establish that it meets the laboratory's specification requirements and complies with the relevant standard specifications. It shall be checked and/or calibrated before use (see 5.6).
- Testing Laboratories sometimes use "uncalibrated" equipment and/or "unvalidated" software.

Examples of Common Non-Conformities

- 5.5.2 Records shall be maintained of each item of equipment and its software significant to the tests performed. The records shall include at least the following:
  - A) the identity of the item of equipment and its software
  - B) the manufacturer's name, type identification, and serial number or other unique identification
  - C) checks that equipment complies with he specification (see 5.5.2)
  - D) the current location, where appropriate
  - E) the manufacturer's instructions, if available, or reference to their location
  - F) dates, results and copies of reports and certificates of all calibrations, adjustments, acceptance criteria, and the due date of next calibration
  - G) the maintenance plan, where appropriate, and maintenance carried out to date
  - H) any damage, malfunction, modification or repair to the equipment
- The records of Testing Laboratories sometimes are missing some of the items from A) through H)

Common problems with ISO/IEC 17025

- The standard is written for both testing and calibration laboratories which results in complex sentences which are difficult to understand (especially for people whose English is a second language)
  - It would be better to have two standards; one for testing labs and one for calibration labs

Common problems with ISO/IEC 17025

- National Metrology Labs have the smallest measurement uncertainties
- Calibration labs have larger measurement uncertainties than National Metrology Labs
  - but smaller than Testing Labs
- Testing labs have the largest measurement uncertainties!

Common problems with ISO/IEC 17025

- Clause 4.13 – Control of Records is written:
  - 4.13.1 – General
  - 4.13.2 – Technical Records
- It should be written
  - 4.13.1 – General
  - 4.13.2 – Quality Records
  - 4.13.3 – Technical Records

Quality Records in ISO/IEC 17025

- Quality Records are:
  - Records of Internal Audit Findings
  - Minutes from Management Reviews
  - Records of Corrective Actions
  - Records of Preventive Actions
  - Records of Customer Complaints
  - Records of Purchased Supplies and Services
  - Records of Qualified Suppliers of Services and Supplies

Technical Records in ISO/IEC 17025

- Technical Records are:
  - Original Observations
  - Work Sheets and Work Books
  - Control Graphs
  - Derived Technical Data
  - Calibration Records
  - Technical Staff training records
  - Test Reports

Accreditation Bodies

- **If a laboratory wishes accreditation for part or all of its testing, it should select an Accreditation Body that operates in accordance with ISO/IEC 17011.**
- ***ISO/IEC 17011 – Conformity Assessment – General Requirements for Accreditation Bodies Accrediting Conformity Assessment Bodies***

United States Accreditation Bodies

- There are 3 US Accreditation Bodies that are recognized by the FCC and ILAC for accrediting EMC Labs:
  - United States Department of Commerce, National Institute of Standards and Technology, National Voluntary Laboratory Accreditation Program (NIST/NVLAP)
  - American Association of Laboratory Accreditation (A2LA)
  - ACLASS – ANSI-ASQ National Accreditation Board
- Other countries have Accreditation Bodies that are internationally recognized by ILAC.
  - ILAC – International Laboratory Accreditation Cooperation

SUMMARY

- **In general, High-Quality EMC Testing labs are accredited to ISO/IEC 17025**
- **ISO/IEC 17025 has both a Quality and a Technical Section**
  - **The latest edition was released in 2005**
- **Accreditation Bodies for EMC Labs should be recognized by ILAC**

Biography

- **Daniel David Hoolihan – 2011 Biography**
- Electromagnetic Compatibility (EMC) Engineering Consultant
- Daniel D. Hoolihan is currently President of Hoolihan EMC Consulting. He specializes in EMC-Laboratory evaluations, EMC Standards, and EMC Education.
- He is a consultant to the United States Department of Commerce National Institute of Standards and Technology (NIST) in the area of Telecom Certification Body (TCB) and Conformity Assessment Body (CAB) evaluations. He is also a laboratory assessor for the NIST National Voluntary Laboratory Accreditation Program (NVLAP).
- Hoolihan has been a member of the IEEE and the EMC Society since 1983. He is the Chairman of the History Committee of the EMC Society and has been on the Board of Directors of the Electromagnetic Compatibility Society (EMCS) since 1987. He is the past-president of the EMCS (1998-1999).
- Chair of the 2002 IEEE International Symposium on EMC. He helped found the EMC chapter of the Twin Cities Section in 1985.
- Currently Vice-Chairman of the United States ANSI-ASC C63R on EMC.
- He worked as Vice-President of Minnesota Operations for TUV Product Service – 1994-2000.
- From 1984 to 1994, he was the Co-Founder/Chief Operating Officer of AMADOR Corporation
- Hoolihan EMC Consulting, 32515 Nottingham Court – Box 367 – Lindstrom, MN 55045
- 651-213-0966 Cell Phone 651-269-3569

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Eliminating the Need for Exclusion Zones in Nuclear Power Plants:

"Where are the New Boundaries?"

Philip F. Keebler
Sr. Research Engineer, EPRI

IEEE EMC Society: Emerging Technologies in EMC
April 26, 2012

POLI USP
Escola Politécnica - University of São Paulo
São Paulo, Brazil

Don’t leave, because I have a surprise (special slide) for you at the end.

IN Compliance Magazine Article
Part I: June 2011

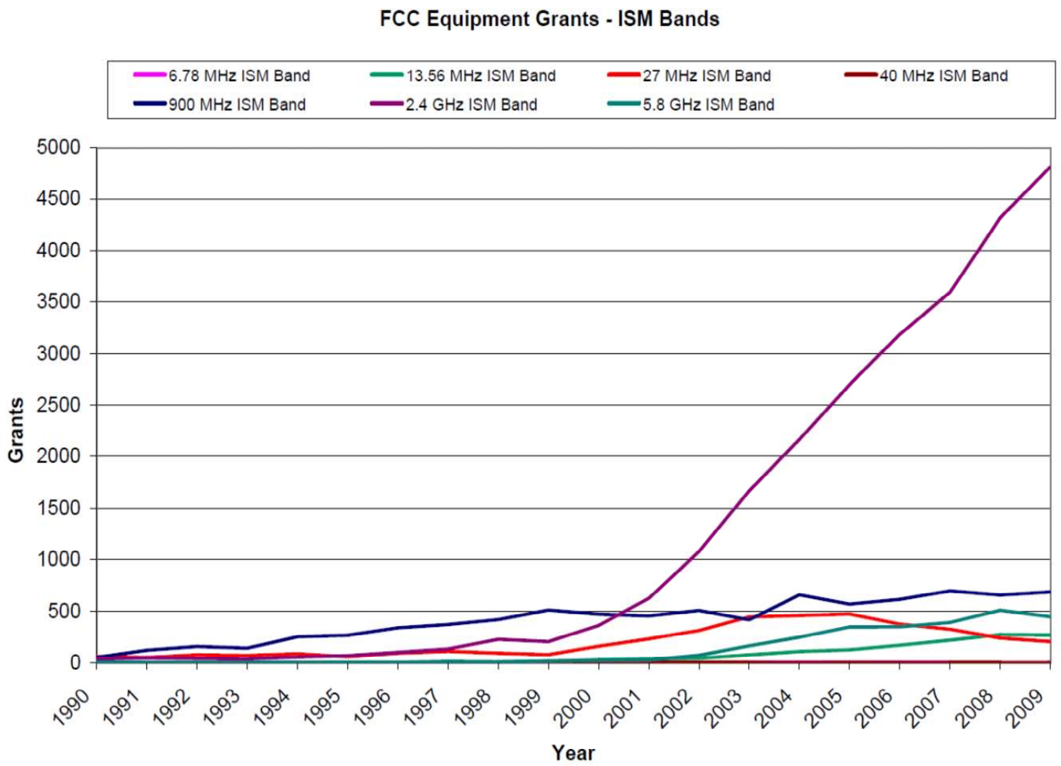
Eliminating the Need for
Exclusion Zones in Nuclear Power Plants

Philip F. Keebler
Electric Power Research Institute

What's one of the Stimuli?

Growth in the 2.4-GHz ISM Bands

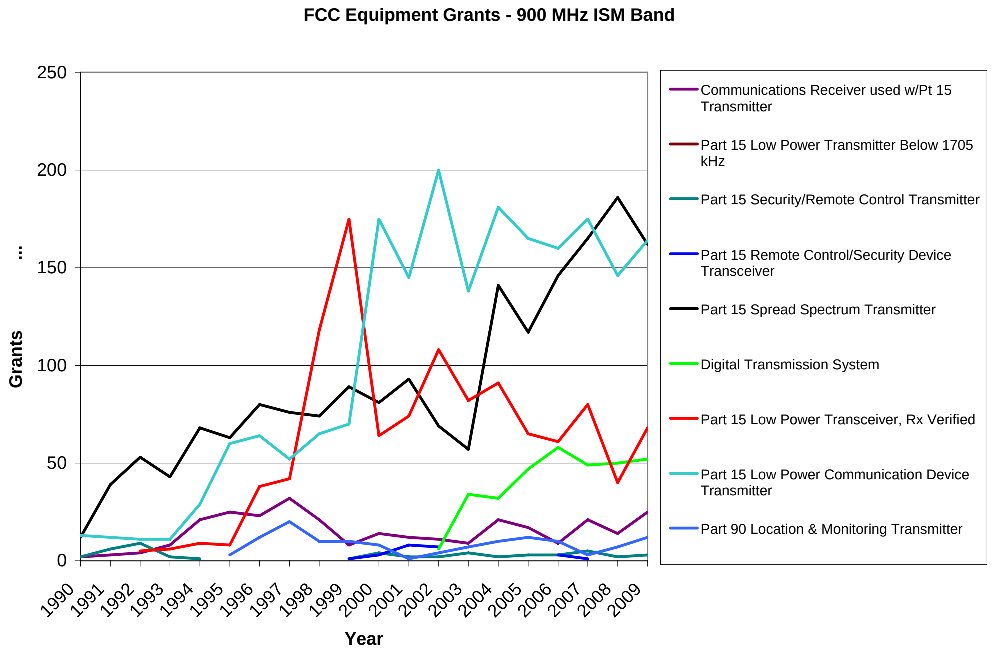
- The 900-MHz, 2.4- and 5.8-GHz bands support by far the most equipment.
- The growth of the 2.4-GHz band is extraordinary.



What's another one of the Stimuli?

