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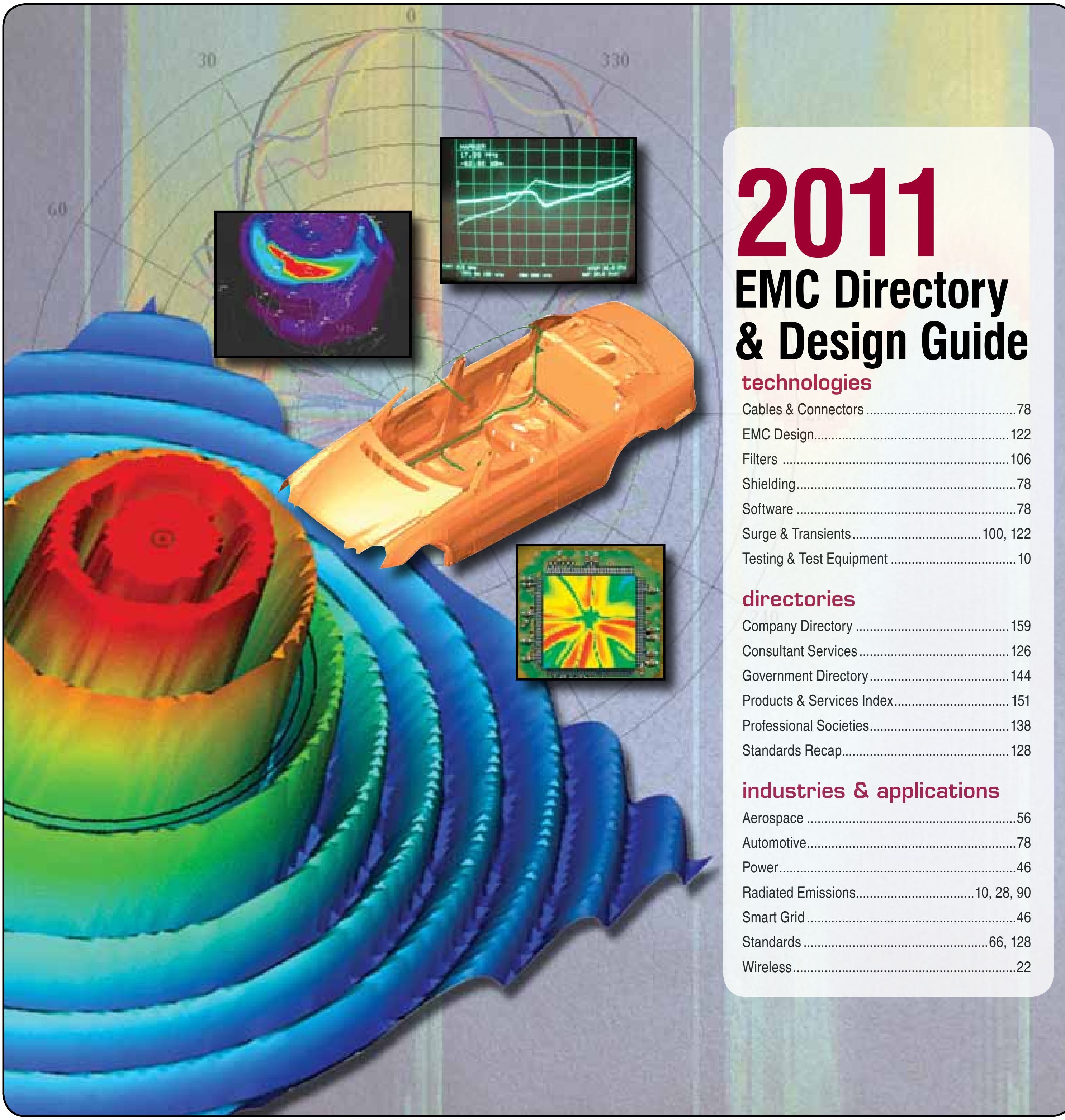

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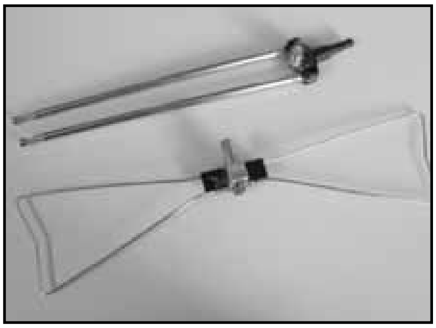

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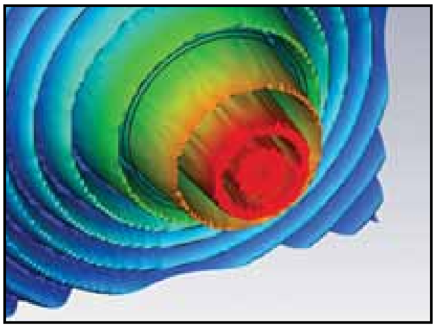

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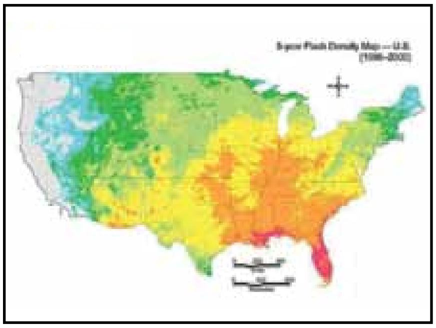

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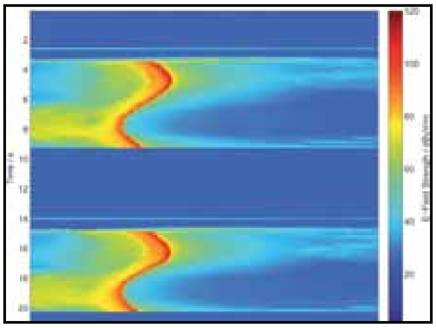

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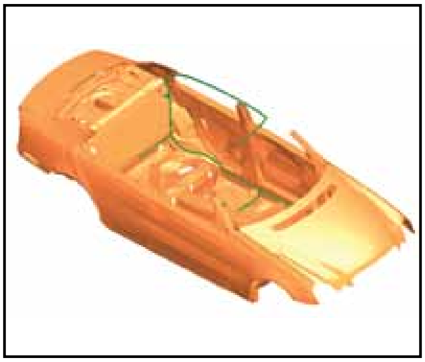

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from the editor

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A LOOK BACK — AND FORWARD

Anniversaries offer the opportunity to look back and reminisce, but it's also a good time to take stock and look ahead. As ITEM noted the passing of its 40th anniversary, I pulled the 1971 edition of the *Interference Technology Directory & Design Guide* off its dusty shelf and cracked open the stiff spine.

What immediately struck me in perusing the pages of the inaugural issue was not how far we've come but, instead, how little has changed.

In introducing ITEM, Publisher & Editor-in-chief Robert D. Goldblum wrote:

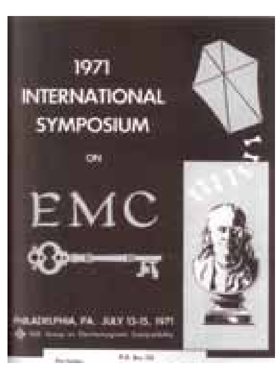
"Radiated and electrical interference has once been stated as "Everyone's Problem". If you are involved with engineering, whether it be research, design, applications management or purchasing, the problems associated with electrical noise and radiation are all around you. The EMC (Electromagnetic Compatibility) engineer is a specialist in the control and measurement of noise, but there are too few of these specialists to go around. Thus, there are several alternatives; hiring an EMC specialist, obtaining consulting services, and educating each engineer and manager to deal effectively with the noise problems. These are the objectives of ITEM."

And these remain our objectives today. Many of the topics covered in that first issue — electro-explosive devices, EM susceptibility generators, military EMI specifications, transients caused by inductive loads – are still actively covered by ITEM's authors. Ever-growing demand for electrical devices and electronic goods means EMC specialists are more valuable than ever before. Just as the focus has remained on these timeless topics for the last few decades, where we go in the next 40 years will be dictated by those specialists working in the field.

What are you working on? Whether it's the technologies of tomorrow – hybrid and electric cars, wind and solar generated power, the Smart Grid and nanotechnology – or always-useful troubleshooting tips from the bench top, we want you to share your knowledge and findings with your colleagues. If you've heard about a topic, technology or standard that deserves to be publicized, email me at slong@interferencetechnology.com.

Anyone who is interested in the *1971 Directory & Design Guide* can contact me for a copy. I hope you'll enjoy the trip down memory lane as much as I did.

Sarah Long, *Editor*



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Editor
Sarah Long

Graphic Designer
Ann Schibik

Editorial Assistant
Cait O'Driscoll

Marketing Specialist
Jacqueline Gentile

Business Development Manager
Bob Poust

Business Development Executives
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President
Graham S. Kilshaw

Publisher Emeritus
Robert D. Goldblum

ITEM™

USA
1000 Germantown Pike, F-2
Plymouth Meeting, PA 19462
Phone: (484) 688-0300
Fax: (484) 688-0303
E-mail:
info@interferencetechnology.com
www.interferencetechnology.com

CHINA, TAIWAN, HONG KONG
Leadzil
Jenny Chen, +86-010-65250537
E-mail: service@leadzil.com

JAPAN
TÜV SÜD Ohtama, Ltd.
Miho Toshima, +81-44-980-2092
E-mail: m-toshima@tuv-ohtama.co.jp

Troubleshooting Radiated Emissions Using Low-Cost Bench-Top Methods

KENNETH WYATT, SR.
Wyatt Technical Services
Woodland Park, Colorado USA

Because time-to-market and budget factors often drive many of today's high-tech designs, electromagnetic compatibility (EMC) issues often surface at the last moment in the design cycle, potentially delaying product introductions. Very often, simple troubleshooting techniques can identify issues early when the cost of implementation is substantially lower and design improvements may be made with less impact on schedules. This article describes a number of simple probing tools and techniques useful in reducing the radiated emissions (RE) of a product that will better prepare it for a successful radiated emission compliance test.

INTRODUCTION

There are usually five key threats that comprise most electromagnetic compatibility (EMC) problems: radiated emissions, electrostatic discharge (ESD), susceptibility to RF fields, power disturbances and internal crosstalk. Of these, radiated emissions (RE) can be the most difficult test for a product to pass. Because emissions limits are established worldwide, products that don't meet the limits may not be placed on the market. The best way to achieve compliance is through proper product design, but often these design techniques are not taught in universities, nor are these techniques fully understood by many experienced engineers. The result is that EMC is considered "black magic" and many products must be tested repeatedly through a system of trial and error, in order to finally achieve compliance.

This is unfortunate, because the emissions a product may produce is easily understood if the designer considers that high-frequency currents in circuit loops tend to broadcast these emissions. These circuit loops may be in the form of printed circuit traces (differential-mode currents) or cables connecting two subsystems (common-mode currents). There may also be combinations of these phenomenon, as well as poor printed circuit board layout practices. The circuit and system design of a product usually falls within the domain of the electronic engineer. The other consideration is the shielding properties of the product, which typically falls within the domain of the mechanical engineer. Ideally, these two must work together as a team to address the whole product in order to be successful in addressing EMC.

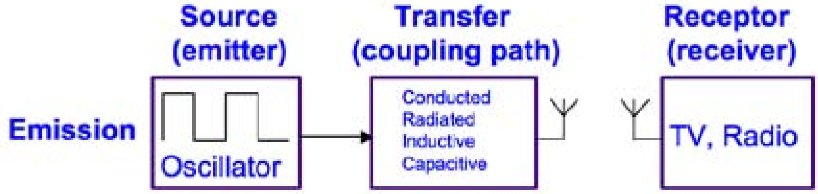

Figure 1. *Source-path-receptor model.*

TROUBLESHOOTING PHILOSOPHY

In troubleshooting any radiated emission problem, it's useful to think of the problem in the form of a "source-path-receptor" model. See Figure 1.

Typically, the source of radiated emis-

sions is a high-frequency crystal oscillator or other high-frequency, fast-edged, high-current signal. ASICs, FPGAs and A/D or D/A converters may also generate these high-frequency harmonics. Sources of common-mode currents include simultaneous switching noise (SSN) through common impedances, routing of clock traces over gaps in return planes and unbalanced physical structures or resonances in PC boards or enclosures.

The "path" is the coupling mechanism, or the means, by which the high-frequency energy is coupled to the radiating element (enclosure slot, cable, etc.). This may include conducted, radiated, inductive or capacitive couplings.

The "receptor", in most cases, is the EMI receiver at the test site with specified emission limits, but in the real world could include interference to radio, television, or communication systems.

By using simple measurement probes, it should be possible to identify the source or sources. Once the sources are identified, the path or coupling mechanism must be identified and fixed. What's difficult is that there may be multiple sources and coupling mechanisms to identify and fix, before passing results are achieved. In addition, if a fix is improperly installed, the emission can actually get worse! That's probably why the field of EMC is considered so mysterious.

By using a structured approach, the troubleshooting phase should go smoothly. Generally, you'll want to diagnose the issues first – then try various fixes. Leave these fixes installed as you continue the troubleshooting process. By setting up a simple antenna and EMI receiver or spectrum analyzer a fixed distance away (1 to 3m) from where you're troubleshooting you can monitor your results real-time. Note, however, a 10 dB drop in emissions at 1m does not necessarily indicate the same drop in the measurement chamber, due to near-field effects.

Identify the sources

The first step should always be to identify the likely sources. If you're failing at 300 or 500 MHz, for example, are these the third or fifth harmonics of a 100 MHz clock oscillator? How about the memory clocking? Generally memory address and data busses are fairly random. The exception would be the A0 or D0 line, which is clocking at a relatively non-random rate. What about clock lines to ASICs or FPGAs? If you have multiple crystal oscillators, which could be the cause of a particular harmonic, applying freeze spray on one, then the other, can often identify the offending oscillator.

Frequency

The frequency is key to any radiated emission problem. As a quick rule of thumb, the higher the frequency, the more

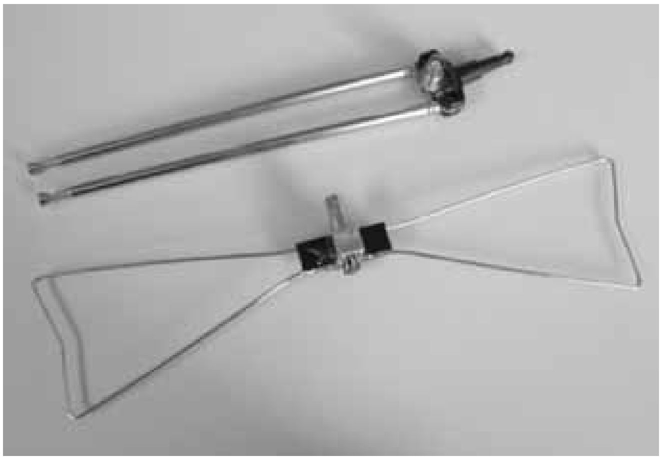

Figure 2. *Examples of DIY antennas for radiated emissions troubleshooting. The "rabbit ears" are resonant from 65 to 200 MHz, while the bowtie works well from 300 to 800 MHz. I installed a television-style balun to better match to 50-ohm coax for the bowtie.*

likely the coupling path is radiated. The lower the frequency, the more likely the path is conducted. In fact, the common break frequency during compliance testing is 30 MHz. Below that, we measure conducted emissions (CE) – above that we measure RE. If your product uses a high-frequency crystal oscillator with fast edge speeds, the harmonic content can be estimated with the formula in Equation 1.

$$f = \frac{1}{\Pi \times t_r}$$

Equation 1. *Maximal RE frequency estimate, where f = EMI frequency (Hz) and t_r = risetime (seconds).*

For example, with 1 nsec logic, the harmonic content may be centered around 300 MHz. Another rule of thumb is that for frequencies below about 300 MHz, the problem is most likely due to common-mode emissions from cables and above that; the problem is most likely radiation from slots or seams in the metal chassis or circuit board radiation.

Dimensions

The dimensions of physical structures are also an important factor in troubleshooting an emissions problem. Recall that the wavelength (m) of a resonant wire at frequency, f, in free space is:

$$\lambda = \frac{c}{f} = \frac{3 \times 10^8}{f}$$

Equation 2. *Wavelength of a wire in free space, where c = speed of light in m/s and f = frequency in Hz.*

The dimensions of physical structures, like circuit boards, must be reduced by the velocity factor of the board mate-

Figure 3. *Examples of commercial E- and H-field probes from Beehive Electronics.*

Figure 4. *Examples of homemade H-field probes.*

Figure 5. *I made my own broadband preamp using a Mini-Circuits model ZX60-3018G-S. It is powered it with two 6V Duracell #28A batteries, which happen to fit in a standard "AA" battery holder. The amplifier covers 20 to 3000 MHz at 20 dB gain and is used to boost the probe signals.*

rial (example, 4.7 for FR4 circuit boards). However, typical cables, such as USB or video, are approximately 1m long and can be considered as being in free space. Wires or slots may resonate strongly at multiples of a quarter wavelength. For example, a 1m long cable has a full-wave resonance of 300 MHz, but may also radiate strongly at 150 and 75 MHz. Slots or seams of 8 to 15 cm may resonate in the area of 500 to 800 MHz. As a general rule of thumb, radiating cables or chassis slots of 1/20th wavelength or greater, start to become significant radiating elements (or antennas) for RE.

USEFUL TOOLS

Antennas

The antenna you select should ideally be somewhere near resonance for the frequencies of concern, however, it's not really that critical for troubleshooting purposes. So long as the antenna is fixed in length and fixed in place on the bench, you'll receive consistent results. During troubleshooting, it's more important to know whether the fix is "better" or "worse" or "no change" and as long as the test setup doesn't change, the results should be believable.

