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# THE 2024 ANNUAL REFERENCE GUIDE

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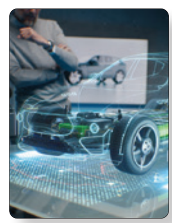

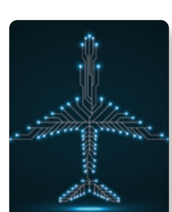

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# LETTER From the Editor

Welcome to 2024 and this year's edition of *In Compliance Magazine's* Annual Reference Guide!

Some 30 years ago, a group of eighth and ninth graders from a public school in Harlem (New York City) faced off against the strongest national chess players in the National Junior High Chess Championship. The Raging Rocks, as they were known, didn't have any of the advantages of their competitors, most of whom were from elite private schools and who entered the competition with years of training and experience playing the game. By contrast, each of the Rocks' team members learned chess relatively late in their young lives, somehow managing to navigate life in neighborhoods overrun by crime, violence, and drugs to carve out time to learn the game.

Fortunately, the Raging Rocks were coached by Maurice Ashley, a 20-something man originally from Jamaica, who could "see potential where others had missed it." Unlike other coaches who tap into the existing talent of their players, Ashley instead focused on fostering his players' interest in the game, finding ways to make learning chess fun, and letting his team members find their "hidden potential."

In the end, the Raging Rocks beat their competitors from the Dalton School in the final round of the competition, ending up tied for first place in the National Junior High Chess Championship. Coach Ashley's approach, building on the intrinsic motivation of his team players, took the Raging Rocks from nonplayers to national champions.

The story of the Raging Rocks, shared by Adam Grant in his latest book, *Hidden Potential: The Science of Achieving Greater Things*, gives fresh meaning to the mantra "what counts is not how hard you work but how much you grow." At a time when chaos and uncertainty seem to be ever-present in our daily lives, focusing our time and energy on doing what we love and discovering (or rediscovering) how we can grow can provide us with a strong and positive focal point as we navigate the future. And it can also inspire others to follow our example by taking on challenges and opportunities that help us all to emerge stronger.

Here at *In Compliance Magazine*, an important part of our mission is to help each and every one of our readers grow by building their knowledge and understanding of the increasingly complex regulatory compliance landscape. Our publication provides an essential forum for the sharing of our collective experience and expertise, while also providing the members of our community with important information they need to further develop their own knowledge. Toward that end, the 2024 edition of our Annual Reference Guide reprints 16 of the articles we published in 2023 that were most frequently read and referenced by our readers. In this way, our Annual Reference Guide can serve as a valuable resource in our individual efforts to grow.

As always, we thank our wonderful team of editorial contributors who, by sharing their knowledge, help all of us to grow. We also thank our readers for their continuing commitment to our publication and for freely sharing their perspectives on how we do even better. And, finally, we couldn't do what we do without our loyal advertisers, whose financial support makes our vision a reality. Together, we can all face the future together with optimism, hope, and happiness.

Sincerely,

*Bill von Achen*

Features Editor
*In Compliance Magazine*

# IN THIS COMPETITIVE BUSINESS WORLD, EVERY LITTLE THING MAKES A BIG DIFFERENCE.

## A.H. Systems, Inc.

When you think of Quality, Reliability, Portability, Fast Delivery, and Customer service, the first name that comes to your mind is A.H. Systems, Inc.

Every engineer wants a good deal. Especially when it comes to purchasing one or more antennas. But what exactly are they paying for? It isn't just getting the cheapest price for the antenna. It's what you get with that antenna that matters. What makes A.H. Systems better than the competition? We provide what really matters. In this competitive business world, every little thing makes a big difference.

### QUALITY

A.H. Systems is proud to know it is providing the highest quality products available. Quality problems arising in various areas are to be identified and solved with speed, technical efficiency and economy. We focus our resources, both technical and human, towards the prevention of quality deficiencies to satisfy the organizational goal of "right the first time... every time."

### RELIABILITY

We manufacture a complete line of affordable, reliable, individually calibrated EMC Test Antennas, Preamplifiers, Current Probes and Low-Loss, High-Frequency Cables. All Products are available directly from our facility in Chatsworth, CA and through our Distributors and Representatives worldwide. Our products keep on working, which enable us to give a 3-year warranty, the longest in our industry.

### PORTABILITY

How many times have you purchased several antennas and then you forget what department has them or where they are? You discover parts are missing and the data is lost. You are now frantic because you have a scheduled deadline for your testing. At A.H. Systems we bring portability to a new level. We specialize in Portable Antenna Kits and provide many models covering the broadband frequency range of 20 Hz to 40 MHz. Excellent performance, compact size and a lightweight package make each Antenna Kit a preferred choice for field-testing. Loss and breakage are virtually eliminated because each component has a specific storage compartment in the carrying case. When testing out in the field or traveling, keep them all in one case. Travel made easy!

### FAST DELIVERY

A.H. Systems provides next-day, on-time delivery for a fast turn around schedule to help minimize any down time the customer may be experiencing during testing. We maintain stock of all of our products and to satisfy frantic customers, we have orders shipped the "same-day."

### CUSTOMER SERVICE

When you have a problem in the field during testing, you need fast answers to solve your problem. How many times have you called a company to speak to an engineer for a technical problem you are experiencing? And it takes many days to get a call back, let alone the answer to your problems. At A.H. Systems you get great personal service. A live person to talk to! We are here to assist customers with their EMC/EMI testing requirements. We try to solve your problems while you are experiencing them. Even before, during and after the Purchase Order. Our knowledge in EMC testing and antenna design enables us to offer unique solutions to specific customer problems. Not only do we solve your problems, we help you find the right antenna. Talking with our customers and hearing what they have to say enables us to provide better products, services and more options for our customers. Call us. We are here to make your problems, non-problems. For more information about our products visit our website at www.AHSystems.com.

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# IS YOUR ORGANIZATION PREPARED FOR THE NEW BATTERY CE MARKING REQUIREMENTS?

**Batteries have an important role to play** in the global push for sustainable power, but without adequate oversight, battery manufacturing can be very harmful to the environment. A new EU Battery Regulation, Regulation (EU) 2023/1542, adopted in July 2023, introduced new battery safety and sustainability rules. It represents a significant change in how battery manufacturers will need to evaluate battery products sold in the EU.

Regulation (EU) 2023/1542 aims primarily to reduce carbon emissions and promote the recyclability of battery materials, with mandates applying to a wide range of battery types. One noteworthy change is the requirement for CE marking on batteries sold in the EU. Although CE marking is already required for most electronics, previous battery directives have not included a CE marking requirement for batteries.

To display a CE mark, a product must meet various health, safety, and environmental standards, and ensuring compliance with these standards is the manufacturer's responsibility. Many manufacturers have their products assessed by a third-party laboratory like Element rather than relying on a self-assessment. Under previous regulations, battery manufacturers had some leeway to make their own decisions about safety testing and assessments, but the requirements of Regulation (EU)2023/1542 are more specific.

Key aspects of this regulation include:

- Battery Categories: It introduces specific categories such as portable, industrial, automotive, electric vehicle (EV), and light means of transport (LMT) batteries, each with distinct requirements.
- CE Marking: Starting August 18, 2024, batteries must have CE markings to indicate compliance with EU standards. In some cases, this process may involve a notified body.
- Battery Passport: Effective February 18, 2027, certain large batteries must be electronically registered with a battery passport containing a QR code and CE marking. Passports provide information about the battery's safety, sustainability, and recyclability.
- Carbon Footprint and Recycled Content: The regulation mandates that batteries' carbon footprints must be calculated, and sets recycled content targets for elements like cobalt, lead, lithium, and nickel, starting from August 18, 2024.
- Removability and Replaceability: Portable batteries should be easily removable and replaceable by end-users, while LMT, EV, and industrial batteries should be replaceable by independent professionals, effective February 18, 2027.
- Safety Testing (SBESS): Specific safety testing requirements for stationary battery energy storage systems (SBESS).
- Due Diligence: Producers must adopt a due diligence policy, establish management systems, assess supply chain risks, and devise strategies to address these risks, effective from August 18, 2025. Third-party verification by a notified body is required.
- Recycling and Material Recovery Targets: The regulation sets efficiency targets for recycling and material recovery for specific elements, applicable from December 31, 2027.
- Information and Labeling: Enhanced labeling requirements include a battery passport, specific product labeling, electronic databases, and second-life data sets to improve information and traceability.
- Shipment of Waste Batteries: The regulation covers the shipment of waste batteries outside the EU.
- Reporting Obligations: Various reporting obligations are introduced, with specific deadlines for implementation phased in from 2024 to 2028.

Because different batteries have different requirements, this regulation will have varying impacts on individual manufacturers. Different aspects of the regulation also have different effective dates or deadlines. A third-party testing partner can help you understand how this and other new regulations will affect you, providing additional certainty that your products are compliant. The experts at Element have the regulatory expertise to help manufacturers evaluate, test, and certify batteries for their intended markets. If you have questions about battery requirements and how they apply to you, reach out today.

element

# Why Buy ETS-Lindgren?

ETS-Lindgren is an international manufacturer of systems and components that measure, shield, and control electromagnetic and acoustic energies. Our products are used for electromagnetic compatibility (EMC), microwave and wireless testing, electromagnetic field (EMF) measurement, radio frequency (RF) personal safety monitoring, magnetic resonance imaging (MRI), and control of acoustic environments.

Having the technical depth expected of an industry leader with more than 50,000 RF shielded installations worldwide, ETS-Lindgren guides our customers to optimal Test and Measurement Solutions for their specific product applications. Customers appreciate knowing our vertically integrated capabilities ensure quality and schedule control since some 90% of the products on any given project are manufactured by ETS-Lindgren. And our team of 750+ employees in six manufacturing sites worldwide provide continual customer support.

ETS-Lindgren's leading-edge technology is evident in the many markets we serve, resulting in numerous patents and "Industry Firsts." For example, ETS-Lindgren is the first and only manufacturer to have its complete EMP protection system performance acceptance-tested to the requirements of MIL-STD-188-125 by an independent lab: Little Mountain Test Facility operated by Boeing at Hill Air Force Base, in Ogden, Utah.

Other examples include: The world's first CTIA-Authorized Test Lab (CATL) for mobile station over-the-air (OTA) performance testing; first to provide in-house certified Building Information Modeling (BIM) services; first to design, manufacture, and install the world's largest RF shielded anechoic chamber; first to design and manufacture a pneumatic RF shielded sliding door; first to manufacture RF shielded panels and components on a global level; and first to use an in-house NVLAP-accredited acoustic test lab (NVLAP Code 100286-0) to develop and produce acoustic chamber solutions.

ETS-Lindgren's proven expertise in the diverse markets we serve fosters innovative solutions that can be individually tailored to meet a customer's specific performance requirements and budget parameters. Partnering with our customers and drawing on our expertise and desire to continuously innovate we are Committed to a Smarter, More Connected Future.

*ETS-Lindgren's Vehicle Antenna Measurement Arch (VAMA)*

For more information on ETS-Lindgren, visit our website at www.ets-lindgren.com or contact your local ETS-Lindgren representative.

# COMMITTED TO A SMARTER, MORE CONNECTED FUTURE.

With our lives continuously improved by new, innovative products, EMC is increasingly dominating our lives as well. Surpassing the standards of EMC performance while developing ground-breaking EMC test techniques, ETS-Lindgren is dedicated to measurement and regulatory compliance testing. In short, ETS-Lindgren is Committed to a Smarter, More Connected Future.

As an international manufacturer of market-leading solutions and products that measure, shield, and control electromagnetic and acoustic energy, ETS-Lindgren is the driving force allowing industry innovators to develop the latest technological advances and meet compliance standards. The result? We set the stage to successfully bring the next generation of innovative products to market. From chambers to test cells, absorbers, positioners, antennas, and software, ETS-Lindgren's EMC solutions are intelligently designed for reliability, diversity, ingenuity, and precision.

More importantly, our ability to create real-world test scenarios, develop innovative testing solutions, troubleshoot potential failures, perform production testing, and maximize the chance of passing standards on time and on budget helps our customers bring life-changing products to market – faster. For more information on our EMC solutions, visit our website at www.ets-lindgren.com/industries/emc-testing.

**Connect with us at:**

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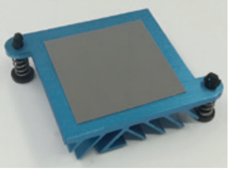
# *When Technology, Design, and Performance Meet.*

**Schlegel Electronic Materials, Inc. (SEM)** pioneered fabric-over-foam EMI (electromagnetic interference) shielding technology and is a global leader in manufacturing EMI shielding and thermal management materials that protect sensitive electronics.

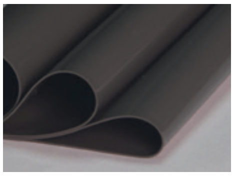
In addition to the innovative fabric-over-foam (FOF) gaskets, our high-performance products include I/O backplane shielding gaskets, Conductive Elastomers, RF Absorber Materials, and other enclosure gaskets and board-level shielding products. We manufacture Thermal Materials, EMI Shielding Materials, Polymer and Adhesives Materials, Insulation Materials, Inductive Components, and Bulk Molding Compounds.

From concept to production, Schlegel's complete portfolio of shielding products combines highly conductive materials with flexible foams and coatings to provide the latest EMI containment solutions. The company's world-renowned EMI shielding gaskets are available in hundreds of profiles and unique designs, with attachment options that include mechanical self-attaching, clip, rivet, and pressure-sensitive adhesives.

***Here are just a few of our solutions that customers rely on to support their innovative technologies:***

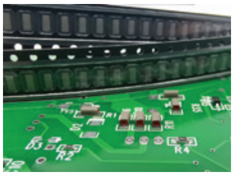


Our **OpTIM®** materials include phase change, putty, grease, insulators, gap fillers, and foam. Our highest thermal fillers are 14W/mK & 12W/mK and use silicone-based materials. We offer non-silicone-based materials that can reach up to 5W/mK.



**BandSorb®** elastomer absorbers position Schlegel as a leader in the design, development, and manufacturing of EMI/RF absorber materials. Engineers can explore our robust line of high-performance absorber products. We ensure quality and offer customized design sizes. Our unique quality control process includes measurement to ensure products meet your requirements.

**TIMSorb®** series is the latest hybrid thermal/absorber management material that combines thermal and absorber materials with a high thermal conductivity of 4W/mK. These innovative materials serve as thermal interfaces between heat sources and heat transfer devices or metal chassis while mitigating unwanted energy coupling, resonances, and surface currents causing board-level EMI issues.



The **DoubleShield Pad** combines unsurpassed conductivity with the convenience of an SMT-compatible format. These materials support automotive electronic designers' need for grounding and shielding products that ensure electrical performance without breaking under mechanical or environmental stress throughout the product's lifetime.

Our solutions meet or exceed every customer's expectations, including ISO 9001 and RoHS compliance, ITAR registration, and UL approval.

Schlegel has been a trusted source for high-performance custom EMI/thermal solutions worldwide for 100 years. Our technical team has decades of experience designing solutions for complex heat, EMI, and compliance-related problems. That's why Schlegel is trusted worldwide by leading technology brands for customized solutions for heat transference, lower thermal resistance, or reducing the effects of radiated energy.

Schlegel's products enable the automotive, aerospace, computer, telecommunications, military, medical, and electronics industries to meet global requirements for EMI and thermal management.

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## Your Source for EMI Shielding Solutions

Spira's patented EMI and environmental shielding gaskets offer excellent solutions for both cost-sensitive and high-performance applications. The unique spiral design offers extremely low compression set, long life and high shielding. The company was founded by one of the leading EMI design engineers in the industry. Gaskets meet requirements including ITAR, DFAR, RoHS, FCC, EC, HIRF, & TEMPEST. Configurations are available both in groove and surface mount options, in diameters from .034" up to 1.5".

**CUSTOM CONFIGURATIONS:** Spira specializes in meeting customers' unique shielding needs. All our products are available in custom configurations.

**PRODUCT SELECTOR:** Our website features a Product Selector feature to assist you in determining which Spira EMI gaskets will best meet your shielding needs.

**TECH INFO:** Spira was built on engineering excellence. Our library of technical papers assists design engineers in solving their EMI design challenges, and learning the latest breakthroughs in EMI shielding theory.

**FASTENER SPACING CALCULATOR:** Our updated Fastener Spacing Calculator is now available online to make designing your EMI gasket solution quicker and easier.

**APPLICATION SUPPORT:** Get your FAQ's answered, and peruse our video library featuring application techniques and the World's Greatest episode featuring Spira as one of the world's greatest in EMI gaskets and shielding products.

**FEATURED PRODUCTS:** Two of Spira's most popular products are featured here.

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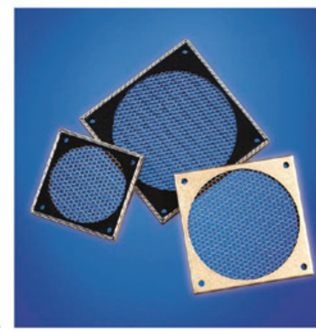

Spira's Shielded Fan Filters provide a high and reliable level of shielding at a great price. They include our patented spiral gasket and patented honeycomb "blending" process of the aluminum panels that provides up to 80dB of shielding at 1GHz. The filters are compatible with 40, 60, 80, 92 and 120mm fans or custom sizes with no additional design fees. Available in 1/8" cell by 1/4" or 1/2" thick honeycomb panels. Excellent EMI Shielded Air-Vent Filters also available in custom configurations.

### Standard or Front-Mount EMI and Environmental Connector-Seal Gaskets

Spira's Connector-Seal gaskets, in standard and front-mount configurations, provide the best EMI and environmental protection on the market! Our unique design includes a rigid layer between either silicone or fluorosilicone elastomeric sealing, and includes our patented spiral gasket for excellent EMI shielding. This gasket is extremely durable and provides reliable one atmosphere environmental sealing for flange-mounted connectors.

SPIRA

www.spira-emi.com

# Impact of Decoupling Capacitors and Trace Length on Radiated Emissions in a CMOS Inverter Circuit

By Bogdan Adamczyk and Mathew Yerian-French

In [1], we discussed the impact of decoupling capacitors and a PCB trace length on the signal integrity in a CMOS inverter circuit. In this article, we evaluate the impact of the capacitors and trace length on radiated emissions. It is shown that the radiated emissions from the PCB with short traces are lower than those with long traces. It is also shown that the decoupling capacitors have little impact in the monopole antenna range, a significant positive impact in the bicon antenna range, and a negative impact in the log-periodic antenna range.

## 1. CMOS INVERTER CIRCUIT

Figure 1 shows the block diagram of the inverter circuit and the PCB.

In this study, trace length is varied between 3,000 mils (short trace) and 20,000 mils (long trace). Additionally, the PCB is tested in two configurations: without the decoupling capacitors and with decoupling capacitors by each inverter (0.1 μF and 1 μF).

## 2. RADIATED EMISSIONS MEASUREMENT SETUP

The measurements were performed in a semi-anechoic chamber, in accordance with CISPR 25 Edition 5 automotive standard. A monopole antenna was used in the frequency range of 150 kHz – 30 MHz with a bandwidth of 9 kHz and vertical polarization. A biconical antenna was used in the range of 30 MHz – 300 MHz with a bandwidth of 120 kHz and both horizontal and vertical polarization. A log-periodic antenna was used in the range of 300 MHz – 1GHz with a bandwidth of 120 kHz and both horizontal and vertical polarization. All measurements were taken with the average, peak, and quasi-peak detectors.

## 3. IMPACT OF THE TRACE LENGTH ON RADIATED EMISSIONS

In this section, we evaluate the radiated emission results from the PCB with short traces (3,000 mils) and long traces (20,000 mils) without decoupling capacitors by the inverters.

### *Case 3A: Short trace vs. long trace – Monopole antenna*

Radiated emission results are shown in Figure 2.

### *Observations*

Both traces showed similar failures at 1 MHz. Long trace failed average detector at 6 MHz. At 27 MHz, the short trace failed average detector while the long trace failed quasi-peak and average detector. The average detector failure for the long trace was about 7.5 dB higher than that for the short trace. Overall, the short trace outperformed the long trace.

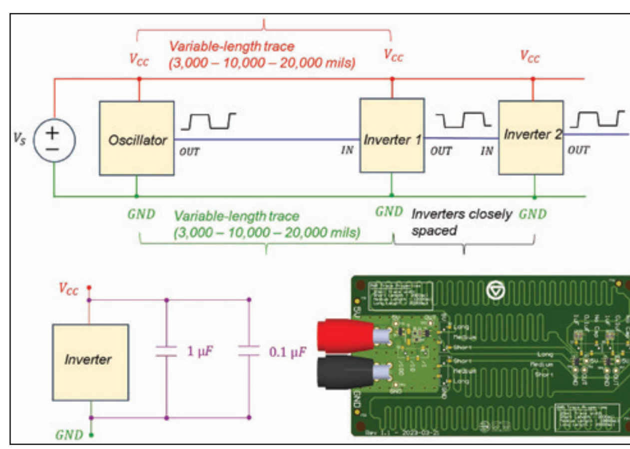


Figure 1: Block diagram of the inverter circuit and the PCB

*Dr. Bogdan Adamczyk is professor and director of the EMC Center at Grand Valley State University (http://www.gvsu.edu/emccenter) where he performs EMC educational research and regularly teaches EM/EMC courses and EMC certificate courses for industry. He is an iNARTE-certified EMC Master Design Engineer. He is the author of two textbooks, "Foundations of Electromagnetic Compatibility with Practical Applications" (Wiley, 2017) and "Principles of Electromagnetic Compatibility: Laboratory Exercises and Lectures" (Wiley, 2024). He has been writing "EMC Concepts Explained" since January 2017. He can be reached at adamczyb@gvsu.edu.*

*Mathew Yerian-French is an electrical engineer specializing in EMC design and diagnostic testing. He received his B.S.E in Electrical Engineering from Grand Valley State University. He focuses on preventing EMC issues through design reviews and early EMC pre-compliance testing and diagnostics. Mat participates in the industrial collaboration with GVSU at the EMC Center. He can be reached at mathew.french@e3compliance.com.*

***Case 3B: Short trace vs. long trace – Bicon antenna***

Radiated emission results for both traces are shown in Figure 3.

***Observations***

Both traces showed multiple failures. The short trace failed quasi-peak detector in the frequency range 72 – 173 MHz by the margin 4.26 – 24.09 dB. It failed average detector in the frequency range 42 – 300 MHz by the margin 0.67 – 38.12 dB.

The long trace failed quasi-peak detector in the frequency range 33 – 174 MHz by the margin 1.31 – 26.32 dB. It failed average detector at every frequency in the range 33 – 300 MHz by the margin 0.48 – 38.24 dB.

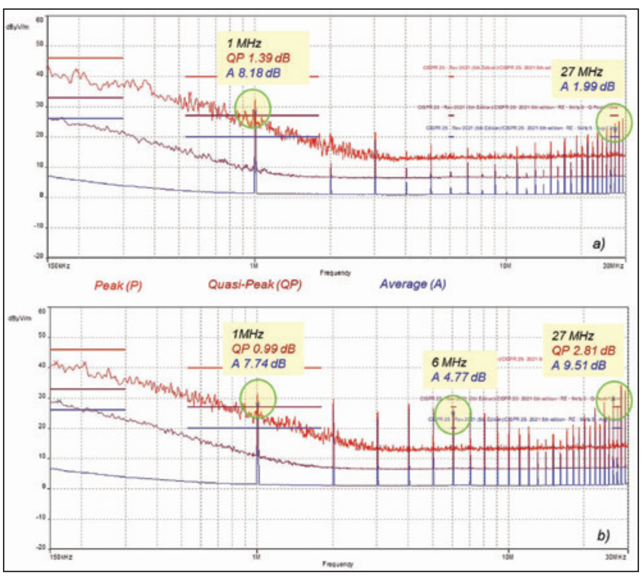


Figure 2: Monopole antenna: a) short trace b) long trace

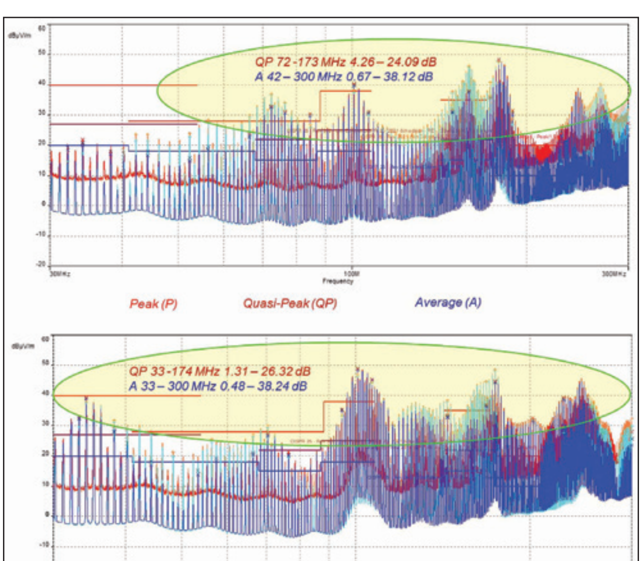


Figure 3: Bicon antenna a) short trace b) long trace

Overall, the long trace showed more failures over a wider frequency range.

***Case 3C: Short trace vs. long trace – Log-periodic antenna***

Radiated emission results for both traces are shown in Figure 4.

***Observations***

Both traces showed quasi-peak detector failures in the similar frequency range of 380 – 511 MHz, with the long trace exceeding the limits by a higher margin. The short trace showed average detector failures in the frequency range of 317 – 521 MHz, while the long trace showed failures in the frequency range of 308 – 844 MHz. Overall, the long trace showed more failures over a wider frequency range.

## 4. IMPACT OF THE DECOUPLING CAPACITORS ON RADIATED EMISSIONS – SHORT TRACE

In this section, we evaluate the radiated emission results from the PCB with short traces, without the decoupling capacitors, and with the decoupling capacitors by each inverter (0.1 µF and 1 µF).

***Case 4A: Short trace with and without decoupling capacitors – Monopole antenna***

Radiated emission results for both traces are shown in Figure 5 on page 28.

***Observations***

The decoupling capacitors had a negligible impact at the frequencies where the failures occurred.

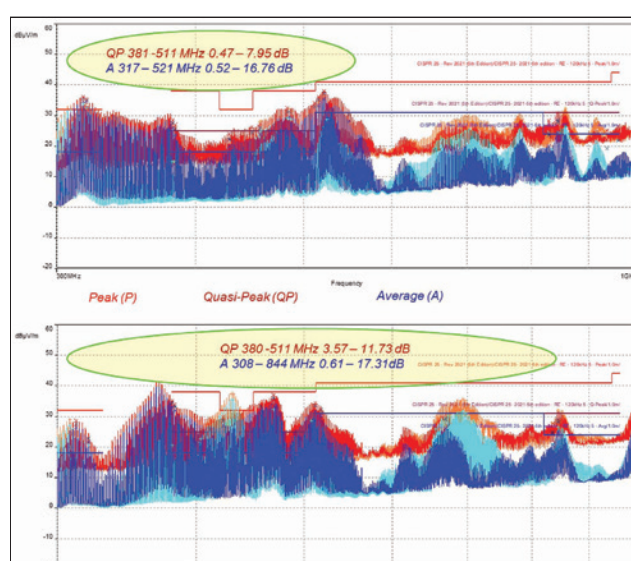


Figure 4: Log-periodic antenna: a) short trace b) long trace

***Case 4B: Short trace with and without decoupling capacitors – Bicon antenna***

Radiated emission results for both traces are shown in Figure 6.

***Observations***

Quasi-peak detector: Capacitors eliminated failures in the frequency range 72 – 150 MHz. In the frequency range 150 – 173 MHz, many failures were eliminated, and the remaining ones decreased by 3 - 7 dB.

Average detector: Capacitors eliminated failures in the frequency range 42 – 100 MHz. In the frequency range 150 – 300 MHz, multiple failures were eliminated, and the remaining ones decreased by 2 - 10 dB.

Overall, the capacitors had a *significant positive* impact on radiated emissions.

***Case 4C: Short trace with and without decoupling capacitors – Log-periodic antenna***

Radiated emission results for both traces are shown in Figure 7.

***Observations***

Quasi-peak detector: Capacitors did not eliminate or reduce the failures in the frequency range 380 – 511 MHz. They increased the failures by 0.3 – 4 dB. Additionally, the capacitors created a new failure at 843 MHz.

Average detector: Capacitors did not eliminate or reduce the failures in the frequency range 317 – 521 MHz. They increased the failures by 0.8 – 4.5 dB. Additionally, the capacitors created new failures at 843 MHz.

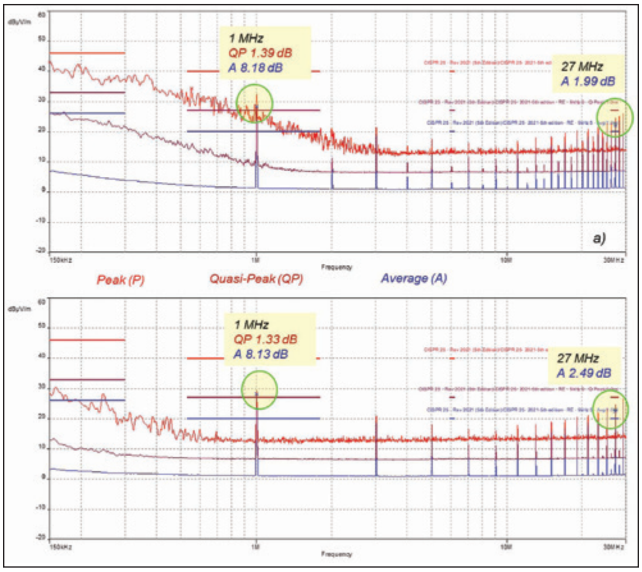


Figure 5: Monopole antenna, short trace: a) without capacitors b) with capacitors

Overall, the capacitors had a *negative* impact on radiated emissions.

## 5. IMPACT OF THE DECOUPLING CAPACITORS ON RADIATED EMISSIONS – LONG TRACE

In this section, we evaluate the radiated emission results from the PCB with long traces, without the decoupling capacitors, and with decoupling capacitors by each inverter (0.1 μF and 1 μF).

***Case 5A: Long trace with and without decoupling capacitors – Monopole antenna***

Radiated emission results for both traces are shown in Figure 8.

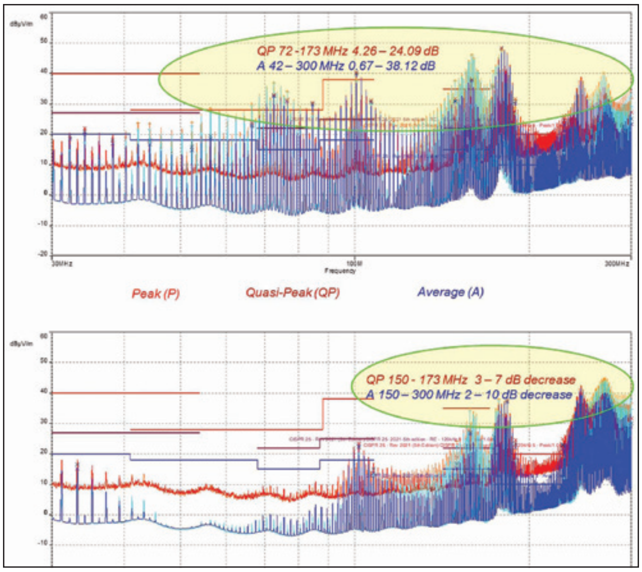


Figure 6: Bicon antenna, short trace: a) without capacitors b) with capacitors

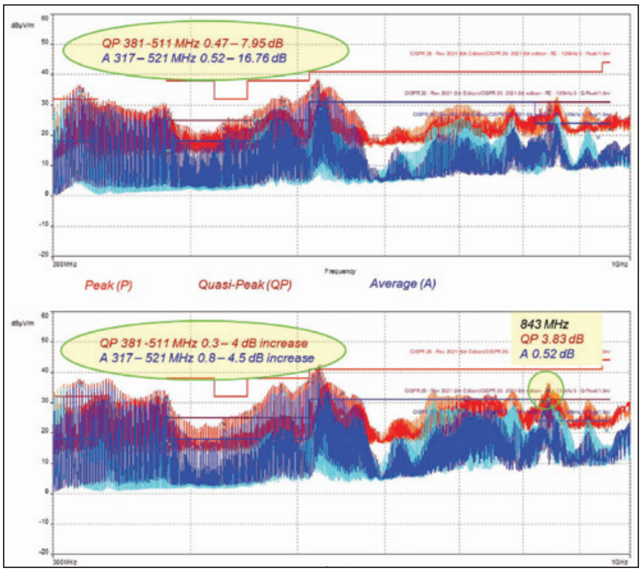


Figure 7: Log-periodic antenna, short trace: a) without capacitors b) with capacitors

***Observations***

The decoupling capacitors had minimal impact at 1 MHz. However, they eliminated failures at 6 MHz and 27 MHz.

***Case 5B: Long trace with and without decoupling capacitors – Bicon antenna***

Radiated emission results for both traces are shown in Figure 9.

***Observations***

Quasi-peak detector: Capacitors eliminated failures in the frequency range 33 – 100 MHz. In the frequency range 100 - 174 MHz, several failures were eliminated, and the remaining ones decreased by 6 – 14.5 dB.

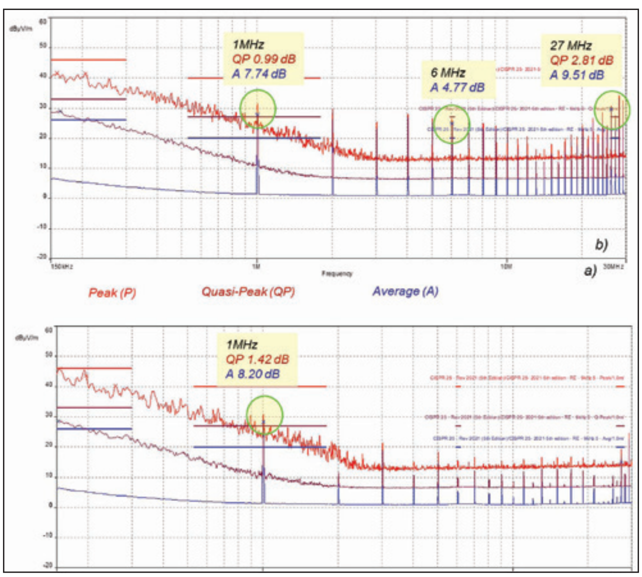


Figure 8: Monopole antenna, long trace: a) without capacitors b) with capacitors

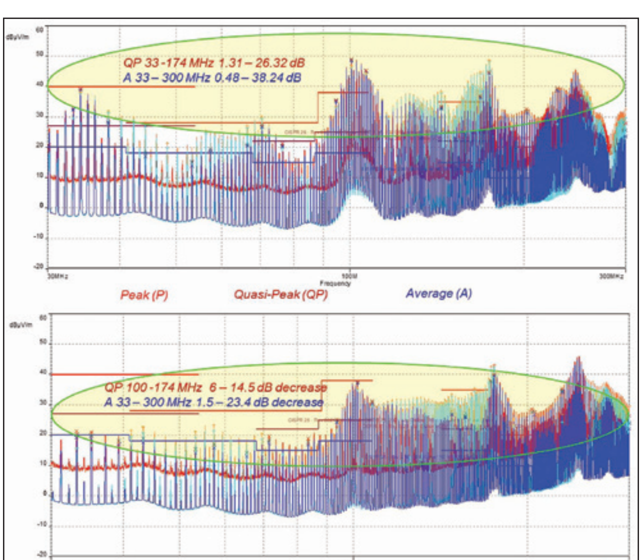


Figure 9: Bicon antenna, long trace: a) without capacitors b) with capacitors

Average detector: Capacitors eliminated several failures in the frequency range 33 – 65 MHz. The remaining failures over the entire frequency region were either eliminated or decreased by 1.5 – 23.4 dB.

Overall, the capacitors had a *significant positive* impact on radiated emissions.

***Case 5C: Long trace with and without decoupling capacitors – Log-periodic antenna***

Radiated emission results for both traces are shown in Figure 10.

***Observations***

Quasi-peak detector: Capacitors increased the failures in the frequency range 380 – 511 MHz by 2 - 10.6 dB. They introduced a new failure at 844 MHz.

Average detector: Capacitors increased the failures in the frequency range 319 – 511 MHz by 2.1 - 10.7 dB. They introduced a new failure at 844 MHz.

Overall, the capacitors had a *negative* impact on radiated emissions.

## 6. FUTURE WORK

The next article will present the conducted emissions results for the configurations discussed in this article.

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1. Bogdan Adamczyk and Mathew Yerian-French, "Impact of a Decoupling Capacitor and Trace Length on Signal Integrity in a CMOS Inverter Circuit," *In Compliance Magazine*, January 2024.

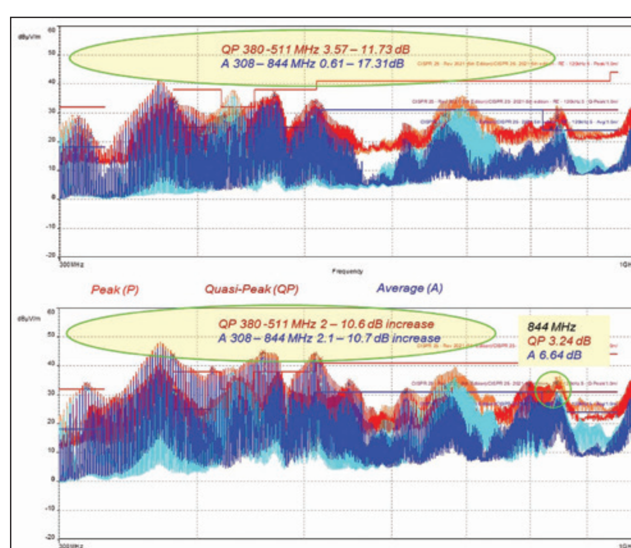


Figure 10: Log-periodic antenna, long trace: a) without capacitors b) with capacitors

# The Future of Wi-Fi

## How Wi-Fi 7 Will Make Innovative New Applications Possible

*By the IEEE Standards Association (IEEE SA)*

Wi-Fi technology is based on the IEEE 802.11™ series of wireless connectivity standards that have revolutionized how we communicate and access information. Today, billions of Wi-Fi-enabled devices are in use worldwide, dramatically impacting how individuals, businesses, government agencies, and societies interact. It is no exaggeration to say that the IEEE 802.11 series of standards has significantly supported the deployment of high-quality global communications Wi-Fi technologies through inexpensive, equitable internet access.

Since its debut 25 years ago, Wi-Fi has played a vital role in helping us be connected at home, work, and in public places. You may recall a time when Wi-Fi wasn't so readily available, but today we expect a standard level of connectivity wherever we go – even in large outdoor spaces such as parks and baseball stadiums. Typical of technology, the earliest versions of Wi-Fi were considered slow by today's standards and its use was more limited. Today, we now use an enormous number of Wi-Fi-enabled devices – computers, smartphones, game consoles, health/fitness devices, and much more – for productivity, organization, entertainment, health, and even security.

In recognition of the Internet's 40th anniversary, we examine how the IEEE 802.11 series of standards has driven the evolution of Wi-Fi technology and how new additions to the series will enable greater Wi-Fi capabilities, making innovative new applications possible.

### THE GENESIS OF WI-FI

Wi-Fi is a wireless local area network (WLAN) technology that enables digital devices within a certain area to communicate through wireless transmitters and radio signals. When a transmitter receives data from the internet, that data is converted into a radio signal that can be received and read by Wi-Fi-enabled devices. An exchange of information occurs between the transmitter and the device.

The origins of Wi-Fi can be traced back to a 1985 ruling by the U.S. Federal Communications Commission that released the bands of the radio spectrum at 900 megahertz (MHz), 2.4 gigahertz (GHz), and 5.8 GHz for unlicensed use by anyone. Technology companies built wireless networks and devices to take advantage of the newly available radio spectrum, but

*The IEEE Standards Association (IEEE SA) is a collaborative organization where innovators raise the world's standards for technology. IEEE SA provides a globally open, consensus-building environment and platform that empowers people to work together in the development of leading-edge, market-relevant technology standards, and industry solutions shaping a better, safer, and sustainable world.*

> In 1997, IEEE SA unveiled its groundbreaking IEEE 802.11™ technical standard and introduced Wi-Fi to the market, enabling wireless data transmission at up to 2 Mbit/s using an unlicensed 2.4 GHz radio spectrum.

the lack of a common technical standard resulted in fragmentation because manufacturers' devices were rarely compatible.

In 1997, IEEE SA unveiled its groundbreaking IEEE 802.11™ technical standard and introduced Wi-Fi to the market, enabling wireless data transmission at up to 2 Mbit/s using an unlicensed 2.4 GHz radio spectrum.

The promising Wi-Fi technology and a new common technical standard were embraced by technology innovators, particularly Apple's then-CEO Steve Jobs, who was enamored by the idea of wireless connectivity for laptops. This led to Wi-Fi's first major commercial breakthrough in 1999 when Jobs and Apple introduced the first mass-marketed consumer products with Wi-Fi connectivity, the AirPort wireless base station, and iBook. At that time, the newly released IEEE 802.11b™ amendment to the original Wi-Fi standard pushed theoretical data rates up to 11 Mbit/s. Jobs showed off the world's first Wi-Fi-enabled laptop at MacWorld in New York City, demonstrating wireless Internet by passing the iBook through a hula hoop to a cheering crowd.

Just a few years later, Apple introduced an updated version of the AirPort base station. Based on the newly developed IEEE 802.11g™ specification, Apple's new base station could communicate at 54 Mbit/s. When the updated base station was released in 2003, Jobs exclaimed that Apple kick-started the wireless revolution. While Jobs and Apple deserve credit for product innovation, the Wi-Fi revolution would not have been possible without the IEEE 802.11 standards family and the volunteers who made it happen.

The evolution of IEEE 802.11-based Wi-Fi standards continues today, providing much faster data transmission rates, longer ranges, and more reliable and secure connections. All IEEE 802.11 standard amendments are constructed in a manner such that devices which operate according to their specifications will be backward compatible with earlier versions, enabling any modern IEEE 802.11-based device to communicate with older products.

## IEEE STANDARDS FOR WI-FI

The Wi-Fi Alliance ("Wi-Fi #") developed a naming convention to help the general public better distinguish between various IEEE 802.11 implementations:

- *IEEE 802.11™* is the aforementioned pioneering 2.4 GHz Wi-Fi standard from 1997, and it is still referred to by that nomenclature. This standard and its subsequent amendments are the basis for Wi-Fi wireless networks and represent the world's most widely used wireless computer networking protocols.
- *IEEE 802.11b™*, or *Wi-Fi 1*, was introduced in 1999 with Apple's announcement of its Wi-Fi-enabled base station and laptop computer. It also operated at 2.4 GHz, but it incorporated modulation schemes called direct-sequence spread spectrum/complementary code keying (DSSS/CCK). This helped reduce interference from devices such as microwave ovens, cordless phones, baby monitors, and other sources, and it also achieved higher data rates. Wi-Fi 1 enabled wireless communications at distances of ~38m indoors and ~140m outdoors.
- *IEEE 802.11a™*, or *Wi-Fi 2*, also introduced in 1999, was the successor to IEEE 802.11b. It was the first Wi-Fi specification to feature a multi-carrier modulation scheme (OFDM) to support high data rates, unlike Wi-Fi 1's single-carrier design. It supported 5 GHz operation and its 20 MHz bandwidth supported multiple data rates.
- *IEEE 802.11g™*, or *Wi-Fi 3*, was introduced in 2003. Wi-Fi 3 achieved faster data rates of up to 54 Mbit/s in the same 2.4 GHz frequency band as IEEE 802.11b, made possible by an OFDM multi-carrier modulation scheme and other enhancements. Additionally, Wi-Fi 3 appealed to mass market manufacturers and users because 2.4 GHz devices were less expensive than 5 GHz devices.
- *IEEE 802.11n™*, or *Wi-Fi 4*, was introduced in 2009. Wi-Fi 4 supported the 2.4 GHz and 5GHz frequency bands, with up to 600 Mbit/s data rates, multiple channels within each frequency band, and other features. IEEE 802.11n data throughputs enabled the use of WLAN networks in place of wired networks, a significant feature, enabling new use cases and reducing operational costs for end users and IT organizations.

- *IEEE 802.11ac™*, or *Wi-Fi 5*, was introduced in 2013. Wi-Fi 5 supported data rates at up to 3.5 Gbit/s, with still-greater bandwidth, additional channels, better modulation, and other features. This was the first Wi-Fi standard to enable the use of multiple input/multiple output (MIMO) technology, which enabled multiple antennas to be used on both sending and receiving devices to reduce errors and boost speed.

## WI-FI 6 ADDRESSES NETWORK DENSITY DEEDS AND PROVIDES SPECTRAL EFFICIENCY

*IEEE 802.11ax™*, or *Wi-Fi 6*, is the most recent standard in the series, published in 2021. Wi-Fi 6-based devices – including IoT devices – are now being deployed in billions per year.

Although the theoretical data rate for Wi-Fi 6 is 9.6 Gbit/s, this standard is more focused on usage density rather than boosting speed. The pervasive use of Wi-Fi today creates issues whereby network performance can be degraded in areas of dense Wi-Fi traffic. Examples of problem areas include sports stadiums, concert halls, and public transportation hubs. But the issue isn't only in large venues. Homes are increasingly problematic due to the need for routers that must communicate simultaneously with a growing number of digital gadgets.

IEEE 802.11ax offers many enhancements including a multi-user mechanism that allows the 9.6 Gbit/s data rate to be split among various devices. It also supports routers sending data to multiple devices in one broadcast frame over the air, and it allows Wi-Fi devices the ability to schedule transmissions to the router. Mechanisms to support longer-range outdoor operations are also added.

Collectively, these features improve aggregate throughput and support the increasing use of Wi-Fi in data-heavy situations and in applications such as video and cloud access, where real-time performance and low power consumption for battery-powered devices are required. Of great importance and focus is the expectation for high-definition video to be the dominant type of traffic in many forthcoming Wi-Fi deployments.

## WI-FI 7: THE NEXT EVOLUTIONARY STEP FOR WI-FI

Next to take center stage will be Wi-Fi 7.

There are numerous drivers for even faster, better Wi-Fi, including the rapid growth and adoption of the Internet of Things (IoT), with more devices expanding their

> From the user's perspective, Wi-Fi 7 will be much faster, have much lower latency, will support many more devices, and will perform much better in congested Wi-Fi spaces and where Wi-Fi networks overlap.

capabilities through connectivity. Sensor technology embedded in IoT devices continues to become less expensive, more advanced, and more widely available. In turn, widespread availability and cost-effectiveness are pushing innovation of new sensor applications, including large-scale monitoring and detection.

In homes, an increasing number of commonplace items are transforming into connected devices every day. Today's modern smart homes include IoT thermostats, alarm systems, smart televisions, fitness, and home healthcare monitors, as well as other devices such as gaming systems and wireless speakers requiring speed and low latencies. Consumers will benefit from Wi-Fi 7 for gaming, AV/VR and video applications, and smart-home services.

For enterprises, Wi-Fi 7 will benefit IoT and IIoT applications, such as industrial automation, surveillance, remote control, AV/VR, and other video-based applications. Additionally, Wi-Fi 7 brings more flexibility and capabilities to enterprises as they engage in digital transformation.

Wi-Fi 7 is based on features defined in the *IEEE P802.11be™* draft amendment. A major evolutionary milestone in Wi-Fi technology, Wi-Fi 7 will provide quadruple – that's four times – faster data rates (~40 Gbit/s) and twice the bandwidth (320 MHz channels vs. 160 MHz channels for Wi-Fi 6). Wi-Fi 7 also supports more efficient and reliable use of available and contiguous spectrum through multi-band/multi-channel aggregation and other means. The standard features numerous enhancements to MIMO protocols and many other advancements and refinements of existing Wi-Fi capabilities.

The Wi-Fi 7 specification also features multi-link operation (MLO), which is similar to the carrier aggregation that mobile phone providers use to increase data throughput by combining the abilities of separate channels. MLO can elevate data rates to be seven times faster while also lowering latency and improving dependability because linked channels work in parallel.

Wi-Fi 7 also doubles Wi-Fi 6's eight independent streams of data to 16 spatial streams. It uses coordinated multiuser MIMO (CMU-MIMO), which is a significant improvement from multi-user multiple-input, multiple-output.

The new Wi-Fi 7 specification also uses multi-user resource unit (MRU) to avoid interference, allowing selective puncturing of overlapping portions of the spectrum to let the data flow only on frequencies that are clear. It can help raise data rates and reliability in congested Wi-Fi environments, such as in an apartment building or large office environment.

Summing up, from the user's perspective, Wi-Fi 7 will be much faster, have much lower latency, will support many more devices, and will perform much better in congested Wi-Fi spaces and where Wi-Fi networks overlap. Of course, to harness the benefits, users will need significantly faster internet speeds from their service providers.

But the IEEE 802.11 series work doesn't end here. The drive to improve Wi-Fi is a continuous focus of IEEE SA and its army of volunteer experts.

## LOOKING AHEAD: IEEE 802.11 STANDARDS FOR NEW AND EMERGING WI-FI USE CASES

*IEEE P802.11be*, along with *IEEE 802.11ax* and future iterations of IEEE 802.11 standards, also could support many next-generation Wi-Fi applications. The IEEE 802.11 Working Group has established several special-interest groups to investigate many of them. Here are a few examples:

- The Artificial Intelligence/Machine Learning Topic Interest Group (AIML TIG) is focused on describing use cases for artificial intelligence/machine learning (AI/ML) applicability in 802.11 systems and investigating the technical feasibility of features enabling support of AI/ML. Developers and deployers of AI/ML protocols over wireless networks are expected to benefit from more optimized and efficient support for exchanging AI/ML-related data exchanges, such as reduced overhead and reduced delay. WLAN users, OEMs, and network operators are expected to benefit from improved user experience and higher efficiency of resources, and improved network performance.

- The Ambient Power for WLAN IoT Topic Interest Group (AMP TIG) is describing use cases for 802.11 ambient power-enabled IoT devices and investigating the technical feasibility of features to enable 802.11 WLAN support of ambient power-enabled IoT devices. Battery-free IoT technologies are expected to significantly reduce maintenance efforts of IoT networks and devices and extend the application scenarios featured as more environmentally friendly and much safer. This technology would see application in verticals such as agriculture, Smart Grid, mining, manufacturing, logistics, smart home, transportation, etc.
- The ***Ultra High Reliability (UHR) Study Group*** is investigating technology that may improve the reliability of WLAN connectivity, reduce latencies, increase manageability, increase throughput including at different SNR levels, and reduce device-level power consumption. Due to the growing importance of metaverse and AR/VR communications, the need for more throughput/data rate is in constant evolution. The study group started early in 2023; a task group is targeted to start in May 2023.

## HOW IEEE SA SUPPORTS THE DEVELOPMENT AND LAUNCH OF WI-FI STANDARDS

Through our IEEE 802 LAN/MAN Standards Committee, IEEE SA develops and maintains networking standards and recommended practices for local, metropolitan, and other area networks. As Wi-Fi networks continue to progress on multiple fronts, so will IEEE Standards, to help to bring out the full potential of Wi-Fi technology and serve the future industry and human needs.

We welcome the involvement of participants from academia, government, and industry. For more information or to join the standards activity, please visit the IEEE 802 LAN/MAN Standards Committee webpage (https://standards.ieee.org).

# CPSC GETS AGGRESSIVE ABOUT FAILURE TO REPORT

## Civil Penalties Significantly Increase

*By Kenneth Ross*

The most important responsibility of any manufacturer or product seller under the Consumer Product Safety Act (CPSA) is to report product safety issues to the U.S. Consumer Product Safety Commission (CPSC) that meet the statutory requirements under the Act.

In the last few years, the compliance staff of the CPSC has reached settlements with a number of companies over allegations that they failed to either report relevant product safety issues or failed to report them in a timely manner. These settlements included significant civil penalties. Before I describe some of the specific allegations in these matters, I want to describe the reporting requirements.

### REPORTING REQUIREMENTS

Section 15(b) of the CPSA requires manufacturers, importers, distributors, and retailers to notify the CPSC immediately if it obtains information that reasonably supports the conclusion that a product distributed in commerce: 1) fails to comply with a voluntary standard upon which the Commission has relied under the CPSA; 2) fails to meet a consumer product safety standard or banning regulation; 3) contains a defect which could create a substantial product hazard to consumers; or 4) creates an unreasonable risk of serious injury or death.

The most important basis for reporting to the Commission is Section 15(b)(3), which requires reporting when the product has both a defect and the defect creates the possibility of a substantial product hazard. A Recall Handbook published by the CPSC in September 2021[1] provides a description of the law and regulations and other helpful information on how to analyze the need to report.

### REPORTING LAW AND REGULATIONS

#### Defect

The first question is whether there is a defect. To help a company decide whether they have a defect, the Commission's regulations say:

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*"At a minimum, defect includes the dictionary or commonly accepted meaning of the word. Thus, a defect is a fault, flaw, or irregularity that causes weakness, failure, or inadequacy in form or function. A defect, for example, may be the result of a manufacturing or production error; that is, the consumer product as manufactured is not in the form intended by, or fails to perform in accordance with, its design. In addition, the design of and the materials used in a consumer product may also result in a defect…A design defect may also be present if the risk of injury occurs as a result of the operation or use of the product or the failure of the product to operate as intended. A defect can also occur in a product's contents, construction, finish, packaging, warnings, and/or instructions. With respect to instructions, a consumer product may contain a defect if the instructions for assembly or use could allow the product, otherwise safely designed and manufactured, to present a risk of injury."*

16 CFR §1115.4

The CPSC regulations say that the term "defect" used in this section is not necessarily the same as the term "defect" in product liability law. But, in general, CPSC regulations do require product liability law and lawsuits to be considered in connection with a determination of whether a product is defective.

In addition, in 16 CFR §1115.4, the CPSC lists the following factors to determine whether the risk of injury associated with the product is the type of risk that would render the product defective.

1. The utility of the product
2. The nature of the risk of injury that the product presents
3. The necessity of the product
4. The population exposed to the product, and its risk of injury
5. The obviousness of such risk
6. The adequacy of warnings and instructions to mitigate the risk
7. The role of consumer misuse of the product, and the foreseeability of such misuse
8. The Commission's experience and expertise
9. The case law interpreting federal and state public health and safety statutes
10. The case law in the area of products liability
11. Other information relevant to the determination

The CPSC distinguishes products that hurt people but aren't defective by stating:

*"We note, however, that not all products that present a risk of injury are defective. A typical kitchen knife is one example. A knife blade must be sharp for a consumer to cut or slice food. The knife's sharpness is not always a product defect, even though some consumers may cut themselves while using the knife. On the other hand, if the handle or blade of a particular knife is prone to breaking that may constitute a defect."*

*CPSC Recall Handbook,* page 12

### Substantial Product Hazard

The next question to be answered is whether this "defect" could create a "substantial product hazard." The Commission starts this analysis by stating:

*"Because a product may be defective even when it is designed, manufactured, and marketed exactly as intended, a company in doubt about whether a defect exists should still report."*

*CPSC Recall Handbook*, page 12

Then the regulations provide the following factors a manufacturer must consider in determining if there is a substantial product hazard:

1. Pattern of defect;
2. Number of defective products in commerce;
3. Severity of risk; and
4. Likelihood of injury.

Concerning the severity of the risk, the CPSC has said:

*"The definition of a serious injury is set forth in 16 CFR 1115.5(c) and includes grievous bodily injuries or injuries requiring hospitalization, medical treatment, or missing work or school for more than one day."*

*CPSC Recall Handbook*, page 13

In addition, some of the important limitations on these factors are statements to the effect that a defective product that has no risk of serious injury or has little chance of causing even a minor injury would not ordinarily constitute a substantial hazard. Also, the CPSC considers injuries that have occurred or could occur in determining severity. Last, determining the likelihood of future injury considers the "intended or reasonably foreseeable use or misuse of the product…" (*CPSC Recall Handbook*, page 13).

### Non-compliance with Standards

Sections 15(b)(1) and (2) state that a manufacturer has a reporting responsibility if the product does not comply with a mandatory standard or banning regulation or does not comply with a voluntary standard that is relied on or has been adopted by the CPSC. While this non-compliance is reportable, it is possible to argue that there is no significant hazard and therefore no corrective action needs to be undertaken with products in-consumers' hands.

### Unreasonable Risk

There is an additional reporting responsibility that applies even if there is no defect and the product complies with all CPSC standards. Section 15(b)(4) requires a report if there is an unreasonable risk of serious injury or death. The critical term is "unreasonable," which is defined as follows:

> *"The use of the term 'unreasonable risk' suggests that the risk of injury presented by a product should be evaluated to determine if that risk is a reasonable one. In determining whether a product presents an unreasonable risk, the firm should examine the utility of the product, or the utility of the aspect of the product that causes the risk, the level of exposure of consumers to the risk, the nature and severity of the hazard presented, and the likelihood of resulting serious injury or death. In its analysis, the firm should also evaluate the state of the manufacturing or scientific art, the availability of alternative designs or products, and the feasibility of eliminating the risk. The Commission expects firms to report if a reasonable person could conclude given the information available that a product creates an unreasonable risk of serious injury or death."*

16 CFR §1115.6(b)

The applicable regulation, 16 CFR §1115.6(a), does not require that a product be defective before a reporting responsibility arises. However, for such reports, the regulation requires firms to consider:

> *"Reports from experts, test reports, product liability lawsuits or claims, consumer or customer complaints, quality control data, scientific or epidemiological studies, reports of injury, information from other firms or governmental entities…"*

The regulations then go on to say:

> *"While such information shall not trigger a per se reporting requirement, in its evaluation of whether a subject firm is required to file a report under the provisions of section*

*15 of the CPSA, the Commission shall attach considerable significance if such firm learns that a court or jury has determined that one of its products has caused a serious injury or death and a reasonable person could conclude based on the lawsuit and other information obtained by the firm that the product creates an unreasonable risk of serious injury or death."*

Therefore, experiences during product liability litigation must be considered in determining whether a report to the CPSC is advisable. This includes expert reports, deposition testimony, jury verdicts, judge rulings, and settlements.[2]

## TIMING OF REPORT

If there is a situation that meets the threshold for reporting or the company does not know if they have a duty to report either under Section 15(b)(3) or (4), the CPSA requires companies to report immediately. The Commission defines this requirement as follows:

> *"A company must report to the CPSC within 24 hours of obtaining reportable information. The CPSC encourages companies to report potential substantial product hazards, even while their own investigations are continuing. However, if a company is uncertain about whether information is reportable, the company can take a reasonable time to investigate the matter. That investigation should not exceed 10 working days, unless the company can demonstrate that a longer time is reasonable under the circumstances."*
>
> *CPSC Recall Handbook*, page 8

In order to encourage manufacturers to report even when they aren't sure if they are required to do so, the Commission has said:

> *"Reporting a product to the CPSC under Section 15 does not automatically mean that the agency will conclude that the product creates a substantial product hazard or determine that corrective action is necessary. CPSC staff will evaluate the report and work with the reporting company to determine whether corrective action is necessary. Many of the reports received require no corrective action because staff concludes that the reported product defect does not create a substantial product hazard."*
>
> *CPSC Recall Handbook*, page 6

In any report to the CPSC, the company can clearly state that they do not believe that the product has a defect that could create a substantial hazard, but that they are still voluntarily reporting this matter to the CPSC. Unfortunately, the CPSC has recently gotten very aggressive in requiring recalls even for situations where a recall is arguably not warranted. Despite that, the CPSC states that a significant percentage of filings under section 15(b) does not result in a recall.

## SECTION 37

Section 37 of the CPSA requires manufacturers of consumer products to report information about settled or adjudicated civil actions. Manufacturers and product sellers should be aware of the details of this section. However, normally a manufacturer or product seller will have already filed under Section 15(b) before the threshold for reporting under Section 37 is met. This is because litigation and the results of the resolution of litigation must be considered by companies and significant settlements or adverse verdicts could result in a report. (See *CPSC Recall Handbook,* page 9, and *16 CFR §1115.7* for more information on Section 37.)

## CIVIL PENALTIES

Manufacturers and others in the chain of production and distribution need to make some critical decisions so they can meet their statutory obligations and avoid being charged with violating these requirements. This is particularly important as the CPSC has recently ramped up its efforts to fine those companies that violate these reporting requirements.

Since early 2021, the CPSC has significantly increased the number of cases where civil penalties are being sought. Given these efforts and statements from the current CPSC commissioners, manufacturers should assume that the CPSC will continue to look for cases where late reporting or failure to report might justify civil penalties.

The Commission is supposed to consider the following in determining the amount of penalties sought:

> *"… the Commission shall consider the nature, circumstances, extent, and gravity of the violation, including the nature of the product defect, the severity of the risk of injury, the occurrence of absence of injury, the number of defective products distributed, the appropriateness of such penalty in relation to the size of the business of the person charged, including how to mitigate undue adverse economic impacts on small businesses… "*
>
> 15 U.S.C. §2069(b)

Since early 2021, the Commission has settled four civil penalty cases for late reporting with the highest amount being $16,025,000 (there was an additional penalty for selling recalled products) and others being $6 million, $7.5 million, and $7.95 million.

In the case involving $16 million, the manufacturer reportedly received 150 reports of incidents including one death and 13 injuries before they reported. In another case, the manufacturer received reports of injuries for seven years before filing with the CPSC.

In 2018, there was a $27.75 million civil penalty agreed to but it involved multiple violations of the reporting requirements. Just prior to 2018, most civil penalties were in the range of $2 million to $5 million. However, in 2016, there was a civil penalty of $15,450,000 for a particularly egregious situation that ultimately also resulted in criminal prosecutions.

I reviewed a number of penalty matters for many years prior to 2021 and came up with some factual scenarios that were different than just a failure to report to the CPSC after learning of accidents. In some of these penalty cases, one of the following things occurred:

- The manufacturer made a design or manufacturing change (sometimes several times) because of a safety issue (in the eyes of the Commission, they were fixing a defective product) and didn't report to the CPSC or notify prior customers about the change.
- The manufacturer issued a dealer alert (sometimes several) concerning a safety problem but did not report to the Commission or alert its customers.
- The manufacturer supplied incomplete or inaccurate information to the CPSC when they investigated a safety issue.
- The CPSC had to request the manufacturer to provide information.

It is easy to review the publicly available information concerning civil penalties. The CPSC website[3] at shows civil penalty cases by fiscal year, product, and company. Therefore, anyone can review the facts surrounding each of these cases to better understand the trends and the facts on which these penalties were based.

## CONCLUSION

Given the significant number of fines being levied and the increase in the potential for fines, it is clear that manufacturers and others in the chain of distribution should, when in doubt, err on the side of reporting.

As the CPSC has said over the years, a significant percentage of reports to the CPSC do not result in any corrective action. As a result, it makes sense for the company to seriously consider reporting to the CPSC even if there is a possible defect and a small chance of a serious injury. In that case, you can report, deny that it is a substantial product hazard, and argue that no corrective action is necessary.

Of course, it is possible that the CPSC will disagree and will encourage or try to force (by litigation) a manufacturer to undertake a remedial program. Or, as has happened a number of times recently, the CPSC can issue a unilateral press release on the safety issue involving the specific product involved.

Therefore, when in doubt, the prudent course of action may be to report early and cut off any chance of a late reporting fine. In that case, you are still able to argue that there is no defect or no substantial product hazard and that a corrective action on products in consumers' hands is not warranted. If that argument is not successful and the company refuses to do a recall, they could wind up with a unilateral press release which will encourage consumers to not use a product but will not actually institute a recall. Or it might result in no further action by the CPSC.

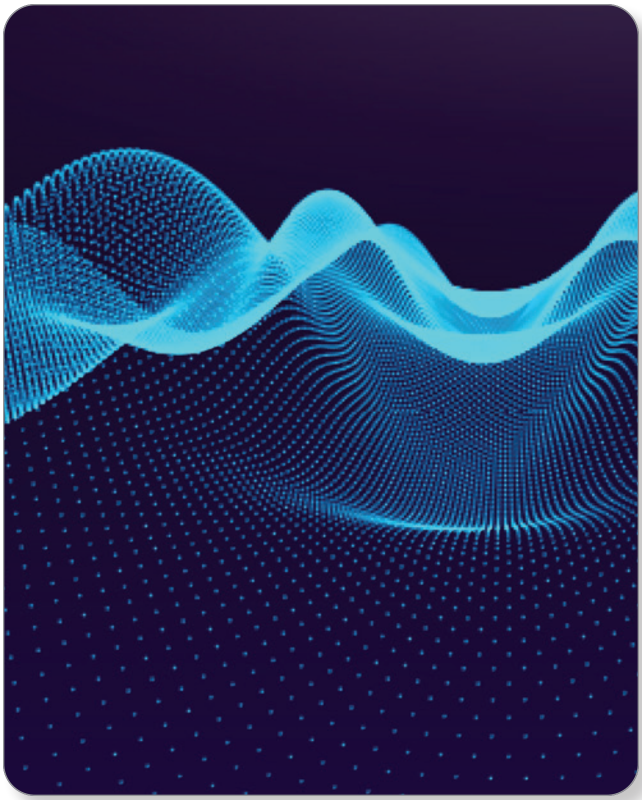
## ENDNOTES


1. The complete title of the handbook is "Product Safety Planning, Reporting, and Recall Handbook," and is available at https://www.cpsc.gov/s3fs-public/CPSCRecallHandbookSeptember2021.pdf.
2. K. Ross, "Product Liability Litigation and its Effect on Product Safety Regulatory Compliance," *In Compliance Magazine*, August 2020.
3. https://www.cpsc.gov/Business--Manufacturing/Civil-and-Criminal-Penalties


## ADDENDUM

The U.S. Consumer Product Safety Commission has continued to aggressively assess civil penalties against companies for late reporting. Since this article was written, during Fiscal Year 2023 (October 2022 to September 2023), there were four new civil penalty agreements involving BJ's Wholesale Club ($9 million), Generac ($15.8 million), Peloton ($19 million), and Whirlpool ($11.5 million). In addition, Fiscal Year 2024 started with a $16 million civil penalty against HSN Inc. (Home Shopping Network). Lastly, on November 16, 2023, two executives from Gree Electric Appliances Inc. were convicted by a jury of conspiracy and failure to report information related to defective residential dehumidifiers. This is the first-ever criminal prosecution for failure to report under the Consumer Product Safety Act (CPSA).