Growth in the 900-MHz ISM Bands

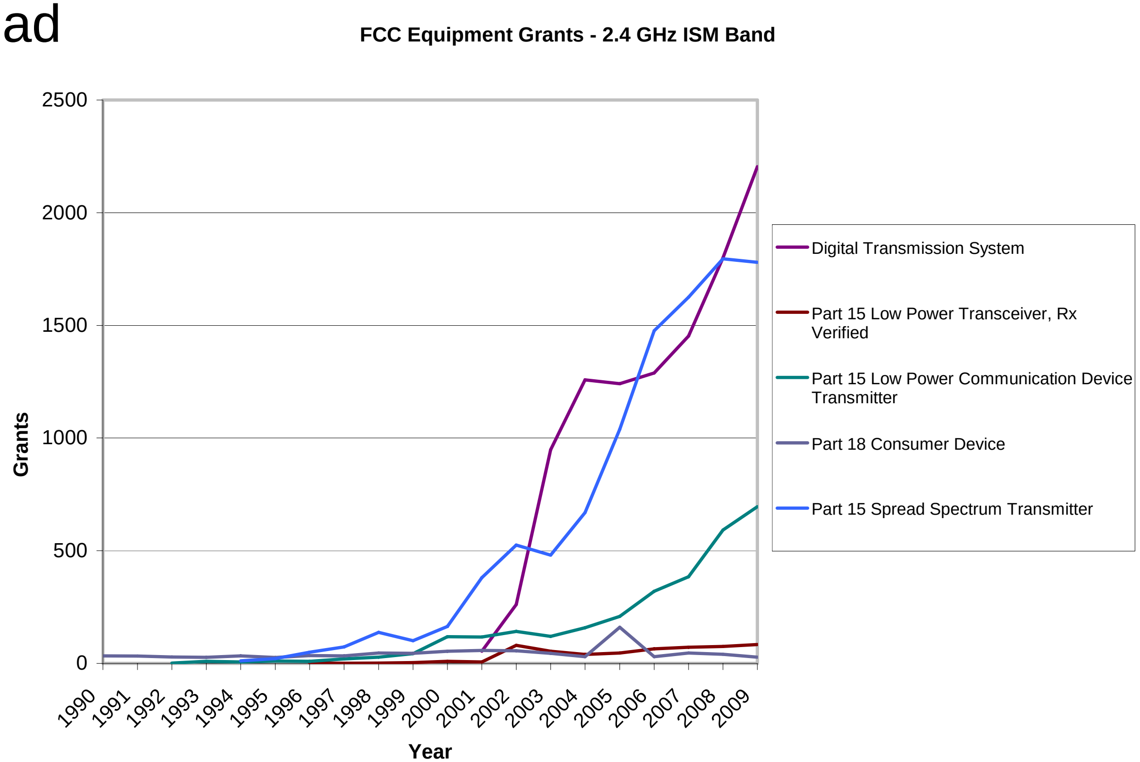
- The growth in the number of FCC grants issued for the 900-MHz ISM band has been with Part 15 spread spectrum transmitters.
- This is followed by Part 15 low-power communication device transmitters and Part 15 low-power transceivers (Rx verified) devices.



What's another one of the Stimuli?

Growth in the 2.4-GHz ISM Bands (Digital & Spread Spectrum)

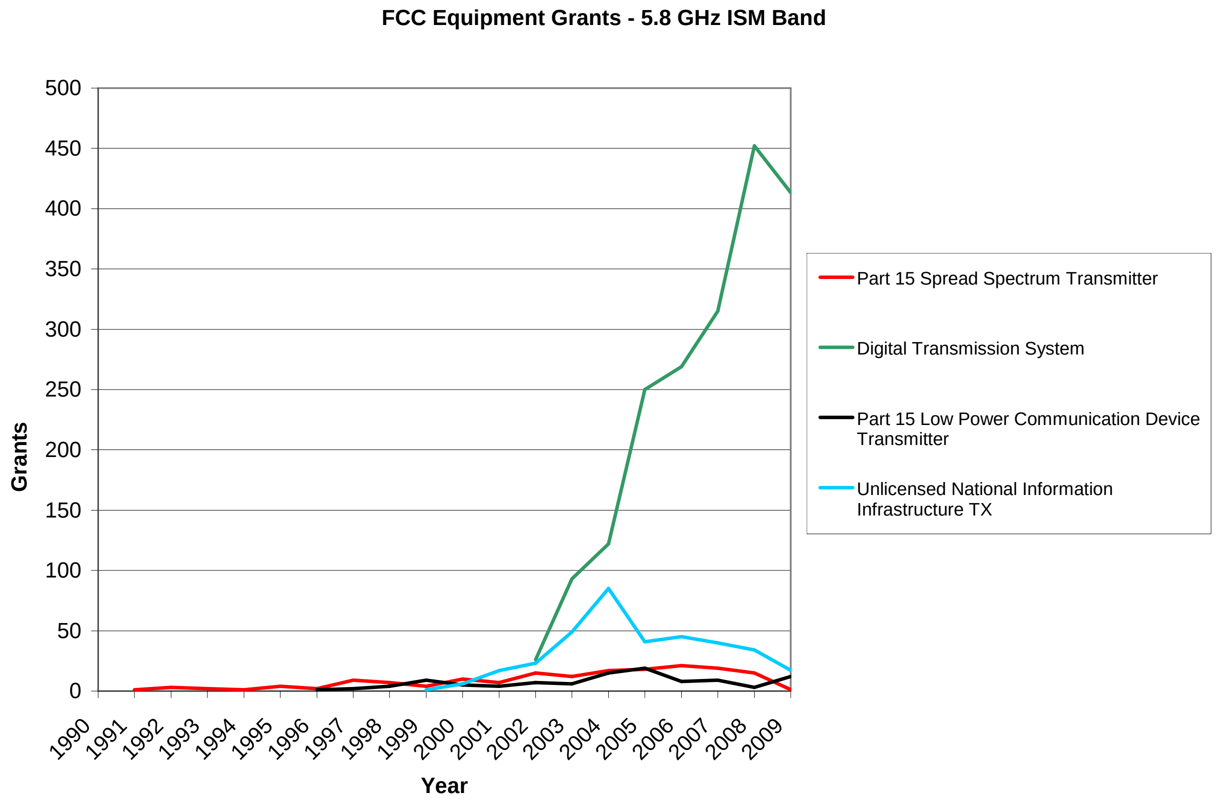
- The growth in the number of FCC grants issued for the 2.4-GHz ISM band has been with Part 15 digital transmission systems followed by Part 15 spread spectrum transmitters



What's another one of the Stimuli?

Growth in the 5.8-GHz ISM Bands

- The growth is obviously in the 5.8-GHz digital transmission systems as well.



More Stimuli: Increasing Number of EMI Events in Nuclear Power Plants (by year)

Types of Events by Year

The number of EMI-related events shows an increase in frequency (i.e., how often they occur) over time as illustrated in Figure 2-1. Since 2000, there has been a steady rate of one to five events per year reported into the INPO system.

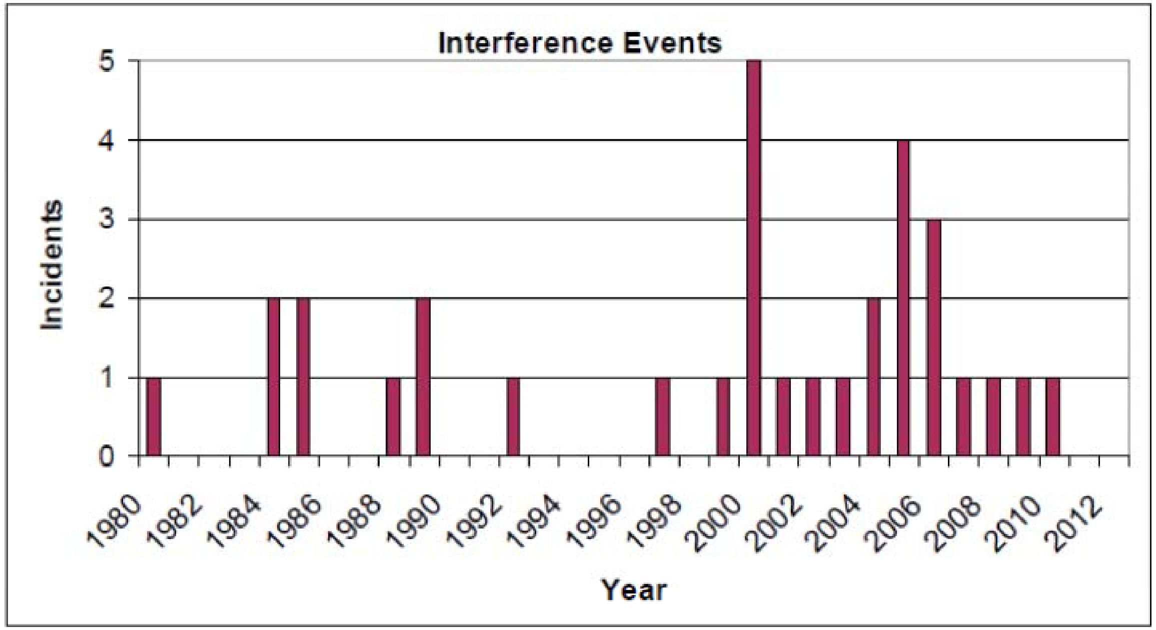


Figure 2-1
Base (Rev. 0) Analysis: Total EMI Related Events

Assessment of Electromagnetic Interference Events in Nuclear Power Plants, Reported to INPO:1975 to 2011. EPRI, Palo Alto, CA: 2011. 1022984.

More Stimuli: Increasing Number of EMI Events in Nuclear Power Plants (by I&C equipment)

Types of Events by I&C Equipment

Interference to instrumentation and control (I&C) systems is a major concern when evaluating the risk to plant operations from EMI. As Figure 2-2 shows, if anything the number of reported events has risen or at best stayed constant in recent years.

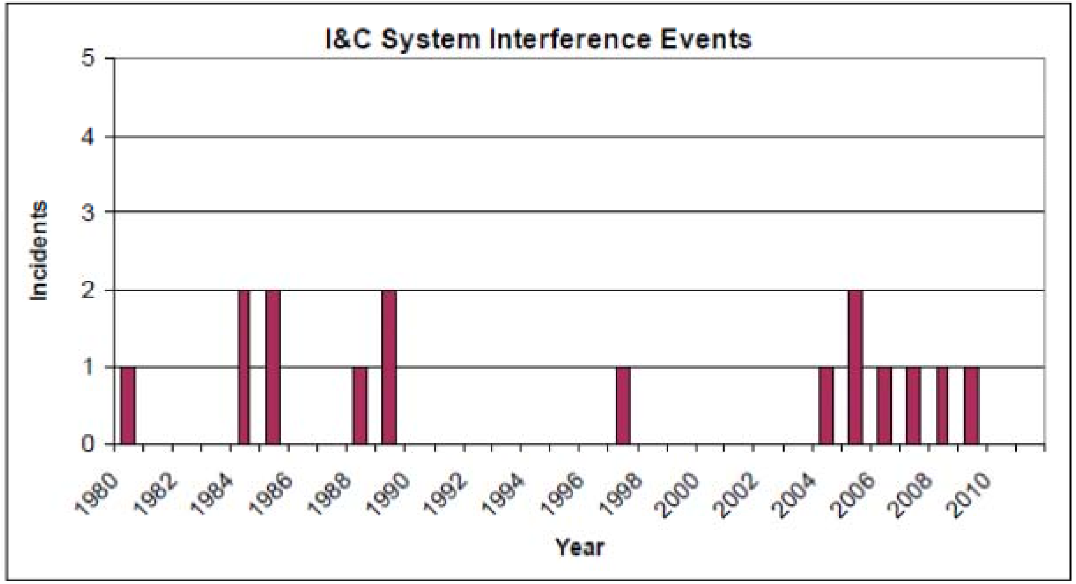


Figure 2-2
I&C System Interference Events

Assessment of Electromagnetic Interference Events in Nuclear Power Plants, Reported to INPO:1975 to 2011. EPRI, Palo Alto, CA: 2011. 1022984.