Now, EMC antennas are not inexpensive, as you might imagine, so for general troubleshooting, I tend to use a couple inexpensive television antennas - a pair of "rabbit ears" and a UHF "bowtie" (with TV balun to match 50-ohm coax). See Figure 2. If the workbench is wooden, I'll extend the antenna to approximate resonance (if possible) and tape it down to the bench with duct tape. If the bench is metallic, I'll find a non-conductive support and position it some distance away from the bench. I usually use a test distance of about a meter, but as long as you can see the product's harmonics on a spectrum analyzer, you'll be able to determine your progress. Sometimes I need to insert a low-noise wide-band preamp between antenna and analyzer.

Now, obviously, ambient signals from broadcast radio, television mobile phones and two-way radio services will tend to interfere with observing the product harmonics. You may need to bring the antenna closer or set up the troubleshooting measurement in a basement or building interior away from outside windows. I usually record the known harmonics of concern using an H-field probe or by bringing the measurement antenna in close and then try to characterize them in relation to other nearby ambient signals.

Probes

There are a variety of useful probes that may be used to troubleshoot RE problems; E-field, H-field and current probes.[1] All are easily made in the lab or are available from several manufacturers. An E-field probe may be made by extending the center conductor about 0.5 cm from a section of semi-rigid coax or high-quality flexible coax; then attaching a coax connector to the other end. Shorting of the probe to circuit traces may be avoided by wrapping insulating tape around the end. A useful H-field probe may be fashioned by looping the center conductor around and soldering it to the shield to form a small loop of 0.5 to 5 cm in diameter - the larger the loop, the more sensitivity. A better

[1] *Probe manufacturers include Fischer Custom Communications, Beehive Electronics or Teseq.*

H-field probe design uses semi-rigid coax to form the loop (see examples in Figures 3 and 4). Occasionally, I'll need to amplify the harmonic signals and so use a DIY broadband preamplifier as shown in Figure 5. Beehive Electronics also makes a low-cost amplifier.

TROUBLESHOOTING STEPS

Locating internal sources

Connect your probe to the input of an EMI receiver or spectrum analyzer to display the harmonics as the probe is brought into close contact with the circuit traces or chassis slots. Depending on the diameter of your H-field probe, you may need to use a broadband preamplifier between the probe and analyzer.[2]

Generally, once you are finished mapping out your sources, you should start with the lower harmonics and work upwards. Often, lower-frequency sources will cause significant high-frequency harmonics, depending upon the rise time. By fixing the low-frequency source, you'll often resolve the high-frequency harmonics, as well. Next, check cables and then the enclosure.

Cables

Check your cables next, as they are often the worst offenders. Moving a "hot" cable will alter the RE levels. I usually unplug all cables; then try plugging each one in individually to find all that are radiating. Remember that there may be more than one bad cable! Snapping a ferrite choke around the base of the cable will probably help as an interim fix. I've found that most cable emissions are very likely due to poor grounding to the enclosure at the I/O connector.

Cable common-mode currents may also be measured directly versus frequency with a current probe.[3] Use of current probes usually works better than antennas, because they tend to pick up fewer ambient signals due to their e-field shield. Clamp the probe around the cable in question and move it back and forth to maximize the readings – then fix it in place while you apply potential fixes.

You can make your own current probe or purchase commercial versions. The advantage of commercial versions is that they can open up and snap around a cable. Examples of my DIY probe is shown in Figure 7, while commercial versions are shown in Figure 8.

It is possible to predict whether a particular cable will pass or fail by measuring the CM current at the offending frequency, solving for Ic (Figure 11 and Equation 3 on the next page) and plugging this into Equation 4 to solve for the field level in V/m. The length of the cable is L and the offending harmonic frequency is f. Use a test distance of either 3 or 10m to predict the outcome at those test distances.

Figure 6. *Use of simple H-field probes to locate emission sources.*

Figure 7. *Examples of DIY current probes. These photos were taken prior to installing the E-field shield by wrapping a layer of copper tape over the windings, leaving a small gap around the inside of the probe. 14 turns of Teflon-insulted wire wound around a Würth Electronik #74270097 ferrite core (4W620 material) was used, which is useful from 10 to 1000 MHz.*

Figure 8. *Examples of commercial current probes.*

---

[2] *I made my own broadband preamp using a MiniCircuits model ZX60-3018G-S, which covers 20 to 3000 MHz at 18-23 dB gain and 2.7 dB noise figure. It sells for USD 50.*

[3] *Commercial current probes are available from Fischer Custom Communications, Teseq or Solar Electronics, as well as many others.*

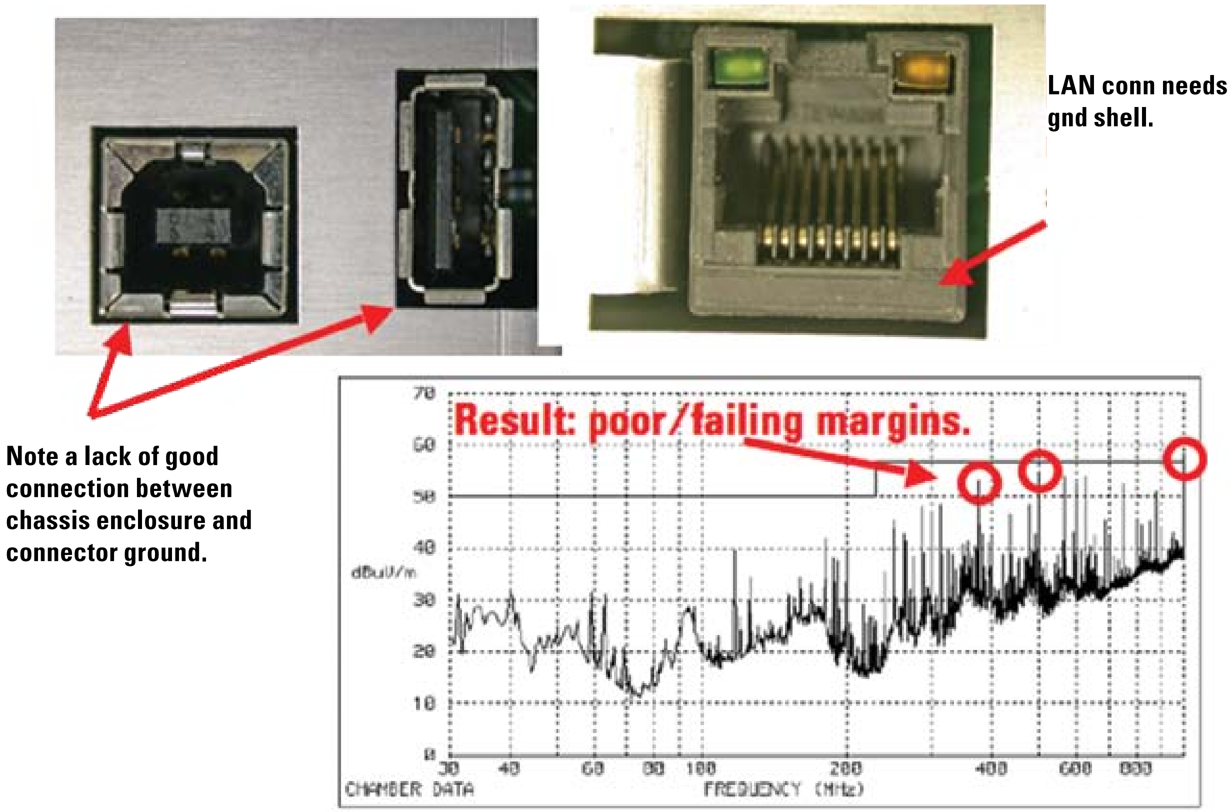

Figure 9. A lack of solid ground can allow CM currents generated inside the product to flow out the I/O cable and radiate – usually causing RE failures. The included graph shows poor margins to the CISPR 11 Class A 3m RE limit (for ISM products, in this case). ITE products, such as PCs and printers have a limit 10 dB lower.

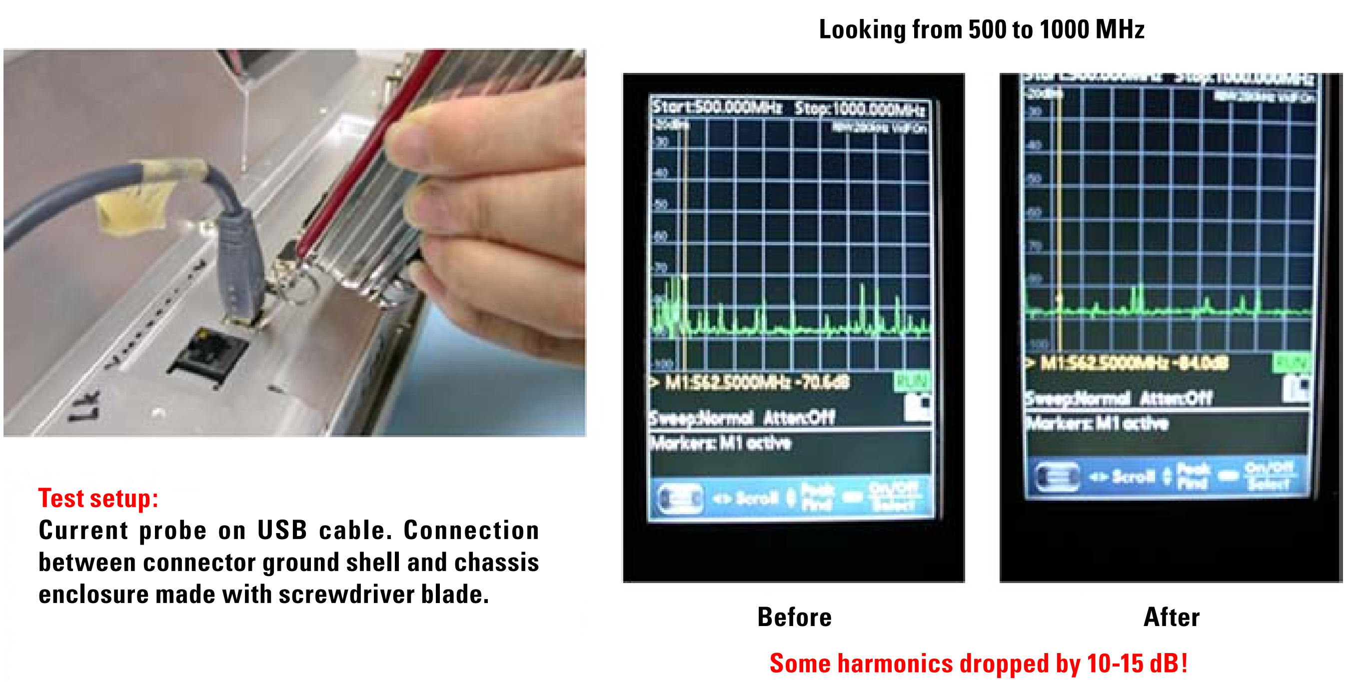

Figure 10. Cables should be tested individually. Here, I have a current probe clamped around the cable under test and am monitoring the harmonics with a simple hand-held spectrum analyzer.4 As I ground the connector shell to the chassis with the screwdriver blade, the harmonics are reduced 10 to 15 dB!

[4] *The handheld spectrum analyzer being used for the cable test is made by Thurlby Thander Instruments. It sells for approximately USD 1995 and covers 1 MHz to 2.7 GHz.*

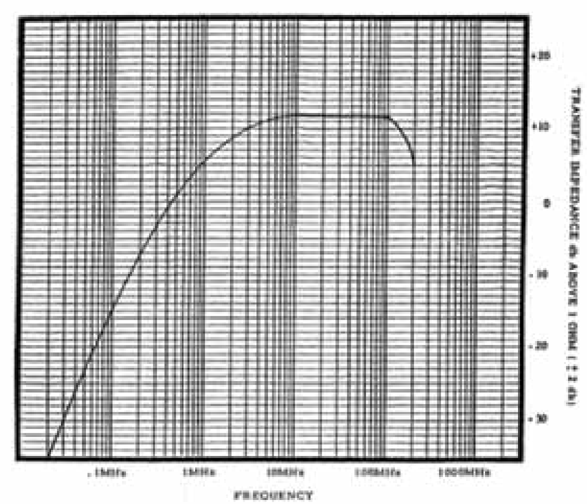

Figure 11. *Transfer impedance (Zt) graph of a typical current probe (courtesy of Fischer Custom Communications). The x-axis is frequency, while the y-axis is dB . Use this to calculate the value of Ic, given the measured voltage at the probe terminals V(dBuV) and Zt.*

$$\left|\hat{I}_C\right|_{dBuA} = \left|\hat{V}\right|_{dBuV} - \left|Z_T\right|_{dB\Omega}$$

Equation 3. *Calculation of Ic given the measured V and Zt (from Figure 11). Next, plug Ic into Equation 4 to calculate the predicted E-field emission level in V/m. Converting this to dBuV/m will indicate a pass or fail due to the cable being measured.*

The equation for calculating the emission level in volts/meter for a CM signal is shown below in Equation 4.

$$\left|\hat{E}_{C,max}\right| = 1.257\times10^{-6}\frac{\left|\hat{I}_C\right| fL}{d}$$

Equation 4. *Field level (V/m) due to CM current, where f = frequency (Hz), L = length of the wires (m) and d = the measurement distance (typically 3m or 10m).*

Slots & seams

Once the cables and associated I/O connectors are addressed, it's time to probe for radiation leakage through slots or seams in the chassis. Remember, that the length of the slot or seam is important. Any seam with leakage whose effective length is longer than 1/20th of a wavelength at the harmonic of concern has the potential to be an effective radiator. For example, a slot of 2.5 cm can just start radiating harmonics at 1000 MHz. I use a permanent marking pen to record the areas of leakage and frequencies of concern from every seam/slot on the enclosure.

Once these are marked, I'll carefully cover over all the openings with copper tape and re-measure the RE levels. Keeping an eye on the RE levels, I'll start removing the tape piece-by-piece to determine which slots or seams are actually causing problems. Often, just a few slots or seams will cause the most problems. Once the leakages are identified, you can determine the appropriate fixes with your mechanical engineer.

Troubleshooting kit

For speedy troubleshooting and analysis, I've assembled an EMC troubleshooting kit into a portable Pelican case, which can be wheeled right to an engineer's workbench. Major contents include a small spectrum analyzer (Thurlby Thander PSA2701T, available from Newark Electronics), a broadband preamplifier (Mini-Circuit Labs or Beehive Electronics), small DIY antennas, various probes and other accessories. Other useful items for your troubleshooting kit include ferrite chokes, aluminum foil, copper tape, power line filters, signal filters and various values of resistors and capacitors. Figure 12 shows an overall view of the contents.

Figure 12. *Contents of the special EMC troubleshooting kit I've assembled. I can probe for various RE problems, as well as test for ESD and radiated immunity. Performing these tests early in the design cycle, results in a greater chance of passing the required EMC product qualification tests.*

SUMMARY

In order to pass required EMC tests for radiated emissions, it is necessary to understand the basic concepts of current flow through loops, as well as differential- and common-mode currents and how they're generated. Troubleshooting an existing design is simply the process of identifying the likely sources, determining the coupling paths through probing, and applying temporary fixes. Once these fixes have been applied and the product passes, then the electronic and mechanical engineers may determine the most cost-effective solutions. Obviously, troubleshooting or characterizing products early in the design cycle are preferred in order to reduce overall implementation costs.

Kenneth Wyatt, Sr. *EMC Engineer, Wyatt Technical Services LLC, holds degrees in biology and electronic engineering and has worked as a senior EMC engineer for Hewlett-Packard and Agilent Technologies for 21 years. He also worked as a product development engineer for 10 years at various aerospace firms on projects ranging from DC-DC power converters to RF and microwave systems for shipboard and space systems. He can be contacted at ken@emc-seminars.com.* ■

Wireless Approvals for Japan: A Hiro's Tale

MIKE VIOLETTE
American Certification Body, Inc.
McLean, Virginia USA

Hiro dug into his soup.

"Did your dad fight in the war?"

Nodding, slurping up fat udon noodles, "Korea," pausing and picking up a napkin to dab his chin. "My father was an engineer, highways and bridges, mostly in the North." Hiro put down his napkin, laid his fast-food chopsticks across his bowl and picked up the chopstick wrapper. He meticulously folded the long paper in thirds and then lengthwise, making a little tent that he put on the table next to the tall can of Kirin beer we were sharing. "That was a long time ago." He moved his chopsticks onto the paper rest and lifted the bowl to his lips, the steamy broth fogging his glasses. "Why do you ask?"

"Just curious." It was a long time ago. So much has changed and the vast Pacific theatre of conflict in the mid-20th century is now crisscrossed by cargo ships and frequent-flyers. Japan, at the center of so much history in the region, figures prominently in technology trade, and recent regulatory changes have propped the door open—a little.

Figure 1. Zen garden.

Hiro put down his bowl. "And now, U.S. manufacturers can get radios certified in the U.S.—but it is necessary to understand the process." He took off his glasses and wiped them slowly with the dry end of the napkin.

"Can you tell me?"

Hiro put his glasses back on and pushed back from the table, gracefully straightening in his chair. "Hai."

We sat at one of the quickie eateries that are clustered around the departure gates in Terminal 1 at Narita Airport—an East-West melting pot of travelers and outpost of diversity on an island of monolithic ethnicity.

Narita, opened in 1978 after much local protest and the lobbing of Molotov cocktails (!), is now an international hub, knitting together destinations such as Taipei, Beijing, San Francisco and Seoul. In the 70s, though, the construction of the airport was not a universally popular notion; years of protest preceded its opening and lasted well into its operations. In sharp contrast to the notion that Japan is a society of conformists, considerable resistance was mounted to try to block the construction of the airport, including protests and riots and, in the manner of the 60s and 70s crowd control: water cannons and tear gas.