# Performing Proximity Magnetic Fields Immunity Testing



## How to Conduct Testing in Accordance with IEC 60601-1-2:2014 Amendment 1:2020

*By Grace Lin and Brian Lackey*

IEC 60601-1-2 is the international standard on electromagnetic disturbances to medical electrical equipment and is used in support of worldwide regulatory approvals for medical electrical equipment. The latest edition of the IEC 60601-1-2 standard, IEC 60601-1-2:2014 Amendment 1:2020 (referenced as Edition 4.1 hereafter), was published September 1, 2020. This latest edition includes the following significant technical changes with respect to its previous edition (IEC 60601-1-2 Edition 4.0 2014-02, referenced as Edition 4.0 hereafter):

- Normative references – As listed in Table 1 on page 44, standard versions of eleven normative references are updated. In addition, ISO 7137:1995 is deleted and IEC 61000-4-39:2017 is added.
- Power input voltages – Power input voltage requirements for the following tests have been clarified: conducted disturbances (CISPR 11), voltage dips immunity (IEC 61000-4-11), and voltage short interruptions and voltage variations immunity (IEC 61000-4-11).
- For conducted disturbances and voltage dips immunity measurements, testing shall be performed at both minimum and maximum rated voltages. If the difference between the minimum and the maximum rated input voltages is less than 25% of the highest rated input voltage, the tests may be performed at any one rated voltage. Please note each economy/region may have its own requirements. For example, South Korea requires that testing be performed at 220 V.
- Testing of voltage short interruptions and voltage variations immunity shall be performed at any one voltage. Again, each economy/region may have its own requirements.
- Conducted immunity to SIP/SOPS (IEC 61000-4-6) – This test is now applicable to SIP/SOPS on cables equal to or greater than 1 m in length (versus 3 m from Edition 4.0).
- Immunity to proximity magnetic fields – This is a newly added requirement stipulated in Subclause 8.11 of Edition 4.1 with the title of "Immunity to proximity

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*Brian Lackey is an EMC engineer and member of the technical staff at Intertek in Lexington, Kentucky. He is a member of the TCB Council, an organization responsible for directly interfacing with the FCC, and is developing standards with the IEEE for statistical process control. Lackey can be reached at brian.lackey@intertek.com.*

# MIL-STD-461 TESTING

## SIMPLIFIED WITH PEARSON PRODUCTS

## CS114/115/116

New Injection Probe, Current Probe and Test Fixture specifically designed for sections CS114/115/116 in MIL-STD-461 (including "G") and RTCA/DO-160 requirements.

- Consists of 3 Components
  - 8700i Injection Probe
  - 8705C Current Probe
  - F-3 Test Fixture (accomodates both probes)
- Wideband response - 10 kHz to 400 MHz
- Max Input Power - 100W for 30 minutes
- Max RMS Current - 4 Amps
- Max Peak Current - 15 Amps
- Compact design with 2.0 inch aperture

## CS101


Greatly simplifies the measurement of injected audio-frequency ripple on an AC or DC power bus in EMI tests such as MIL-STD-461G CS101.

- Two Models - PRD-120 & PRD-240
- Measure audio frequency (CS101) ripple injected on power buses
- Separates ripple from power waveform
- Used with a spectrum analyzer
- Max Voltage 120-240 Vac, 270 Vdc
- Switch selectable frequency response:
  - Flat response 10 Hz to 150 kHz
  - CS101 setting provides constant output over entire frequency range

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magnetic fields in the frequency range 9 kHz to 13.56 MHz." It applies to medical electrical equipment or systems that contain magnetically sensitive components or circuitry with a less than 0.15 m separation distance from the field sources of 30 kHz, 134.2 kHz, and 13.56 MHz.

- Annex F – Annex F, an informative annex, has been replaced by a new one. The title of the annex has been changed from "RISK MANAGEMENT for BASIC SAFETY and ESSENTIAL PERFORMANCE with regard to ELECTROMAGNETIC DISTURBANCES," to "Guidance on the application of RISK MANAGEMENT with regard to ELECTROMAGNETIC DISTURBANCES in this collateral standard."

The following sections describe the proximity magnetic fields immunity test, and the key technical changes.

## TEST REQUIREMENTS

Proximity magnetic fields immunity test requires three frequencies to be tested: 30 kHz, 134.2 kHz, and 13.56 MHz. Test frequencies, test signal modulation, and test levels are listed in Table 2.

Test levels listed in Table 2 are the amplitude of unmodulated carrier signal (i.e., continuous wave, CW). For testing at the frequencies of 134.2 kHz and 13.56 MHz, the carrier signals are pulse-modulated using a 50% duty cycle square wave signal and with specified modulation frequencies.

## TEST EQUIPMENT

Test equipment includes a generator, an optional compensation network, a radiating loop antenna, a monitoring loop antenna, and an electromagnetic interference (EMI) receiver or spectrum analyzer.

The generator must have the capability of generating the desired test levels. It includes a signal generator and a power amplifier. A signal generator must be capable of generating a carrier signal for the frequencies of interest and be equipped with pulse modulation capability internally or externally.

| | |
|---|---|
| IEC 60601-1-2:2014 | IEC 60601-1-2:2014<br>Amendment 1:2020 |
| IEC 60601-1:2005<br>Amendment 1:2012 | IEC 60601-1:2005<br>Amendment 1:2012<br>Amendment 2:2020 |
| IEC 60601-1-8:2006<br>Amendment 1:2012 | IEC 60601-1-8:2006<br>Amendment 1:2012<br>Amendment 2:2020 |
| IEC 60601-1-11:2010 | IEC 60601-1-11:2015<br>Amendment 1:2020 |
| IEC 60601-1-12 | IEC 60601-1-12:2014<br>Amendment 1:2020 |
| IEC 61000-4-5:2005 | IEC 61000-4-5:2014<br>Amendment 1:2017 |
| IEC 61000-4-11:2004 | IEC 61000-4-11:2004<br>Amendment 1:2017 |
| CISPR 11:2009<br>Amendment 1:2010 | CISPR 11:2015<br>Amendment 1:2016<br>Amendment 2:2019 |
| CISPR 14-1:2005 | CISPR 14-1:2016 |
| CISPR 16-1-2:2003<br>Amendment 1:2004<br>Amendment 2:2006 | CISPR 16-1-2:2014<br>Amendment 1:2017 |
| CISPR 32:2012 | CISPR 32:2015 |
| ISO 7137:1995 | (Delete) |
| ISO 14971:2007 | ISO 14971:2019 |
| - | IEC 61000-4-39:2017 |

Table 1: Normative references

| Frequency | Modulation | Immunity Test Level @ 50 mm (A/m) |
|---|---|---|
| 30 kHz | Continuous Wave (CW) | 8 |
| 134.2 kHz | Pulse Modulation 2.1 kHz | 65 |
| 13.56 MHz | Pulse Modulation 50 kHz | 7.5 |

Table 2: Test frequency, modulation, and test levels

| Type of Loop Antenna | Frequency | Loop Diameter (mm) | No. of Turns | Wire Diameter |
|---|---|---|---|---|
| Radiating Loop | 9 kHz – 150 kHz | 120 ± 10 | 20 | ~ 2.0 mm (AWG 12) |
| Monitoring Loop | 9 kHz – 150 kHz | 40 ± 2 | 51 | ~ 0.07 mm (7 Stand 41 AWG) |
| Radiating Loop | 150 kHz – 26 MHz | 100 ± 10 | 3 | ~ 1.0 mm |
| Monitoring Loop | 150 kHz – 26 MHz | 40 ± 2 | 1 | ~ 0.5 mm |

Table 3: Loop antenna specifications

Based on experience using radiating loop antennas from two manufacturers, an 80 watts power amplifier should be able to generate the desired test levels. Manufacturers of radiating loop antennas typically provide drive power information for its radiating loop antennas. It is important to ensure the power amplifier is not saturated and the EMI receiver or spectrum analyzer is not overloaded.

A test laboratory with IEC 61000-4-6 10 $V_{emf}$ test capability may use the same signal generator and power amplifier from its IEC 61000-4-6 test equipment if the signal generator and power amplifier cover frequencies of 30 kHz and 134.2 kHz. Though IEC 61000-4-6 specifies the test frequency range from 150 kHz to 80 MHz (not covering 30 kHz and 134.2 kHz), a power amplifier may work for frequencies below 150 kHz even if its specification starts at 150 kHz.

A matching network (compensation network) is used to better match the voltage standing wave ratio (VSWR) in the system to reduce needed power and to prevent damage to the power amplifier from reverse power. If a matching network is used, it connects directly to a radiating loop or through a specially designed cable. At the time of this writing, a 13.36 MHz matching network is commercially available, but a matching network can be made in-house with all the required components typically costing less than $100. A vector network analyzer (VNA) is used to tune the matching network.

A radiating loop antenna is a field-generating device. A monitoring loop antenna is a magnetic field sensor loop. Specifications for these loop antennas are listed in Table 3.

Both radiating and monitoring loop antennas are commercially available. Equipment manufacturers offer loop antennas as individual parts or as kits. Kits typically come with 50 mm fixtures.

Radiating loop antennas can also be made in-house. Step-by-step instructions are provided below to construct a 134.2 kHz radiating loop antenna:

1. Find a cylindrical form 120 ±10 mm in diameter, and 100 mm in height. The cardboard center of a wire spool of about 120 mm should work for the purpose.
2. Wrap 20 turns of AWG 12 wire around the center of the form, leaving a few feet free on either end.
3. Create a compensation network using a piece of prototyping board or other material with a coaxial connection for the amplifier on one side and terminals for the loop on the other. An optional step-down transformer may be used to increase the impedance as recorded by the amplifier and to produce the necessary drive current in the loop. The transformer must be rated for the test frequency and drive current.
4. Connect the loop and the compensation network to a calibrated VNA and measure the impedance at the design frequency (e.g., 134.2 kHz).
5. Add series capacitance to the compensation network to move the impedance to the Re(Y) = 1 circle, Im(Y) < 0.
6. Add parallel capacitance to the compensation network to move the impedance to the center (match).

Build up the capacitors on a breadboard first, then solder them on a prototyping board, and place the board in an enclosure with dual banana jacks. A TESEQ NSG 4070 conducted immunity system is used to power the loop antenna and obtain the required 65 A/m with less than 10 watts of power.

## ESTABLISHING TEST LEVELS

Figure 1 shows the test setup to establish test levels.

The monitoring loop antenna is positioned on the center axis of the radiating loop antenna and at a distance of 50 mm. Loop antenna manufacturers offer fixtures to keep the monitoring loop antenna at a distance of 50 mm from the radiating loop antenna.

The monitoring loop antenna is connected to an EMI receiver or a spectrum analyzer. The magnetic field strength (in dBµA/m) at the distance of 50 mm is calculated as the sum of the measured voltage level (in dBµV) and the conversion factor (in dB/Ωm) of the monitoring loop antenna. The conversion factor is used to convert the monitoring loop antenna voltage to magnetic intensity. The relevant conversion factor can be found in the datasheet of the monitoring loop antenna. The measured field strength must be within ± 10 %. of the specified test level.

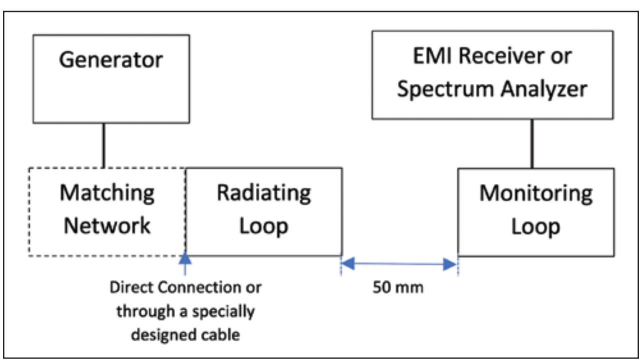


Figure 1: Test setup—Establish test levels

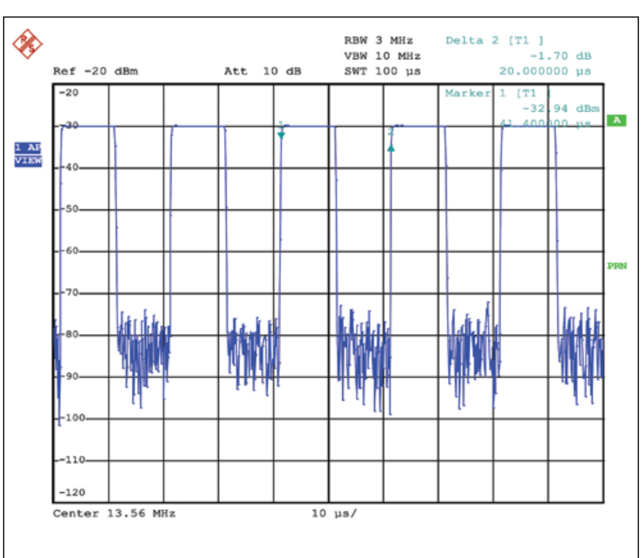


Figure 2: Screenshot—Verifying modulation

To achieve the desired magnetic field strength (for example, 7.5 A/m (137.5 dBµA/m) at 13.35 MHz), increase the power of the generator at the input of the radiating loop antenna (or the input of the matching network if a matching network is used) until the measured voltage at the output of the monitoring loop antenna is reached. For a conversion factor of 18.3 dB/Ωm, the measured voltage is 119.2 dBµV. No modulation signal is applied while establishing test levels. Record the signal generator output levels for testing.

Once the measured voltage is reached, switch on the modulation of the test signal to verify the correct modulation of the test signal. To verify the modulation, set the span of an EMI receiver (in spectrum mode) or a spectrum analyzer to zero, as shown in Figure 2. A pulse frequency of 50 kHz is equivalent to a pulse period of 20 µs.

## EXECUTING TEST

Figure 3 shows the test setup to execute the test.

Test methods are specified in IEC 61000-4-39:2017. The test is performed by exposing the equipment under test (EUT) to the test signals at 30 kHz, 134.2 kHz, and 13.56 MHz. Place the radiating loop antenna at the test distance of 50 mm from a test point on the EUT. Orient the plane of the radiating loop antenna parallel to the EUT's faces. Set the signal generator's output level to the level recorded from established test levels.

The dwell time must be long enough for the EUT to adequately respond to the test signal. The minimum dwell time is 2 seconds.

## CONCLUSION

IEC 60601-1-2 Edition 4.1 2020-09 CONSOLIDATED VERSION supersedes IEC 60601-1-2 Edition 4.0 2014-02. Each economy/region sets its own transition

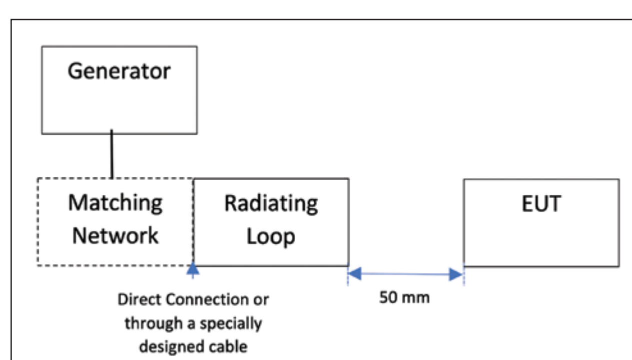


Figure 3: Test setup—Execute tests

period. In the U.S., the Food and Drug Administration (FDA) will no longer accept Edition 4.0 test reports after the end of the transition period of December 17, 2023.

Being prepared for the changes and requirements is important to your success. Table 4 lists a summary of tests required and specified in Edition 4.1, including the completely new proximity magnetic fields immunity test.

## REFERENCES


- IEC 60601-1-2:2014 Amendment 1:2020, Medical electrical equipment – Part 1-2: General requirements for basic safety and essential performance – Collateral Standard: Electromagnetic disturbances – Requirements and tests
- IEC 61000-4-39:2017, Electromagnetic compatibility (EMC) – Part 4-39: Testing and measurement techniques – Radiated fields in close proximity – Immunity test
- IEC 61000-4-6:2013, Electromagnetic compatibility (EMC) – Part 4-6: Testing and measurement techniques – Immunity to conducted disturbances, induced by radio-frequency fields
- Schwartzbeck FESP 5132 Datasheet http://schwarzbeck.de/Datenblatt/k5132.pdf
- AMETEK CTS LAS 6100 Datasheet https://www.ametek-cts.com
- AMETEK CTS LAS 6120 Datasheet https://www.ametek-cts.com


| Test | Basic Standard | Applicable Ports |
|---|---|---|
| Electromagnetic radiation disturbance (Radiated Emissions) | CISPR 11:2015 A1:2016 A2:2019 | enclosure |
| Conducted Disturbances (Conducted Emissions) | CISPR 11:2015 A1:2016 A2:2019 | input a.c. power |
| Harmonic Current Emissions | IEC 61000-3-2:2005 A1:2008 A2:2009 | input a.c. power |
| Voltage Changes, Voltage Fluctuations and Flicker Emissions | IEC 61000-3-3:2013 | input a.c. power |
| Electrostatic Discharge Immunity | IEC 61000-4-2:2008 | enclosure<br>patient coupling<br>signal input/output parts |
| Radiated RF Electromagnetic Field Immunity | IEC 61000-4-3:2006 A1:2007 A2:2010 | enclosure |
| Proximity Fields from RF Wireless Communications Equipment | IEC 61000-4-3:2006 A1:2007 A2:2010 | enclosure |
| Electrical Fast Transient/Burst Immunity | IEC 61000-4-4:2012 | input a.c. power<br>input d.c. power<br>signal input/output parts |
| Surge Immunity | IEC 61000-4-5:2014 A1:2017 | input a.c. power<br>input d.c. power<br>signal input/output parts |
| Immunity to Conducted Disturbances induced by RF Fields (Conducted RF Disturbance Immunity) | IEC 61000-4-6:2013 | input a.c. power<br>input d.c. power<br>patient coupling<br>signal input/output parts |
| Power Frequency Magnetic Field Immunity | IEC 61000-4-8:2009 | enclosure |
| Voltage Dips Immunity | IEC 61000-4-11:2004 A1:2017 | input a.c. power |
| Voltage Short Interruptions and Voltage Variations Immunity | IEC 61000-4-11:2004 A1:2017 | input a.c. power |
| Proximity Magnetic Fields | IEC 61000-4-39:2017 | enclosure |
| Electrical Transient Conduction Along Supply Lines | ISO 7637-2:2011 | input d.c. power |

Table 4: Summary of tests specified in IEC 60601-1-2 Edition 4.1

# Seventy Years of Electromagnetic Interference Control in Planes, Trains, and Automobiles (and Ships and Spaceships, as well)

## Understanding Today's EMI Limits and Test Methods Begins With Knowing How We Got Here

*By Ken Javor*

### EXPLANATORY NOTE[1]

This is the first in a multi-part series of articles exploring the background of modern electromagnetic interference (EMI) requirements and test methods. In this first part, we'll cover general topics. Part 2, "Line Impedance Stabilization is in its Seventieth Year and Still Going Strong," on page 58 will address the line impedance stabilization network (LISN) and test methods based on it. Subsequent parts will be devoted to radiated emission control and will address the important topic of "(Re)Discovering the Lost Science of Near Field Measurements" on page 110.

In each of these articles, there is a preponderance of references to various military electromagnetic interference specifications.[2] This should not be interpreted as limiting the subject matter discussed to the military sector. Both aerospace and automotive EMI specifications/standards bear a strong resemblance to military EMI standards, and that resemblance has been tracked over decades as these specifications/standards evolved. That is, commercial aerospace specifications from the 1960s and 1970s look like contemporaneous military specifications, and when the automotive industry later instituted EMI qualifications, those qualifications were similar to contemporaneous military practices.

This is not to say that these industry sectors simply copied military practices. At any particular point in time, radios,[3] culprit noise sources, and their installations tend to be similar, causing similar EMI issues and consequently similar EMI controls (limits and test procedures).

It is commonplace to contrast military vs. commercial EMI test practices, but that is not a fundamental distinction. Commercial aerospace and automotive EMI test practices have much more in common with military practices than they do with the qualification of consumer items on open area test sites (OATS) or in fully or semi-anechoic chambers (FAC/SAC). The fundamental difference is in installation in a vehicle (usually metal) vs. equipment slated for use in homes, offices, and industrial plants. EMI testing of equipment installed in vehicles requires acknowledgment of the immediate proximity of electrical ground (vehicle structure) and the possibility that vehicle antennas will be placed in close proximity to culprit electrical noise generators.


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Vehicles of all kinds – even large ships – must countenance culprit-victim separations in the very near field. Not all antenna-culprit separations will be precisely one meter, and while one-meter measurements are not scalable as are far-field measurements, the vehicle EMC verification process takes that into account.

The subject matter in this multi-part series of articles has been limited to a length and level of detail appropriate for magazine publication. An expanded discussion of these topics will be posted on the author's website in the near future.[4] Sections with significantly expanded coverage in the website version are flagged with an asterisk (*).

## INTRODUCTION

This year marks the seventieth anniversary of several developments that culminated in the birth of the modern EMC discipline. EMI specifications released in late 1952 and throughout 1953 incorporated technical improvements in test equipment and measurement procedures that previously didn't exist, or existed in a more primitive state.

We shall take as an example MIL-I-6181B, whose seventieth anniversary is this month.[5] While the improvements in MIL-I-6181B showed up in multiple contemporaneous specifications, MIL-I-6181B has two very important aspects that the other specifications don't. The MIL-I-6181 series (1950 – 1967) ran right up until MIL-STD-461 superseded all Service-specific EMI specifications, whereas most of the other specifications dead-ended prior to that. MIL-I-6181B changes stood the test of time.

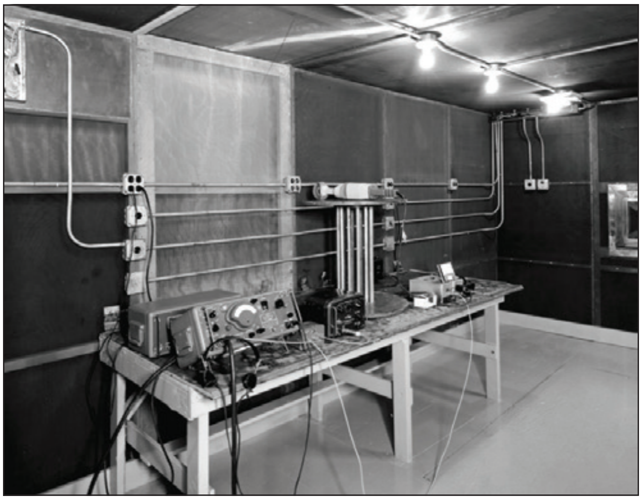
Secondly, we have a rationale or white paper report detailing the engineering behind the radiated emissions portions of MIL-I-6181B. NADC-EL-5515 precisely documents the problem and the solutions developed, and the process between problem and solution.[6] This report, authored in 1955 by William Jarva of the Naval Air Development Center, serves as a Rosetta Stone, unlocking the mystery behind the limits and test methods used to control unintentional radiated emissions. It should be required reading for anyone involved in vehicle EMC.

## THE WAY THINGS WERE (PRE-1967)

Some brief background is in order for those readers unfamiliar with anything before the Tri-Service MIL-STD-461 (1967 forward).[7]

Prior to the end of World War II, there were no EMI specifications at all.[8] Instead, there were specifications describing how to verify that integrated vehicles (planes, trains, automobiles, ships, and submarines) had sufficient EMI suppression to ensure the vehicle's suite of radios would operate free from interference. Such EMC specifications were accompanied by quite sophisticated handbooks and suppression specifications showing proper installations of both radio and non-radio electrical equipment so as to minimize the probability of radio frequency interference. Eventually, it was determined that designing a certain amount of suppression and immunity into electrical and electronic equipment was more efficient overall than trying to solve everything during vehicle integration, and this gave birth to JAN-I-225, the first EMI specification.[9]

From 1945 to 1967, there were individual Service-unique EMI specifications. During that period, there were multiple standards that were similar to but slightly different from each other. So test engineers had to have intimate familiarity with each of as many as a dozen



1950s EMI test set-up. (Photo courtesy of Ed Price.)

21st century EMI test chamber. (Photo courtesy of Rohde & Schwarz.)

specifications and their various nuances, and also access to and knowledge of different fully manual EMI receivers required in various specifications. Any reader who works for a living in the business of EMI testing should be grateful for a single Tri-Service specification![10]

While MIL-I-6181B evolved from a predecessor specification, it was revolutionary in many aspects.[11,12]

## TECHNOLOGICAL CHANGES

Two big technology changes appeared between 1950 and 1953. These were the widespread adoption of the 5 uH LISN, still in use in aerospace and automotive EMI practice to the present day, and the commercial availability of the AN/PRM-1 EMI receiver. Developed by the Stoddart Aircraft Radio Company circa 1950, this was the first EMI receiver operating below 30 MHz (conducted emission and rod antenna frequency range) with a peak detector.

Both of the EMI receivers shown in Figure 1 were designed for direct attachment of a 41" rod. Only the AN/PRM-1 has a (slide-back) peak-detecting capability.[13] The Ferris meter was much older, dating from 1932. According to Al Parker, the AN/PRM-1 was developed between the end of WWII and 1950.[14]

The advent of an EMI receiver with a peak detector operating in the conducted emission measurement frequency range meant it was no longer necessary to count the repetition rate of broadband impulses in order to apply correction factors based on the rep rate. This

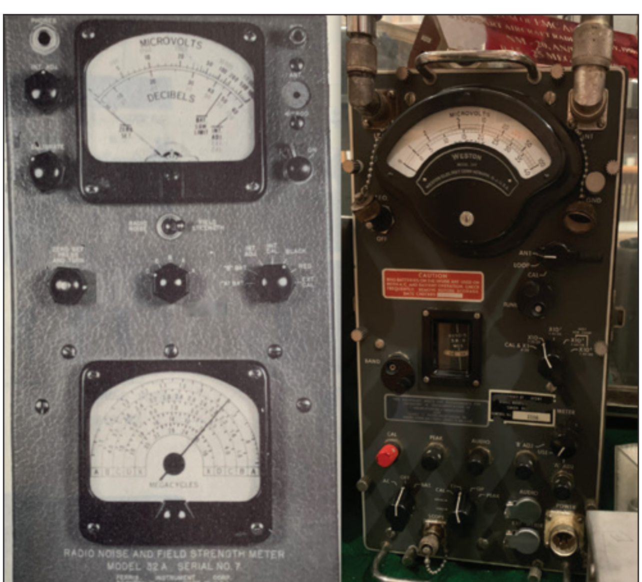



Figure 1: Ferris 32-A and Stoddart's AN/PRM-1 EMI receivers.
(Photo courtesy of the Museum of EMC Antiquities.)

resulted in a less complex measurement set-up, and much less time analyzing EMI signatures.

(The 5 uH LISN was such an important development that it gets its own separate discussion in Part 2 of this article series.)

## BANDWIDTH MATTERS

Discrimination between narrow and broadband interference sources is dealt with in detail in MIL-I-6181B, whereas the issue had been largely ignored before that. That is, where multiple EMI receivers are available, utilizing different measurement bandwidths, some with and some without peak detection, the measurement of broadband signals must be normalized on a per-unit bandwidth basis. Not only that, but the BC-348Q radio, which was the actual victim used to determine the limit, had a bandwidth of about 2 kHz, whereas the Ferris meter had a 10 kHz bandwidth.[15,16] Further, if a peak detector is not available, the response of the EMI receiver is dependent on the repetition rate of the impulses, so that a repetition rate correction factor curve is provided in MIL-I-6181B.

This was the inception of narrowband-broadband discrimination and separate limits. While that is largely obsolete today, it is not without merit. The demise of separate limits in MIL-STD-461D in 1993 was largely based on the perception that not enough people were doing it correctly, and the procedure had to be simplified to the point where people were all doing it the same way.[17] Hence, single-bandwidth measurements are ubiquitous today. These rely on CISPR 16-1 specifying these bandwidths for all EMI receivers, and also on these bandwidths being representative of those used by the actual radios protected by emission limits.

But the failure of such simplifications is evident in cases where multiple bandwidths are in use by various radio services. For instance, dithered clocks spread clock harmonics across several measurement bandwidths, decreasing the signal measured in any one bandwidth. This is a fine design technique as long as the radio protected from such interference has a bandwidth similar to that mandated by CISPR 16-1. But when the victim radio has a much larger bandwidth, such as broadcast television, then even the dithered clock energy falls within a single channel. So even though the dithered clock amplitude

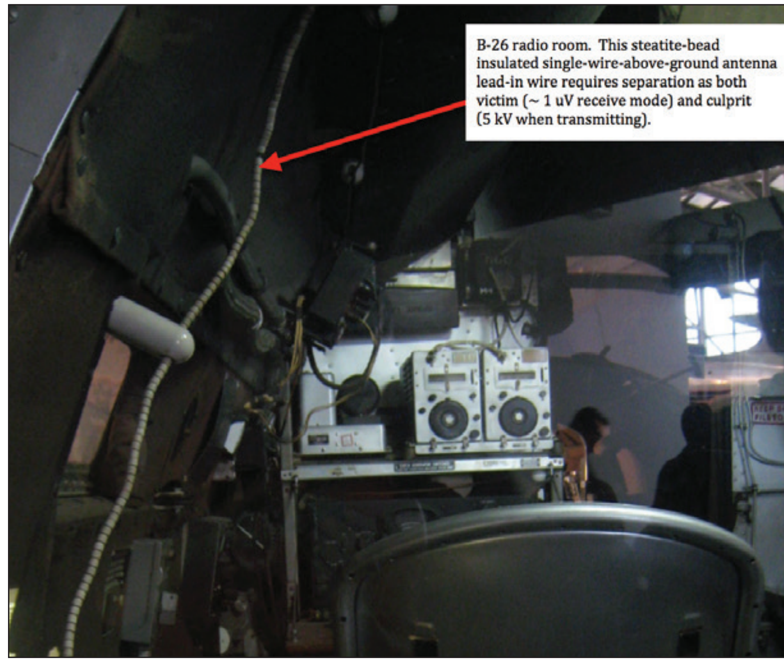



Figure 2: Unshielded antenna lead-in WWII-era B-26 bomber radio room. The BC-348 radio to which it connects is forward of the seat back and below silver-colored radio equipment in the rack. BC-348 is shown to better effect in Figure 4. (Photo taken by the author at Smithsonian National Air & Space Museum.)

Figure 3: The circular ceramic is the fuselage penetration treatment for the unshielded antenna lead-in. It wasn't just the 5 kV transmit voltage driving the treatment, but also the high frequency requiring control of shunt capacity. Control of shunt capacity was provided within the aircraft by ceramic standoffs. The 2" distance between the base and the hole is the basis for the 2" (5 cm) standoff requirement in all subsequent EMI specifications and standards. (Photo courtesy of the Museum of EMC Antiquities.)

is under the limit measured with a 120 kHz bandwidth, such signals can cause TVI. If a separate bandwidth such as 1 MHz or better yet 6 MHz were used, that would tell the tale for the TV receiver.

Nowadays this is easily achieved with FFT or time-domain type receivers, which can look at a very large spectrum and then digitally simulate what would be measured using various smaller bandwidths and detectors, all from a single high-speed sweep. It may be time to take a look at this 1953 innovation once again.

## THE ANSWER TO AN OFT-POSED QUERY

Sometimes a complex subsystem has a great number of attached cables. MIL-STD-462D (and subsequent versions of MIL-STD-461 that rolled MIL-STD-462D into MIL-STD-461) requires that the cable closest to the front edge of the ground plane be 10 cm back from the edge, and then 2 cm between each succeeding cable and the last.[18] With enough attached cables, the ground plane may not provide enough depth. It is often asked if the first cable may be pushed closer to the edge to free up some room. Or is it better to bunch cables closer than 2 cm separation?

Another question less often posed is if the installation is known to hold cables much closer to the structure than 5 cm, can the test set-up simulate that?

The closer that first cable is to the ground plane edge, the more efficiently it radiates (RE102), and the more efficiently a radiated field can couple to it (RS103) – hence the need for standardization. As illustrated in Figures 2 and 3, the separation of cables on standoffs holding them 2” (now 5 cm) above a ground plane is first found in MIL-I-6181B. Previously in JAN-I-225 (and thus MIL-I-6181 which relied on JAN-I-225 for test procedures) it was a quarter-inch over the ground plane. Separation between cables was also 2”, but that has decreased to 2 cm in MIL-STD-461. For a “seeing is believing” demonstration of the reason behind the cable-to-cable separation requirement, see https://youtu.be/uiyLQpsOqX8. Armed with this information, the reader may now make informed decisions.

## EVOLUTION OF CONDUCTED EMISSION LIMITS*

As evidenced in the above-cited YouTube video, the BC-348 radio had very little EMI filtering on its 28 Vdc power input and was susceptible to very low levels of RF noise on its power input. MIL-I-6181B conducted emission limits protecting the BC-348 radio are portrayed in Figure 5, with the superseding CE03 limits superimposed. MIL-I-6181B imposed a value of 1 mV for conducted susceptibility. This level increased to 100 mV in subsequent releases of MIL-I-6181, and then up to 1 volt in MIL-STD-461.


Figure 4: The author's unaltered BC-348Q radio, the specific radio model whose performance characteristics drove the emissions and susceptibility requirements in MIL-I-6181B below 20 MHz. The photo shows a noisy but audible response to a 1 kHz modulated radio frequency signal at a level of – 3 dBuV. (Photo courtesy of the Museum of EMC Antiquities.)

These measures were taken to gradually force improvement in power-line EMI filtering. At the same time, the very stringent conducted emission limits found in MIL-I-6181B had to be levied to protect the existing inventory of installed radios with little or no power-line filtering. As time went by, these stringent conducted emission limits were relaxed as the inventory of obsolete susceptible receivers declined, being replaced by receivers that met the higher level conducted susceptibility limits.

But the conducted emission limits could not be relaxed as much as the conducted susceptibility limits had strengthened, because conducted emissions cause radiated emissions, and radiated emissions must be controlled to protect antenna-connected receivers. The narrowband CE limit in radio bands were relaxed to about 1 mV, where the -6181B conducted susceptibility started out. This amounted to at most a 26 dB relaxation. Paradoxically, the broadband limit became more stringent. The MIL-I-6181B broadband limit protected the 2 kHz BC-348 radio bandwidth. Later broadband limits protected wider bandwidths.

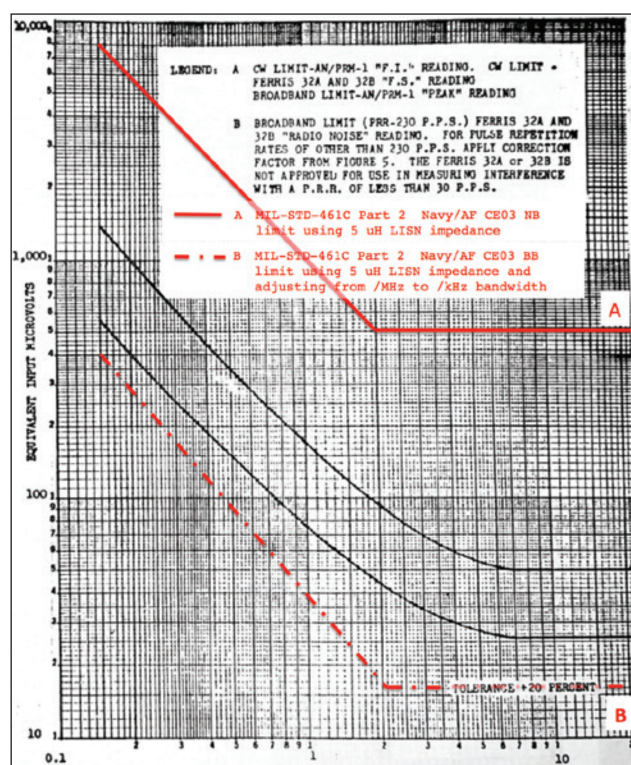



Figure 5: MIL-I-6181B conducted emission limits, with superimposed MIL-STD-461 CE03 limits.

## CONTROLLING RADIATED EMISSIONS – THE SCIENCE OF NEAR-FIELD MEASUREMENTS*

A huge advance in -6181B is described in detail in NADC-EL-5515. This is the concept that, when making near-field measurements, the way the measurement is made materially affects the result. The type of antenna, its physical size, orientation, and distance from the test sample all bear strongly on the measured test result. While this may seem obvious, earlier specifications allowed the use of various different antennas or pickup devices. This topic is complex, important, pertinent, and applicable to present practice in making radiated emissions measurements. As such, it merits its own separate treatment, which will be discussed in "(Re)Discovering the Lost Science of Near Field Measurements."

## CONTROLLING AMBIENT LEVELS TO 6 DB BELOW THE EMISSION LIMIT*

Prior to MIL-I-6181B, the ambient level was required to be 14 dB below the emission limit.[19] With very low emission limits to begin with, this was very onerous.[20] The 6 dB requirement has a good rationale: a signal that would be measured right at the limit with a very low ambient is boosted by 1 dB when the ambient is 6 dB below the limit. That makes the -6 dB ambient limit a well-justified line in the sand. All that being said, when making a post-1993 MIL-STD-461/2 measurement system integrity check, the measurement system noise floor needs to be closer to 14 dB below the limit than 6 dB below the limit, because the measurement system integrity check is done at 6 dB below the limit. But that is noise floor vs. ambient, two very different quantities.

## THE FIRST APPEARANCE OF AN AUDIO FREQUENCY CONDUCTED SUSCEPTIBILITY REQUIREMENT

A novel requirement in -6181B is the forerunner of modern audio frequency conducted susceptibility testing. This requirement and test method is the direct ancestor of MIL-STD-461 CS01/CS101, RTCA/DO-160 section 18 (commercial aerospace), and ISO-11452-10 (automotive). The test method did not utilize an audio amplifier. Instead, MIL-I-6181B used a signal source with 500 Ω output impedance driving a filament transformer (line voltage in, 6.3 Vac out, so about 20:1 turns ratio) to yield an output impedance of around 1 Ω.[21] This was further finessed down to 0.5 Ω in the 1957 MIL-I-6181C revision, where the modern treatment using a low impedance amplifier or power oscillator first appears.

## THE FIRST APPEARANCE OF ANTENNA PORT EMI CONTROLS

Two antenna-port requirements first appear in MIL-I-6181B. These are filtering for the front end to improve out-of-band rejection (modern equivalents MIL-STD-461 CS103/104/105), and suppression of noise emanating from antenna ports (modern equivalent MIL-STD-461 CE106). Consider recent events where front-end filtering has not been applied. The GPS-Light

It is the author's hope that this trip down memory lane inspires aspiring EMC engineers to study their craft and more fully understand it, as opposed to just copying the requirements of the last program, on the basis of not reinventing the wheel.

Squared and FCC/FAA 5G vs. radar altimeter operation brouhahas are examples of what can happen, and these did not involve co-located radios and antennas on the same vehicle.

## EVOLUTION*

Many of the requirements in present-day standards with which the reader may be familiar have their origin in MIL-I-6181B but have evolved over time to look quite different. One such requirement is radiated (electric field) susceptibility. The evolution of this requirement is traced in detail in the unabridged website version. In particular, one can trace the audio frequency amplitude modulation requirements universally used today for any sort of electronics being EMI-qualified to requirements specifically applicable to amplitude-modulated radio receivers.

## CONCLUSION

It is the author's hope that this trip down memory lane inspires aspiring EMC engineers to study their craft and more fully understand it, as opposed to just copying the requirements of the last program, on the basis of not reinventing the wheel. For more information, search the unabridged version of this article on the author's website. Look for more information on the origin and use of LISNs in Part 2, and (much) more detail on radiated emissions measurements in subsequent parts. In any case, we should understand the principle behind the wheels we use. Or, as a senior engineer used to tell the author when he was young, "You've got to be smarter than what you're working on."

## ACKNOWLEDGMENTS

The author wishes the thank reviewers for their time and effort in making this article useful. Any errors of omission or commission are the author's own.

## NOTES AND REFERENCES

1. Explanatory note adapted from "EMI vs. EMC: What's in an Acronym," *In Compliance Magazine*, February 2014. Much more on the topic of how equipment EMI qualification relates to vehicle self-compatibility (EMC) demonstration may be found there.
2. All specifications/standards/books/handbooks referenced in this article are available at http://www.emccompliance.com or on request from the author.
3. The term "radio" as used in this article is shorthand for "antenna-connected receiver" meaning a device designed to receive information wirelessly over the airwaves. This includes voice and data radios, but also navigational aids, radar, and anything designed to connect to an antenna.
4. See Reference 2
5. MIL-I-6181B, Interference Limits, Tests and Design Requirements, Aircraft Electrical and Electronic Equipment, 29 May 1953
6. NADC-EL-5515, Final Report, Evaluation of Radio Interference Pick-Up Devices and Explanation of the Methods and Limits of Specification No. MIL-I-6181B, 10 August 1955
7. Much of the historical content was sifted from the author's earlier handbook, namely, "Introduction to the Control of Electromagnetic Interference," *EMC Compliance*, 1993.
8. For a detailed explanation of the difference between a specification or standard controlling electromagnetic interference vs. one controlling electromagnetic compatibility, see "EMI vs. EMC, What's in an Acronym," in the February 2014 issue of this magazine.
9. JAN-I-225, Interference Measurement, Radio, Methods Of, 150 Kilocycles to 20 Megacycle (For Components and Complete Assemblies), 14 June 1945
10. Insight into the times just prior to the adoption of MIL-STD-461 and -462 is found at White, Donald R. J. "A Handbook on Methods and Procedures for Automating RFI/EMI Measurements," White Electromagnetics, Inc. Rockville, MD, 1966. White was a pillar of the EMC community at a time when he was about the only pillar.

11. The reader may well ask what happened to MIL-I-6181A. It was released 23 January 1953, just four months prior to "B." The author has never found a copy, which is not surprising given the short lifespan. Some of the changes in "B" vs. the original release of MIL-I-6181 may have appeared in "A," but there is no way to know for sure. One may infer from the release of "B" four months after "A" that the "B" revision was quite comprehensive in scope, and further, we know from NADC-EL-5515 that the radiated emission portion was new for "B."
12. MIL-I-6181, Interference Limits and Tests: Aircraft Electrical and Electronic Equipment, 14 June 1950
13. Functionally, a slide-back peak detector may be thought of as a comparator circuit. One input is the detected (demodulated) signal envelope, and the other is a dc level derived from a potentiometer. The potentiometer is adjusted until the dc input to the comparator is at precisely the same level as the peak of the demodulated pulse train. At that point, no audio can be detected, and the dc level drives the meter deflection. In this way, peak detection is entirely independent of pulse repetition rate and duty cycle.
14. Parker, A. T. "A Brief History of EMI Specifications," presented at the 1992 IEEE EMC Symposium.
15. 12R2-3BC-112, Technical Order, Maintenance Instructions, Radio Receivers BC-224 & BC-348, 20 July 1945. Section IV, Theory of Operation, paragraph 3b, gives bandwidth information.
16. Instruction Book, Radio Noise and Field Strength Meter Ferris Model 32-B, Ferris Instrument Company, Boonton, NJ undated but no earlier than 1947. General Theory and Description section D Frequency Range, page 4.
17. The proper way to do it in the age of semi-automated receivers (for MIL-STD-461 prior to "D") is well described in an application note on the topic authored by Mr. John Zentner, retired from Wright Patterson Air Force Base. Mr. Zentner was the guiding technical force behind much of what became MIL-STD-461D and -462D. See ASD/ENA-TR-80, Identification of Broadband and Narrowband Emissions, 01 May 1980.
18. MIL-STD-462, Electromagnetic Interference Characteristics, Measurement of, 31 July 1967, and MIL-STD-462D, Measurement of Electromagnetic Interference Characteristics, 11 January 1993. A little remarked but quite significant change between these two successive standards (no B or C releases) is that the original requires "all leads and cables shall be within 10 +/- 2 cm from the edge of the ground plane…" The "D" revision requires just the opposite: "… the cable closest to the front boundary shall be placed 10 centimeters from the front edge of the ground plane." The original release acts to maximize radiated emissions and susceptibility, while the "D" revision acts to put an upper bound on both.
19. See Reference 9.
20. See Reference 12.
21. For mains frequencies (60 & 400 Hz), a 500 Ω resistor was inserted between the mains source and the filament transformer. At other frequencies, the HP 205A audio oscillator could be configured with a suitable output and a 500 Ω output impedance: Hewlett-Packard Operating and Service Manual, Audio Signal Generator Models 205A and 205AG, copyright 1955.


# Line Impedance Stabilization is in its Seventieth Year and Still Going Strong

## What a Long, Strange Trip It's Been…

*By Ken Javor*

### INTRODUCTION[1]

Seventy years ago in May, the 5 microhenry line impedance stabilization network (LISN) made its debut in MIL-I-6181B.[2] Aside from the EMI receiver itself, the LISN is one of the oldest and most successful pieces of EMI test equipment in existence. And while EMI receivers have changed a great deal since 1953 (see images in last month's MIL-I-6181B anniversary article),[3] the 5 uH LISN is not only still with us, but almost unchanged and used in commercial aviation and the automotive industry, as well as military applications worldwide.[4] Other LISNs have come and gone, and others are with us still. The way we use LISNs has changed over time, not always for the better. But the LISN is here to stay in the world of EMI testing.

### IN THE BEGINNING

Radio receivers used on WWII Army aircraft were quite susceptible to very low levels of noise on their primary (28 Vdc) power input. Further, unshielded antenna lead-ins (see Reference 3) were very susceptible to capacitive crosstalk from noisy 28 Vdc electrical power feeds.

The first EMI standards tried to control both these radio frequency interferences (RFI) coupling paths. Prior to 1953, JAN-I-225[5] used a pair of 4 uF bypass capacitors in shunt (8 uF total capacity between power feeder and ground plane) and a 10' length of power wire suspended not more than ¼" from the ground plane for what they called power supply stabilization (see Figure 1 on page 60). Because these receivers tuned from 0.15 to 20 MHz, JAN-I-225 conducted and radiated emission measurements covered that same range. The resonant frequency of the 10' wiring and 8 uF capacity occurred below the test frequency range, so that the impedance looking back into the capacitors through 10' of wiring was inductive in character.

JAN-I-225 was superseded in 1953 by MIL-I-6181B, which included both required impedance (Figure 2 on page 60) and construction drawings (Figure 3 on page 61 for the 5 uH LISN. These same drawings, with two minor tweaks, appeared in RTCA/DO-160 for commercial aircraft avionics, up to 1989.[6] After that, they required the extended impedance control as in DEF STAN 59-411, but don't include the construction details of DEF STAN 59-411. The two tweaks already appeared in MIL-I-6181C[7] which replaced MIL-I-6181B in

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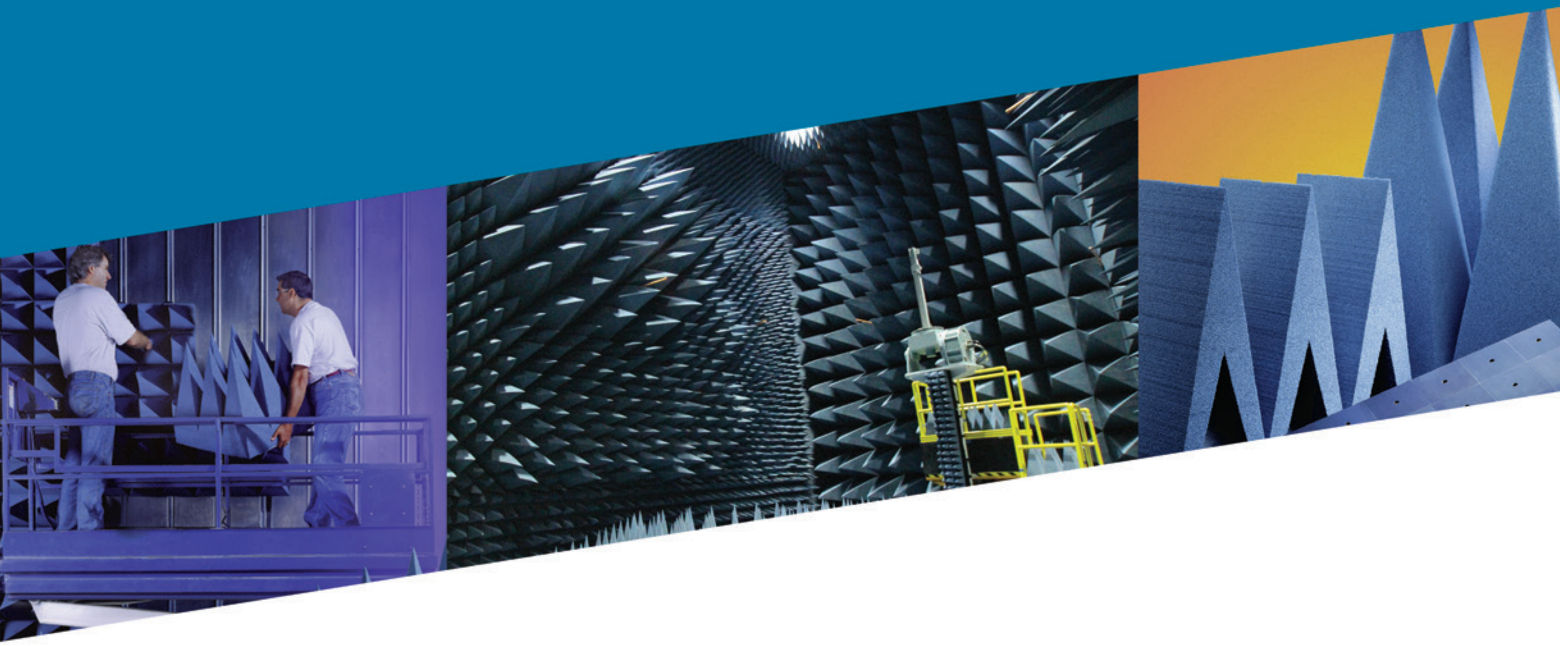


1957: a 1 kΩ bleeder resistor from the EMI port center conductor to case and the removal of the 1 Ω resistor in series with the input side 1 uF filter capacitor.

The upper frequency of the controlled impedance bounced around some over the years. MIL-I-6181B has it at 25 MHz, as does MIL-I-6181D[8] (1959), but the intervening "C" in 1957 pushed it out to 100 MHz. It had settled down to 30 MHz in most specifications and standards, as that was the upper limit for conducted emissions and radiated emissions with the rod antenna. But in the past few decades, various specifications have pushed the upper end as far up as 400 MHz for rf conducted susceptibility, and the automotive world (CISPR 25[9]) has pushed it to 100 MHz for conducted emissions.

It would surely be gratifying for the originator of the 5 uH LISN to know that his work has gained this much success and acceptance worldwide. Who was this person, and how did the 5 uH LISN come about in the first place? We are indebted to A. T. Parker (1915 – 2000), for the following historical snippet. In 1960, Parker founded Solar Electronics, a designer and supplier of EMI test equipment. Previously he had worked at the Stoddart Aircraft Radio Company, which was the company that produced the first commercial 5 uH LISN. In Parker's own words:

> *"Early in WW2, an aircraft propulsion engineer named Alan Watton working for the Air Corp was concerned about the r.f., being conducted along wiring in a military aircraft of the Douglas DC-3 type. He devised the first Line Impedance Stabilization Network which simulated the impedance of the d.c. power leads in the aircraft. It used a five microhenry choke and a means for coupling voltages developed across this inductance to a 50-ohm receiver over the frequency range 150 KHz to 25 MHz."*[10]

This is all that Parker has to say about its inception, but there are additional facts and deductions that apply.

The DC-3 (military version C-47 "Skytrain") was all aluminum. Aluminum aircraft return current on structure, except where inductance causes excessive voltage drop. No such problem occurs with dc power. Electrical power was from engine-mounted generators. Engine centerlines were about three meters from the aircraft centerline. Thus, using a nominal value, such as one microhenry per meter for a wire suspended above a ground plane, 5 uH seems a reasonable value if the measurement was taken in the cockpit-mounted breaker boxes, which act as the point of distribution for electrical power in the aircraft.

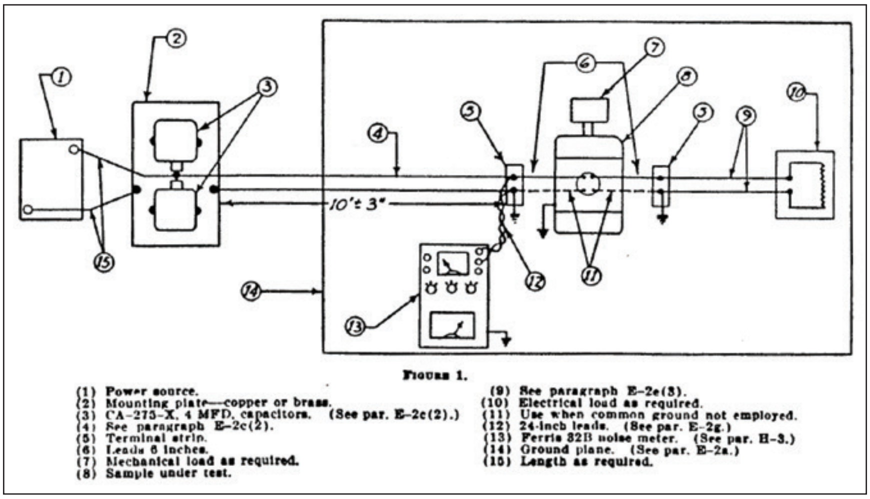



Figure 1: JAN-I-225 EMI test set-up, showing details of how line impedance stabilization was achieved without a "LISN in a box."

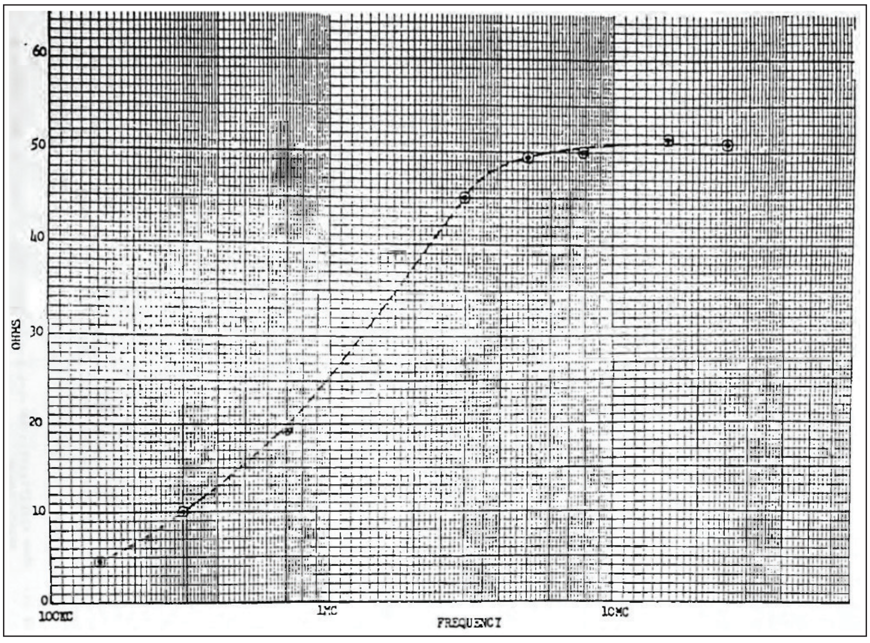



Figure 2: MIL-I-6181B 5 uH LISN impedance plot

This point is critical. People often assume that a LISN represents the impedance the test sample sees as installed in the platform. But this is not the case.[11] As shown in Figure 4, a LISN simulates the common bus impedance seen by all loads, so that noise currents drawn by a culprit load, acting through the common bus impedance, generates a noise potential inflicted on all other victim loads.

It is specifically this property of a LISN that allowed it to be used in MIL-I-6181B through "D" (the last revision prior to MIL-STD-461) in mirror image roles when measuring conducted emissions (Figure 5 on page 62) and conducted susceptibility (Figure 6 on page 62).

## AS TIME GOES BY

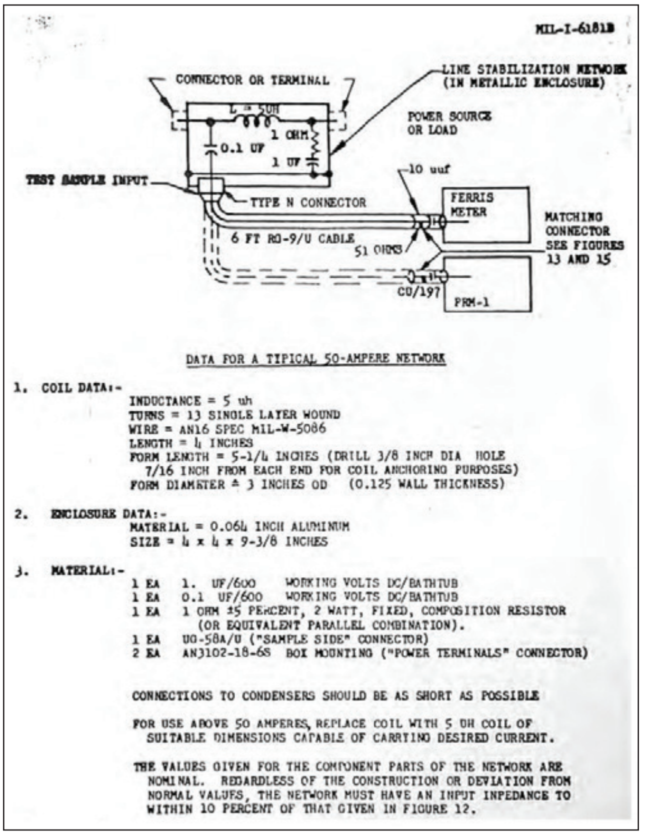
In all versions of MIL-I-6181B-D, a LISN is inserted in each power feeder, ac or dc. The return is always through the ground plane. But Navy ships never return current on structure, and Navy EMI specification MIL-I-16910A[12] reflected that practice, inserting a 5 uH LISN in both feeder and return.

When all the Service- and platform-specific EMI specifications released prior to 1967 were superseded by the Tri-Service EMI standards MIL-STD-461[13] and MIL-STD-462,[14] it was the Navy practice of inserting line impedance stabilization in each power conductor that was adopted for Tri-Service use. That is, instead of running return current back through the ground plane, it is returned through a wire and LISN instead.

This has several problematical consequences that reverberate down to the present day. But before delving into that issue, we should note that MIL-STD-461 and MIL-STD-462 1967 releases followed a new practice introduced in MIL-STD-826,[15] replacing the 5 uH LISN with a 10-microfarad feed-through capacitor. This then became the standard practice for a quarter-century, until MIL-STD-461D[16] and MIL-STD-462D[17] reinstated rf potential instead of current control. This necessitated a LISN again, albeit now a 50 uH LISN in lieu of the original 5 uH LISN, for reasons related further on.

We return once again to Mr. Parker for the rationale behind current measurements in lieu of measuring rf potential across a LISN.[18] This is follow-on to the material quoted earlier from Reference 10.

> *"So the Line Impedance Stabilization Network (LISN) was born. It was a pretty good simulation of that particular aircraft and the electrical systems it included. But then*




DATA FOR A TIPICAL 50-AMPERE NETWORK

1. COIL DATA:-
INDUCTANCE = 5 uh
TURNS = 13 SINGLE LAYER WOUND
WIRE = AN16 SPEC MIL-W-5086
LENGTH = 4 INCHES
FORM LENGTH = 5-1/4 INCHES (DRILL 3/8 INCH DIA HOLE 7/16 INCH FROM EACH END FOR COIL ANCHORING PURPOSES)
FORM DIAMETER ≐ 3 INCHES OD (0.125 WALL THICKNESS)

2. ENCLOSURE DATA:-
MATERIAL = 0.064 INCH ALUMINUM
SIZE = 4 x 4 x 9-3/8 INCHES

3. MATERIAL:-
1 EA 1. UF/600 WORKING VOLTS DC/BATHTUB
1 EA 0.1 UF/600 WORKING VOLTS DC/BATHTUB
1 EA 1 OHM ±5 PERCENT, 2 WATT, FIXED, COMPOSITION RESISTOR (OR EQUIVALENT PARALLEL COMBINATION).
1 EA UG-58A/U ("SAMPLE SIDE" CONNECTOR)
2 EA AN3102-18-6S BOX MOUNTING ("POWER TERMINALS" CONNECTOR)

CONNECTIONS TO CONDENSERS SHOULD BE AS SHORT AS POSSIBLE

FOR USE ABOVE 50 AMPERES, REPLACE COIL WITH 5 UH COIL OF SUITABLE DIMENSIONS CAPABLE OF CARRYING DESIRED CURRENT.

THE VALUES GIVEN FOR THE COMPONENT PARTS OF THE NETWORK ARE NOMINAL. REGARDLESS OF THE CONSTRUCTION OR DEVIATION FROM NORMAL VALUES, THE NETWORK MUST HAVE AN INPUT IMPEDANCE TO WITHIN 10 PERCENT OF THAT GIVEN IN FIGURE 12.

Figure 3: LISN construction details in MIL-I-6181B

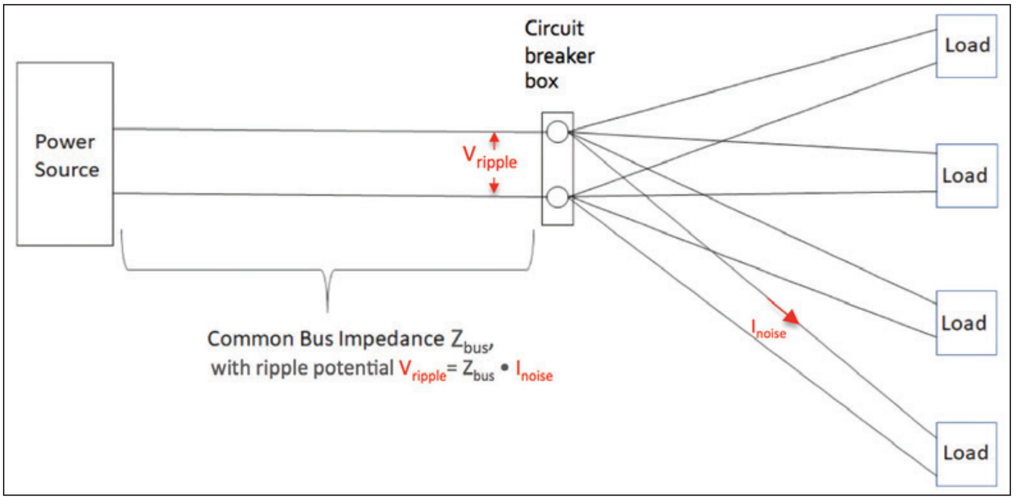



Figure 4: A LISN simulates the common bus impedance, not power source-to-load impedance.

*someone arbitrarily decided to use this artificial impedance to represent* ***any*** *power line.*

*"At any rate, this impedance suddenly began appearing in specifications which demanded its use in each ungrounded power line for determining the conducted EMI (then known as RFI) voltage generated by any kind of a gadget. The resulting test data, it was argued, allowed the government to directly compare measured RFI/EMI voltages from different test samples and different test laboratories.*

*"No one was concerned about the fact that filtering devised for suppressing the test sample was based on this artificial impedance in order to pass the requirements, but that the same filter might have no relation to reality when used with the test sample in its normal power line connection.*

*"Not until 1947, that is. At that time, this same Alan Watton, a propulsion engineer having no connection with the RFI/EMI business, decided to rectify the comedy of errors which had misapplied his original brainchild. He was in a position to place a small R and D contract with Stoddart for the development of two probes; a current measuring probe and a voltage measuring probe. Obviously, he felt that one needed to know at least two parameters for a true understanding of conducted interference...*[19]

*"As it turned out, Stoddart was successful in developing a current probe based on Alan Watton's suggestions regarding the toroidal transformer approach which is still the primary basis used today. However, the development of the voltage measurement probe suffered for lack of sensitivity. Watton's hope had been to provide a high impedance voltage probe with better sensitivity than was then available for measurement receivers designed for rod antennas and 50-ohm inputs. Since this effort failed and Watton's funds (and probably his interest in the subject) faded out of the picture, the program came to a halt.*

*"This meant that the RFI/EMI engineer could either measure EMI voltage across an artificial impedance which varied with frequency, or he could measure EMI current flowing through a circuit of unknown r.f. impedance. Either way, the whole story is not known. In spite of the unknown impedance, the military specifications began picking up the idea of measuring EMI current instead of voltage…"*

One may infer that what Watton was after was a Thévenin-like model of the test sample: "open circuit" output rf potential and short-circuit rf current. By this

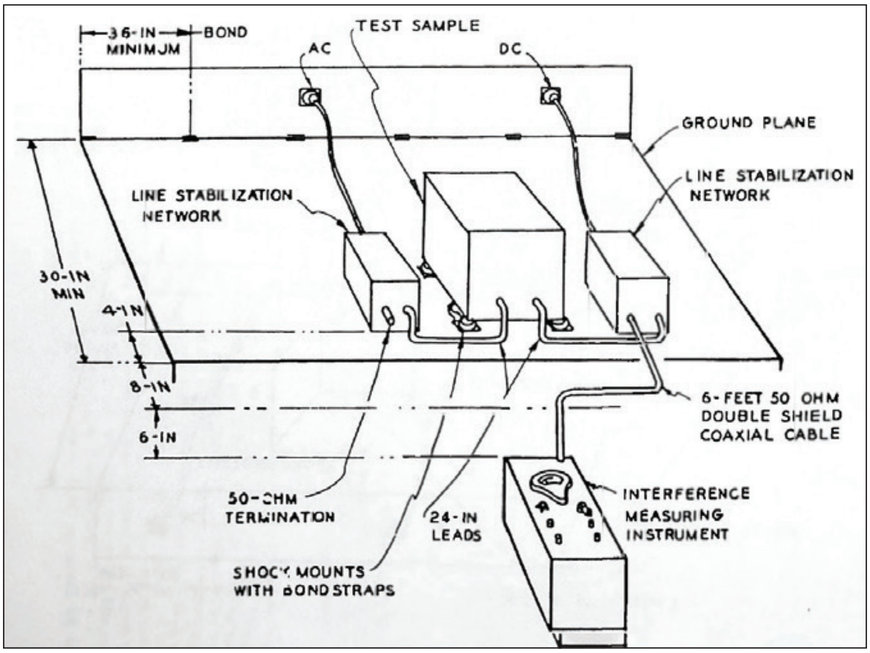



Figure 5: MIL-I-6181B conducted emission set-up (figure actually copied from MIL-I-6181C, because easier to see what is going on for instructional purposes).