Example Case

Open cabinet doors is a common contributor observed in a set of interference incidents.

It is also noted that while the risk of interference from RF transmitters was known and exclusion zones have established as a protective measure for some time, in a number of cases the exclusion zone strategy was not effective.

In mid-winter of 1985 at one unit at another nuclear plant during normal power operation, a safety injection signal, turbine trip, and reactor trip resulted from security personnel using a portable radio transmitter. The plant had previously established "no-radio-transmission" areas based on testing and analysis. However, during this event the metal cabinet doors to the main steam-line pressure transmitters were open for temporary startup test connections.

In the analysis of the 1985 incident at this plant, specific mention was made of the 1980 warning. It was stated that the recommended RF immunity survey was performed, but was flawed in that is missed the vulnerability experienced:

> *Unit 1 was surveyed for areas sensitive to RFI in the late spring of 1981, as recommended in IE Circular 80-09. At that time, all Unit 1 areas found susceptible to RFI were posted, and warnings of instrumentation susceptibility were added to general employee and security training. The cause of this event was an inadequate RFI survey performed by plant engineering personnel in that same month of 1981. The list of areas surveyed did not include at area around the steam line pressure transmitters; thus, there were no radio use warning signs posted in the area.*

Two observations are made here but discussed in greater detail later in this report in the context of analyzing the full EMC protection system. First, it is observed that open cabinet doors are a common component to these interference incidents. Second, while the risk of interference from RF transmitters was known and exclusion zones were established as a protective measure; in these cases the exclusion zone strategy was not effective.

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Think about it….

But are portable transceivers the only problem? More specifically are portable transceivers a significantly worse source of EM fields than other sources? If they are, then exclusion zones are an effective remedy.

The use of exclusion zones is increasingly rejected. Other methods of EMC control are found more effective. Shielding, filtering or improved immunity, but implemented at the right level, are increasingly the preferred methods for EMC control.

Why are Exclusion Zones a problem for NPP?

- *Major Concern:* It is difficult to control the inventory and use of wireless devices inside the plant.

Why is it difficult to control wireless device inventory?

- Plant staff check WDs *in* and *out* of “stock”.
- Managing a “divided” inventory presents problems for plant staff.
- Often, there is a shortage of radios (walkie-talkies).
- In the event of an emergency, plant staff will use whatever radios are available.
- Contractors are constantly trying to bring WDs into the plant.
- WDs find their way into the plant without going through proper approval channels.

Where does the use of exclusion zones take the plant?

"…the question is not whether exclusion zones should be used or not, but rather is their use, coordinated with other components of a total control strategy optimal for the current and future EM environment that plants will operate in."

Exclusion Zones affect plant resources

- Assignment of personnel
- Expenditures of labor – to use & train on use of exclusion zones
- Use of higher RF power levels = new exclusion zone calculations and modifications
- Managing zones is an on-going cost
- Overly conservative and redundant monitoring to assure continual and effective compliance
- Create conflicts for plant workers between the need to protect sensitive I&C systems and the need to use wireless services

One event leads to a widespread set of “ineffective” rules

- These kinds of conflicts are exacerbated because exclusion zones must be implemented as general rules, without regard for the differences in wireless services. If, for example cell phones are discovered to cause an EMI problem in a nuclear plant then all cell phones, in all frequency bands and at all power levels must be excluded. However, personnel will often discover that their cell phone creates no interference, making the exclusion zone seem arbitrary and needless. This may lead some plants to issue ‘blanket approval’ for the use of all cell phones—a strategy that presents undefined risks to the operation of I&C equipment.

More Concerns with the Use of Exclusion Zones

- When an EMI problem occurs:
  - The exclusion zones get larger.
- When new wireless devices replace old ones:
  - The exclusion zones get larger.
- Encroachment of zones into human traffic areas:
  - Steps, ladders, walkways: interfering with exclusion zones
- Exclusion zones require painting (and repainting) of floor areas.
- EMI problems have been reported even when exclusion zones are obeyed!

Other Concerns with Use of Exclusion Zones

- System cabinets not EMC qualified
  - Most do not have EMC seals & gaskets
  - Cable penetrations do not use EMC-rated feedthroughs
- Wireless devices dynamics:
  - New models developed frequently
  - Use of many parts of the spectrum
  - Transmit power not controlled by device, but by tower
- Zone can reach "expiration" quickly
  - Total immunity depends on several layers of immunity
  - Equipment change-out voids "expected" immunity
  - Effective immunity dependent upon quality of seals & gaskets

Exclusion Zone Guidance became more stringent

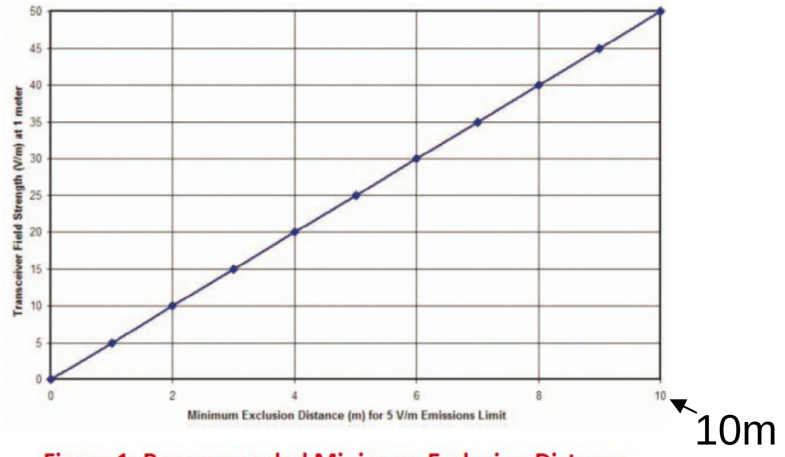


Figure 1: Recommended Minimum Exclusion Distance (in meters) as a Function of Transceiver Field Strength (V/m) at 1 Meter. (EPRI TR-102323 (1997) Revision 1)

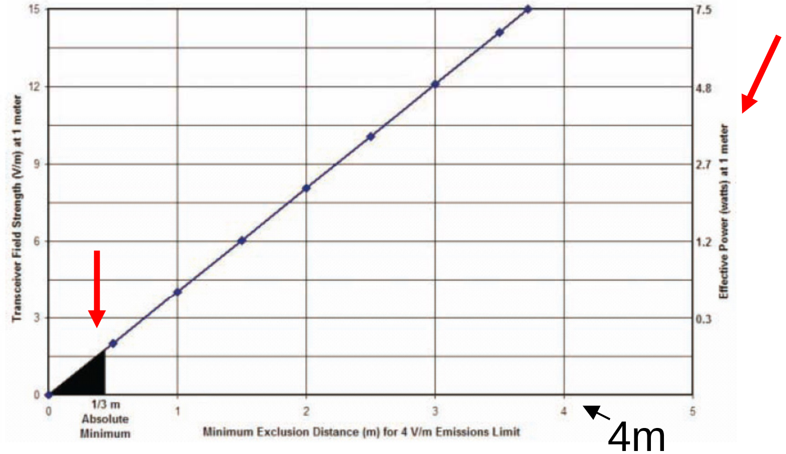
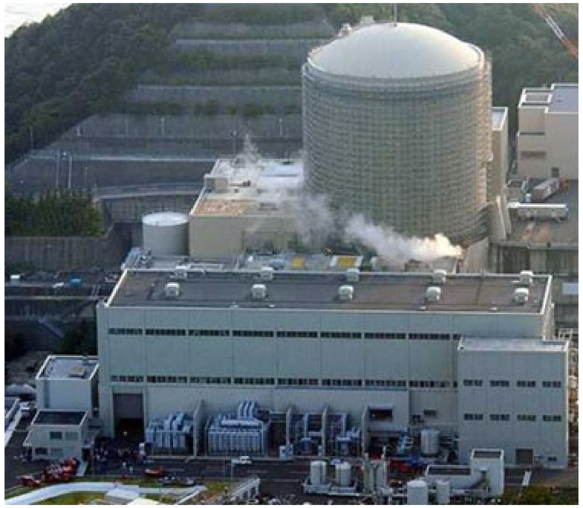


Figure 2 (Figure 6-1 in EPRI TR-102323 Rev. 2): Recommended Minimum Exclusion Distance (in meters) as a Function of Transceiver Field Strength (V/m) at 1 Meter. (EPRI TR-102323 (2000) Revision 2)

- By the Rev. 2 of the EPRI TR-102323 report, the graph (shown in Figure 2) was modified to indicate a 4 V/m maximum emission limit, reduced from the 5 V/m defined in Rev. 1. In addition, a 1/3 meter absolute minimum protection distance was added. The total distance scale was reduced from 10 meters to 4 meters. In addition, a second scale was added to the vertical axis showing the effective radiated power as well as the field strength. While the guidance and verbiage remains relatively the same, these differences indicate a growing need for additional EMC protection while also the difficulty of enforcing an exclusion zone over larger areas.

Exclusion Zones can place the plant at higher risks during an emergency situation



- Plant workers will use radios & other wireless devices in any place in the plant to deal with emergency situations.
- Emergency staff will not deal with exclusion zones in the event of dealing with an emergency.

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Elements of the Current Exclusion Zone Strategy

- I&C equipment is required to have a broadband immunity of 4 V/m.

Table 1
Logic behind the Use of Current Exclusion Zones

#	Element	Component		Level
1	Electromagnetic Immunity of I&C Equipment	Immunity	↓	≥ 10 V/m
2	Safety Margin (8 dB)	Immunity	↓	≥ 4 V/m
3	Exclusion Zone	Emissions	↓	≤ 4 V/m
4	EM Fields from Portable Transceivers	Emissions	↑	Potentially > 300 V/m

Elements of the Current Exclusion Zone Strategy

- To this, an 8-dB safety margin was added (see Part 1 of this article for a history of this safety margin), which results in strategy seeking to insure that I&C equipment and systems are not exposed to fields greater than 4 V/m.