But by the 1990s Narita became a key Asian hub and started accruing an interesting legacy. In 2001, Kim Jong-Nam, eldest son of North Korea's King Jong-Il, was arrested at the airport with a fake passport. He apparently wanted to visit Disneyland Japan, but instead got a ride to China. His fake Dominican Republic passport failed to get him to "Space Mountain" and the jaunt allegedly cost him rule over his own "Magic Kingdom," the anointment ultimately passing to his younger brother Kim Jong-Un.

We were just passing through—heading home—and Hiro was keeping us company during our extended layover after the APEC (Asia-Pacific Economic Cooperation) Telecommunications meetings, a biannual event

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that links the 21 economies that form the trading group. Mutual Recognition Arrangements and Agreements (MRAs) are a hallmark of that work. Several such agreements, based on harmonized conformity assessment regimes, have facilitated much of the enormous trade between the U.S. and Asia. It is one of the reasons we're spending a few hours in the large international airport outside of Tokyo.

Some 10 years after the implementation of the APEC Mutual Recognition Arrangement (MRA), trade between the 21 economies is around $9.4T (that's Trillion with a capital "T"), according to the office of the U.S. Trade Representative, accounting for 44% of world trade. That is a lot of noodles.

The APEC Mutual Recognition Arrangement for conformity assessment of telecommunications equipment, the world's first multi-lateral MRA, celebrated its 10th anniversary in July 2009. Developed by the APEC Telecommunications and Information Working Group (APEC TEL), the MRA benefits manufacturers by reducing the cost of getting a product approved and by reducing the time to market.

The MRA, a voluntary agreement, has fostered the expansion of technology and the access to competitively priced products amongst partner countries by reducing barriers to trade. Just as APEC continues to pursue its goals of "stability, security and prosperity," the APEC TEL MRA Task Force continues to meet twice a year to discuss and develop additional arrangements, work out MRA issues and create bonds of friendship that reach across the oceans [1].

That beats fighting every time.

OPPORTUNITY FOR U.S. ORGANIZATIONS

The reality of U.S.-Japan trade in the past 40 years—since the mass proliferation of transistor-based devices—has been quite one-sided. One of the last access-issues to fall is the certification of wireless devices by U.S. Conformity Assessment Bodies (CABs). In contrast, CBs in the European Union have enjoyed this privilege since Valentine's day 2003. (Singapore, too, has had an operating MRA since the early 2000s.)

So, for roughly the past seven years, European CBs (and implicitly European manufacturers) have had a greater access to the Japanese radio market than U.S. organizations. Of course, there are other economic realities that skew this benefit, such as the desirability of U.S. products on the Japanese market and other flavors of the U.S.-Japan cultural and business inter-relationship.

But now, at least, the U.S. is catching up.

Within the context of the APEC TEL MRA, Japan and the U.S. have implemented the MRA for wireless devices. The initial agreement was signed Feb. 16, 2007. Another three years passed before the technical and administrative details and criteria were hammered out.

Forged after a series of correspondences, meetings, queries, clarifications, discussions, understanding (and misunderstandings) between the U.S. National Institute of Standards and Technology (NIST) and the Japanese Ministry of Internal Affairs and Communications (MIC), the U.S.-Japan MRA is now in full-force. Effective Nov. 1, 2010, NIST has been accepting applications from CABS that meet the specific criteria laid out under the agreement (for all of the bloody details, see [2]).

The agreement, like a difficult childbirth, was a bit painful and took some postpartum nursing, but it is finally standing and walking. In essence, the criteria require the CAB seeking approval to gain the necessary accreditation from a designated Accreditation Bodies, and ABs can now accept and process applications from Certification Bodies accredited to meet the international requirements in ISO Guide 65. The food chain is now established and looks a little like this:

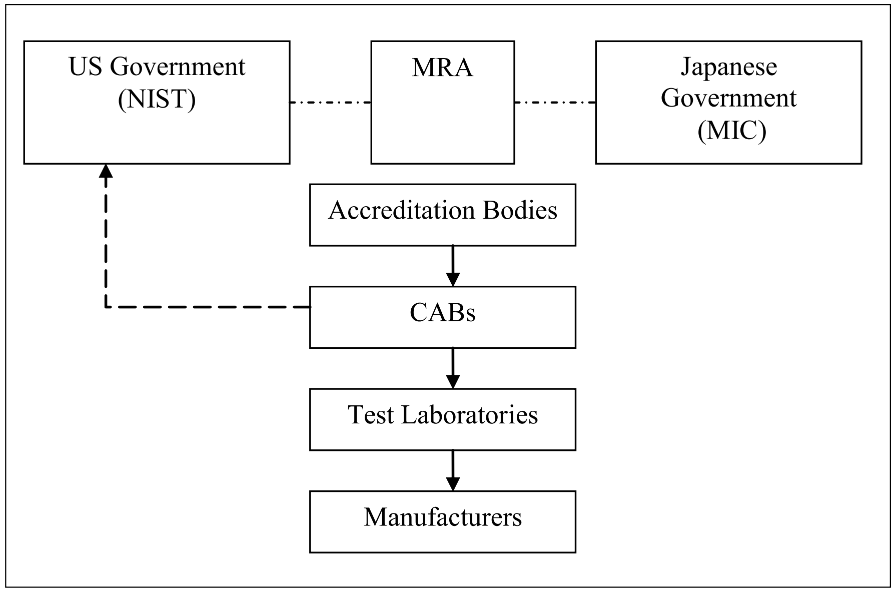

Figure 2. *Regulatory food chain.*

Under the MRA, once a candidate CAB passes muster with its domestic "Designating Authority" or DA (NIST in the U.S.), then the DA advances the proposed CAB to the DA of the other country. There is a period of review and comment and, if the CAB is accepted, then the authority to issue certifications is granted by the process of a Joint Committee, which is composed of one or more members of each DA.

To understand why the agreement and final implementation were so stretched out, it is necessary to understand a few fundamental differences between U.S. and Japan practices. Some of the more interesting bits include challenges relating to differences in:

1) **Laboratory/CAB Acceptance.** An informal "Accreditation system" in Japan is the most different aspect between the systems. In contrast to the U.S., which relies on established mix of private and public-sector independent accrediting bodies, the Japanese system of accepting lab results was more on a relationship basis—not surprisingly given the customary and traditional internally focused system of *kyoryoku* (meaning "collaboration" and obliquely referring to a system of preference that makes it difficult for outsiders to break into Japan's business circles.)
2) **Regulatory structure difficulties** in aligning methods and product certification schemes.
3) **Test methods.** Test procedures for measuring specific devices are difficult to identify and cross-reference.

Items 2) and 3) are essentially linked together. The method of organizing the regulations in the U.S. under the FCC system is essentially based on a Byzantine division of general device functionality and intended use mapped against frequency allocation; the requirements are, however, all covered under a single title (47) of the "Code of Federal Regulations", the how-to manual of the United States federal government. The method of organizing the regulations in Japan is, at first, a little inscrutable and buried under a half-dozen or so ordnances and radio laws, with the technical requirements based on specific device type rather than general usage. This makes the mapping of well-understood methods of device assessment here (FCC) against there (MIC) quite, er, challenging.

A private sector organization and CB in Japan (DSP Research: http://www.dspr.co.jp/) has developed an English-language database that eases this issue. Still, it would be useful to understand a bit of kanji.

Note that there are similarities under both regimens for how non-licensed and licensed devices are handled. Non-licensed equipment (such as low power devices, cordless phones and the like) can be placed on the market without secondary licensing. Cellular phones, on the other hand, must have a "blanket license" that applies to the system operator; this is not unlike the U.S., where cell phones are licensed to the operator and the process is transparent to the end-user.

One of the requirements of the MRA is to demonstrate that a Conformity Assessment Body is approved to a scope that is equal to or greater than the requirements outlined in the MIC regulations. This bit of cross-referencing requires a deep dive into the methods for the devices, sorting through the technical requirements and demonstrating "competency by association."

I WANT MY RADIO CERTIFIED. WHERE TO BEGIN?

For any type of produce certification, one asks the same questions: What Provisions? What Requirements? What Limits?

Any roadmap to certify a radio to Japanese law includes three main documents, starting with the Radio Law (Law No. 131 of May 2, 1950, as amended) which says that radios of a certain type (Specified Radio Equipment) must be certified. The Radio Law covers the usual administration and authority requirements, as well as spelling out a path for certifying equipment and operators. Other various topics include operation of coast guard stations and aeronautical stations and there are chapters on lawsuits and penal provisions. (Note that Terminal Equipment is covered by the Telecommunications Business Law—Law No. 86 Dec. 25, 1984, as amended. In short, the approval process is similar for wireless and wireless telephony.)

Article 38-2 of the Radio Law covers the requirements for Certification Bodies, to wit "…a person who wishes to conduct the business of certifying such radio equipment's conformity with the technical regulations specified in the preceding Chapter may obtain registration from the Minister…[The Radio Law includes, by the way, requirements for maintaining decency and decorum on the air. George Carlin would certainly balk:

"Article 108: Any person who transmits a message with indecent contents by means of radio equipment or communications equipment under Article 100 paragraph (1) item (i) shall be guilty of an offense and liable to imprisonment with work for a period not exceeding two years or to a fine not exceeding one million yen."

Note that this is not your ordinary imprisonment, it is imprisonment with work—breaking rocks. This is where they get all the nice stone for their Zen gardens.]

Chapter 3 of the Radio Law is specific to radio equipment and this is where we dig into the details and how, ultimately, the MRA provides the bridge between the U.S. certification bodies (more properly: Conformity Assessment Bodies) and wireless certifications for Japan. NIST is now actively in the process of approving CABs for this process. As stated before, the private sector has existing capacity (under the APEC Tel MRA and the Japan-EU MRA).

To get an approval, one must generate a report and demonstrate conformance (and submit to a Certification Body). To determine what data must be collected, it is necessary to refer to the ordnances that cover the specified equipment, notably the "Ordinance concerning Technical Regulations Conformity Certification of Specified Radio Equipment (aka Ordinance of the Ministry of Posts and Telecommunications No. 37, 1981)." This document lays out the various types of equipment and what data are to be collected and what instrument is used to collect the data.

Table No. 1 (which covers eight pages) breaks down the action in a paragraph-by-paragraph cross-reference dependent on device function, providing the general quantity to be measured—"Frequency" and "Occupied Frequency Bandwidth"—and the type of instrumentation necessary. A fragment is shown in Figure 3 for illustrative purposes.

By way of example, Article 2 (Specific Radio Equipment, etc.) calls out the frequency allocation and power limits for marine mobile equipment as follows:

1 Device	2 Test Item	3 Measuring Instruments etc.	4 Classification											
			Radio equipment specified in Item (41) of Article 2 Paragraph 1	Radio equipment specified in Item (42) of Article 2 Paragraph 1	Radio equipment specified in Item (43) of Article 2 Paragraph 1	Radio equipment specified in Item (44) of Article 2 Paragraph 1	Radio equipment specified in Item (45) of Article 2 Paragraph 1	Radio equipment specified in Item (46) of Article 2 Paragraph 1	Radio equipment specified in Item (47) of Article 2, Paragraph 1	Radio equipment specified in Item (48) of Article 2, Paragraph 1	Radio equipment specified in Item (49) of Article 2, Paragraph 1	Radio equipment specified in Item (50) of Article 2, Paragraph 1	Radio equipment specified in Item (51) of Article 2, Paragraph 1	Radio equipment specified in Item (52) of Article 2, Paragraph 1
	Frequency	Frequency counter or spectrum analyzer	•	•	•	•	•	•	•	•	•	•	•	•
	Occupied frequency bandwidth	False voice generator or false signal generator, band meter or spectrum analyzer	•	•	•	•	•	•	•	•	•	•	•	•
	Spurious emission or unwanted emission intensity	Low frequency oscillator, spurious wattmeter or spectrum analyzer	•	•	•	•	•	•	•	•	•	•	•	•

Figure 3. *A fragment of Table No. 1 from the Radio Law.*

"(1)-13 The radio equipment with an antenna power of 50 W or less which is used at a radio station for maritime mobile service using class A3E emissions of a frequency in a range of higher than 26.1 MHz to 28 MHz, higher than 29.7 MHz to 41 MHz, or higher than 146 MHz to 162.0375 MHz."

For this specific equipment, referring to Table No. 1, the following data need to be collected:

Frequency, Occupied Bandwidth, Spurs, Deviation, Power, Overall Frequency Characteristics, Distortion... etc. Requirements also exist for the receiver: Spurious radiated emissions, Sensitivity, Passing bandwidth, Attenuation and Spurious response, Fluctuation of LO and overall distortion and noise.

Now that we know what data must be collected, the question becomes: what are the limits? The answer is to be found, in part, in the Radio Regulatory Commission Regulations No. 18, 1950. The 293-page document has the technical details, limits on power, use, and construction, viz "The high-frequency section and modulation section (except for the antenna system) shall not be capable of being opened easily."

To figure out where the requirements are in this document, one starts at the table of contents and reads through the description in the "Conditions for Radio Equipment Classified by Service or Emission Class and Frequency Band." This index is invaluable.

For example, Article 49.20 of No. 18 covers the requirements for low power spread spectrum devices operating in the ISM 2.4 GHz band, a pretty popular spot for WiFi, Bluetooth, etc.

These three critical documents can be found online: http://www.soumu.go.jp/main_sosiki/joho_tsusin/eng/laws_dt02.html

If you're adept at reading Japanese, you can always download the original versions; it is a little tricky because the documents don't have traditional title pages, at least in the English form.

To summarize,

The Radio Law (Law No. 131 of May 2, 1950) has the general requirements (akin to Part 2 of CFR47). Ordinance of the Ministry of Posts and Telecommunications No. 37, 1981 contains the parameters to measure, and Radio Regulatory Commission Regulations No. 18, 1950 has the limits.

"So, Hiro, it's really necessary to understand ordnances 37 and 18, right?"

He nodded, smiled and said, "And, maybe get a little help from your friends."

United Flight 890 to Los Angeles now boarding Gate 8.

My friend polished off the last drops of soup and sat back, smiling.

"Ready to go?"

"Always. Arigato!"

REFERENCES

- [1]" Fostering International Trade: Ten Years of MRA Success," APEC, Sep. 2010, <http://www.apec.org/en/Press/Features/201%906_Fostering_International_Trade_Ten_Years_of_MRA_Success.aspx>.
- [2] "Criteria for Designation of U.S. Conformity Assessment Bodies under the US-Japan Mutual Recognition Agreement," NIST, Oct. 2010, <http://gsi.nist.gov/global/docs/mra/2010_10_01_Final_Criteria_for_CAB_Designation_to_Japan_V1_0.pdf>.

MIKE VIOLETTE is founder and director of American Certification Body and president of Washington Laboratories. Violette oversees operations of ACB's activities in the U.S., Asia and the EU and knows where to find decent sushi at Narita. He can be reached at mikev@acbcert.com.

Measurement Uncertainty for Conducted and Radiated Emissions

DANIEL HOOLIHAN
Hoolihan EMC Consulting
Lindstrom, Minnesota USA

One of the key elements to making scientific measurements in an EMC lab in today's modern world is having the engineers understand and control the Measurement Uncertainty (MU) of the instrumentation used for making conducted and radiated emission measurements. The emission levels measured by an accredited lab must have measurement uncertainties below certain levels to be acceptable to its accreditation body. Also, some international standards have begun to quote levels of acceptable measurement uncertainties for electromagnetic emissions. This article outlines a brief history of MU, reviews the MU for equipment used for typical conducted and radiated emission measurements, and give some hints on how a lab can reduce its Measurement Uncertainty for instrumentation used for emission measurements.

GENERAL

In this article, Measurement Uncertainty will refer to the Instrumentation's Measurement Uncertainty. At first glance, MU is a complex subject, however, with a little study it becomes more understandable and more easily understood. Most practicing engineers are familiar with tolerances and error and similar terms. In general, the concept of MU is not as well known. One of the reasons for this is that the theory and practice of measurement uncertainty has only been around about 20 years.

BRIEF HISTORY OF MEASUREMENT UNCERTAINTY

The ISO/IEC Guide 98-3 is the "father" of all Measurement Uncertainty documents. It is commonly just called the "GUM." It was first released in 1993 and, then, corrected and reprinted in 1995. It changed the world of measurements and the associated errors of measurement instrumentation.

The world's highest authority in metrology, CIPM (Comite International des Poids et Mesures) realized that there was a need to convene the world's experts on Measurement Uncertainty in order to arrive at a consensus position on the subject. In 1977, the CIPM requested the BIPM (Bureau International des Poids et Mesures) to communicate with the national metrology laboratories around the world and assess the situation.

By early 1979, responses had been received from 21 laboratories and the great majority of the labs thought that something needed to be done. Specifically, the labs thought that "it was important to arrive at an internationally accepted procedure for expressing measurement uncertainty and for combining individual uncertainty components into a single total uncertainty."

A working group was formed, developed a process, and released Recommendation INC-1 on Expression of Experimental Uncertainties in 1980. This Recommendation was approved by the CIPM in 1981 and reaffirmed by the same body in 1986.

The ISO (International Organization for Standardization) was given the responsibility of developing a detailed Guide based

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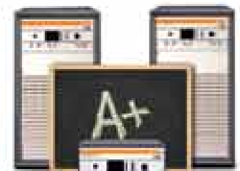

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In Europe, call ar United Kingdom 441-908-282766 • ar France 33-1-47-91-75-30 • emv GmbH 89-614-1710 • ar Benelux 31-172-423-000 on the 1980 Recommendation. The responsibility was assigned to ISO Technical Advisory Group on Metrology (TAG 4) which promptly established Working Group 3 comprised of experts nominated by BIPM, IEC (International Electrotechnical Commission), ISO, and OIML (International Organization of Metrology). This TAG labored throughout the 1980s and into the early 1990s to produce the "Guide to the Expression of Uncertainty in Measurement" in 1993. This guide was corrected and reprinted in 1995 and then eventually published as ISO/IEC Guide 98-3 in 2008.