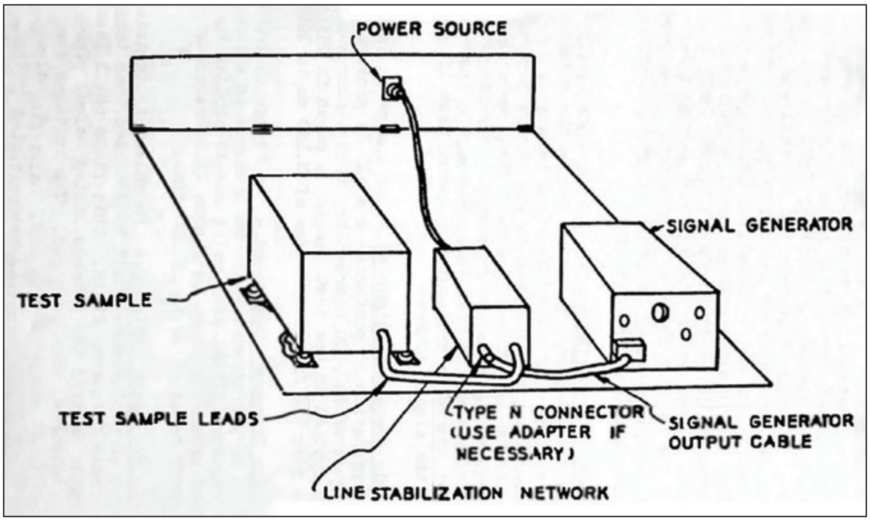



Figure 6: MIL-I-6181B conducted susceptibility set-up (figure actually copied from MIL-I-6181C, because easier to see what is going on for instructional purposes).

means, one could then predict noise potentials and currents into any arbitrary power source impedance. This interpretation is bolstered by material in the appendix of MIL-STD-462D:

> *"The (LISN) impedance is standardized to represent expected impedances in actual installations and to ensure consistent results between different test agencies. Previous versions of MIL-STD-462 used 10 microfarad feedthrough capacitors on the power leads. The intent of these devices was to determine the current generator portion of a Norton current source model. If the impedance of the interference source were also known, the interference potential of the source could be analytically determined for particular circumstances in the installation. A requirement was never established for measuring the impedance portion of the source model. More importantly, concerns arose over the test configuration influencing the design of power-line filtering. Optimized filters are designed based on knowledge of both source and load impedances. Significantly different filter designs will result for the 10-microfarad capacitor loading versus the impedance loading shown in Figure 7 of the main body." (Author's note: Figure 7 in MIL-STD-462D shows the impedance of the 50 uH LISN.)*

The concern over designing an EMI filter for a specific (but different) source impedance is of the same type that Watton was concerned about a half-century earlier.

The more things change, the more they stay the same!

Completing our "as time goes by theme," it is worth noting why MIL-STD-462D went with a 50 uH LISN instead of the 5 uH LISN. In fact, the original proposal for MIL-STD-462D going in was the 5 uH LISN. The same section of the MIL-STD-462D appendix says,

> *"A specific 50 microhenry LISN was selected to maintain a standardized control on the impedance as low as 10 kHz."*

The low frequency end of the 5 uH LISN is 150 kHz. The desire to begin making rf potential measurements well below 150 kHz nixed the selection of the 5 uH LISN. In turn, the reason for wanting to make rf potential measurements down to audio frequencies was based on the previous quarter-century of making CE03 measurements down to audio frequencies. They wanted the break between CE101 and CE102 to be roughly the same as between CE01 and CE03. None of which is to say that the 50 uH LISN is a better simulation of most vehicle electrical bus impedances…

## SIMPLE THINGS BECOME COMPLICATED[20]

From MIL-STD-826 (1964) forward, the practice of placing an impedance stabilizing device in each ungrounded power lead (both feeder and return) resulted in at best questionably useful data. When a single device is used, the measured rf potential or current is simply that in the loop comprised of LISN, power feeder, load (test sample), and ground plane. Using two such devices result in measuring vector sums of differential mode (dm) and common mode (cm) currents/potentials.

Figures 7a and 7b show differential and common mode current paths when current returns above structure on a dedicated ground wire – i.e., isolated from chassis ground within the test sample. Inspection of Figures 7a and 7b indicates that, when there is an above ground current return path, differential and common mode currents sum in the feeder, but subtract in the return, as indicated in Figure 7c. Figure 7d shows how all current, regardless of the current-generating mechanism, is constrained to flow in the same path in the original structure return 5 uH LISN configuration.

This means that with above ground current return, as shown in Figure 7c, measured single line currents or rf potentials look similar but not identical. The traces are identical for feeder and return when one or the other mode dominates, but where they are of similar amplitude and add on the feeder and subtract on the return, they differ. Separation of cm and dm modes to assist filter design has been a topic of interest since the late 1970s.[21,22,23]

It is of note that in most standards, if there is any question as to how power current

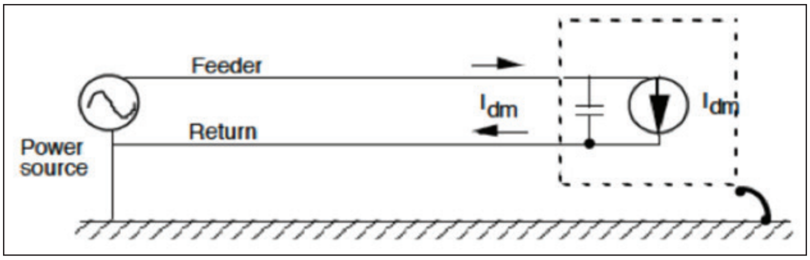



Figure 7a: Differential mode current path

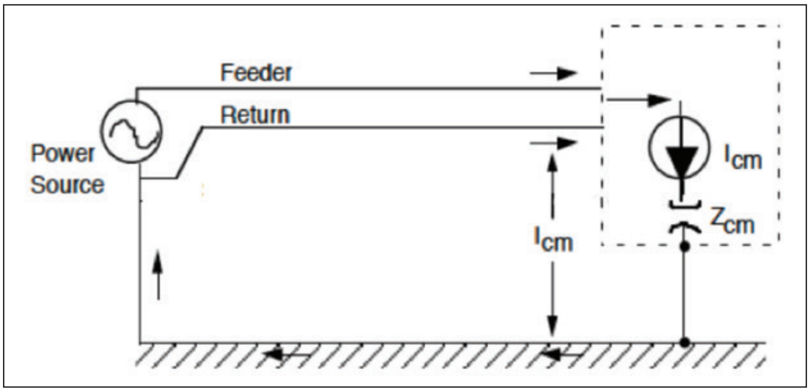



Figure 7b: Common mode current path

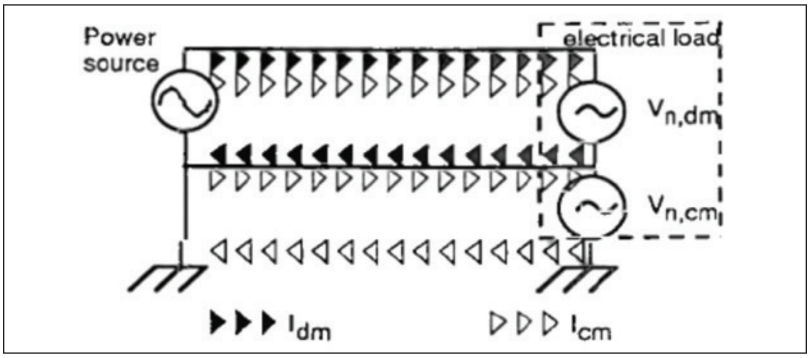



Figure 7c: CM & DM currents adding and subtracting in feeder and return

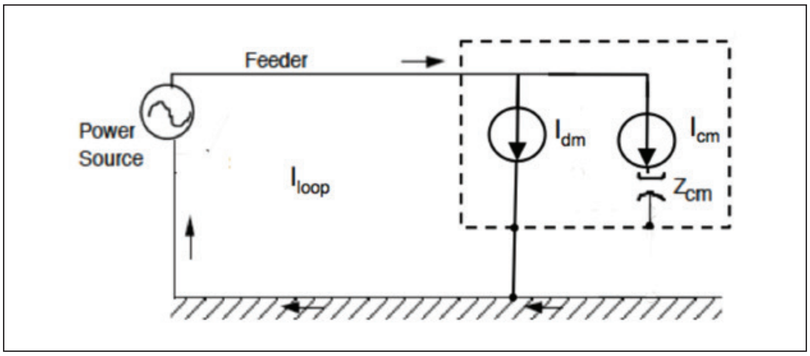



Figure 7d: All noise currents flow in the same path when structure is the return path.

will return (structure or dedicated wire), the default test method is to use a pair of LISNs and measure the vector sums and differences of common and differential mode signals on each LISN separately. It is not obvious why this is the go-to default. Particularly for radiated emissions, this technique decreases the radiation efficiency of the differential mode component of the composite noise (especially if, as is common, the wire pair is twisted). Figure 7d makes it clear that using a single LISN keeps the radiation efficiency of each mode identical.

When we know that current will be returned on a dedicated wire, not on structure, a better technique than controlling emissions on each individual lead is controlling emissions by mode. Separating modes may be done directly off the LISN (References 20 – 22) or using current probes. Regardless, if we control emissions via mode, not line, we can then assign limits based on what the modes actually affect:

- Differential mode noise currents cause ripple, and
- Common mode currents cause radiated emissions

Therefore, when the feeder and return wires are twisted or held tightly together throughout the vehicle, it is reasonable to relax the differential mode limit compared to the common mode limit. Even if no radios operate in the conducted emission frequency range, it may be worthwhile to control common mode emissions to limit crosstalk to adjacently placed cables that might carry potentially susceptible low level signals.[24]

A concrete and illuminating example of the problem of LISN misuse may be found in a report by the author dating to the late 1990s.[25] This report showed that the (now obsolete) FCC Class B 48 dBuV conducted emission limit was in fact 20 dB too stringent for differential mode noise but was precisely correct for common mode noise. The problem arose because the original work done to establish the 48 dBuV limit was performed using a single 5 uH LISN, but the FCC test method was based on a pair of (50 uH) LISNs.[26] It was not the disparity in the LISN impedance but the mode separation inherent in a pair of LISNs that demonstrated the disparity.

Another modern confusion is using long power leads between the LISN and test sample. Such values range from one meter (for conducted emissions) in MIL-STD-462 (1967 – 1993), 2 – 2.5 meters in MIL-STD-462D and follow-on versions of MIL-STD-461, one meter in RTCA/DO-160, and 1.5 meters in CISPR 25. By way of contrast, the specified length in MIL-I-6181B was 24 inches.

To echo Parker about the comedy of errors, and intentionally misquote Gall's Law, "A complex system that works poorly is invariably found to have evolved from a simple system that worked well."

Consider the ramifications with respect to measurement uncertainty. First, MIL-I-6181B conducted emission limits stopped at 20 MHz. The electrical length of a 24" long wire at 20 MHz is a twenty-fifth wavelength. VSWR will be negligible, and therefore the LISN does in fact control the power source impedance seen by the test sample. MIL-STD-462D and follow-on MIL-STD-461 versions using a 2.5-meter-long power lead and 10 MHz upper CE102 limit frequency come in at less than a tenth-wavelength, so the LISN controls the power source impedance.

But look at specifications such as RTCA/DO-160 and DEF STAN 59-411, with 400 MHz LISNs and 100 MHz conducted emission control. A one-meter-long power lead is a third wavelength at 100 MHz. And for CISPR 25, using a two-meter-long power wire, the LISN is over a half-wavelength from the test sample. All the work and expense that went into the extended frequency range LISN is wasted when the parasitics controlled within the LISN is simply migrated to the LISN – test sample interconnection.[27]

## CONCLUSION

Alan Watton bequeathed us a great gift some seventy years ago. It is up to us to use it wisely, and well. To echo Parker about the comedy of errors, and intentionally misquote Gall's Law, "A complex system that works poorly is invariably found to have evolved from a simple system that worked well."

## ACKNOWLEDGMENTS

The author wishes to thank the reviewers for their time and effort in making this article useful. Any errors of omission or commission are the author's own.

## ENDNOTES

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3. Javor, K. "Seventy Years of Electromagnetic Interference Control in Planes, Trains and Automobiles (and Ships and Spaceships, as well)," *In Compliance Magazine*, May 2023.
4. Ministry of Defence Standard 59-411 and the older 59-41 all use a modification of the 5 uH LISN.

   The modification extends the frequency range of controlled impedance down to 1 kHz and up to 400 MHz. It is less than obvious why the LISN impedance needs to be controlled to 400 MHz when it is placed several meters from the test sample. The mismatch between power wire transmission line characteristic impedance and the 50 Ω LISN is always going to generate reflections, no matter how well the LISN impedance is controlled. If it is desired to have true impedance control, the LISN needs to be within a tenth-wavelength of the test sample power input. A 10 uF feedthrough capacitor would function admirably so used, at a tenth the cost of the 400 MHz LISN.
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11. Some exceptions that prove the rule are many spacecraft line impedance simulation networks that appear to be designed to include the dedicated wiring

to the test sample itself. See the line impedance simulation section of older print Solar catalogs (they no longer supply spacecraft LISNs, so the on-line catalog is of no value here). Pay special attention to the series resistance value. Values above a few tens of milliohms mean they are simulating the entire power distribution network, not the main bus. As Mr. Parker said in his catalogs, in his gentlemanly way, "Spacecraft designers do not always agree on the characteristics of the d.c. power source aboard the vehicle. The inductance in series with the load, the resistance across the inductor, and the series resistance in each leg of the unit are variables specified by different spacecraft engineers."

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27. MIL-STD-462 (1967) had a unique approach to this conundrum. It specified one-meter-long wires for conducted tests, and two-meter-long wires for radiated. The only problem with that approach was not enough people followed directions; opting for one or the other length for both conducted and radiated measurements. The end result was that when the "D" revisions came along, they "dumbed down" the standard to one length optimized for radiated and reduced the conducted frequency range accordingly. Hence the 10 MHz upper limit for conducted emission control, unique amongst conducted emission limits. The goal for standardized test results outweighed the desire to control conducted emissions out to the traditional 30 MHz.

# ESD Designers' Headache With Multiple Automotive Test Requirements, Part 1

## A Review of ESD-EMC Co-Design Challenges

*By Gianluca Boselli*

The trend toward society's "smart-electrification" is driving the need for ESD immunity at the system-level. IEC 61000-4-2 [1] defines how to perform the electrostatic discharge immunity test at the system level. Until about 15 years ago, protecting against such events involved implementing ad-hoc ESD protections (TVS – transient voltage suppressors) at board/system-level in proximity to the connectors interfacing with the "external world."

However, a new trend of implementing system-level robustness at the component level (i.e., on-chip) is quickly becoming standard practice, mainly stemming from the desire to reduce system/board design costs.

While this may sound like a logical step on paper, it poses enormous challenges to the component ESD designer in that:

- IEC 61000-4-2 is not applicable at the component level, so every company is struggling to understand/design proprietary characterization methods at the component level to extrapolate performance at system-level; and
- ESD designers are now responsible for the performance of systems that they neither build nor, in many cases, know anything about.

In the automotive world, the situation is even more challenging. In addition to ESD immunity at the system level (ISO 10605 [2], adapted from IEC 61000-4-2), there is a plethora of other requirements addressing immunity to both electrical disturbances (ISO 7637 [3, 4, 5]) and to RF disturbances (IEC 62132 [6]) that must be met.

This article is divided into two parts. This first part addresses the ESD design challenges stemming from ISO 10605 specs, while the second part will review the trade-offs between ESD design and EMC immunity requirements.

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## AUTOMOTIVE SYSTEM-LEVEL (ISO 10605) ESD DESIGN CHALLENGES

To address the demand for area-competitive on-chip IEC ESD Solutions (with targets in excess of 30A for Level-4 spec), the implementation of an SCR-based protection scheme is a must. Thanks to its low holding voltage, this solution is extremely advantageous in terms of power dissipation. However, this may come at a cost of a large swing between triggering voltage and holding voltage, which may cause non-uniform current conduction and render the solution ineffective. This will play a role in the specific differences between IEC 61000-4-2 and ISO 10605 from an ESD design perspective.

### Different R&C Modules to Be Tested

ISO 10605 specifies four different RC combinations (R=330Ω, R=1.5KΩ, C=150pF, and 330pF), leading to pulse decay times ranging from 60ns to 600ns. The actual RC combination(s) required at the board/system level may not be known at the time of component design. The straightforward consequence is that the ESD designer needs to validate the ESD solution on all four stress waveforms, with completely different pulse widths, energy contents, and rise times.

In [7], it was reported that an HV SCR meeting IEC Level 4 requirements (corresponding to ISO with R = 330Ω, and C = 150pF) miserably failed all other ISO stress permutations with larger capacitance and resistors. The root cause was identified in the lack of power scalability of the HV SCR caused by a static filament formation for pulses in excess of 100ns. A first-order correlation between TLP stress duration and ISO level was also established (see Figure 1 [7]).

To meet the performance target, a new architecture had to be devised with the obvious delay in product development efforts. A similar issue (i.e., lack of correlation between TLP and ISO test with R=1.5K Ω) was also reported in [8].

| | R=330Ω C=150pF | R=330Ω C=330pF | R=1500Ω C=330pF |
|---|---|---|---|
| ISO Level | 15KV | 2KV | 2KV |
| TLP $I_{T2}$ | 17A | 2A | 1.2A |
| | TLP Pulse =100ns | TLP Pulse =200ns | TLP Pulse =500ns |

Figure 1: Long-pulse TLP can mimic the impact of the various combinations of the ISO test [7]

### Rise-Time Sensitivity

While the four stress waveforms in ISO 10605 are fairly well defined, there is no guarantee that the same waveforms are actually exercised at the component level. This is the main conceptual issue behind the notion of implementing system-level ESD robustness at the component level, that is, the actual waveforms seen at the externally connected pins of the component are a function of the board/system-specific implementation (connecting traces and/or discrete components).
In particular, inductive loads (i.e., long board traces, presence of common mode chokes, or discharges through long cables) will cause significant departure from the expected ISO 10605 waveforms, both in duration (can become much longer) and shape (oscillatory, instead of exponentially decaying).

Unfortunately, the behavior of ESD clamps components used for system-level robustness is a strong function of the stress waveform. The bottom line is that it is virtually impossible to guarantee ESD system-level robustness at a component level without knowing all the details of the system/board implementation. A consequence of this fact is that the practice of specifying system-level ESD robustness on a component's datasheet is useless and could be misleading.

A typical parameter impacted by system implementation is rise time seen at the component level. It was reported in [9] that large inductive loads on CAN pins could increase the rise time of an ISO 10650 stress to >50ns. These slow values impacted the triggering mechanism of the ESD cell, causing non-uniform triggering, hence failing to meet the specifications. Again, a novel layout with internal back-ballasting was devised to minimize the reliance of the ESD cell on rise time.

### Common Mode Choke

Common mode chokes (CMCs) are often required to meet EMC emission requirements in differential communication busses (LIN, CAN, etc.), with a typical inductance of 100 µH. A CMC is placed directly in the ESD discharge path and, in principle, one would expect a beneficial high-frequency damping of the ESD energy. Unfortunately, a CMC displays a strong saturation behavior (due to the ferrite saturation), which results in a drastic reduction of the inductance over a certain threshold current. In addition, a CMC typically features an undesirable snapback characteristic for ESD current densities. This highly non-linear behavior can force the component-level ESD protection in and out of snapback multiple times, depending on the current density. This could lead to a non-uniform turn-on (Figure 2), causing premature failure of the component-level ESD protection [10].

### TRADE-OFFS BETWEEN ESD DESIGN AND EMC IMMUNITY REQUIREMENTS

The automotive environment is extremely harsh for electronic systems. To guarantee reliable operation in all possible conditions, strict EMC immunity requirements are enforced. From an ESD perspective, EMC immunity requirements sometimes conflict with ESD requirements, making ESD-IP co-design extremely challenging.

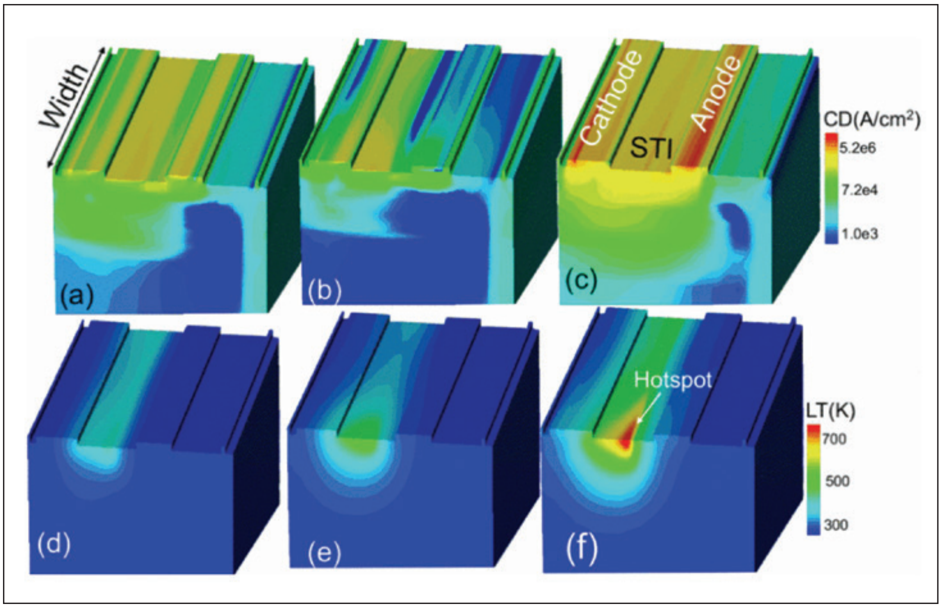


Figure 2: Current density and lattice temperature of an SCR subjected to a double triggering pulse, caused the CMC presence. It can be seen that the second pulse will cause filamentary conduction in the device, which is not able to meet the ISO specification target [10]

### Immunity to Electrical Disturbances

As previously mentioned, ISO 7637 is used to characterize automotive systems against a variety of transient electrical disturbances that may occur in an automotive environment. These are caused by the various scenarios through which inductive loads (like the motor) or the battery can be switched/disconnected. The most common test pulses are 1, 2a/2b, 3a/3b, 4, and 5a/b, which differ in terms of polarities, amplitudes, pulse width, and rise time. While all different, these test pulses feature an energy content far superior to that a component level rated (HBM, CDM) ESD cell can withstand [11].

However, component-level ESD cells designed to meet system-level ESD immunity can withstand a much higher energy level. Hence, it is becoming standard practice to have component-level ESD cells perform dual duty, i.e., to guarantee both ESD and EMC immunity to electrical disturbances. Hence, more and more component datasheets report robustness against ISO 7637 of pins that will connect to the external world.

The co-design of ESD immunity and immunity to electrical disturbances is not trivial. Besides the ability to withstand DC-like durations with test pulses 1, 2, and 5, slow rise times associated with them will require the ESD protection to be level-triggered. This implies the availability of a junction with appropriate breakdowns to support both ESD and EMC requirements.

### Immunity to RF Disturbances

In addition to immunity to electrical disturbances, automotive systems must be robust in their defense against RF disturbances as well per IEC62132-4. A direct power injection (DPI) method is used to measure the electromagnetic immunity of an IC from 150KHz to 1GHz. The interaction between ESD immunity and DPI is not straightforward, as both ESD and DPI have fast-rising voltage edges, although with different amplitudes.

In [11], the case of a LIN pin passing ESD immunity but failing the DPI test was reported. It was found that the noise injected into the substrate (and then coupled to the LIN pin) by the RC-triggered ESD cell during the DPI test was the culprit for the test failure. A new, level-triggered ESD cell had to be devised to address the issue. In a similar fashion, in [12], a robust RC-triggered ESD cell failed DPI testing, mainly at low frequencies. A redesign of the RC-triggering circuit was needed to address the issue, as it was not possible to design an effective level-trigger ESD cell for ESD immunity.

> The trend of progressively migrating both ESD and EMC immunity from the system/board to the component level is creating unprecedented challenges for the component ESD designer.

From these examples, it would seem that level-triggered ESD cells are necessary to meet DPI requirements. However, there are situations where RC-triggered ESD cells are highly desirable. One such scenario is when inductive fly-back protection is needed. This is typically the case for output pins driving inductive loads, such as external cables and/or chokes. When the power supply is switched off, it is convenient (i.e., no additional inductive flyback protection is needed) to release the energy stored in the inductors through the ESD cell. This is typically done through RC-triggering the ESD cell in MOS conduction mode to keep voltages at safe levels. As seen from the above example, functional requirements can lead to opposite design requirements on ESD cells.

## CONCLUSIONS

The trend of progressively migrating both ESD and EMC immunity from the system/board to the component level is creating unprecedented challenges for the component ESD designer. Implications of EMC-ESD immunity co-design were reviewed here, along with several case studies. In Part 2 of this article on page 74 we'll review the trade-offs between ESD design and EMC immunity requirements.

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# ESD Designers' Headache with Multiple Automotive Test Requirements, Part 2

## A Review of ESD-EMC Co-Design Challenges

*By Gianluca Boselli and Hans Kunz*

In Part 1 of this article on page 68, we showed that the trend of progressively migrating both ESD and EMC immunity from the system/board level to the component level is creating unprecedented challenges for the component ESD designer. We reviewed the implications of EMC-ESD Immunity co-design, along with several case studies.

With the unavoidable re-purposing of the system-level standards to validate component-level robustness (IEC 61000-4-2 [1], ISO 10605 [2]), several gaps at the standards level place ESD engineers in the awkward position of creating their own standards. Even worse, the practice of reporting system-level performance in components datasheets is completely dependent on each ESD engineer's interpretation of the standards, hence making those specs of questionable value.

Part 2 of this article focuses on the specific ESD design challenges stemming from the fact that all relevant system-level standards were created to validate systems and not components.

To rigorously assess the impact of the setup differences detailed in the previously mentioned standards, we offer the circuit analog shown in Figure 1 on page 76. Each major component of the testing setup is included as a circuit element and the impact of those elements allowed variation to the entire circuit performance that can then be assessed. The specific components of the analog are the ESD generator (or, colloquially, ESD gun), the impedance coupling between the ESD gun and the target/DUT, the target/DUT, and the ground return path between the ESD gun and the target/DUT.

*Dr. Gianluca Boselli has been with Texas Instruments, Inc., Dallas, Texas, since 2001, and is currently the manager of the corporate ESD Team. Boselli has authored and presented numerous papers about ESD and latch-up. He has also served in multiple leadership positions in EOS/ESD Association, as President in 2018-2019 and currently as a member of the Association's Board of Directors. Boselli can be reached through the ESDA at info.eosesd@esda.org.*

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1 GHz quasi-peak real-time bandwidth.
Multi GHz in real-time up to 44 GHz.
Fully compliant in all modes.
The ULTIMATE performance.
The ULTIMATE speed.
GAUSS INSTRUMENTS
TDEMI Ultimate
GEN
RF 1
RF 2
The TDEMI® Ultimate is the only solution providing all the features of the "FFT-based measuring instrument" according to the new standards with 1000 MHz real-time bandwidth and CISPR detectors.
GAUSS
by the inventors of the full compliance real-time FFT based measuring instrument.
gauss-instruments.com

## IEC GUN

The calibration current waveform presented in IEC 61000-4-2 [1] has become the *de facto* specification for system-level ESD (Figure 2). It defines a peak current, rise-time, and current values at 30 ns and 60 ns. However, as we will show, it is dangerous to use this as a design specification. Specifically, much work has been done showing large variations between ESD guns which are allowed under the the standard. Even with the same gun, the actual test setup drives significant variations. Some of the reasons/practical implementations are:

- Calibration method/set-up does not allow a "hand-held" gun; the gun must be mounted ("tripod or equivalent non-metal low loss support" [1]). Unfortunately, the gun is made to be "hand-held" and it is commonly used in this way.
- There are numerous reports of operator dependent variations, which are not included in the standard, and impact the calibration waveform [3]. We have experienced first-hand not only significant IEC level differences between guns from different manufacturers, but also from different gun models from the same manufacturer.
- In general, the impact of gun positioning and operator to gun coupling cannot be ignored.

## SERIES ELEMENTS

While system level standards do provide expected current waveforms (and a calibration method to verify them), the test-setup for which these waveforms are produced varies significantly from the test-setup in which actual device testing is performed. As highlighted in Figure 3, the calibration setup consists of a vertical ground plane which contains a specially designed target/load. The ESD gun is mounted on mechanical holder, and the ground return (or tether) is pulled into a specific shape. When devices are tested, the special target is replaced by the actual device, placed over a horizontal ground plane, with a much more arbitrary ground connection than the vertical plane presents to the target.

The ESD gun can now be held by a human operator and the position and shape of the tether is much less stringently controlled. One should not assume that the current waveform introduced to a device under test (DUT) is exactly the same as the waveform produced in

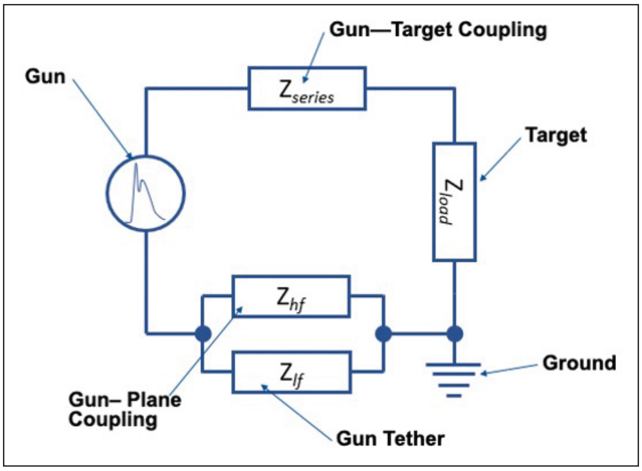


Figure 1: Circuit analogue of calibration and actual testing setups

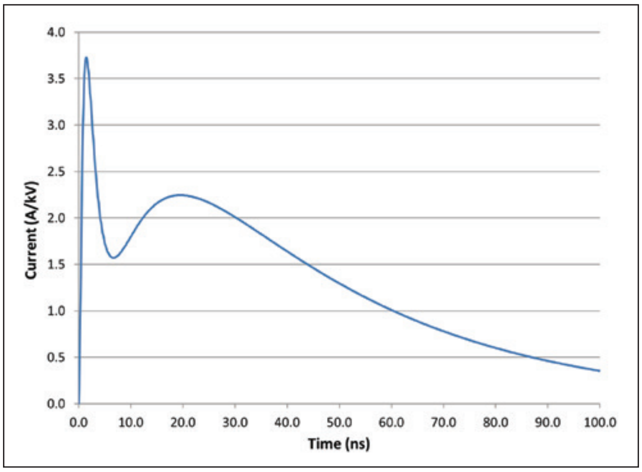


Figure 2: IEC 61000-4-2 calibration current waveform [1]

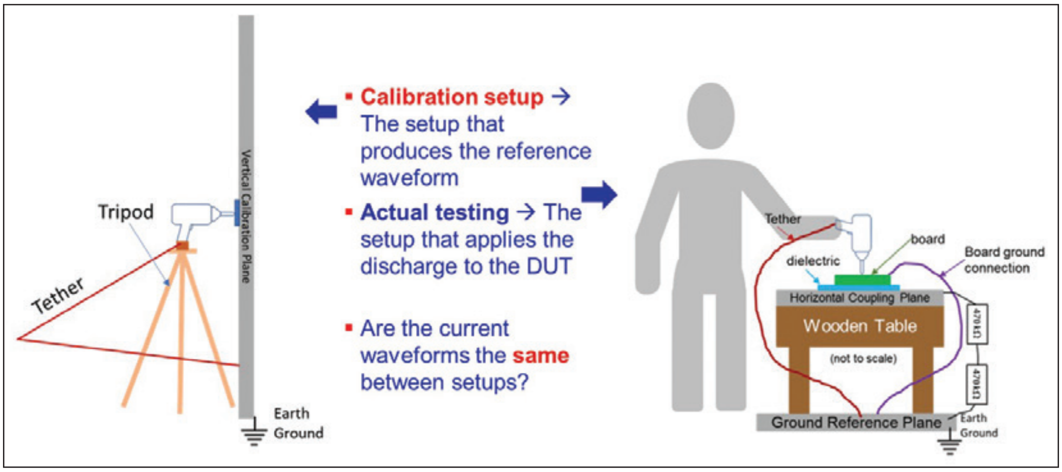


Figure 3: Comparison of the calibration setup and a typical actual testing setup

the calibration setup. In fact, significant deviations in the current waveform can result, leading to unexpected performance (both pass and fail) and unrepeatable results.

While the coupling between the ESD gun and the target/DUT ($Z_{series}$ in Figure 1) may seem like an insignificant contributor to the overall performance of the circuit, remember that an ESD gun in direct contact with the target/DUT is not the only configuration—in fact, the coupling between the ESD gun and the target/DUT can be quite different for some configurations. Many automotive system-level test standards [4-7] apply discharge through a variety of gun-target couplings. In addition to the most common gun-target coupling (i.e., contact discharge), there are four other couplings (some used in conjunction), namely:

- Spark: air discharge
- Wiring harness/cable
- Common-mode choke
- Series resistor

### Spark: Air Discharge

Air-discharge is already known to produce a large variation of current waveforms—with no single waveform being deemed as "correct." This is acknowledged in the two primary general system-level ESD Standards [1, 2]. The IEC standard describes it as:

> "*The spark is a very complicated physical phenomenon. It has been shown that with a moving spark gap the resulting rise time (or rising slope) of the discharge current can vary from less than 1 ns and more than 20 ns*" [1].

The ISO standard states it as:

> "*The air discharge method virtually replicates ESD, as it would occur in the actual environment. In effect, this means that the impulse current waveforms delivered to the DUT are allowed (and expected) to vary significantly from pulse to pulse.*" [2].

The strong relationship between the length of the air-discharge spark and the severity of the resulting current waveform means that variations in spark length translate directly into variations in current waveform. There are known factors which lead to variation in spark formation, with humidity and speed-of-approach being commonly recognized causes. However, other factors also play a role, including the shape of the electrodes between which the spark forms, and, while the standards do closely control the shape of the electrode on the ESD gun, there is no control on the shape of the target electrode.

This becomes an extremely important factor in J2962-x automotive standards [4, 5], in which air-discharges are applied directly to the BUS signal wires in the wiring harness. But current waveforms are not generally monitored *in-situ* during system-level testing; the person applying the discharge has no reasonable gauge of the severity of the current pulse that was actually delivered.

The current waveform shown in the IEC 61000-4-2 standard consists of a fast-rise time to a peak current, followed by a drop in current and a slower rise-time to a second peak. Figure 4 shows an expectation of two clearly distinguishable peaks (for a negative discharge) in the lower left corner. This expected waveform has a green region (indicating the 1st peak region) and a blue region (indicating the 2nd peak region). To the right of Figure 4, actual measured current waveforms are shown. These waveforms were all generated in the same test setup, by the same operator, at the same voltage level. The only variances were the speed and angle at which the operator approached the target with the ESD gun.

More troubling is that a single waveform in this set actually damaged the DUT, while others did not. If the exact speed and angle was not reproduced by the operator, then damaged DUT did not occur, leading to a high-level of unrepeatability in testing results. Because there is no accepted air-discharge current waveform shape, it is unclear what should be expected during design and, further, what should be allowed during testing.

Another factor in air-discharge testing is the challenge of holding the pre-charge voltage on the ESD gun before spark formation. In cases where the target is a very sharp geometry (such as a wire) it is quite possible to lose charge through corona discharge. While the ESD gun may have been programmed to deliver a 10-kV discharge, at the time of spark formation perhaps only a 5-kV equivalent charge remains. In fact, doubling the discharge voltage in this case may lead to no increase in discharge current whatsoever.

So what does it mean to apply a 10-kV air-discharge to a DUT and observe no failure? Is the DUT robust or was a "soft" current waveform delivered? If a DUT fails 10-kV, does this mean it will be weak in a different test environment (or in the actual application)? Given the lack of fidelity between the programmed discharge voltage and the actual current-waveform delivered, no meaningful conclusions can be reached about the robustness of a DUT by a simple statement that the DUT passed or failed discharge voltage-level testing.

### Wiring Harness/Cable

Having established the consequences of discharging through a series spark, other series elements should

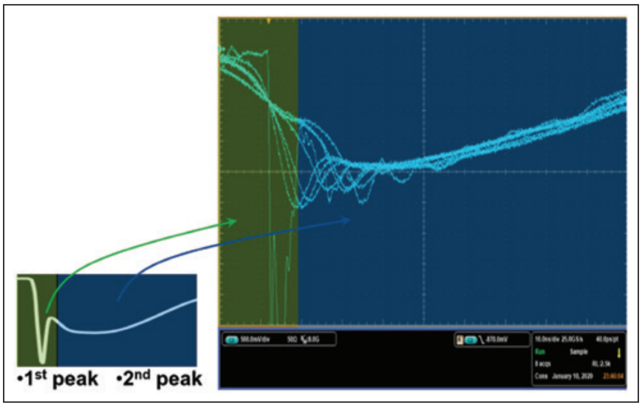


Figure 4: Possible expected waveform shape and actual waveform shapes from testing

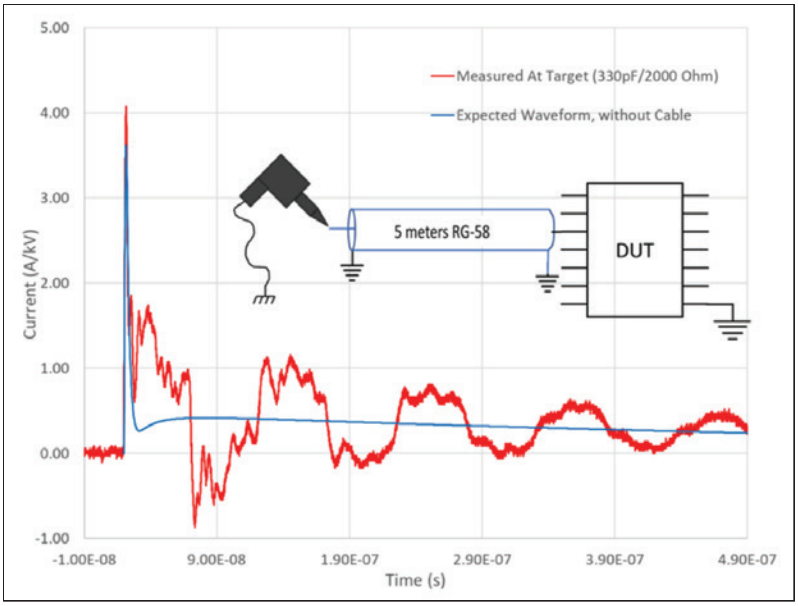


Figure 5: Example of an ESD discharge through a cable

also be evaluated. For example, requirements to apply the discharge through a series wire or cable are not uncommon. Just as with the spark in air-discharge, the impedance of a wire or cable is not trivial, especially when considered across the large frequency spectrum of the ESD pulse. In fact, these configurations must be evaluated as transmission-line, which is not matched on either the stimulus or the load side. Reflects should be expected, resulting in deviations from a direct contact waveform.

Figure 5 shows an example of an ESD discharge applied through 5 meters of RG-58 cable, relative to the expected waveform without a cable present. If the significant reflections demonstrated in Figure 5 are not anticipated during the DUT design phase, unexpected failures can result.

### Common Mode Choke

Common mode chokes (CMCs) are often required to meet EMC emission requirements (more on that in the next paragraph) in differential communication busses (LIN, CAN, …), with a typical inductance of 100 µH. The CMC is placed directly in the ESD discharge path and, in principle, one would expect a beneficial high-frequency damping of the ESD energy.

Unfortunately, a CMC can display a strong saturation behavior (due to the ferrite saturation [10-12]), which results in a drastic reduction of the inductance over a certain threshold current. In addition, a CMC features an undesirable snapback characteristic for ESD current densities. This highly non-linear behavior can force the component-level ESD protection in and out of snapback multiple times, depending on the current density. Figure 6 shows the typical non-linear waveform of a CMC in response to a full IEC event.

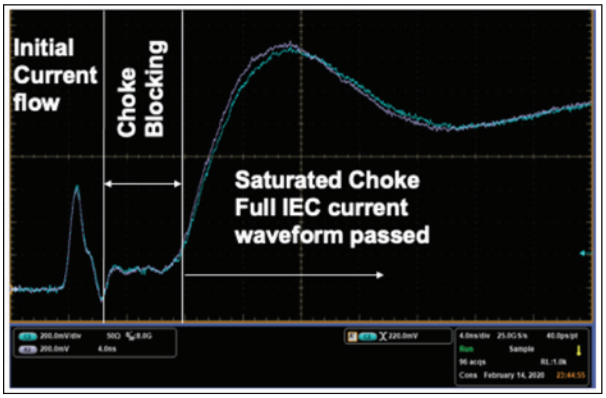


Figure 6: CMC response to a full IEC event

The choke allows initial current flow, due to displacement current of the quasi-differential signal. This is followed by a "blocking" period, corresponding to the common mode signal. Eventually, the choke saturates, causing low impedance, and therefore high current flow.

This complex waveform depends on several parameters, including:

- Discharge level;
- Board parasitics; and
- Unspecified/ uncharacterized choke parameters (i.e., two nominally identical CMCs will yield completely different IEC results).

### Series Resistors

Some automotive system-level ESD standards require testing through series resistance. When using large resistance values, the expectation is to limit the current (Figure 7). Unfortunately, there is nothing to limit voltage build-up on discharge side of resistor. Therefore, spark-over of the resistor is likely, thereby causing a full discharge into DUT (effectively emulating an air-discharge test.)

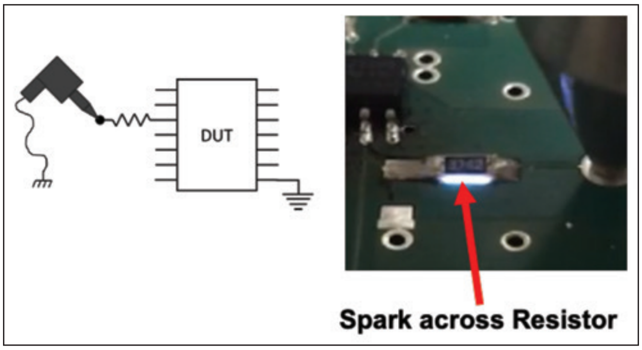


Figure 7: spark-over mechanism of contact discharge through a series resistor

## RETURN PATH

The testing setup strongly influences the ground return path. With reference to Figure 8, the common setup for IEC 61000-4-2 features:

- Board to horizontal coupling plane (HCP) capacitance inserted in the high-frequency path, and
- Added wire impedance in the low-frequency path.

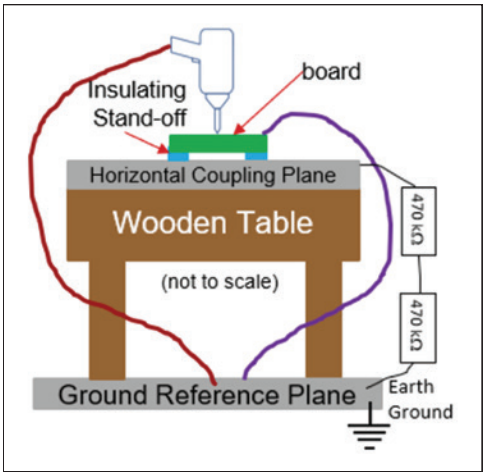


Figure 8: Common IEC 61000-4-2 implementation

This article focuses on the specific ESD design challenges stemming from the fact that all relevant system-level standards were created to validate systems and not components.

The common setup for IEC62228 [8] features:

- Metal fixture between board and HCP, tether directly to grounded HCP, and
- Strong low-impedance bond between board and HCP.

If we look at the two return paths separately, the high-frequency return path is primarily a capacitive coupling, from the gun to the coupling plane. Coupling between board/plane adds series impedance, which can cause significant degradation of 1st peak (Figure 9).

If we look at the low frequency return path, it is mainly driven by the gun tether. Inserting a wire between the board and the ground reference plane adds impedance in the low frequency return path (Figure 10).

As shown, the test-setup with respect to the ground return path can have significant impact on the shape and severity of the current waveform delivered to the DUT. Seemingly subtle changes in the test-setup can lead to consequential changes in testing results, leading to repeatability issues. Similarly, seemingly subtle differences between different test-setups can lead to differing testing results between two test facilities, leading to reproducibility issues.

## LOAD

The ESD gun is calibrated to a 2 Ohm (high bandwidth) load. Specifying a single load allows significant deviation/differences between guns— this was a "painful" lesson already learned with HBM test standards. Not only do guns vary significantly, models used for pre-silicon validation vary. A large set of guns/simulation models were evaluated in [9]. From Figure 11, it can be seen that there is a good agreement between a specific model and a specific ESD gun's waveform for 2 Ohm load.

However, the agreement is not good for a 100 Ohm load (Figure 12), which begs the question of whether the gun or the model is more correct. Because the standards do not set an expectation, the question cannot be answered.

## CONCLUSION

This article focuses on the specific ESD design challenges stemming from the fact that all relevant system-level standards were created to validate systems and not components. Applying these standards to individual components requires interpretation, which leads to ambiguity in the meaning of the results. Additionally, there are poorly controlled aspects of the test standards, which can create large variations in the applied stress.

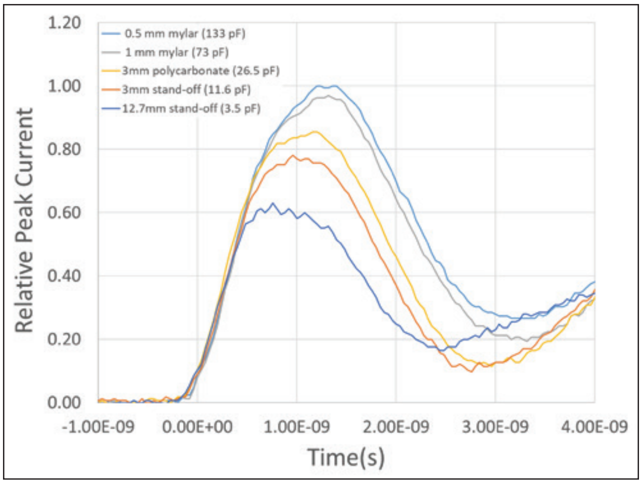


Figure 9: First peak modulation caused by different material and thickness of the dielectric between board and HCP

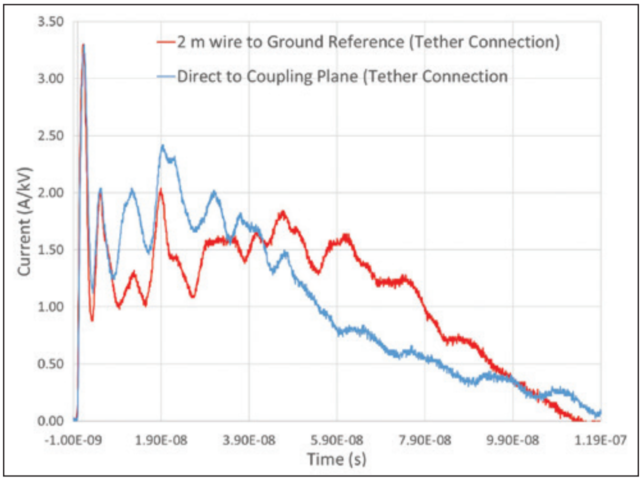


Figure 10: Effect of inserting a wire between the board and ground reference plane adds impedance in low frequency return path

Our examples place particular emphasis on the air discharge test and the shortcomings that make it a virtually unreproducible test and, hence, of questionable usefulness.

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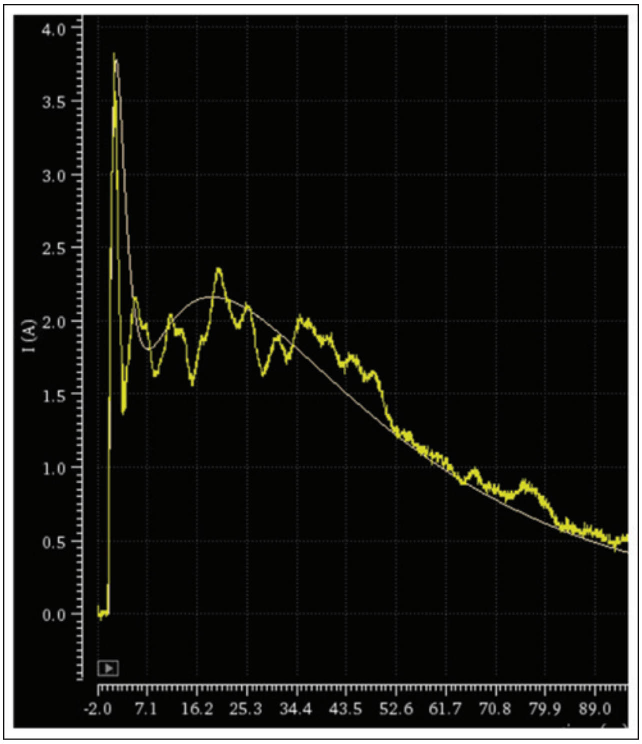


Figure 11: Model vs waveform for 2 Ohm load

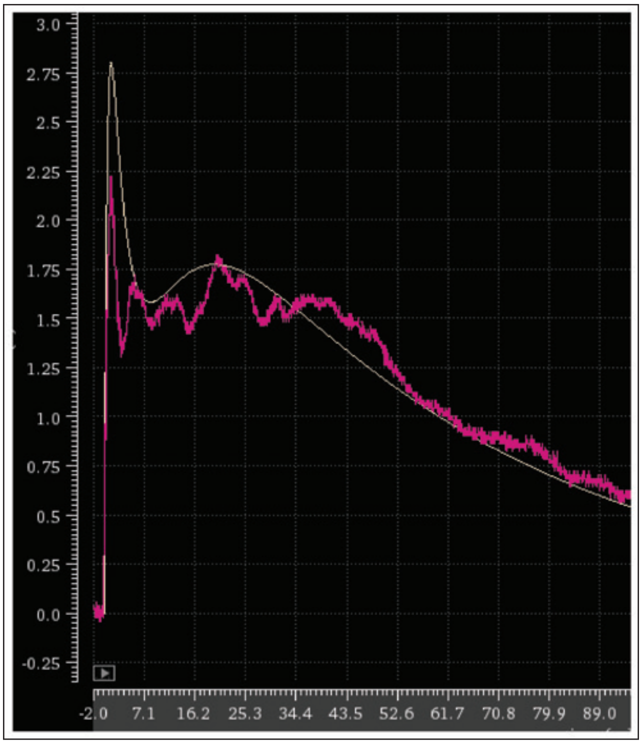


Figure 12: Model vs waveform for 100 Ohm load

# Top 10 ISO/IEC 17025:2017 Deficiencies Found in Electronics Testing Laboratories

## Consider These Clauses When Conducting Your Laboratory's Internal Audit

*By Rob Miller*

Achieving ISO/IEC 17025:2017 accreditation for your electronics testing laboratory can be an exhaustive and time-consuming process. But an outside evaluation based on internationally recognized standards can improve your organization's overall competitive advantage. Accreditation not only showcases your organization's commitment to quality work but also demonstrates the integrity of your personnel and supports the validity of your test results.

Whether your organization is seeking ISO/IEC 17025 accreditation for the first time or renewing your current accreditation, there are a few frequently overlooked or misunderstood sections of the ISO/IEC 17025 standard to pay close attention to. If you and your team members are aware of the common deficiencies most often experienced in connection with these sections, you're better positioned to identify them through internal audits and address them before seeking accreditation from an outside accreditation body.

Testing laboratories should always conduct an internal audit to identify gaps or weaknesses in their systems and procedures to determine if additional resources are needed to ensure compliance. Sufficient records must be kept of the internal audit results and any follow-up actions taken. The outcome of the internal audit may help determine if your laboratory is, in fact, ready for an external assessment or if additional work is needed before applying for accreditation.

## THE MOST IMPORTANT ISO/IEC 17025 CLAUSES TO CONSIDER

Here is a brief summary of the ten clauses in ISO/IEC 17025 to consider when seeking testing laboratory accreditation.

### *7.2.1: Validation of Methods*

This clause has multiple parts, all of which cover the selection, verification, and validation of methods. Laboratories not only have to select methods appropriate for their customer's needs but must also have the appropriate documentation and records to show verification and validation of those methods.

Additionally, 7.2.1.5 requires that laboratories verify that they are capable of performing a method before introducing

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it to their scope. Furthermore, when a method is revised by the issuing body, this verification must be repeated. The depth of this verification is to be determined by the laboratory. However, records must be maintained. This is commonly missed by laboratories adding new methods to their scope or updating existing methods consistent with standard revisions.

### *8.8: Internal Auditing*

An internal audit needs to confirm that a testing laboratory's management system and activities are in compliance with ISO/IEC 17025. The language in this section is broad so as to allow laboratories to determine the frequency and depth of the audits, depending on the laboratory's needs and risk tolerance. Once the internal audit plan is decided, records of implementation are required.

While ISO/IEC 17025 ultimately leaves it up to the laboratory to determine the frequency and depth of internal audits, it is important that laboratories adhere to their own internal procedures and plans. When it comes to internal audits, deficiencies are often cited against the laboratory's own procedures rather than those described in ISO/IEC 17025.

### *7.8: Reporting of Results*

This section details the requirements for reporting lab results. There are many variables regarding these reports, depending on the customer contract, the type of laboratory activities performed, and the methods used. Organizations must take an attentive and individualized approach to applying the requirements of this section.

One area commonly missed in this section is 7.8.2.2, which requires the laboratory to identify within the report any data that was supplied by the customer. Additionally, a disclaimer must be made on the report when data provided by the customer can impact the validity of results.

### *7.7: Ensuring the Validity of Results*

This section specifies that the laboratory must document procedures intended to continuously monitor the validity of test results and the required elements of the procedures that must be included. The laboratory must collect and analyze data from monitoring activities to evaluate and potentially improve their activities. This section also states that laboratories must compare their actual performance and results against that of other laboratories, referred to as proficiency testing. This section frequently uses phrases such as "where appropriate" and "where available."

For some laboratories, specific elements of these requirements will not be applicable, but the laboratory should be prepared to account for why that is the case.

Regardless of the monitoring activities chosen by the laboratory, it is important that pre-defined criteria are determined, and that results are recorded in a way to easily detect and evaluate trends. Oftentimes, laboratories overlook these requirements, resulting in a deficiency. These steps are crucial in maintaining confidence and quality in a laboratory's results.

### *7.5: Technical Records*

The focus of this section is the traceability and reproducibility of results. All laboratory activities must have technical records that are detailed enough to reproduce the exact process that initially produced them. This means that many factors will need to be consistently and diligently recorded, and that both original records and their amendments must be retained. Commonly cited deficiencies in this area include failing to record relevant environmental conditions such as temperature and humidity, or simply omitting data on when the test was performed and who performed it.

### *6.6: Externally Provided Products and Services*

It is impossible to completely control what goes on outside your testing laboratory, but the quality of externally provided products and services is still within your control. This section requires that laboratories determine the suitability of externally provided products and services in a way that supports compliance. It requires that the testing laboratory create, document, and maintain procedures, evaluation criteria, and communication methods.

Oftentimes, deficiencies are cited because a laboratory does not document or record the appropriate processes and criteria required by 6.6.2, parts a) through d). Furthermore, it is common for a laboratory to define its requirements for evaluating a supplier but then fail to include how the supplier will be re-evaluated and what actions will be taken based on this evaluation.

### *6.2.5: Personnel Procedures and Records*

This clause requires that laboratories have procedures for various activities related to the competence, training, and monitoring of personnel, as well as for retaining records of those activities. There is a list of specific topics that need to be addressed, either in one procedure or individual procedures. All relevant personnel must adhere to these procedures and records of implementation must be maintained in all cases as objective evidence the procedures are being followed.

Similar to section 6.6 discussed previously, laboratories oftentimes fail to define the various processes and criteria required by this section. Clause 6.2.5 a) through f) requires that the laboratory maintain procedures and records for determining competence requirements as well as selection, training, supervision, authorization, and monitoring of personnel. It is common for a laboratory to miss one or more of these items in their personnel procedures or records.

### *6.2.2: Documented Competencies and Supporting Records*

The standard states that that several elements of competencies must be documented, including education, training, and experience. Each position category that has an influence on laboratory results must have a documented level of competency. Additionally, it is important to keep in mind that 6.2.5 a), discussed previously, requires that the laboratory maintain a procedure for determining competence requirements, an area commonly missed.

### *8.9.2: Management Review Inputs*

This clause contains a list of 15 items that must be recorded as part of a management review, all of which the laboratory must take care to cover and record. This section may be removed from the list in the next year or so as laboratories undergoing certification renewal must work in advance to get their management review process in order and conduct these reviews with records showing each input.

Often cited deficiencies in this area include all 15 items required by 8.9.2 a) through o). Similar to internal audits discussed above, it is up to the laboratory to determine the frequency of their management reviews. However, the intervals shall be planned. It is important for the laboratory to follow its own internal procedures here as deficiencies are often cited for not adhering to planned schedules or processes.

***6.4.: Equipment***

Based on our data, this section of the standard is the one that has most frequently proven to challenge electronics testing laboratories. In the most recent version of the standard, the term "equipment" is used to refer to all types of laboratory resources, including measuring equipment, reference standards, reference materials, reagents, consumables, and more. This section requires procedures for all equipment, including, but not limited to, accessibility, maintenance, storage, calibration, and record-keeping. It lists the specific equipment records that laboratories must maintain for all the equipment in their facility which can influence the activities listed on their scope of accreditation.

The most commonly cited deficiencies in this area are related to equipment calibrations. When sending equipment out for calibration, it is imperative for the laboratory to be aware of specific calibration requirements (procedures, frequency ranges, etc.) outlined in a given test method. Other commonly cited deficiencies in this area include failing to record software and firmware versions in equipment records (6.4.13a), not labeling, coding, or otherwise identifying the calibration status of laboratory equipment so that it is clear to all personnel (6.4.8), and failing to maintain a maintenance plan and maintenance records for relevant equipment (6.4.13g).

## TAKING CORRECTIVE ACTION AND AVOIDING DEFICIENCIES

All deficiencies found during an assessment must be addressed by conducting a root cause analysis, taking corrective action, and providing objective evidence that the deficiency has been corrected. By going back to the problem, asking the right questions, and thoroughly investigating it, you can determine what caused the issue and potentially eliminate the risk of non-conformity recurrence.

In addition, implementing and maintaining a Quality Management System (QMS) can greatly reduce your risk of deficiencies. A QMS is where documented processes and procedures are kept and maintained so that personnel can reference them at any time, ensuring consistency and efficiency. It serves as a framework for all laboratory activities, reducing the likelihood of deficiencies, and offering a competitive advantage.

Another option to consider when seeking accreditation is training for you and your laboratory staff. Although it is not mandatory, training can be done early in the accreditation process to help personnel gain an understanding of the standard, the overall importance of accreditation, and the need for continuous competency improvement. Training can be done in-house or through a public venue, and a variety of options may be found through a simple internet search. There are also virtual course options that allow you to receive the training you and your team need while keeping costs low.

When in doubt, always refer to your copy of the ISO/IEC 17025:2017 standard. The accreditation process is thorough so it's critical to pay close attention to each clause and perform corrective actions when deficiencies are found.

## CONCLUSION

Once accredited, your lab may advertise its accreditation, giving you a competitive advantage and instilling confidence in your test results and product quality—not only with customers but also with shareholders and other industry professionals. Frequently promote your accreditation to acknowledge the hard work put into achieving accredited status. If you have any questions about the process, you can always contact your accreditation body to discuss any references to your accreditation that you wish to publish.

# Why Histograms and Free Run Matter

## A New Method for Oscilloscope-Based Power Integrity Testing

*By Joel Woodward*


With the continual decrease in power rail DC voltages and tolerances, oscilloscopes remain a key tool for development teams tasked with power integrity measurements. The continual trend to lower voltages and tolerances has driven the proliferation of power rail probe usage with oscilloscopes. The question of "should we purchase our first power rail probe" has changed to "what's the best measurement technique". Initial techniques have been refined as users and oscilloscope manufacturers collaborate and share insights and experiences.

A relatively unknown yet superior technique emerged from experts making power integrity measurements. This approach involving histograms and free-run trigger mode offers three key improvements compared to the traditional approach:

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- By using a waveform histogram, users can visually and statistically compile power rail attributes;
- By using a single histogram measurement across all acquired waveforms instead of a measurement on each waveform, speed-of-test is accelerated, and with great accuracy; and
- By using free trigger mode, users get increased real-time power rail coverage versus instrument dead-time when the instrument is blind to power rail signal activity.

All major oscilloscope manufacturers offer power rail probes, and these probes incorporate several attributes that make them superior for highly accurate measurement of small voltages with tight tolerances. Lots of material is available on the benefits of using power rails. This includes the probes' minimal DC loading impact on the power rail, built-in offset to enable users to take advantage of small vertical scaling, and a 1:1 attenuation ratio to minimize noise. The relatively new histogram approach to power rail measurements accelerates test time by more than 50 times while providing more accurate measurement results.

## TRADITIONAL APPROACH

The long-used approach for measuring power rail tolerance is to have the oscilloscope use a voltage peak-to-peak measurement to determine the overall amplitude from noise, ripple, and periodic disturbances (see Figure 1).

Oscilloscope users agree that a key issue with this traditional approach continues to be oscilloscope blind time. All oscilloscopes are subject to blind time between acquisitions. During this time, the oscilloscope is processing the last acquisition and cannot perform any new acquisitions until the previous one has been processed. While engineers are generally aware of this, many are not aware that the ratio between blind time and real-time signal acquisition can be extremely large. It is not uncommon to have 1000 times the amount of blind time compared to acquisition time.

Several attributes related to testing power rails lead to additional undesired blind time. Oscilloscope users never achieve the faster update rate needed for better testing and hence are only able to test snippets of time, while missing large amounts of rail signal activity between acquisitions.

Oscilloscope manufacturers communicate a waveform update rate (wfms/s) for specific oscilloscope families. This value describes the maximum speed at which the instrument can acquire and display signals. The fastest oscilloscopes in the world have a waveform update rate in excess of one million waveforms per second, while slower ones will have an update rate in the tens of waveforms per second. Waveform update rate describes a maximum value, but this value is not typical for power integrity measurements.

Maximum update rates occur at a specific time base setting, with the fastest sample rate, and without any measurements turned on. However, this is not descriptive of a power integrity test setup. At time bases of 1 uS/ and slower that are typically used for power rail measurements, blind time increases.

Testing power rails varies from other types of testing in that a trigger signal is not always readily available. Most oscilloscopes require a minimum voltage swing for detecting a trigger event. Power rails often do not have enough signal swing and hence users choose auto-trigger, which means if the oscilloscope does not find a suitable trigger it will table an acquisition after a predefined period of waiting, typically a few mS.

This triggering issue also contributes to users missing significant time when the oscilloscope is not acquiring power rail activity. Alternatively, in normal mode when the oscilloscope is triggering on the signal, it still needs to re-arm the trigger after each acquisition, which in turn slows down the waveform update rate.

Lastly, turning on measurements on all oscilloscopes reduces the instrument's acquisition rate. An oscilloscope that acquires 1 M waveforms per second without any measurements on might have a reduction to 350 acquisitions per second when measurements are turned on. An oscilloscope that normally acquires 50 waveforms per second might be slowed down to 5 acquisitions per second when a measurement is enabled. The need to process a measurement results in additional time during which the instrument is not actively acquiring power rail activity.

How much power rail activity do oscilloscopes miss? It is not uncommon for an oscilloscope with a fast update rate, a time base setting of 1 uS/div, and a single waveform measurement to have an update rate of 300 to 400 measurements per second. Is this fast? This update rate and time base combination means the oscilloscope is missing 99.6% of real-time power rail activity. Any anomalies that occur on the power rail during this blind time will not be recognized or measured by the oscilloscope. This processing speed tops other oscilloscopes where the update rate is just a few measurements per second, resulting in missing > 99% of power rail signal behavior.

Peak-to-peak voltage measurements are made on each individual waveform with results accumulated across multiple acquisitions. This provides a peak-to-peak range

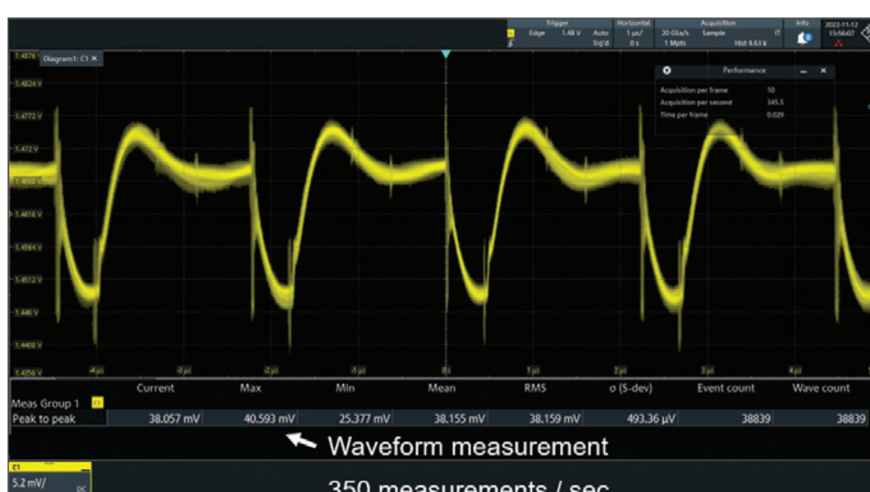



Figure 1: Making a measurement on each acquired oscilloscope waveform slows the update rate and increases blind time when the oscilloscope is not seeing or measuring power rail signal activity.

for each individual waveform, but it does not incorporate the largest maximum value versus the smallest minimum value that is acquired over successive acquisitions. What is needed is a peak-to-peak measurement that encompasses all acquisitions and updates as the oscilloscope acquires new power rail signal activity.