Table 1
Logic behind the Use of Current Exclusion Zones

#	Element	Component		Level
1	Electromagnetic Immunity of I&C Equipment	Immunity	↓	≥ 10 V/m
2	Safety Margin (8 dB)	Immunity	↓	≥ 4 V/m
3	Exclusion Zone	Emissions	↓	≤ 4 V/m
4	EM Fields from Portable Transceivers	Emissions	↑	Potentially > 300 V/m

Elements of the Current Exclusion Zone Strategy

- To ensure that I&C equipment and systems are not exposed to fields beyond 4 V/m, exclusion zones are recommended as discussed in Part 1 of this article. An exclusion zone is intended to keep wireless transceivers far enough away from I&C equipment and systems, so that their radiated emissions will not subject the I&C equipment to more than 4 V/m.

Table 1
Logic behind the Use of Current Exclusion Zones

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4	EM Fields from Portable Transceivers	Emissions	↑	Potentially > 300 V/m

Elements of the Current Exclusion Zone Strategy

- The threat!

Table 1
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3	Exclusion Zone	Emissions	↓	≤ 4 V/m
4	EM Fields from Portable Transceivers	Emissions	↑	Potentially > 300 V/m

Electromagnetic (Electric) Field Strengths

- **Close to a device field strengths can be surprisingly high.**
- **The following slides present data gathers from FCC test files.**
- **The measurements were made at 1.5 centimeters from the device.**

Electric Field Strengths

Model	Freq	Max Power		Field Strength
	(MHz)	(dBm)	W	V/m
LG VS740	850	26.2	0.42	98.4
	1909	25.2	0.33	51.6
Palm P121UNA	837	23.1	0.20	236.3
	1907	22.0	0.16	92.0

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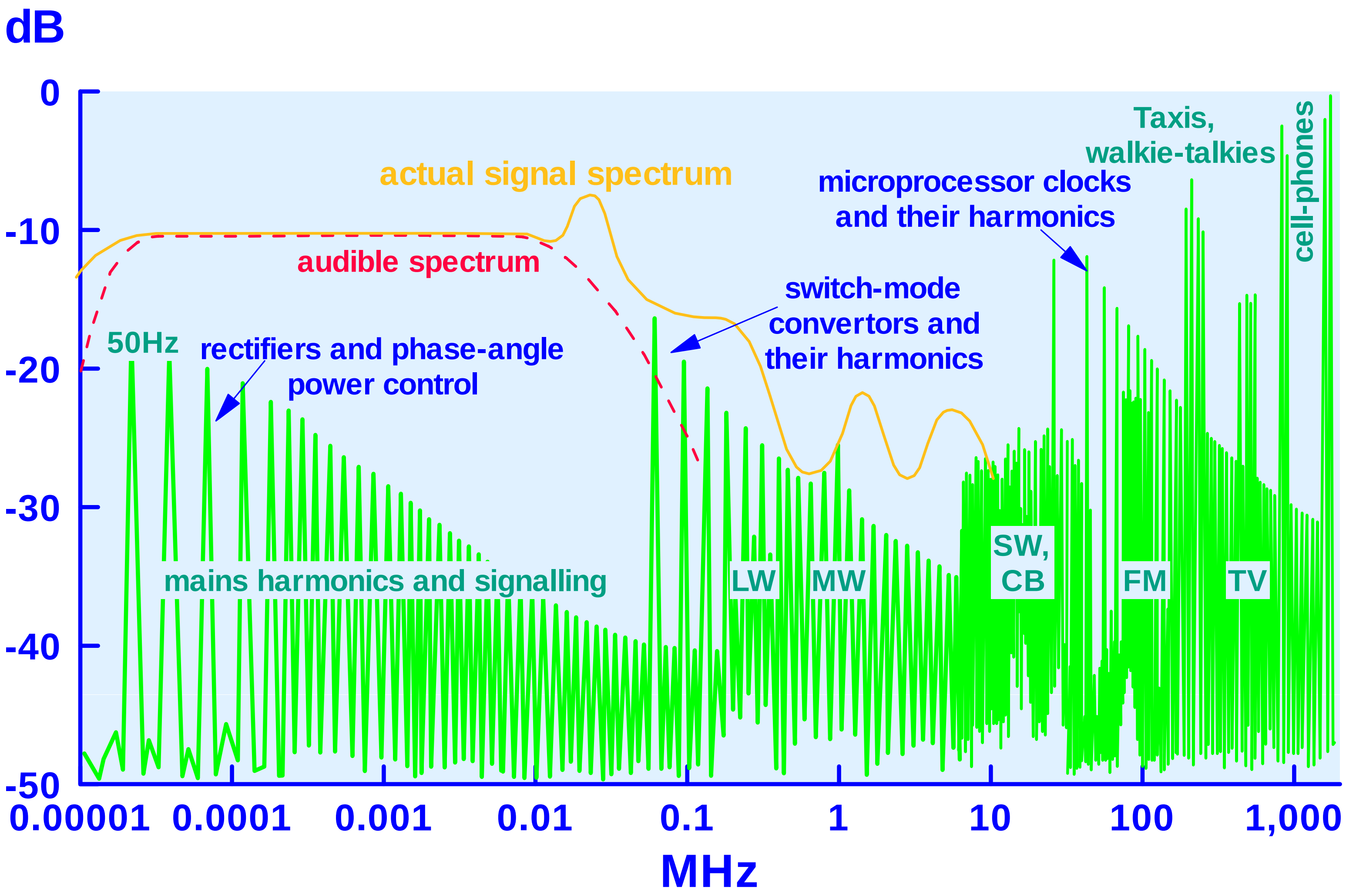
Electric Field Strengths

Model	Freq (MHz)	Max Power (dBm)	Max Power W	Field Strength V/m
HTC PB65100	849	33.2	2.11	187.8
	1910	31.0	1.25	79.7

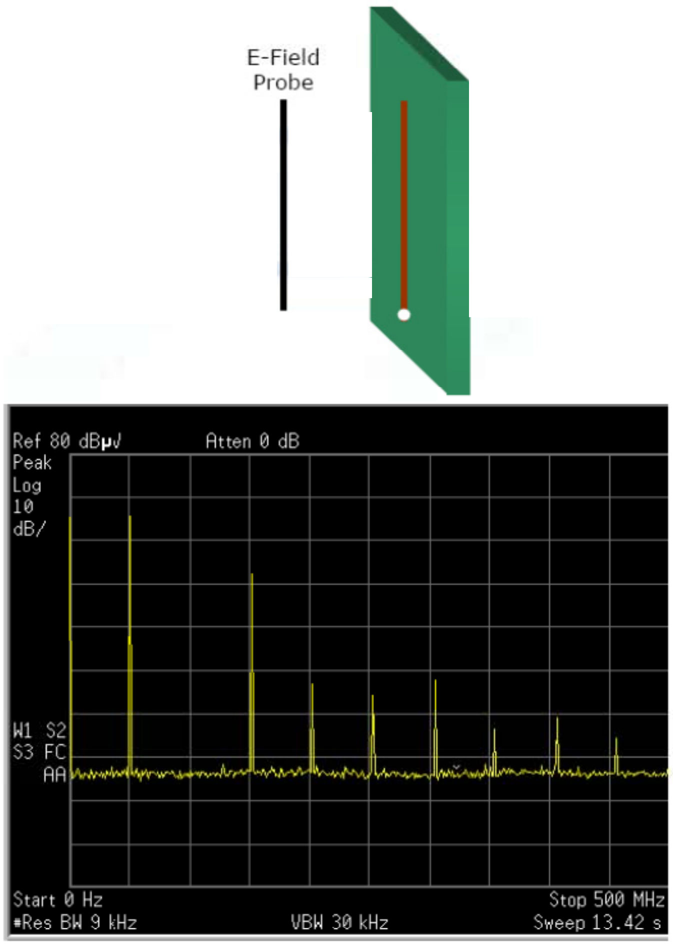
Model	Freq (MHz)	Max Power (dBm)	Max Power W	Field Strength V/m
HTC PC70110	824	24.2	0.27	221.7
	1852	23.4	0.22	79.7

Layer 1: Components – Analog-Digital Environment

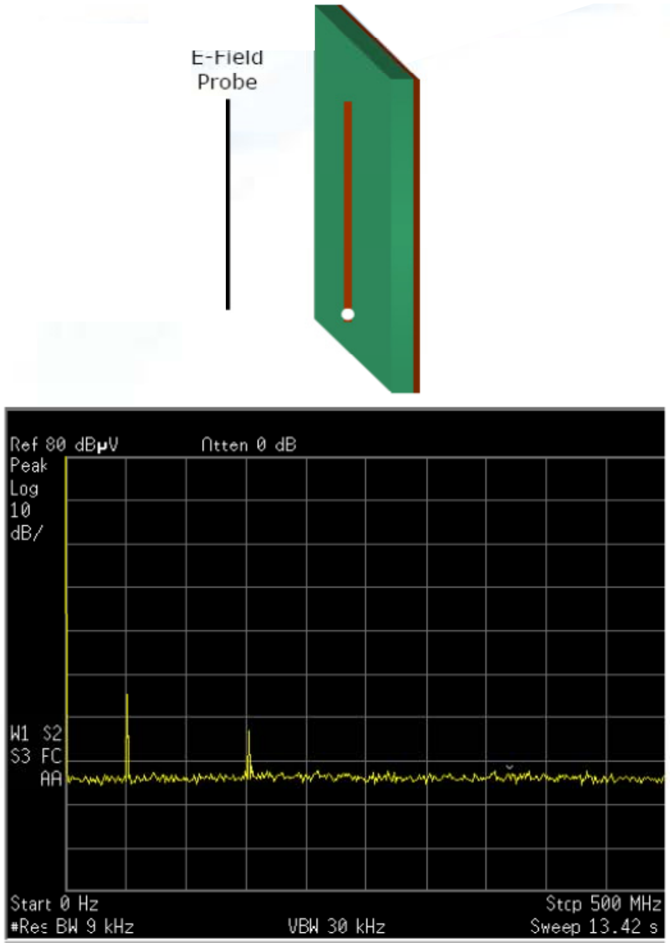
A Mixed Environment is More Energetic & Cluttered