Because of its historical significance, Recommendation INC-1 (1980) is reproduced below for your convenience.

Recommendation INC-1 (1980) - Expression of Experimental Uncertainties

1. The uncertainty in the result of a measurement generally consists of several components which may be grouped into two categories according to the way in which their numerical value is estimated:

A. those which are evaluated by statistical methods

B. those which are evaluated by other means

There is not always a simple correspondence between the classification into categories A or B and the previously used classification into "random" and "systematic" uncertainties. The term "systematic uncertainty" can be misleading and should be avoided.

Any detailed report of the uncertainty should consist of a complete list of the components, specifying for each the method used to obtain its numerical value.

2. The components in category A are characterized by the estimated variances s2i (or the estimated "standard deviations" si) and the number of degrees of freedom vi. Where appropriate, the covariances should be given.

3. The components in category B should be characterized by quantities u2j, which may be considered as approximations to the corresponding variances, the existence of which is assumed. The quantities u2j may be treated like variances and the quantities uj like standard deviations. Where appropriate, the covariances should be treated in a similar way.

4. The combined uncertainty should be characterized by the numerical value obtained by applying the usual method for the combination of variances. The combined uncertainty and its components should be expressed in the form of "standard deviations."

5. If, for particular applications, it is necessary to multiply the combined uncertainty by a factor to obtain an overall uncertainty, the multiplying factor used must always be stated.

REFERENCES FOR MEASUREMENT UNCERTAINTY

ISO/IEC Guide 98-3 - Uncertainty of Measurement - Part 3: Guide to the Expression of Uncertainty in Measurement (GUM: 1995).

IEC CISPR 16-4-2: Specification for Radio Disturbance and Immunity Measuring Apparatus and Methods - Part 4-2: Uncertainties, Statistics and Limit Modeling - Uncertainty in EMC Measurements -First Edition - 2003-11.

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

Table 1. *150 kHz to 30 MHz with a 50 ohm/50 microhenry Line Impedance Stabilization Network (LISN).*

United Kingdom Accreditation Service - LAB34 - The Expression of Uncertainty in EMC Testing - Edition 1 - August 2002.

Two Examples of Measurement Uncertainty – Conducted Emissions and Radiated Emissions

The following paragraphs go into detail on the MU for instrumentation for conducted and radiated emissions. The presentation of the table is different from what is seen in the usual MU references; namely CISPR 16-4-2 and LAB34.

First of all, we have listed our Sources of Uncertainty in the two accompanying tables in order of the largest contributor to the smallest contributor. This allows us to see which Source is contributing the most to the Measurement Uncertainty.

Secondly, we are going to assume the sensitivity coefficient is one for all our contributing factors thus eliminating one column in our table of standard uncertainties (the sensitivity coefficient is effectively a conversion factor from one unit to another). This is logical in the EMC Engineering world since almost every contributing factor is quoted in "dBs."

Our table then becomes easier to understand with the Value of the Sources of Uncertainty (second column) being divided by its accompanying Probability Distribution Function Divisor (fourth column) to arrive at the standard uncertainty for that uncertainty component [U(y)] in the fifth column. The sixth column is arrived at by simply squaring the "result in the fifth column." Summing all the factors in the sixth column and taking the square root of the total, we arrive at the Combined Standard Uncertainty. The Expanded Uncertainty is achieved by multiplying the Combined Standard Uncertainty by two for a coverage of 95%. The Expanded Uncertainty is the engineer's "padding factor" to make sure he has the answer covered in the range of values quoted.

By using the Expanded Uncertainty, we arrive at a 95% probability that the true answer lies within a band of values bracketed by the measured value plus or minus the Expanded Uncertainty.

CONDUCTED EMISSIONS

The above table assumes typical values from LAB34 and CISPR 16-4-2 and is ordered from the largest contributor to the smallest contributor. In order to reduce the Combined Standard Uncertainty, the lab should start with the largest contributors and try to reduce their values.

In the case of the conducted emissions, the largest contributor is the LISN Impedance.

A check of the calibration certificate of one of the well-known calibration labs in the country indicates a maximum measurement uncertainty of plus or minus 1.2 ohms for a LISN Calibration. This maximum uncertainty was arrived at by the calibration lab by a Type A evaluation using at least 10 data sets. The 1.2 ohms translates into a value in dBs equivalent to +/- 1.6 dB. If we substitute this 1.6 dB value into the table for the present 2.7 dB, we lower our combined standard uncertainty to 1.71 dB which lowers our Expanded Uncertainty to 3.42 dB or a reduction of 0.32 dB. One of the reasons that the LISN factor reduction does not make a big difference is that it is divided by the square root of 6 (2.449) for a triangular distribution.

We would next have to look at the biggest contributors to the Measurement Uncertainty after the LISN Impedance. They would be the Receiver Pulse Amplitude and the Receiver Pulse Repetition. One way to reduce these two contributions from the Re-

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

***Table 2.** 30 MHz to 300 MHz with a biconical antenna in the vertical polarization – 3 & 10 meters.*

ceiver is to have it calibrated a number of times (it could be over a period of years). Then, you can divide the "mean value of n measurements" by the square root of "n" to arrive at the standard deviation of the mean. If we could lower the two receiver 1.5 dB values to 1.0 dB,(in tandem with lowering the LISN contribution), we would arrive at a combined standard uncertainty of 1.45 dB or an Expanded Uncertainty of 2.90 dB.

All the other sources of uncertainty in the conducted emission table are 1.0 dB or less, and, it will be difficult to lower those to make a significant change in the total MU for conducted emissions.

So, we can conclude that it would be very difficult to get the Expanded Uncertainty of conducted emissions below 3 dB.

RADIATED EMISSIONS

30 MHz to 300 MHz with a biconical antenna in the vertical polarization – 3 & 10 meters

Again, the above table assumes typical values from LAB34 and CISPR 16-4-2 and is ordered from the largest contributor to the smallest contributor. In order to reduce the measurement uncertainty for radiated emissions, an EMC lab should start with the largest contributors and try to reduce their values.

The table also assumes a horizontally-polarized biconical antenna having a uniform pattern in the vertical plane so that the antenna factor height deviation and the antenna factor directivity difference contributions are zero. (Note - a Complex antenna would have non-zero components for both of those factors).

The Site Imperfections is the largest contributor to the Radiated Emission Measurement Uncertainty. In order to reduce that, labs can use antennas with smaller antenna factors, receivers with smaller measurement uncertainties, and semi-anechoic chambers with improved anechoic material. It would then be reasonable for the lab to lower that contribution to plus or minus 3 dB. Substituting that value into the equation, gives us a Combined Standard Uncertainty of 2.26 dB and an Expanded Uncertainty of 4.52 dB or a reduction of 0.48 dB from the original 5.00 dB. Again, one of the reasons for the relatively small reduction in the expanded uncertainty is the large divisor value for site uncertainty, that is, the square root of 6 (2.449) for a triangular probability distribution.

The Mismatch factor can be reduced by increasing the attenuation of the well-matched two port network preceding the receiver, however, the penalty of that maneuver is a reduction in measurement sensitivity. Let's assume we can add some attenuation to the front-end of the receiver and lower the Mismatch contribution to -0.65. Substituting this value in combination with the Site Imperfection reduction, allows us to lower the Expanded Uncertainty to 4.3 dB or a total reduction from the original 5.00 dB of 0.7 dB.

If we then look at the next two biggest contributions, we have, again, the Receiver Pulse Amplitude and the Receiver Pulse Repetition. If we again, using the same technique as for conducted emissions, lower the two receiver 1.5 dB values to 1.0 dB,(in tandem with lowering the Site Imperfections and the Mismatch contributions), we would arrive at a combined standard uncertainty of 1.83 dB or an Expanded Uncertainty of 3.66 dB. This would be a reduction of 1.34 dB from the original value.

The Remaining Factors are all 1.0 dB or less and they would be difficult to lower in sufficient amplitude to make a significant difference to the Expanded Measurement Uncertainty for radiated emissions.

Thus, we conclude that the minimum value for Expanded Uncertainty for radiated emissions, with present-day equipment, is around 3.5 dB.

SUMMARY

Measurement Uncertainty of the instrumentation used for emission testing in an EMC Lab is an important part of the lab's overall technical capability. We know that Measurement Uncertainty is a relatively new concept and has only been around the EMC Labs of the world for about 20 years.

We see from the above two specific examples that it is difficult to lower the Expanded Uncertainty values of a typical EMC Lab for both conducted emissions and radiated emissions.

We saw that reducing the two largest values in the table of standard uncertainties for conducted emissions only lowered the Expanded Uncertainty by about 0.74 dB so that the Expanded Uncertainty for conducted emissions was approximately 3.0 dB.

We also observed that lowering the top four contributors to the Combined Standard Uncertainty value for radiated emissions, only lowered the Expanded Uncertainty value from 5 dB to around 3.5 dB.

We concluded that even when a lab is logically concentrating on lowering its Equipment Measurement Uncertainty by reducing the largest contributors to the Combined Standard Uncertainty for emission testing, it is difficult to significantly lower the overall Expanded Uncertainty of the instrumentation of the EMC lab for conducted and radiated emissions.

Daniel Hoolihan is a past president of the IEEE EMC Society. He has been a member of the Board of Directors since 1987 and has held numerous leadership positions in the society. Hoolihan is also active on the ANSI Accredited Standards Committee on EMC, C63 as Vice Chairman. He was co-founder of Amador Corporation (1984-1995). He can be reached at DanHoolihanEMC@aol.com.

On the Radiation Patterns of Common EMC Antennas

VICENTE RODRIGUEZ
ETS-Lindgren L.P.
Cedar Park, Texas USA

Antennas have been used in EMC measurements since the early days. Knowledge of the antenna pattern was not a requirement of the standards. While MIL STD 461 and some SAE standards called for information on the half power beamwidth, most standards did not require any knowledge of the antenna radiation characteristics. With the evolution of standards to cover frequencies above 1 GHz knowledge of the pattern has become more important. Since above 1 GHz most antennas are very directive and very un-dipole-like, information on the pattern has become very important, especially when it comes to understanding how much area the main beam is covering. The present paper starts by giving the reader a refresher on antenna pattern parameters and then shows typical patterns for the most common antennas used in EMC. The antennas covered are biconicals, log periodic dipole arrays, hybrid antennas and dual ridge horns. Measured data is presented except for patterns above 18 GHz.

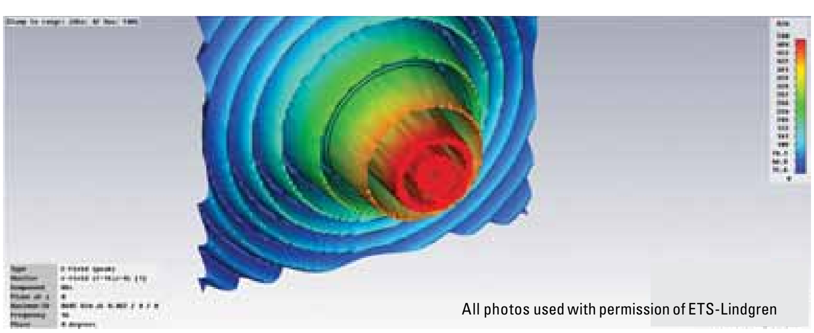

Figure 1. *A modified shaped dipole (biconical) radiating; example of a resonant antenna.*

INTRODUCTION

An antenna is a device that radiates and receives radio waves. There are different methods or mechanisms by which antennas radiate. We all are familiar with resonator antennas. Dipoles are a clear example of this type on antennas. In resonant antennas there is a movement of charges as the energy changes between the electric field and the magnetic field. This movement of the charges on the antenna causes the field lines to vibrate, generating waves that propagate in free space away from the resonant antenna. Figure 1 shows this type of behavior. Another mechanism by which antennas radiate is by having an impedance transition that causes the energy being propagated in a transmission line to be launched into free space. Horn antennas are an example of a travelling wave antenna. Their method for radiation is based on a wave impedance transition from the transmission waveguide or line to the impedance of free space. Figure 2 shows this mechanism of radiation on a horn antenna.

RADIATION PATTERNS

An antenna radiation pattern or antenna pattern is a mathematical function or a graphical representation of the radiation properties of the antenna as a function of space coordinates [1]. That is, as we rotate the antenna around on two orthogonal axes we measure the intensity of the radiated field. Figure 3 shows one of these plots of magnitude of radiation versus direction.

E and H plane

While today it is really easy to create pat-

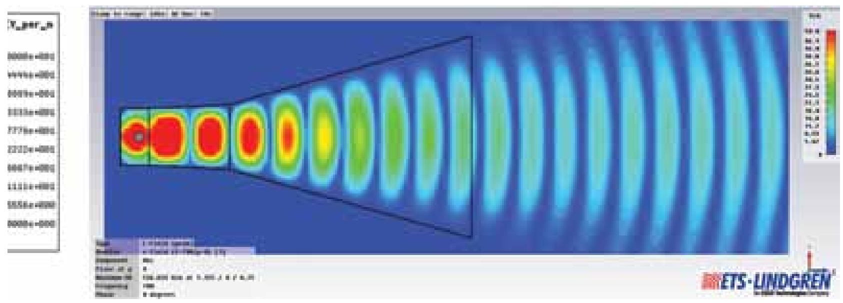

Figure 2. *A pyramidal horn radiating; a sample of an impedance transition between the transmission line and free space.*

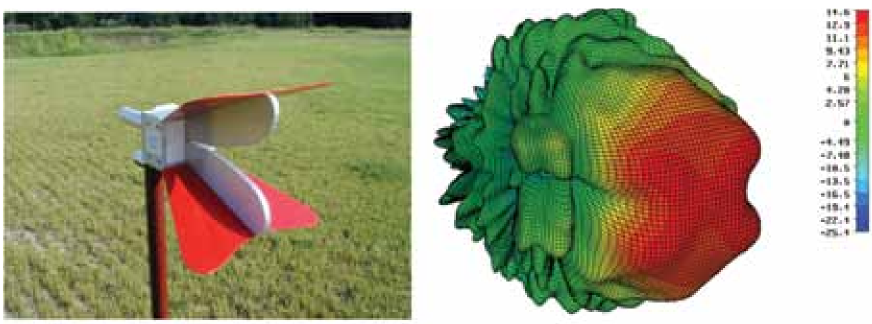

Figure 3. *A horn antenna and its radiation pattern at a given frequency.*

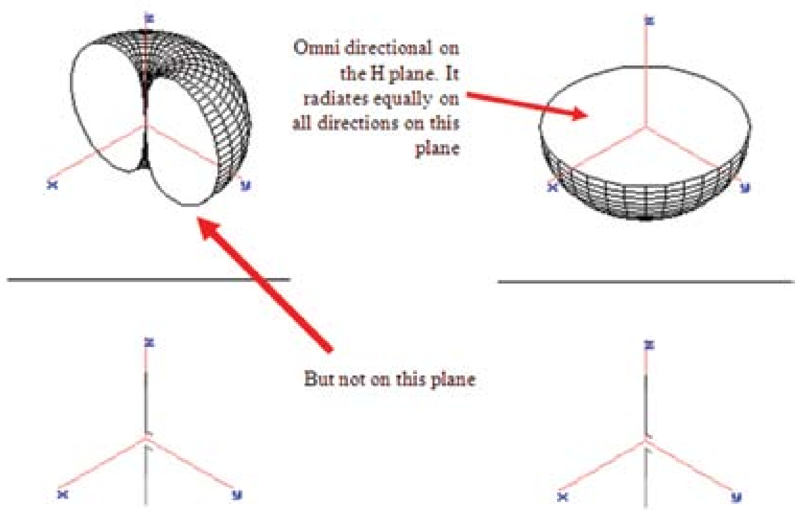

Figure 4. *Omnidirectional antenna.*

terns such as the one in Figure 3 and to manipulate them on the computer, this was not the case in the earlier days of antenna engineering. Hence, to facilitate the graphical representation of radiation patterns, engineers usually plotted two single orthogonal planes of the pattern. Rather than arbitrarily plot a plane for a given angle of the spherical coordinate system (for example $\phi=90^{o}$), engineers chose the plane on which the Electric field was oscillating. This plane was called the E plane. The orthogonal plane to this one was named the H-plane. Even today patterns are commonly shown in E and H planes in the literature.

Omnidirectional and Directional

Like many other things in nature, the human brain likes to classify things to make it easier to study them. Radiation patterns are no different. One of the first divisions that we can do is to break patterns into two principal groups: Directional and Omnidirectional patterns. Omnidirectional comes from the Latin word omni meaning "every" or "all" and "direction". These, it appears, are patterns that radiate in all directions. That is not exactly it. Omnidirectional antennas, which radiate omnidirectional patterns, radiate in all directions on a given principal plane (the E or the H plane. Figure 4 shows the most simple of all omnidirectional antennas, the dipole. The dipole radiates in all directions on the H plane, but it has two nulls (areas of little or no radiation) on the E plane.

Omnidirectional should not be confused with isotropic. Isotropic (from the Greek, isos meaning "the same" or "equal" and tropos meaning "direction") implies that the radiator puts exactly the same radiation in all directions around it. There is no such thing as an isotropic antenna. A combination of three dipole-like antennas may have certain isotropicity, but it will never be a perfect isotropic source. Isotropic sources are a mathematical tool that is used in describing the gain of antennas. Directional antennas are clearly antennas where the radiation is mainly on one direction as we rotate around the antenna.

Main lobe, side lobes, back lobe

We now continue our human approach to classify things to make them easier to study. If we look at a radiation pattern we observe a series of features. There is going to be an area of the pattern where most of the radiation is directed. That is the main lobe. To the sides of the main lobe we may find areas where the radiation is higher than the adjacent areas. These are side lobes. The side lobes are usually separated by areas of little radiation called nulls. There is usually a side lobe in the direction opposite the main lobe. This special side lobe is known as the back lobe. Figure 5 shows a pattern and the features described above.