## A SUPERIOR APPROACH

Several modifications to the traditional approach enable users to dramatically increase test time coverage and achieve more accurate measurements. The improved measurement techniques build on less frequently used oscilloscope settings that have existed for a long time, but that have not been exploited collectively for a specific application. Power integrity happens to be the key application where these capabilities combine to produce a result far better than the traditional power integrity measurement approach used by most engineers today.

### *1. Use Waveform Histogram*

A number of currently available oscilloscopes offer a less commonly known feature called waveform histogram (see Figure 2). The instrument computes all waveform values and produces a corresponding histogram that shows what vertical values the waveform had, and what percentage of acquisition samples were at a specific amplitude. In a sense, histograms are very compact representations of waveform amplitude values at each sampled point. The histogram does not retain the detail related to the shape of each waveform, but rather just the vertical values. This is exactly what is needed for power integrity measurements.

Figure 3 shows a waveform histogram of a power rail. From the histogram, the user can quickly determine how much of the time the signal under test spends on each level. The histogram incorporates information from all acquired samples in each acquisition and builds up with each successive acquisition.

Why use a waveform histogram? For voltage tolerance testing, the shape of the waveform is not important. What is important are the minimum and maximum values. Rather, ripple, noise, and disturbances present themselves as anomalies that exceed voltage tolerance levels. A histogram is a great visualization tool to see if tolerance levels have been violated.

For many oscilloscopes, waveform histogram processing is done in hardware, and the oscilloscope experiences little to no drop in the maximum waveform update rate. With waveform histograms, such instruments can measure 20 times more acquisitions per second versus using a $V_{pp}$ measurement on each acquisition. Such oscilloscopes capture as much as 20 times more real-time signal activity on the rail.

### *2. Make the Peak-to-Peak Voltage Measurement ($V_{pp}$) on the Histogram*

Apply $V_{pp}$, min, or max measurement to the waveform histogram instead of measuring each individual waveform. Why is applying a $V_{pp}$ measurement to a waveform histogram better than applying to individual waveforms? Since the waveform histogram contains power rail waveform information from all past acquisitions, the measurement applies to all acquisitions. For example, if a histogram is composed of 1000 repetitive acquisitions, a

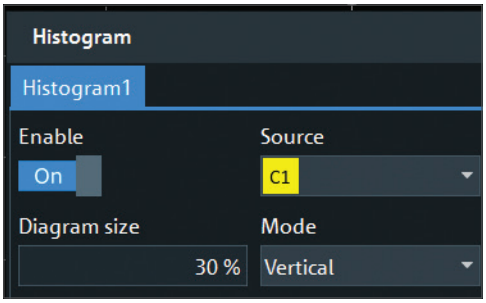



Figure 2: Turning on an oscilloscope waveform histogram creates a compressed statistical model of all vertical waveform values across all past acquisitions that the oscilloscope can quickly measure.

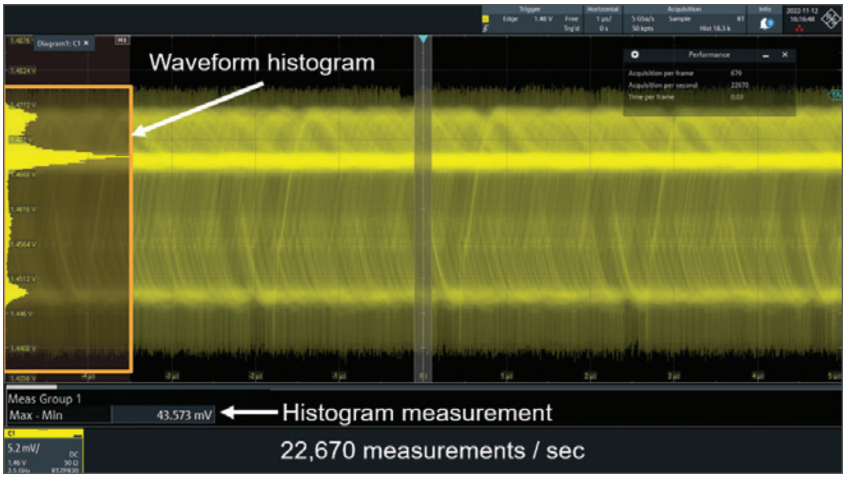



Figure 3: For some advanced oscilloscopes, a max peak-to-peak histogram measurement with free run trigger mode can yield nearly 23,000 power rail measurements per second. This is a >60X improvement over the traditional method, allowing users to see and measure over 20% of real-time rail signal activity.

single peak-to-peak measurement on the histogram covers the composite information from all 1000 acquisitions. But the oscilloscope only needs to make a single measurement, instead of 1000 measurements, meaning the oscilloscope's update rate stays faster.

In addition to the speed increase, the peak-to-peak measurement on the histogram is made across all acquired data. It constitutes the true max peak-to-peak voltage from the highest value versus the smallest value. This provides the correct overall peak-to-peak value overall acquired data, versus the less accurate traditional approach that measures just the worst-case single acquisition that may not include the highest maximum voltage and the lowest minimum voltage of all acquisitions.

### *3. Use Free Run Trigger Instead of Auto or Norm Trigger*

The third technique to achieve a more comprehensive, hence more accurate, power integrity test on power rails includes a change in how engineers trigger their oscilloscope. For testing rail voltage tolerances, triggering on a specific part of the waveform is not required. In fact, in many cases, oscilloscopes require larger voltage swings than occur on power rails. Because of this, testing of power rails is often done with the oscilloscope set to the default auto-trigger mode. If the oscilloscope does not find a trigger within a short period of time, typically a few mS, it goes ahead and acquires. The auto trigger mode inherently slows down the oscilloscope acquisition rate, meaning testing includes a small portion of the power rail real-time signal activity. Switching the trigger mode to norm yields a similar update rate as the auto trigger.

For power integrity tolerance testing, a trigger on a specific part of the waveform is not critical. Many oscilloscopes incorporate a less common trigger mode known as free run (see Figure 4). With the trigger set to free run, the oscilloscope captures data, processes the data, and then captures the next acquisition without having to look for or wait for a trigger event. The tradeoff is that the trigger does not occur at the same point of the waveform each time. For power integrity tolerance testing, triggering on the same part of the signal each time is not needed and there are benefits in asynchronous triggering. Free run mode yields a waveform update rate dramatically faster than in auto or normal trigger modes.

For example, on a specific oscilloscope tested with a time base setting of 1 uS/, in auto trigger mode the capture rate is 1,200 wfms/s while in free run the acquisition rate increases to 22.7 K wfms, almost 20 times better.

Table 1 shows the difference between the traditional measurement-per-waveform approach, versus the refined histogram combined with free-run trigger mode. (An R&S model RTO6 oscilloscope was used to highlight the differences between the two approaches.)

Like many approaches, combining multiple techniques yields significant advantages. For power rail testing with oscilloscopes, using waveform histograms, plus measurement on histograms, plus free run trigger mode enables users to capture and analyze a significantly higher percentage of rail activity than the traditional method of making peak-to-peak voltage measurements on individual waveforms with the oscilloscope's trigger set to auto or normal mode.

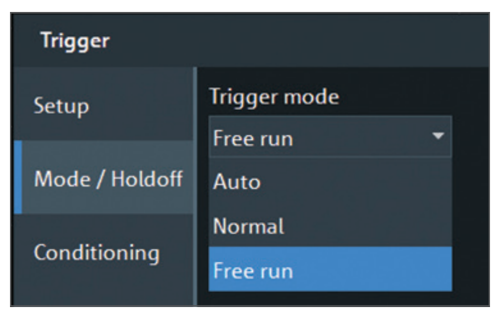
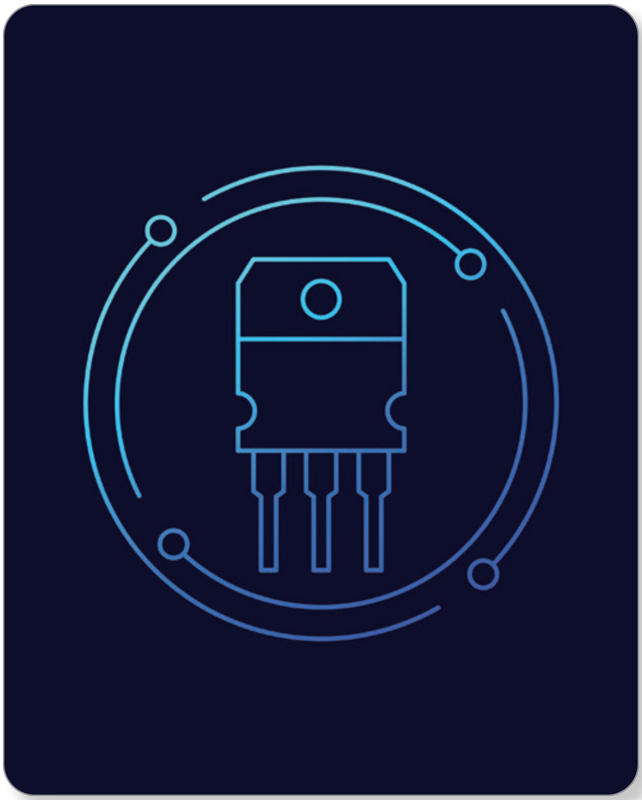



Figure 4: Setting the oscilloscope trigger mode to Free run matches power integrity test needs and maximizes the instrument's ability to see and measure the maximum amount of real-time rail signal activity.

| | **R&S RTO6 Oscilloscope** time base = 1 uS/, SR = 5 Gsa/s | | | |
|---|---|---|---|---|
| **Trigger setup** | auto | norm | **free run** | |
| **Measurement** | none | Vpp on waveform | none | **Vpp on histogram** |
| **Acquisitions/s** | 500 | 350 | 22.6 K | 22.6 K |
| **Time to measure 50K acquisitions** | NA | 143 sec | NA | 2 sec |
| **% of real-time rail activity captured** | 0.35% | | 22.6% | |
| **% rail signal activity missed** | 99.65% | | 77.4% | |
| **Vpp max** | NA | 40.6 mV | NA | 42.7 mV |
| **Improvement** | | 1X | | 65X |

Table 1: Comparison of traditional one measurement per acquisition approach, versus the superior histogram with free run trigger approach. The latter method enables the user to see and measure >60X more real-time power rail signal activity.

# GaN/SiC Transistors for Your Next Design: Fight or Flight?



## Getting EMC Ready for the Next Generation of Power Electronics Devices

*By Dr. Min Zhang*

As a technical consultant, I have seen various new technologies implemented in both new and old applications. In the semiconductor industry, WBG devices such as SiC and GaN transistors have been gaining attention due to their small size, fast speed, and better thermal performance. The introduction of these new semiconductors into the consumer market came after a series of military and other commercial applications of the technology in everything from electric vehicles to radar systems.

GaN devices have enabled a much better form factor for product design than their silicon counterparts. As they become cheaper and more available, it is expected that we will see them widely adopted in power-switching modules worldwide.

Technically speaking, GaN semiconductors are high-electron-mobility transistors (HEMTs), meaning they do not have the doped region in a PN junction like MOSFETs. This enables faster electron flow, hence higher switching speed. Because HEMTs do not have the PN structure, they also do not have a body diode. This can have a great impact in applications such as motor drives, where we can now switch on the HEMT for freewheeling rather than relying on the body diode.

From the EMC perspective, this feature can be useful as, traditionally, EMI issues associated with the reverse recovery charge of a body diode during deadtime can be a problem [1]. To fix the issues, engineers often place a Schottky diode in parallel with the MOSFET as Schottky diodes switch faster and do not have a reverse recovery charge effect [1]. Now that the switching speed of a GaN is faster than a Schottky diode, it does not have a reverse recovery charge effect either. The HEMT has a "quasi diode" mode in the deadtime region, and we need to control the deadtime well.

But new technology often presents a double-edged sword. The most significant advantage of a GaN device (superfast switching, say 100V/ns) also brings a challenge for controlling EMI. As we all know, the faster the switching action (i.e., defined by the rise time), the harder it is to contain EMI, especially above the frequency of $1/\pi t$, where $t$ is the rise/fall time of a switching event. This can be seen in Figure 1.

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Facing an EMC test failure, many engineers have chosen to swap the WBG device with a silicon MOSFET to pass EMC tests, considering time-to-market is often critical for companies to profit. But this defeats the spirit of making a higher-efficiency product. Facing greater EMI challenges, many engineers choose to "flight" rather than "fight" under time and cost pressure.

In other cases, engineers have chosen to use silicon MOSFETs based on trade-off calculations in the design. For instance, if using a WBG device results in requiring an additional filter to pass EMC, it is not a good idea as the filter would add cost and weight. But, given a good product design with EMC consideration in the design stage, it is believed that a WBG device should be the device of choice, supporting efforts to achieve the best possible product form factor and resulting in higher performance and lower cost. This can already be seen in the laptop/mobile phone charger market, where GaN chargers have started dominating the market.

## THE MAIN CHALLENGES

The main EMI challenges in WBG-based power converters can be summarized as shown in Figure 2. These challenges can be categorized into different frequency ranges:

1. *150 kHz to 5 MHz range*: This constitutes the low-frequency conducted emission test range. Here, strong electromagnetic noise is generated due to the hard switching event, typically associated with the switching frequency. While most of the noise in this range is differential mode, in high-power applications with WBG devices it can also be common mode dominant, as demonstrated in [2].
2. *5 MHz to 30 MHz range:* In this range, common mode noise becomes prevalent. It's important to note the presence of a "hump" in this region, caused by structural resonance introduced by the test setup. When the device under test experiences a hard switching event, it exhibits a resonance peak in the test results [3]. The energy level is determined by the rise time of the switching event in the 10s of MHz frequency range.
3. *30 MHz to 300 MHz range:* This is the far-field radiated emission test range. In this frequency range, it is most likely that the failure mode is caused by the cable acting as an efficient antenna, leading to radiated emission issues. Beyond 300 MHz, radiated emission failures caused by power electronic devices become less common.

In addition to the EMI challenges mentioned earlier, there are other EMC-related concerns in such applications. These include low-frequency harmonics and immunity to surge and electric fast transients (EFTs). To improve harmonics and power quality performance, incorporating a power factor correction (PFC) circuit in the front end can be beneficial and has become a general practice in mains-powered products. A front-end filter can enhance immunity to surge and electric fast transients. This will be explored in more detail later.

## BENCHTOP TESTS AND TROUBLESHOOTING

Before delving into the design techniques for WBG device applications, it is essential to touch on the subject of benchtop tests and troubleshooting, which

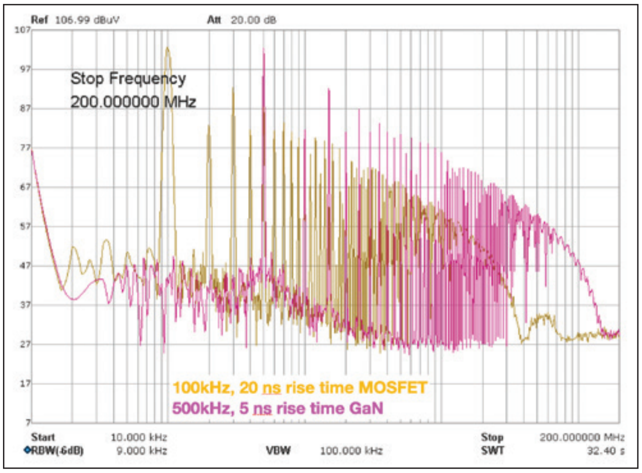


Figure 1: Near-field probe measurement of two switching devices, the device under test is a forward converter, with a duty ratio close to 50%.

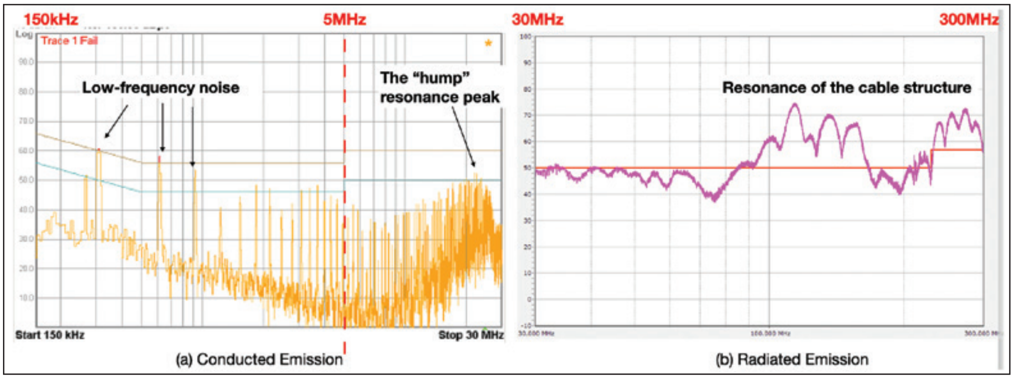


Figure 2: Common EMC test failures seen in applications with wide band gap devices

become more expensive and critical due to the unique characteristics of WBG devices:

1. *Expensive test equipment:* With faster switching frequencies and shorter rise times, an oscilloscope with a bandwidth of at least 500 MHz is necessary to accurately measure the rise time. This means investing in higher-end and more expensive testing instruments. It's worth mentioning that a 500 MHz bandwidth oscilloscope proves more advantageous for electronics development tasks than for EMC purposes (although a higher bandwidth always helps). This is particularly beneficial as engineers frequently require accurate rise time measurements to calculate switching losses and ensure overall system efficiency.
2. *Challenges with measuring:* Using a standard 500 MHz passive probe might not yield the most accurate results when measuring the switching events of WBG devices. Probe resonance and ground lead issues can introduce common impedance-induced errors, leading to inaccuracies in the measurements [4]. For precise measurements, a high-end optical isolated differential probe is preferred, but the cost of such a probe alone can easily exceed $10,000.

Moreover, the cost and lead time associated with taking the unit to an anechoic chamber for EMC tests adds further challenges to the development process. For companies with limited budgets, the high cost associated with developing new technology should not become a stumbling block. Therefore, we present here some effective and low-cost benchtop test methods that can often achieve reasonably accurate results. These methods are summarized in Table 1.

| Tests | Option 1 – with a spectrum analyzer | Option 2 – with an oscilloscope |
|---|---|---|
| Conducted Emissions | Test the unit with a LISN (with a transient limiter preferred). | Use an oscilloscope and then perform FFT analysis. |
| Radiated Emissions | Measure the common-mode noise on the cables with an RF current probe and predict far-field radiation. | Measure the voltage difference between primary and secondary ground or measure the common-mode noise on the cables with an RF current probe. |
| Troubleshooting | Combine both options using a near-field probe and an RF current probe. | |

Table 1: Proposed benchtop EMC tests for WBG applications

The test set-up for Option 1 is illustrated in Figure 3, where the device under test is a GaN transistor-controlled, mains-powered power supply. Conducted emission testing using a LISN is relatively straightforward, and the method of using an RF current monitoring probe to predict far-field emissions is detailed in [5].

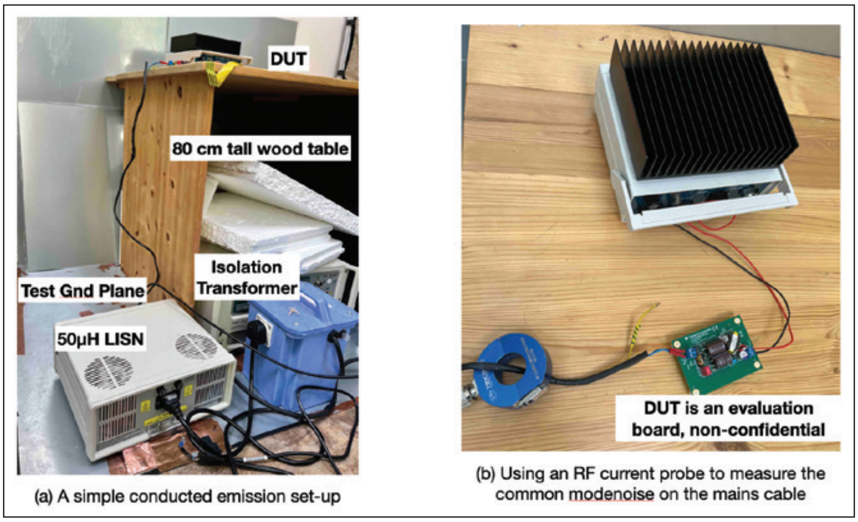


Figure 3: Proposed benchtop EMC tests, (a) measuring conducted emissions, and (b) measuring common mode current on cables to predict far-field emissions

For the Option 2 test setup, it's worth noting that one can accurately measure the rise time without the need for an expensive probe. Instead, a near-field magnetic field probe (even a simple homemade one like the 2 cm field loop in Figure 4) can be employed [6]. The significant advantage of this non-contact method is that it avoids direct electrical connections to the circuit under test, thereby eliminating common measurement errors.

Common-mode noise currents have the ability to flow between an isolated output ground (often referred to as 0V_gnd or secondary ground) and the power supply input ground (commonly known as HV- or primary ground). These currents can attain considerable amplitudes, leading to Ldi/dt voltage drops between the grounds. Additionally, when both input and outputs are wire-connected to the source and the load, these wires function as efficient dipole antennas.

A near-field probe can also serve to estimate the emissions level, although not with pinpoint accuracy; however, we can rely on some useful rules of thumb. For instance, as illustrated in Figure 5, using a square-shaped, near-field probe (with a measuring side conductor length of 1 cm in this case) to measure the potential difference between the primary and secondary "ground," any voltage exceeding 50 mV (I normally use 50 mV/cm rule) would be cause for concern in passing CE/FCC emission tests.

## USEFUL DESIGN TECHNIQUES

In this section, we will delve into the converter design, front-end filter, and shielding techniques, taking a GaN transistor-based charger as an example.

For chargers below 100 watts, the most popular topology is an active-clamped flyback converter. On the other hand, for chargers above 100W, the design of choice often involves an LLC with a PFC converter. Despite the topology specifics, we can generalize this type of isolated power supply as depicted in Figure 6.

### The Converter Design

In converter design, WBG devices find their primary application in the switching circuit on the primary side, including the PFC circuit (if present). However, on the secondary side, due to the lower voltage requirements, engineers tend to favor the use of MOSFETs for synchronous switching. As the power level increases, achieving this is often accomplished by either putting MOSFETs in parallel or employing interleave methods. To ensure the best EMC performance given design constraints, engineers should focus on three areas:

- *Transformer:* Whether designed in-house or bought off-the-shelf, the key consideration for EMC is the parasitic capacitance introduced by the windings. Minimizing the parasitic capacitance is essential, preferably aiming for it to be at least ten times smaller than the capacitance value of the Y-class capacitors used in such systems. Detailed design techniques for various converters are beyond the scope of this article. Another useful technique is to use a copper sheet (nicknamed "belly band") around the transformer (see Figure 7(a) on page 94). This sheet acts as a "flux cancellation" plane (as the induced eddy current forms a magnetic flux which is opposite to the transformer flux), and there is no need to "ground" the sheet, easing the manufacturing process.

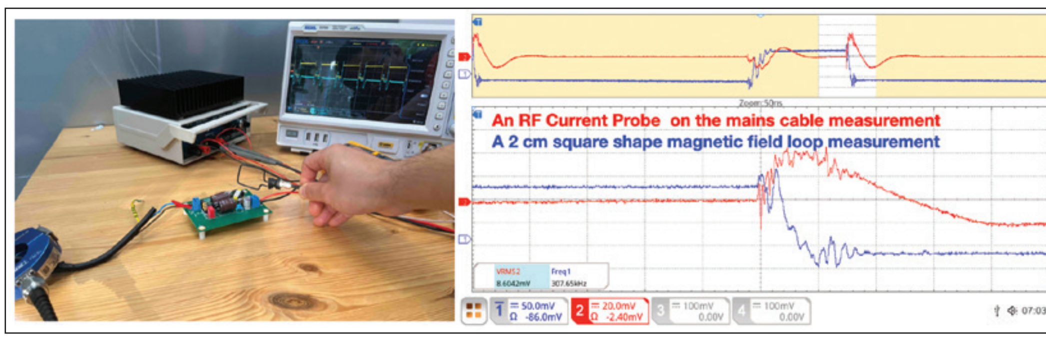


Figure 4: Using a near-field magnetic field loop to determine the switching characteristics

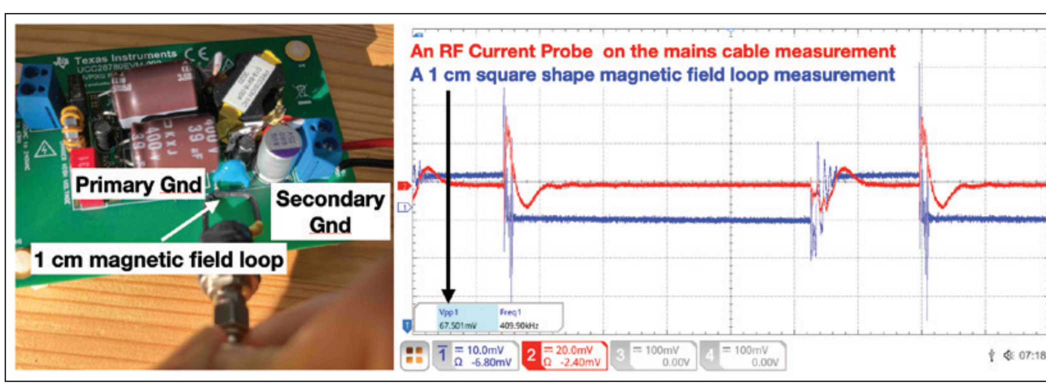


Figure 5: A 1 cm magnetic field loop can be used to predict far-field emissions

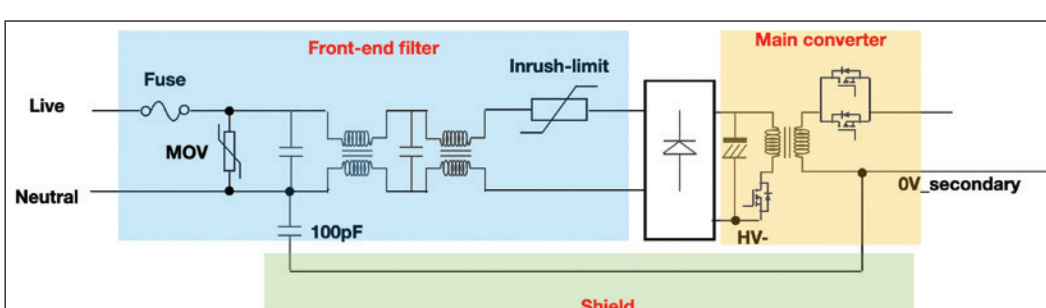


Figure 6: A simplified isolated power supply circuit

- *Grounds:* Both the primary and secondary grounds should have substantial copper areas on the PCB, preferably placed on the same side, with minimal distance between them (HV safety permitted). A Y-class capacitor is essential to join the two grounds, providing a low-impedance path for common mode currents. However, the capacitance value is limited by the maximum leakage current requirements.
- *DC link capacitors:* Achieving a low-impedance DC link is crucial, and this is typically accomplished through a combination of electrolytic capacitors and ceramic caps. Film caps are not suitable for the DC link in this application due to cost and size requirements. There have been discussions within some R&D projects regarding the replacement of electrolytic capacitors with high-capacitance ceramic capacitors to achieve a higher form factor. However, this proposition faces challenges currently:

1. Too many ceramic capacitors in parallel can lead to excessive and uncontrollable system resonance; and
2. Datasheets suggest that ceramic capacitors can exhibit very high equivalent series resistance (ESR) in the very low-frequency range, which adversely affects the performance of low-order harmonics if they replace electrolytic caps (see Figure 7 (b)).

As of now, these obstacles prevent the practical replacement of electrolytic capacitors with high-capacitance ceramic capacitors.

If not designed properly, significant ringing can be observed on the primary side switching with a GaN/SiC device. The ringing frequency depends on the stray inductance in the design (often the transformer leakage inductance) and the parasitic capacitance of the switching device. To reduce this ringing, considerable effort should be focused on the following approaches:

1. Implementing an RC snubber circuit;
2. Placing DC link decoupling capacitors close to the switch; and
3. Optimizing transformer design and implementing a shield over the transformer.

Since the primary switching event contributes significantly to high differential mode noise in the low-frequency range, minimizing the DC link impedance is crucial. This can often be achieved by optimizing the layout between the DC link and the switch. Additionally, utilizing spread spectrum techniques can help reduce low-frequency conducted emissions. From a control perspective, incorporating zero voltage switching (ZVS) as a feature in the control chip can lead to reduced switching loss and EMI.

It is worth noting that a control feature such as ZVS can sometimes introduce noise in light load conditions. It is the design engineer's job to check the EMI performance in all operation modes (light and heavy loads).

### The Front-End Filter

Considering the EMC challenges posed by WBG devices, the front-end filter plays a crucial role in ensuring the product passes EMC tests. While the MOV and in-rush current limiter designs follow standard processes, special attention must be given to the RF filter design.

Employing a two-stage filter is critical. The low-frequency conducted emission failures seen in the evaluation board

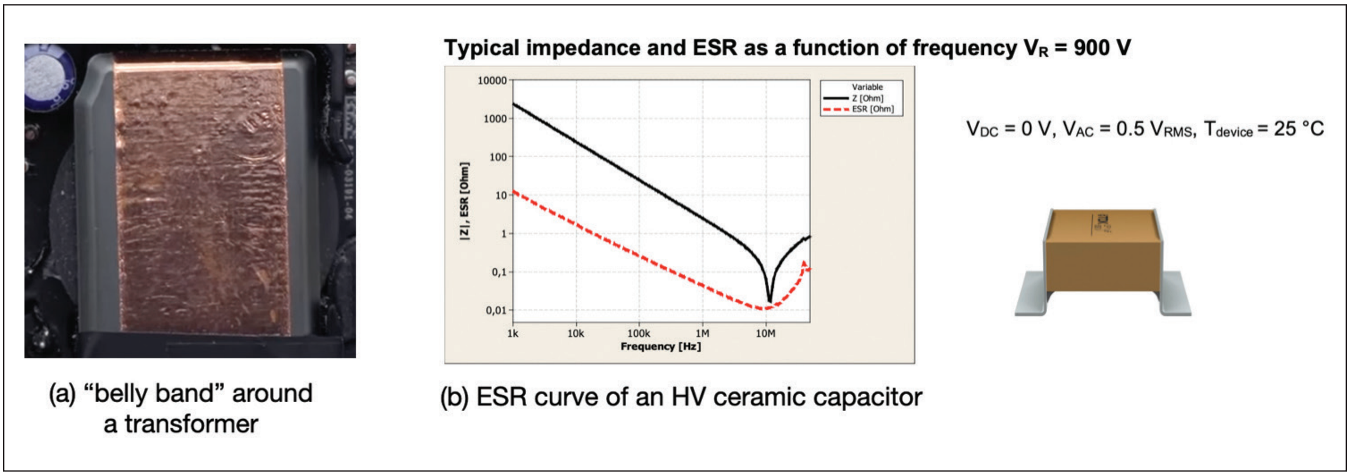


Figure 7: (a) a magnetic flux band around a transformer (b) High-voltage ceramic capacitors enjoy lower ESR & ESL at high frequencies, making them perfect for WBG applications. However, it's worth noting that at low frequencies, the ESR is high, courtesy of TD

(in Figure 2) occur due to the sole use of a one-stage filter. The capacitors used in the front-end filter should be film-type. For a more effective solution, a typical two-stage filter should incorporate two types of common mode chokes as key magnetic components:

- A sectional wound high inductance common mode choke to suppress noise between 150 kHz and 5 MHz; and
- A bi-filar wound, low inductance common mode choke for higher frequency noise suppression.

The sectional wound common mode choke, with its numerous turns and flat wire winding, unavoidably possesses high turn-to-turn capacitance, rendering it unsuitable for high-frequency suppression. However, it boasts a high leakage inductance, allowing for add-on differential mode filtering.

On the other hand, the bifilar wound common mode choke, designed for high-frequency filtering, cannot have too many turns. Its bifilar winding configuration wound on a toroidal core offers minimum leakage inductance (close to zero), making it ideal for high common mode noise suppression. Figure 8 illustrates both types of common mode chokes used in a charger.

By strategically combining these two-stage filters with different choke designs, a comprehensive and effective front-end filter can be achieved, ensuring successful EMC performance for WBG-based devices.

### The Shielding

In a GaN charger, a thin aluminum or copper sheet is often employed to further enhance EMC performance. While the metal's thickness means it may not be as effective for low-frequency magnetic fields, the shield serves its purpose due to the following reasons:

1. When wrapped around a transformer, it cancels some of the magnetic field by inducing eddy currents on the metal sheet; and
2. It provides electrical field shielding when properly "grounded." For manufacturing convenience, the ideal "grounding" point should be 0V_ground on the secondary side of the transformer. The other grounding point should be the earth point (if present). In the case of safety Class II products, where user protection from electric shock is achieved through two levels of insulation (double or reinforced) without the need for earthing, the shield is often connected to the neutral line via a small Y-class capacitor, as depicted in Figure 6.

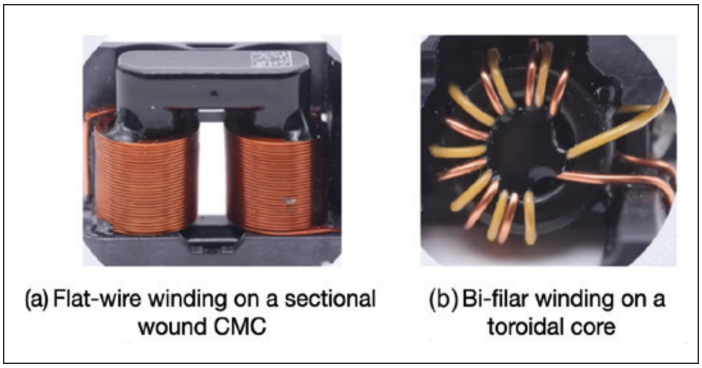


Figure 8: Two types of common-mode choke used in a front-end filter; photo taken from a 140 W Apple charger

## SUMMARY

This article aims to educate design engineers who are tasked with creating a product using wide-band-gap devices like GaN or SiC transistors. We've introduced the EMC challenges associated with WBG devices and propose cost-effective benchtop tests and troubleshooting methods. Additionally, we've presented useful design techniques that design engineers can follow to ensure their product's compliance when conducting EMC tests for the first time.

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# In-Situ Radiated Emission Testing of Large Systems Installations

## Combination of Near- and Far-Field Measurements for Radiated Emissions

*By Dr. Min Zhang*

As an EMC consultant, assessing the EMC performance of large systems and machines is a common task. Over the years, I have encountered a wide range of equipment, including high-power variable-speed drives (VSDs) in factories, specialized equipment installed on ships, food processing equipment, and many others. With technological advancements, there are now even more large systems that require in-situ EMC assessment, such as quantum computers, additive manufacturing machines, waste recycling equipment, renewable energy power generators, high-power electric vehicle chargers, and more.

While testing equipment in an accredited EMC chamber is ideal, it may not be a realistic option for large machines for several reasons. First, a large chamber is required to accommodate these machines. Second, while the chamber is being charged for use, it can take days or even weeks to install the machine in a chamber and then disassemble it after the testing is complete. Finally, logistics and lead time for using the chamber can also add to the overall cost and time required for EMC testing of large machines.

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Fortunately, the Technical Construction File (TCF) route to EMC compliance is available for everyone except those who manufacture radiocommunication transmitting products. Engineering companies, rather than those manufacturing mass-produced electronic products, may find the TCF route more cost-effective than the self-certification to standards route. For very large products or those that only come together on the customer's premises, it may be impossible to test to harmonized standards anyway. In such cases, the TCF route may be the only feasible option for EMC compliance. [1]

Among the various in-situ EMC tests that manufacturers can perform, the radiated emission test is one of the most important as it demonstrates that the unit does not interfere with other equipment nearby through electromagnetic radiation. However, the radiated emissions of a large unit can be challenging to assess in situ due to two main factors.

The first factor is ambient noise, which consists of nearby radio and TV broadcast transmitters, handheld devices like walkie-talkies, equipment and machinery used during the assessment, and ESD events.

The second factor is reflections caused by metal structures, including racks, cabinets, junction boxes, conduits, and pipes. If in-situ testing is not designed and performed correctly, there can be a significant difference between chamber testing and in-situ testing, sometimes up to a 20 dB difference. Therefore, it is essential to carefully consider and address these challenges during in-situ testing to ensure an accurate assessment of a unit's radiated emissions.

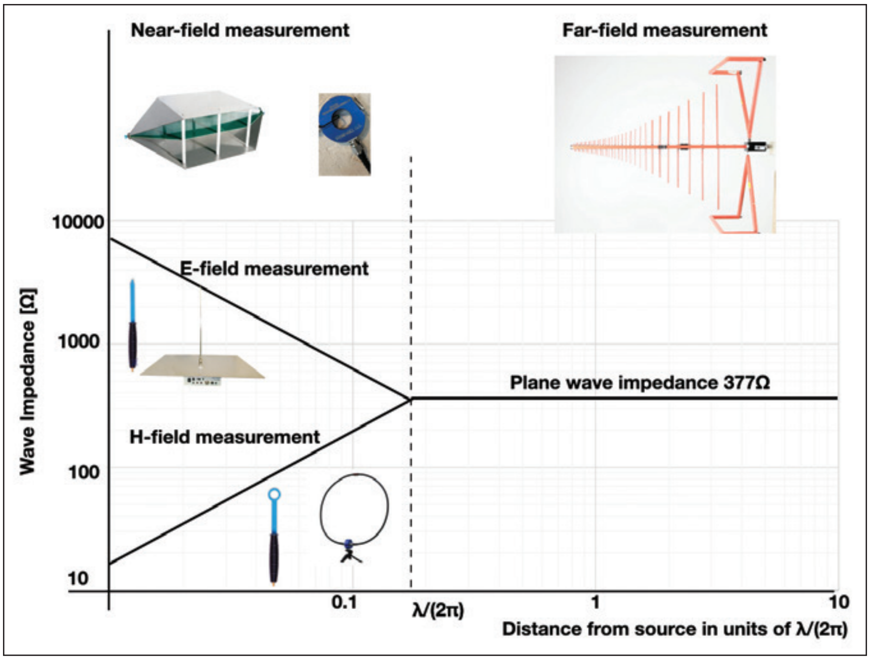


Figure 1: Near and far field measurement tools

## THE "THREE-STEP" APPROACH

In reference [2], Wyatt introduced a practical three-step approach for in-situ radiated emission assessment. The approach can be summarized as follows:

- *Step 1:* Conduct a near-field assessment to identify the sources of emissions, such as individual modules/components, and to determine their frequency and amplitude characteristics. This assessment often consists of two parts, one is a paper exercise, and the other is based on measurement results using near-field measurement tools;
- *Step 2:* Perform a cable structure radiation assessment to evaluate the emissions from cables and identify potential coupling paths; and
- *Step 3:* Conduct far-field measurements to assess the radiated emissions from the system as a whole.

This approach is theoretically sound and can be performed at a relatively low cost. Figure 1 lists some of the equipment that is often involved in performing both near- and far-field measurements. This article provides a detailed explanation of each step in the approach to facilitate a thorough understanding and effective implementation of the method for in-situ radiated emission assessment.

## STEP 1 – NEAR-FIELD ASSESSMENT

In a large unit, there can be many subsystems/modules, each with its own EMC characteristics. Some of the components are developed in-house. Therefore, engineers/system integrators will know the subsystem's electrical and electronics architecture (EEA). From the EMC perspective, we need to know:

1. The switched mode power supplies/motor drives in the subsystem, their switching frequency, and, if possible, their switching speed;
2. The ICs used in the subsystem, the clock frequency, the oscillator frequency, etc.;
3. Communication lines between the subsystems, whether the communication line is based on SPI, I2C, Ethernet, CAN, LIN, etc.; and
4. Wireless devices, such as WiFi and BLE modules, etc.

In a large unit, it is likely that many of the modules are commercial-off-the-shelf (COTS) parts, which means that the system integrators may not have the requisite knowledge of the internal design of these devices. COTS parts may or may not come with relevant regulatory certification (e.g., CE, FCC, etc.), and it is rare for them to be accompanied by EMC test results.

It is important to note that the idea of "CE+CE=CE" is a misconception [3]. When subsystems are integrated into a single system, the EMC performance is unknown, and it cannot be assumed that the final product will automatically meet the necessary EMC requirements.

Therefore, a near-field measurement of the subsystems is essential to ensure that all clock frequencies and their harmonics are recorded, as these spectrums may appear in the far-field measurement. In cases where the subsystem/module can fit in a TEM cell, I prefer to test and record the module using the TEM cell quickly. Most of the time, the modules in a large unit may not fit in a TEM cell; therefore, we use near-field probes (both magnetic and electric field loops) to "sniff" the subsystem and

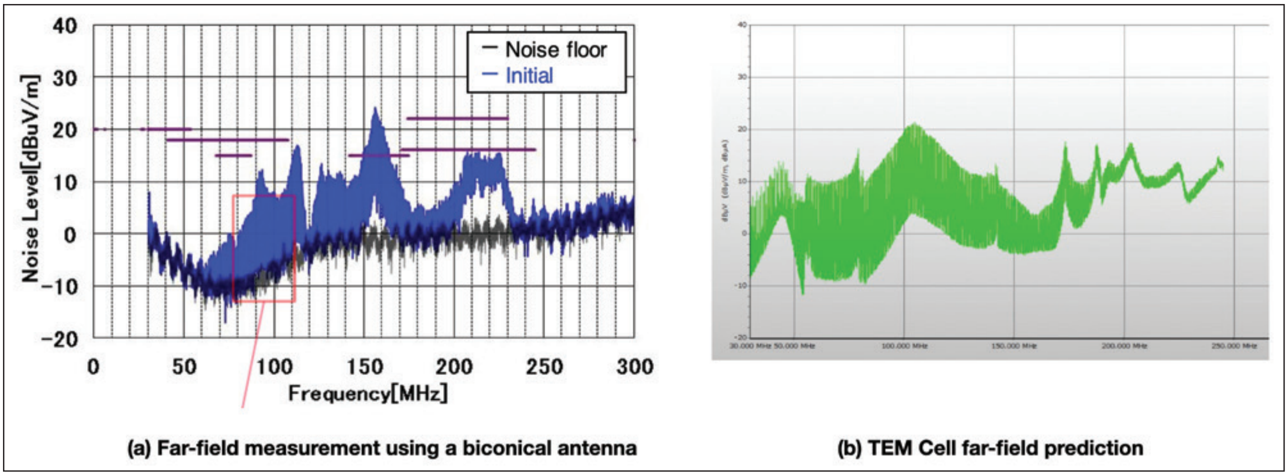


Figure 2: Difference between a far-field antenna measurement result and the TEM cell-predicted result

record spurious levels that could potentially radiate in the far field.

It should be noted that the purpose of these measurements is not to correlate the results in the far field. Instead, the information obtained from the near-field measurements is used to determine the frequencies of critical spurious emissions in the far-field results.

### Harmonics of Clock Frequencies

When documenting clock frequencies, it is important to consider their harmonics (up to the 9th harmonic). Certain harmonics can radiate more strongly than others depending on the physical structure, so it is important to take this into account during EMC testing.

A case study highlights this issue. In this example, a WiFi module from a trusted, well-established supplier was implemented in a large unit. The WiFi module passed all EMC and radio performance tests. However, the stacked board design of the unit (where the WiFi module is mounted) resulted in a structural resonance between 100 and 200 MHz. The communication between the WiFi module and the signal processing board was through the motherboard, and the clock frequency was initially set at 48MHz.

During far-field measurement, a 144MHz noise (the 3rd harmonic) was detected, exceeding the limit line. It was observed that odd harmonics of the clock frequency were radiating because of the 50% duty ratio of the clock signal. However, the data line had a broadband noise profile. When the clock frequency was reduced to 24 MHz, the 5th (120MHz) and 7th (168MHz) harmonics became high, indicating a structural resonance in the design.

This case study highlights the importance of considering the harmonics of each clock frequency during EMC testing. A noise source requires an antenna-like structure to radiate efficiently in the far field, so paying attention not only to the fundamental frequency but also its harmonics is crucial to identify potential sources of EMI and to develop appropriate mitigation strategies.

### Correlation Between the Near- and Far-Field Radiation

It is not recommended to use near-field measurement results to directly predict far-field emissions. This is because near-field readings are highly dependent on the geometry of the source and its properties, making it difficult to provide correlations between measurements performed in the near field and those done in the far field. While it is generally true that the stronger the field near the source, the stronger it will register in the far field, this correlation is not precise enough to provide reliable predictions [4].

IEC 61000-4-20 describes several methods for predicting radiated emissions using a transverse electromagnetic (TEM) cell, which differ in how many orientations of the device under test (DUT) are measured in the TEM cell to calculate the vector sum of emissions. The main simplifying assumption in this algorithm is that the radiating structures of the DUT have no greater gain than a dipole and a dipole radiating pattern [5]. The output of the algorithm measurements is then converted into an equivalent far-field value.

However, the effectiveness of this algorithm is limited, and a simple correlation between near-field and far-field measurements is not achievable based on tests we performed in the field. This is especially true if the module has cable connections to other modules in the system. Figure 2 demonstrates the difference between a far-field antenna measurement result and the TEM cell-predicted result.

## STEP 2 – MEASURING RF CURRENT ON CABLES

After conducting a near-field assessment, the next step is to use an RF current probe to measure a sampling of cables [2]. Inside the metal chassis (this often is the cabinet that hosts the overall system), there can be hundreds of wire connections. Monitoring each individual wire or cable bundle inside the metal chassis may not be practical, so attention should be paid to cables outside the metal chassis, such as power and signal leads. A metal cabinet often serves as a Faraday cage and attenuates the field generated inside the cabinet. It is also worth "sniffing" the seam or opening of the cabinet to check for any leakage fields that could potentially radiate.

When using an RF current probe to measure cables, it is recommended to make several measurements along the cable, as standing waves on the cable can cause readings to differ between different parts of the cable. Harmonics between 30 and 500 MHz should be noted down.

While there have been discussions on predicting far-field results using current probe readings, it is often found that the cable radiation prediction method works well up to a few hundred MHz. Above 300 MHz, cables start to attenuate RF current, which may cause the prediction method to over-predict the far-field results. Readers who want to explore this topic may find References [6] and [7] useful (in which the detailed calculation method is presented), and there are software tools available that can automate the whole process and present the results once the measurement is made, as demonstrated in reference [8]. Figure 3 shows the results of the RF current prediction method against antenna measurement. Notice that the antenna measurement inevitably picks up the radio transmitter signals (in this case, both FM and DAB), while the cable prediction method does not show these ambient spectrums.

## STEP 3 – FAR-FIELD MEASUREMENTS

In the final step of the radiated emission assessment, the radiated emissions from the DUT are measured using antennas. Both full-size and reduced-size antennas are available in the market for this purpose. While reduced-size antennas can be advantageous for far-field measurements above 200 MHz, as they can be moved around easily and placed in locations where a full-size antenna may not fit, they may not be suitable for measuring radiation fields between 30 MHz and 200 MHz. This is because reduced-size antennas often have lower sensitivity and a higher antenna factor (AF) compared to full-size antennas, resulting in higher system noise floors that can exceed the test limits being used for comparison. Therefore, it is always recommended to use a full-size antenna for measuring radiated emissions between 30 and 200 MHz.

Reference [2] proposes a circle 3 m from the faces of the system under test, and every 30 degrees should be measured. In some cases, due to the limited space where the large unit is located, moving the antenna closer to the DUT is an option. Reducing the measurement distance from 3 m to 1 m equals approximately 10 dB less free space loss or lifting the limits 10 dB higher. However, one should consider that the antenna may move into the near-field zone at lower frequencies.

One misconception is that using an active reduced-size antenna or connecting a low noise amplifier to a passive reduced-size antenna will lower the noise floor and increase sensitivity. However, this is only true in a chamber environment where the noise floor is generally low. In a non-chamber environment, the low noise amplifier amplifies both ambient noise and the signal being measured. As a result, the spectrum analyzer will beep constantly due to RF input overloading. Therefore, reduced-size antennas are always inferior to full-size antennas in terms of performance in the lower frequency range.

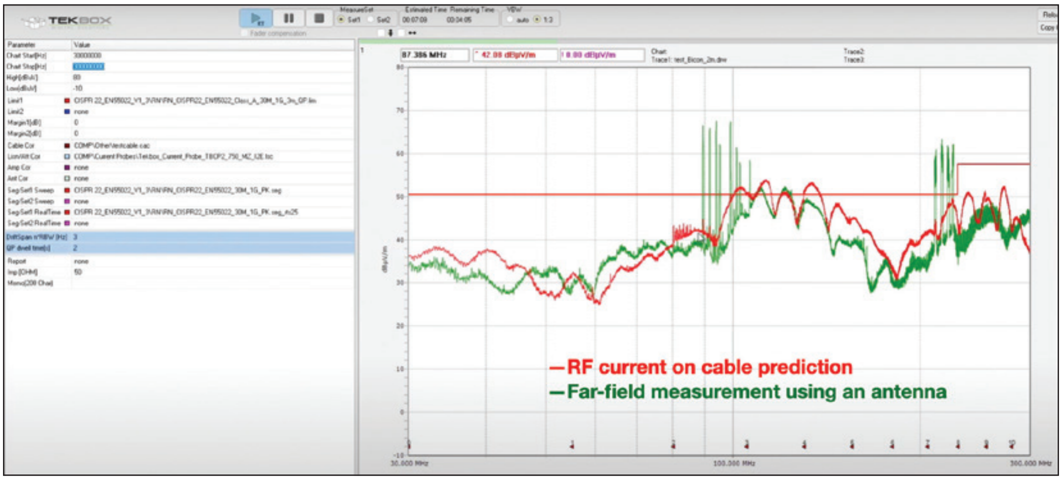


Figure 3: The RF current prediction method compared with an antenna measurement

When performing the far-field measurement, it is always recommended to measure the ambient noise first (i.e., while the DUT is in its off-state). For systems that cannot be easily shut down, such as quantum computers or additive manufacturing equipment, an EM survey before the system is installed is necessary, which requires early planning. Figure 4 shows an EM survey performed in a data center before the DUT was installed. One can spot the fire detection device on the wall, which radiates some narrow band spectrums. This information should be recorded in the ambient sweep.

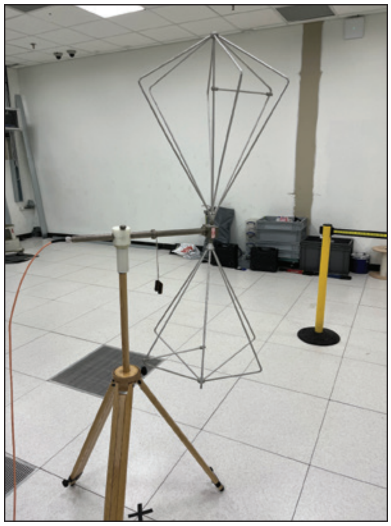

Figure 4: Ambient measurement before the DUT was installed

When conducting a pre-sweep of ambient noise, it is important to keep in mind that not all noise sources may be captured. Some sources may be intermittent or may only be present when other equipment nearby is turned on. Additionally, ESD events can also contribute to far-field radiation and may be picked up by the measurement antenna. In these cases, previously recorded near-field measurement results can be useful in determining whether the far-field radiation is coming from the DUT or ambient noise. Software that can load multiple results can be helpful in comparing and analyzing both the near- and far-field measurements.

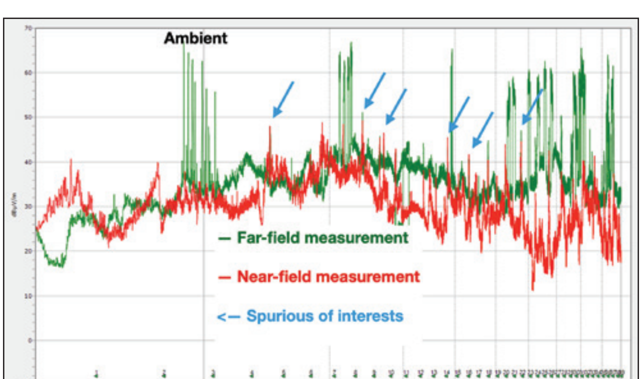


Figure 5: Using near-field measurement to help determine far-field emissions

An example of this is shown in Figure 5. In this case, the red trace shows the near-field measurement results while the green trace shows the far-field measurement. As it can be seen, the ambient noise can be distinguished so that we can focus on the noise generated by the DUT (the blue pointers shown in Figure 5). Quasi-peak scans can then be performed on selected points to determine whether the noise exceeds the limit line.

## SUMMARY

This article presents a step-by-step approach to in-situ radiated emission tests. A combined near-field current probe, and far-field measurement are essential to get the true characteristics of the EMC performance of a large unit. Correlation methods between the near- and far-fields are discussed, and their accuracy is presented. Readers should now have a good idea of how to perform in-situ radiated emission tests.

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# The EU's New Product Safety Law Will Be a Game Changer

## Companies Must Prepare to Embrace the New Rules

*By Rutger Oldenhuis*

On April 25th, the Council of the European Union (EU) adopted the long-awaited EU General Product Safety Regulation (GPSR). The adoption of the GPSR was the final step of the revision of the outdated EU General Product Safety Directive (Directive 2001/95/EC, or GPSD). The GPSR will enter into application on 13 December, 2024.

The ink has yet to dry, but one thing is certain: selling consumer products in the EU will never be the same. That applies both to manufacturers based in and outside the EU. In this article, I summarize the main highlights of the GPSR.

### A REGULATION AND NOT A DIRECTIVE

First of all, the GPSR is a regulation and not a directive. A regulation has a direct effect in all EU Member States without the intervention of national legislators. A directive needs to be transposed into national law and often allows Member States to include deviating provisions, which obviously jeopardizes the single market principle. That is no longer possible with a regulation. The provisions of the GPSR, therefore, apply in full in all EU Member States.

### SAFETY NET

Like the GPSD, the GPSR is a legal safety net, but it contains more extensive and more far-reaching provisions than the GPSD. Some of the provisions do not apply to products covered by Union harmonization (or sectoral) legislation since they are already covered in such legislation. Other provisions do apply in order to complement Union harmonization legislation, for example, when certain types of risks are not covered by that legislation. This sometimes makes it a difficult puzzle to determine which provisions of the GPSR do or do not apply to a specific product. It is important to note that the provisions in some areas (for example, recalls and remedies) apply to all products within the scope of the GPSR.

### THE SCOPE OF THE GPSR

The GPSR applies to consumer products but excludes the following products:

a. Medicinal products for human or veterinary use;

b. Food;

c. Feed;

d. Living plants and animals, genetically modified organisms, and genetically modified microorganisms

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in contained use, as well as products of plants and animals relating directly to their future reproduction;

e. Animal by-products and derived products;
f. Plant protection products;
g. Equipment on which consumers ride or travel where that equipment is directly operated by a service provider within the context of a transport service provided to consumers and is not operated by the consumers themselves;
h. Aircraft referred to in Article 2(3), point (d) of Regulation (EU) 2018/1139; and
i. Antiques.

It is worth noting that the GPSR now also covers software embedded into a product as well as stand-alone software. The GPSR also addresses the safety of products linked to new technologies and the new risks to consumer health, safety, and personal security posed by these technologies.

The regulation is applicable to new, used, repaired, or reconditioned products but does not extend to products marked for repair or reconditioning before use. Furthermore, the GPSR operates without prejudice to the rules established by Union law on consumer protection.

## INTRODUCTION OF "HEALTH" CONSIDERATIONS

Remarkably, the GPSR refers to the WHO definition of "health:" *"The World Health Organization defines 'health' as a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity."* The term "product safety" thus takes on a much broader meaning and a whole new dimension.

We should not underestimate the profound implications that this legislative shift can bring to the legal landscape. Manufacturers should adopt a broader and more comprehensive perspective when assessing potential health risks associated with the products they bring to the market.

Let's use mobile phones as an illustrative example. It has become increasingly evident that providers of social media applications employ algorithms intentionally designed to foster addictive behavior. Additionally, a growing body of scientific research underscores the potential adverse effects of mobile phones on the mental well-being of children.

While an outright ban on mobile phones may appear implausible when compared to the regulation of, for example, alcohol or cigarettes, there is a growing recognition of the need for measures to significantly reduce their usage. Within the EU, we are already witnessing the emergence of initial initiatives aimed at addressing this issue.

Furthermore, the proposed EU Product Liability Directive notably introduces a clear definition of "product" that explicitly encompasses "software." Additionally, it specifies that the term "damage" should be understood as "material losses resulting from death or personal injury, including medically recognized harm to psychological health." This reflects the EU's efforts to adapt product liability regulations to the digital age and acknowledge that software, as a product, can have wide-ranging implications, including not only physical harm but also harm to mental health.

The possibility of class-action lawsuits against mobile phone manufacturers and social media giants like Facebook is not beyond consideration.

## RISK ASSESSMENT (PRE-MARKET)

Compared to the GPSD, the GPSR gives much more attention to risk assessment. Unless already covered by Union harmonization legislation, the GPSR requires manufacturers to conduct an internal risk analysis and draw up technical documentation. In other words, in most cases, a manufacturer will have to conduct a risk analysis and prepare technical documentation before a product is put on the market.

In line with the previous section, it is remarkable that "mental health" must also be included in that risk assessment. The GPSR, for example, stipulates that a risk assessment:

> *"[…] should take into account the health risk posed by digital connected products, including on mental health, especially on vulnerable consumers, in particular children. Therefore, when assessing the safety of digital connected products likely to have an impact on children, manufacturers should ensure that the products they make available on the market meet the highest standards of safety, security and privacy by design in the best interests of children."*

This may influence the way we assess the risks of, for example, gaming and social media. And what to think of the metaverse?

## QR CODE NOT ACCEPTED AS THE ONLY MEANS OF PROVIDING PRODUCT SAFETY INFORMATION

The QR code has been commonly accepted as a means to provide consumers with product safety information and instructions. However, despite heavy lobbying, the

GPSR does not accept E-labelling as a replacement for old-fashioned labeling and thick multilingual manuals. Pursuant to the GPSR:

> *"…manufacturers shall ensure that their product is accompanied by clear instructions and safety information in a language which can be easily understood by consumers, as determined by the Member State in which the product is made available on the market. That requirement shall not apply where the product can be used safely and as intended by the manufacturer without such instructions and safety information."*

However, this provision does not apply to products covered by Union harmonization (or sectoral) legislation. For example, pursuant to the upcoming EU Machinery Regulation, which will replace the current Machinery Directive, instructions may be provided digitally.

## ONLINE PLATFORMS ARE THE "NEW MARKET SURVEILLANCE AUTHORITIES"

An entirely new section has been included in the GPSR, detailing obligations for "providers of online platforms." This seems to be a real game changer for both providers of online platforms and all economic operators who sell products through online platforms. Although providers of online platforms are not liable for the compliance and safety of the products themselves sold through their platform, they must ensure – through a battery of due diligence obligations – that traders using their platform only sell products that comply with applicable laws and regulations.

These provisions make providers of online platforms *de facto* the new "gatekeepers" when it comes to product compliance and safety. Since most traders sell products through online platforms, this could have a tremendous (and hopefully positive) impact on the level of product compliance and safety. If traders want to sell their products via Amazon or the like, they should be in control of their product compliance and safety processes. In case of repeated non-compliance, pursuant to the GPSR, providers of online platforms will have to suspend their services to that trader until further notice.

## TRADERS OUTSIDE THE EU SELLING DIRECTLY TO THE EU SHOULD ESTABLISH IN THE EU

Pursuant to the GPSR, economic operators established outside the EU can no longer sell directly to consumers in the EU through online channels without having a representative established in the EU. The representative established in the EU is the person or entity to be contacted if products do not comply with EU legislation.

The GPSR states:

> *"Direct selling by economic operators established outside the Union through online channels hinders the work of market surveillance authorities when tackling dangerous products in the Union, as in many instances economic operators may neither be established nor have a legal representative in the Union. It is therefore necessary to ensure that market surveillance authorities have adequate powers and means to tackle in an effective manner the sale of dangerous products online."*

Economic operators established outside the EU must:

> *"…ensure that there is a responsible economic operator established in the Union, which is entrusted with tasks regarding such products, providing market surveillance authorities with an interlocutor and, where appropriate with regard to the possible risks related to a product, performing specific tasks in a timely manner to ensure that the products are safe. Those specific tasks should include regular checks with regard to compliance with the technical documentation, product and manufacturer information, instruction and safety information."*

Companies located in countries outside the EU (e.g., the United States) that wish to sell directly to consumers and other parties in the EU will have to prepare to comply with this new requirement.

## ACCIDENT REPORTING DUTY

The GPSR introduces an obligation for manufacturers to report "without undue delay" accidents caused by products they have placed on the market. Accidents are defined as occurrences that result in an individual's death or serious adverse effects on their health and safety. The report must be made to the competent Market Surveillance Authority of the Member State where the accident occurred. Importers and distributors also play an important role since they must report accidents to the manufacturer.

## DO YOU HAVE A RECALL PLAN?

The GPSR prescribes that economic operators shall ensure that they have internal processes for product safety in place, allowing them to comply with the relevant requirements of the GPSR. This typically includes a Corrective and Preventive Action (CAPA) plan. Again, a reservation must be made regarding products subject to specific Union harmonization legislation.

In any case, it is highly recommended to properly safeguard internal processes for product safety within an organization. For example, companies may ask themselves the following:

- Do we have an adequate risk analysis procedure in place?
- Do we have a CAPA procedure in place?
- Do we have proper design validation procedures in place, considering the intended users and use?
- Do we have a proper complaint system in place?
- Does the executive management team take ownership of product compliance and safety within your company?
- Do we have proper procurement procedures and supplier agreements in place?

Companies seeking to enhance their product safety and recall procedures can consider using two ISO standards that are not widely known: ISO 10377, "Consumer product safety – Guidelines for suppliers," and ISO 10393, "Consumer product recall – Guidelines for suppliers." Both large and small businesses can use these standards to evaluate and enhance their safety procedures throughout the product development, production, and distribution phases. These standards emphasize that defects in design and production can be significantly reduced through preventative measures.

## RECALLING A PRODUCT? AT LEAST TWO REMEDIES

In the event of a product recall, the GPSR stipulates that consumers should be given a choice of *at least two* of the following remedies: repair, replacement, or a refund. Consumers may only be offered one remedy if the other remedies are impossible or disproportionate. This obviously leads to a discussion about what is meant by "disproportionate."

I often make a comparison with the car industry, where repair seems the only proportionate remedy. We can all understand that, with some exceptions, a replacement or refund for a car that can be repaired would be disproportionate. Another example of a recall remedy that appears disproportionate is when a regulatory body responsible for market surveillance demands that a manufacturer of premium e-bikes provide consumers with a refund instead of a repair.

Moreover, from a sustainability point of view, repair is probably the better option. With the new EU proposal on the "right to repair" for consumers, it is remarkable that a minimum of two remedies must be offered for recalls, while repair is clearly the most proportionate and sustainable remedy.

## A SNAG THAT CAN MAKE THE BURDEN OF A RECALL EVEN BIGGER THAN IT ALREADY IS

EU legislation normally excels with vague texts and open norms, which need further clarification by means of guidelines or that are expected to be further fleshed out by judges in court. It is, therefore, remarkable that some provisions of the GPSR contain very detailed provisions.

On the one hand, that is commendable; on the other hand, it can be very tricky. Here's an example. In Chapter VIII, the GPSR prescribes that, in the event of a recall, the consumer must be instructed to "immediately stop using the affected product." In addition, the GPSR stipulates that, in the event of a recall, the economic operator must collect the unsafe product from the consumer "if it is not portable."

If we take this literally and apply it to dangerous cars, for example, consumers should stop using that car immediately, and the car would be required to be collected from the consumer by the manufacturer (or dealer). The question is whether this is really intended. It would undoubtedly lead to a logistical nightmare and a huge financial burden. Stakeholders, such as trade associations, seem to have overlooked this in the drafting phase of the GPSR.

## GPSR VS. SECTORAL LEGISLATION

I contacted the EU Commission to highlight what appears to be a snag in the GPSR. Using cars as an example, their first reaction was that Chapter VIII of the GPSR does not apply to cars since there is already harmonized legislation in place providing certain provisions, including on recalls (EU Regulation 2018/858). However, the question is whether that is a correct assessment.

The EU GPSR is a so-called horizontal regulation that sets out general safety requirements for all consumer products (except if explicitly excluded from its scope) sold in the EU, including motor vehicles. Sectoral car legislation, such as EU Regulation 2018/858 on the approval and market surveillance of motor vehicles and their trailers, provides more specific safety requirements for motor vehicles and their components. However, it does not replace or derogate from the requirements of the GPSR. The sectoral legislation sets out additional requirements for the safety and performance of motor vehicles and their components but does not relieve manufacturers of their obligations under the GPSR. Therefore, any additional obligations under the GPSR would still apply to the car industry alongside the requirements of the sectorial car legislation.

Since the GPSR stipulates more detailed obligations with regard to remedies and recalls, such obligations would apply to all consumer products sold in the European Union that fall within the scope of the GPSR, including motor vehicles. The sectoral car legislation does not exempt motor vehicles from the requirements of the GPSR. Therefore, any additional obligations under the GPSR regarding recalls would be applicable to the car industry, as well as other industries. There are no provisions in Regulation 2018/858 specifically dealing with recall notices (e.g., "stop riding") and remedies (e.g., collecting non-portable products). Hence, we may argue that Chapter VIII is also applicable to cars and other products that are covered by sectoral legislation.