Layer 2: PCB Immunity



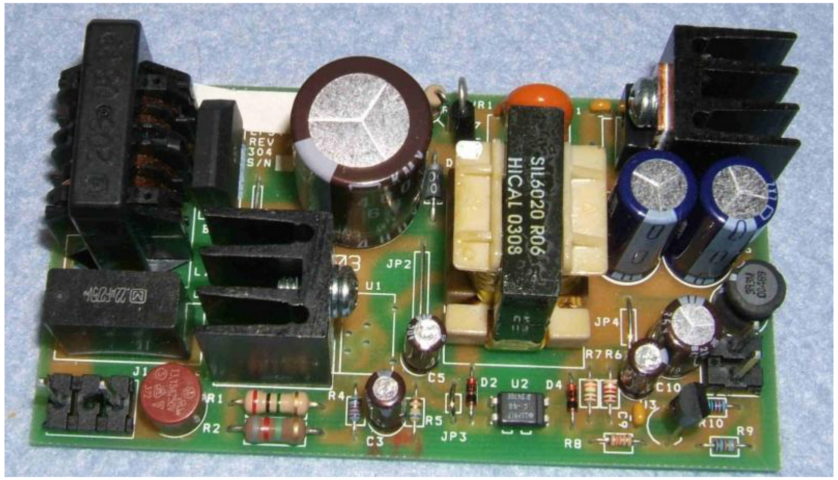
No Ground Plane



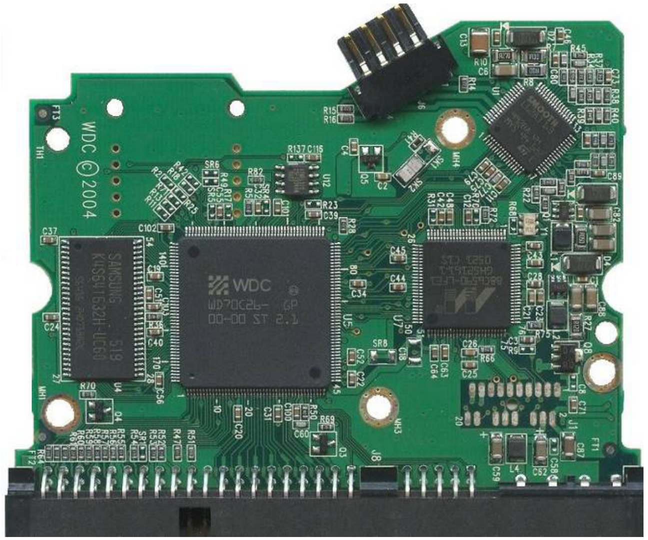
With Ground Plane (Micro-Strip)

Layer 3: Subassemblies – EMI Impacts Analog ***and*** Digital Equipment

- **Examples of Analog Equipment**
  - Source-Range Nuclear Instrumentation
  - Radiation Monitors
  - Gas Analyzers
  - Bi-stable/Alarm Circuits
- **Examples of Digital Equipment**
  - Programmable Logic Controllers
  - Digital Control Systems

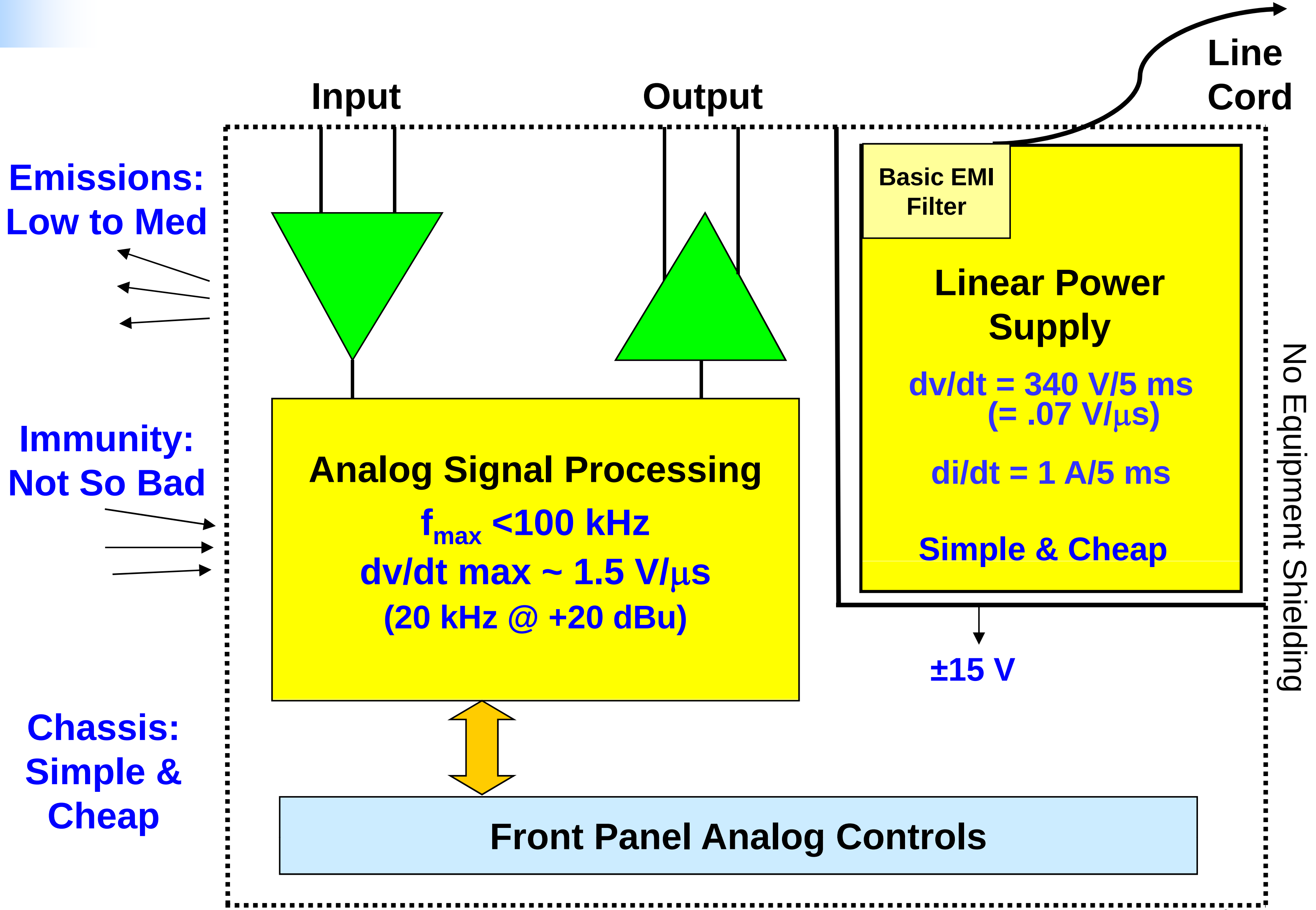


Typical Analog Power Supply from I&C Equipment



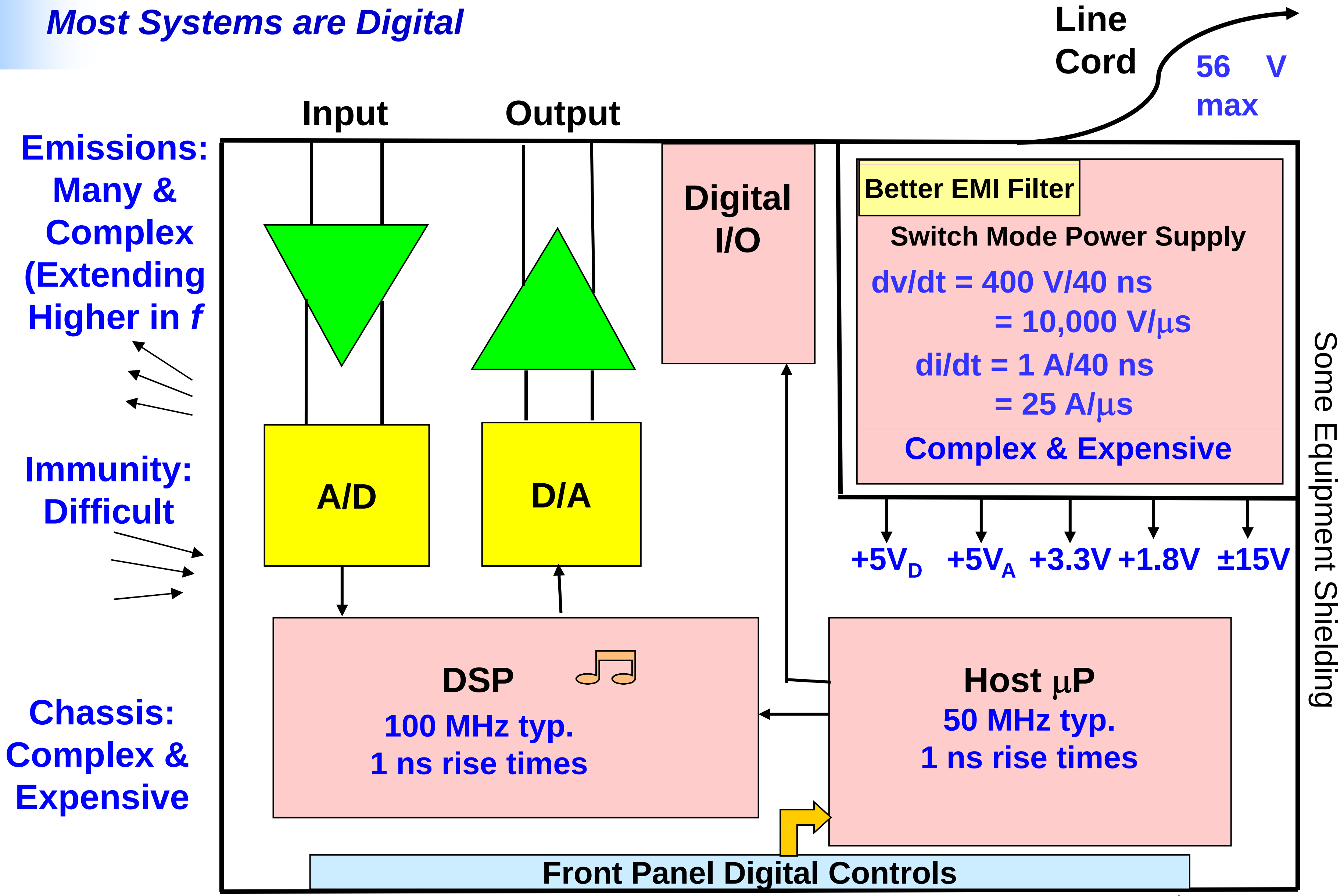
Example Digital Board from I&C Equipment