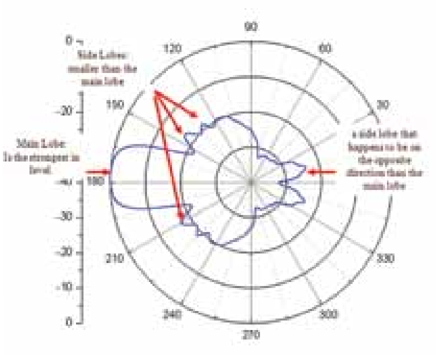

Figure 5. A pattern showing typical features.

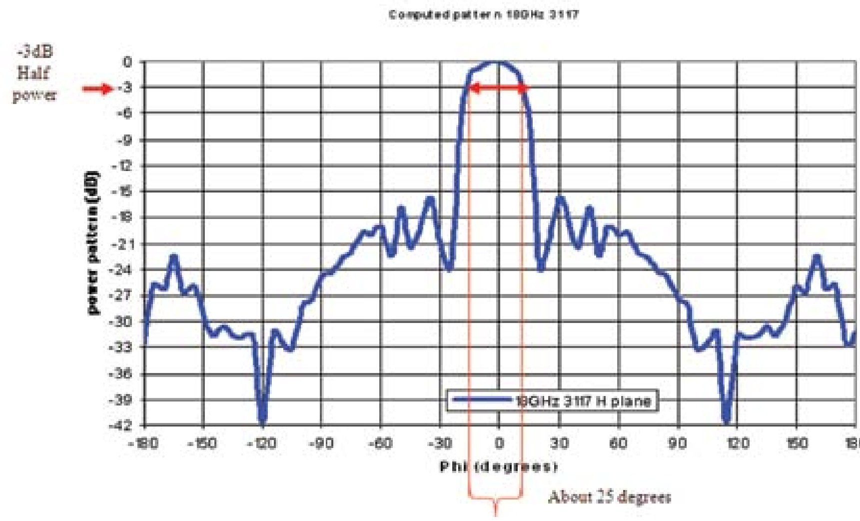

Figure 6. HPBW identified in red for a given pattern.

Half power beam width

It should be clear that the most important lobe is the main lobe. After all, the main lobe contains most of the radiated energy. This does not mean that the other lobes are irrelevant. The back lobe should be small. We do not want to send too much radiation towards the back. This is especially important during immunity at frequencies above 1 GHz, when usually the amplifiers are placed inside the chamber close to the antenna to reduce cable losses. Side lobes are also important; high side lobes illuminating the sides of a chamber will affect the field uniformity if the absorber treatment is not adequate. Outside of EMC these parameters of the patterns are even more important.

But clearly, as mentioned above, the main lobe is the most important as it is the one that should encompass the EUT. The parameter that describes the main lobe size is the half power beamwidth. Since ½ is 0.5 and $10Log_{10}(0.5) \approx -3dB$, the half power beamwidth

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SCCX500	.01-220	500	57
M404	.01-220	500	57
M406	.01-220	1000	60
TCCX2000	.01-220	2000	63
TCCX2200	.01-220	2200	63
TCCX2500	.01-220	2500	64
CMX/SMX Series • *.01-1000 MHz*			
SMX301	.01-1000	300/100	55/50
SMX302	.01-1000	300/200	55/53
SMX303	.01-1000	300/300	55/55
SMX501	.01-1000	500/100	57/50
SMX502	.01-1000	500/200	57/53
SMX503	.01-1000	500/300	57/55
CMX10001	.01-1000	1000/100	60/50
CMX100010	.01-1000	1000/1000	60/60

Microwave Solid State and TWT Amplifiers

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T-200 Series • *200-300 Watts CW 1-21.5 GHz*			
T251-250	1-2.5	250	54
T82-250	2-8	250	54
T188-250	7.5-18	250	54
T2118-250	18.0-21.7	250	54
T-500 Series • *500 Watts CW 1-18 GHz*			
T251-500	1-2.5	500	57
T7525-500	2.5-7.5	500	57
T188-500	7.5-18	500	57
MMT Series • *5-150 Watts, 18-40 GHz*			
T2618-40	18-26.5	40	46
T4026-40	26.5-40	40	46
S/T-50 Series • *40-60 Watts CW 1-18 GHz*			
S21-50	1-2	50	47
T82-50	2-8	50	47
T188-50	8-18	50	47

Solid State Amplifiers

Model Number	Freq Range (MHz)	Min Pwr Out (Watts)	Min Sat Gain (dB)
SMCC Series • *200-1000 MHz*			
SMCC350	200-1000	350	55
SMCC600	200-1000	600	58
SMCC1000	200-1000	1000	60
SMCC2000	200-1000	2000	63
SMC Series • *80-1000 MHz*			
SMC250	80-1000	250	54
SMC500	80-1000	500	57
SMC1000	80-1000	1000	60
SMX-CMX Series • *.01-1000 MHz*			
SMX100	.01-1000	100	50
SMX200	.01-1000	200	53
SMX500	.01-1000	500	57
SVC-SMV Series • 100-1000 *MHz*			
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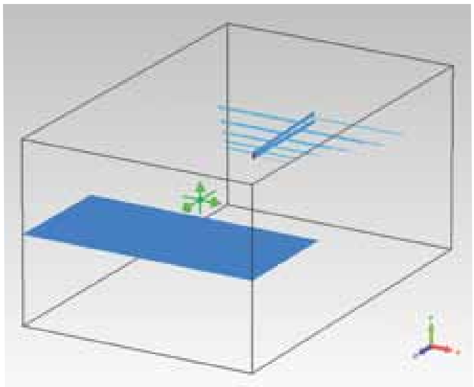

Figure 7. *Model of a log periodic in front of a metal top bench (the ground is metallic).*

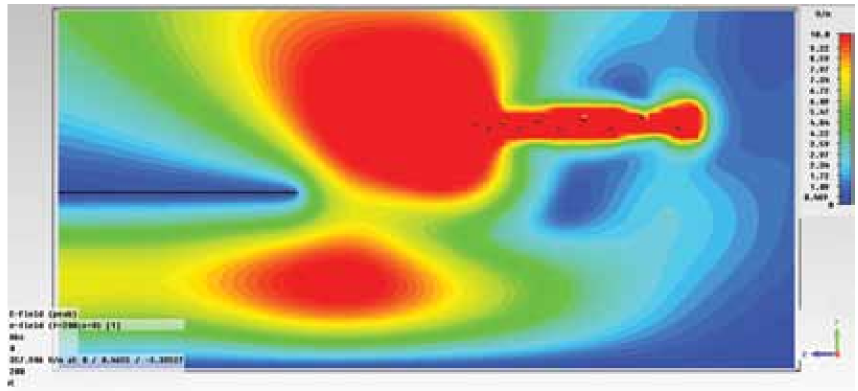

Figure 8. *Results for the model in Figure 7. Notice that the radiation is deflected by the presence of the metallic top bench.*

(HPBW) is also known as the 3dB beam width. The HPBW is given in degrees and it describes the arc of the angle between the two points to the side of the point of highest radiation that are 3dB lower in radiated power. Figure 6 shows the half power beamwidth for the pattern shown in Figure 5. For clarity, the pattern is represented in Cartesian coordinates rather than polar coordinates. It is important to note that the HPBW is from -3dB point to -3dB point not from -3dB point to peak.

Manufacturers should supply the HPBW information to users of their antennas. The HPBW will be given for the E and H plane. For a linearly polarized antenna, the E plane will be vertical when the antenna is on vertical polarization. When the antenna is rotated to horizontal polarization, the E plane will be horizontal. Similarly the H plane will be horizontal when the antenna is set for vertical polarization and the H plane will be vertical when the antenna is on horizontal polarization.

Another important issue is that the HPBW, like any other pattern parameter, is a free space, far field parameters. The beamwidth will give you an idea of the area covered, but in some cases structures in the test area such as grounded benches and ground planes will affect the radiation pattern and the beamwidth. Figures 7 and 8 show a log periodic antenna placed on horizontal polarization radiation 1 meter away from a bench. This is a common set up in CISPR 25 and other standards [2-4].

So the user must be careful when using the HPBW extracted from the pattern to estimate the area of coverage of the main beam. In some cases, such as the new set up from above 1GHz testing [5], it will provide a good estimate. In other cases, such as in the presence of benches and other features, it will be better to use field probes to estimate the coverage of the main beam.

PATTERN MEASUREMENTS

As mentioned above, in most cases the measured pattern and HPBW is good enough to give the user of the antenna an idea of the coverage. Since the HPBW gives you an arc or coverage given the test distance and some trigonometry it is possible to estimate an area of coverage for a given antenna. In the next sections we show typical patterns for the most common antennas used in EMC. Rectangular Anechoic chamber and Tapered Anechoic chambers were used to measure the radiation pattern of typical EMC antennas from 400 MHz to 18 GHz.

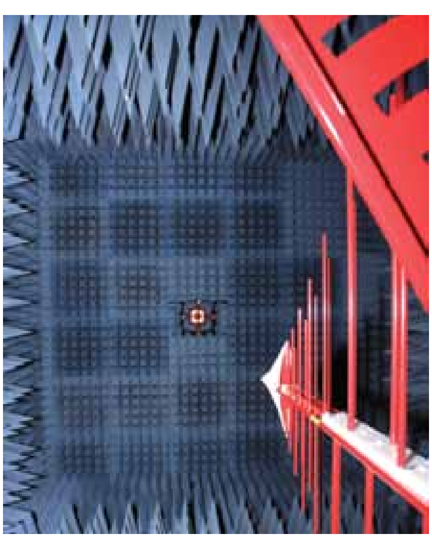

Figure 9. *The test set up in the rectangular anechoic chamber.*

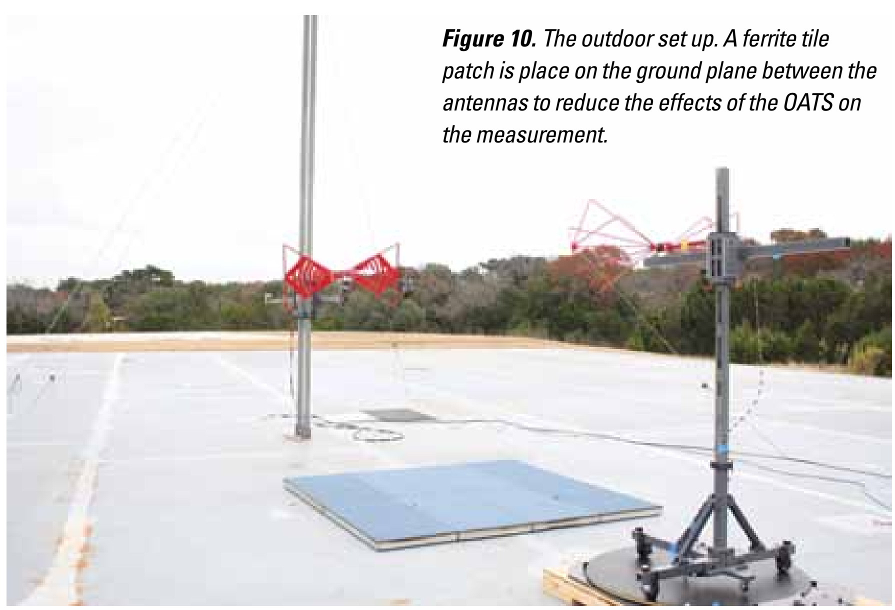

Figure 10. *The outdoor set up. A ferrite tile patch is place on the ground plane between the antennas to reduce the effects of the OATS on the measurement.*

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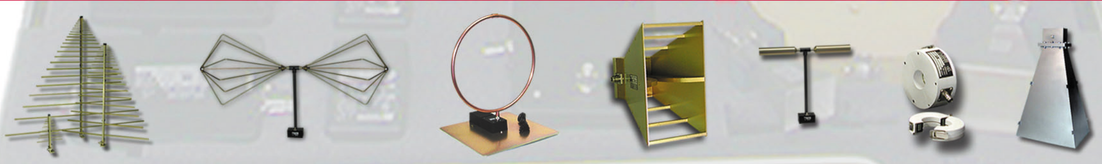

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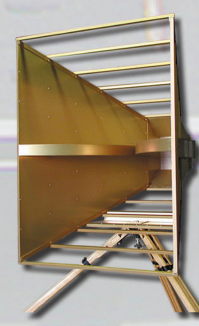

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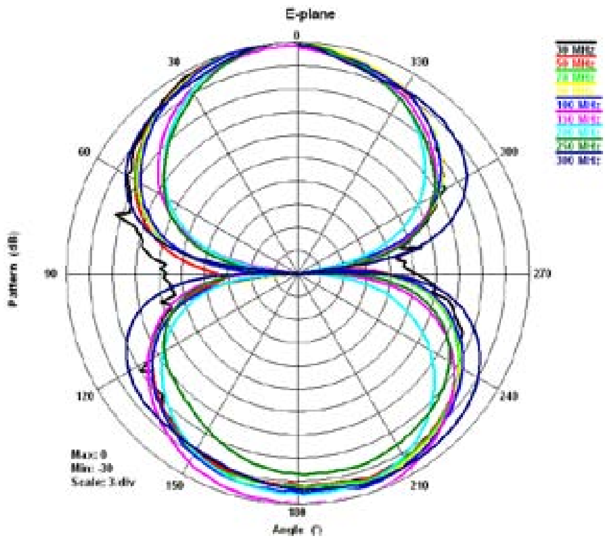

Figure 11. *E plane patterns. Notice that the low dynamic range at 30 MHz causes a poor definition of the null.*

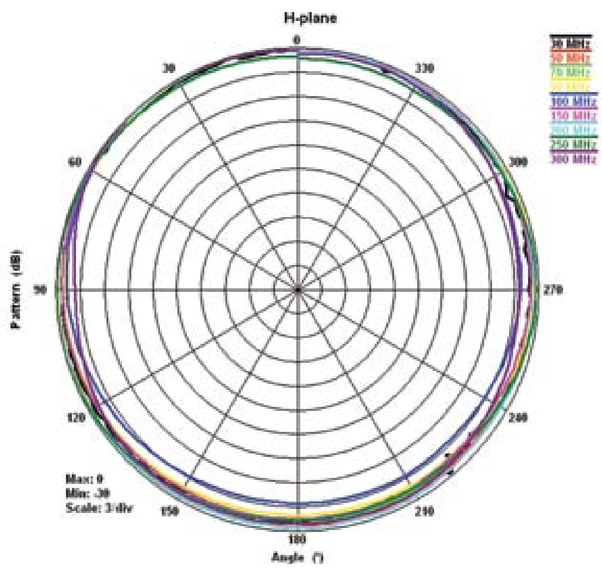

Figure 12. *H plane patterns for a biconical antenna.*

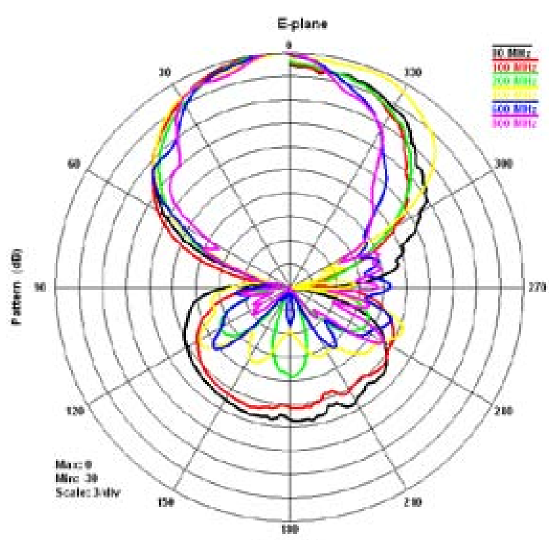

Figure 13. *E plane pattern from 80 MHz to 800 MHz for an LPDA antenna.*

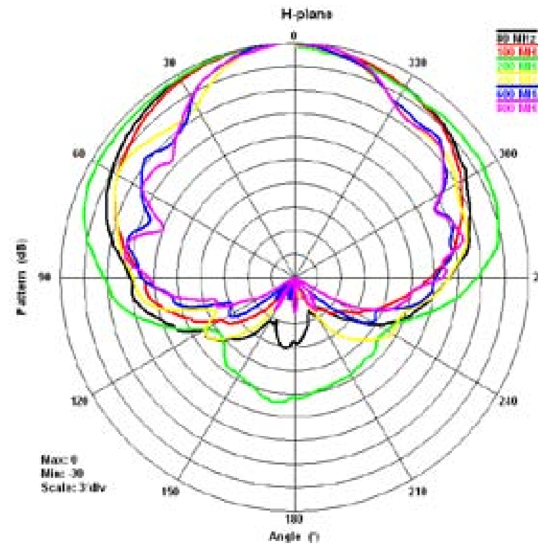

Figure 14. *H plane pattern from 80 MHz to 800 MHz for an LPDA antenna.*

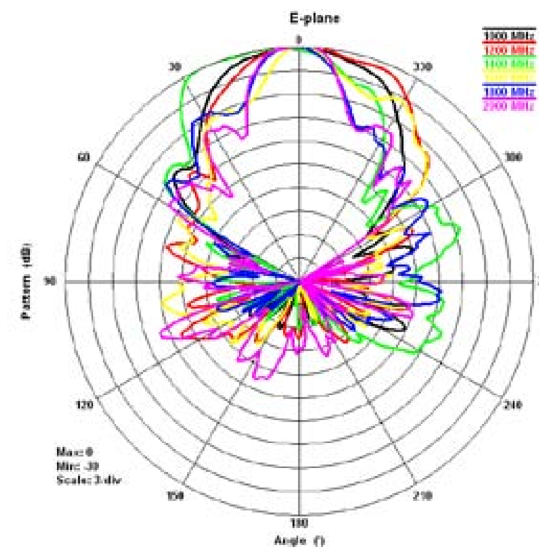

Figure 15. *E plane pattern from 1 to 2 GHz for an LPDA antenna.*

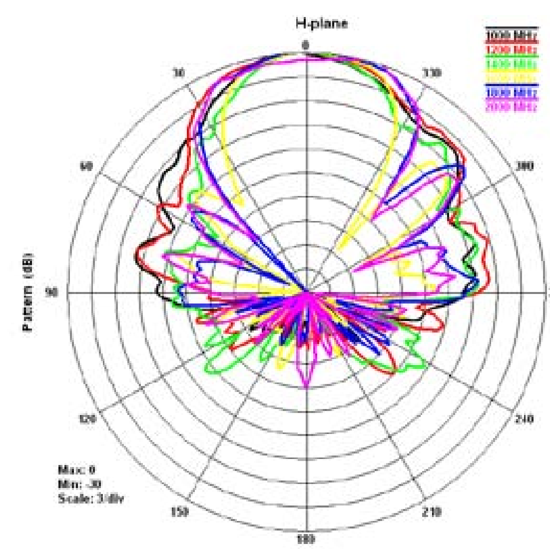

Figure 16. *H plane pattern 1 to 2 GHz for an LPDA antenna.*

Below that, the antennas were set on the OATS and the patterns on the two principal planes were measured. Figure 9 shows a hybrid antenna covering from 30 MHz to 6 GHz being measured inside a rectangular anechoic chamber. The rectangular anechoic chamber provides better results for the 2 to 6 GHz range when compared to the taper anechoic chamber, which covers from 400 MHz to 2 GHz optimally. Figure 10 shows the outdoor set up. A biconical antenna is being measured in this case. A hybrid antenna is used as the source antenna while the antenna under test (AUT) is rotated in its presence.