If the Commission intended to exempt products covered by sectoral legislation from the application of Chapter VIII of the GPSR, then Chapter VIII should have been listed in Article 2(1)(b), which outlines the chapters exempted from the scope of the GPSR.

At the time of writing this article, my discussion with the EU Commission was still ongoing. Based on their latest reaction, it seems that they understand my concern. The EU Commission is still in the process of internal discussions regarding this matter. It is anticipated that the EU Commission will release guidelines aimed at assisting industries and other stakeholders in comprehending and applying the GPSR. These guidelines might offer some flexibility and proportionality with regard to the concerns addressed.

However, it is important to note that these guidelines do not carry the same legal weight as the GPSR itself, which is an official law. Consumers or their representative associations have the right to directly reference the explicit text of the GPSR when seeking to address related issues.

## IT WILL BE EASIER FOR CONSUMERS TO SUBMIT COMPLAINTS TO AUTHORITIES

The "Union Rapid Information System," previously known as RAPEX, will be modernized to enable more efficient corrective measures to be taken across the EU. One of the aims is to make it easier to inform the public and enable consumers to submit complaints. Manufacturers and their reputation for product quality and safety will, therefore, have increased exposure.

## PENALTIES

As a final comment, it is important to realize that the GPSR introduces penalties for those who violate the GPSR. *"Member States shall lay down the rules on penalties applicable to infringements of the GPSR that impose obligations on economic operators and providers of online marketplaces and shall take all measures necessary to ensure that they are implemented in accordance with national law."*

The EU Commission *"should carry out an evaluation of the implementation of the penalties laid down under the GPSR as regards their effectiveness and deterrent effects, and, where appropriate, adopt a legislative proposal in relation to their enforcement."*

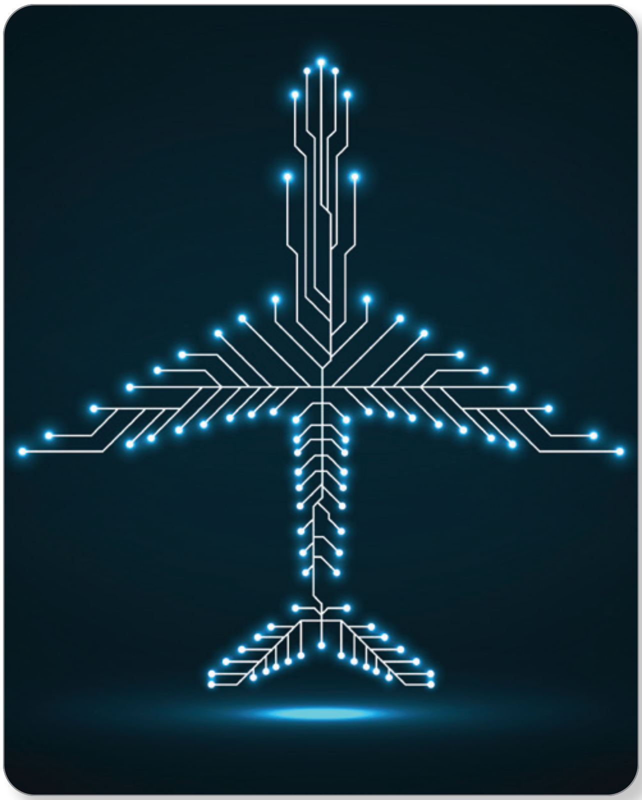
## CONCLUSION

A new wind is blowing in the EU in the field of product safety. Although the GPSR is not perfect, we can only welcome its arrival. Clearly, if you sell consumer products in the EU, you need to have your product compliance and safety processes in place. Only companies that take product safety seriously will be the winners in a market where product laws and regulations are becoming increasingly complex and demanding.

# An Overview of Aerospace Battery Compliance

## Performance and Safety Requirements for Batteries Installed in Aircraft

*By John C. Copeland*



Like everything else in our modern world, electrification is extending to aviation. Although much of this transformation involves the aircraft's onboard power generation capabilities such as generators, alternators, magnetos, and auxiliary turbines, battery energy storage systems are becoming increasingly more important. This ranges from small format batteries that provide keep-alive power for memory circuits in avionics to larger battery devices that provide the main source of power to propel the aircraft.

Given the nature of air travel, such batteries and their component cells must perform as designed and operate safely in their applications. In the United States, the Federal Aviation Administration (FAA) is the primary regulatory authority for aviation and is responsible for developing, implementing, and enforcing regulations to protect the public. This authority extends to the regulation of portable energy products that are considered a part of the aircraft itself.

The FAA produces a multitude of regulations and supporting guidance documents. As a point of fact, there are over fifty types of documents that are used for both internal and external purposes. General guidance on these document types can be found at https://www.faa.gov/guidance. Of interest to aerospace battery compliance, we will focus on two of these document types used to promulgate regulatory information to both FAA personnel and the public, as follows:

- *Advisory Circulars* (AC's) are used to uniformly *"…deliver advisory material to FAA customers, industry, the aviation community, and the public."* All such ACs are maintained in a common database.
- *Technical Standard Orders* (TSO's) are intended to provide guidance of a technical nature to FAA personnel. However, the aviation industry as well as the general public make use of these documents to aid in compliance efforts and to foster a general understanding of the agency's efforts. Like the ACs, TSOs are maintained in a common database by the FAA.

Like many other regulatory agencies, the FAA will sometimes rely on the industry being regulated as a partner in establishing specific testing requirements.

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Although this may seem to some as a classic case of "the fox guarding the hen house," the truth is that the industry is incentivized to help develop a reasonable set of tests sufficient to support the stated intent of showing an acceptable level of both safety and performance. The industry knows that any safety failure has negative consequences for the entire industry, not just the company impacted, both in terms of governmental response as well as damage to the public's view of the industry itself. They also fully understand that if they fail to develop an acceptable test standard, the regulatory agency could take steps to develop one unilaterally without direct industry participation. Such an outcome would be considered less than ideal by most industry participants.

In the case of aviation, such standards development is commonly coordinated through the Radio Technical Commission for Aeronautics, now referred to simply as RTCA (https://www.rtca.org). RTCA is a non-profit organization founded in 1935 and is self-described on its website as "…the premier Public-Private Partnership venue for developing consensus among diverse, competing interests on critical aviation modernization issues in an increasingly global enterprise." (The RTCA test standards referenced here are copyrighted materials and can be purchased through RTCA.)

In the case of aviation battery regulations, several standards have been developed over time to address different chemistries. A summary of the regulatory references and their associated standards is given in Table 1.

The requirements for rechargeable lithium (typically lithium-ion) reflect some further nuanced specifications based upon their configuration and sample size. These requirements are detailed in Table 2.

In addition to the test requirements previously cited, the TSOs noted in Table 1 also refer to other RTCA standards for various design aspects (see Table 3).

Note also that certain types of battery-supported equipment have their own separate TSOs that may have battery requirements in addition to those noted so far. An example of this is TSO-C200a, titled "Airframe Low Frequency Underwater Locating Device (Acoustic) (Self-Powered)." These devices use non-rechargeable lithium batteries, but the TSO requires that the requirements given in RTCA/DO-227A be supplemented with selected tests from RTCA/DO-347, which is intended for rechargeable lithium batteries.

It should be clear that compliance with the stated requirements can be complex. The discussion in the preceding paragraphs does not cover every situation but rather attempts to depict those cases considered most typical to illustrate concepts common to the various regulatory requirements. Users of this information are cautioned to fully research their product's regulatory situation to ensure that the appropriate guidelines are being utilized.

As a general rule, the regulatory requirements should be confirmed early in the process with one's customer as well as the FAA or their Designated Engineering Representative (DER). From some perspectives, these discussions may be considered a negotiation as it is

| Battery Chemistry | Advisory Circular | Technical Std Order | Referenced Test Standard |
|---|---|---|---|
| Rechargeable Lithium | AC 20-184 | TSO-C179b | See Table 2 |
| Non-Rechargeable Lithium | ----- | TSO-C142b | RTCA/DO-227A |
| †Lithium Sulfur Dioxide | ----- | TSO-C97 | 14 CFR § 37.209 |
| Nickel Cadmium, Nickel Metal Hydride, Sealed Lead Acid | ----- | TSO-C173A | RTCA/DO-293A |

*†Lithium Sulfur Dioxide is a specific type of non-rechargeable lithium batteries that have unique regulatory requirements.*

Table 1: Linkage of battery chemistry to test standards

| Battery Size | Configuration | Energy (Watt-Hours) | Referenced Test Standard |
|---|---|---|---|
| Coin and Button Cells | Single or Multi-Cell | Wh < 2 | UL 1642, UL 2054, IEC 62133 |
| Small/Medium* | Single Cell | 2 ≤ Wh < 60 | RTCA/DO-347 |
| | Multi-Cell | 2 ≤ Wh < 300 | |
| Large | Single Cell | Wh ≥ 60 | RTCA/DO-311A plus selected tests from RTCA/DO-347 |
| | Multi-Cell | Wh ≥ 300 | |

**The terms "small" & "medium" are not differentiated in TSO-C179b but appear to generally reference the Energy Categories given in RTCA/DO-347. As noted above, they are treated the same for test purposes.*

Table 2: Rechargeable lithium test requirements

| Design Aspect | Advisory Circular | Referenced Test Standard |
|---|---|---|
| Software | AC 20-115C | RTCA/DO-178C |
| Complex Hardware | | RTCA/DO-254 |
| Flammability | AC 20-152 | |

Table 3: Additional standards to consider

Like the negotiation around the test requirements, there will need to be an agreement with the party responsible for conducting the testing. In some cases, the equipment vendor may have the expertise and equipment necessary to do the work in-house.

possible in some cases to modify requirements or have them waived altogether if the specific situation warrants. Any such changes will be recorded in a document known as a Quality Test Plan (QTP).

A QTP is a detailed document that describes the product but, more importantly, defines in detail how the tests are to be run. Development of this document is accomplished by the client with input from their test provider that might include equipment types and additional product-specific detail. The intent is to provide enough detail to reconstruct the test but not so much detail that the document becomes encumbered with information that does not significantly impact the conduct of the testing. It is not uncommon for such documents to be anywhere from 50-150 pages in length. The QTP will also form the basis for the final report.

It is important to realize that the scope of the testing includes the entire tier structure of the device. This may include component cells, battery packs, or the supported device (the equipment under test or EUT).

The testing itself may include:

- Electrical performance tests like capacity at temperature or high current discharge;
- Mechanical or environmental tests like vibration, drop, or thermal cycling. These are commonly specified as tests from the current revision of RTCA/DO-160, which covers environmental requirements for aviation electronics;
- Safety tests such as short-circuit or overcharge; and
- EUT-level tests such as thermal runaway containment.

Like the negotiation around the test requirements, there will need to be an agreement with the party responsible for conducting the testing. In some cases, the equipment vendor may have the expertise and equipment necessary to do the work in-house. For others without such internal resources, an external lab that has been accredited to the test standards involved may be selected. There also exists the possibility that a hybrid testing model will be used where both internal and external resources are being used to accomplish the needed testing.

Because of sensitivity around lithium battery safety due to widely publicized incidents both within the aviation industry as well as other non-aviation industries, it is not uncommon for customers further down the value chain to request the opportunity to witness some of the testing that is considered to represent greater risks. In some cases, the DER/FAA may also wish to witness certain tests. Such monitoring may be done onsite or remotely through commonly available meeting applications.

Unlike many other standards, the total number of samples required for RTCA rechargeable battery test regimes is relatively small (by its very nature, non-rechargeable battery testing requires larger sample sizes). This is achieved by specific samples being assigned to specific tests (very significant reuse), the sequential order of the testing being defined for each sample, and the number of replicates for any given test kept to a minimum. On balance, the testing takes longer than some other regimes since much of the testing is run in series instead of parallel.

Conduct of the test regime requires that all samples be "conformed" prior to the start of any testing. This means that all test samples are verified to ensure that they are in the correct state for testing and are not damaged in a way that might negatively impact the test. The QTP is the reference for defining the correct pre-test state. Pre-test documentation will also include pictures. Execution of certain tests may require video of testing in progress in addition to the various parametric measurements called for in the test descriptions. Finally, post-test, the units are inspected with any anomalies being documented in writing and with pictures.

Formal report generation can be extensive due to the significant number of tests involved as well as the supplemental data and photo requirements. Having a report template developed at the beginning of the process can minimize the reporting effort required at the end of the test. It also helps identify key test aspects that must not be overlooked. Some labs will go a step further and develop lab-specific checklists or data sheets. These documents may be included in the QTP and/or report template.

Any negative findings will require some degree of analysis and corrective action once it has been established that the finding was attributable to the product itself and not the result of a test anomaly. Once the corrective actions have been implemented, a recovery test plan will be developed between the product manufacturer, their customer, and the FAA representative or their designate. It is possible that the implemented changes may require that other non-failed tests be repeated if there is a potential that the changes may have an impact on those test outcomes. Once again, a revision to the report will be generated that appends the existing report with the new data.

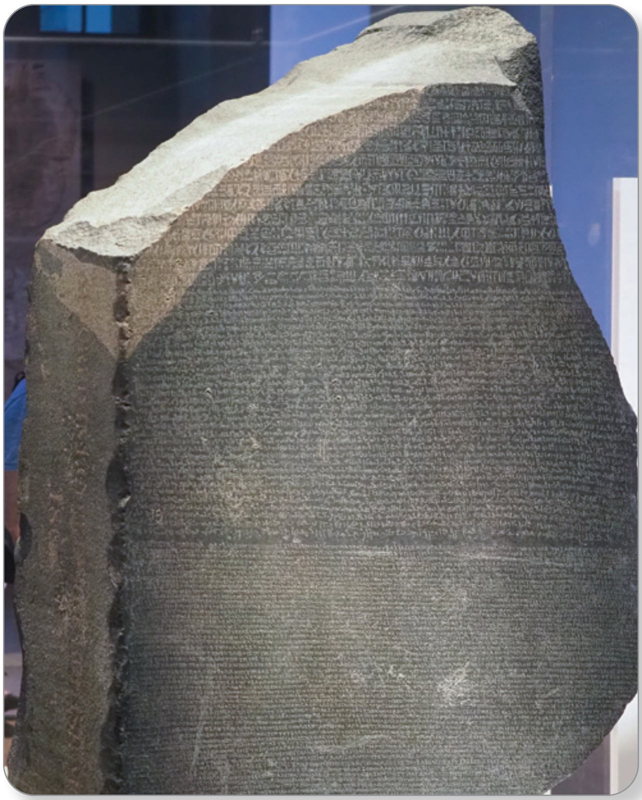
In conclusion:

- The method of compliance for aerospace battery applications in the United States is specified in the regulations and supporting guidance published by the FAA.
- The relevant FAA guidance document types include Advisory Circulars and Technical Standard Orders.
- Such regulations reference industry-developed test standards available from sources like RTCA, UL, and IEC.
- Common chemistries such as lithium-ion, NiCd, NiMH, SLA, and non-rechargeable lithium are included.
- The testing may include cells, battery packs, or the supported device (EUT).
- The process for complying with such standards is formally documented in a QTP that serves as an agreement with the manufacturer, their customers, and the FAA. It also provides the detailed test plan and reporting requirements for the test laboratory conducting the test program.
- The testing uses a minimum number of samples overall because it is sequential in nature. But this usually equates to a longer test duration than some other standards that utilize parallel testing.
- There are many nuances to FAA compliance, so it is imperative that the specific requirements for a given product are thoroughly researched and verified prior to beginning what is a rather extensive compliance effort.

# (Re)Discovering the Lost Science of Near-Field Measurements

## Understanding Radiated Emissions Measurements Made at One-Meter Separation: It's Not What You've Been Led to Believe

*By Ken Javor*



### BACKGROUND[1]

The first article in this series (see "Seventy Years of Electromagnetic Interference Control in Planes, Trains, and Automobiles (and Ships and Spaceships, as well) on page 48) described in detail the use of radios that used unshielded connections (termed antenna lead-ins) between the radio and the external antenna.[2] The antenna lead-in was a single wire above ground, using aircraft structure for a return path, that was connected to high impedances at both ends. That is, the radio input was the grid of a vacuum tube, so basically a small capacitance, and the external antenna was an electrically short wire over most of the 0.15 – 20 MHz (200 –15 meters) frequency (wavelength) range of the radio.

Figure 1 shows a WWII-era handbook drawing of such an installation.[3] Handbooks of the time went to great lengths showing photographs of poor and good radio antenna lead-in installations.[4] Controlling the loop area of the lead-in over ground relative to that of adjacent culprit noise emitters (crosstalk) was emphasized.

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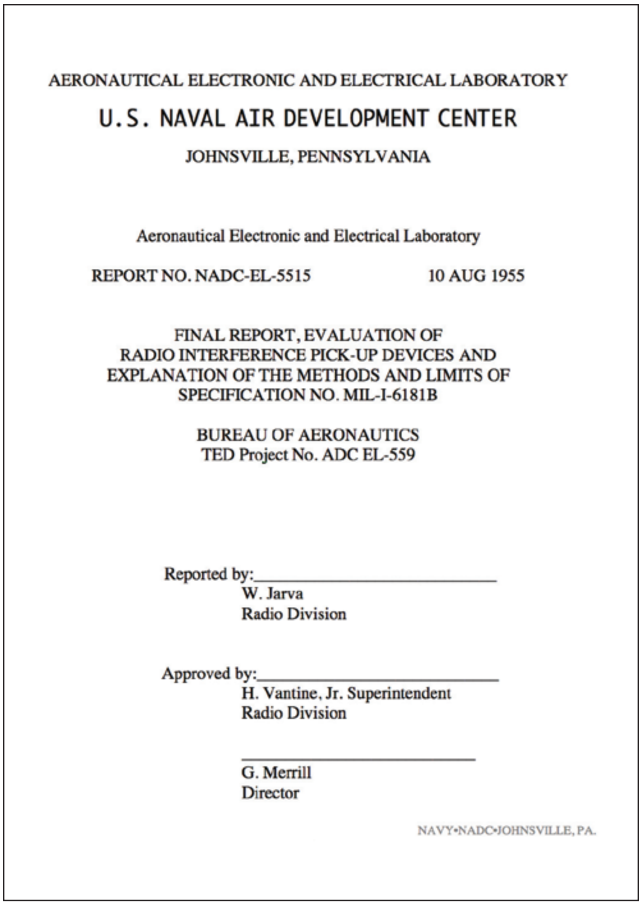

AERONAUTICAL ELECTRONIC AND ELECTRICAL LABORATORY

U.S. NAVAL AIR DEVELOPMENT CENTER

JOHNSVILLE, PENNSYLVANIA

Aeronautical Electronic and Electrical Laboratory

REPORT NO. NADC-EL-5515 10 AUG 1955

FINAL REPORT, EVALUATION OF
RADIO INTERFERENCE PICK-UP DEVICES AND
EXPLANATION OF THE METHODS AND LIMITS OF
SPECIFICATION NO. MIL-I-6181B

BUREAU OF AERONAUTICS
TED Project No. ADC EL-559

Reported by:____________________
W. Jarva
Radio Division

Approved by:____________________
H. Vantine, Jr. Superintendent
Radio Division

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G. Merrill
Director

NAVY•NADC•JOHNSVILLE, PA.

NADC-EL-5515 is the Rosetta Stone of the EMC discipline

The specification that introduced EMI requirements based on controlling interference to/from these unshielded transmission lines was MIL-I-6181B, released in May 1953.[5] As described in Reference 2, a report is available describing the selection of test antennas and set-ups for measuring to limits controlling radiated coupling to the unshielded antenna lead-in.[6] NADC-EL-5515, released in 1955, is the rationale behind the radiated emission measurement limits and test methods of MIL-I-6181B.

NADC-EL-5515 should be required reading for every vehicle EMC engineer. If the physics described in NADC-EL-5515 were universally understood by EMC engineers, there would be no need for the near field physics discussion in this article. Unfortunately, this knowledge is truly lost, and it is apparent from the state of aerospace (RTCA/DO-160 section 21) and automotive vehicle radiated emission EMI specifications (CISPR 25), and standards that support them (SAE ARP-958), that such understanding is sadly lacking.[7,8,9]

## PURPOSE

Hence, the true purpose of this article, which is only peripherally historical. The reader is requested to be patient, as much of what is presented will appear at first rather obvious. The more obvious, the better, because the conclusion is antithetical to most people's thinking, and a surprising conclusion is much more convincing if the trail there is familiar and well-worn. The conclusion is this simple: only a far-field measurement results in a true field intensity measurement. That is, the signal level measured at the EMI receiver, adjusted for any losses/gains in the transmission line path, is only relatable to a specific field intensity when the antenna's physical aperture is immersed in a field of constant amplitude across it.

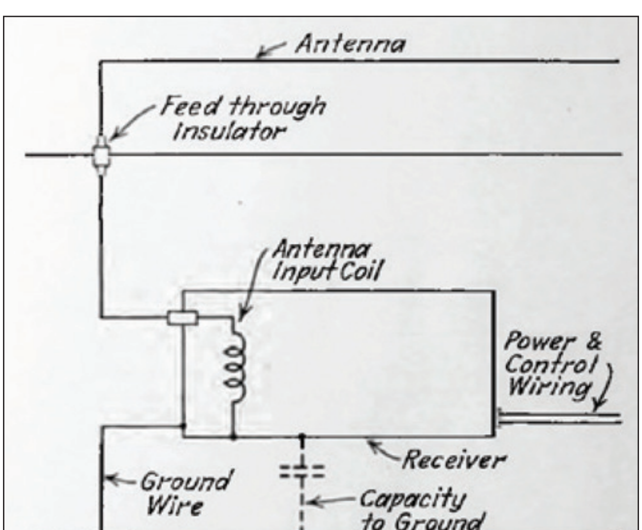


Figure 1: Typical installation of radio, antenna, and ground connections for a WWII-era 0.15 – 20 MHz radio installation.

Under any other conditions (the near field) that relationship cannot be made, and any artificial attempts (one-meter field intensity limits supported by a one-meter antenna factor) are not only doomed to failure but also wrongheaded. This means that there is no valid use for such artificial constructs, and they lead to bad engineering decisions. This is not to say that near-field measurements are useless – far from it. A near-field measurement is absolutely necessary when the actual culprit - victim interaction is near field. But the point is, far- vs. near-field measurements are not simply quantitatively, but also qualitatively different.

We will start by defining and differentiating the concepts of far and near fields, all from an EMI test point of view. Far field is easiest, so we begin there.

## FAR FIELD

The far field as an abstraction is a simple concept to visualize and understand intuitively. The near field is more complex, but as a starting point, we are in the near field when we are not in the far field. In terms of radiated emission measurements, the concept of far field is mostly associated with standards such as CISPR 22 and the newer 32.[10,11] These standards provide for test sample/antenna separations of 3 to 30 meters at and above 30 MHz. The far field assumption means limits scale directly with separation distance. It also means that – and this is key – these standards do not specify antenna types, only that they be calibrated in the far field. As we shall see, limit scaling with distance and the assumption that the same result may be obtained with any suitably calibrated antenna are hallmarks of a far-field measurement. Neither of these is true in the near field. And this is what MIL-I-6181B and NADC-EL-5515 first presented to the EMC world, and which remains true to the present day, albeit too few practicing EMC engineers appreciate it.

All of the following criteria need to be met in order to be in the far field of a transmitting source:

1. The far field is traveling electromagnetic energy. That means the far field propagates independently of the existence of the transmitting antenna once it is launched. The electric and magnetic field components of a traveling wave (Poynting's theorem) are in contrast to the quasi-static and induction field components close to the antenna, which begin and end on antenna elements, and vanish when the antenna excitation is removed. An example of the

independence of the traveling wave from its source is the light from a distant star reaching Earth. The star may in fact no longer exist, but the light it radiated away is still traveling through space. Closer to home, one necessary (but insufficient in and of itself) requirement for achieving the far field is being at or beyond the distance at which the amplitude of the traveling wave exceeds that of the quasi-static and induction components. Heinrich Hertz derived this criterion for an electrically short dipole.

2. A far-field traveling electromagnetic wave emanates from a point source. This means that the wave front has spherical curvature. This doesn't mean that the radiating source is literally a point, which would yield not only spherical curvature but also spherical symmetry. It means the transmitting source is so far away from the observation point that it appears as a point; the distance from the observation point to any point on the transmit antenna is equal. This assumption is inherent in the derivation of the Hertzian short dipole field components.
3. The wave front is not only spherical but also plane. Meaning that the sphere's radius of curvature is large enough that over the physical aperture of our receive antenna there is no variation in field intensity or power density. The spherical wave front approximating a plane wave is the source of expressions for the far field such as $2D^2/\lambda$.

Now for the distance from an observation point to *any* point along an extended structure to be equal, the observation point must be infinitely far away. Similarly, a plane surface may be described as the surface of a sphere of infinite radius. But none of that is very practical for daily use. Instead, we decide on how closely our spherical surface needs to approximate a plane surface, typically by positing a maximum phase difference between any two lines from the observation point to different portions of the transmitting source. Figure 2 shows this process specifying the allowable variation from a plane wave as a fraction of a wavelength.

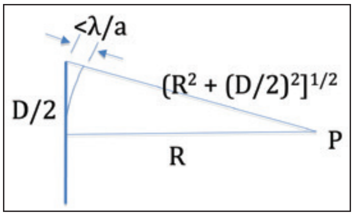

Figure 2: Geometry for determination of far-field distance based on how close a spherical wave front approximates a plane surface

In Figure 2, the circular arc struck between the radius labeled R and the radius that is its hypotenuse marks off the length of the hypotenuse that is greater than R and denotes it as a fraction of a wavelength. The value we assign to "a" depends on the application of interest.

Setting

$$R + \lambda/a = \sqrt{(R^2 + (D/2)^2)}$$

and solving for R, we get

$$R = (a/2\lambda)\,(D/2)^2 - \lambda/2a \quad \text{or}$$
$$R = aD^2/8\lambda - \lambda/2a$$

When we pick a maximum phase front variation of a sixteenth wavelength (a = 16), we get

$$R = 2D^2/\lambda - \lambda/32$$

In order for this to approximate the familiar $2D^2/\lambda$, the first term must greatly exceed the second term. This is certainly the case when the transmit antenna is at least a half-wavelength long.

From this analysis, in addition to learning/reviewing the derivation for $2D^2/\lambda$, we understand that it is based on a traveling electromagnetic wave far from the point source. We can also see that if the antenna is electrically short, the derivation doesn't work at all. The phase difference between the two radial distances in Figure 2 will always be smaller than the phase difference associated with distance d/2. If the antenna dimensions are an insignificant fraction of a wavelength this problem formulation says the far field is at any distance from the antenna, including zero. That is, if the phase difference from the center of the antenna to its end is the same or smaller than the phase difference we posit as acceptable for the far field criterion, then even a point on the antenna centerline is in the far field in terms of the above analysis. This merely emphasizes that the analysis assumes an electrically long antenna and a traveling electromagnetic wave.

## NEAR FIELD

Now let's look at the opposite situation: the one-meter radiated emission measurements that are very similar between MIL-STD-461, and RTCA/DO-160 section 21 and CISPR 25.[12] In these standards, minimum lengths of cables vary from 1.5 m (CISPR 25) to 3.3 meters (RTCA/DO-160). This means that the antenna separation from the radiating structure is much less than the length of the radiating structure.

Figure 3a demonstrates that the radiating structure is not a point source. Further, the dimensions of the antennas used below 1 GHz are on the order of the separation distance, so that the test antenna is not measuring a single, constant amplitude of field intensity over its physical aperture, but instead is integrating a complex variation of field intensity over its physical length. Figure 3b shows the radiation situation most people visualize when making antenna measurements. Figure 3c is similar to Figure 3a and in direct contrast to Figure 3b, showing the extreme near field. Figure 3c is an end view of the isometric view shown in Figure 3a, showing the electric field due to a wire over a ground plane.

In Figure 3b, the voltage measured at the antenna port where the phase front is constant over the antenna physical length is directly proportional to the field intensity impinging upon it. In contrast, in Figure 3c the single value of "field strength" derived from the voltage at the antenna is only representative of what is measured

Figure 3c emphasizes that antenna placement is critical. Placement of identical antenna types at various positions from A to C reveals that the received signal will be dependent on the orientation of field lines, which is strongly a function of the position close to the test sample. Inspection of two of the same type antennas with different lengths at position D emphasizes that the longer antenna is not measuring constant field intensity over its physical aperture, but instead is integrating a variation of field intensity over its physical length. We cannot predict from the position D measurement with the smaller antenna what the larger antenna would measure because while the smaller antenna is illuminated by a near-constant amplitude electric field, the larger antenna is not. And we cannot extrapolate from the measurement with the larger antenna to using the same antenna or another antenna at another position, for the same reason.

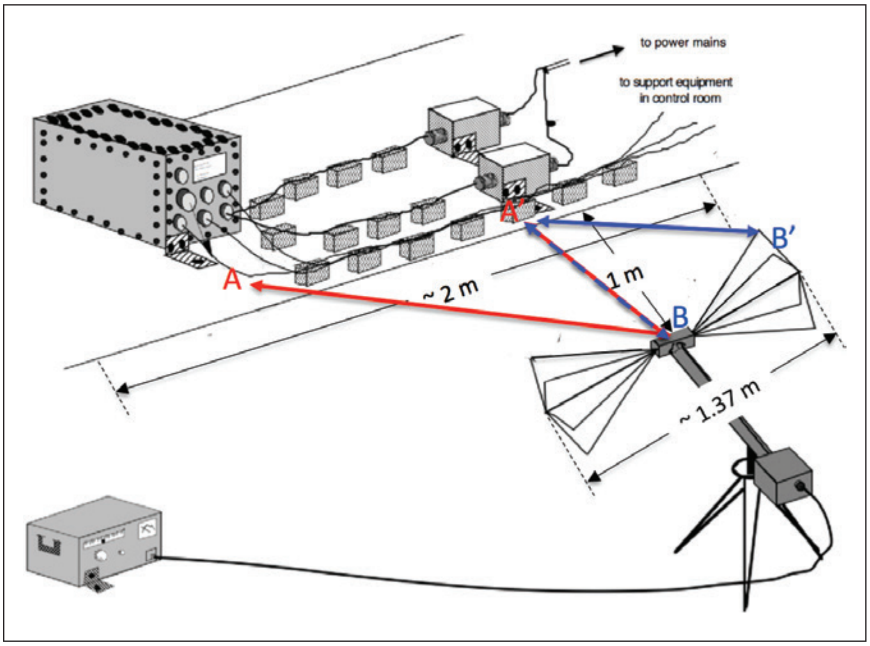


Figure 3a: One-meter separation radiated measurements are near-field measurements. The test set-up boundary is longer than the distance to the measurement antenna. The antenna physical aperture (length in the case of the biconical) is of the same order of magnitude as the separation from the test sample. For the test set-up to be in the far field of the antenna, line segments AB and A'B would need to be approximately equal in length. Likewise, for the antenna to be in the far field of the test set-up, line segments A'B and A'B' would need to be nearly equal in length. In a one-meter separation measurement, neither condition is obtained.

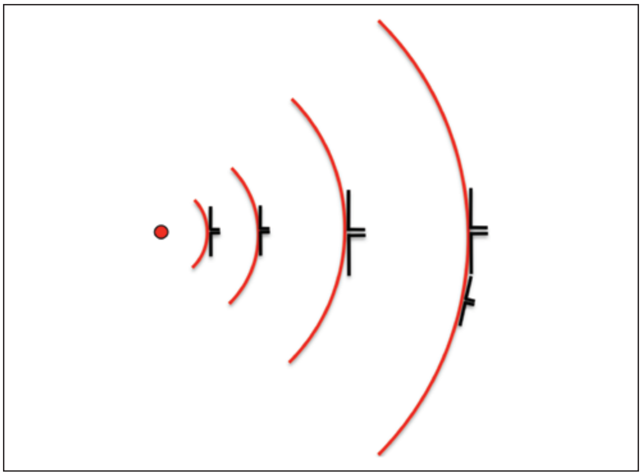

Figure 3b: The spherical wave front of a point source radiator. As the distance from the source increases, the spherical wave front appears increasingly planar. But planar is a relative quantity. The dimensions of the receive antenna also determine the far field distance. When the wave front is plane enough, measurements using different antennas will correlate.

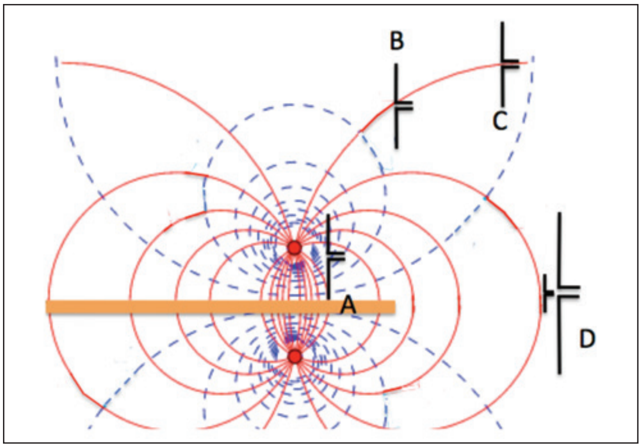


Figure 3c: The electric field (red) of a wire suspended over a ground plane (orange). Field lines below the ground plane are images. Field lines to the right of the ground plane's end point are not accurately rendered. They would curve around and connect at right angles to the ground plane. Wave front or field curvature is far from the plane, and correlation to another measurement at another distance using a different or even similar antenna is impossible.

at this particular position relative to the test sample, and using a particular antenna, at a particular orientation. The measured value is not a scalable far field “field intensity” in the sense that one can use it to predict the field intensity at some other distance or measured with a different antenna.

A real-world example of these limitations is FCC rules for EMI testing on an open area test site (OATS) back in the 1980s. The original test method used half-wave dipoles at a three-meter separation from the test sample. At 30 MHz, this placed a 5-meter-long antenna at 3 meters distance. The antenna was longer than the separation: near field. When biconicals started to become popular as tunable dipole replacements, the FCC ruled that while biconicals were acceptable, if there were any question about whether the test sample met the limit, a dipole measurement would be made, and that result would be used. The ~140 cm biconical was actually a better far-field measurement due to its much shorter length, but the point was that a standard had to be maintained, and they knew that biconical and 30 MHz half-wave dipole measurements would not agree.

A final note about Figures 3a, 3b, and 3c: The issues illustrated are frequency independent. Regardless of frequency – dc to light – if the above conditions apply, the measurement is near field.

In the words of NADC-EL-5515, referring to antenna types used for EMI testing in the 1950s:

> *“For instance, a resonant dipole antenna has good sensitivity to low-impedance (magnetic) fields near its center and high-impedance (electric) fields near its ends. Other antennas, such as the discone, have a completely different distribution of impedance, polarization, physical size, and contour. Obviously, a comparison of the effect of a given interference field upon the dipole and the same field on a discone can only be made in a very general manner. For this reason, (MIL-I-6181B) radio interference limits are derived expressly for each particular antenna that is to be used, and an exact correlation between different types of antennas is not expected.”*[13]

## NEAR AND FAR FIELD LIMIT DERIVATION

It is instructive to compare and contrast how the limits in standards such as CISPR 22/32 were determined, vs. those in MIL-I-6181. Limit derivation for standards like CISPR 22/32 comes directly from specifications on the quality of radio services.[14]

Figure 4 is an example excerpted from Reference 14. Such specifications state that a certain quality of baseband signal results when a specified level of broadcast signal is received. From this level, an EMI limit may be counted down using the signal-to-noise ratio required to get the specified baseband quality. Thus, it is completely natural to specify limits protecting such services in terms of field intensity, especially when the compliance measurement is made in the far field (or nearly so).

But the limits in MIL-I-6181B were not determined that way at all, and the success criterion for vehicle EMC is also not so determined. NADC-EL-5515 describes how the MIL-I-6181B limits were obtained, and this limit-setting exercise also determined the test method:

> *“These limits were decided upon as a result of tests made on a BC-384Q receiver installed in a shielded room. A 24-inch lead-in and a 12-foot straight wire antenna outside the shielded room were used to simulate an aircraft set-up. Various types of radio interference sources such as d-c motors, poorly shielded dynamotor cables, an adjustable output ignition source, etc., were installed at a distance of one foot from the lead-in. At those frequencies where interference sources happened to produce an interference signal which was slightly above the background of the BC-348Q, a measurement was made with an AN/PRM-1 in conjunction with its rod antenna. The rod was located one foot from the noise source, and the resultant measurement was taken as an approximation of the desired radio interference limit.”*

Figure 5 is a recreation of the described limit setting measurement, based on the above passage. Two key points immediately suggest the vast difference from the CISPR 22/32 limit derivation. The first is this is entirely

Table 5-6. Typical Received Field Strengths – VHF/UHF Radio Services

| Service (MHz) | Band No. | Field Strength (dBμV/m) | Comment |
|---|---|---|---|
| Public Safety | | | |
| 30-54 | 1 | 31 | Service Grade |
| 136-174 | 5 | 37 | Service Grade |
| 420-470 | 9 | 39 | Service Grade |
| Broadcast FM | | | |
| 88-108 | 3 | 70-74 | Principal City |
| | | 60 | City, Business or Factory Area |
| | | 34 | Rural Area |
| Civil Aeronautical | | | |
| 108-136 | 4 | 12-16 | FAA Squelch Setting |
| 216-420 | 7/8 | 20 | FAA Squelch Setting |

Figure 4: Published expected signal levels for various broadcast radio services (from Reference 14)

empirical, as opposed to using established specifications as a benchmark. The second is that the measurement distance is extremely near field, and the limits are in terms of the induced noise in the victims – no field intensities involved. When noise above the background is detected from the speaker connected to the radio's audio output, the measured level at the AN/PRM-1 is recorded. The AN/PRM-1-meter displays microvolts and decibels above a microvolt. There is no antenna factor involved here. This is termed an *antenna-induced* limit and is a key concept that has been largely lost but is every bit as pertinent today as it was in 1953. Figure 6 shows MIL-I-6181B antenna-induced radiated emission limits.

Rigorously, "antenna-induced" means the theoretical open-circuit voltage that would appear at the antenna terminals with an electric field impinging upon it. Losses associated with any circuitry necessary to adapt from

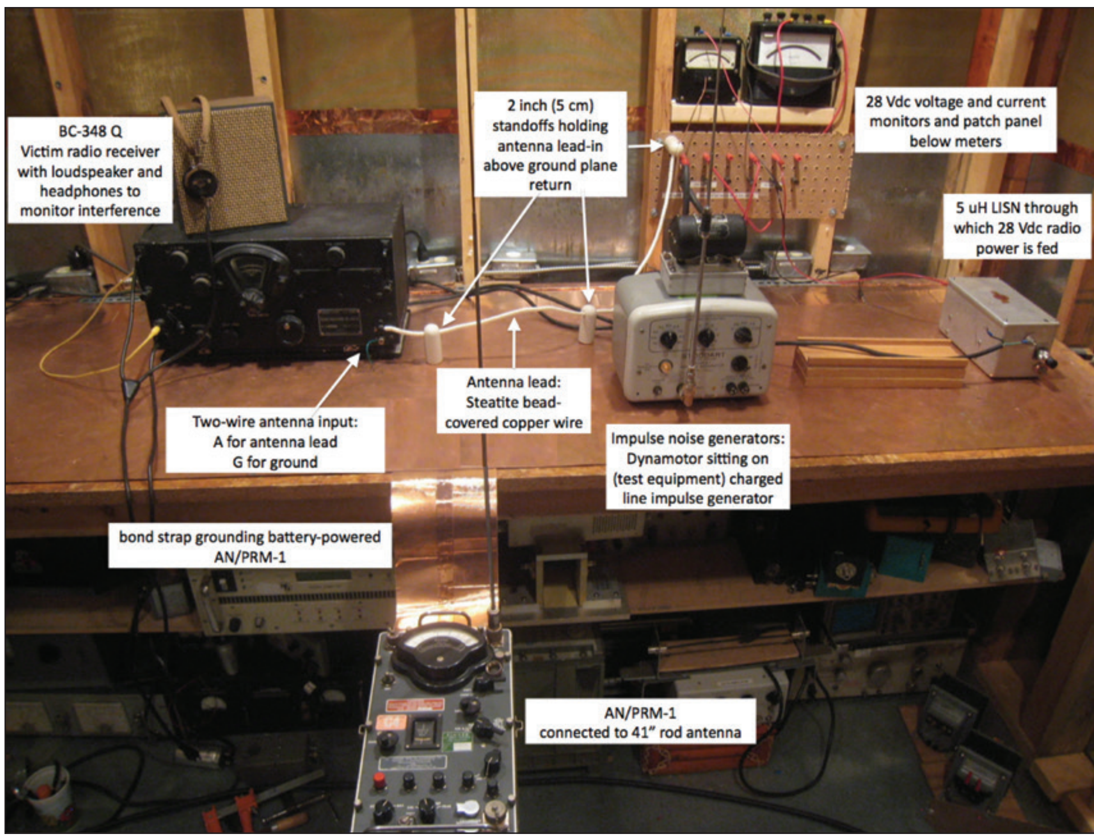


Figure 5: Reenactment of MIL-I-6181B radiated emission limit setting procedure in the EMC Compliance screened test chamber

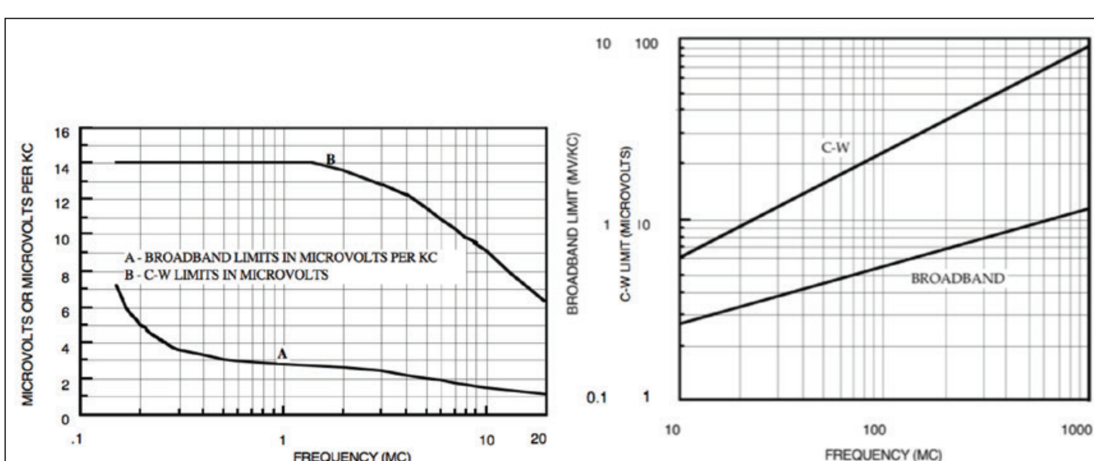


Figure 6: Figure 6a (41" rod) and Figure 6b (resonant dipole) antenna-induced radiated emission limits from NADC-EL-5515

that open-circuit potential to a signal that can be piped down a transmission line must be accounted for. So, with the 41" rod antenna used as in Figure 5, there is no data reduction necessary: the receiver meter reading (plus any attenuation selected) is the reading to be compared to the limit.

But above 30 MHz, where half-wave dipoles are employed, balun losses must be factored in, and NADC-EL-5515 explains how to do that. In the days of antenna-induced limits, the loss associated with a matching network was termed the antenna factor. But unlike modern practice, the antenna-induced antenna factor is a unit-less loss factor (dB), whereas the modern antenna factor, being the inverse of antenna effective height, has units of meter$^{-1}$, or dB per meter.

Of course, any cable losses must be accounted for as well, just as in a field intensity measurement. The concept of an antenna-induced limit may seem foreign, but there is a close modern example with which an EMC engineer should be familiar. Radiated emission measurements such as those described above are designed to force good EMC design at the equipment level, so that at system or platform integration, there are no ugly surprises resulting in delays or costly modifications at the last minute. The "proof of the pudding" is verification that all platform antenna-connected receivers can operate interference-free.

With such receivers often being tunable over thousands of channels, it is impractical to tune to and check each frequency. Instead, standards such as MIL-STD-464 mandate a "spectrum analyzer noise floor survey."[15] The transmission line connecting the receiver's antenna is disconnected from the receiver, and instead attached to a spectrum analyzer or EMI receiver, which is set to sweep over the entire tunable range of the receiver, or multiple sub-bands if that is necessary. Signals appearing above the substituted receiver's noise floor or some other level are then checked to see if they actually cause interference.

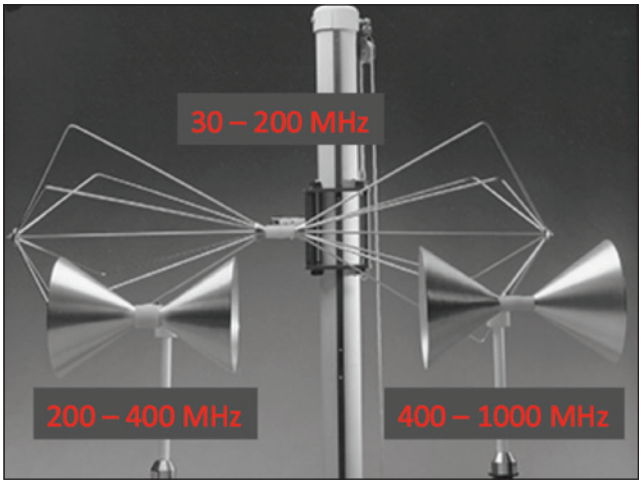


Figure 7: Compliance Design biconical antennas covering 30 MHz to 1 GHz (no longer manufactured). Frequency ranges shown are approximate. Smaller biconicals have identical elements, but different baluns. Photo courtesy of Glen Dash Foundation.

This is almost an antenna-induced measurement. The pass/fail criterion is a dBuV or more likely dBm level based on the particular receiver's performance specification. A similar example may be found in the C & D revisions of MIL-STD-464, where antenna-induced measurements at a distance of one meter from Army ground vehicles are made using not EMI test antennas as in MIL-STD-461, but rather antennas representative of those next to which the ground vehicle might be parked (typically whips). The whips are connected to a spectrum analyzer, and the limit is again in terms of the rf potential or power at the connected spectrum analyzer.

The reader should be able to appreciate the high degree of similarity between these modern measurements and those described in NADC-EL-5515. The only difference is that the noise floor measurement is referenced to the receiver's antenna input, so the matching of the antenna to the transmission line and any line losses are part of the answer and for which separate accounting is unnecessary.

One other important facet of antenna-induced limits and the passages from NADC-EL-5515 is worth mentioning here. NADC-EL-5515 went to some length to explain the selection of antennas used for MIL-I-6181B 12" measurements. They were supposed to simulate the coupling to platform antenna-connected conductors (open-wire transmission lines). If one looks at antennas used beyond the biconical frequency range in vehicle EMI testing today, one finds horns and log-periodic arrays. The simulation of platform antennas for a good quality radiated emission test uses antennas with dipole-like patterns, because such are either used on platforms, or in the case of high gain platform antennas, noise sources are typically in the back or at most side lobes of such, and thus are coupling via a low gain mechanism.

It is the author's belief that biconical antennas such as the Compliance Design collection shown in Figure 7 would serve admirably. Even if antenna-induced limits were not invoked, it is the author's opinion that such antennas are superior to what is used today above 200 MHz. With an antenna-induced limit, one could compare the output of the Figure 7 antennas to what would be required at a platform-level spectrum analyzer survey. Even without an antenna-induced limit, given the similarity between the EMI test and platform-installed antennas, one could do the comparison to get a much better prognostication of the actual EMC "proof-of-the-pudding" test results.

## THE SWITCH FROM ANTENNA-INDUCED TO FIELD INTENSITY EMI LIMITS

MIL-I-6181B instituted antenna-induced limits measured at 12” from the test sample and attached cables. NADC-EL-5515 explains why, and that MIL-I-6181B also prohibited the future procurement of receivers requiring the unshielded high-impedance lead-ins. This means the stringent limits applied at 12” from the test sample were a grandfather clause, protecting the current inventory of high input impedance installed radios until such time as they had all been replaced by more modern receivers designed to work with 50 Ω coaxial transmission lines. In the words of NADC-EL-5515:

> *“(MIL-I-6181B) requires that all equipment used with antennas be designed for use with a shielded antenna lead. If and when the unshielded antenna lead is completely eliminated from use in aircraft, a review of present methods and limits in the frequency range 0.15 to 20 mc will be required.”*

With the prohibition of the unshielded transmission line, the radiated emission problem is greatly ameliorated. Instead of what amounts to a crosstalk control, coupling is now to an antenna, and antennas are mounted externally and are further removed from most noise sources than the transmission line between the antenna and the antenna-connected receiver.

When the Tri-Service Committee convened circa 1966 to fashion MIL-STD-461/2/3 out of the various Service and platform-unique EMI specifications, they apparently deemed it time to abandon the 12” grandfather clause. Army and Navy EMI specifications of the time were already making some radiated emission measurements at distances greater than one foot, and the one-meter separation that resulted may have been nothing more than a “metricized” average of the Army (5’ minimum), Navy (3’) and Air Force (1’) separations.[16, 17, 18, 19]

MIL-STD-462 (1967) required the present one-meter separation between the test sample and the antenna.[20] With an antenna as the radiated emission victim, as opposed to a transmission line, it might have seemed natural to transition to a field strength type control. Whatever the reason, the move to a one-meter separation

What is fundamental is that the assumption that extreme near-field intensity measurements are scalable violates one of the most fundamental laws of physics, namely the conservation of energy or power.

was accompanied by a shift to a field intensity limit, and the consequent need for the kinds of antenna factors we use today. Thus, SAE ARP-958 was published in 1968; one year after MIL-STD-462 was released.

For the record, it should be noted that forerunners to RTCA/DO-160 included antenna-induced radiated emission controls.[21, 22] RTCA/DO-160 was first released in 1975, and by that time field intensity limits had superseded antenna-induced, as described. Automotive radiated emission practice was always field intensity control but that did not begin until the 1970s.

## PRACTICAL PROBLEMS ARISING FROM THE USE OF FIELD INTENSITY LIMITS IN THE EXTREME NEAR FIELD[23]

The term “extreme near field” has a specific quantitative meaning in this context. It means that the transmit-receive antenna separation is of the same magnitude as its physical aperture, or less. In the case of radiated emission measurements made one meter away from a test sample with 1.5 m or longer attached cables, not even the Hertzian dipole equations suffice to describe the near field. The Hertzian dipole field equations only apply when the separation distance is much larger than the radiating structure dimensions.[24]

SAE ARP-958 uses the physical model of two identical antennas in each other’s far field (Friis equation) to calculate an “effective” gain at one-meter separation. This is an effective gain because the antennas are in each other’s extreme near field. Therefore, the antenna factor so derived is only valid for measuring the field at that distance, and the standard of value is that antenna’s response to its own field at that distance. There is no particular value to comparing the “field intensity” measured by (for example) a biconical to the field intensity that biconical would see from another biconical a meter away. In fact, it is quite harmful in that there is an unspoken (and incorrect) assumption on the part of many EMC engineers that the field intensity measured at one-meter separation is scalable in some prescribed manner so as to be able to predict what the measured field intensity would be at another distance.

Figure 8 presents data gleaned from an old EMCO catalog. The same sort of information may be found on the ETS-Lindgren website antenna page.[25] If one-meter “field intensity” measurements were scalable, the antenna factors would be identical. Now proponents of field intensity measurements and one-meter antenna factors will rebut the use of such data, saying that one- and three-meter antenna factors are measured differently. And this is true, but it is not fundamental.

What is fundamental is that the assumption that extreme near-field intensity measurements are scalable violates one of the most fundamental laws of physics, namely the conservation of energy or power. And only some high school physics and algebra is necessary to comprehend this.

Based on the diagram of Figure 9, the Friis equation may be written as:

$$P_R/P_T = G_T\, G_R \lambda^2 / (4\pi r)^2$$

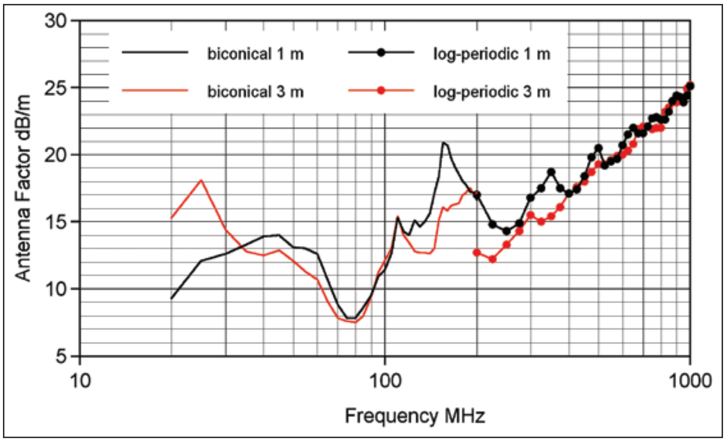

Figure 8: One- and three-meter antenna factors

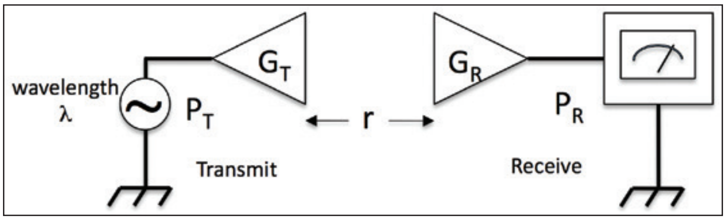

Figure 9: Set-up for understanding Friis equation

The Friis equation assumes that the separation distance places the antennas in the far field. In that asymptotic condition, the gain values are independent of separation, which is what makes far-field antenna calibration useful. But two elementary observations are apparent:

- The left-hand side ratio is bounded by unity, and in practice will always be less than unity, or 0 dB; and
- The right-hand side increases without bound as the separation decreases unless the gain values decrease commensurately.

The inescapable conclusion is that in close, gain is in fact a function of antenna separation. While gain or antenna factor asymptotically approaches a fixed far field value, this means nothing when the antennas are closer in than that.

Assuming half-wave dipoles (far field gain = 1.64 numeric, 2.15 dBi), one may solve the Friis equation for the distance at which the left-hand side ratio is unity, or 0 dB.

$r = 0.13\lambda$, or
$r = D/4$
where D is the half-wave dipole length

This is a purely theoretical construct that just says the gain must roll off at closer separations than this. Of course, the gain begins to roll off well before this calculated separation. The measured received power levels plotted in Figure 10 were taken using the set-up of Figure 9, with separation "r" variable between 2 meters and 30 cm. Two different frequencies were evaluated: 400 MHz ($\lambda$ = 75 cm, D = 37.5 cm) and 1 GHz ($\lambda$ = 30 cm, D = 15 cm). Figure 10 shows measured vs. theoretical far field $P_R/P_T$ ratios as a function of separation distance and wavelength. An inspection of Figure 10 shows that long before the far field calculation of received power shows it equal to transmit power, the response has rolled off.

There are complicating factors involved in the close placement of two wire-type antennas, which include dipoles and biconicals. In very close proximity, there is capacitive coupling with which to contend and, above a ground plane, inductive coupling. Further, the direction of energy flow away from the antenna is different close to the antenna than farther away. Schelkunoff and Friis pointed this out long ago.[26] Figure 11a is copied from Reference 26 and shows the direction of energy flow (Poynting vector) away from the antenna element as a function of distance along the quarter-wave long antenna element itself and as a function of distance from the antenna. While the mathematics behind Figure 11a are complex, the notional Figure 11b drawing of the electric and magnetic fields from such an antenna provides an intuitive grasp.

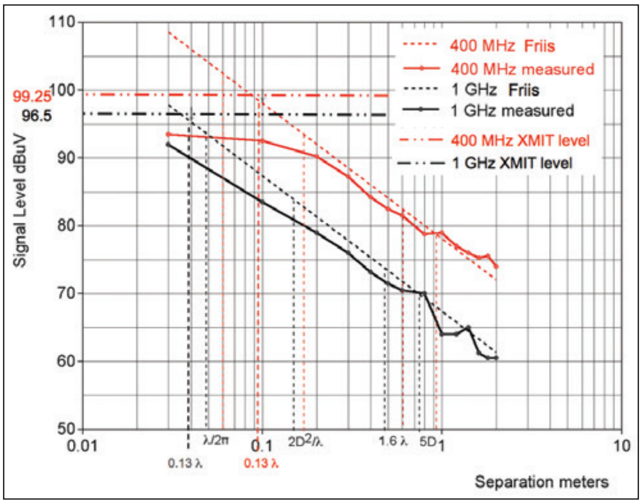


Figure 10: Ratio of received vs. transmit power vs. half-wave dipole separation comparing the Friis equation and measured data

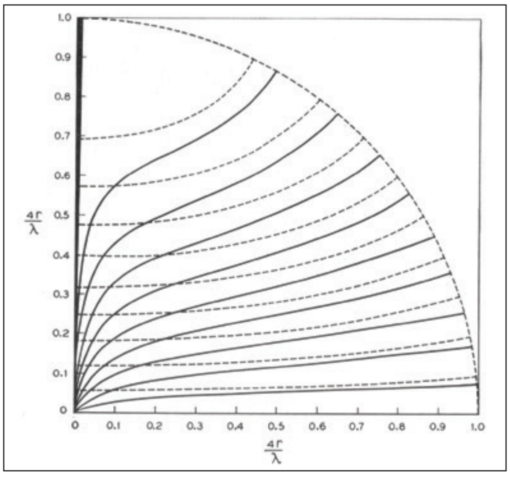


Figure 11a: Poynting vector direction as a function of position along the antenna and distance from the antenna. The solid lines are for an antenna element with a practical length-to-diameter ratio. The dashed lines are for a theoretical antenna element of vanishing diameter. (Reference 26, page 124)

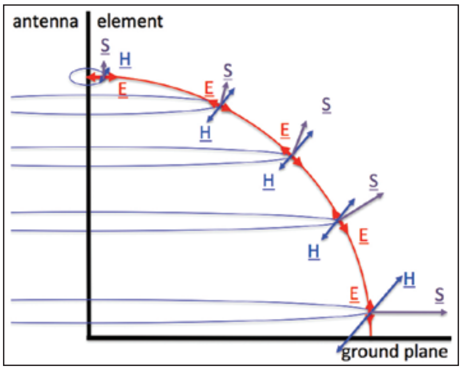


Figure 11b: The ordinate axis represents a quarter wave stub over the abscissa ground plane. Electric field lines are constrained to be at right angles to a perfect conductor. The orientation of the electric field and the circulating magnetic field sets up the Poynting vector direction, as shown in the direction of the two axes. Note that the current vanishes at the tip of the quarter-wave stub, so no current means the Poynting vector amplitude vanishes, as well.

The exact same effect is seen with higher gain antennas: gain derates rapidly from the far field values at separations less than a tenth of the far field distance $(2D^2/\lambda)$.[27] Figure 12 is copied from Reference 27 and shows gain derating for both dish and horn aperture-type antennas. Figure 12 is used in the following manner.

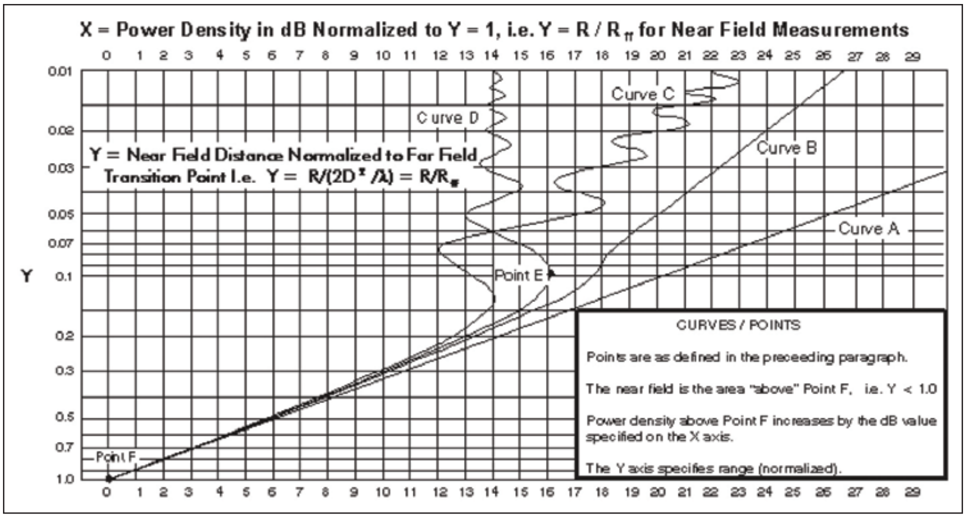


Figure 12: Fresnel zone power density from high gain aperture-type antennas normalized to the power density obtained at the far field boundary (copied from Reference 27).

Power density or equivalent field intensity is calculated using the far field gain at the $2D^2/\lambda$ far-field boundary. Then the appropriate curve is followed inward to the Fresnel zone distance of interest. Here there are no complicating near-field effects from capacitive or inductive coupling, and the quasi-static and inductive regions are contained well within the antenna feed point or phase center. They do not propagate down the waveguide to reach the antenna aperture itself.

The Reference 27 handbook citation is not the origin for this work. It goes back over sixty years and is hardly new.[28]

## THEORETICAL PROBLEMS RESULTING FROM USING FIELD INTENSITY LIMITS WHERE ANTENNA-INDUCED IS MORE APPROPRIATE

Ignorance of the fundamentals of extreme near field measurements and of gain derating and the nature of the Fresnel zone has pronounced and dangerous impacts on both EMI and EMC requirements and verification. The following sections provide some relevant case histories.

### Conflating Radiated Emissions and Radiated Susceptibility

With radiated emission and radiated susceptibility requirements both having field intensity limits, the idea that radiated emission (RE) and radiated susceptibility (RS) control were somehow two sides of the same coin became prevalent. People claiming that one controls RE to avoid RS was enough of a problem that in 1993 instructions were included in MIL-STD-461D specifically saying that this belief is not true and that, in fact, RE limits protect antenna-connected receivers and RS limits provide a level of immunity to intentionally generated RF fields from high-power RF transmitters. These instructions have remained in all subsequent revisions of the standard.

Although the RE/RS comparison is extremely damaging, it is still assumed to be true by many engineers, often in the space community.[29] It is easy to see why: the space community doesn't typically use the rf spectrum below several hundred megahertz, so there is no need for RE limits at lower frequencies, and often no or rudimentary RS limits there. Since they have used military limits covering as low as 10 kHz without comprehending the real need for such, they substitute this incorrect duality to justify using incorrect requirements. This leads to two errors. One is complete disrespect for the discipline, since comparing stringent RE limits to even the most rudimentary RS limits shows "margins" on the order of 100 dB.

The second error is to attempt to show the "margins" aren't that high because a culprit (unintentional) emitter source may be placed very close to an (unintentional) victim receiver, requiring "scaling" of the one-meter RE limit to a distance of just a few centimeters. Such "scaling" is done using Hertzian dipole field intensity behavior vs. distance, typically third order (cube of distance ratio).[30] Such comparisons are not accurate in the extreme near field, since the Hertzian dipole derivation assumes the observation distance is large with respect to the radiating structure dimensions – clearly not the case a meter away from a two-meter-long test sample.

While Hertzian dipole equations are often applied to various EMC-related problems and analyses, it is not difficult to see that they are inapplicable or at best only partially applicable to one-meter radiated emission measurements. One need not wade through the several-page derivation in Reference 30. The inapplicability is at the very beginning, where the expression for the magnetic vector potential is derived.[31] The requirement that the distance to the observation point be large with respect to the dimensions of the radiating element is inherent in the Hertzian expression for the magnetic potential vector, from which the entire derivation proceeds. It should not be surprising that the Hertzian dipole field expressions all "blow up" close to the source. The simplifying assumption that the distance to the observation point is large with respect to the dimensions of the radiating element means that the radiating source is a point. If there is current (flow of charge) on a point source, charge separation and potential differences follow.

Reference 24 derives and shows that, in the direction of maximum radiation, the Hertzian expression for the electric field is off by 3 dB when the separation distance is twice the dipole length, and that the electric field in closer than that approaches a fixed level proportional to the charge separation divided by the dipole length. When the observation point separation is one-tenth the dipole length, the Hertzian expression is 60 dB too high.

Since 1993, MIL-STD-461 has included in the CE102 limit rationale the information that, in the rod antenna range, the relationship of the measured radiated field to the voltage on a 2.5-meter-long wire is such that the wire potential is 40 dB higher numerically than the radiated signal measured. Reference 32 provides analytical details.[32] If the wire potential is 40 dB above the signal measured a meter away, and the wire is suspended 5 cm above the ground plane (-26 dB above one meter), that makes the field intensity between the wire and ground plane 66 dB higher than at one meter. That is an upper bound on such scaling.

A shorthand model for this is shown in Figure 4 in Reference 24. One end of the dipole is now a wire suspended 5 cm above the tabletop ground plane and its image below the ground plane is the other end, for a net dipole separation of 10 cm. Looking at the circled point on Figure 4 of Reference 24, the field falls off beyond 20 cm from the wire as the cube of the distance ratio. So, from 20-cm to 1 meter away, the field falls off by a ratio of $5^3$, or 42 dB. From 20 cm away from the wire to the wire, the field intensity increases by about 20 dB. The ratio of the field intensity between the wire and the ground plane beneath it to the field intensity found at a point a meter away is 62 dB. That calculation is for a pair of separated charges. The answer is within a few dB of the exact calculation for a cable of significant extent, measured not at a point but using a 41" rod antenna. Not bad, and it serves to dispel the mistaken superstition that Hertz says things should blow up.