Analog-Only I&C Product



Analog-Digital I&C Product

Most Systems are Digital



Layer 4: Enclosure

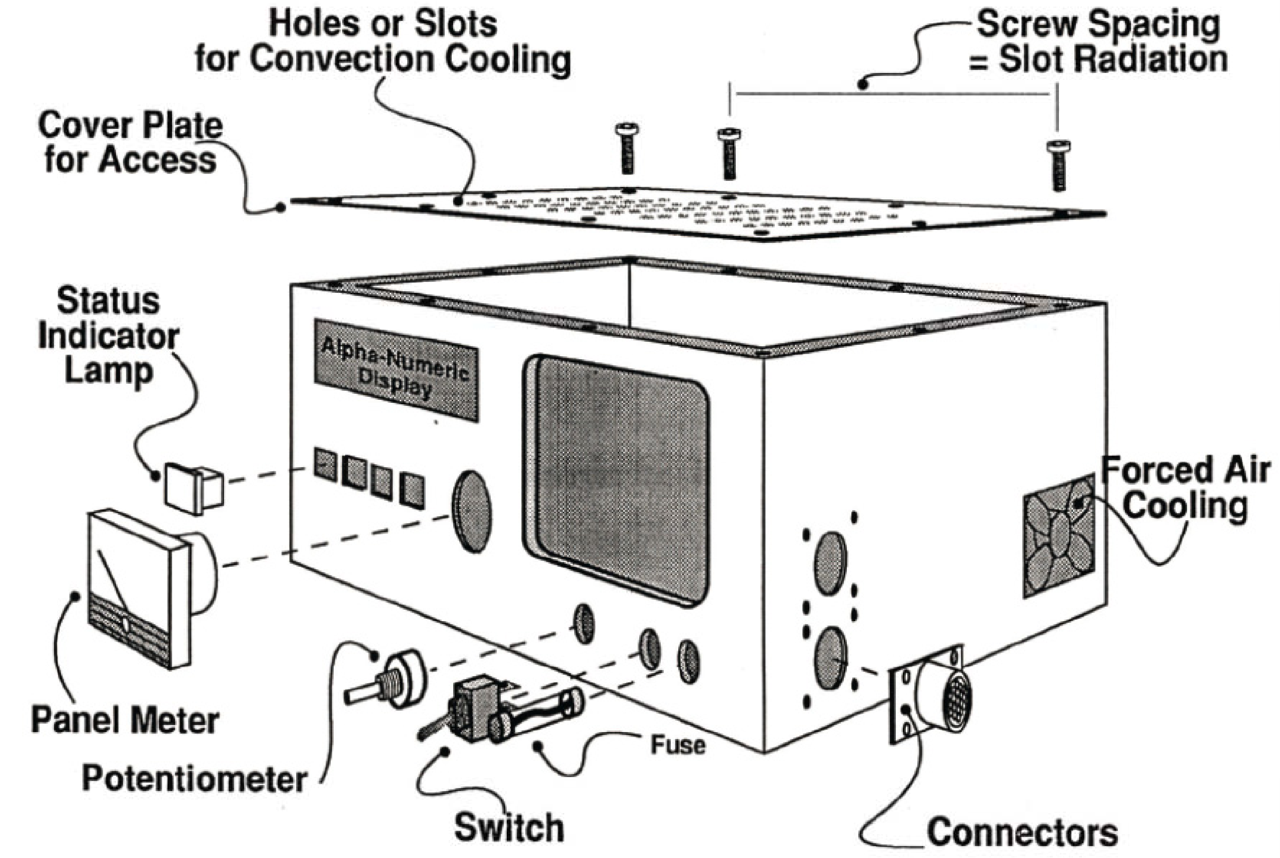
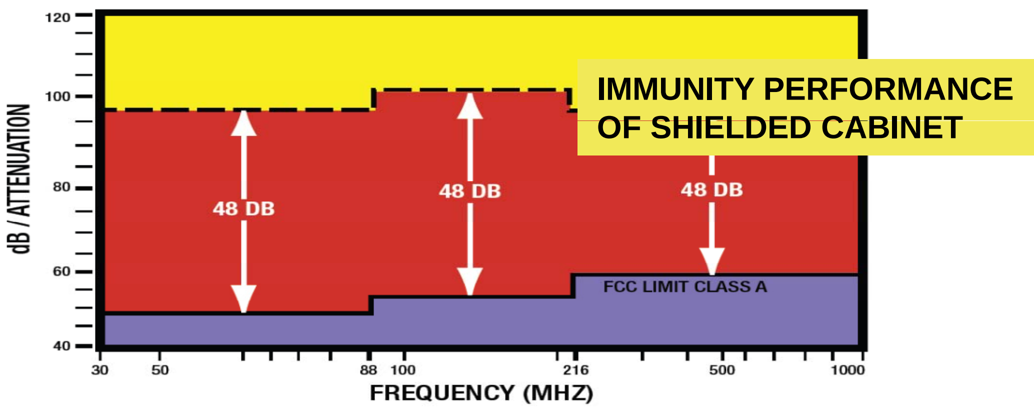


Figure 2
Example of Equipment Housing (Case or Enclosure) for a Piece of Electronic Equipment

Layer 5: System Cabinet

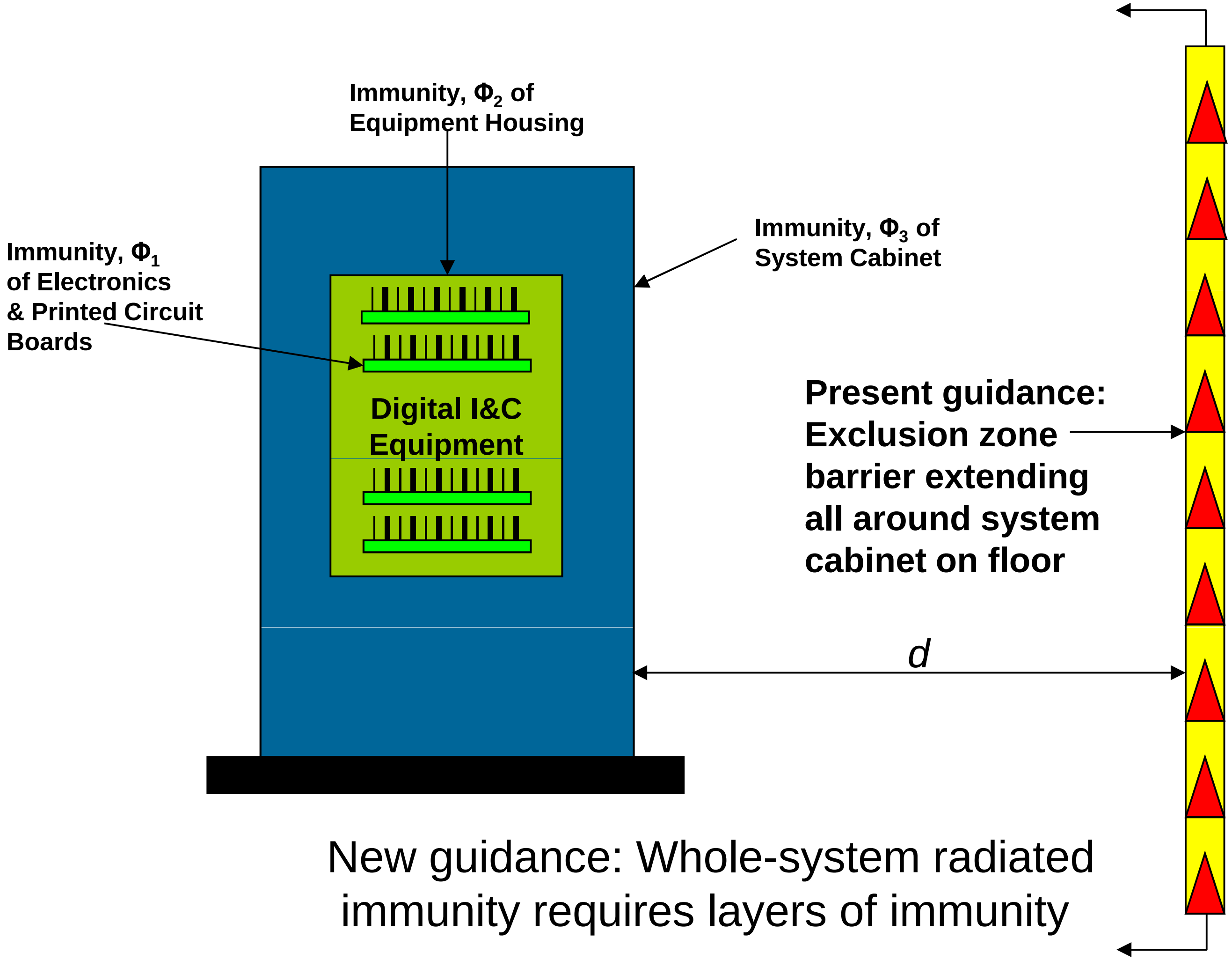


Example Calculations of Exclusion Zones

Table 2
Required Exclusion Zone Distances Assuming Two-Ray Propagation Model and Dipole Antenna with 2.4 dB Gain

Exclusion Zone Limit (Electric Field in V/m)	RF Power (Watts) Portable Transceiver (Intentional Radiator)						
		Cordless Phone ≈ 0.1 w	CDMA Cell Phone ≈ 0.6 w	PCS Cell Phone ≈ 1-2 w		Hand-Held Walkie-Talkies ≈ 5-8 w	
	0.01	0.1	0.5	1	2	4	8
	Size of Exclusion Zone (meters)						
2.0	0.5	1.6	3.6	5.1	7.2	10.2	14.4
4.0	0.3	0.8	1.8	2.5	3.6	5.1	7.2
8.0	0.1	0.4	0.9	1.3	1.8	2.5	3.6

Immunity should be addressed as a "Layered Approach"