BICONICALS

To start we look at the biconical antenna. These antennas are the workhorse of EMC from 30 MHz to 200 MHz. In general models are available covering from down on the 20 MHz range to up in the 300 MHz range. Biconical antennas are an example of omnidirectional antennas. Its pattern is omnidirectional on the H plane and has two nulls on the E plane. Figures 11 and 12 show the typical measured pattern for a biconical antenna commonly used in EMC.

From these patterns we can extract the HPBW. For the H plane it is clear that the HPBW is larger than 180 degrees; there is no main beam. For the E plane the beamwidth ranges between 45 and 90 degrees.

LPDAS

The other workhorse for the EMC engineer is the Log Periodic Dipole Array (LPDA) antenna. These are directional antennas and have a very well defined main beam as well as all the other features commonly seen in directional patterns. In this particular case we measured an LPDA model covering from 80 MHz to 2 GHz. The most common models are those covering from 200 MHz to 2 GHz. Their patterns are very similar as long as their geometry has the same design parameters [1]. Figures 13 and 14 show the pattern for the log periodic antenna for frequencies below 1GHz. Notice that the E plane pattern has a null in the 90 and 270 degrees direction. This is similar to dipoles, which are the elements that make the array on a LPDA. Figures 15 and 16 show the patterns at different frequencies above 1GHz.

The HPBW of LPDA antennas is usually fairly flat. This is especially the case for the center of the frequency band that the antenna covers. From about 200 to 1500 MHz the antennas being measured exhibit an HPBW averaging 50 degrees for both planes.

HYBRID ANTENNAS

Although hybrid antennas are not particularly liked by CISPR 16 [5] because of their length, other standards do not have a problem. Additionally, because of their wide coverage they are ideal for preliminary scans of the EUT prior to the final compliance measurement. These antennas are a hybrid of the two types shown before. The biconical elements have been transformed into bowties to better match the geometry of the LPDA section. Their patterns clearly show this. At low frequency they behave like biconical antennas and at high

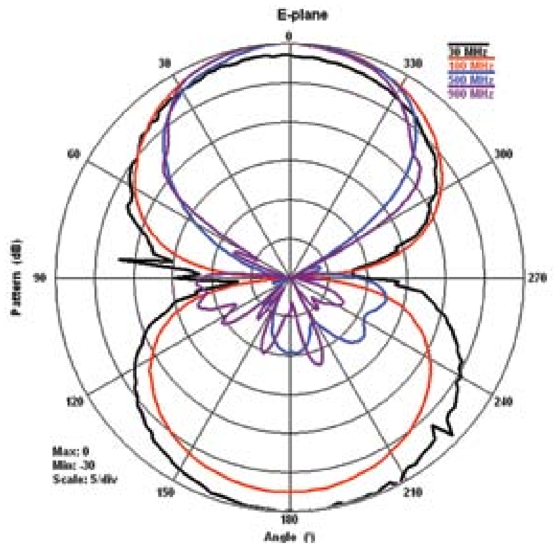

Figure 17. *E plane pattern from 30 to 900 MHz for a hybrid antenna.*

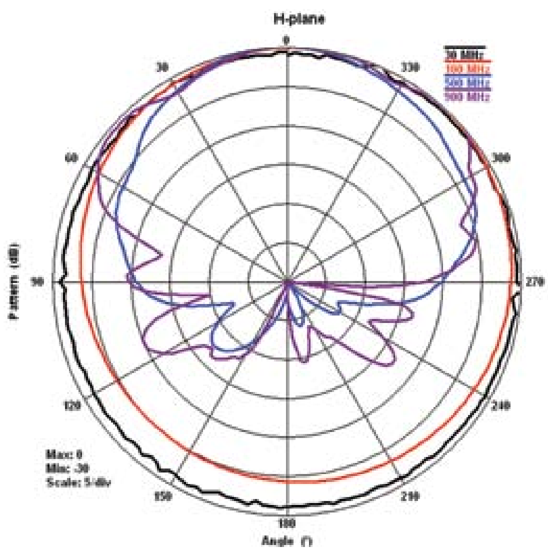

Figure 18. *H plane pattern from 30 to 900 MHz for a hybrid antenna.*

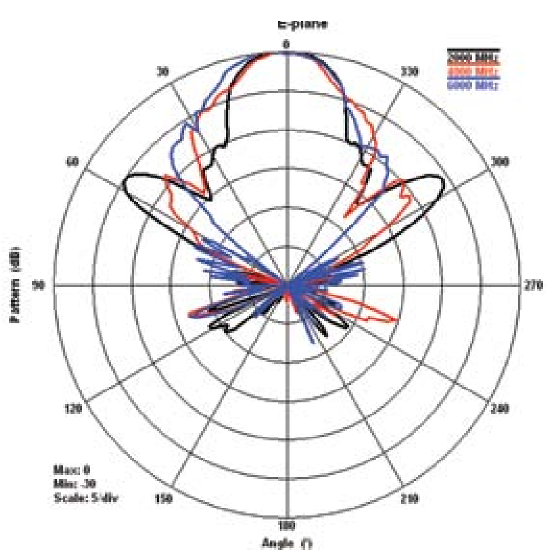

Figure 19. *E plane pattern from 2 to 6 GHz for a hybrid antenna.*

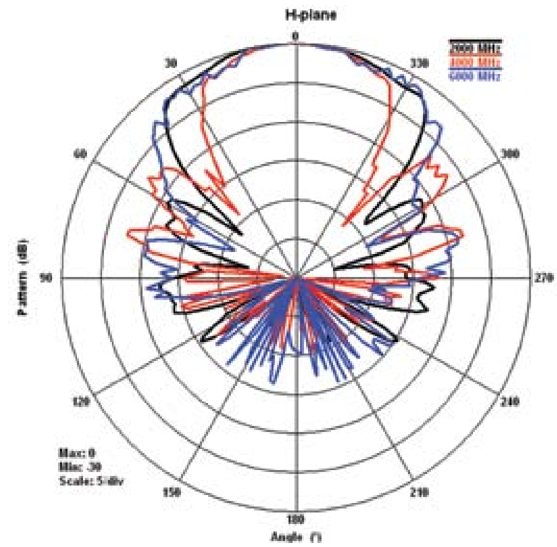

Figure 20. *H plane pattern from 2 to 6 GHz for a hybrid antenna.*

frequencies the log periodic behavior is evident. Figures 17 to 20 show the patterns at the principal planes for lower and upper frequencies of the range. It is important to notice the biconical behavior at the lower frequencies of the range.

As with the biconical antennas the hybrids have HPBW larger than 180 degrees at the frequencies below 100 MHz. Once the log periodic section is active, the HPBW is fairly flat unless there are changes to the LPDA design parameters.

DUAL RIDGE HORNS

Dual Ridge Horn Antennas (DRHA) are the antenna of choice for MIL STD [2]. This family of antennas have been the best described family in the literature. This is especially true regarding their radiation patterns. Starting with [6] there was a big issue with the upper frequency behavior of the patterns of Dual Ridge Horn Antennas. In [7-10] several improvements were done to the radiation patterns of these antennas to avoid nulls in the middle on the main beam. HPBW information for the three most common models of dual ridge horn antennas are shown in Figures 21 to 23. These are the models where the pattern performance has been improved as described in the references [8-10].

CONCLUSION

The reader has been introduced to antenna pattern nomenclature. The different concepts and parameters that describe patterns have been defined and illustrated. Finally pattern and HPBW information has been given for the most common EMC antennas used.

ACKNOWLEDGEMENTS

The author would like to thank the antenna calibration lab at ETS-Lindgren in Cedar Park, Texas for their help in setting up the OATS for measuring the patterns below 400 MHz. The author also would like to thank the staff of the CTIA authorized test laboratory (CATL) at ETS-Lindgren for their help in measuring the patterns in two of their four anechoic

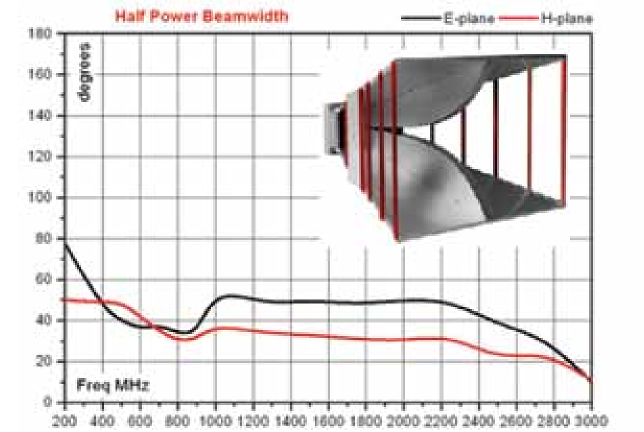

Figure 21. *HPBW for both principal planes for an improved designed of the 200 MHz to 2 GHz DRHA.*

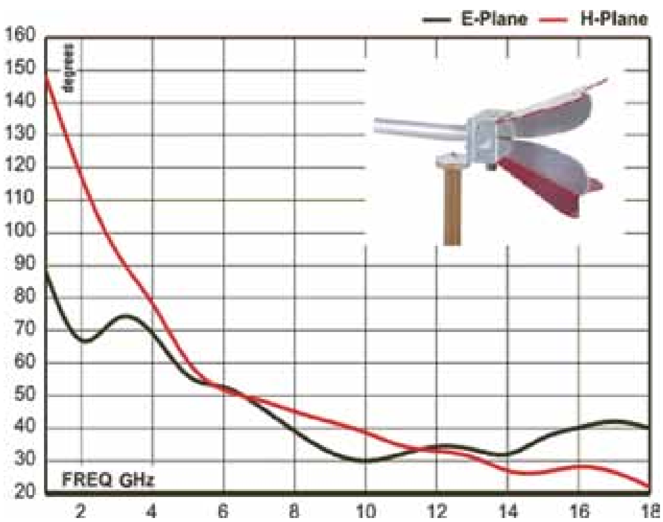

Figure 22. *HPBW for both principal planes for the improved design of the 1 to 18 GHz DRHA.*

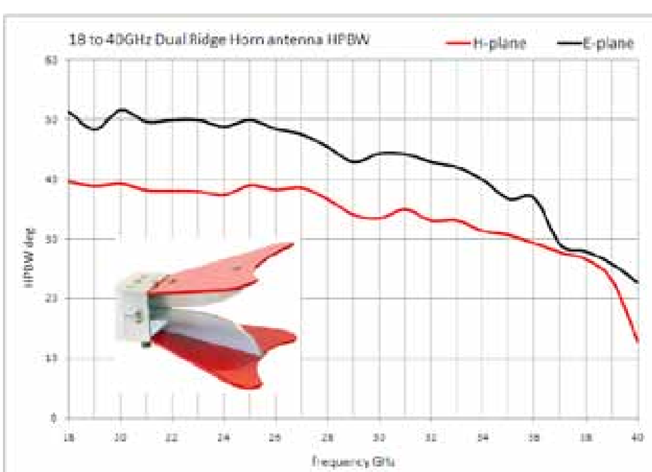

Figure 23. *HPBW for both principal planes for an improved design of the 18 to 40 GHz DRHA.*

chambers. Finally, the author thanks the marketing department at ETS-Lindgren for the pictures taken of the different set-ups needed for the measurement of the patterns.

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VICENTE RODRIGUEZ attended Ole Miss, in Oxford Miss., where he obtained his B.S.E.E. M.S. and Ph.D. degrees in 1994, 96 and 99 respectively. In June 2000, after a short period as visiting professor at the department of Electrical Engineering and Computer Science at Texas A&M University-Kingsville, Dr. Rodriguez joined EMC Test Systems (now ETS-Lindgren) as an RF and Electromagnetics engineer. In September 2004, Dr. Rodriguez took over the position of Senior Principal Antenna Design Engineer, placing him in charge of the development of new antennas for different applications and on improving the existing antenna line. In 2006, Dr. Rodriguez became Acting Antenna Product Manager placing him in charge of the development, marketing and maintenance of the antenna product line. During the fall of 2010, Dr. Rodriguez became the official Antenna Product Manager.

During his time at ETS-Lindgren, he has been involved in the RF anechoic design of several chambers, including rectangular and taper antenna pattern measurement chambers, some of which operate from 100 MHz to 40 GHz. He was also the principal RF engineer for the anechoic chamber at the Brazilian Institute for Space Research (INPE), the largest chamber in Latin America and the only fully automotive EMC and Satellite testing chamber. Among the antennas developed by Dr. Rodriguez are new broadband double and quad-ridged guide horns with single lobe pattern and high field generator horns for the automotive and defense industry, as well as omnidirectional antennas for field surveying. He can be reached at Vince.Rodriguez@ets-lindgren.com

High Power Electromagnetic (HPEM) Threats to the Smart Grid

WILLIAM A. RADASKY
Metatech Corporation
Goleta, California USA

This paper is focused on the threats and impacts of High Power Electromagnetic (HPEM) environments on the U.S. Power Grid and further introduces the implications of making the power grid "smarter" through the introduction of additional electronics. These Smart Grid electronics may introduce additional vulnerabilities if the grid is exposed to the high power EM threats of High-altitude Electromagnetic Pulse (HEMP) from a nuclear detonation in space over the U.S.; Intentional Electromagnetic Interference (IEMI) from terrorists or criminals who wish to attack and create regional blackouts using electromagnetic weapons; and, finally, from an extreme geomagnetic storm (initiated by solar activity) that could create damage to the high-voltage electric grid. This author has previously referred to these three electromagnetic environments as a "triple threat" [1].

This paper will briefly introduce the basic electricity delivery system as it exists today with an explanation of the trends that are underway to make the grid "smarter". Some discussion of the impacts of electromagnetic interference on the existing grid will be mentioned, including the fact that standards have been developed to protect existing power grid electronics from these "standard" electromagnetic threats. Next, the relationship of these HPEM threats to the existing EM environments will be explained, including work initiated by the EMP Commission where tests were performed to determine vulnerability levels of the existing grid.

The next portion of this paper discusses an approach to be taken to protect both the current power grid and the future Smart Grid from these HPEM threats. This paper will then conclude with a summary of the activities of various national and international organizations working to develop HPEM procedures and standards to protect power grids and other critical infrastructures throughout the world.

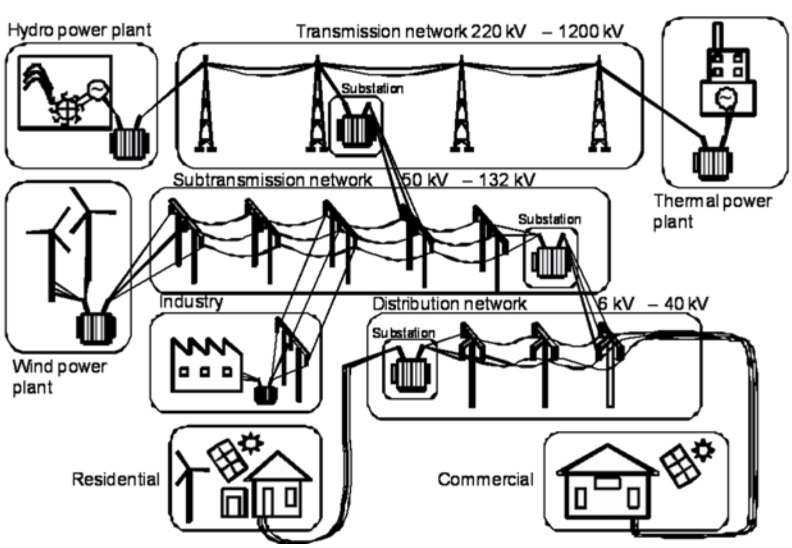

Figure 1. *Basic elements of a power grid [2].*

WHAT IS THE SMART GRID?