It should be noted that this is not about radiated energy at all. This is the fringing field from a source of charge separation. In this model, the only current that could contribute to actual radiation is the displacement current between the wire and the ground plane, and using a value such as 10 pF/m yields next to no current over most of the rod antenna frequency range. The fringing field dominates, and it dominates even more so at 12" than at a one-meter separation. Citing NADC-EL-5515:

> *"In general, the ratio of the electric to the magnetic components surrounding an unshielded lead will vary directly as the impedance of the load terminating the lead, and the apparent impedance presented to the various pick-up antennas will vary in the same manner. This statement applies to radial and tangential field components as contrasted with the more usual concept of wave impedance encountered in shielding theory, which applies only to the components tangential to the line of propagation."*

### One-Meter Measurements Are Not Scalable Outwards, Either

Similar to the conflation misconception just described, people attempt scaling the one-meter results to a larger distance. Figure 13 portrays this type of an error. Some people advocate changing the one-meter measurements to three meters or more, based on the assumed accuracy superiority of far-field measurements. Some advocate for including the option of three-meter measurements in lieu


Figure 13: Controlling emissions at three meters or more for an interaction occurring at a one-meter separation

of a one-meter measurement. The erroneous assumption is that one can adequately replace the other. As explained earlier, there are two errors here: 1) the radiation source is not a point source at either one- or three-meter distance; and 2) the one-meter measurement is not the field at some point in space but the average over the physical dimensions of the EMI test antenna. So not a scalable value in any way, shape, or form.

### Misapplying Antenna Factors

SAE ARP-958E (2021) now provides for separate horizontal and vertical polarization antenna factors for dipole-like antennas (dipoles, biconicals, log-periodic arrays). Under the right conditions this might make sense (given the *a priori* use of field intensity limits in the extreme near field) but it is indefensible given how they measure antenna factors.

The 1968 release SAE ARP-958 was for the newly mandated log spirals of MIL-STD-461.[33] SAE ARP-958 did not specify the height of the antennas above the floor, nor even if the floor would be reflective or not. But SAE ARP-958A (1992) specified a reflective floor and a three-meter height above the floor.[34] The purpose was to control ground plane effects and make them negligible relative to the direct coupling between transmit and receive antennas. All subsequent revisions maintained the three-meter height and the reflective ground plane.

Note that, while all one-meter separation radiated emission requirements (CISPR 25, RTCA/DO-160, and all revisions of MIL-STD-461/-462) place the antennas approximately one meter above the ground plane, SAE ARP-958E measures the separate polarization-based antenna factors three meters above the ground plane. Ground plane effects measured at three meter height are not even remotely applicable when antennas are one meter above the ground plane. Consider that over fifty years ago, just a few years after the biconical antenna was introduced in MIL-STD-461 (1967), a handbook warned that placing the lower tip of a vertically oriented biconical within two feet (61 cm) of the floor would capacitively load it sufficiently to change the antenna factor.[35]

The point is this: if you want the biconical placed with the lower tip one foot above the floor (CISPR 25), then fine, make it so. And make everyone do it the same way. But then don't apply a correction factor measured at three meters above the ground to correct for that. Don't correct for it at all. Just mandate the proper antenna, and its separation and orientation, and then record antenna output, adjusted for balun and cable losses.

### Misapplying Far-Field Gain in Computing Power Density

The EMC departments of two aerospace vehicle manufacturers refused to perform system-level EMC verifications that required the use of RF absorber panel emplacements around their respective platforms. They based their decisions on the belief that the computed RF power density from a platform high-gain microwave dish exceeded the absorber power rating. This was based on computing the power density using the far-field gain (only achieved beyond 50 meters distance) at a distance of two meters from the dish.

In reality, the actual power density based on Figure 12 was orders of magnitude less and much less than the absorber panel rating. Further, an elementary calculation of the area over which the far-field gain would concentrate the beam at a two-meter distance would have been a few centimeters on a side, which should have been a tip-off. Another tip-off would have been a Friis equation calculation showing more received power than transmitted using the far-field gain close in.

### Basing RE Limits on the Far-Field Gain of a High-Gain Dish

A non-US space agency levied a millimeter wave radiated emission limit based on the far-field gain of a high-gain dish. The resulting limit was such that it could not possibly be instrumented. The Fresnel-zone gain of such a dish at a one-meter distance is again orders of magnitude less than in the far field, plus the potential noise sources are in the back lobes of the antenna or, in a worst-case scenario, a 90-degree side lobe, but certainly not in the main beam.

### Antennas Are Not Interchangeable in the Near Field

Both RTCA/DO-160, section 21, and CISPR 25 recommend but do not require the use of standardized antennas for radiated emission measurements. This is a direct consequence of using field intensity limits, and the assumption that the use of antenna factors is enough to yield the proper result no matter what antenna is chosen. The 1995 release of CISPR 25 went so far as to claim:

> *6.5.1 Antenna systems*
>
> *"The limits … are listed in dB(uV/m), and thus theoretically any antenna can be used, provided that … the antenna correction factor is applied..."*

This type of error was identified in 1967 when MIL-STD-461 popularized the change from antenna-induced to field intensity limits.[36] The 2016 edition


Figure 14: A very small sampling of electromagnetics texts from Hertz onwards, in chronological order, with representation from every decade to one hundred years after Hertz (from the Museum of EMC Antiquities collection).

removes the egregious statement but only *recommends* standard antennas. In this regard, all versions of MIL-STD-461/-462 RE02/RE102 since 1967 are superior to RTCA/DO-160, section 21, and CISPR 25 in recognizing and accommodating the near-field nature of the measurement at a one-meter distance. The 41" rod antenna and 137 cm tip-to-tip length biconical have been required since 1967. From 1967 – 1993, log spirals were required from 200 MHz to 10 GHz. After 1993, the log spirals were replaced by double-ridge guide horns of specified aperture dimensions. Since 1993 the following rationale appendix wording explains the use of standardized antennas for requirement RE102:

> *"Specific antennas are required by this test procedure for standardization reasons. The intent is to obtain consistent results between different test facilities.*
>
> *"In order for adequate signal levels to be available to drive the measurement receivers, physically large antennas are necessary. Due to shielded room measurements, the antennas are required to be relatively close to the EUT, and the radiated field is not uniform across the antenna aperture. For electric field measurements below several hundred megahertz, the antennas do not measure the true electric field."*

The first clause of the very last sentence is unnecessary since even if the calculated far field of the test antenna is no greater than one meter, the far field of the two-meter-long test set-up is clearly well beyond one meter. It is not enough for the transmitting source to be in the far field of the receive antenna; the receive antenna must also be in the far field of the source transmitter. Now it could certainly be the case that the transmitting source at microwave frequencies happened to be a small slot or aperture in the test sample enclosure, and if that were the sole radiating structure, it could be a far-field measurement. But the point is, one cannot know that *a priori*.

## CONCLUSION

Converting near-field radiated emission control from field intensity to antenna-induced limits brings the following advantages:

- Clear delineation between near-field vehicle and home/office/industrial plant far-field radiated emission controls;
- Better correlation between equipment-level radiated emission limits and system-level EMC goals (direct correlation with spectrum analyzer noise floor surveys of platform antenna-connected receivers);
- Diminution of wrong-headed EMC "engineering" comparing RE and RS controls as complementary functions; and
- As a corollary, it would raise awareness of the real issues involved in RE control and improve the quality of EMC engineering, reducing episodes where bad science is used to justify programmatic decisions.

Even if a majority of the EMC discipline found these arguments persuasive, it would be wildly unrealistic to expect that over a half-century of tradition would be overturned. Given that reality, but with the understanding that antenna-induced is the ideal for one-meter radiated emission control, significant benefits could still result. The major such benefit would be dropping SAE ARP-958 altogether and using polarization-independent far-field antenna factors. Another possible advantage would be the adoption of EMI test antennas that better modeled those connected to platform-installed receivers that are the motivation for the levying of radiated emission controls.

And whether or not we return to antenna-induced near-field limits, the discipline would benefit immensely if EMC engineers rediscovered the lost science of near-field measurements. They could do worse than reading NADC-EL-5515. It also might not hurt to read Hertz's original work on his dipole.

A WWII historian once remarked that other historians read books previous historians wrote, and then write a new book based on what they had read. In contrast, this historian always cited WWII-era sources. There is something to be said for original sources. The Museum of EMC Antiquities exists to preserve such knowledge and foster its study until such time that the present Dark Ages give way to an EMC Renaissance.

## ENDNOTES


1. All standards and specifications referenced herein which are not copyrighted are available from http://www.emccompliance.com.
2. Javor, Ken, "Seventy Years of Electromagnetic Interference Control in Planes, Trains and Automobiles," *In Compliance Magazine*, May 2023.
3. Also see Figures 2 and 3 of Reference 2.
4. NAVAER 16-5Q-517, Elimination of Radio Interference Problems in Aircraft, circa 1946-47.
5. MIL-I-6181B, Interference Limits, Tests and Design Requirements, Aircraft Electrical and Electronic Equipment, 29 May 1953.
6. NADC-EL-5515, Final Report, Evaluation of Radio Interference Pick-Up Devices and Explanation of the Methods and Limits of Specification No. MIL-I-6181B, 10 August 1955.
7. RTCA/DO-160, original through C revision, Environmental Conditions and Test Procedures for Airborne Equipment.
8. CISPR 25, all editions, various titles. "Limits and methods of measurement of radio disturbance characteristics for the protection of receivers used on board vehicles" is the 1995 title.
9. SAE ARP-958, all revisions, Broadband Electromagnetic Interference Measurement Antennas; Standard Calibration Requirements and Methods, 01 March 1968.
10. CISPR 22 - Information technology equipment - Radio disturbance characteristics - Limits and methods of measurement (withdrawn).
11. CISPR 32 - Electromagnetic Compatibility of multimedia equipment – Emission requirements.
12. MIL-STD-461E, and newer, Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment, 1999-present.
13. A discone antenna is half of a biconical, mounted vertically above or below a ground plane that provides the missing biconical element as an image in the ground plane.
14. CBEMA Report – CBEMA/ESC5/77/29 – "Limits and Methods of Measurement of Electromagnetic Emanations from Electronic Data Processing and Office Equipment," 20 May 1977.
15. MIL-STD-464 and newer, Electromagnetic Environmental Effects Requirements for Systems, 1997 - present.
16. MIL-E-55301(EL), Electromagnetic Compatibility, 01 April 1965.
17. MIL-I-16910A(SHIPS), Interference Measurement, Radio, Methods, and Limits, 14 Kilocycles to 1000 Megacycles, 30 August 1954.
18. MIL-I-26600(USAF), Interference Control Requirements, Aeronautical Equipment, 02 June 1958.
19. The late Steve Caine was the chairman of the Tri-Service Working Group that revised MIL-STD-461C (1986) and MIL-STD-462 (1967) into MIL-STD-461D and MIL-STD-462D in the 1989 – 1993-time frame. He introduced the committee to the public at the 1989 IEEE EMC Symposium in Denver, saying that as he was the last surviving member of the original committee that fashioned MIL-STD-461/2/3 back in the '60s, it fell on him to lead the effort to clean up the mess they had made of it. When he was asked at another

time about how some of the MIL-STD-461 limits and -462 test methods came about back in the '60s, he sighed and said, "Well, there was a lot of horse-trading going on back then."

20. MIL-STD-462, Electromagnetic Interference Characteristics, Measurement of, 31 July 1967.
21. RTCA/DO-119, Interference to Aircraft Electronic Equipment from Devices Carried Aboard, 12 April 1963.
22. RTCA/DO-138, Environmental Conditions and Test Procedures for Airborne Electronic/Electrical Equipment and Instruments, 27 June 1968.
23. One prominent physicist refers to what the author terms the "extreme near field" as "inside the dipole."
24. A complete mathematical treatment may be found in "Journey To The Center of The Dipole," *In Compliance Magazine*, September 2023.
25. https://www.ets-lindgren.com/products/antennas?page=Products-Landing-Page
26. Schelkunoff, S.A. & Friis, H.T., *Antennas, Theory and Practice*, John Wiley & Sons, Inc. 1952.
27. NAWCAD TP 8347, *Electronic Warfare and Radar Systems Handbook*, October 2013
28. Hansen, R.C., and Bailin, L.L., "A New Method of Near Field Analysis," IRE Transactions on Antennas and Propagation, December 1959.
29. Pearlston, C.B. Jr., "The Systems Approach in Designing a Specification for the Control of Radio Interference in an Airborne Environment," Proceedings of the 5th Conference on Radio Interference Reduction and Electronic Compatibility. October 1959. In this work, Pearlston compares RE limits for protecting radio reception to susceptibility limits simulating rf transmitters, and while acknowledging the true purposes of each type of control, still manages to compare such limits and conclude that "100 dB" margins exist.
30. A complete derivation, leaving no "exercises for the reader," is presented in Adamczyk, Bogdan, *Foundations of Electromagnetic Compatibility with Practical Applications*, John Wiley & Sons, 2017.
31. Javor, K. "Journey To The Center of The Dipole," *In Compliance Magazine*, September 2023.
32. Javor, K., "On the Nature and Use of the 1.04 m Electric Field Probe," *ITEM 2011*.
33. MIL-STD-461, *Electromagnetic Interference Characteristics, Requirements for Equipment*, 31 July 1967.
34. SAE ARP-958A, *Electromagnetic Interference Measurement Antennas; Standard Calibration Method*, November 1992.
35. White, Donald R. J., "EMI Test Instrumentation and Systems," Volume 4, Section 3.3.4 of the Handbook Series on EMI & EMC, 1971.
36. Pearlston, C.B. Jr., Air Force Report No. SSD-TR-67-127, dated 1967. "Historical Analysis of Electromagnetic Interference Limits." Pearlston makes the exact same points back at the inception that were presented in this article; these observations are hardly new:

    *"An academic argument could be made, and often has been, that "field intensity" is not a proper term to use in describing the phenomenon being measured and that "antenna-induced voltage" is much more descriptive of that phenomenon. Field intensity is generally defined as a measure of the intensity of the electric field; the term implies that the measured electric field gives a valid indication of the power density in the wave front, and permits an estimate to be made of the power coupled into a receiving antenna. Such an estimate is valid only in the far field where the plane wave phase relationships of electric and magnetic fields are fixed. Thus, the measurement does not give a valid indication of power coupling.*

    *"Field intensity is also defined as the voltage induced in a conductor one meter long when held so that it lies in the direction of the electric field and at right angles to the direction of propagation and to the direction of the magnetic field. It can be argued that the equipment near-field does not have a uniphase front, and so the straight rod or dipole antenna will not necessarily be in the direction of the electric field. These near-field effects become even more marked at the higher frequencies where horn and parabolic reflectors are used.*

    *"The term field intensity should refer to a phenomenon which is independent of the measuring instrument rather than, as in the present case, being so highly dependent upon the particular antenna used. The phenomenon measured is not the actual electric field of the wave front, but consists of indications of partial components of that wave front in the near-field of the test sample. A better name for the phenomenon would be "apparent field intensity", but, as long as there is no confusion as to what is being measured, the name given to the phenomenon is not of great importance."*

    Except of course his prognostication that the name change from "field intensity" to "apparent field intensity" is not really important was proven wrong, and in this case at least, Shakespeare may be more accurately paraphrased by saying that "A rose by any other name would stink."

# Automotive EMC Testing

## CISPR 25, ISO 11452-2 and Equivalent Standards, Part 1

*By Garth D'Abreu, Craig Fanning, and Ammar Sarwar*

*This article is an update of the original article authored by Dr. Vince Rodriguez, then with ETS-Lindgren. An earlier update was published in the February 2016 issue of* In Compliance Magazine.

Automotive standards addressing electromagnetic compatibility (EMC) are developed mainly by CISPR, ISO, and SAE. CISPR and ISO are organizations that develop and maintain standards for use at the international level. SAE develops and maintains standards mainly for use in North America. In the past, SAE developed many EMC standards which were eventually submitted to CISPR and ISO for consideration as an international standard. As the SAE standards become international standards, the equivalent SAE standard is then withdrawn as a complete standard and reserved for use to document differences from the international standard.

Each vehicle manufacturer has internal corporate standards that specify the testing, severity, and sensitivity levels that components used in their vehicles, and the complete vehicle must meet. As with the government standards, these documents usually refer to the CISPR and ISO documents with differences in scope or test levels. In the past, a vehicle manufacturer based in the U.S. referenced SAE documents in their corporate standards, today most U.S.-based vehicle manufacturers market worldwide. Therefore, they reference CISPR and ISO standards in their internal corporate standard, and this is also true for other established and emerging manufacturers.

CISPR/D is responsible for developing and maintaining the standards used to measure the emissions produced by vehicles and their components. ISO/TC22/SC32/WG3 is responsible for developing and maintaining the standards used for immunity testing of vehicles and their components. ISO standards for the vehicle industry are mainly broken into two categories, vehicle (ISO 11451-xx) or component (ISO 11452-xx, ISO 7637-xx). Table 1 on pages 128 and 129 provides an


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overview of the CISPR and ISO EMC standards for the automotive industry.

As with the ISO EMC standards, SAE EMC standards are mainly broken into two categories, vehicle (SAE J551-xx) and component (SAE J1113-xx). As can be seen in the notes of Table 1, many of the SAE standards are inactive because they have been withdrawn as complete standards and reserved for use to document differences from the international standards. Table 2 on page 130 does not show all the EMC standards related to automotive published by the SAE, but it gives an overview of the main standards and cross-references to the equivalent ISO or CISPR document. Table 2 shows the main SAE standards that are still active for both vehicle components and vehicles.

As with Table 1, Table 2 is not intended to show all the different parts of the standard, but to show the complexity of the standard documents and the many parts and methods that are covered under them. As mentioned above, government standards and directives in many cases refer to the CISPR or ISO methods. 2004/104/EC, which surpassed 95/54 EC, is a European directive for vehicle EMC. Its sections related to automotive components follow the directions given in the CISPR 25 document.

## CISPR 12, CISPR 25, AND CISPR 36

CISPR 12 and CISPR 36 deal with "radio disturbance characteristics for the protection of off-board receivers" [1] [6]. CISPR 25 deals with "radio disturbance characteristics for the protection of receivers used on-board vehicles, boats and on devices" [2]. It is important to remember that CISPR 12 and CISPR 36 (the test methods and/or limits) are commonly used for regulatory purposes. The regulatory bodies want to make sure that an item with an internal combustion engine or electric propulsion system does not cause unwanted interference with TV and radio reception when it drives past (or is used nearby) a residence or business. These standards also cover electrically driven vehicles while stationary and in the charging mode of operation. CISPR 25 is not typically used for regulatory purposes, it is commonly used by vehicle manufacturers to assure good performance of receivers mounted on-board the vehicle.

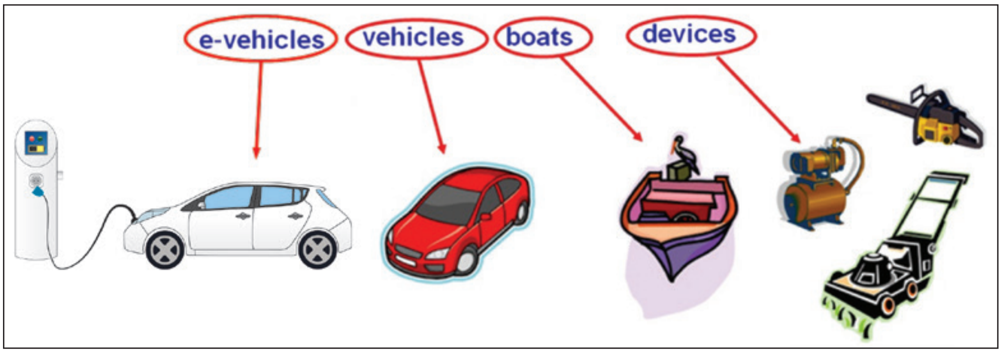

Figure 1: EUTs within the scope of CISPR 12 and CISPR 25

If the radio mounted in the vehicle, boat or other device does not perform reliably, then consumer satisfaction and ultimately product sales could suffer.

Both CISPR 12 and CISPR 25 deal with automobiles (vehicles that operate on land) powered by internal combustion engines or an electric propulsion system, boats (vehicles that operate on the surface of water) powered by internal combustion engines, and devices powered by internal combustion engines (but not necessarily for the transport of people). This last category includes compressors, chainsaws, garden equipment, etc. CISPR 12 would apply to all of these devices since they could affect the performance of nearby (off-board) receivers. CISPR 36 only applies to road vehicles driven by an electric propulsion system. It should be noted that CISPR 25 should only be considered for items that contain on-board receivers. As an example, a chainsaw with an internal combustion engine (but with no on-board receivers) would need to meet the requirements of CISPR 12, but CISPR 25 would not apply to this chainsaw since it does not utilize any on-board receivers.

CISPR 12 radiated emissions measurements are made at either 3-meter or 10-meter test distances (although the limits are for the protection of off-board receivers at a distance ≥ 10 meters). The measurements are normally done on an outdoor test site (OTS) or in an absorber-lined shielded enclosure (ALSE) if the ALSE can be correlated to an OTS. Measurements for boats can also be made on the water. The correlation of the ALSE to an OTS has been a point of discussion over the past few years within the group of experts who are responsible for the maintenance of CISPR 12. The specification currently does not provide a method to achieve this correlation. A working group has been tasked with developing a method to validate an ALSE, OATS, or OTS that could be used for vehicle measurements. The plan is to add a site validation annex to CISPR 12 7th Edition when it is published.

| Document No. | Title | Type | Equivalent | Test Setup | Chamber Requirement |
|---|---|---|---|---|---|
| ISO-11451-1 | Road vehicles — Vehicle test methods for electrical disturbances from narrowband radiated electromagnetic energy — Part 1: General principles and terminology | N/A | SAE J551/1 | Definitions | N/A |
| ISO-11451-2 | Part 2: Off Vehicle Radiation Sources | RI | SAE J551-11 (Note 1) | Vehicle Radiated Immunity test in an anechoic chamber | Vehicle Absorber lined chamber |
| ISO-11451-3 | Part 3: On-board transmitter simulation | RI | SAE J551-12 (Note 2) | Vehicle Absorber Lined Shielded Enclosure (ALSE) is required | Vehicle Absorber lined chamber |
| ISO-11451-4 | Part 4: Bulk Current Injection (BCI) | RI | SAE J551/13 (Note 3) | Test was designed for machines and vehicles too large to fit in a standard vehicle EMC | Outdoor Test Site (OTS) or Vehicle Absorber lined chamber |
| ISO-11451-5 | Part 5: Reverberation chamber | RI | None | Vehicle Radiated Immunity test in a reverberation chamber | Reverberation chamber |
| ISO-11452-1 | Road vehicles — Component test methods for electrical disturbances from narrowband radiated electromagnetic energy — Part 1: General principles and terminology | N/A | SAE J1113/1 | Definitions | N/A |
| ISO-11452-2 | Part 2: Absorber lined chamber | RI | SAE J1113/21 (Note 4) | An absorber lined chamber is required. Antennas and field generator to cover the range are required. No need to scan | Absorber lined chamber |
| ISO-11452-3 | Part 3: Transverse electromagnetic (TEM) cell | RI | SAE J1113/24 (Note 5) | TEM cell | N/A |
| ISO-11452-4 | Part 4: Bulk current injection | RI | SAE J1113/4 | Radiated immunity using the BCI method | Shielded room |
| ISO-11452-5 | Part 5: Stripline | RI | SAE J1113/23 (Note 6) | Radiated immunity using a stripline | Shielded room |
| ISO-11452-7 | Part 7: Direct radio frequency (RF) power injection | RI | SAE J1113/3 (Note 7) | Conducted immunity test 250 kHz to 500 MHz | Bench or Shielded room |
| ISO-11452-8 | Part 8: Immunity to magnetic fields | RI | SAE J1113/22 (Note 8) | Helmholtz coils are used | Bench test: no shielded room required |
| ISO-11452-9 | Part 9: Portable transmitters | RI | None | Small antennas are used in conjunction with amplifiers and signal sources to simulate portable transmitters | Absorber lined chamber |
| ISO-11452-10 | Part 10: Immunity to conducted disturbances in the extended audio frequency range | CI | SAE J1113/2 (Note 9) | Conducted immunity test 15 Hz to 500 MHz | Bench test: no shielded room required |
| ISO-11452-11 | Part 11: Reverberation Chamber | RI | SAE J1113/28 (Note 10) | Reverberation chamber – Mode Tuned | Reverberation chamber |
| ISO 7637-1 | Road vehicles — Electrical disturbances from conduction and coupling — Part 1: Definitions and general considerations | N/A | SAE J1113/1 | Definitions | N/A |
| ISO-7637-2 | Part 2: Electrical transient conduction along supply lines only | CI | SAE J1113/11 | Conducted immunity to transients as they are applied directly to the power leads of the test item. | Bench test: no shielded room required |
| ISO-7637-3 | Part 3: Electrical transient transmission by capacitive and inductive coupling via lines other than supply lines | CI | SAE J1113/12 | Conducted immunity to transients as they are applied directly to the I/O lines of the test item. | Bench test: no shielded room required |

| Document No. | Title | Type | Equivalent | Test Setup | Chamber Requirement |
|---|---|---|---|---|---|
| ISO-10605 | Road vehicles — Test methods for electrical disturbances from electrostatic discharge | ESD | SAE J1113/13 J551/15 | ESD testing performed on a module on a bench or a vehicle in a temperature and humidity-controlled environment | Bench test: no shielded room required |
| CISPR 12 | Vehicles, boats and internal combustion engines – Radio disturbance characteristics – Limits and methods of measurement for the protection of off-board receivers | RE | SAE J551/2 (Note 11) | Vehicle Radiated Emissions | OTS or Vehicle Absorber lined chamber |
| CISPR 25 | Vehicles, boats and internal combustion engines – Radio disturbance characteristics – Limits and methods of measurement for the protection of on-board receivers | RE | SAE J551/4 (Note 12) | Clause 5: Vehicle portion of the standard. This is to measure the amount of noise generated by the vehicle will be induced into the on-board receiver antenna port. | Vehicle Absorber lined chamber |
| CISPR 25 | Vehicles, boats, and internal combustion engines – Radio disturbance characteristics – Limits and methods of measurement for the protection of on-board receivers | CE & RE | SAE J1113/41 (Note 13) | Clause 6: Component (module) test section where conducted and radiated emissions are measured. | Absorber lined chamber |
| CISPR 36 | Vehicles, boats and internal combustion engines – Radio disturbance characteristics – Limits and methods of measurement for the protection of off-board receivers | RE | SAE J551/5 (Note 14) | Vehicle Radiated Emissions | OTS or Vehicle Absorber lined chamber |

Note 1 SAE J551-11 Withdrawn as a complete standard and reserved for use to document differences from ISO 11451-2. At the present time J551-11 is not used.

Note 2 SAE J551-12 Withdrawn as a complete standard and reserved for use to document differences from ISO 11451-3. At the present time J551-12 is not used.

Note 3 SAE J551-13 Withdrawn as a complete standard and reserved for use to document differences from ISO 11451-4. At the present time J551-13 is not used.

Note 4 SAE J1113-21 Withdrawn as a complete standard and reserved for use to document differences from ISO 11452-2. At the present time J1113-21 is not used.

Note 5 SAE J1113-24 Withdrawn as a complete standard and reserved for use to document differences from ISO 11452-3. At the present time J1113-24 is not used.

Note 6 SAE J1113-23 This standard has been withdrawn.

Note 7 SAE J1113-3 Withdrawn as a complete standard and reserved for use to document differences from ISO 11452-7. At the present time J1113-3 is not used.

Note 8 SAE J1113-22 Withdrawn as a complete standard and reserved for use to document differences from ISO 11452-8. At the present time J1113-22 is not used.

Note 9 SAE J1113-2 Withdrawn as a complete standard and reserved for use to document differences from ISO 11452-10. At the present time J1113-2 is not used.

Note 10 SAE J1113-28 Withdrawn as a complete standard and reserved for use to document differences from ISO 11452-11. At the present time J1113-28 is not used.

Note 11 SAE J551-2 Withdrawn as a complete standard and reserved for use to document differences from CISPR 12. At the present time J551-2 is not used.

Note 12 SAE J551-4 Withdrawn as a complete standard and reserved for use to document differences from CISPR 25. At the present time J551-4 is not used.

Note 13 SAE J1113-41 Withdrawn as a complete standard and reserved for use to document differences from CISPR 25. At the present time J1113-41 is not used.

Note 14 SAE J551-5 Withdrawn as a complete standard and reserved for use to document differences from CISPR 36. At the present time J551-5 is not used.

Table 1: Some of the main CISPR and ISO EMC standards for the automotive industry

CISPR 36 radiated emissions measurements are made at 3-meter test distance with a loop antenna (although the limits are for the protection of off-board receivers at a distance ≥ 10 meters). The magnetic field emissions measurements are normally done on an OTS, open area test site (OATS), or in an ALSE. Site correlation/ validation is currently not covered in CISPR 36. However, site validation is being considered as a work item for future editions.

CISPR 25 has two parts. One part deals with a full vehicle or system test in which the antennas mounted on the vehicle are used to sense the noise generated by the different electric and electronic systems mounted on the same vehicle. This test shows how much noise generated by the vehicle will be introduced into the radio antenna port (sort of a self-immunity test). The other section of the standard deals with conducted and radiated measurements of vehicle components and modules. In this article, we are going to concentrate on the module radiated emissions test section of CISPR 25, and only briefly highlight some of the additions needed to support electric vehicles. More specifically, this article will concentrate on the chamber requirements for the standard.

CISPR 25 states that the electromagnetic noise level in the test area has to be 6 dB lower than the lowest level being measured. Some of the radiated emissions limits found in CISPR 25 are as low as 18 dB (μV/m). This means that the ambient noise must be 12 dB (μV/m) maximum for a compliant environment. An RF-shielded

| SAE Doc No. | Title | Type | Equivalent | Test Setup | Chamber Requirement |
|---|---|---|---|---|---|
| SAE J551/1 | Performance Levels and Methods of Measurement of Electromagnetic Compatibility of Vehicles, Boats (up to 15 m), and Machines (16.6 Hz to 18 GHz) | | | | SAE J551/1 |
| SAE J551/5 | Performance Levels and Methods of Measurement of Magnetic and Electric Field Strength from Electric Vehicles, 150 kHz to 30 MHz | RE | CISPR 36 Vehicles | Vehicle ALSE may be used | OTS or Vehicle Absorber lined chamber |
| SAE J551/15 | Vehicle Electromagnetic Immunity – Electrostatic Discharge (ESD) | ESD | ISO-10605 Clause 10 | ESD test at the vehicle level would not need a shielded enclosure. | No shielded room required |
| SAE J551/16 | Electromagnetic Immunity - Off-Vehicle Source (Reverberation Chamber Method) - Part 16 - Immunity to Radiated Electromagnetic Fields | RI | None | Vehicle Sized Reverberation Chamber is needed for this test. Method allows for the reverberation test along with a "hybrid test which utilizes direct illumination and reverberation. | Vehicle Sized Reverberation Chamber |
| SAE J551/17 | Vehicle Electromagnetic Immunity - Power Line Magnetic Fields | RI | None | Magnetic Field RI testing at the vehicle level would not need a shielded enclosure. | No shielded room required |
| SAE J1113/1 | Electromagnetic Compatibility measurement procedures and limits for vehicle components (except aircraft), 60 Hz-18 GHz | N/A | ISO-11452-1 | Definitions | N/A |
| SAE J1113/4 | Immunity to radiated electromagnetic fields- bulk current injection (BCI) method | RI | ISO-11452-4 | Radiated immunity using the BCI method | Shielded room |
| SAE J1113/11 | Immunity to conducted transients on power leads | CI | ISO-7637-2 | Conducted immunity to transients | Bench test: no shielded room required |
| SAE J1113/12 | Electrical interference by conduction and coupling - coupling clamp | CI | ISO-7637-3 | Conducted immunity to different coupling mechanisms | Bench test: no shielded room required |
| SAE J1113/13 | Electromagnetic compatibility procedure for vehicle components- immunity to electrostatic discharge | ESD | ISO-10605 | ESD testing performed on a bench in a temperature and humidity-controlled environment | Bench test: no shielded room required |
| SAE J1113/27 | Immunity to radiated electromagnetic fields reverberation method | RI | None | Reverberation chamber – Continuous Stirred | Reverberation chamber |

Table 2: Some additional active SAE automotive EMC standards

room is typically used to keep RF signals from the external environment out of the test area so that the equipment under test (EUT) remains the dominant source of any radiated interference.

Although the shielded room is too small to support resonant modes at low frequencies, the number of modes increases with frequencies above the cut off of the chamber. When these resonant modes appear, they can add significant errors to the measurements. To reduce these errors, the shielded room covered with RF absorber material on its ceiling and interior walls greatly suppresses internal reflections so that the dominant coupling path is between the EUT and measurement antenna. By adding RF absorber to the walls and ceiling of the shielded room, the room becomes an absorber-lined shielded enclosure (ALSE). CISPR 25 in its current version (Ed 5:2021) covers a frequency range of 150 kHz to 5.95 GHz and to date absorber technology is unable to provide appreciable absorption at levels down in the 150 kHz range. One beneficial consequence of the low measurement frequency and the 1-meter measurement distance is the fact that the chamber sizes are electrically small at these low frequencies, so no significant resonant behavior appears. Therefore, the standard concentrates on absorber performance at 70 MHz and above. The standard requires that the absorber used must have better than -6 dB absorption at normal incidence. To achieve these levels, there are several types of absorber technology on the market today.

One of the most efficient and cost-effective is a polystyrene-based absorber that combines a high-performance ferrite tile with a polystyrene EMC absorber, having a 60cm x 60cm base and 60cm height. The main absorber substrate is based on expanded polystyrene (EPS), which is volumetrically loaded with lossy materials, and environmentally friendly fire retardants. Advanced uniform loading in the manufacturing process results in superior RF performance and excellent absorption uniformity. The closed cell structure of this type of absorber makes it suitable for use even in high-humidity environments. These features all contribute to providing a better controlled and predictable chamber test environment. Figure 3 presents the performance of one type of hybrid polystyrene absorber.

An alternative polyurethane absorber typically 36 inches (1m) in depth, EHP 36, can be used with improved high frequency performance due largely to the increased material length. But, without the benefit of the matching ferrite material used in the hybrid, the polyurethane only absorber suffers from reduced low frequency performance. Figure 4 shows the typical performance of this material and its compliance with the CISPR 25 limit.

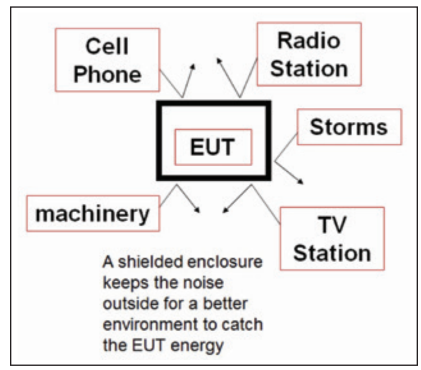


Figure 2: A shielded room blocks the noise from outdoor sources of EM interference

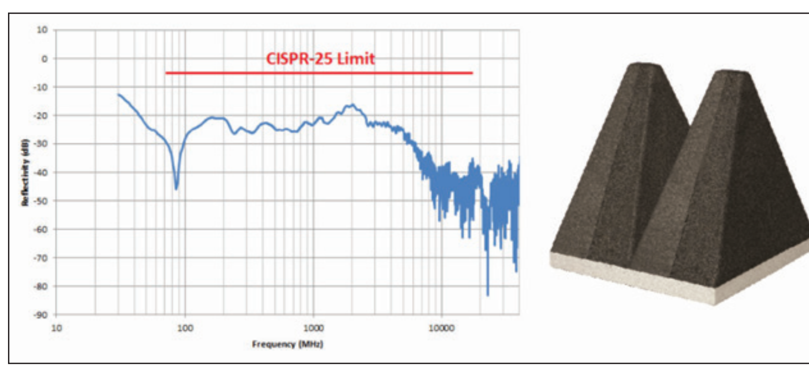


Figure 3: Typical performance of polystyrene absorber

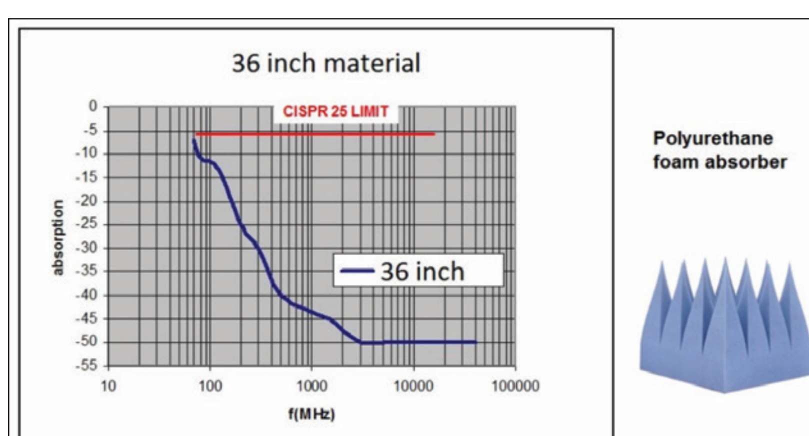


Figure 4: Typical performance of 36" polyurethane absorber material

The layout and dimensions of the typical CISPR 25 ALSE is guided by the standard. Several guidelines must be followed when sizing the chamber and the starting point is the EUT, which determines the size of the test bench. Figure 5 shows a typical test bench used in a CISPR 25 and ISO 11452-2 type chamber.

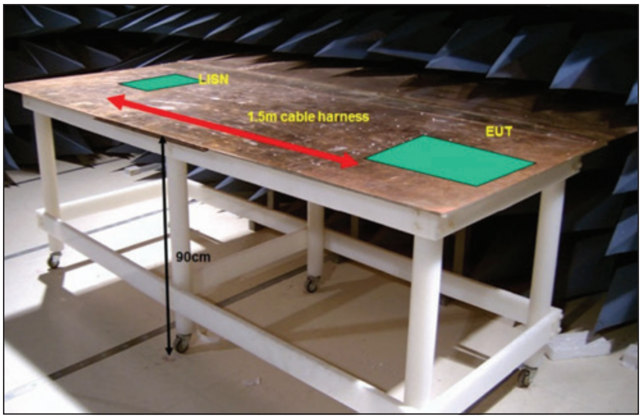

Figure 5: A typical conductive test bench

As Figure 5 shows, the bench must accommodate the largest EUT and all the cables that are needed to power and communicate with the device. The cables are routed in a cable harness that is positioned along the front edge of the bench. The cable harness itself is a significant component of the EUT and is the main component illuminated by the measurement antenna since at lower frequencies (frequencies for which the device under test is electrically small) the main coupling to radiated fields will occur through the cables feeding the device. This same procedure is used in MIL-STD 461 [3] and in ISO 11452 [4] and as shown in the illustration, a line impedance stabilization network is used to provide a defined impedance for the power to the device.

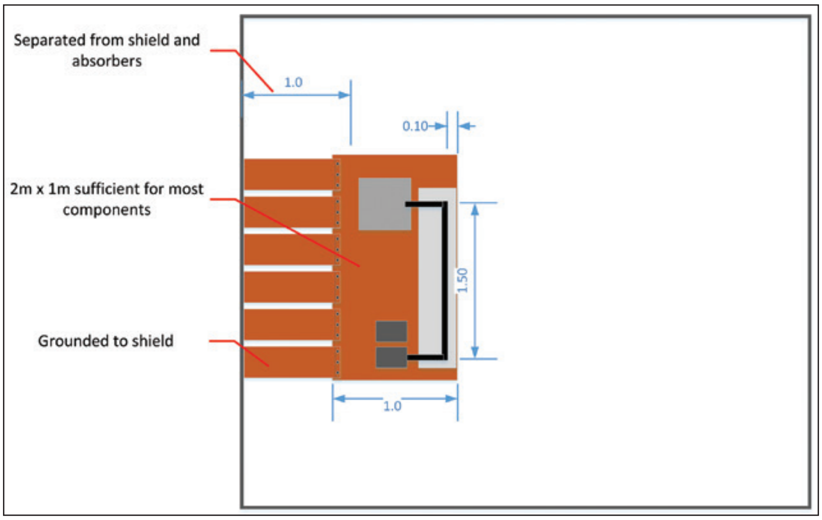

Figure 6: Sizing the bench

Figure 6 shows how the size of the bench is determined. The ground plane bench must extend all the way to the shield and in most cases, it is grounded to the wall of the shielded room. Grounding of the ground plane to the wall of the ALSE, especially if the chamber utilizes hybrid (ferrite/foam) absorbing material, has shown to reduce measurement system resonant conditions that may occur in the 10-70 MHz frequency range. The standard, however, does permit the bench to be grounded to the floor as an alternative.

As defined in CISPR 25, the minimum width of the reference ground plane (bench) for radiated emissions shall be 1000 mm, the minimum length of the ground plane for radiated emissions shall be 2000 mm, or the length needed to support the entire EUT plus 200 mm, whichever is larger.

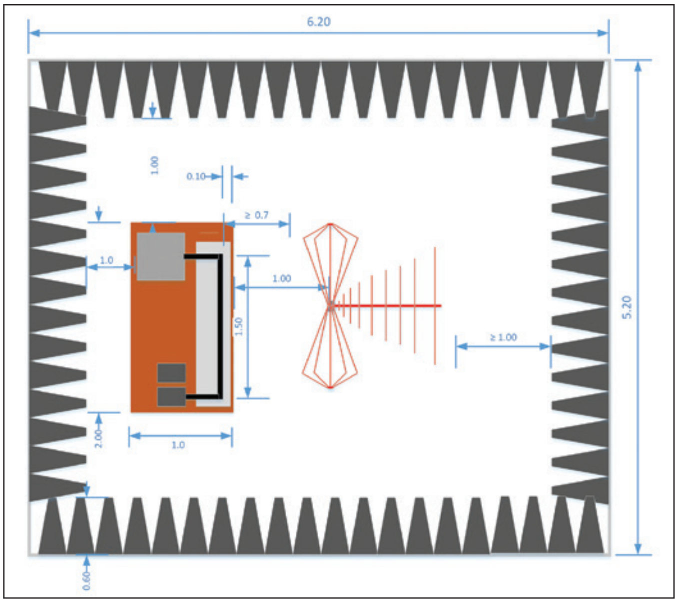

Figure 7: Width and length of the CISPR 25 chamber (multiple antenna types shown for reference)

The minimum overall dimensions of the compliant chamber are determined by a series of dimensional relationships based primarily on the size of the test bench. With the use of a hybrid absorber with a depth of 60 cm to line the walls and ceiling of the chamber, Figure 7 shows that the width and length of the chamber is determined by the length of the absorber material with a one-meter space left between the bench (actually the DUT) and the tips of the absorbing material. For chambers that will also be used for e-motor testing, the motor is also part of the EUT. In some cases, the motor is supported on a separate structure adjacent to the test bench for mechanical reasons as shown in Figure 8. In this case, it still needs to be connected to the ground plane so in effect it will be an extension of the ground plane bench and subject to the minimum distances as defined in the standard.

For the height and the length of the chamber, CISPR 25 further defines the separation distances to be followed in determining the minimum space needed. The first and most critical is the test distance where emissions are to be measured at a minimum distance of 1 m from the cable harness to the antenna.

The other rule states that no part of the antenna can be closer than 1 m away from the tips of the absorbing material. These rules and recommended antennas define the length and height of the chamber. The 1 m distance to the cable harness is measured from the axis of the antenna elements for the monopole rod and the biconical antenna. For the log periodic dipole array (LPDA), the distance is measured from the tip of the antenna. Finally, for the horn antennas the distance is measured from the front face or aperture plane of the antenna. The longest antenna is usually the LPDA. A typical LPDA for the 200 MHz to 1 GHz range is about 1 m in overall length. In addition to the 1 m test distance and the 1 m for the antenna length, we have a 1 m clearance from the back of the antenna to the tips of the absorber. Figure 8 also shows the reference distances for an LPDA and bicon antennas in the chamber for the CISPR 25 setup.

The height of the chamber will be driven by the longest antenna. The longest vertical antenna is usually the active rod monopole. The monopole is used with an extremely electrically small ground plane. Per the standard, the monopole rod is about 80 cm in length and it is positioned such that the ground plane is at the same level as the bench which as Figure 5 suggests is nominally 90 cm in height. The 1 m rule for the separation between the antenna and the absorber tip will again determine the minimum height of the chamber as shown in Figure 9.

With the components discussed in the previous sections, a chamber lined with 0.6m long hybrid absorber with a size of 5.2 meters wide by 6.2 meters long and 3.6 meters high will meet the minimum size requirements for performing compliant CISPR 25 tests. And, as we will see in the next section of this article, this chamber will also meet the requirements of ISO 11452-2. Furthermore, since this is a shielded environment, most of the tests defined in standards requiring a shielded room can be performed inside the chamber described in the present section.

The CISPR 25 document prepared by the CISPR organization, and the requirements and guidelines on antennas and receivers, are already comprehensively defined in the CISPR 16-1-4 document [5]. The recommended antenna types used for the CISPR 25 measurements are therefore cross-referenced to the CISPR 16 document. For low frequencies, an active rod monopole antenna is preferred. At frequencies between 30 MHz and 200 MHz, a typical biconical antenna is the recommended antenna. From 200 MHz to 1 GHz,

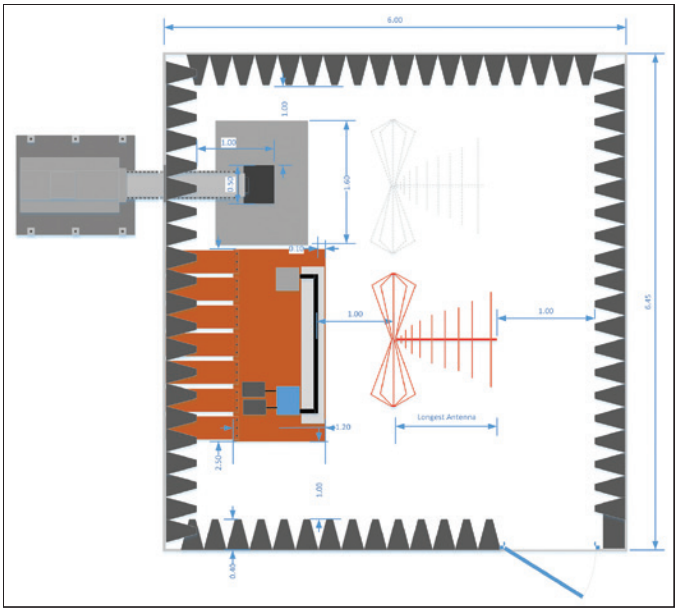

Figure 8: Increased width of CISPR 25 chamber for e-motor dyno (multiple antennas shown for reference)

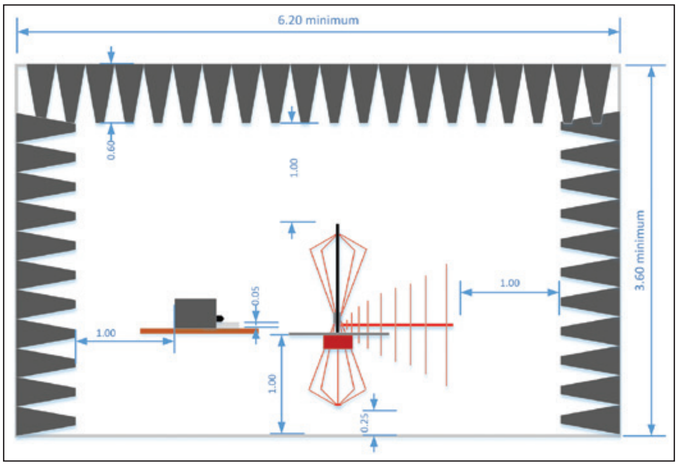

Figure 9: Height of the CISPR 25 chamber with multiple antennas shown for reference.

the antenna of choice is an LPDA and finally, from 1 to 5.95 GHz, the dual ridge horn (DRH) antenna can be a more compact and efficient antenna that easily meets the cross pole requirements of the standard, although lower gain LPDAs can still be used. It should be noted that bi log antennas are not allowed for CISPR 25 measurements and all references to the bi-log antenna have been removed from CISPR 25 5th Edition.

CISPR 25 5th Edition contains an annex (Annex I) that provides methods to validate the performance of an ALSE used for component-level radiated emission tests. The ALSE validation annex (Annex J) in CISPR 25 4th Edition contained two methods (one method based upon reference measurements and another method based upon modeling) for validating the ALSE. However, after the 4th Edition validation methods were used for several years, the experts responsible for CISPR 25 decided to include only the chamber validation method based upon modeling for CISPR 25 5th Edition. The ALSE validation method in CISPR 25 currently covers the frequency range of 150 kHz to 1 GHz. However, this remains an informative annex and experts are discussing ALSE validation methods >1GHz for future editions of CISPR 25.

As mentioned at the beginning of the article, CISPR 25 also covers the measurement of emissions received by a vehicle antenna for a full vehicle setup. CISPR 25 5th Edition contains special setups to be used for the testing of electric vehicles (EVs) and hybrid electric vehicles (HEVs) and the modules (inverters, batteries, etc.) to be used on EVs and HEVs. The committee found that special testing and limits are required for the testing of these electric-driven vehicles and their components.

These vehicles represent a special case since there are high currents and voltages involved not only in normal operation but also during charging cycles. There will be more detailed information on the measurement setups to be used for EV and HEV measurements under different connection and charging scenarios. The testing adds new conditions for when the vehicle is not being driven, but connected to the mains or a charging station. This is currently already required as part of the European directive ECE Regulation 10, which outlines the EMC requirements for wheeled vehicles marketed in the European Union. Although ECE Reg 10 has its own limits for vehicle and ESA testing, it references both CISPR 25 and CISPR 12 for test setups and measurement techniques.

## ISO 11452-2

ISO 11452-2 is a vehicle component immunity standard that applies to the 200 MHz to 18 GHz range. This standard, like many automotive, military, and aerospace standards, calls for moderately high fields to be generated. Table 3 shows the severity levels. At frequencies below 200 MHz, antennas get physically larger and also less efficient. For frequencies below 200 MHz, the standard recommends the methods stated in parts 4, 3, and 5 of the ISO 11452 standard. Those sections describe the bulk

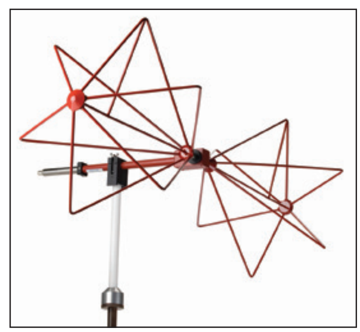

Figure 10: Typical biconical antenna

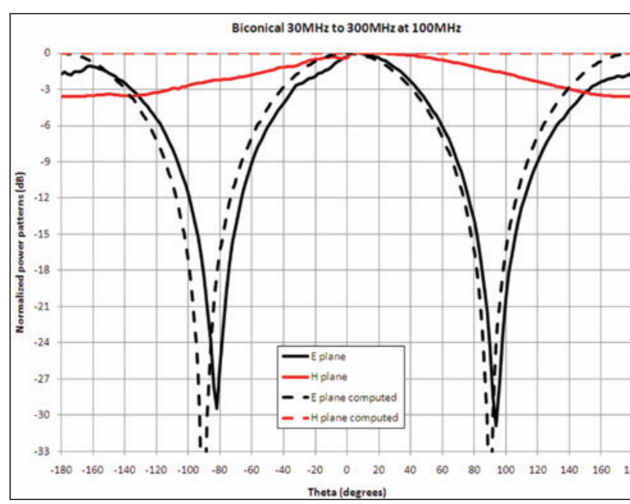


Figure 11: Measured and computed patterns at 100 MHz

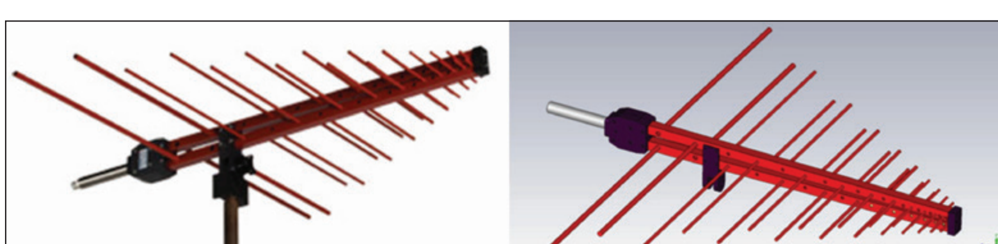

Figure 12: A picture of the measured LPDA antenna and the numerical model geometry.

current injection, TEM, and stripline test methods. These other methods are far more efficient and economical to test for immunity to high fields.

The ISO 11452-2 standard also requires that the tests be performed in an ALSE. As is common with most immunity measurements, the intent of the test is to produce RF field levels that can be disruptive or damaging to the EUT; the shielded room removes the risk of unintended disruption to other sensitive devices or equipment outside of the test region. In the US, as in most other countries, there are limits on the radiation of energy without licenses, at frequencies that could affect licensed broadcasts.

These tests are conducted at frequencies above 200 MHz and as discussed previously, the chance of resonant modes being developed inside the shield room is increased, so to reduce measurement errors the use of an absorber is required. The chamber is treated such that the reflectivity in the area of the EUT is -10 dB. Figures 3 and 4 show that for the 200 MHz to 18 GHz range, the -10 dB level is higher than the typical reflectivity of the recommended materials. This means that the same absorber used in the CISPR 25 chamber can be used in the ISO 11452-2 chamber, with the relevant guidance on minimal separation distances between DUT, absorbers, and antennas.  Antenna selection is in keeping with the need to generate the required field levels in the most effective and efficient manner given the cost of amplifiers. It is recommended that a dual ridge horn antenna be used for the 200 MHz to 2 GHz range. Above that, octave horns and standard gain horns with high gain are the preferred antenna choice.

## ON ANTENNAS, PATTERNS AND GROUND BENCHES

Let's now talk a bit about the antennas used for automotive EMC testing. Specifically, we are going to concentrate on the typical biconical, LPDA, and DRH antennas recommended for CISPR 25, and the DRH antenna recommended for ISO 11452-2.

Recently it has become important to understand the radiation characteristics of these antennas. The typical biconical antenna as shown in Figure 10 is an omnidirectional radiator. Its pattern shown in Figure 11 at 100 MHz is typical of the radiation pattern across the entire range. From these patterns, we can extract the half power beam width (HPBW). For the H plane, it is clear that the HPBW is larger than 180 degrees, and there is no main beam. For the E plane, the beamwidth ranges between 40 and 90 degrees. On the measured data, we can see the effects of the stem and balun holder on the pattern. The stem is oriented to the 180-degree mark. We can see how on the H plane the balun holder reduces the intensity of the radiation by 2 to 3 dB. The beamwidth of the measured data and the computed data track each other nicely.

Figure 12 shows a picture of an LPDA antenna and the numerical model created with specialized software. This is the other typical antenna type recommended by CISPR.

In Figures 13 and 14, we see the measured and modeled performance of the LPDA antenna. There are clearly some differences between the measured data and the computed results. Close examination reveals that the error is under 3 dB. There are several sources of error in the measurement. Using the measured values for the HPBW, the EMC engineer will err on the side of safety.

Figure 13 shows the data at 400 MHz, in which there is very good agreement between the measured and the

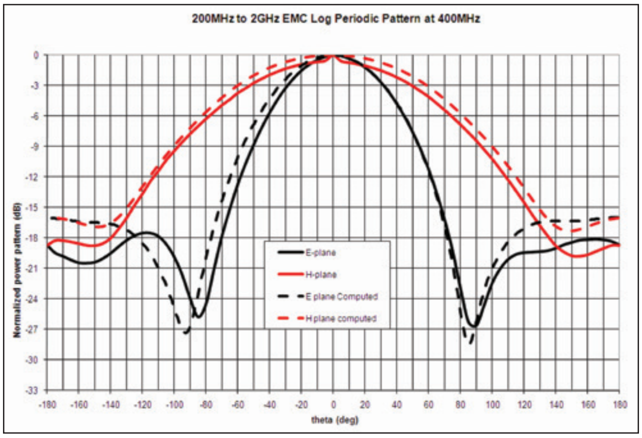


Figure 13: LPDA measured and computed pattern at 400 MHz

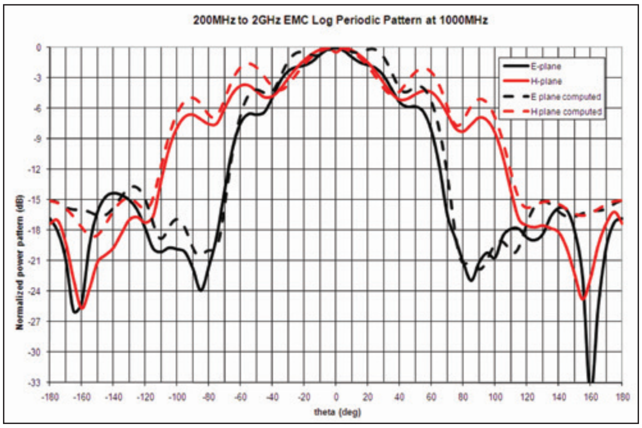


Figure 14: LPDA measured and computed pattern at 1 GHz

computed results. The data for 1 GHz (shown in Figure 14) shows good agreement between measured and computed data for the main beam.

The HPBW of the LPDA antenna is usually fairly flat. This is especially the case for the center of the frequency band covered by the antenna. From about 200 to 1000 MHz, the antenna being measured exhibits an HPBW ranging from 100 to about 60 degrees for both planes.

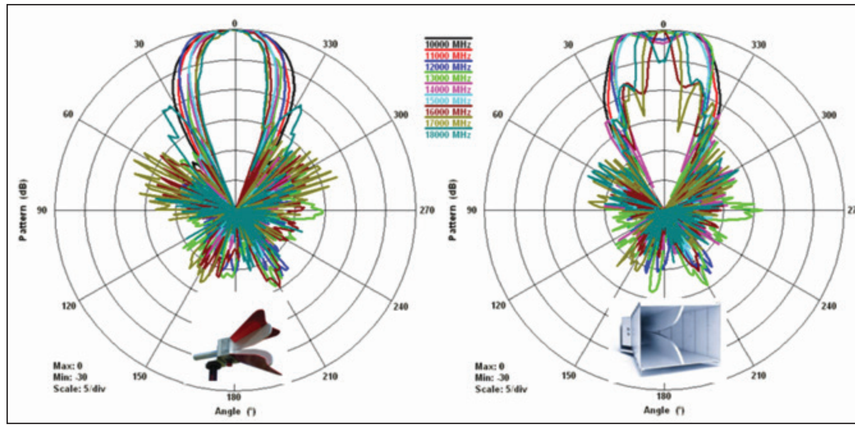


Figure 15: H plane radiation patterns from 10 to 18 GHz. The new (left) and traditional (right) DRH antenna for the 1 to 18 GHz range are shown.

DRH antennas are the antenna of choice for higher frequencies. This family of antennas has been described numerous times in the literature. Their radiation pattern has been widely described. Reference [6] describes issues with the radiation pattern of these antennas at frequencies above 12 GHz for models operating in the 1 to 18 GHz range. References [7] and [8] introduce a new design for the 1 to 18 GHz range that has a better-behaved pattern where the main beam does not split into multiple beams. Figure 15 shows the measured radiation patterns for the horn analyzed in [6] and the one introduced in [7] and [8]. The data on the left shows a better-behaved pattern than the antenna on the right without the narrow beams and the split main lobe of the pattern.

In References [8, 9] several improvements were made to the radiation patterns of DRH antennas operating in the 200 MHz to 2 GHz range. These are the horns we recommend for ISO 11452-2 since the modifications correct the nulls in the middle of the main beam.

It is important to keep in mind that the data shown for the patterns is free space and far-field data. While it is true that it provides an idea of the antenna coverage, it can be misleading once we are in the presence of conductive benches. Figure 17 shows a typical setup for either CISPR 25 or ISO 11452-2. An antenna is placed 1 m away from the bench that is grounded.

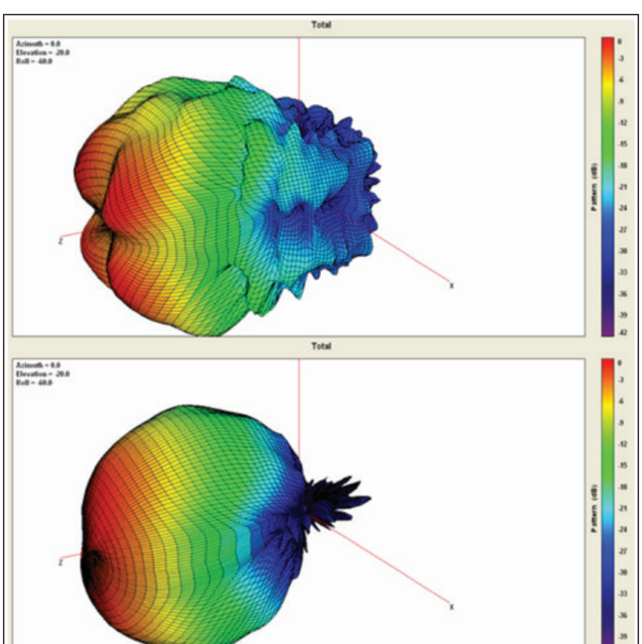


Figure 16: Comparison of a pattern at 2 GHz for the traditional and improved 200 MHz to 2 GHz DRHA

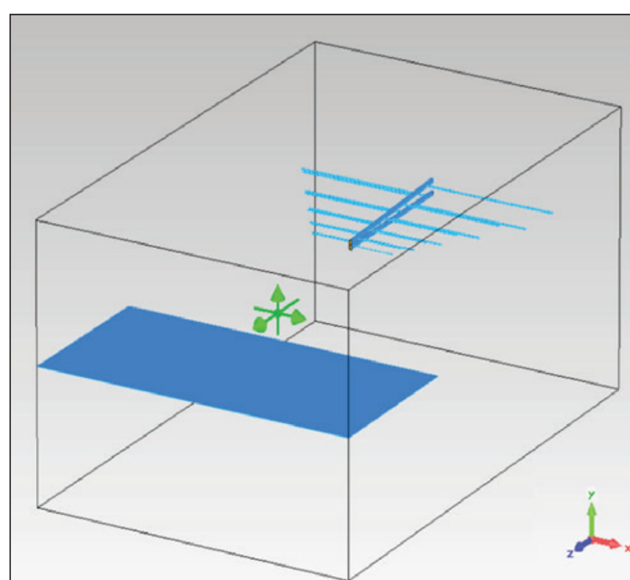

Figure 17: A horizontally polarized LPDA antenna placed in front of a conductive bench

For the horizontal polarization case, Figure 18 shows the dramatic effect that the bench has on the fields. While the cable harness will be covered by the antenna, the EUT will barely be in the illumination. This happens at all frequencies and it is related to the boundary conditions that are part of the electromagnetic phenomena.

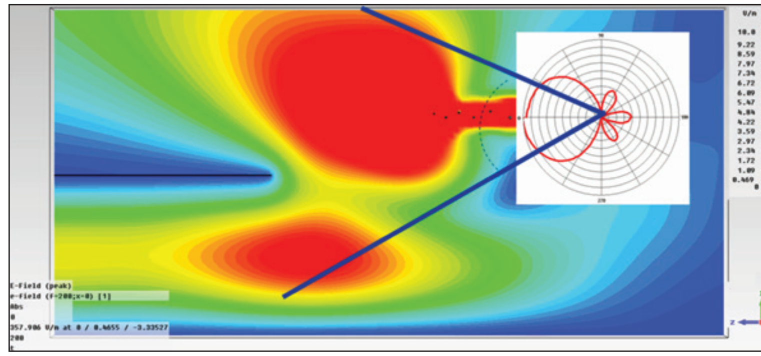

Figure 18: Field distribution from the LPDA shown in Figure 8. The cable harness which rests 5 cm above the bench is covered, but most of the EUT will not be covered.

The LPDA, DRH, and SGH antennas have been a stable and long-standing part of immunity measurements for many years. Within this period we have witnessed the development of model variants with higher gain, customized bandwidths (for radar pulse testing, for example), extended bandwidths, and higher power handling, all in an effort to improve the efficiency of the measurement setup with reduced antenna changes and reduced amplifier power.

This trend is continuing, and we have already started seeing the emergence of the next generation of immunity antennas.

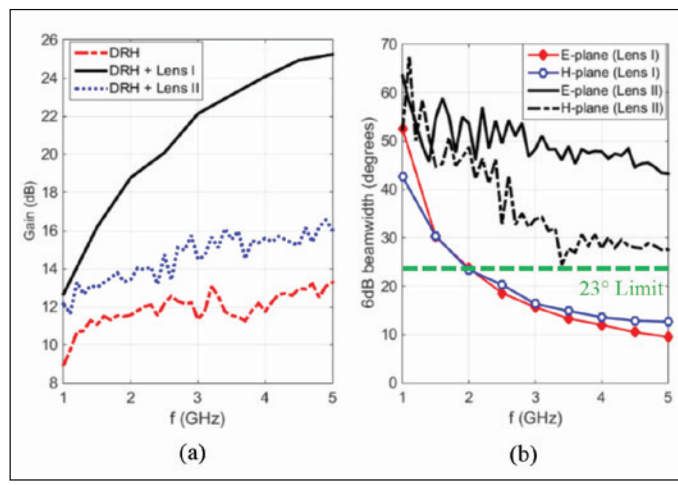


Figure 19: Simulated results of a typical DRH with lenses, (a) gain, (b) 6 dB beamwidth

The DRH antenna remains an attractive antenna for automotive EMC testing largely due to its wide operating bandwidth, stable radiating characteristics, and small size. However, the lower gain at its lower frequency end drives the need for high amplifier input power, making it impractical to achieve the required high field strength as required by ISO 11542-2 in some instances. In addition to achieving higher field levels for many immunity tests, it is also critical that the field uniformity (FU) requirements are satisfied (also required by ISO 11451-2). It is accepted that higher antenna gain is typically associated with narrower beam width which may lead to FU deterioration, so finding the correct compromise of size, gain, bandwidth, and beamwidth remains one of the antenna designer's goals.

To solve this problem, horn antennas with lenses have become increasingly popular for automotive EMC testing applications. With dielectric lenses having properties such as low loss and wide operational frequency range, ridged horn antennas have been able to meet both field strength and FU requirements for automotive EMC testing in the 1 - 5 GHz frequency range. Figure 19 shows how adding a lens to a ridged horn antenna can drastically improve the gain vs bandwidth balance.