New guidance: Whole-system radiated immunity requires layers of immunity

Effective EMC Protection Requires Immunity at Multiple Levels

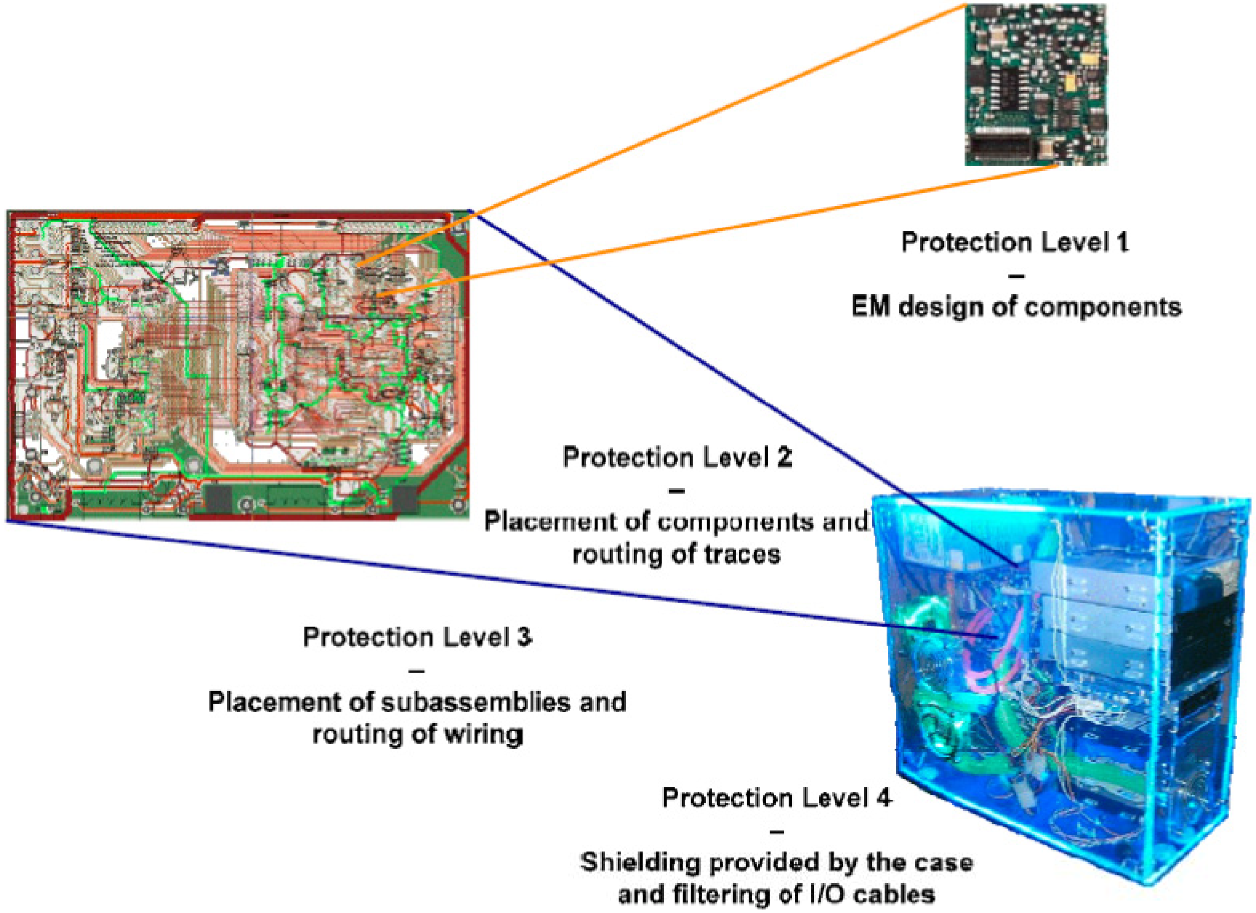


Figure 2-4
Depiction of Four EMC Control Levels

All EMC Control Levels Impact Overall Immunity

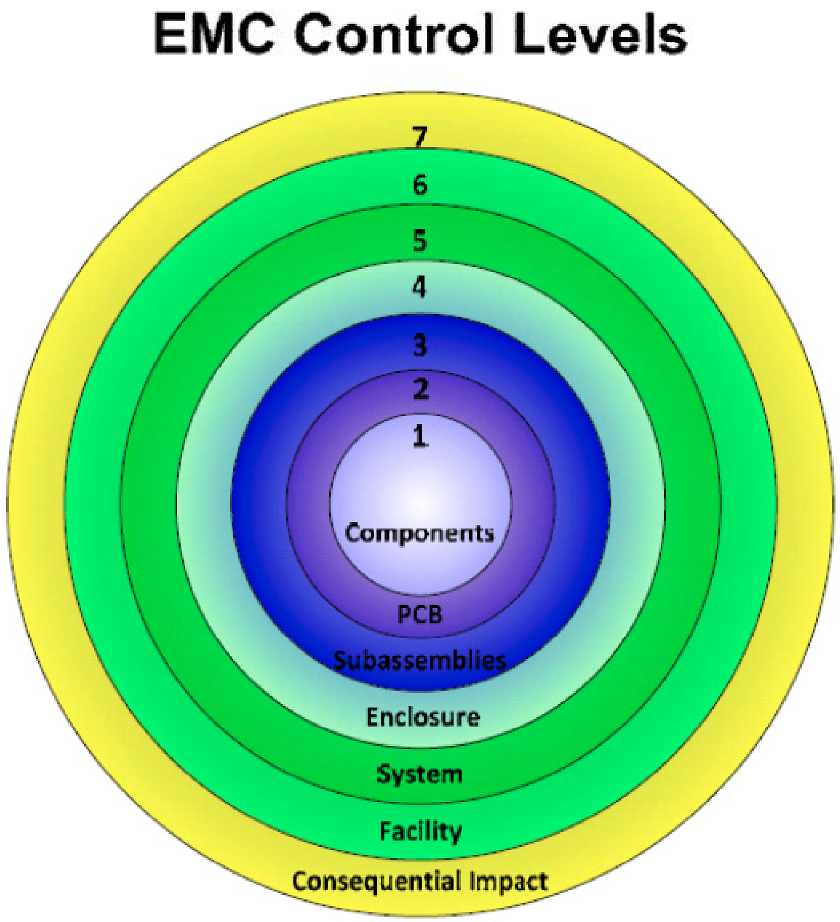


Figure 3-1
EMC Control Levels

All EMC Control Levels Impact Overall Immunity

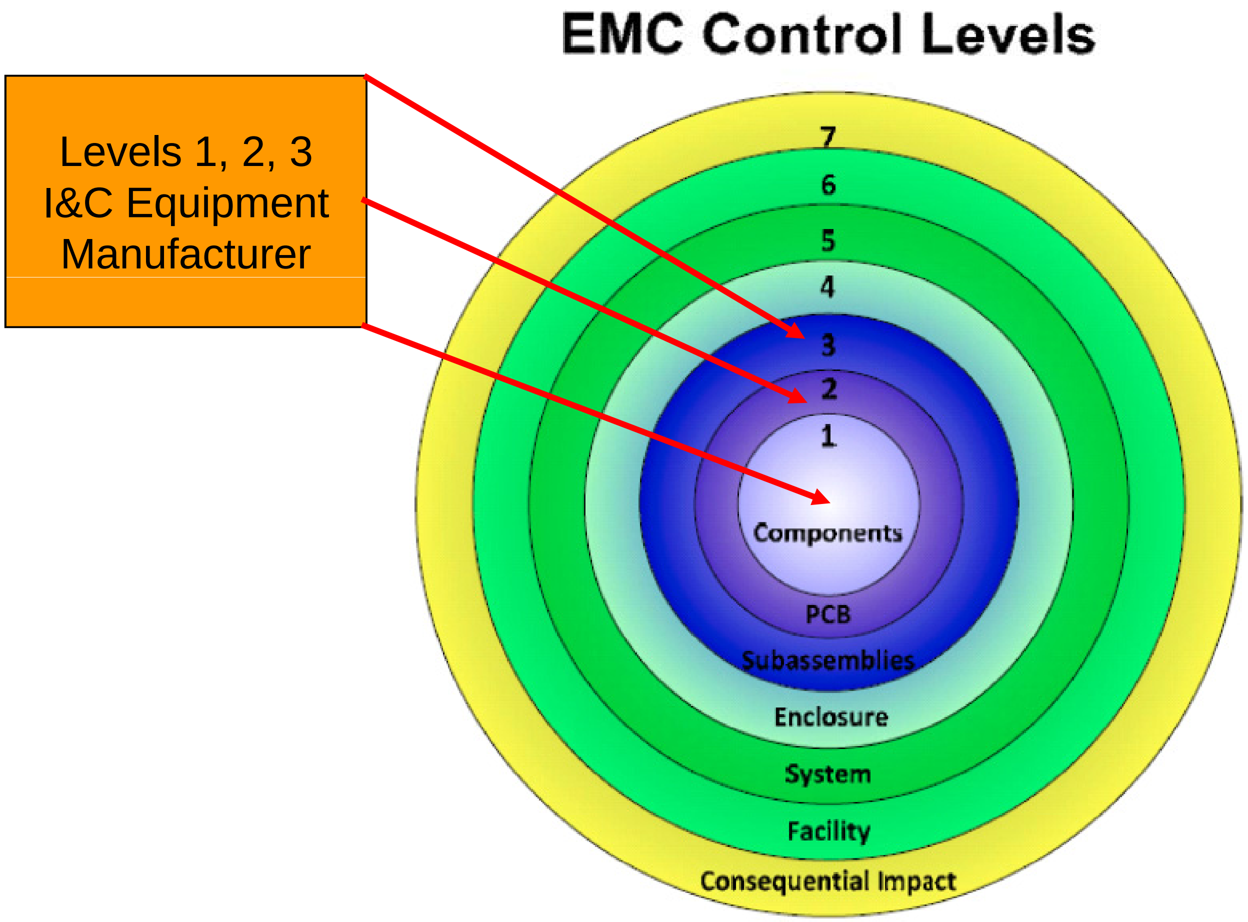


Figure 3-1
EMC Control Levels

All EMC Control Levels Impact Overall Immunity

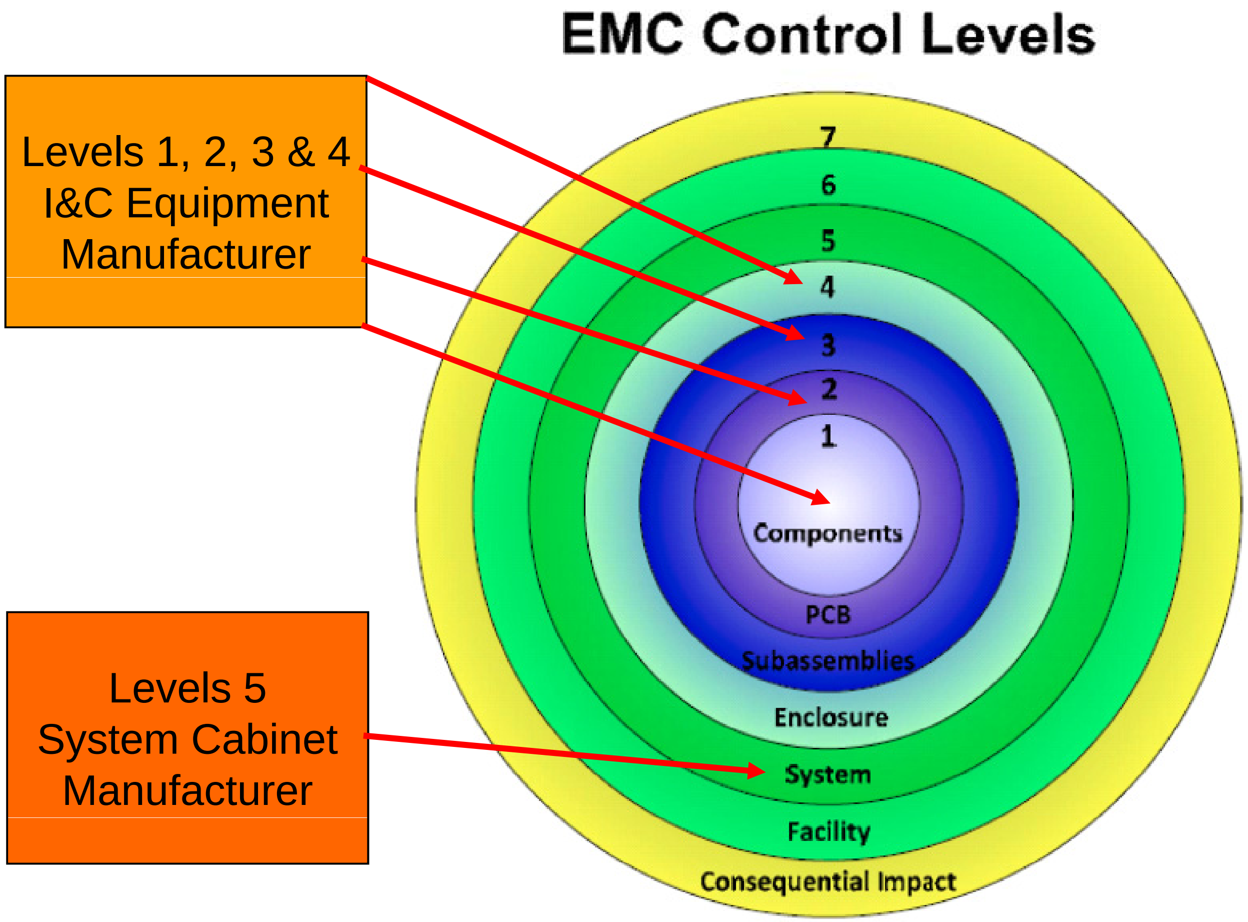
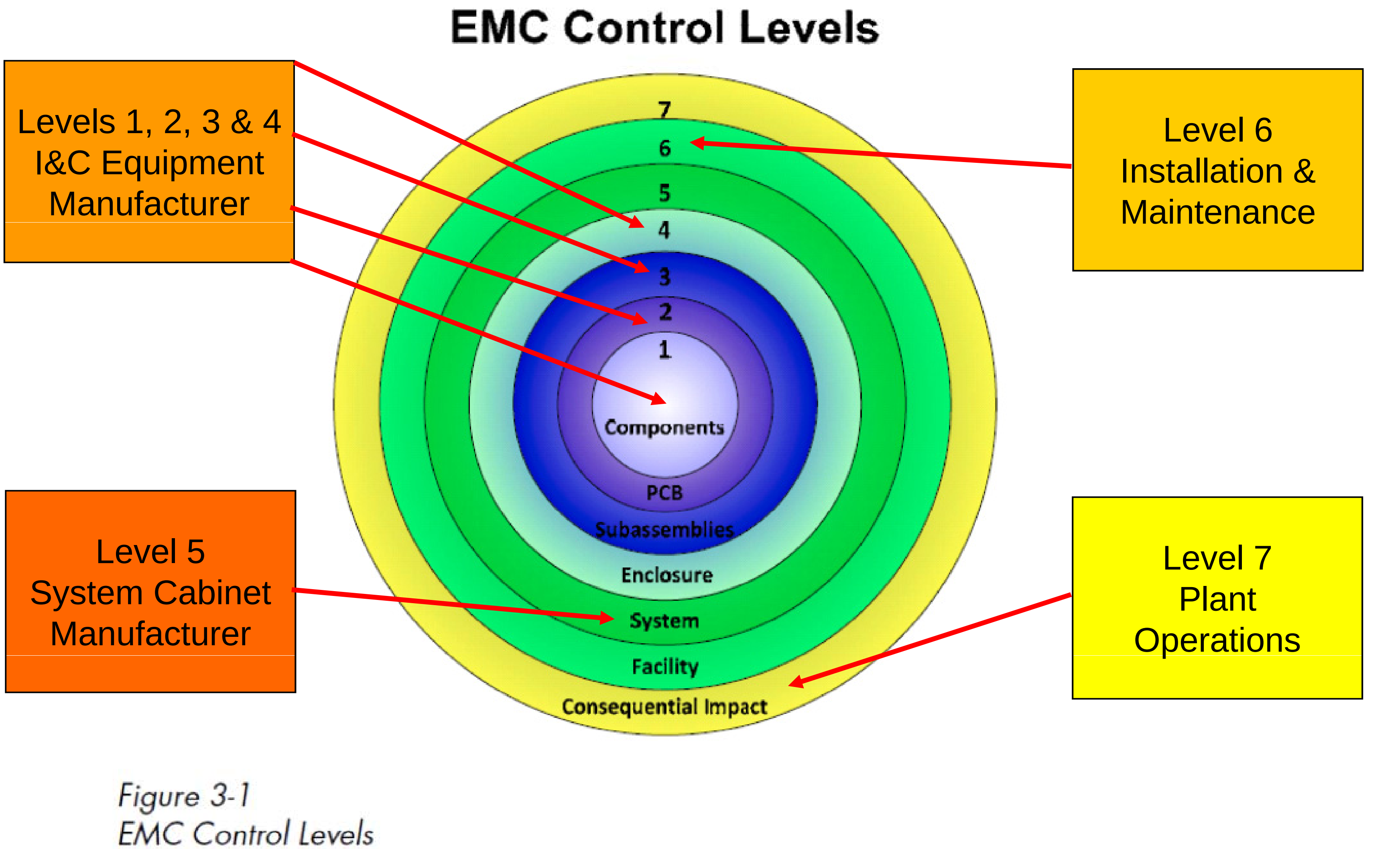
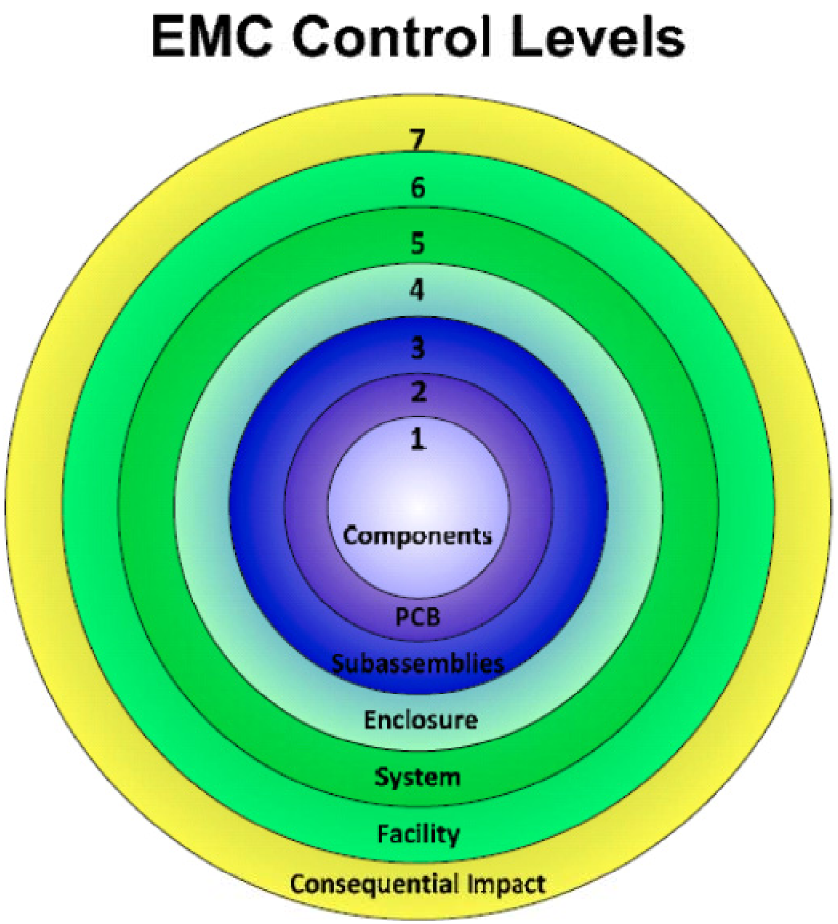


Figure 3-1
EMC Control Levels

All EMC Control Levels Impact Overall Immunity



Which levels affect the size of the Exclusion Zone?



- Level 1: Yes, better overall immunity at the component level reduces the burden on Levels 2-7.
- Level 2: Yes, better immunity at the PCB level reduces the burden on Levels 3-7.
- Level 3: Yes
- Level 4: Yes
- Level 5: Yes
- Level 6: Yes, proper installation of the system in the plant reduces coupling from external threats to the cabinet & equipment inside.
- Level 7: Overall superior immunity equates to less pre-planning in the event that an EMI problem develops.

EPRI Research in 2010 Recommended a New Strategy for Providing Needed Immunity to I&C Equipment

Objectives of the New Strategy

- In this alternate strategy, rather than use distance to lower the emissions from portable wireless devices, cabinet and cable shielding is used.
- The goal here is to provide the required level of radiated EMC immunity for the digital I&C equipment inside the cabinet without having to implement an exclusion zone around the outside of the cabinet.

EPRI Research in 2010 Recommended a New Strategy for Providing Needed Immunity to I&C Equipment

- The digital I&C equipment is still required to have a broadband RF immunity of 10 V/m.
- A safety margin of 40 dB is recommended, in contrast to the previous 8 dB defined in previous EPRI guidance (see EPRI TR-102323, Rev. 3). The safety margin is increased to provide an increased level of safety, which is achievable because significant levels of shielding effectiveness are obtainable for shielded cabinets at reasonable price levels.
- A shielding effectiveness of 80 dB is recommended, which is achievable with commercially available shielded enclosures.