The electric power grid consists of basic elements of generation, transmission, distribution and users. Currently, power generators are dispatched based on the projected power needs for each day, and in some states auctions are held to achieve the best price and reliability outcome for the

E3 Electromagnetic Environmental Effects

EMC
EMI
EMP
EMR
EMV
ESD
EMCON
HERF
HERO
HERP
HIRF
TEMPEST
COMSEC
LIGHTNING
P-STATIC
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For more information or for full brochure contact:

Mark Mallory
301-342-1663
MARK.MALLORY@NAVY.MIL

Kurt Sebacher
301-342-1664
KURT.SEBACHER@NAVY.MIL

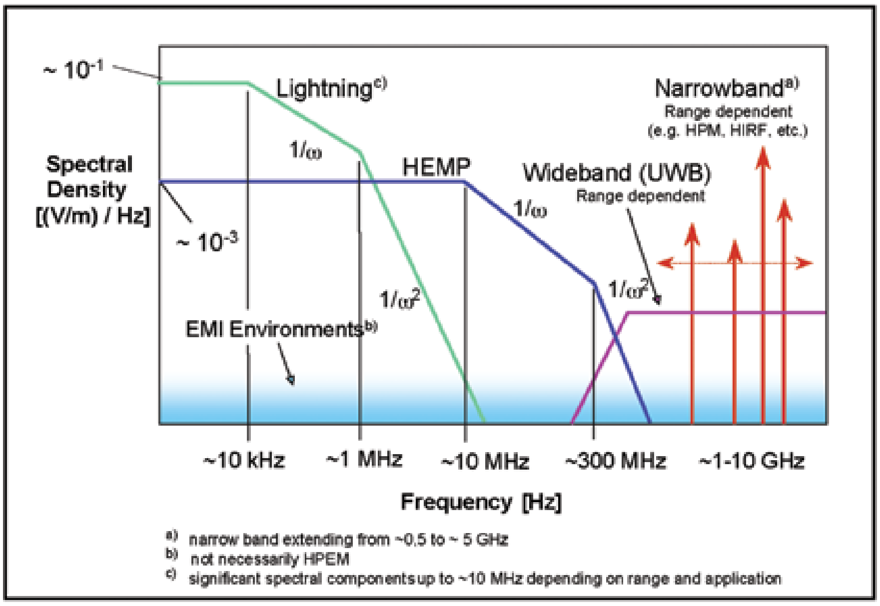

Figure 2. *Comparison of IEMI wideband and narrowband threats with the early-time HEMP and lightning electromagnetic fields [4].*

consumer. Each large power company has a control center that works to keep the power generated and used in balance, through diverse communications networks. In addition, they use communications networks to keep track of the health of the control electronics within substations to react in case of faults or equipment failures. Figure 1 illustrates a basic power grid example with three types of power-generating plants illustrated and three types of users (residential, commercial and industrial). It should be noted that the terminology of transmission, subtransmission and distribution in the figure may vary with respect to particular voltage levels in different parts of the U.S. and the world. In addition, the IEC [3] defines a.c. high-voltage as above 100 kV, low voltage as below 1 kV, and medium voltage as in between these two levels. Additionally, the term EHV (extra high voltage) is usually defined above 345 kV, and a new term of UHV (ultra high voltage) is defined above 800 kV, both for a.c. power flow.

With regard to the trends for Smart Grid, there are several aspects to consider. Due to the emphasis put on renewable sources of energy, there are large numbers of wind turbines and solar farms being built by power companies. As these forms of generation become a larger portion of the power generation availability, sensors to track the actual flow of power over short periods of time become more important (as is the reliability of the communications networks to provide this information to the control centers). In addition, forecasting of wind velocity over hours and even minutes may become important in the future. If the wind generation drops suddenly, the control center needs to have this information in order to bring up alternate power generators (or drop load) to avoid a power blackout.

Another area of Smart Grid activity is to upgrade the electronics in high voltage and medium voltage substations and to develop new rapid communications methods to relay status information and to take actions when necessary. Another area of power company activity is to increase the monitoring in the distribution network to determine the location of local outages if they occur and to command the opening of sectionalizing switches if needed.

A final area of Smart Grid activity involves the actual consumer of electricity through the rollout of Smart Meters. These electronic meters can communicate back to the control center through a new communications network providing information regarding the use of electricity. In addition, consumers may be given alerts regarding the use of power and changes in the price of electricity during different times of the day. There is even a concept to build in control chips for consumer appliances that would allow particular items to be turned off remotely by the power company (presumably with the permission of the consumer, with a possible benefit of lower power rates). There is work ongoing now in the Smart Grid community to develop the communications protocols for this aspect of appliance control. It should be noted that this "demand response" aspect of Smart Grid is viewed as a way to avoid building too many power plants by reducing the margin between the peak power required and the peak power available.

In reviewing the paragraphs above, it is clear that the main aspect of Smart Grid is to introduce new electronics in large numbers with new ways to communicate to them. It is of some concern that with a small operational margin, if the ability to communicate is disturbed or if Smart Grid equipment is damaged, then the smaller margin that we have today would likely result in a lower reliability of operation of the power grid. As described below it will be clear that severe (yet infrequent) electromagnetic threats have the capability to both damage and disrupt the current and future power grids.

HPEM THREATS

IEMI background

To refresh the reader regarding the terminology employed here, the term Intentional Electromagnetic Interference (IEMI) refers to the deliberate attempt to produce electromagnetic radiated and/or conducted disturbances to interfere with the operation of commercial equipment or to create damage to that equipment [4-6]. This could be done for criminal or terrorist purposes, although the purpose of the technical work is to determine the feasibility of such attacks and to determine ways to detect an attack and/or to protect against the types of disturbances that might be generated. As shown in Figure 2, the IEMI environments are split into two categories known as wideband and

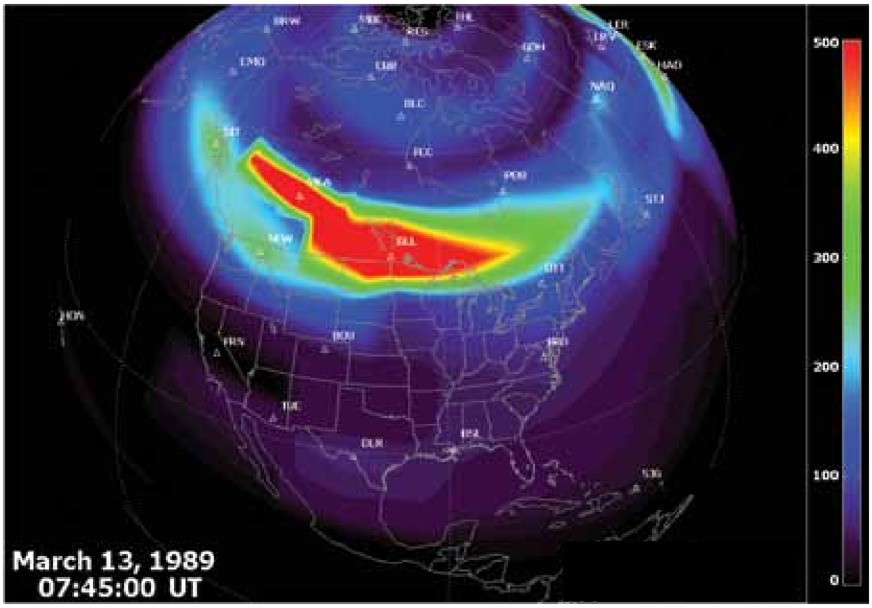

Figure 3. Level of B-dot disturbance (measured) from the severe geomagnetic storm that created the blackout in the Quebec power system a few minutes earlier [8]. (Source: Metatech Corporation Applied Power Solutions)

narrowband, with both normally produced at frequencies above 100 MHz. In the time domain, the peak electric fields exposing equipment are typically higher than 10 kV/m. Standardization work dealing with IEMI is moving forward in the IEEE EMC Society, IEC SC 77C, Cigré and ITU-T and will be discussed later in this paper.

HEMP background

The terminology of the electromagnetic pulse has evolved over the years, but today the generic term for all types of nuclear generated electromagnetic transients is EMP. Sometimes one will see the term NEMP, which clearly identifies the particular pulse of interest as being generated by a nuclear detonation. Of interest here is the EMP created by a high-altitude burst, generally defined as one occurring at a burst height greater than 30 km. For this altitude regime, the radiation produced by the nuclear burst does not reach the Earth's surface, but several types of intense electromagnetic signals will. Because the burst is at high altitudes (in space), this type of EMP is usually referred to as HEMP. The HEMP has three time (and frequency) portions with the early-time (E1) HEMP reach-

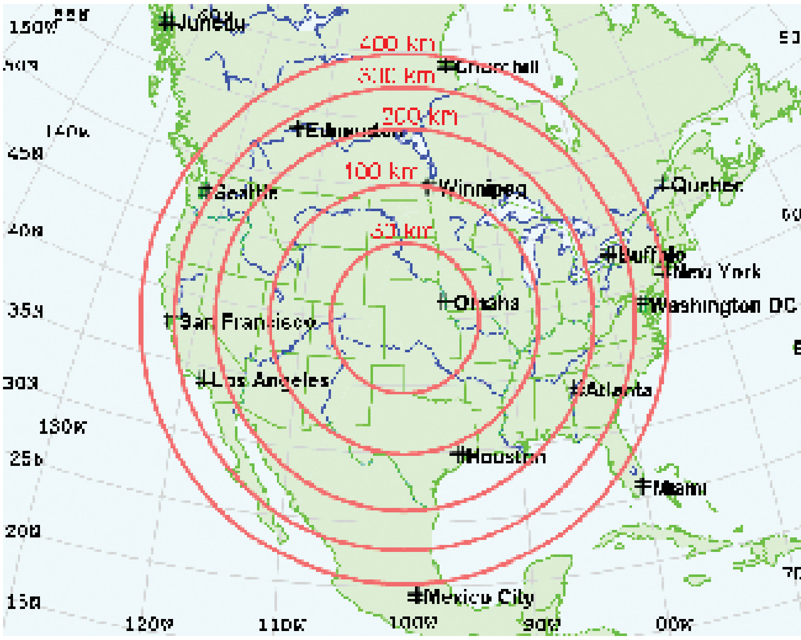

Figure 4. *Indication of the area exposed to E1 HEMP from a high-altitude burst over the central United States for various burst altitudes given in km.*

ing field levels of 50 kV/m within 10 ns, the intermediate-time (E2) HEMP reaching 100 V/m between 1 microsecond and 1 second, and the late-time (E3) HEMP reaching 40 V/km for times between 1 and several hundred seconds [1,7]. Based on research performed over the years, it has been concluded that the E1 and E3 HEMP are the biggest concerns to the power system due to their high peak field levels and efficiency in coupling to power and control lines. They both have an area coverage that can exceed several thousand kilometers from a single burst.

The concern is that these high-level electromagnetic fields and their area coverage will create simultaneous problems for computers and other electronic systems on the Earth's surface, including the critical infrastructures (power, telecommunications, transportation, finance, water, food, etc.). This was the focus of the U.S. Congressional EMP Commission studies [8, 9].

Extreme geomagnetic storm background

The first two high-power threats and environments discussed above are man-made. There is, however, a natural environment known as an extreme geomagnetic storm that has strong similarities (spatial distribution and time variation) to the late-time (E3) portion of the HEMP [10]. Because of this, the protection methods are also very similar, although the specification levels of protective devices may vary. It should be noted that the term extreme geomagnetic storm is used here to indicate that the level of the storm exceeds the usual description by NOAA of a severe geomagnetic storm, which may occur more than once during a solar cycle (11 years). The extreme geomagnetic storm is defined as a 1 in 100 year storm [8].

In brief, a large increase in charged particles ejected from the Sun and into the solar wind can interact with the Earth's magnetic field and produce a significant distortion of the geomagnetic field at the surface of the Earth. This rapid variation of the geomagnetic field (on the order of seconds to minutes) induces time varying electric fields in the Earth, which through the neutrals of transformers create time-varying (yet quasi-dc relative to 60 Hz) currents in the high-voltage power network. These currents induce severe harmonics, increase inductive load and produce heating in each exposed transformer. This can lead to voltage collapse of the network as experienced by the power grid in Quebec in March 1989 and damage to highly exposed transformers. Figure 3 illustrates the contours of the B-dot environment at the Earth's surface (in nT/min), minutes after the collapse of the Quebec power network. The spatial extent of the severe fields is quite large, and the footprint can move (and has moved) further south during other storms. For additional information about geomagnetic storms and their impact on power grids, one should consult the literature [11, 12].

Shielding Measurements		
Normal Shielding, dB	**Room**	**Shielding, dB**
0	All wooden building	2
5	Room under wood roof	4
	Wood Bldg-Room 1	4
	Concrete - no rebar	5
10	Wood Bldg-Room 2	6
	Concrete + rebar-room1	7
	Concrete + rebar-room2	11
	Concrete + rebar-room3	11
20	Concrete + rebar-room4	18
	Metal bldg.	26
30	Concrete + well-prot. room	29

Table 1. *Shielding effectiveness measurements for various power system buildings and rooms.*

POTENTIAL IMPACTS OF HPEM WITH THE POWER GRID

Early-time (E1) HEMP impacts

The early-time (E1) HEMP produces a fast rising and narrow electric field pulse (2.5/25 ns) that propagates at the speed of light from the burst point. Figure 4 illustrates that the area coverage depends on the burst height. Due to the rapid rise of the E1 HEMP in the time domain, the frequency content is much higher in magnitude and frequency than lightning electromagnetic fields and normal substation electric fields produced by switching events in the high voltage yard. These electromagnetic fields can couple to low voltage control cables in a substation and propagate levels on the order of 20 kV to the control house electronics. This presents a severe disturbance to existing substation solid-state protective relays. In addition, the EM fields are high enough also to penetrate the walls of most substation control houses, as the walls are not designed to attenuate EM fields significantly (as shown in Table 1). As more Smart Grid electronics are placed in substations, these E1 HEMP fields become a significant concern to their performance. Also the placement of new Smart Grid communication antennas and electronics in substations should consider the threat of E1 HEMP. It is noted that microwave towers with their long cables extending to the ground are an ideal pickup geometry for E1 HEMP fields, and unless good grounding practices (circumferential bonding) are employed at the entrance of the cables to communications buildings, the high-level induced E1 HEMP currents and voltages will propagate efficiently to the cable connections of the electronics, creating likely damage.

E1 HEMP will also couple efficiently to aboveground medium and low voltage power lines that are typical for the distribution grid and also to the low voltage drop lines to homes or businesses. While burial of distribution lines is becoming more common in the U.S., there are still on the order of 70% of U.S. distribution lines at medium voltage that are above ground. The problem with this is that the E1 HEMP can couple voltages up to 1 MV common mode with a rise time of 10 ns and a pulse width of 100 ns [13]. These levels will create insulator flashover on many distribution lines (simultaneously) and can cause mechanical damage to some insulators [14]. For the shorter drop lines to homes, levels on the order of several hundred kV are possible that could seriously damage solid-state Smart Meters. As for distribution sensors and electronic controls, these would also be fully exposed to the E1 HEMP environment; without protection for the sensors, cables, electronics and communications, damage could be expected.

Another concern is the protection of the control center for each power company that consists of computers/terminals and displays to keep track of the status of the power system under control and the supporting computer and communications rooms to send and receive data to and from substations. Currently there is some variation in the building construction quality used at different power companies (Table 1), but the best approach to avoid problems is to place the control center in the middle of the building on a low floor or in the basement. This is because soil and concrete provide some protection from high frequency EM fields. Locating the control center on the top floor with outside walls and windows increases the penetration of EM fields inside the building where they can interact directly with the computers and their ubiquitous Ethernet cables (which are extremely vulnerable to high levels of pulsed EM fields). In the context of Smart Grid, it is likely that more electronics and communications will be added to the control centers, increasing the likelihood of damage or upset to equipment that are required to operate at a higher data rate than today's equipment.

In terms of power generation, E1 HEMP is a threat to the low voltage controls of power plants, including those SCADA systems that control the flow of fuel to the generator. If additional communications are added to the generators to update the power control center periodically for Smart Grid, then these communication antennas, cables and electronics should be protected at least against damage (upset can be handled more easily as personnel are present). For the issue of distributed generation, the proliferation of variable generators such as wind turbines will require new communications for Smart Grid applications to keep track of the amount of power being generated on a shorter time basis. Both wind and solar power generators will be exposed to E1 HEMP fields, and additional test data are needed to determine whether the turbine electronics and power converters themselves will be able to survive the effects induced by E1 HEMP.

Intentional electromagnetic interference (IEMI) impacts

As indicated in Figure 2, IEMI environments tend to be present at somewhat higher frequencies than the E1 HEMP. The typical field levels are also on the order of 10s of kV/m (depending on the location of the attacker relative to the sensitive electronics), but because of the higher frequency content, most electronics appear to be slightly more vulnerable than when exposed to E1 HEMP. This is due to the fact that the penetration of EM fields into an equipment case is typically more efficient as the frequency increases. Also the ability to upset electronics is increased when the frequencies of the EM environment are similar to the operational frequency of a microprocessor (typically in the GHz range). E1 HEMP has most of its field energy below 100 MHz.

While the IEMI threat field level is similar to E1 HEMP, it does not resemble a plane wave field that is propagating downward from space. Since the attacker for IEMI is likely within 100 meters, the EM field propagating away from the weapon tends to decrease as 1/r. This variation in field level with distance (unlike E1 HEMP) does not allow significant coupling to lines with length on the order of 100 meters or more. Therefore, IEMI is not a significant threat to insulators on medium voltage power lines. On the other hand, the IEMI threat to Smart Meters, distribution electronics, substation electronics, substation communications, control rooms and power generating facilities (including wind and solar facilities) is the same as for the E1 HEMP. Of course only one facility at a time is exposed by IEMI, but a team of criminals or terrorists could expose a significant set of assets in a city or town by using a weapon mounted inside a vehicle.