Figure 20: A ridged horn lens antenna

A ridged horn antenna with a lens (1-3.1GHz), mounted over a stand, is shown in Figure 20. Its lightweight meta-material lens increases the gain of the horn at a 1 m distance by 9 dBi. This characteristic makes the antenna ideal for automotive component immunity testing. Such high-gain antennas help to meet the narrow band high field strength requirement with less input power for automotive immunity testing. Figure 21 shows the power vs frequency plots required for this antenna to achieve 200V/m and 600V/m.

As described previously, a compliant CISPR 25 chamber with a 2m long ground plane bench for component testing can be as small as 6.2m x 5.3m x 3.6m. For full vehicle testing, however, a larger chamber is needed depending on vehicle size, test range length, and testing scope. The EMC chamber facility shown in Figure 22 is an example of a full vehicle chamber where the hybrid polystyrene absorbers previously mentioned in Part 1 of this article have been used to achieve the desired test volume reflectivity performance. The interior dimensions of this 10-meter chamber are approximately 20.8m x 12m x 8m with a 5m diameter quiet zone and 10m range according to CISPR 16-1-4. Absorber coverage was provided on all wall and ceiling surfaces (see Figure 22). This newly retrofit chamber has been designed for automotive and commercial EMC testing in accordance with international standards CISPR 12, CISPR 25, ISO 11451, ISO 11452, and IEC 61000-4-3, as well as military standard MIL-STD-461E/F.

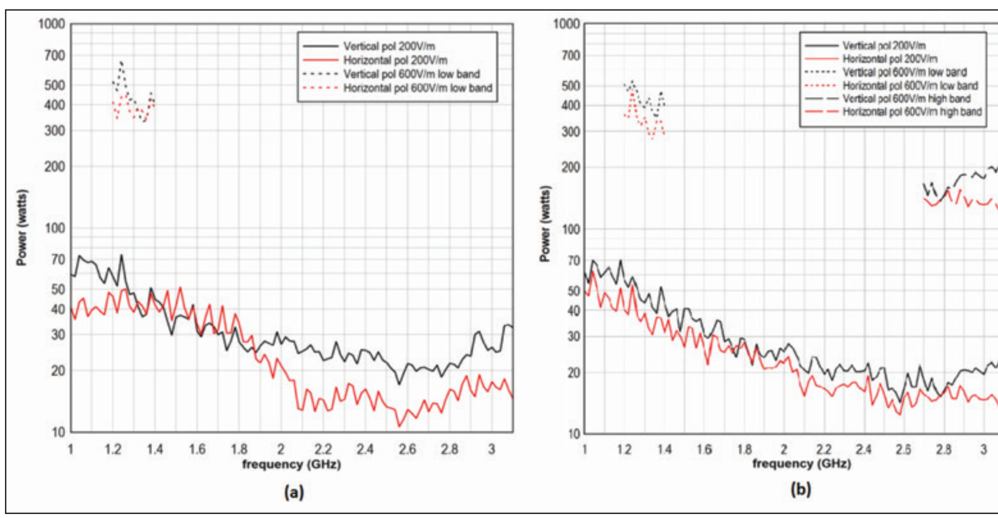


Figure 21: Typical power of ridged horn antenna with lens, (a) for conductive bench, (b) for non-conductive bench

More recent chambers with a hybrid layout as the example shown in Figure 23 have been designed to also support antenna pattern measurements. In this example, the chamber has overall dimensions of 54m x 15m x 14m height including the 18m x 15m rectangular section. This chamber is also fully lined with the polystyrene absorber material providing optimum performance for EMC measurements with satisfactory performance for the low and intermediate frequency antenna pattern measurements. This chamber was designed to meet the CISPR 12/16/25, ISO 11451/11452, R10, SAE, and ANSI C63.4 standards.

## CONCLUSION

In this article, we have introduced the two main standards for automotive vehicles and components with an overview of the revision status of these and several related standards produced by CISPR and ISO. We have concentrated on designing a chamber to meet the requirements of CISPR 25 and showed that the same chamber is usable for

Figure 22: Automotive test chamber using polystyrene absorber (image courtesy of ETS-Lindgren)

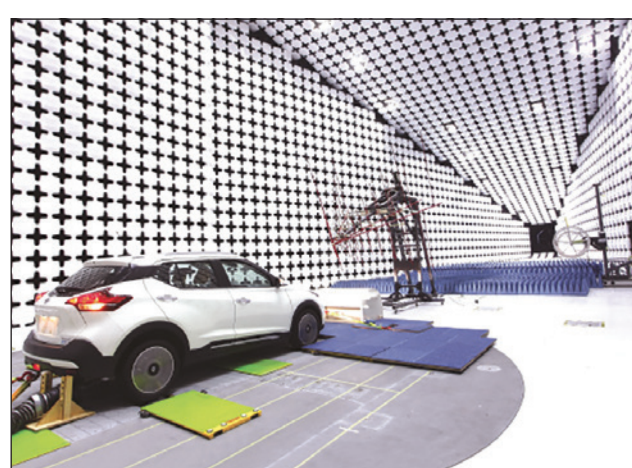

Figure 23: Chamber designed with a hybrid layout

| Nr. | Test type | Standard | Freq. range | Performance |
|---|---|---|---|---|
| 1. | NSA at 10m for 4m dia. QZ | CISPR-16-1-4 | 30 - 1000 MHz | <4 dB |
| 2. | sVSWR | CISPR-16-1-4 | 1 - 18 GHz | compliant |
| 3. | Absorber reflectivity | CISPR 25 Ed 5 | 70 M - 2500 MHz | Better than 6 dB |
| 4. | Site Performance | CISPR 25 Ed 5 | 150 k - 1 GHz | Long wire compliant |
| 5. | Field Uniformity | IEC-61000-4-3 | 60 M - 6 GHz | Less than 6 dB |
| 6. | Absorber reflectivity | MIL-STD-461E | | Better than 6 dB from 80 M-250 MHz Better than 10 dB above 250 MHz |
| 7. | Shielding effectiveness | EN 50147-1 | | Compliant |

Table 3: Chamber verification methods and performance results for the chamber in Figure 13

ISO 11452-2. Finally, we have shown some radiation patterns of the typical antennas recommended by the standards, the performance improvements for a ridged horn fitted with a lens, and the benefits of reducing the power demand. The various patterns will give the user an idea of the illumination area that the antennas cover when used, and how the presence of the bench can have a dramatic effect on the radiation pattern and the coverage of the antennas. This is clearly an aberration caused by the setup used for these standards and not by the antennas being used. So, as with most measurements, caution is recommended in the selection of antennas, set up, and validation steps taken to verify that the intended fields are present over the entire area of the EUT to account for any distortions or resonances that may be present.

In closing, the chamber installation example we've presented here highlights the notion that, wherever possible, new installations should take advantage of the best available technology and the latest revisions of the relevant standards, as is shown with the use of the proposed CISPR 25 5th Edition chamber validation method and, as in the case of a hybrid design, other tests and standards can be accommodated with careful absorber selection and treatment.


## ACKNOWLEDGMENT

The authors would like to thank Mr. Stéphane Blanc of UTAC CERAM Group for providing the measurement data of their automotive EMC 10-meter chamber, and the engineers at NISSAN for the opportunity to collaborate on a novel chamber design to support EMC as well as antenna pattern measurements.


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# Pre-Compliance EMI Testing

## Passing Compliance Tests the First Time

*By Paul Denisowski*


Most electrical and electronic devices must be tested by third-party labs to ensure that they comply with the relevant conducted and radiated emissions standards. The failure rate in compliance tests is often high, requiring costly and time-consuming redesign. With pre-compliance testing of electromagnetic interference (EMI) as part of the design process, manufacturers can identify problems early in the product cycle. Pre-compliance testing makes it easier to modify the design and electromagnetic properties of a product and increases the probability of passing compliance tests the first time.

Devices must be tested to show that they comply with the requirements of various standards, such as CISPR or MIL-STD. These standards are specified by the responsible regulatory authority, such as the Commission of the European Union (EU) or the Federal Communications Commission (FCC) in the U.S. The required compliance tests must be passed before a device can be put on the market.

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Compliance testing is usually performed by a certified third-party test lab or test house. They have specialized equipment, special facilities (such as anechoic chambers), and trained testing personnel, all of which make compliance testing expensive. Testing fees can reach thousands or even tens of thousands of dollars (U.S.) per attempt.

Unfortunately, failing compliance tests is a common occurrence. Depending on the type of testing and the standards involved, the failure rate can be in the range of 70 to 90 percent. If a single part of the test is failed, the entire test is considered unsuccessful, and the device manufacturer must schedule a new test. Any necessary product redesign or remediation must be performed before retesting, and this requires additional time and money.

### EMC TESTING BECOMES PART OF THE DESIGN PROCESS

Formal compliance testing only yields "pass-fail" results and does not provide much insight into the causes of the failure. Pre-compliance testing, on the other hand, can be stopped at any time and the reasons for issues can be thoroughly analyzed, tested, and debugged.

Figure 1 illustrates the electromagnetic compatibility (EMC) testing process. EMI debugging and analysis should be incorporated into the design process itself.

If initial measurements do not reveal any serious issues, the equipment under test (EUT) moves into pre-compliance testing. The pre-compliance tests should come as close as possible to the associated compliance tests. If an EUT fails any of these pre-compliance tests, it goes back to the design and debugging phase for modification. Once pre-compliance tests have been successfully passed, the EUT then moves to full compliance testing at a lab or test house. Successfully passing the required compliance tests results in formal certification, allowing the device to be marketed.

### Test Location and Site

Formal compliance tests require specific test environments and specific test setups. For assessing conducted EMI, the required equipment and environment are quite simple. In addition to the test instruments and accessories, the test engineer needs only a simple ground plane and a non-conductive table. Therefore, conducted pre-compliance tests are often almost identical to full compliance tests.

On the other hand, radiated EMI compliance testing generally requires a shielded chamber or a suitable open-air test site. Due to the size, cost, and complexity of configuring these types of facilities, most radiated pre-compliance tests cannot precisely duplicate the compliance test environment.

As a result, modifications are often made when performing radiated pre-compliance tests, such as adding margins to the measurement results. For example, a smaller chamber leads to higher emissions than in the final compliance test as the distance between the antenna and EUT is smaller. In this case, emission limits must be raised to take the stronger signals into account. Going from a typical compliance distance of ten meters to a typical pre-compliance distance of three meters, as shown in Figure 2, might require approximately 10 dB higher emission limits.

## TEST INSTRUMENTS: EMI RECEIVERS AND SPECTRUM ANALYZERS

There are two main categories of test instruments used for pre-compliance testing. Spectrum analyzers and EMI receivers are most commonly used to measure emission limits, whereas oscilloscopes are primarily used for debugging and troubleshooting.

EMI receivers and spectrum analyzers (Figure 3) are frequency-domain instruments. They measure and display power as a function of frequency. Frequency domain analysis is essential for EMI testing since conducted or radiated power levels are measured over a range of frequencies defined by a standard. Spectrum analyzers and EMI receivers use automated routines that step through or scan the frequency range of interest. This functionality is either a built-in feature of the instrument or implemented by software.

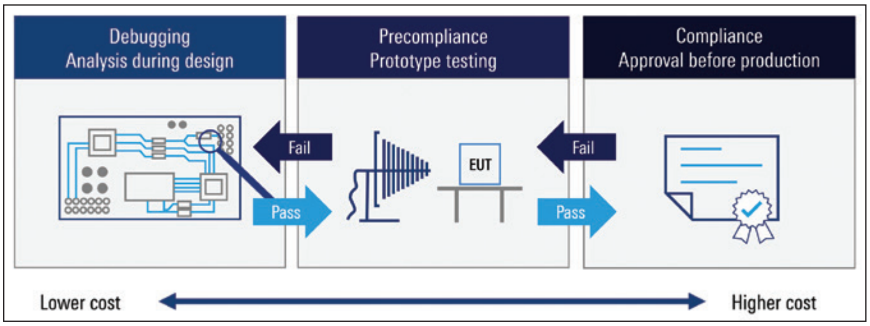

Figure 1: The EMC testing process (Source: Rohde & Schwarz)

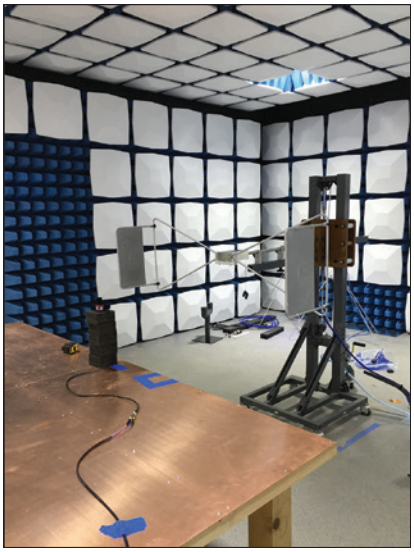
Figure 2: For radiated pre-compliance tests the distance between EUT and antenna is relevant for determining proper limits. (Source: Rohde & Schwarz)

Figure 3: EMI receivers and spectrum analyzers are typical test instruments for pre-compliance tests. (Source: Rohde & Schwarz)

### Limit Lines

A "passing" result occurs when all measured values fall below a defined power-versus-frequency limit line. These maximum power values can either be configured directly on or loaded into the test instrument.

### Detector types

Detectors determine how measurements during an interval are combined into a single measurement point. In Figure 4, you see the measurement of a pulsed signal. The results were calculated for each signal interval using different detector types. The average detector simply yields the average value over each interval. The peak detector selects the maximum value in each interval. Quasi-peak detectors were originally developed to better indicate the subjective annoyance level experienced by a listener hearing impulsive interference to an AM radio station. Quasi-peak or CISPR detectors are now generally used to measure the interference of a signal using a type of charging and discharging behavior. The effect of different detector types is shown in Figure 4.

Measurements made with a peak detector are much faster than those made with a quasi-peak detector, usually by at least several orders of magnitude. Additionally, peak detector results are always higher than quasi-peak results. If an EUT passes pre-compliance testing using the faster peak detector, it will also pass the slower tests with a quasi-peak detector. For this reason, the peak detector is more common in pre-compliance testing and the quasi-peak detector is more common in compliance testing.

### Spectrograms

In addition, EMI pre-compliance tests often use spectrograms. A spectrogram is a plot of power versus frequency versus time. In order to display these three quantities in only two dimensions, signal power or intensity is mapped to the visible color spectrum, with red indicating maximum power and purple or violet indicating minimum power. The most recent measurements appear in the top line of the display and then "flow" downwards.

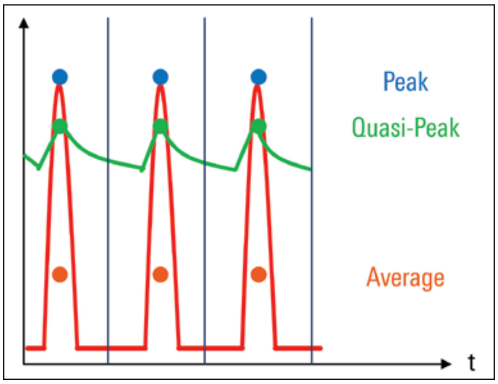


Figure 4: Common detector types (Source: Rohde & Schwarz)

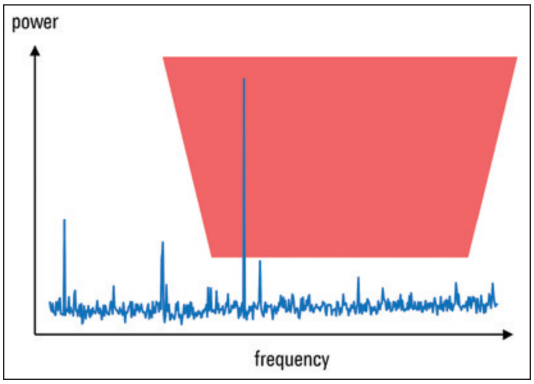


Figure 5: A frequency mask trigger can be used to help identify the cause of this violation in the time domain. (Source: Rohde & Schwarz)

Spectrograms are useful because they show how signals change over time and over a range of frequencies. This enables easy identification of time-varying signal behavior such as drifting or frequency hopping. Spectrograms also make it easy to see small signals in the presence of larger signals. Most spectrum analyzers and EMI receivers have spectrograms as a standard feature, and spectrograms are also common for oscilloscopes when displaying frequency-domain information in so-called FFT (fast Fourier transform) mode.

### Preselection

In EMI testing, the input signal is neither known nor controllable. Therefore, it is possible that out-of-band or "off-screen" signals could overload the test instrument's first mixer and cause compression or distortion, leading to invalid or misleading measurement results.

Preselection protects the first mixer. It is implemented as a switchable bank of filters that allows an EMI receiver to select only the frequencies of interest. The particular filter is chosen automatically by the receiver based on the configured input frequency. Many EMI standards require that the "measuring instrument" have preselection, and this is why compliance testing is performed with EMI receivers rather than with spectrum analyzers. Many spectrum analyzers also have a feature called preselection, but this is usually a high-pass filtering based on YIG technology and not a switchable filter bank.

### Time Domain Scan

The classic measuring method of EMI receivers is the stepped frequency scan with a small resolution bandwidth. It is a highly accurate but slow method, especially for applications with wide spectral ranges such as radiated emissions measurements.

Modern EMI receivers support time domain scans by splitting the measurement range into large spectrum blocks. The instrument digitizes and processes each of them by using FFT. Time domain scan provides a significant speed improvement over the stepped scan without sacrificing accuracy. Time domain scan has been approved for usage in most types of compliance testing and also can save significant time during pre-compliance testing.

### Test Instruments: Oscilloscopes

Oscilloscopes are primarily time domain measurements. They are a valuable measuring tool for locating, debugging, or remediating sources of non-complying emissions. Many modern oscilloscopes also support frequency domain measurements. In addition, modern oscilloscopes generally have a wide bandwidth. Oscilloscopes can be used to examine both conducted and radiated signals.

One potential drawback of using oscilloscopes for pre-compliance testing is that they usually do not natively support limit lines, although limit lines and other EMI-related features can be implemented in external software.

### Fast Fourier Transform (FFT)

Some oscilloscopes can be used to display and analyze frequency domain data by performing FFT on acquired time domain data. This is helpful for pre-compliance testing as they display time and frequency domain data simultaneously. Users can correlate events in one domain with events in another domain. This is extremely helpful when debugging EMI issues, especially if the oscilloscopes are equipped with a frequency domain trigger. This trigger occurs when a frequency mask or region is violated, as shown in Figure 5. Once the oscilloscope has been triggered by this frequency-domain event, the related time-domain event can be analyzed to determine the root cause of this violation.

Wide bandwidth and the ability to correlate time and frequency domain data make oscilloscopes very valuable for debugging issues discovered during pre-compliance testing. Features such as spectrograms and limit lines can be supported by all three instruments. EMI receivers additionally offer preselection and time domain scans. EMI receivers are used for full compliance testing and using them for pre-compliance tests leads to a closer correlation with compliance test results.

Figure 6: Typical near-field probes used in pre-compliance testing (Source: Rohde &Schwarz)

## ACCESSORIES USED FOR PRE-COMPLIANCE TESTING

In addition, there are a number of different tools and accessories which are necessary for pre-compliance measurements.

### LISN

A line impedance stabilization network (LISN) is used in conducted emissions testing. One of the main functions of a LISN is to provide a stable impedance on the AC mains line end of the EUT's power cord. Since power outlet impedance can vary widely, a LISN ensures consistent, repeatable results regardless of where the test is conducted. In addition, it blocks any RF signals present on the AC mains from entering the EUT via the EUT's power cord. This ensures that any measured emissions are coming from the EUT rather than being conducted in from the AC mains network.

### Antennas

Radiated compliance testing is always done in the so-called far field, with the antenna placed several meters from the EUT. Because of the wide frequency ranges required by most radiated testing standards, typically 1 GHz or more, a broadband antenna or a combination of antennas is needed to efficiently cover the entire frequency range. Some common examples are log-periodic antennas or biconical antennas.

The same types of antennas can be used in both compliance and pre-compliance tests but recall that the distances between the antenna and EUT are often shorter in pre-compliance testing, requiring modifications to the radiated limit lines.

However, with regard to troubleshooting or debugging the causes of emissions, these types of antennas are not appropriate. They are too large and too bulky to provide precise information about which part or component of the EUT is generating non-compliant emissions.

### Near-Field Probes for EMI Debugging

Near-field probes are the appropriate tools for use in close physical proximity to the source of an emission. As a practical matter, the near field in EMI debugging is of the order of a few centimeters. Because of their small size and the ability to physically position them close to the source, near-field probes have high spatial resolution. They allow users to precisely locate the source of an emission, for example, a pin of a chip or a trace on a printed circuit board. On the other hand, near-field probes only support relative measurements. They can be used to find sources of emissions but cannot be used to measure accurate power levels for the purpose of verifying limits.

### Software

Specialized software is commonly used in pre-compliance testing, most often for scripting or automating tests. The software communicates with or controls multiple instruments and accessories via a single user interface. It can also easily incorporate antenna factors, cable loss, etc. into the measurement results. It also collects and displays the measured data with advanced options, such as customized limit lines. This provides higher speed and better repeatability than manual operation, allowing rapid and accurate pre-compliance testing to be performed even by users who are relatively new to pre-compliance testing.

## SUMMARY

Pre-compliance testing saves time and money by discovering potential issues early in the design cycle. Using the proper tools and techniques during pre-compliance testing greatly increases the chance of passing full compliance tests the first time.

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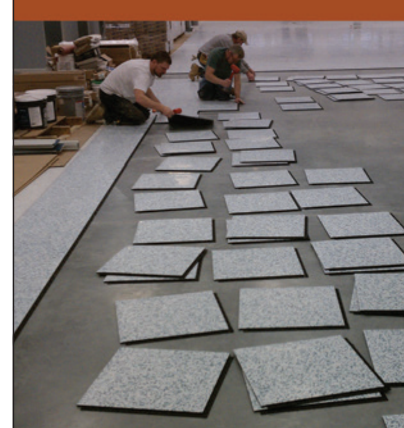

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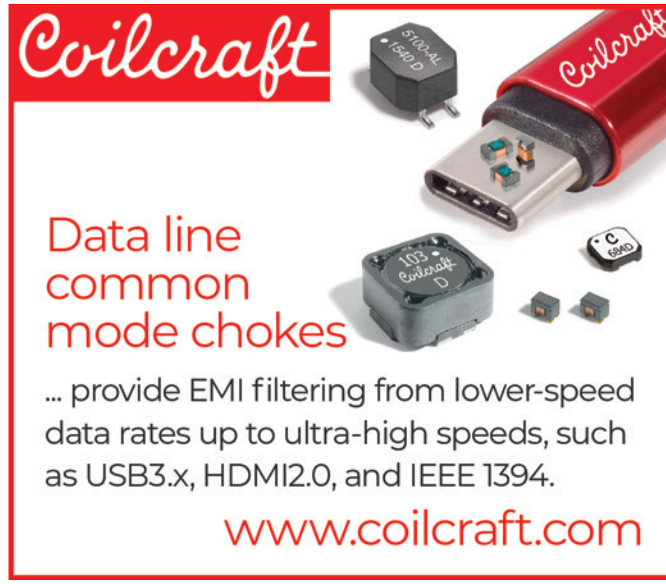


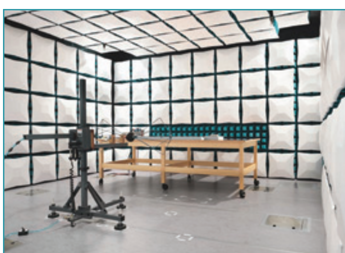

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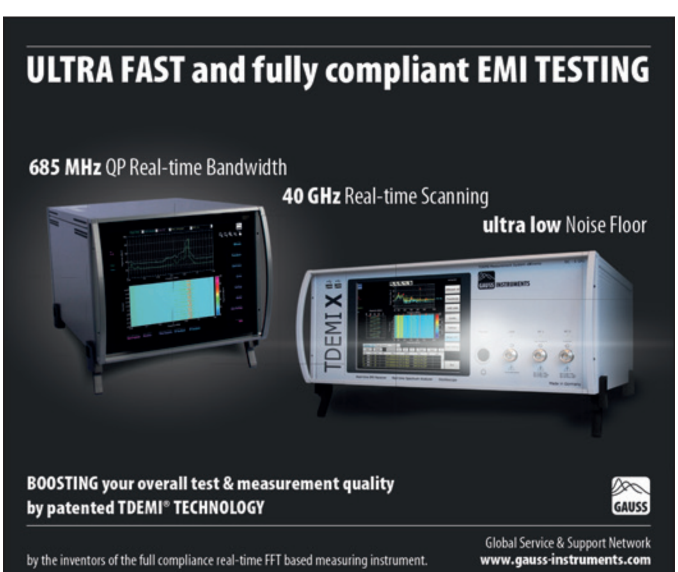



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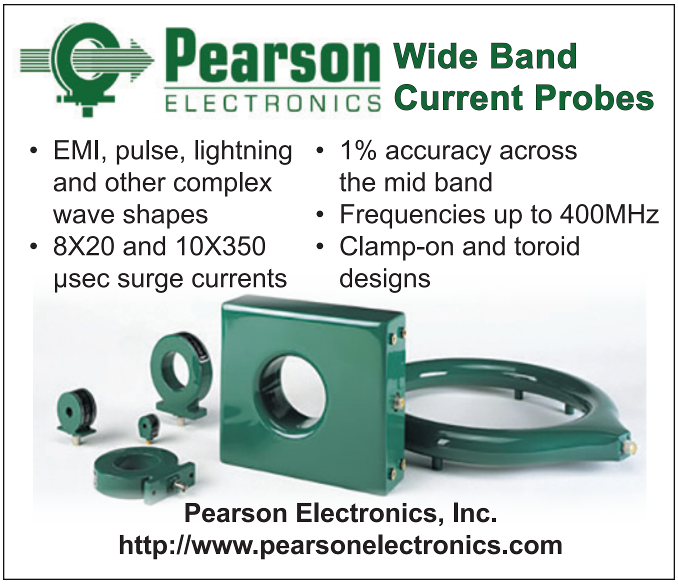






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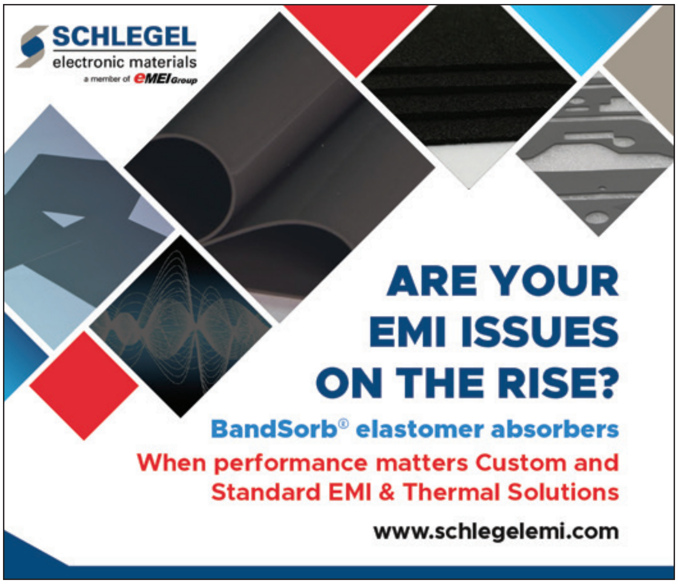



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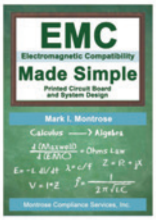


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tel: (800) 362-1495
https://www.raymondemc.com

Raymond EMC specializes in the design, fabrication, installation and testing of custom radio frequency shielded enclosures, anechoic chambers and secure processing and secure discussion facilities for military, government, high tech, industrial, automotive, aviation and medical applications. With over 30 years of experience serving our industries, Raymond EMC prides itself on being a leader in product quality, performance and innovation while providing unmatched client care and product support through all processes. See how Raymond EMC can take your projects to the next level - learn more and request pricing at https://www.raymondemc.com.

### Raymond RF Measurement Corporation
Snow Road Station, ON Canada https://www.raymondrf.ca

### RCD Components
Manchester, NH USA https://www.rcdcomponents.com

### Reality Consulting Yemen
San'a Yemen http://www.reality-consulting.com

### Reliant EMC LLC
Kansas City, MO USA https://www.reliantemc.com

### Remcom
State College, PA USA https://www.remcom.com

### Retlif Testing Laboratories
Ronkonkoma, NY USA https://www.retlif.com

### RF Solutions, LLC.
Syracuse, NY USA https://rf-solutions.com

### RIGOL Technologies USA, Inc.
Portland, OR USA https://www.rigolna.com

### RMV Technology Group LLC
300 S. McCord Avenue
Moffett Field, CA
tel: (650) 964-4792
https://www.esdaerospacetraining.org

RMV Technology Group LLC is the leading Industry Expert for ESD Virtual/On-Site hands-on and interactive training for Industry and Government. In partnership with Exemplar Global, the 3rd party certification body and member of the American Society of Quality (ASQ) family of companies, the iNARTE® global certification is intended for technicians and engineers that package, handle, store, and transport ultra-sensitive EEE parts by air, land, and sea.™

Located on-site at NASA Ames Research Center, RMV is the largest and most advanced accredited ESD Laboratory for materials, packaging, and products located on a NASA site.

### Rogers Labs
Lenexa, KS USA https://www.rogerslabs.com

### Rohde & Schwarz
Columbia, MD USA https://www.rohde-schwarz.com

### Ross Engineering Corp.
Campbell, CA USA https://www.rossengineeringcorp.com

### Roxburgh EMC
North Lincolnshire, Yorkshire Great Britain https://www.dem-uk.com/roxburgh

### Saf-T-Gard International, Inc.
Northbrook, IL USA https://www.saftgard.com

### Safe Engineering Services & Technologies
Laval, QC Canada https://www.sestech.com

### Sanwood Environmental Chambers Co., Ltd
Dongguan City, Guangdong China https://www.sanwood.cc

### SAS Industries, Inc.
Manorville, NY USA https://www.sasindustries.com

## Schaffner EMC Inc.

52 Mayfield Avenue
Edison, NJ 08837 USA
tel: (732) 225-9533
usasales@schaffner.com
https://schaffner.com

Schaffner is the expert for EMC-filter solutions, harmonic filters, and electromagnetic components for seminal industrial markets as well as e-mobility.

Schaffner provides its customers electromagnetic solutions to operate their electronic systems reliably and efficiently, empowering them to focus on their great inventions.

### Schlegel Electronic Materials

Rochester, NY USA — https://schlegelemi.com

### SCHURTER, Inc.

Santa Rosa, CA USA — https://www.schurter.com/en

### Schwarzbeck Mess-Elektronik OHG

Schönau, Baden-Württemberg Germany — https://www.schwarzbeck.de

### SCI

Lake Forest, IL USA — https://www.hipot.com

### SCR ELEKTRONIKS

Dist. Thane, Maharashtra India — https://www.screlektroniks.com

### Seal Science, Inc.

Irvine, CA USA — http://sealscience.com

### Select Fabricators, Inc.

Canandaigua, NY USA — https://www.select-fabricators.com

### SF Cable

Hayward, CA USA — https://www.sfcable.com

### Siglent Technologies North America

Solon, OH USA — https://www.siglentamerica.com

### Signal Hound

La Center, WA USA — https://www.signalhound.com

### SILENT Solutions LLC

Amherst, NH USA — https://www.silent-solutions.com

### Simco-Ion

Alameda, CA USA — https://www.simco-ion.com

### Slayson

San Diego , CA USA — https://slayson.com

### Solar Electronics Co.

North Hollywood , CA USA — https://www.solar-emc.com

### Southwest Research Institute

San Antonio, TX USA — https://www.swri.org

### Spectrum Control

Fariview, PA USA — https://www.spectrumcontrol.com

### Spectrum EMC, LLC

Sierra Vista, AZ USA

### Spes Development Co

Ann Arbor, MI USA — https://www.spesdev.com

### Spira Manufacturing Corporation

San Fernando, CA USA — https://www.spira-emi.com

### Sprinkler Innovations

Seabrook, NH USA — https://www.sprinklerinnovations.com

### Static Solutions, Inc.

Hudson, MA USA — https://staticsolutions.com

## StaticStop ESD Flooring

33 Wales Avenue, Suite F
Avon, MA 02322 USA
tel: (877) 738-4537
https://www.staticstop.com

StaticStop manufactures a full line of ESD/Static Control Flooring, including an adhesive-free interlocking flooring that can be used over bad subfloors and installed directly on top of existing floors without any disruption to operations. We offer the most comprehensive line of ESD flooring solutions available, including installation and maintenance options to provide the right product at the best price for any application.

### StaticWorx, Inc.

Williston, VT USA — https://staticworx.com

## SteppIR Communication Systems

13406 SE 32nd Street
Bellevue, WA 98040 USA
tel: (425) 453-1910
https://steppir.com

SteppIR Communications Systems is the manufacturer of the SY3-EMC antenna system, the solution for a 50-year-old problem with MIL-STD-461 RS103 radiated susceptibility in the frequency range of 30-200 MHz. Our system utilizes a mechanically adjustable Yagi antenna, which with the help of a sophisticated software algorithm, creates unique, fully optimized antennas at every frequency within its range, in both horizontal and vertical polarization. NOW CE Listed.

### SunAR RF Motion

Dublin, CA USA — https://www.sunarrfmotion.com

## Suzhou 3ctest Electronic Co., Ltd.

No. 99 E'meishan Road, SND
Suzhou, Jiangsu, 215153, China
tel: +86-512-68077192
https://www.3c-test.com

3CTEST was founded in 2004 as a renowned manufacturer of EMC test equipment and provider of EMC system solutions. With our dedicated team for research and development, manufacturing, sales, and service, we offer an extensive range of products that encompass various test standards, including IEC 61000-4-X for generic testing, ISO 7637, ISO 16750 for automotive testing and OEM requirements, MIL-STD series for military testing proposes, as well as RTCA-DO160 series for direct and indirect lightning testing. Committed to delivering exceptional product quality and outstanding service experience, we strive to be your trusted professional partner in EMC testing.

### SW Safety Solutions

Union City, CA USA — https://www.swsafety.com

### Swift Textile Metalizing LLC

Bloomfield, CT USA — https://www.swift-textile.com

### Syntakt Packaging Integration

Spokane, WA USA — https://syntaktsystems.com

### TDK Electronics

Iselin, NJ USA — https://www.epcos.com

## TDK RF Solutions

1101 Cypress Creek Road
Cedar Park, TX 78613 USA
tel: 512-258-9478
https://www.tdkrfsolutions.tdk.com

TDK RF Solutions is a world leader in the design, development & manufacture of technical solutions for the EMC testing and Antenna measurement industries. We offer a complete range of solutions including automated test systems, anechoic chambers, RF absorber, antennas, software, RF filters, and a wide range of test products & accessories. We call it Total System Technology®, and it means TDK RF Solutions is your best choice of partner for proven solutions & services. If you are in the market for a complete turnkey solution or looking to expand your test capabilities with a new antenna, contact us to see what TDK can do for you.

### TECH WEAR, INC.

Mesa, AZ USA — https://www.techwear.com

### Tech-Etch

Plymouth, MA USA — https://www.tech-etch.com

### Techmaster Electronics

Vista, CA USA — https://techmaster.us

### Technical Safety Services

Berkeley, CA USA — https://techsafety.com/services/test-certification/cleanroom-testing

### Teledyne LeCroy

Chestnut Ridge , NY USA — https://teledynelecroy.com

### TESEO SpA

Druento, Terni Italy — http://www.teseo.net

### Test Site Services Inc

Milford, MA USA — http://www.testsiteservices.com

### Testing Partners

Boardman, OH USA — https://testingpartners.com

### TestWorld Inc

Rocklin, CA USA — https://testworld.com

### Thermo Fisher Scientific

Tewksbury, MA USA — https://www.thermofisher.com

### Thermotron

Holland, MI USA — https://www.thermotron.com

### Thermtest

Fredericton, New Brunswick Canada — https://thermtest.com

### Timco Engineering, Inc.

Newberry, FL USA — https://www.timcoengr.com

### Times Microwave Systems

Wallingford, CT USA — https://www.timesmicrowave.com

### TJS Technical Services Inc.

Airdrie, AB Canada — https://tjstechnical.com

### TOYO Corporation

Fremont, CA USA — https://toyotechus.com

### Transient Specialists, Inc.

Burr Ridge, IL USA — https://transientspecialists.com

### Transtector

Hayden, ID USA — https://www.transtector.com

### Trescal

Hartland, MI USA — https://www.trescal.com

### TTE Filters

Arcade, NY USA — https://www.tte.com

## TÜV Rheinland of North America
Littleton, MA USA https://www.tuv.com

## TÜV SÜD America Inc.
Wakefield, MA USA https://www.tuv-sud-america.com

## United Static Control Products Inc.
Bradenton, FL USA https://ultrastatinc.com

## Universal Shielding Corp.
20 West Jefryn Boulevard
Deer Park, NY 11729 USA
tel: (631) 667-7900
info@universalshielding.com
https://www.universalshielding.com

Universal Shielding Corp. was established in 1972 and is a pioneer in providing pre-fabricated shielded enclosures for the military, commercial, and medical industries. USC has the capabilities to provide a shielded enclosure of any size; from the smallest prefabricated unit for an R & D lab to the largest and most complex installations for a computer or communications center. USC offers a full range of RF Shielded Enclosures, RF Shielded Doors, RF Shielded Cabinets, Exterior Doors and RF Shielding Accessories.

## University of Oxford Continuing Professional Development - Technology Programme
Oxford, Oxfordshire Great Britain https://www.conted.ox.ac.uk/about/continuing-professional-development

## US Microwave Laboratories
Summerfield, NC USA http://usmicrolabs.com

## V Technical Textiles, Inc.
Palmyra, NY USA https://www.vtechtextiles.com

## Vanguard Electronics
Huntington Beach, CA USA https://www.ve1.com

## VDE Americas
Burlington, MA USA https://vdeamericas.com

## Vectawave Technology Limited
Newport, Isle of Wight Great Britain https://vectawave.co.uk

## VEROCH - Testing Equipment USA
Sunrise, FL USA http://www.veroch.com

## Versus Technology (Versus Global LLC)
Wilmington, DE USA http://www.versusglobal.com

## VIAVI Solutions
Wichita, KS USA https://www.viavisolutions.com

## Vitrek Corporation
Poway, CA USA https://www.vitrek.com

## VPI Laboratories, Inc.
Draper, UT USA https://www.vpilaboratories.com

## VTI Vacuum Technologies, Inc.
Reedsburg, WI USA https://www.vactecinc.com

## W. L. Gore & Associates, Inc.
Landenberg, PA USA https://www.gore.com

## Washington Laboratories
Frederick, MD USA https://www.wll.com

## Wave Computation Technologies, Inc.
Durham, NC USA https://www.wavenology.com

## Wavecontrol Inc.
Roseland, NJ USA https://www.wavecontrol.com/rfsafety/en

## WECO Electrical Connectors
Kirkland, QC Canada https://www.wecoconnectors.com

## WEMS Electronics
Hawthorne, CA USA https://www.wems.com

## Wewontech
Dongcheng, Hong Kong China https://www.wewontech.com

## Willrich Precision Instrument Company, Inc
Cresskill, NJ USA https://willrich.com

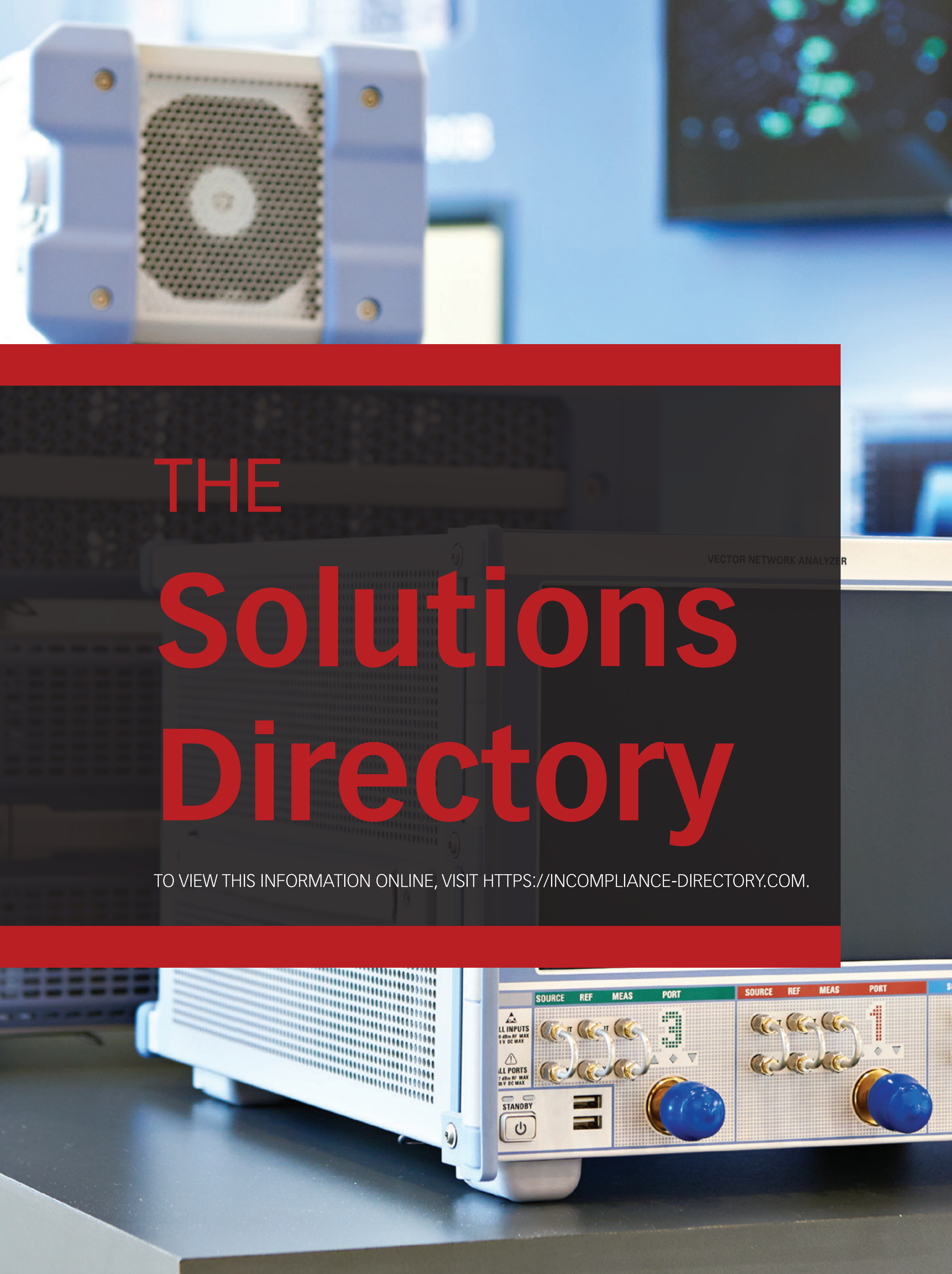
## WorkHub
Calgary, AB Canada https://www.workhub.com

## Würth Elektronik
Waldenburg, Baden-Württemberg Germany https://www.we-online.com

## Wyatt Technical Services LLC
Woodland Park, CO USA https://www.emc-seminars.com

## XGR Technologies
Newark, DE USA https://www.xgrtec.com

## Yazaki Testing Laboratory
Canton, MI USA https://www.yazaki-na.com




THE

# Solutions Directory

TO VIEW THIS INFORMATION ONLINE, VISIT HTTPS://INCOMPLIANCE-DIRECTORY.COM.

# Antennas+

## Antenna Couplers

**AP Americas Inc.**
KYOCERA AVX Components Corporation
Mag Daddy, LLC

## Antenna Masts

**Amplifier Research Corporation**
**AP Americas Inc.**
C-Wave, Inc.
Com-Power
Electronic Instrument Associates
**ETS-Lindgren**
Frankonia GmbH
**HV TECHNOLOGIES, Inc.**
Innco Systems GmbH
Mag Daddy, LLC
Reliant EMC LLC
Schwarzbeck Mess-Elektronik OHG
SunAR RF Motion
**TDK RF Solutions**

## Biconical Antennas

**A.H. Systems, Inc.**
Aaronia USA
Advanced Test Equipment Corporation
C-Wave, Inc.
Clark Testing
Com-Power
**ETS-Lindgren**
Frankonia GmbH
Mag Daddy, LLC
Schwarzbeck Mess-Elektronik OHG
**SteppIR Communication Systems**
SunAR RF Motion
**TDK RF Solutions**
Techmaster Electronics

## Broadband Antennas

**A.H. Systems, Inc.**
Aaronia USA
**Absolute EMC Llc.**
Advanced Test Equipment Corporation
**Amplifier Research Corporation**
**Barth Electronics, Inc.**
C-Wave, Inc.
Com-Power
EMC Test Design, LLC
**ETS-Lindgren**
Eurofins York
Frankonia GmbH
**HV TECHNOLOGIES, Inc.**
Laplace Instruments Ltd
Mag Daddy, LLC
**Microwave Vision Group**
**NSI-MI Technologies**
Reality Consulting Yemen
Schwarzbeck Mess-Elektronik OHG
**SteppIR Communication Systems**
SunAR RF Motion
**TDK RF Solutions**

## EMI Test Antennas

**A.H. Systems, Inc.**
Aaronia USA
**Absolute EMC Llc.**
Advanced Test Equipment Corporation
**Amplifier Research Corporation**
**AP Americas Inc.**
Applied Physical Electronics, L.C. (APELC)
**Barth Electronics, Inc.**
C-Wave, Inc.
Clark Testing
Com-Power
Electronic Instrument Associates
The EMC Shop
EMC Test Design, LLC
Enerdoor
**ETS-Lindgren**
Eurofins York
Frankonia GmbH
Lionheart Northwest
Mag Daddy, LLC
Narda STS, USA
QAI Laboratories
Reliant EMC LLC
**Rohde & Schwarz**
Schwarzbeck Mess-Elektronik OHG
Siglent Technologies North America
Solar Electronics Co.
**SteppIR Communication Systems**
SunAR RF Motion
**TDK RF Solutions**
TOYO Corporation

## Horn Antennas

**A.H. Systems, Inc.**
Advanced Test Equipment Corporation
**Amplifier Research Corporation**
C-Wave, Inc.
Com-Power
**ETS-Lindgren**
Mag Daddy, LLC
**Microwave Vision Group**
**NSI-MI Technologies**
Schwarzbeck Mess-Elektronik OHG
**SteppIR Communication Systems**
SunAR RF Motion
**TDK RF Solutions**
Techmaster Electronics

## Log Periodic Antennas

**A.H. Systems, Inc.**
Aaronia USA
Advanced Test Equipment Corporation
**Amplifier Research Corporation**
C-Wave, Inc.
Com-Power
**ETS-Lindgren**
Mag Daddy, LLC
**NSI-MI Technologies**
Schwarzbeck Mess-Elektronik OHG
**SteppIR Communication Systems**
SunAR RF Motion
**TDK RF Solutions**

## Loop Antennas

**A.H. Systems, Inc.**
**Absolute EMC Llc.**
Advanced Test Equipment Corporation
AFJ INSTRUMENTS Srl
C-Wave, Inc.
Com-Power
**ETS-Lindgren**
General Test Systems LLC
Mag Daddy, LLC
**NSI-MI Technologies**
Schwarzbeck Mess-Elektronik OHG
Solar Electronics Co.
**SteppIR Communication Systems**
**TDK RF Solutions**

## Non-ionizing Radiation Hazard Antennas

EMC Test Design, LLC
Mag Daddy, LLC
Narda STS, USA
Wavecontrol Inc.

## Rod Antennas

**A.H. Systems, Inc.**
C-Wave, Inc.
Com-Power
**ETS-Lindgren**
**Fair-Rite Products Corp.**
Mag Daddy, LLC
Narda STS, USA
**NSI-MI Technologies**
Schwarzbeck Mess-Elektronik OHG

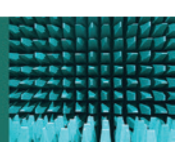
## Tunable Dipole

**A.H. Systems, Inc.**
Advanced Test Equipment Corporation
Applied Physical Electronics, L.C. (APELC)
C-Wave, Inc.
Com-Power
**ETS-Lindgren**
General Test Systems LLC
**SteppIR Communication Systems**

## Whip Antennas

Com-Power

# Chambers+



## Absorbers

### EMC Absorbers

**AP Americas Inc.**
ARC Technologies, a Hexcel Company
Comtest Engineering
Dutch Microwave Absorber Solutions
Electronic Instrument Associates
**ETS-Lindgren**
Frankonia GmbH
General Test Systems LLC
Leader Tech Inc.
MAJR Products
Marktek Inc.
**Microwave Vision Group**
**PPG Aerospace Cuming-Lehman Chambers**
**Raymond EMC Enclosures Ltd.**
Reliant EMC LLC
**TDK RF Solutions**

### Honeycomb RF

**AP Americas Inc.**
ARC Technologies, a Hexcel Company
Diamond Microwave Chambers Ltd
Leader Tech Inc.
**Microwave Vision Group**
**PPG Aerospace Cuming-Lehman Chambers**
**TDK RF Solutions**

### Low Frequency Absorber

**AP Americas Inc.**
ARC Technologies, a Hexcel Company
Comtest Engineering
Dutch Microwave Absorber Solutions
Leader Tech Inc.
Magnetic Shield Corporation
**Microwave Vision Group**
The MuShield Company, Inc.
**PPG Aerospace Cuming-Lehman Chambers**
**TDK RF Solutions**

### Microwave Absorber

**AP Americas Inc.**
ARC Technologies, a Hexcel Company
Diamond Microwave Chambers Ltd
Dutch Microwave Absorber Solutions
Eeonyx Corporation
**ETS-Lindgren**
Frankonia GmbH
Leader Tech Inc.
MAJR Products
**Microwave Vision Group**
**PPG Aerospace Cuming-Lehman Chambers**
**Raymond EMC Enclosures Ltd.**
Seal Science, Inc.
**TDK RF Solutions**

## Anechoic Materials

**AP Americas Inc.**
ARC Technologies, a Hexcel Company
Diamond Microwave Chambers Ltd
Dutch Microwave Absorber Solutions
Frankonia GmbH
General Test Systems LLC
**HV TECHNOLOGIES, Inc.**
Langer EMV-Technik GmbH
**Microwave Vision Group**
**PPG Aerospace Cuming-Lehman Chambers**
**Raymond EMC Enclosures Ltd.**
**TDK RF Solutions**
TESEO SpA

## Cells

### GTEM Cells

**Absolute EMC Llc.**
**ETS-Lindgren**
GTEMCELL Group
Laplace Instruments Ltd
Reliant EMC LLC

### TEM & Strip Line

**Absolute EMC Llc.**
ARC Technical Resources
**ESDEMC Technology LLC**
**ETS-Lindgren**
Fischer Custom Communications, Inc.
GTEMCELL Group
**TDK RF Solutions**

## Test Chambers

### Anechoic Chambers

**AP Americas Inc.**
Clark Testing
Comtest Engineering
Diamond Microwave Chambers Ltd
Electronic Instrument Associates
Enerdoor
**ETS-Lindgren**
Faraday Defense Corp.
General Test Systems LLC
Lionheart Northwest
Magnetic Shield Corporation
**Microwave Vision Group**
**NSI-MI Technologies**
**PPG Aerospace Cuming-Lehman Chambers**

QAI Laboratories

**Raymond EMC Enclosures Ltd.**

Reliant EMC LLC

**TDK RF Solutions**



TESEO SpA

**Universal Shielding Corp.**



## Environmental Chambers

Advanced Test Equipment Corporation

Alltest Instruments

Axiom Test Equipment Rentals

Cincinnati Sub Zero, LLC

Electro-Tech Systems

HEMCO Corporation

inTEST Thermal Solutions

Product Safety Consulting

QAI Laboratories

Sanwood Environmental Chambers Co., Ltd

Thermotron

VEROCH - Testing Equipment USA

## Fire Protection Chambers

MPB Measuring Instruments

QAI Laboratories

Sprinkler Innovations

## Portable Structures

Marktek Inc.

QAI Laboratories

Sanwood Environmental Chambers Co., Ltd

Select Fabricators, Inc.

**Universal Shielding Corp.**

V Technical Textiles, Inc.

## Reverberation Chambers

Comtest Engineering

**ETS-Lindgren**

Faraday Defense Corp.

**HV TECHNOLOGIES, Inc.**

**Microwave Vision Group**

QAI Laboratories

**Raymond EMC Enclosures Ltd.**

V Technical Textiles, Inc.

## Turntables

**Amplifier Research Corporation**

**AP Americas Inc.**

**ETS-Lindgren**

Frankonia GmbH

General Test Systems LLC

**HV TECHNOLOGIES, Inc.**

Innco Systems GmbH

**NSI-MI Technologies**

Raymond RF Measurement Corporation

Reliant EMC LLC

SunAR RF Motion

VEROCH - Testing Equipment USA

# Components

## Attenuators

**Barth Electronics, Inc.**

Cinch Connectivity Solutions

ES Components

**Pearson Electronics, Inc.**

Solar Electronics Co.

TTE Filters

## Bluetooth Modules

TDK Electronics

## Cabinets & Enclosures

Deltron Enclosures

Diamond Microwave Chambers Ltd

Elma Electronic Inc.

**ETS-Lindgren**

Fibox Enclosures

General Test Systems LLC

HEMCO Corporation

HM Cragg

Lubrizol Engineered Polymers

Slayson

V Technical Textiles, Inc.

## Cable Assemblies

Americor Electronics Ltd.

Captor Corporation

Cinch Connectivity Solutions

CONEC Corporation

EMI Solutions, Inc.

HM Cragg

Isodyne Inc.

Lubrizol Engineered Polymers

Magnetic Shield Corporation

MegaPhase, LLC

METZ CONNECT

Pickering Interfaces

Times Microwave Systems

TOYO Corporation

W. L. Gore & Associates, Inc.

## Connectors

Americor Electronics Ltd.
Amphenol Canada
Amphenol Industrial Products Group
Aries Electronics Inc.
Cinch Connectivity Solutions
CONEC Corporation
Connectronics
Curtis Industries/Tri-Mag, LLC
EMI Solutions, Inc.
Gemini Electronic Components, Inc.
Isodyne Inc.
MegaPhase, LLC
METZ CONNECT
**Nolato Jabar LLC**
Quell Corporation
SCHURTER, Inc.
**Spectrum Control**
Tech-Etch
TTE Filters
WECO Electrical Connectors

## Displays

### Digital LED Display

DELO Adhesives

### Touch Screen Display

DELO Adhesives
Parker Chomerics

## Electrical Distribution & Protection

### Braid, Bonding & Ground Accessories

HM Cragg
Magnetic Shield Corporation
Megger

### Circuit Breakers

SCHURTER, Inc.

### Fuses

HM Cragg
SCHURTER, Inc.
**Würth Elektronik**

### Grounding Rods

HM Cragg
SCHURTER, Inc.
**Würth Elektronik**

### Lightning Protection Systems

Captor Corporation
HM Cragg

## Electromechanical

### Electronic Cooling Fans

Americor Electronics Ltd.
Gemini Electronic Components, Inc.
Jaro Thermal
Seal Science, Inc.

### Motors

Equipnet
Globe Composite Solutions
Omni Controls
**Ross Engineering Corp.**

### Solid State Relays

Applied Physical Electronics, L.C. (APELC)

### Switches

Betatronix
Bourns, Inc.
C&K Components, now a part of Littelfuse, Inc.
EaglePicher Technologies
ES Components
Gemini Electronic Components, Inc.
Pickering Interfaces
**Ross Engineering Corp.**
SCHURTER, Inc.
**Würth Elektronik**

## Filters

### Absorptive Filters

**KITAGAWA INDUSTRIES America, Inc.**
MH&W International Corportion

### Air Filters

HEMCO Corporation
Metal Textiles Corporation

### Antenna Filters

**Würth Elektronik**

### EMC & RFI Filters

Americor Electronics Ltd.
Astrodyne TDI
BLOCK USA, Inc.
Captor Corporation
**Coilcraft Critical Products & Services**
**Coilcraft, Inc.**
CONEC Corporation
Curtis Industries/Tri-Mag, LLC
Diamond Microwave Chambers Ltd
EMC Instrument & Solution
EMI Filter Company
EMI Solutions, Inc.
EMZER
Enerdoor
Gemini Electronic Components, Inc.
High & Low Corporation
**KITAGAWA INDUSTRIES America, Inc.**
Knowles (UK) Ltd
Leader Tech Inc.
Metal Textiles Corporation
MH&W International Corportion
NexTek, Inc.
**Nolato Jabar LLC**
Okaya Electric America, Inc.
OnFILTER
Premier Filters
Quell Corporation
Roxburgh EMC
**Schaffner EMC Inc.**



Solutions Directory

SCHURTER, Inc.
Solar Electronics Co.
**Spectrum Control**
**Spira Manufacturing Corporation**
TDK Electronics
**TDK RF Solutions**
Tech-Etch
TTE Filters
WEMS Electronics
**Würth Elektronik**

### Filter Coils

**Coilcraft Critical Products & Services**
Curtis Industries/Tri-Mag, LLC
TTE Filters

### Filter Pins

EMI Solutions, Inc.

## Frequency Converters

TTE Filters
VEROCH - Testing Equipment USA

## Oscillators

Gemini Electronic Components, Inc.

## Passive & Discrete

### Capacitors

#### Ceramic Capacitors

Dexter Magnetic Technologies, Inc.
ES Components
Knowles (UK) Ltd
KOA Speer Electronics
KYOCERA AVX Components Corporation
RCD Components
TDK Electronics
**Würth Elektronik**

#### Decoupling Capacitors

Oak-Mitsui Technologies

#### EMC Feedthrough Capacitors

Captor Corporation
NexTek, Inc.
RCD Components
**Schaffner EMC Inc.**
WEMS Electronics

#### EMC Suppression Capacitors

Americor Electronics Ltd.
Captor Corporation
Oak-Mitsui Technologies
RCD Components
**Würth Elektronik**

#### Filter Capacitors

Captor Corporation
CONEC Corporation
EMI Solutions, Inc.
NexTek, Inc.
Oak-Mitsui Technologies
Okaya Electric America, Inc.
RCD Components
**Würth Elektronik**

#### Planar Array Capacitors

CONEC Corporation
EMI Solutions, Inc.
Oak-Mitsui Technologies

#### Tantalum Capacitors

KYOCERA AVX Components Corporation
RCD Components

### Ferrite Beads, Rods & Forms

**Fair-Rite Products Corp.**
Faraday Defense Corp.
Gowanda Electronics
iNRCORE, LLC
KOA Speer Electronics
Leader Tech Inc.
MAJR Products
MH&W International Corportion
TDK Electronics
Vanguard Electronics

### Inductors/Chokes

#### Data & Signal Line Chokes

iNRCORE, LLC
NRD LLC
SCHURTER, Inc.
TDK Electronics
WEMS Electronics

#### EMI/RFI Inductors

Captor Corporation
**Coilcraft Critical Products & Services**



**Coilcraft, Inc.**
iNRCORE, LLC
KYOCERA AVX Components Corporation
MH&W International Corportion
NRD LLC
WEMS Electronics

#### Power Line Chokes

**Coilcraft Critical Products & Services**
Gowanda Electronics
iNRCORE, LLC
MH&W International Corportion
SCHURTER, Inc.
Vanguard Electronics
WEMS Electronics

#### Reactors for Frequency Converters

**Coilcraft Critical Products & Services**
NRD LLC
OnFILTER

#### RF Chokes

**Coilcraft Critical Products & Services**
Gowanda Electronics
iNRCORE, LLC
NRD LLC
**Schaffner EMC Inc.**
Vanguard Electronics

# Passive & Discrete

## Inductors/Chokes

### Surface Mount Inductors

**Coilcraft Critical Products & Services**
Gowanda Electronics
iNRCORE, LLC
KYOCERA AVX Components Corporation
Vanguard Electronics

### Switchmode Inductors

**Coilcraft Critical Products & Services**
Gowanda Electronics
iNRCORE, LLC
Vanguard Electronics

### VHF Chokes

**Coilcraft Critical Products & Services**
NRD LLC

## Mains (X & Y)

Okaya Electric America, Inc.

## Resistors & Potentiometers

### Electronic Loads

ES Components
Gemini Electronic Components, Inc.

### Potentiometers

Betatronix
Bourns, Inc.

### Power Line Isolation

iNRCORE, LLC
RCD Components

### Signal Line Isolation

iNRCORE, LLC
RCD Components

### Transformers

Americor Electronics Ltd.
Bourns, Inc.
**Coilcraft, Inc.**
ELSCO Transformers
Gowanda Electronics
iNRCORE, LLC
**Pearson Electronics, Inc.**
RCD Components
Vanguard Electronics

### Varistors

KOA Speer Electronics
KYOCERA AVX Components Corporation

# Power Supply & Conditioning

## Adapters

Americor Electronics Ltd.
Astrodyne TDI
Curtis Industries/Tri-Mag, LLC
DANA Power Supplies
Oak-Mitsui Technologies
Siglent Technologies North America

## Converters

Astrodyne TDI
Curtis Industries/Tri-Mag, LLC
Equipnet
Oak-Mitsui Technologies

## Interruptions, AC Power

Astrodyne TDI
DANA Power Supplies
Hilo-Test

## Isolators, Power/Signal Line

OnFILTER

## Line Conditioning Equipment

DANA Power Supplies
Merus Power
Okaya Electric America, Inc.

## Power Amplifiers

Astrodyne TDI

## Power Cords

Americor Electronics Ltd.
DANA Power Supplies
SCHURTER, Inc.

## Power Generators

DANA Power Supplies
Preen AC Power Corp.

## Power Rectifier

Astrodyne TDI
DANA Power Supplies

## Power Strips

DANA Power Supplies
SCHURTER, Inc.

## Power Supplies

Americor Electronics Ltd.
AMETEK Programmable Power Supplies
Astrodyne TDI
Curtis Industries/Tri-Mag, LLC
DANA Power Supplies
EaglePicher Technologies
Equipnet
Foster Transformer Company
Hilo-Test
**Kikusui America Inc.**
Langer EMV-Technik GmbH
Preen AC Power Corp.
Siglent Technologies North America

## Switching Power Supplies

Astrodyne TDI
Bourns, Inc.
Curtis Industries/Tri-Mag, LLC
DANA Power Supplies
**Kikusui America Inc.**
**Würth Elektronik**

## Voltage Regulators

Astrodyne TDI
DANA Power Supplies
Preen AC Power Corp.

# Printed Circuit Boards

Americor Electronics Ltd.
Candor Industries Inc
Captor Corporation
Curtis Industries/Tri-Mag, LLC
Elma Electronic Inc.
KYOCERA AVX Components Corporation
MegaPhase, LLC
Oak-Mitsui Technologies
Polyonics
SCHURTER, Inc.

# Resonators

ES Components

# Semiconductors

ES Components
Gemini Electronic Components, Inc.
MH&W International Corportion
Nexperia Semiconductor

## Surge Suppressors

Captor Corporation
CITEL, Inc.
Curtis Industries/Tri-Mag, LLC
EMI Solutions, Inc.
ES Components
Faraday Defense Corp.
Fischer Custom Communications, Inc.
Gemini Electronic Components, Inc.
NexTek, Inc.
Okaya Electric America, Inc.
OnFILTER
TDK Electronics
Transtector

# Materials

## Absorbing Materials

3Gmetalworx Inc.
ARC Technologies, a Hexcel Company
Diamond Microwave Chambers Ltd
Dutch Microwave Absorber Solutions
Frankonia GmbH
Globe Composite Solutions
**KITAGAWA INDUSTRIES America, Inc.**
Leader Tech Inc.
Marktek Inc.
**Microwave Vision Group**
**PPG Aerospace Cuming-Lehman Chambers**
**Raymond EMC Enclosures Ltd.**
Seal Science, Inc.
**TDK RF Solutions**
V Technical Textiles, Inc.

## Additives

Marktek Inc.

## Adhesives

Alpha Assembly Solutions
ARC Technologies, a Hexcel Company
DELO Adhesives
Master Bond
Metal Textiles Corporation
Polyonics
Seal Science, Inc.

## Coatings and Sealants

Eeonyx Corporation
Enviro Tech International
Oak-Mitsui Technologies
Seal Science, Inc.

## Conductive Materials

Faraday Defense Corp.
Globe Composite Solutions
Kemtron Ltd., now part of TE Connectivity
**KITAGAWA INDUSTRIES America, Inc.**
Leader Tech Inc.
Marktek Inc.
**MFG Tray Company (Molded Fiber Glass Tray Co.)**
MH&W International Corportion
**Nolato Jabar LLC**
Parker Chomerics
Polyonics
Quell Corporation
Seal Science, Inc.
Tech-Etch
Thermtest

## Foams & Insulation

Enertech UPS Pvt Ltd

## Metals and Alloys

3Gmetalworx Inc.
Alpha Assembly Solutions
Bolting Specialist, a division of Resistant Metal Alloys LLP
Eastern Steel Manufacturing Co., Ltd
Ferrotec-Nord
Globe Composite Solutions
Johnson Bros Metal Forming Co
Leader Tech Inc.
Magnetic Shield Corporation
The MuShield Company, Inc.
PPG Engineered Materials
Syntakt Packaging Integration
Testing Partners

## Plastics

### Resins & Compounds

ARC Technologies, a Hexcel Company
Bicerano & Associates Consulting
DELO Adhesives
Globe Composite Solutions
Jordi Labs
Lubrizol Engineered Polymers
Seal Science, Inc.

### Thermoplastics & Thermoplastic Materials

ARC Technologies, a Hexcel Company
Bicerano & Associates Consulting
Conductive Containers Inc
Crystal Rubber Ltd
Globe Composite Solutions
Lubrizol Engineered Polymers
**MFG Tray Company (Molded Fiber Glass Tray Co.)**
Parker Chomerics

# Resources

## Associations

A2LA
EOS/ESD Association Services, LLC
Saf-T-Gard International, Inc.