Combining the New Requirements….

- The combination, then of a 10 V/m immunity level in the digital I&C equipment, with a 40 dB safety margin and 80 dB of cabinet and cable shielding, results in an RF immunity level greater than 1,000 V/m.
- This is sufficient to meet even the 600 V/m field strength calculated from an eight-watt device at distance of five (5) centimeters, with margin to spare.
- Table 3 provides a numerical summary of the above discussion.

New Guidance

- Table 4 presents the calculated separation distance at which a portable wireless device will place the current guidance (see EPRI TR-102323, Rev. 3) for an electric field limit of 4 V/m on a digital I&C system inside of an 80 dB shielded enclosure.
- As can be seen, even the most powerful device must come within 0.7 mm to achieve this level. Certainly, the thickness of the cabinet wall alone will ensure that this distance is always achieved.

New Guidance

Table 4
Required Exclusion Zone Distances for 4 V/m Protection with Cabinet Shielding Assuming Two-Ray Propagation Model and Dipole Antenna with 2.4 dB Gain

Cabinet and Cable Shielding (dB)	RF Power (Watts) Portable Transceiver (Intentional Radiator)						
		Cordless Phone ⟷ ≈ 0.1 w	CDMA Cell Phone ⟷ ≈ 0.6 w	PCS Cell Phone ⟷ ≈ 1-2 w		Hand-Held Walkie-Talkies ⟷ ≈ 5-8 w	
	0.01	0.1	0.5	1	2	4	8
	Size of Exclusion Zone (meters)						
40.0	2.5	8.1	18.0	25.5	36.1	51.0	72.1
60.0	0.3	0.8	1.8	2.5	3.6	5.1	7.2
→ 80.0	0.0	0.1	0.2	0.3	0.4	0.5	0.7
100.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1

New Logic for New Radiated Immunity Requirements

Table 3
New Logic for Radiated EMC Protection from Portable Wireless Devices

#	Element	Component		Level
1	Electromagnetic Immunity of I&C Equipment	Immunity	↓	≥ 10 V/m
2	Safety Margin (40 dB)	Immunity	↓	≥ 0.1 V/m
3	Shielding Effectiveness for I&C System Cabinet (80 dB)	Emissions	↓	≥ 1,000 V/m
4	EM Fields from Portable Transceivers	Emissions	↑	< 700 V/m

Transitioning

- Existing nuclear plants must support installed systems and legacy equipment.
- When engaging in a digital I&C upgrade, migration paths must be planned which continue to support existing installations.
- These plans must assure that existing systems continue to give adequate levels of EM protection, while also allowing a change to new equipment and system, with better levels of EM immunity.

Together…Shaping the Future of Electricity