## Education

### Seminars

**André Consulting, Inc.**
Archambeault EMI/EMC Enterprises
BestESD Technical Services
**Cherry Clough Consultants Ltd**
D. C. Smith Consultants
Eisner Safety Consultants
Equipment Reliability Institute (ERI)
ESD Association
**Go Global Compliance Inc.**
**Hoolihan EMC Consulting**
Keysight Technologies Inc.
**Kimmel Gerke Associates Ltd.**
LearnEMC
Lewis Bass International Engineering Services
**Montrose Compliance Services, Inc.**
Purdue Engineering Professional Education
**RMV Technology Group LLC**
Safe Engineering Services & Technologies
**SILENT Solutions LLC**
WorkHub
**Wyatt Technical Services LLC**

# Education

## Training Courses

A2LA
**André Consulting, Inc.**
ARC Technical Resources
**Cherry Clough Consultants Ltd**
D. C. Smith Consultants
DEKRA
DG Technologies
Eisner Safety Consultants
Electronic Instrument Associates
EMC FastPass
EOS/ESD Association Services, LLC
Equipment Reliability Institute (ERI)
Eurofins York
**Hoolihan EMC Consulting**
iNARTE
**Kimmel Gerke Associates Ltd.**
LearnEMC
Lewis Bass International Engineering Services
Lion Technology, Inc.
**Montrose Compliance Services, Inc.**
Purdue Engineering Professional Education
**RMV Technology Group LLC**
Safe Engineering Services & Technologies
**SILENT Solutions LLC**
University of Oxford Continuing Professional Development - Technology Programme
Washington Laboratories
WorkHub
**Wyatt Technical Services LLC**

## University

Purdue Engineering Professional Education
WorkHub

## Videos

ARC Technical Resources
ESD Association
Keysight Technologies Inc.
Purdue Engineering Professional Education
Washington Laboratories
WorkHub
**Wyatt Technical Services LLC**

## Webinars

**Cherry Clough Consultants Ltd**
Eisner Safety Consultants
**Element Materials Technology - Atlanta-Gainesville, GA**
**Element Materials Technology - Brooklyn Park, MN**
**Element Materials Technology - Dallas-Plano, TX**
**Element Materials Technology - Irvine, CA**
**Element Materials Technology - Washington, Columbia, Oakland Mills**
EOS/ESD Association Services, LLC
ESD Association
LearnEMC
Purdue Engineering Professional Education
Safe Engineering Services & Technologies
WorkHub
**Wyatt Technical Services LLC**

# Publications

## Books

### EMI/EMC Books

**André Consulting, Inc.**
**Cherry Clough Consultants Ltd**
**D.L.S. - Military**
**Montrose Compliance Services, Inc.**
**Wyatt Technical Services LLC**

### Product Safety Books

Lewis Bass International Engineering Services

## Magazines

In Compliance Magazine

# Standards Resellers

ESD Association


## Eyes, Face, and Head

HEMCO Corporation
Saf-T-Gard International, Inc.
WorkHub

## Hand and Foot Protection

Saf-T-Gard International, Inc.
SW Safety Solutions
WorkHub

## Safety & Warning Labels

Abstraction Engineering Inc
Clarion Safety Systems
Coast Label
Enerdoor
HM Cragg
InfoSight Corporation
Lewis Bass International Engineering Services
PAVONE Technologies
Polyonics
Saf-T-Gard International, Inc.
WorkHub

## Safety Clothing

Saf-T-Gard International, Inc.
SW Safety Solutions
TECH WEAR, INC.
WorkHub

# Services

## Calibration & Repair

A.com Electronic Measurement Technology
**A.H. Systems, Inc.**
Advanced Test Equipment Corporation
Alltest Instruments
ARC Technical Resources
Avalon Test Equipment
**Barth Electronics, Inc.**
Electronic Instrument Associates
Enertech UPS Pvt Ltd
**ETS-Lindgren**
Excalibur Engineering Inc., a Transcat Company
Fischer Custom Communications, Inc.
Haefely AG
Keysight Technologies Inc.
**Lightning EMC**
M Precision Laboratories, INC.
MPB Measuring Instruments
NRD LLC
**NSI-MI Technologies**
Omni Controls
**Pearson Electronics, Inc.**
**Ross Engineering Corp.**
Sanwood Environmental Chambers Co., Ltd
Schwarzbeck Mess-Elektronik OHG
Solar Electronics Co.
**TDK RF Solutions**
Techmaster Electronics
Technical Safety Services
TESEO SpA
Trescal
VEROCH - Testing Equipment USA
Willrich Precision Instrument Company, Inc.

## Codes, Standards & Regulations

A2LA
American Certification Body
American National Standards Institute
**Approve-IT, Inc.**
Clarion Safety Systems
CSA Group
DEKRA
DG Technologies
Eisner Safety Consultants
Enerdoor
Enertech UPS Pvt Ltd
**Go Global Compliance Inc.**
GreenSoft Technology
Grund Technical Solutions, Inc.
H.B. Compliance Solutions
iNARTE
InfoSight Corporation
Micom Laboratories Inc
MiCOM Labs
Omni Controls
The Photonics Group
TJS Technical Services Inc.

## Consulting

### Cleanroom/Static Control

BestESD Technical Services
Bystat International Inc
Estion Technologies GmbH
OnFILTER
Protective Industrial Polymers
**RMV Technology Group LLC**

### EMC Consulting

**André Consulting, Inc.**
**Approve-IT, Inc.**
Atlas Compliance & Engineering
BestESD Technical Services
**Cherry Clough Consultants Ltd**
CKC Laboratories, Inc.
D. C. Smith Consultants
**D.L.S. - EMC**
**D.L.S. - Environmental**
**D.L.S. - Military**
**D.L.S. - Product Safety**
**D.L.S. - Wireless**
Dayton T. Brown, Inc.
DG Technologies
DNB Engineering, Inc.
Electro Magnetic Applications, Inc. (EMA)
EMC Instrument & Solution
Enerdoor
**ESDEMC Technology LLC**
**ETS-Lindgren**
Eurofins York
**F2 Labs - Damascus, MD**
**F2 Labs - Middlefield, OH**
**G&M Compliance, Inc.**
**Go Global Compliance Inc.**
Grund Technical Solutions, Inc.
**Hoolihan EMC Consulting**
International Certification Services, Inc.
JBRC Consulting LLC
JDM LABS LLC
**Kimmel Gerke Associates Ltd.**
**Laird Connectivity**
LearnEMC
Machinery Safety & Compliance Services
**Montrose Compliance Services, Inc.**
OnFILTER
R&B Laboratory
Remcom
**SILENT Solutions LLC**
Southwest Research Institute
Spectrum EMC, LLC
Test Site Services Inc
TJS Technical Services Inc.
WEMS Electronics
**Wyatt Technical Services LLC**

### ESD Consulting

BestESD Technical Services
Conductive Containers Inc
D. C. Smith Consultants
**D.L.S. - EMC**
**D.L.S. - Military**
Electro-Tech Systems
EOS/ESD Association Services, LLC
**ESDEMC Technology LLC**
Estion Technologies GmbH
**F2 Labs - Damascus, MD**
**F2 Labs - Middlefield, OH**
JBRC Consulting LLC
**Laird Connectivity**
**Montrose Compliance Services, Inc.**
OnFILTER
**RMV Technology Group LLC**
**SILENT Solutions LLC**
**Wyatt Technical Services LLC**

### Government Regulations

#### BSMI Regulatory Consulting

**Approve-IT, Inc.**
Atlas Compliance & Engineering
**D.L.S. - EMC**
**D.L.S. - Wireless**
**Go Global Compliance Inc.**
TJS Technical Services Inc.

# Consulting

## Government Regulations

### EU (Europe) Regulatory Consulting

ACEMA
**André Consulting, Inc.**
**Approve-IT, Inc.**
Atlas Compliance & Engineering
CKC Laboratories, Inc.
The Compliance Map
Compliance Specialty International Associates
Compliance Worldwide, Inc.
**D.L.S. - EMC**
**D.L.S. - Environmental**
**D.L.S. - Product Safety**
**D.L.S. - Wireless**
Eisner Safety Consultants
Elite Electronic Engineering Inc.
**F2 Labs - Damascus, MD**
**F2 Labs - Indianapolis, IN**
**F2 Labs - Middlefield, OH**
**Go Global Compliance Inc.**
GreenSoft Technology
International Certification Services, Inc.
JBRC Consulting LLC
**Kimmel Gerke Associates Ltd.**
**Laird Connectivity**
**Montrose Compliance Services, Inc.**
TJS Technical Services Inc.
VPI Laboratories, Inc.

### FCC (U.S) Regulatory Consulting

**André Consulting, Inc.**
**Approve-IT, Inc.**
Atlas Compliance & Engineering
CKC Laboratories, Inc.
Compliance Specialty International Associates
Compliance Worldwide, Inc.
**D.L.S. - EMC**
**D.L.S. - Product Safety**
**D.L.S. - Wireless**
**Element Materials Technology - Brooklyn Park, MN**
**Element Materials Technology - Dallas-Plano, TX**
**Element Materials Technology - Irvine, CA**
**Element Materials Technology - Washington, Columbia, Oakland Mills**
Elite Electronic Engineering Inc.
**F2 Labs - Damascus, MD**
**F2 Labs - Middlefield, OH**
**Go Global Compliance Inc.**
International Certification Services, Inc.
JBRC Consulting LLC
**Kimmel Gerke Associates Ltd.**
**Laird Connectivity**
**Montrose Compliance Services, Inc.**
TJS Technical Services Inc.
TÜV Rheinland of North America
VPI Laboratories, Inc.

### GOST (Russia) Regulatory Consulting

**Go Global Compliance Inc.**
TJS Technical Services Inc.

### VCCI Consulting

**Approve-IT, Inc.**
Atlas Compliance & Engineering
CKC Laboratories, Inc.
**D.L.S. - EMC**
TJS Technical Services Inc.

## Lightning Protection

**André Consulting, Inc.**
D. C. Smith Consultants
**D.L.S. - Military**
Electro Magnetic Applications, Inc. (EMA)
NexTek, Inc.

## Medical Device

**André Consulting, Inc.**
**Approve-IT, Inc.**
CertifiGroup Inc
D. C. Smith Consultants
**D.L.S. - EMC**
**D.L.S. - Environmental**
**D.L.S. - Product Safety**
**D.L.S. - Wireless**
Eisner Safety Consultants
Enviropass Expertise Inc.
**F2 Labs - Middlefield, OH**
**G&M Compliance, Inc.**
GreenSoft Technology
**Kimmel Gerke Associates Ltd.**
**Laird Connectivity**
MedicalRegs.com
Orbis Compliance LLC
The Photonics Group
Product Safety Consulting
**RMV Technology Group LLC**
Test Site Services Inc
TJS Technical Services Inc.

## Product Safety Consulting

360 Compliance Partners
**Approve-IT, Inc.**
CertifiGroup Inc
Clarion Safety Systems
Compliance inSight Consulting Inc.
**D.L.S. - Environmental**
**D.L.S. - Product Safety**
Eisner Safety Consultants
Enviropass Expertise Inc.
**F2 Labs - Indianapolis, IN**
**F2 Labs - Middlefield, OH**
**G&M Compliance, Inc.**
**Go Global Compliance Inc.**
InfoSight Corporation
Intertek
JBRC Consulting LLC
Lewis Bass International Engineering Services
M.C. Global Access LLC
Machinery Safety & Compliance Services
Orbis Compliance LLC
PC Squared Consultants
The Photonics Group
Product EHS Consulting LLC
Product Safety Consulting
**RMV Technology Group LLC**
Test Site Services Inc
VDE Americas
VEROCH - Testing Equipment USA

## Quality

DEKRA
Eisner Safety Consultants
Estion Technologies GmbH
Globe Composite Solutions
InfoSight Corporation
Spectrum EMC, LLC

## Telecom

Compliance Specialty International Associates
CV. DIMULTI
D. C. Smith Consultants
**D.L.S. - Wireless**
**F2 Labs - Damascus, MD**

**F2 Labs - Middlefield, OH**
**Go Global Compliance Inc.**
Orbis Compliance LLC
PAVONE Technologies

### Tempest

Dayton T. Brown, Inc.

### Transient

**André Consulting, Inc.**
BestESD Technical Services
D. C. Smith Consultants
**D.L.S. - EMC**
**F2 Labs - Damascus, MD**
**F2 Labs - Middlefield, OH**
Grund Technical Solutions, Inc.
JBRC Consulting LLC
NexTek, Inc.
**SILENT Solutions LLC**

### Wireless

**Approve-IT, Inc.**
PAVONE Technologies

## Design

**André Consulting, Inc.**
BestESD Technical Services
Captor Corporation
Clarion Safety Systems
Conductive Containers Inc
DG Technologies
Empower RF Systems, Inc.
Enertech UPS Pvt Ltd
Globe Composite Solutions
JBRC Consulting LLC
Machinery Safety & Compliance Services
Orbel Corporation
The Photonics Group
**SILENT Solutions LLC**
V Technical Textiles, Inc.
VEROCH - Testing Equipment USA
WEMS Electronics

## Other

### Conductive Painting Services

VTI Vacuum Technologies, Inc.

### Shielded Enclosure Design

3Gmetalworx Inc.
Conductive Containers Inc
Diamond Microwave Chambers Ltd
Elma Electronic Inc.
Leader Tech Inc.
Slayson
VTI Vacuum Technologies, Inc.

### Site Survey Services

Analysis and Measurement Services Corporation
BestESD Technical Services
Clarion Safety Systems
Dayton T. Brown, Inc.
Electronic Instrument Associates
EOS/ESD Association Services, LLC
**F2 Labs - Damascus, MD**
**F2 Labs - Middlefield, OH**
NRD LLC
Spectrum EMC, LLC
WorkHub

### Other Services

E-Fab, LLC
Jay Hoehl Inc.
Machinery Safety & Compliance Services
Technical Safety Services

# Shielding

## Architectural Shielding Products

**ETS-Lindgren**
Faraday Defense Corp.
Leader Tech Inc.
MAJR Products
Marktek Inc.
Metal Textiles Corporation

## Fingerstock

3Gmetalworx Inc.
Leader Tech Inc.
Metal Textiles Corporation
Orbel Corporation
Parker Chomerics
**Raymond EMC Enclosures Ltd.**
**Schlegel Electronic Materials**
Tech-Etch

## Shielded Air Filters

Leader Tech Inc.
MAJR Products
**Nolato Jabar LLC**
Nolato PPT
Parker Chomerics
Premier Filters
**Spira Manufacturing Corporation**
Tech-Etch
**Universal Shielding Corp.**

## Shielded Cable Assemblies & Harnesses

CONEC Corporation
Leader Tech Inc.
MAJR Products

## Shielded Coatings

A&A Coatings
ARC Technologies, a Hexcel Company
Leader Tech Inc.
Marktek Inc.
Parker Chomerics
VTI Vacuum Technologies, Inc.

## Shielded Compounds

Kemtron Ltd., now part of TE Connectivity
Leader Tech Inc.
Marktek Inc.
Parker Chomerics

## Shielded Conduit

Electri-Flex Company
Leader Tech Inc.
Magnetic Shield Corporation

## Shielded Connectors

American Swiss
Amphenol Industrial Products Group
Cinch Connectivity Solutions
CONEC Corporation
Gemini Electronic Components, Inc.
Isodyne Inc.
Leader Tech Inc.
Metal Textiles Corporation
Quell Corporation
**Spira Manufacturing Corporation**
Tech-Etch
**Würth Elektronik**

## Shielded Enclosures

3Gmetalworx Inc.
Comtest Engineering
Diamond Microwave Chambers Ltd
Elma Electronic Inc.
Emcor Enclosures
**ETS-Lindgren**
Faraday Defense Corp.
Frankonia GmbH
Leader Tech Inc.
Lionheart Northwest
Magnetic Shield Corporation
Marktek Inc.
The MuShield Company, Inc.
**PPG Aerospace Cuming-Lehman Chambers**
**Raymond EMC Enclosures Ltd.**
Select Fabricators, Inc.
Slayson
**Universal Shielding Corp.**
V Technical Textiles, Inc.
VTI Vacuum Technologies, Inc.

## Shielded Tubing

Electri-Flex Company
Kemtron Ltd., now part of TE Connectivity
Leader Tech Inc.
Magnetic Shield Corporation
Marktek Inc.

## Shielded Wire & Cable

Cinch Connectivity Solutions
CONEC Corporation
Isodyne Inc.
Leader Tech Inc.
Metal Textiles Corporation
SF Cable

## Shielding Gaskets

3Gmetalworx Inc.
Kemtron Ltd., now part of TE Connectivity
**KITAGAWA INDUSTRIES America, Inc.**
Leader Tech Inc.
MAJR Products
Metal Textiles Corporation
**Nolato Jabar LLC**
Nolato PPT
Orbel Corporation
Parker Chomerics
Quell Corporation
SAS Industries, Inc.
**Schlegel Electronic Materials**
**Spira Manufacturing Corporation**
Tech-Etch
VTI Vacuum Technologies, Inc.
W. L. Gore & Associates, Inc.
XGR Technologies

## Shielding Materials

### EMI/RFI Shielding Materials

A&A Coatings
Aaronia USA
**Amplifier Research Corporation**
Bal Seal Engineering
Diamond Microwave Chambers Ltd
**Fair-Rite Products Corp.**
Isodyne Inc.
Kemtron Ltd., now part of TE Connectivity
**KITAGAWA INDUSTRIES America, Inc.**
Leader Tech Inc.
MAJR Products
Metal Textiles Corporation
**Nolato Jabar LLC**
Nolato PPT
Orbel Corporation
Polyonics
**PPG Aerospace Cuming-Lehman Chambers**
**Schlegel Electronic Materials**
**Spira Manufacturing Corporation**
Swift Textile Metalizing LLC
**Universal Shielding Corp.**
V Technical Textiles, Inc.
VTI Vacuum Technologies, Inc.
W. L. Gore & Associates, Inc.
**Würth Elektronik**
XGR Technologies

### Magnetic Field Shielding Materials

3Gmetalworx Inc.
Kemtron Ltd., now part of TE Connectivity
**KITAGAWA INDUSTRIES America, Inc.**
Leader Tech Inc.
Magnetic Shield Corporation
MAJR Products
The MuShield Company, Inc.
**PPG Aerospace Cuming-Lehman Chambers**
V Technical Textiles, Inc.

## Shielding, Board-Level

3Gmetalworx Inc.
Conductive Containers Inc
Elma Electronic Inc.
Faspro Technologies
**KITAGAWA INDUSTRIES America, Inc.**
Leader Tech Inc.
MAJR Products
Orbel Corporation
XGR Technologies


## Compliance Management Software

GreenSoft Technology
WorkHub

## EMC Simulation Software

**AE Techron, Inc.**
Altair Engineering Inc.
ANSYS Inc.
Electro Magnetic Applications, Inc. (EMA)
Hilo-Test
Remcom
TESEO SpA
TOYO Corporation
Wave Computation Technologies, Inc.

## ESD/Static Control Software

**ACL Staticide Inc.**
Antistat Inc
Desco Industries Inc.
Estion Technologies GmbH
Langer EMV-Technik GmbH

## Lab Control Software

**Amplifier Research Corporation**
**ETS-Lindgren**
TESEO SpA
TOYO Corporation

## Product Safety Software

OnRule
The Photonics Group

## Signal Integrity & EMC Analysis Software

AFJ INSTRUMENTS Srl
Altair Engineering Inc.
Remcom
**TDK RF Solutions**
TOYO Corporation

## Wireless Propagation Software

Altair Engineering Inc.
Remcom

# Static Control

## Air Ionizers

Bystat International Inc
Desco Industries Inc.
Elimstat.com
Estatec
NRD LLC
Simco-Ion

## Clothing & Accessories

### ESD Garments

Bystat International Inc
Correct Products, Inc.
Desco Industries Inc.
Elimstat.com
Estatec
TECH WEAR, INC.
United Static Control Products Inc.

### Footwear

Amstat Industries, Inc.
Estatec
Lubrizol Engineered Polymers
Saf-T-Gard International, Inc.

### Wrist Straps

Amstat Industries, Inc.
Bystat International Inc
Correct Products, Inc.
Desco Industries Inc.
Estatec
Lubrizol Engineered Polymers
Static Solutions, Inc.
United Static Control Products Inc.

## Containers

Bystat International Inc
Conductive Containers Inc
Correct Products, Inc.
Desco Industries Inc.
Estatec
Lubrizol Engineered Polymers
**MFG Tray Company (Molded Fiber Glass Tray Co.)**


## ESD Tape

Conductive Containers Inc
Correct Products, Inc.
Desco Industries Inc.
Elimstat.com
Leader Tech Inc.
Polyonics
United Static Control Products Inc.

## Flooring

### Carpet

Ground Zero
Julie Industries, Inc.
Protective Industrial Polymers
**StaticStop**
**StaticWorx, Inc.**

### Floor Coatings

**ACL Staticide Inc.**
Correct Products, Inc.
Estatec
Ground Zero
Julie Industries, Inc.
Protective Industrial Polymers
Static Solutions, Inc.
**StaticStop**
**StaticWorx, Inc.**
United Static Control Products Inc.

### Mats

Bystat International Inc
Correct Products, Inc.
Elimstat.com
Estatec
Static Solutions, Inc.
**StaticStop**
**StaticWorx, Inc.**

### Tiles

Bystat International Inc
Ground Zero
Julie Industries, Inc.
**StaticStop**


**StaticWorx, Inc.**

## Furniture

BIMOS
**StaticWorx, Inc.**

## Packaging

Bystat International Inc
Conductive Containers Inc
Correct Products, Inc.
Desco Industries Inc.
EaglePicher Technologies
Elimstat.com
Estatec
Lubrizol Engineered Polymers
**MFG Tray Company (Molded Fiber Glass Tray Co.)**

## Simulators

### EMP Simulators

Fischer Custom Communications, Inc.
Grund Technical Solutions, Inc.
montena technology sa

### ESD Simulators

Electro-Tech Systems
**ESDEMC Technology LLC**
Hilo-Test
**Kikusui America Inc.**
montena technology sa

## Transient Detectors & Suppressors

CITEL, Inc.
EMI Solutions, Inc.
Fischer Custom Communications, Inc.
NexTek, Inc.

## Workstations

**ACL Staticide Inc.**
BIMOS
Bystat International Inc
Conductive Containers Inc
Correct Products, Inc.
HEMCO Corporation
Langer EMV-Technik GmbH
Lubrizol Engineered Polymers
**MFG Tray Company (Molded Fiber Glass Tray Co.)**
NRD LLC
United Static Control Products Inc.

# Test and Measure

## Accelerometers

Clark Testing
Essco Calibration Laboratory
PCE Instruments
Techmaster Electronics

## Amplifiers

### Amplifier Modules

**Amplifier Research Corporation**
Empower RF Systems, Inc.
**Exodus Advanced Communications**
**OPHIR RF/Ophir EMC**
Prana

### Low Power Amplifiers

**A.H. Systems, Inc.**
Advanced Test Equipment Corporation
**Amplifier Research Corporation**
**ETS-Lindgren**
**Exodus Advanced Communications**
Siglent Technologies North America

### Microwave Amplifiers

Advanced Test Equipment Corporation
AMETEK CTS
**Amplifier Research Corporation**
Applied Systems Engineering, Inc.
Axiom Test Equipment Rentals
CPI TMD Technologies
Empower RF Systems, Inc.
**ETS-Lindgren**
**Exodus Advanced Communications**
**HV TECHNOLOGIES, Inc.**
Lionheart Northwest
**OPHIR RF/Ophir EMC**
Prana
Reliant EMC LLC

### Power Amplifiers

Advanced Test Equipment Corporation
**AE Techron, Inc.**


AMETEK CTS
**Amplifier Research Corporation**
CPI TMD Technologies
CPI, Inc.
Empower RF Systems, Inc.
**ETS-Lindgren**
**Exodus Advanced Communications**
**HV TECHNOLOGIES, Inc.**
Laplace Instruments Ltd
Lionheart Northwest
**OPHIR RF/Ophir EMC**
Prana
Reliant EMC LLC
**Rohde & Schwarz**
TESEO SpA
TOYO Corporation
Vectawave Technology Limited

### RF Amplifiers

**A.H. Systems, Inc.**
Advanced Test Equipment Corporation
AMETEK CTS
**Amplifier Research Corporation**
Avalon Test Equipment
Axiom Test Equipment Rentals
ConRes Test Equipment
CPI, Inc.
Empower RF Systems, Inc.

**ETS-Lindgren**
**Exodus Advanced Communications**
**HV TECHNOLOGIES, Inc.**
Laplace Instruments Ltd
Lionheart Northwest
**OPHIR RF/Ophir EMC**
Prana
**Rohde & Schwarz**
US Microwave Laboratories

### Solid State Amplifiers

Advanced Test Equipment Corporation
AMETEK CTS
**Amplifier Research Corporation**
CPI, Inc.
Empower RF Systems, Inc.
**ETS-Lindgren**
**Exodus Advanced Communications**
**OPHIR RF/Ophir EMC**
Prana

### Traveling Wave Tube Amplifiers

Advanced Test Equipment Corporation
AMETEK CTS
**Amplifier Research Corporation**
Avalon Test Equipment
CPI TMD Technologies
CPI, Inc.
Empower RF Systems, Inc.
Hilo-Test
**OPHIR RF/Ophir EMC**

## Analyzers

### EMI/EMC, Spectrum Analyzers

Aaronia USA
**Absolute EMC Llc.**
Advanced Test Equipment Corporation
AFJ INSTRUMENTS Srl
Agile Calibration
Alltest Instruments
Anritsu Company
Axiom Test Equipment Rentals
Electro Rent Corporation
Electronic Instrument Associates
EMC Instrument & Solution
Excalibur Engineering Inc., a Transcat Company
**GAUSS INSTRUMENTS**
Keysight Technologies Inc.
Laplace Instruments Ltd
MPB Measuring Instruments
RIGOL Technologies USA, Inc.
**Rohde & Schwarz**
Siglent Technologies North America
Signal Hound
TOYO Corporation
VIAVI Solutions

### Flicker Analyzers

Advanced Test Equipment Corporation
Eurofins York
**HV TECHNOLOGIES, Inc.**
**Kikusui America Inc.**
Lionheart Northwest

### Harmonics Analyzers

Advanced Test Equipment Corporation
Eurofins York
**HV TECHNOLOGIES, Inc.**
**Kikusui America Inc.**
Laplace Instruments Ltd

### Network Analyzers

AFJ INSTRUMENTS Srl
Agile Calibration
ConRes Test Equipment
Copper Mountain Technologies
Electro Rent Corporation
Excalibur Engineering Inc., a Transcat Company
Keysight Technologies Inc.
PCE Instruments
**Rohde & Schwarz**
Siglent Technologies North America
TOYO Corporation
VIAVI Solutions

### Power Quality Analyzers

Axiom Test Equipment Rentals
Electro Rent Corporation
Excalibur Engineering Inc., a Transcat Company

### Telecom Analyzers

MPB Measuring Instruments

## Audio & Video

### Audio Systems

Audivo GmbH

### CCTV

Audivo GmbH
**TDK RF Solutions**
TESEO SpA

## Automatic Test Sets

AFJ INSTRUMENTS Srl
ARC Technical Resources
Essco Calibration Laboratory
General Test Systems LLC
Omni Controls
Pendulum Instruments
Preen AC Power Corp.
TOYO Corporation
United Static Control Products Inc.

## Avionics Test Equipment

Advanced Test Equipment Corporation
**AE Techron, Inc.**
Alltest Instruments
Cincinnati Sub Zero, LLC
CPI TMD Technologies
The EMC Shop
Essco Calibration Laboratory
**HV TECHNOLOGIES, Inc.**
Omni Controls
Pickering Interfaces
Preen AC Power Corp.
VIAVI Solutions
**Vitrek Corporation**

## Burn-in Test Equipment

ALI Testing
Essco Calibration Laboratory
General Test Systems LLC
inTEST Thermal Solutions
Mechanical Devices
**OPHIR RF/Ophir EMC**
Preen AC Power Corp.
Sanwood Environmental Chambers Co., Ltd

## Data Acquisition Monitoring Systems

Analysis and Measurement Services Corporation
ConRes Test Equipment
Degree Controls, Inc.
Desco Industries Inc.
DG Technologies
Essco Calibration Laboratory
**NSI-MI Technologies**
RIGOL Technologies USA, Inc.

## Fiber-Optic Systems

**Absolute EMC Llc.**
DG Technologies
Essco Calibration Laboratory
Excalibur Engineering Inc., a Transcat Company
Ferrotec-Nord
**HV TECHNOLOGIES, Inc.**
Michigan Scientific Corp.
montena technology sa
**Ross Engineering Corp.**
TESEO SpA

## Flow Meters

Essco Calibration Laboratory
Omni Controls
PCE Instruments
VEROCH - Testing Equipment USA

## Generators

### Arbitrary Waveform Generators

**Absolute EMC Llc.**
AMETEK CTS
Applied Physical Electronics, L.C. (APELC)
Eurofins York
GIGA-TRONICS INCORPORATED
Hilo-Test
Keysight Technologies Inc.
RIGOL Technologies USA, Inc.
Siglent Technologies North America
**Suzhou 3ctest Electronic Co., Ltd.**

### EMP Generator

Advanced Test Equipment Corporation
**HV TECHNOLOGIES, Inc.**
montena technology sa
**Suzhou 3ctest Electronic Co., Ltd.**

### ESD Generators

**Absolute EMC Llc.**
Advanced Test Equipment Corporation
AMETEK CTS
ARC Technical Resources
The EMC Shop
Grund Technical Solutions, Inc.
Haefely AG
**HV TECHNOLOGIES, Inc.**
**Lightning EMC**
M Precision Laboratories, INC.
montena technology sa
**Suzhou 3ctest Electronic Co., Ltd.**

### Fast/Transient Burst Generators

**Absolute EMC Llc.**
Advanced Test Equipment Corporation
ARC Technical Resources
The EMC Shop
Haefely AG
Hilo-Test
**HV TECHNOLOGIES, Inc.**
**Lightning EMC**
M Precision Laboratories, INC.
**Suzhou 3ctest Electronic Co., Ltd.**

### Impulse Generators

**Absolute EMC Llc.**
Advanced Test Equipment Corporation
AFJ INSTRUMENTS Srl
AMETEK CTS
Applied Physical Electronics, L.C. (APELC)
Grund Technical Solutions, Inc.
Haefely AG
Hilo-Test
**HV TECHNOLOGIES, Inc.**
**Lightning EMC**
M Precision Laboratories, INC.
montena technology sa
Solar Electronics Co.
**Suzhou 3ctest Electronic Co., Ltd.**

### Interference Generators

**Absolute EMC Llc.**
**Suzhou 3ctest Electronic Co., Ltd.**

### Lightning Generators

**Absolute EMC Llc.**
Advanced Test Equipment Corporation
ARC Technical Resources
Avalon Test Equipment
The EMC Shop
Haefely AG
**HV TECHNOLOGIES, Inc.**
**Lightning EMC**
M Precision Laboratories, INC.
Solar Electronics Co.
**Suzhou 3ctest Electronic Co., Ltd.**

### Signal Generators

Aaronia USA
Advanced Test Equipment Corporation
AFJ INSTRUMENTS Srl
Alltest Instruments
ConRes Test Equipment
Electro Rent Corporation
Eurofins York
Excalibur Engineering Inc., a Transcat Company
GIGA-TRONICS INCORPORATED
Keysight Technologies Inc.
**Kikusui America Inc.**
Laplace Instruments Ltd
Reliant EMC LLC
RIGOL Technologies USA, Inc.
**Rohde & Schwarz**
Signal Hound
**Suzhou 3ctest Electronic Co., Ltd.**
Techmaster Electronics
TOYO Corporation
VIAVI Solutions

### Surge Transient Generators

**Absolute EMC Llc.**
Advanced Test Equipment Corporation
AMETEK CTS
ARC Technical Resources
Avalon Test Equipment
The EMC Shop
Haefely AG
Hilo-Test

**HV TECHNOLOGIES, Inc.**
**Lightning EMC**
M Precision Laboratories, INC.
Solar Electronics Co.
**Suzhou 3ctest Electronic Co., Ltd.**
Techmaster Electronics
Thermo Fisher Scientific

# Meters

## Field Strength Meters

**Absolute EMC Llc.**
**Amplifier Research Corporation**
Desco Industries Inc.
Narda STS, USA
United Static Control Products Inc.
Wavecontrol Inc.

## Gaussmeters

Omni Controls
PCE Instruments
Wavecontrol Inc.

## Magnetic Field Meters

**Amplifier Research Corporation**
MPB Measuring Instruments
PCE Instruments
Wavecontrol Inc.

## Megohmmeters

**ACL Staticide Inc.**
Amstat Industries, Inc.
Axiom Test Equipment Rentals
Chroma Systems Solutions, Inc
Megger
PCE Instruments
**Ross Engineering Corp.**
Static Solutions, Inc.
United Static Control Products Inc.

## Radiation Hazard Meters

**Amplifier Research Corporation**
EMC Test Design, LLC
Wavecontrol Inc.

## RF Power Meters

**Absolute EMC Llc.**
Alltest Instruments
**Amplifier Research Corporation**
Anritsu Company
ConRes Test Equipment
Electro Rent Corporation
Keysight Technologies Inc.
**OPHIR RF/Ophir EMC**
VIAVI Solutions

## Static Charge Meters

**ACL Staticide Inc.**
Electro-Tech Systems
Estion Technologies GmbH

## Static Decay Meters

Electro-Tech Systems

# Monitors

## Current Monitors

Grund Technical Solutions, Inc.
PCE Instruments
**Pearson Electronics, Inc.**

## EMI Test Monitors

DG Technologies
OnFILTER

## ESD Monitors

Bystat International Inc
Elimstat.com
Estion Technologies GmbH
Static Solutions, Inc.

## Static Voltage Monitors

Desco Industries Inc.
Michigan Scientific Corp.

# Oscilloscopes & Transient Recorders

Agile Calibration
Alltest Instruments
Avalon Test Equipment
Axiom Test Equipment Rentals
ConRes Test Equipment
Electro Rent Corporation
Essco Calibration Laboratory
Keysight Technologies Inc.
PCE Instruments
RIGOL Technologies USA, Inc.
**Rohde & Schwarz**
Siglent Technologies North America
Techmaster Electronics
Teledyne LeCroy

# Pressure Measurement

## Gauges

Willrich Precision Instrument Company, Inc.

# Probes

## Current/Magnetic Field Probes

**A.H. Systems, Inc.**
AEMC Instruments
Alltest Instruments
Fischer Custom Communications, Inc.
General Test Systems LLC
Langer EMV-Technik GmbH
montena technology sa
MPB Measuring Instruments
**Pearson Electronics, Inc.**
Prana
Siglent Technologies North America
Solar Electronics Co.
Techmaster Electronics

## Electric Field Probes

**Absolute EMC Llc.**
Advanced Test Equipment Corporation
**Amplifier Research Corporation**
The EMC Shop
EMC Test Design, LLC
Enerdoor
**ETS-Lindgren**
Langer EMV-Technik GmbH
montena technology sa
MPB Measuring Instruments
Narda STS, USA
Siglent Technologies North America
Wavecontrol Inc.

## Voltage Probes

ConRes Test Equipment
Fischer Custom Communications, Inc.
Hilo-Test
Langer EMV-Technik GmbH
Laplace Instruments Ltd
OnFILTER
**Ross Engineering Corp.**
Solar Electronics Co.

# Receivers

## EMI/EMC Receivers

**Absolute EMC Llc.**
AFJ INSTRUMENTS Srl
**Amplifier Research Corporation**
EMZER
Excalibur Engineering Inc., a Transcat Company
**GAUSS INSTRUMENTS**
**HV TECHNOLOGIES, Inc.**
Laplace Instruments Ltd
Lionheart Northwest
Reliant EMC LLC
**Rohde & Schwarz**
Schwarzbeck Mess-Elektronik OHG

## RF Receivers

AFJ INSTRUMENTS Srl
ConRes Test Equipment
GIGA-TRONICS INCORPORATED
Narda STS, USA
**NSI-MI Technologies**
**Rohde & Schwarz**

## TEMPEST Receivers

**Rohde & Schwarz**

# RF Leak Detectors

**Amplifier Research Corporation**
MPB Measuring Instruments
NRD LLC

# Safety Test Equipment

**Absolute EMC Llc.**
**AE Techron, Inc.**
AEMC Instruments
Chroma Systems Solutions, Inc
Cincinnati Sub Zero, LLC
**ED&D**
EMC Test Design, LLC
**Kikusui America Inc.**
Micom Laboratories Inc
MPB Measuring Instruments
Packaging Compliance Labs
Preen AC Power Corp.
Product Safety Consulting
Saf-T-Gard International, Inc.
Sanwood Environmental Chambers Co., Ltd
United Static Control Products Inc.
VEROCH - Testing Equipment USA
**Vitrek Corporation**

# SAR Testing Equipment

ART-MAN
GIGA-TRONICS INCORPORATED
Lionheart Northwest

# Shock & Vibration Testing Shakers

Cincinnati Sub Zero, LLC
Globe Composite Solutions
Micom Laboratories Inc
Sanwood Environmental Chambers Co., Ltd
Thermotron
Wewontech

# Susceptibility Test Instruments

Advanced Test Equipment Corporation
ARC Technical Resources
DG Technologies
EMC Test Design, LLC
**ESDEMC Technology LLC**
Grund Technical Solutions, Inc.
Laplace Instruments Ltd
Lionheart Northwest
montena technology sa
Pendulum Instruments
**TDK RF Solutions**



# Telecom Test Equipment

**AE Techron, Inc.**
Anritsu Company
Avalon Test Equipment
Axiom Test Equipment Rentals
Cincinnati Sub Zero, LLC
Electro Rent Corporation
Fischer Custom Communications, Inc.
Haefely AG
Megger
Pickering Interfaces
RIGOL Technologies USA, Inc.
VIAVI Solutions

# Test Equipment Rentals

Advanced Test Equipment Corporation
Alltest Instruments
Avalon Test Equipment
Axiom Test Equipment Rentals
**Barth Electronics, Inc.**
ConRes Test Equipment
Electro Rent Corporation
Electro-Tech Systems
The EMC Shop
**ESDEMC Technology LLC**
Excalibur Engineering Inc., a Transcat Company
Grund Technical Solutions, Inc.
Megger
Michigan Scientific Corp.
MPB Measuring Instruments
Techmaster Electronics
TestWorld Inc
Transient Specialists, Inc.
United Static Control Products Inc.
VEROCH - Testing Equipment USA

# Testers

## Common Mode Transient Immunity (CMTI)

**Barth Electronics, Inc.**

## Current Leakage Testers

Associated Research, Inc
Chroma Systems Solutions, Inc
**ESDEMC Technology LLC**
**Kikusui America Inc.**
Megger
**Ross Engineering Corp.**
**SCI**

## Dielectric Strength Testers

Associated Research, Inc
Chroma Systems Solutions, Inc
Megger
**Ross Engineering Corp.**
**SCI**

## Electrical Safety Testers

Associated Research, Inc
Chroma Systems Solutions, Inc
EEC, an Ikonix Brand
**Kikusui America Inc.**
Megger
Saf-T-Gard International, Inc.
**SCI**

## EMC Testers

**Absolute EMC Llc.**
AMETEK CTS
DG Technologies
EMC PARTNER AG
EMC Technologies
EMC Test Design, LLC
**ESDEMC Technology LLC**
Grund Technical Solutions, Inc.
Langer EMV-Technik GmbH
**OPHIR RF/Ophir EMC**
Pendulum Instruments

## ESD Testers

### CDM (Charged Device Model)

**Barth Electronics, Inc.**
Electro-Tech Systems
Thermo Fisher Scientific

### HBM (Human Body Model)

Electro-Tech Systems
Thermo Fisher Scientific

### TLP (Transmission Line Pulser)

**Barth Electronics, Inc.**
Thermo Fisher Scientific

## Ground Bond Testers

EEC, an Ikonix Brand

## Ground Resistance Testers

AEMC Instruments
Associated Research, Inc
Megger
**SCI**

## Hipot Testers

Applied Physical Electronics, L.C. (APELC)
Associated Research, Inc
Chroma Systems Solutions, Inc
EEC, an Ikonix Brand
Electro Rent Corporation
GW INSTEK
**Kikusui America Inc.**
**Ross Engineering Corp.**
**SCI**

## Thermocouples

Applied Physical Electronics, L.C. (APELC)
Pickering Interfaces
VEROCH - Testing Equipment USA

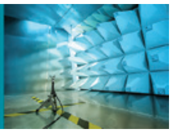
## Used & Refurbished Test Equipment

Advanced Test Equipment Corporation
Alltest Instruments
**Amplifier Research Corporation**
Avalon Test Equipment
Axiom Test Equipment Rentals
ConRes Test Equipment
Electro Rent Corporation
Techmaster Electronics

## Vibration Controllers

ALI Testing
Cincinnati Sub Zero, LLC
Excalibur Engineering Inc., a Transcat Company
Globe Composite Solutions
Micom Laboratories Inc
Thermotron

# Testing



## Accredited Registrar

ANAB ANSI-ASQ National Accreditation Board
DEKRA
**Element Materials Technology - Brooklyn Park, MN**
**Element Materials Technology - Dallas-Plano, TX**
Excalibur Engineering Inc., a Transcat Company
Green Mountain Electromagnetics, Inc.
MiCOM Labs
QAI Laboratories

## Calibration Testing

Agile Calibration
Bharat Test House Group
Essco Calibration Laboratory
Haefely AG
ITC India
M Precision Laboratories, INC.

## CE Competent Body

Bureau Veritas Consumer Products Services Inc.
**D.L.S. - Environmental**
**Element Materials Technology - Dallas-Plano, TX**
**Element Materials Technology - Irvine, CA**
**Element Materials Technology - Washington, Columbia, Oakland Mills**
Enviropass Expertise Inc.
QAI Laboratories
Rogers Labs

## CE Notified Body

American Certification Body
Bureau Veritas Consumer Products Services Inc.
CKC Laboratories, Inc.
Clark Testing
Compatible Electronics, Inc.
DEKRA

## CE Notified Body *continued*

**Element Materials Technology - Brooklyn Park, MN**

**Element Materials Technology - Irvine, CA**

**Element Materials Technology - Washington, Columbia, Oakland Mills**

Elite Electronic Engineering Inc.

Eurofins York

MiCOM Labs

Nemko Canada

Nemko Europe

Nemko USA

QAI Laboratories

Rogers Labs

TESEO SpA

Test Site Services Inc

## Environmental Testing & Analysis Services

Bharat Test House Group

Brighton EMC

Bureau Veritas Consumer Products Services Inc.

CertifiGroup Inc

The Compliance Management Group

**D.L.S. - Environmental**

**D.L.S. - Military**

**D.L.S. - Wireless**

Dayton T. Brown, Inc.

DNB Engineering, Inc.

Elite Electronic Engineering Inc.

Enviropass Expertise Inc.

ITC India

Micom Laboratories Inc

NTS

Quanta Laboratories

Retlif Testing Laboratories

**RMV Technology Group LLC**

Sanwood Environmental Chambers Co., Ltd

Test Site Services Inc

Washington Laboratories

## Homologation Services

American Certification Body

**Approve-IT, Inc.**

Bharat Test House Group

Bureau Veritas Consumer Products Services Inc.

Compliance Specialty International Associates

**Element Materials Technology - Brooklyn Park, MN**

**Element Materials Technology - Dallas-Plano, TX**

Enviropass Expertise Inc.

**Go Global Compliance Inc.**

Lewis Bass International Engineering Services

MiCOM Labs

Orbis Compliance LLC

Versus Technology (Versus Global LLC)

## Pre-Assessments

A2LA

American Certification Body

Analysis and Measurement Services Corporation

Bharat Test House Group

Brighton EMC

Clark Testing

Compatible Electronics, Inc.

Curtis Industries/Tri-Mag, LLC

CVG Strategy

**D.L.S. - EMC**

**D.L.S. - Environmental**

**D.L.S. - Military**

**D.L.S. - Product Safety**

**D.L.S. - Wireless**

DEKRA

Eisner Safety Consultants

**Element Materials Technology - Brooklyn Park, MN**

**Element Materials Technology - Dallas-Plano, TX**

**Element Materials Technology - Irvine, CA**

**Element Materials Technology - Washington, Columbia, Oakland Mills**

Enviropass Expertise Inc.

EOS/ESD Association Services, LLC

**F2 Labs - Damascus, MD**

**F2 Labs - Indianapolis, IN**

**F2 Labs - Middlefield, OH**

International Certification Services, Inc.

Lewis Bass International Engineering Services

Product Safety Consulting

Quanta Laboratories

Rogers Labs

**SILENT Solutions LLC**

Spectrum EMC, LLC

Testing Partners

VPI Laboratories, Inc.

Washington Laboratories

## Product & Component Testing Services

Agile Calibration

Analysis and Measurement Services Corporation

ART-MAN

Bharat Test House Group

Brighton EMC

Bureau Veritas Consumer Products Services Inc.

CertifiGroup Inc

The Compliance Management Group

Compliance Specialty International Associates

Compliance Testing, LLC

CVG Strategy

**D.L.S. - EMC**

**D.L.S. - Environmental**

**D.L.S. - Military**

**D.L.S. - Product Safety**

**D.L.S. - Wireless**

Dayton T. Brown, Inc.

DEKRA

DNB Engineering, Inc.

**Element Materials Technology - Atlanta-Gainesville, GA**

**Element Materials Technology - Brooklyn Park, MN**

**Element Materials Technology - Dallas-Plano, TX**

**Element Materials Technology - Irvine, CA**

**Element Materials Technology - Washington, Columbia, Oakland Mills**

Elite Electronic Engineering Inc.

Energy Assurance LLC

Enviropass Expertise Inc.

EOS/ESD Association Services, LLC

**F2 Labs - Damascus, MD**

**F2 Labs - Indianapolis, IN**

**F2 Labs - Middlefield, OH**

FEMA Corporation

Ferrotec-Nord
Green Mountain Electromagnetics, Inc.
International Certification Services, Inc.
ITC India
Micom Laboratories Inc
PAVONE Technologies
The Photonics Group
Product Safety Consulting
R&B Laboratory
Retlif Testing Laboratories
RF Solutions, LLC
**RMV Technology Group LLC**
Rogers Labs
Sanwood Environmental Chambers Co., Ltd
Southwest Research Institute
Testing Partners
VPI Laboratories, Inc.
Washington Laboratories
**Wyatt Technical Services LLC**

## Testing Laboratories

### Accelerated Stress Testing

Core Compliance Testing Services
**D.L.S. - Environmental**
**D.L.S. - Wireless**
Dayton T. Brown, Inc.
Elite Electronic Engineering Inc.
Intertek
Nemko USA
NTS
Product Safety Consulting
Quanta Laboratories
**Radiometrics Midwest Corporation**

### Acoustical Testing

A2LA
Clark Testing
The Compliance Management Group
Core Compliance Testing Services
**D.L.S. - Environmental**
**D.L.S. - Product Safety**
Dayton T. Brown, Inc.
DNB Engineering, Inc.
Electronic Instrument Associates
**ETS-Lindgren**
Intertek
Nemko Asia
Nemko Canada
Nemko Europe
Nemko USA
Quanta Laboratories
Retlif Testing Laboratories

### BSMI Compliant Certification Testing

Atlas Compliance & Engineering
Compliance Worldwide, Inc.
Core Compliance Testing Services
**D.L.S. - EMC**
**D.L.S. - Wireless**
**Element Materials Technology - Brooklyn Park, MN**
**Element Materials Technology - Dallas-Plano, TX**
**Element Materials Technology - Irvine, CA**
**Element Materials Technology - Washington, Columbia, Oakland Mills**
Nemko Asia
Nemko Canada
Nemko Europe
Nemko USA

### CB Test Report

CSA Group
**Element Materials Technology - Brooklyn Park, MN**
**Element Materials Technology - Dallas-Plano, TX**
**Element Materials Technology - Irvine, CA**
**Element Materials Technology - Washington, Columbia, Oakland Mills**
Energy Assurance LLC
Eurofins MET Labs
**F2 Labs - Indianapolis, IN**
Intertek
Nemko Asia
Nemko Canada
Nemko Europe
Nemko USA
TÜV Rheinland of North America

### CE Marking

Abstraction Engineering Inc
Atlas Compliance & Engineering
Brighton EMC
CertifiGroup Inc
CKC Laboratories, Inc.
Compatible Electronics, Inc.
The Compliance Management Group
Compliance Worldwide, Inc.
Core Compliance Testing Services
**D.L.S. - EMC**
**D.L.S. - Environmental**
**D.L.S. - Military**
**D.L.S. - Product Safety**
**D.L.S. - Wireless**
DNB Engineering, Inc.
**Element Materials Technology - Brooklyn Park, MN**
**Element Materials Technology - Irvine, CA**
**Element Materials Technology - Washington, Columbia, Oakland Mills**
Elite Electronic Engineering Inc.
EMC Bayswater Pty Ltd
Energy Assurance LLC
Enviropass Expertise Inc.
Eurofins MET Labs
**F2 Labs - Damascus, MD**
**F2 Labs - Indianapolis, IN**
**F2 Labs - Middlefield, OH**
**G&M Compliance, Inc.**
Global Testing Laboratories
Green Mountain Electromagnetics, Inc.
H.B. Compliance Solutions
International Certification Services, Inc.
Intertek
**Laird Connectivity**
Lewis Bass International Engineering Services
Nemko Asia
Nemko Canada
Nemko Europe
Nemko USA
NTS
Retlif Testing Laboratories
Rogers Labs
TESEO SpA
Test Site Services Inc
TÜV Rheinland of North America
VPI Laboratories, Inc.

## Testing Laboratories

### China Compulsory Certification

**D.L.S. - EMC**

**D.L.S. - Product Safety**

**G&M Compliance, Inc.**

Nemko Asia

Nemko Canada

Nemko Europe

Nemko USA

### Electrical Safety Testing

Abstraction Engineering Inc

Bharat Test House Group

CertifiGroup Inc

**Coilcraft Critical Products & Services**

CSA Group

CVG Strategy

**D.L.S. - Product Safety**

Dayton T. Brown, Inc.

DNB Engineering, Inc.

**Element Materials Technology - Atlanta-Gainesville, GA**

**Element Materials Technology - Brooklyn Park, MN**

**Element Materials Technology - Dallas-Plano, TX**

**Element Materials Technology - Irvine, CA**

**Element Materials Technology - Washington, Columbia, Oakland Mills**

EMC Bayswater Pty Ltd

Energy Assurance LLC

**F2 Labs - Indianapolis, IN**

**F2 Labs - Middlefield, OH**

**G&M Compliance, Inc.**

Green Mountain Electromagnetics, Inc.

H.B. Compliance Solutions

Intertek

ITC India

MiCOM Labs

Nemko Asia

Nemko Canada

Nemko Europe

Nemko USA

Orbis Compliance LLC

TÜV Rheinland of North America

### EMC Testing

A2LA

Abstraction Engineering Inc

AHD

APREL Inc.

ART-MAN

Atlas Compliance & Engineering

Bharat Test House Group

Brighton EMC

Bureau Veritas Consumer Products Services Inc.

CKC Laboratories, Inc.

Clark Testing

Compatible Electronics, Inc.

The Compliance Management Group

Compliance Worldwide, Inc.

Core Compliance Testing Services

CSA Group

CVG Strategy

**D.L.S. - EMC**



**D.L.S. - Environmental**

**D.L.S. - Military**

**D.L.S. - Product Safety**

**D.L.S. - Wireless**

Dayton T. Brown, Inc.

DNB Engineering, Inc.

Electronics Test Centre

**Element Materials Technology - Brooklyn Park, MN**

**Element Materials Technology - Dallas-Plano, TX**

**Element Materials Technology - Irvine, CA**

**Element Materials Technology - Washington, Columbia, Oakland Mills**

Elite Electronic Engineering Inc.

EMC Bayswater Pty Ltd

**F2 Labs - Damascus, MD**

**F2 Labs - Middlefield, OH**

**G&M Compliance, Inc.**

Global Testing Laboratories

Green Mountain Electromagnetics, Inc.

H.B. Compliance Solutions

International Certification Services, Inc.

Intertek

ITC India

**Laird Connectivity**

MiCOM Labs

**Montrose Compliance Services, Inc.**

National Institute for Aviation Research

Nemko Asia

Nemko Canada

Nemko Europe

Nemko USA

NTS

Parker Chomerics

QAI Laboratories

R&B Laboratory

**Radiometrics Midwest Corporation**

Retlif Testing Laboratories

Rogers Labs

Southwest Research Institute

Spes Development Co

Test Site Services Inc

Timco Engineering, Inc.

TÜV Rheinland of North America

TÜV SÜD America Inc.

VPI Laboratories, Inc.

Washington Laboratories

WEMS Electronics

Yazaki Testing Laboratory

### Energy Efficiency Testing

Bharat Test House Group

Bureau Veritas Consumer Products Services Inc.

CSA Group

Nemko Asia

Nemko Canada

Nemko Europe

Nemko USA

## Environmental Simulation Testing

ALI Testing

**Coilcraft Critical Products & Services**



The Compliance Management Group

Core Compliance Testing Services

CVG Strategy

**D.L.S. - Environmental**



**D.L.S. - Military**

DNB Engineering, Inc.

Energy Assurance LLC

FEMA Corporation

H.B. Compliance Solutions

Nemko Asia

Nemko Canada

Nemko Europe

Nemko USA

Quanta Laboratories

Retlif Testing Laboratories

**RMV Technology Group LLC**

Sanwood Environmental Chambers Co., Ltd

## ESD Testing

**Barth Electronics, Inc.**

Brighton EMC

The Compliance Management Group

Compliance Worldwide, Inc.

CVG Strategy

**D.L.S. - EMC**

**D.L.S. - Military**

DNB Engineering, Inc.

Electro-Tech Systems

**Element Materials Technology - Brooklyn Park, MN**

**Element Materials Technology - Dallas-Plano, TX**

**Element Materials Technology - Irvine, CA**

**Element Materials Technology - Washington, Columbia, Oakland Mills**

EOS/ESD Association Services, LLC

**ESDEMC Technology LLC**

Estion Technologies GmbH

**F2 Labs - Damascus, MD**

**F2 Labs - Middlefield, OH**

H.B. Compliance Solutions

**Laird Connectivity**

Nemko Asia

Nemko Canada

Nemko Europe

Nemko USA

**RMV Technology Group LLC**

Rogers Labs

VPI Laboratories, Inc.

## GOST R Certification

**G&M Compliance, Inc.**

Nemko Asia

Nemko Canada

Nemko Europe

Nemko USA

## Green Energy Compliance

Enviropass Expertise Inc.

## GS Mark Certification

Nemko Asia

TÜV Rheinland of North America

## Lithium-Ion Battery Testing

Bharat Test House Group

CSA Group

**Element Materials Technology - Atlanta-Gainesville, GA**

Energy Assurance LLC

**F2 Labs - Indianapolis, IN**

**F2 Labs - Middlefield, OH**

ITC India

NTS

Quanta Laboratories

## Marine Electronics Testing

Core Compliance Testing Services

**D.L.S. - Military**

**D.L.S. - Wireless**

**F2 Labs - Damascus, MD**

**F2 Labs - Indianapolis, IN**

Green Mountain Electromagnetics, Inc.

Nemko Europe

Nemko USA

R&B Laboratory

Retlif Testing Laboratories

Rogers Labs

## National Recognized Testing Laboratory (NRTL)

Bureau Veritas Consumer Products Services Inc.

CertifiGroup Inc

CSA Group

**Element Materials Technology - Irvine, CA**

Eurofins MET Labs

**F2 Labs - Indianapolis, IN**

Nemko Asia

Nemko Canada

Nemko Europe

Nemko USA

Product Safety Consulting

TÜV Rheinland of North America

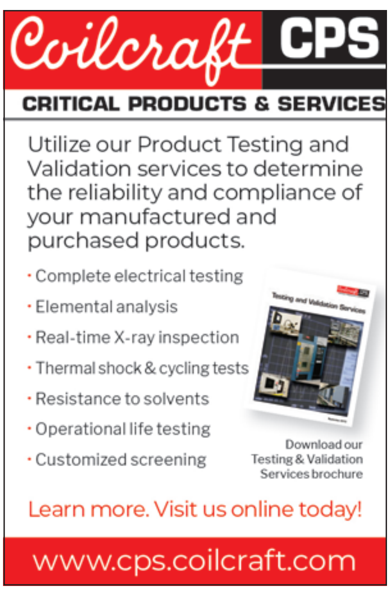
# Testing Laboratories

## Network Equipment Building System (NEBS) Testing

**Element Materials Technology - Dallas-Plano, TX**
Eurofins MET Labs
International Certification Services, Inc.
NTS
Quanta Laboratories

## Product Pre-Compliance Testing

ART-MAN
Atlas Compliance & Engineering
Bicerano & Associates Consulting
Brighton EMC
CertifiGroup Inc
**Coilcraft Critical Products & Services**




Compatible Electronics, Inc.
Compliance Worldwide, Inc.
Core Compliance Testing Services
CVG Strategy
**D.L.S. - EMC**
**D.L.S. - Environmental**
**D.L.S. - Military**
**D.L.S. - Product Safety**
**D.L.S. - Wireless**
**Element Materials Technology - Atlanta-Gainesville, GA**
**Element Materials Technology - Brooklyn Park, MN**
**Element Materials Technology - Dallas-Plano, TX**
**Element Materials Technology - Irvine, CA**
**Element Materials Technology - Washington, Columbia, Oakland Mills**
Energy Assurance LLC
**F2 Labs - Damascus, MD**
**F2 Labs - Indianapolis, IN**
**F2 Labs - Middlefield, OH**
**G&M Compliance, Inc.**
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H.B. Compliance Solutions
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ITC India
**Laird Connectivity**
Lewis Bass International Engineering Services
Nemko Asia
Nemko Canada
Nemko Europe
Nemko USA
Product Safety Consulting
Quanta Laboratories
Rogers Labs
Test Site Services Inc
VPI Laboratories, Inc.
Washington Laboratories

## Product Safety Testing

Abstraction Engineering Inc
Bicerano & Associates Consulting
Bureau Veritas Consumer Products Services Inc.
CertifiGroup Inc
**Coilcraft Critical Products & Services**
Compatible Electronics, Inc.
Core Compliance Testing Services
CSA Group
**D.L.S. - Product Safety**
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**Element Materials Technology - Brooklyn Park, MN**
**Element Materials Technology - Dallas-Plano, TX**
**Element Materials Technology - Irvine, CA**
**Element Materials Technology - Washington, Columbia, Oakland Mills**
Energy Assurance LLC
Ergonomics, Inc.
Eurofins MET Labs
**F2 Labs - Indianapolis, IN**
**F2 Labs - Middlefield, OH**
**G&M Compliance, Inc.**
Global Testing Laboratories
Green Mountain Electromagnetics, Inc.
Lewis Bass International Engineering Services
Nemko Asia
Nemko Canada
Nemko Europe
Nemko USA
NTS
Product Safety Consulting
TÜV Rheinland of North America
TÜV SÜD America Inc.
Washington Laboratories

## Radio Performance & Functionality Testing

American Certification Body
Applied Physical Electronics, L.C. (APELC)
Brighton EMC
CVG Strategy
**D.L.S. - Wireless**
**Element Materials Technology - Brooklyn Park, MN**
**Element Materials Technology - Dallas-Plano, TX**
**Element Materials Technology - Irvine, CA**
**Element Materials Technology - Washington, Columbia, Oakland Mills**
EMC Bayswater Pty Ltd
Eurofins MET Labs
**F2 Labs - Damascus, MD**
H.B. Compliance Solutions
Nemko Asia
Nemko Europe
Nemko USA
Orbis Compliance LLC
**Radiometrics Midwest Corporation**
Test Site Services Inc
Washington Laboratories

## RoHS Directive Compliance

CertifiGroup Inc
**D.L.S. - Product Safety**
Enviropass Expertise Inc.
**F2 Labs - Indianapolis, IN**
**F2 Labs - Middlefield, OH**
ITC India
Nemko Asia
Nemko Canada
Nemko Europe
TÜV Rheinland of North America

## Shock & Vibration

ALI Testing
Clark Testing
**Coilcraft Critical Products & Services**
The Compliance Management Group
CVG Strategy
**D.L.S. - Environmental**
DNB Engineering, Inc.
Elite Electronic Engineering Inc.
Energy Assurance LLC
Eurofins MET Labs
FEMA Corporation
ITC India
Nemko Asia
Nemko USA
NTS
Quanta Laboratories
Retlif Testing Laboratories
Sanwood Environmental Chambers Co., Ltd
WEMS Electronics

## Standards Council of Canada Certification Body

CSA Group
**F2 Labs - Damascus, MD**

## Telecommunications Testing

A2LA
American Certification Body
CKC Laboratories, Inc.
Clark Testing
The Compliance Management Group
Compliance Worldwide, Inc.
**D.L.S. - Wireless**
**Element Materials Technology - Brooklyn Park, MN**
**Element Materials Technology - Dallas-Plano, TX**
**Element Materials Technology - Irvine, CA**
**Element Materials Technology - Washington, Columbia, Oakland Mills**
Eurofins MET Labs
**F2 Labs - Damascus, MD**
Green Mountain Electromagnetics, Inc.
H.B. Compliance Solutions
Megger
Nemko Asia
Nemko Canada
Nemko Europe
Nemko USA
NetSPI
NTS
Orbis Compliance LLC
Retlif Testing Laboratories
Southwest Research Institute

## Wireless

American Certification Body
Brighton EMC
Bureau Veritas Consumer Products Services Inc.
CKC Laboratories, Inc.
Compliance Worldwide, Inc.
**D.L.S. - EMC**
**D.L.S. - Product Safety**
**D.L.S. - Wireless**
Electronic Instrument Associates
**Element Materials Technology - Brooklyn Park, MN**
**Element Materials Technology - Dallas-Plano, TX**
**Element Materials Technology - Irvine, CA**
**Element Materials Technology - Washington, Columbia, Oakland Mills**
Elite Electronic Engineering Inc.
EMC Bayswater Pty Ltd
**ETS-Lindgren**
Eurofins MET Labs
**F2 Labs - Damascus, MD**
International Certification Services, Inc.
Megger
MiCOM Labs
Nemko Asia
Nemko Canada
Nemko Europe
NTS
Orbis Compliance LLC
Rogers Labs
Test Site Services Inc
TÜV Rheinland of North America
TÜV SÜD America Inc.
VPI Laboratories, Inc.

# Events

★ Visit In Compliance's booth at these events!

**March 12-14**
EMV 2024

**March 14**
EU Radio Equipment Directive Update Webinar

**April 11**
Adding UNII-4 Band to Previous UNII Approvals Webinar

**April 16-19**
Applying Practical EMI Design & Troubleshooting Techniques

Advanced Printed Circuit Board Design for EMC + SI

Mechanical Design (Enclosure & Cable shielding) for EMC

**April 21-24**
American Association for Laboratory Accreditation (A2LA) Annual Conference

**April 23**
★ Antenna Measurement Techniques Association (AMTA) Regional Event and Tabletop Show

**April 30- May 2**
★ IEEE International Symposium on Product Compliance Engineering (ISPCE 2024)

**May 14-17**
Applying Practical EMI Design & Troubleshooting Techniques

Advanced Printed Circuit Board Design for EMC + SI

Mechanical Design (Enclosure & Cable shielding) for EMC

**May 14**
★ Annual Chicago IEEE EMC Mini Symposium

**May 16**
★ EMC Fest 2024

**May 16**
Japan Radio Regulations Webinar

**May 19-23**
2024 International Applied Computational Electromagnetics Society (ACES) Symposium

**May 20-23**
IEEE I²MTC 2004 – International Instrumentation and Measurement Technology Conference

**May 20-24**
2024 IEEE Joint International Symposium on Electromagnetic Compatibility, Signal & Power Integrity: EMC Japan/Asia-Pacific International Symposium on Electromagnetic Compatibility (EMC Japan/APEMC Okinawa)

**May 22-23**
★ EMC and Compliance International

**June 13**
mmWave Communications Technologies Webinar

**June 16-21**
★ International Microwave Symposium (IMS)

**June 24-26**
Sensors Converge Expo

**July 11**
MIL-STD 461/810 Webinar

**July 14-19**
2024 IEEE International Symposium on Antennas and Propagation

**July 15-18**
Military Standards 810 (MIL-STD-810) Test Training

**August 5-9**
★ 2024 IEEE International Symposium on Electromagnetic Compatibility, Signal Power Integrity (EMC+SIPI)

**August 15**
Integrating Modules

**September 2-5**
EMC Europe Symposium

**September 12**
Space Applications, EMC, ENV Webinar

**September 19**
★ 2024 Minnesota EMC Event

**September 15-19**
★ 46th Annual EOS/ESD Symposium and Exhibits

**September 22-27**
European Microwave Week 2024

**September 24-27**
Applying Practical EMI Design & Troubleshooting Techniques

Advanced Printed Circuit Board Design for EMC + SI

Mechanical Design (Enclosure & Cable shielding) for EMC

**October 2-4**
Battery Japan: International Rechargeable Battery Expo

**October 7-9**
EMC Compo 2024, International Workshop on the Electromagnetic Compatibility of Integrated Circuits

**October 7-10**
★ The Battery Show

**October 10**
Cyber-Security Webinar

**October 27-November 1**
★ 46th Annual Meeting and Symposium of the Antenna Measurement Techniques Association (AMTA)

**November 15**
IoT Applications Webinar

**November 20-22**
Battery Japan: International Rechargeable Battery Expo

**December 3-5**
Fundamentals of Random Vibration and Shock Testing Training

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https://incompliancemag.com/events

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As much as we're recognized for our technology, innovation, and engineering expertise, we are very much a people company. Across the globe, we bring an understanding that the most effective solutions begin with something far more basic than the products and technology we develop, they begin with a partnership between people. ETS-Lindgren's experts are industry involved within the standards communities and support global initiatives of education and development of the next generation of technical professionals.

Headquartered in Cedar Park, Texas, with offices in North America, Europe, and Asia, we are a multinational organization that celebrates our diversity and encourages both personal and professional growth. ETS-Lindgren is a wholly owned subsidiary of ESCO Technologies, a leading supplier of engineered products for growing industrial and commercial markets. ESCO is a New York Stock Exchange listed company (symbol ESE) with headquarters in St. Louis, Missouri.

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