Late-time (E3) HEMP impacts

The late-time (E3) HEMP produces a disturbed geomagnetic field beneath the burst that induces slow rising (rise time on the order of 1 second) electric fields in the Earth up to 40 V/km. The area coverage beneath the nuclear burst is on the order of several thousand kilometers and long transmission lines (e.g. 100 km) can couple 4000 V between the grounded neutrals of their transformers. With a typical line/transformer/grounding resistance of 5 ohms, this results in a quasi-dc current flow of approximately 800 A (for this example). This is more than enough to create severe levels of transformer saturation, leading to the creation of high levels of even harmonics in the a.c. waveform and also heating and potential damage to the large transformer itself. As these transformers are very expensive and for voltages of 500 kV and higher are manufactured off shore, the loss of a significant number of transformers could create a long-term power outage in the exposed area (months or more). Also a blackout situation is likely to result even where transformers were not damaged, and it would take significant time and effort to restart the grid where assets were not damaged.

A second aspect of the E3 HEMP is the fact that the severe harmonics would propagate throughout the grid and create malfunctions and potential damage to building backup power systems. Harmonic immunity is built into most UPS and backup diesel generator systems; however, the harmonics generated by an E3 HEMP (and also an extreme geomagnetic storm) will greatly exceed those normal immunity levels. As for Smart Grid, there are already concerns that the harmonics normally present in many power systems create accuracy problems for Smart Meters. The IEC is working to add tests to the International Smart Meter standard to cover this problem. The IEC immunity tests do not cover the enhanced levels due to E3 HEMP or geomagnetic storms, so the impact to Smart Meters is not currently known.

Finally the low-frequency HEMP environment occurs immediately after the early-time, high-frequency E1 HEMP. This raises the prospect that control electronics, including high voltage protection relays, may not operate properly due to the E1 HEMP, and this could result in additional damage that would occur due to the E3 HEMP. This is different than the case of the geomagnetic storm that only produces the low frequency environment similar to E3 HEMP.

Extreme geomagnetic storms

While geomagnetic storms are an act of nature (the Sun), they vary in intensity and location on the Earth. Through evaluations of the probability and magnitude of a worst-case geomagnetic storm, Kappenman studied the Carrington storm in 1859 [15] and has estimated that an extreme geomagnetic storm could produce electric fields on the order of 20 V/km, although the spatial extent would likely be larger than that of E3 HEMP (by two to three times). The particular types of impacts on the U.S. power grid would be similar to the E3 HEMP impacts discussed above, although the area coverage would likely be larger, depending on the latitude of the storm and its longitudinal coverage (see Figure 3).

The major difference between the geomagnetic storm and the E3 HEMP is that there is no early-time, high-frequency electric field that precedes the geomagnetic storm. It is therefore likely that in the region of HEMP exposure, the total impacts will be more significant.

HPEM PROTECTION APPROACH

Protection from electromagnetic fields is strongly dependent on the frequency range and magnitude of the environment. This is due to the fact that high frequency transients penetrate more easily through gaps in metal shields or through dielectrics such as windows; they also couple well to "floating" wires, which act as antennas. Also high-frequency conducted transients usually have high power but modest energy, allowing the use of surge protection devices that do not require a high-energy handling capability.

In the case of low-frequency electromagnetic fields, grounding is very important and conducted transients with low voltages can be isolated by relatively small gaps.

For these reasons we will discuss the protection concepts for the high-frequency HPEM threats (E1 HEMP and IEMI) together and the low-frequency HPEM threats (E3 HEMP and Extreme Geomagnetic Storms) together. While there are great similarities within the two groupings, care must be taken to ensure that protective devices are properly sized for both threats within each group.

High-frequency HPEM protection approach

The basic approach for protecting from high-frequency HPEM threats is to first take advantage of the EM shielding that may be available in your installation. This is applicable to cases where the sensitive electronics are inside of a substation building, a power control center building, a generator control building, or a communications control building. Many building materials will attenuate high frequency fields from the outside to the inside. For cases in which the attenuation is insufficient (see examples in Table 1), then one can consider an augmentation of the shielding through external building additions, internal room wall shielding, or even moving equipment to a newly built shielded enclosure.

For electronics that are fully exposed to the E1 HEMP or IEMI (e.g. Smart Meters, distribution system sensors and communications, and antenna systems on substations, control center buildings and power plants), it will be necessary to evaluate by analysis and test the ability of connected electronics to withstand the E1 HEMP or IEMI environment when high-frequency grounding is improved and filters and surge arresters are added.

In both cases, it is necessary to perform detailed assessments that include evaluations of the shielding effectiveness, coupling to cables, consideration of fiber optic cabling, evaluation of existing filters and surge arresters and vulnerability of the equipment before protection is added. This approach is discussed in some detail for E1 HEMP and IEMI in a recent conference paper that provides additional details beyond those given here [16].

Low-frequency HPEM protection approach

The basic approach for protecting against the two low-frequency HPEM threats described here, is to prevent the electric fields induced in the Earth from coupling to the neutral connections of the high voltage transformers in substations. This can be done with neutral capacitors (to block) or resistors (to reduce), but the difficulty is that a fast bypass must be provided to allow for lightning surges and faults to flow safely to ground without damaging the neutral "blocking" device. While these types of devices have been successfully applied in large numbers at lower transformer voltages than we require for the EHV power grid, some techniques have been developed that should work for EHV transformers. The next step is to develop and test prototypes, write standards and then field the devices. If the reader has further interest in this area of protection, see [17].

ORGANIZATIONS DEALING WITH THE THREATS OF HEMP AND IEMI

IEC SC 77C (EMC: High Power Transient Phenomena)

Since 1989, the International Electrotechnical Commission (IEC) headquartered in Geneva, Switzerland has been publishing standards and reports dealing with the HEMP and IEMI threats and methods to protect civilian systems from these threats under IEC SC 77C. As these are electromagnetic threats, it was decided from the beginning that this work would be closely integrated with the EMC work being performed by the IEC and other organizations throughout the world. In fact IEC Technical Committee 77, the "parent committee" of SC 77C, has the title "EMC". There are several recent papers that provide details on the 20 IEC SC 77C publications that can be applied to the definition of the threats, the coupling to systems and the protection of systems [6, 18]. It is noted that these are basic standards and as such do not describe the resultant recommended immunity levels for particular types of equipment. This means that the standards must be applied on a case-by-case basis.

ITU-T Study Group 5

The International Telecommunications Union – Telecommunications Standardization Sector (ITU-T) has been working since 2005 to protect telecommunications and data centers from disruption from HPEM threats, which include HEMP and IEMI. They have relied a great deal on the basic publications of IEC SC 77C to prepare their recommendations. As of 2011 they have completed two recommendations for protecting against the E1 HEMP and IEMI [19, 20].

IEEE P1642

The IEEE EMC Society with the support of TC-5 (High Power EM) has been developing the "Recommended Practice for Protecting Public Accessible Computer Systems from Intentional EMI [21]." The purpose of this work is to provide guidance to businesses and government agencies that are operating computer systems in close proximity to public access. The concern is that criminals and terrorists could use small electromagnetic weapons to disrupt or destroy important computer systems without any trace of an attack. The focus on this work is to establish appropriate threat levels, protection methods, monitoring techniques and to recommend test techniques to ensure that installed protection is adequate. This document is scheduled for publication in early 2012.

Cigré C4 Brochure on IEMI

The International Council on Large Electric Systems has formed a working group WG C4.206 entitled, "Protection of the high voltage power network control electronics against intentional electromagnetic interference (IEMI) [22]." This working group is preparing a brochure that will recommend IEMI protection methods for the control electronics found in high voltage substations. The work is expected to be completed by the end of 2011.

SUMMARY

In this paper we have introduced three severe HPEM threats and discussed their likely impacts on the current and future U.S. power grid (Smart Grid). While we cannot be sure of all of the features of the eventual Smart Grid, there is enough information to evaluate the trends. In addition to pointing out the likely impacts on particular aspects of Smart Grid, assessment methods and protection measures have been described with references to more detailed studies. It is expected that efforts to assess and protect Smart Grid electronics and communications from electromagnetic interference (EMI) from "everyday" threats will continue; it is also recommended that assessments and protection be considered for these "low probability" HPEM threats.

Any readers who are interested in contributing to this research or standards, please contact this author at wradasky@aol.com.

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WILLIAM A. RADASKY, PH.D., P.E., received his Ph.D. in Electrical Engineering from the University of California at Santa Barbara in 1981. He has worked on high power electromagnetics applications for more than 42 years. In 1984 he founded Metatech Corporation in California, which performs work for customers in government and industry. He has published over 400 reports, papers and articles dealing with transient electromagnetic environments, effects and protection during his career. He is Chairman of IEC SC 77C and IEEE EMC Society TC-5. He can be reached at wradasky@aol.com

New EMC Requirements For Commercial Avionics: RTCA/DO-160G

ERIK J. BORGSTROM
Environ Laboratories LLC
Bloomington, Minnesota USA

RTCA/DO-160G, Environmental Conditions and Test Procedures for Airborne Equipment, prepared by RTCA Special Committee 135, was issued on Dec. 8, 2010, superseding the previous version, DO-160F [1].

DO-160G covers standard procedures and environmental test criteria for testing airborne electrical and electronic equipment (avionics). The tests specified in DO-160G are typically performed to meet Federal Aviation Administration (FAA) or other international regulations covering electrical or electronic equipment that is installed on commercial aircraft.

The tests and test levels/limits (also referred to as "Equipment Categories") found in DO-160G are applicable to virtually every type of aircraft in use today, including small general aviation aircraft, business jets, helicopters, regional jets, and "Jumbo Jets," such as the newest airliners from Airbus (the A350XWB) and Boeing (the 747-8).

The document includes 26 sections and three Appendices, but it is Sections 15 through 23 and also Section 25 that cover EMC. Examples of other tests covered in DO-160G are: temperature, altitude, vibration, sand/dust, power input, radio frequency susceptibility, lightning, and electrostatic discharge.

Creation and revision of DO-160G is coordinated with the European Union sister organization to RTCA, EUROCAE. As a result of this trans-Atlantic cooperation and joint effort by the two organizations, RTCA/DO-160G and its European twin, EUROCAE/ED-14G, are identically worded.

The purpose of this article is to provide an overview of each of the sections that deal with EMC in DO-160G. Changes in each section since the release of DO-160F will be summarized. Finally, we will look at the future direction of SC-135, and the timetable for future revisions to DO-160, and the DO-160 Users Guide.

SECTIONS 1-3

The first three sections cover the Purpose and Applicability (Section 1) of DO-160, provide a Definition of Terms (Section 2) used throughout the document, and give Conditions of Tests (Section 3). These first three sections are referenced in all of the subsequent sections of DO-160, and provide the general information and guidance needed to properly perform the specified tests.

What's new for DO-160G?

- In Section 1, a discussion of the Users Guide material found in an appendix after many sections, and the confirmation that any information found in the Users Guide is GUIDANCE ONLY (emphasis added).
- In Section 2, additional guidance covering "Category Tests and Declarations". In particular, Section 2.8 now states that if equipment is qualified to a particular category, the equipment can be considered to be qualified to any other category that is less severe.
- In Section 3, additional guidance covering "EUT Configuration for Susceptibility Tests", with special attention given to the firmware

and/or software used during testing.

SECTION 15: MAGNETIC EFFECT

This "MC" (for "Magnetic Compatibility" as opposed to "EMC" for Electromagnetic Compatibility) test is performed to determine how much the Equipment Under Test (EUT) will deflect a compass needle, or affect the indication from a magnetic field sensor, also known as a "Flux Gate".

A standard compass that has a large enough dial to read one degree of needle deflection, or an "equivalent magnetic sensor" (electronic compass) is the only test equipment required. The EUT is simply moved closer to the compass on an East-West line until one degree of deflection away from magnetic North is observed. The separation distance is then measured and the "Equipment Category" is determined.

Equipment classes

There are five Equipment Categories (Y, Z, A, B, and C) that apply to installation separation distances between the EUT and compass (or compass sensor) of less than 30 centimeters to more than 300 centimeters.

What's new for DO-160G?

• Figure 15-1, showing the Test Installation and Procedure, was revised to better show how the EUT and compass (sensor) are to be properly set up for testing, and how to correctly determine the distance at which one degree of needle deflection is observed.

SECTION 16: POWER INPUT

Although an argument can be made that "Power Input" (or "Power Quality" as they are referred to in other standards) tests are not truly EMC tests, they are included here for two reasons:

1) Power Input/Quality tests are often performed in the EMC lab by the EMC test personnel.

2) In the latest versions of DO-160, the frequency ranges for some of the tests fall well within the realm of typical EMC tests, and the test equipment used is similar to many other "true" EMC tests found elsewhere in DO-160 and other EMC standards.

The tests in Section 16 are performed to determine that the EUT can operate as required during all of the different conditions of AC and/or DC power variations that occur during normal and emergency aircraft operation. In addition, Section 16 contains tests to verify that the EUT does not have a negative influence on the aircraft power system that would be harmful or otherwise cause degraded performance in other installed equipment.

One interesting note about Section 16 is the fact that it is the only section of DO-160 that contains requirements and tests that cover both the susceptibility of the EUT (such as surge, dropout, frequency transients, etc.), and the generation of harmful interference (emissions) from the EUT (such as current harmonics, re-generated energy, power factor, etc.). This fact, along with the increasing complexity and variety of modern aircraft power systems, and the sheer size of Section 16 (69 pages in DO-160G), is spurring some discussion on SC-135 about the possibility of splitting off the Power Input/Quality requirements to a completely different document; although no immediate change is being considered.

In order to keep pace with the "state-of-the-art" in aircraft power system design, Section 16 has seen dramatic changes over the last decade, but (thankfully) the changes made for DO-160G, are not as extensive as previous revisions, and with a couple of exceptions, fall more under the heading of clarification and improvements for ease of use.

Change 2 to DO-160D, issued June 12, 2001, revised Section 16 fairly dramatically, by including new tests, and modifications to existing testing, to address the issues of AC Harmonic Current Content and Variable Frequency AC power systems [2].

In DO-160E, the entire section was re-ordered so that all the AC tests were in one subsection, and all DC tests were in another subsection, making Section 16 easier to use and understand. DO-160E also introduced some new tests, such as a DC Content test for AC powered equipment, and a new sub-section covering "Load Equipment Influence on Aircraft Electrical Power Systems".

In DO-160F, even more tests were added, for both AC and DC powered equipment. In addition, a whole series of new tests and test levels to cover 270 Volt DC power systems, and a greatly expanded list of tests to cover the EUT influence on the aircraft electrical power systems was instituted.

DO-160G does not contain any new tests, but does add some clarification of the applicability of some tests.

DC input tests

On DC inputs, there are tests that cover:

- Steady-state over- and under-voltage conditions
- Ripple voltage
- Momentary power interruption
- Momentary sags and surges
- Exposed voltage decay time (270 Volt only)
- Inrush current

AC input tests

AC inputs are subjected to the following tests:

- Steady-state over- and under-voltage conditions
- Steady-state over- and under-frequency conditions
- Steady-state phase unbalance (three-phase power)
- Voltage and frequency modulation
- Voltage and frequency transients
- Momentary power interruption
- Momentary sags and surges
- DC offset and voltage distortion
- Harmonic current emissions
- Phase unbalance (3 phase inputs)
- DC current content
- Inrush current
- Current modulation
- Power factor

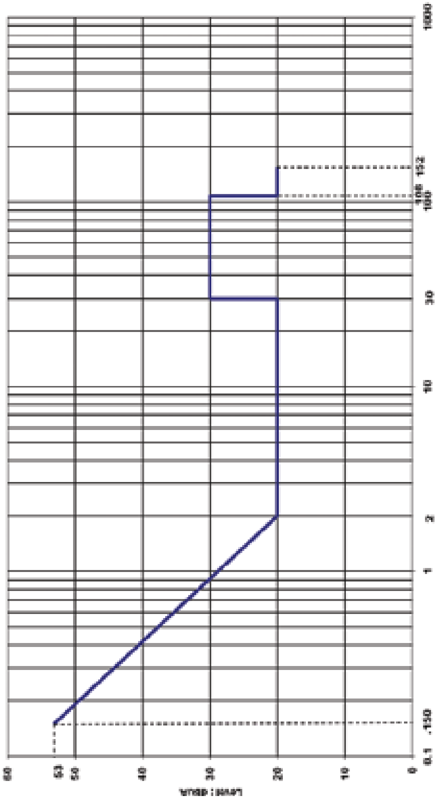

Figure 1. *Category Q conducted RF emissions limit - power leads.*

Equipment categories

There are four Equipment Categories (A, B, D, or Z) that indicate the type of power used by the equipment and the type of AC and/or DC power source with which the equipment is compatible. For AC powered equipment, an additional designator, placed in parenthesis following the Category designator, is a two character code indicating that the equipment has been tested for use with Constant Frequency (CF), Narrow Variable Frequency (NF), or Wide Variable Frequency (WF).

Up to four additional category designators are used to indicate testing for:

- AC current harmonics (H)
- AC current modulation (L)
- AC power factor (P)
- DC current ripple (R)
- AC or DC inrush (I)

What's New for DO-160G

- Directions regarding the testing process for equipment with multiple power sources.
- The requirement to test all AC powered equipment (regardless of whether they contain "Digital Circuits") to the Momentary Power Interruptions given in Table 16-1 (and 16-2 if the equipment uses "Narrow" or "Wide" Variable Frequency AC power).
- Abnormal Surge test is now specified for each individual phase of 3 phase AC powered EUTs.
- Tolerances for some test voltage levels have been added or modified to make the test easier to perform, and also more accurately simulate the intended conditions that would be seen on the aircraft.
- Revisions to Momentary Interruptions Tables 16-1, 16-2, and 16-3, to make it much easier to understand the test requirements.

SECTION 17: VOLTAGE SPIKE

This test determines whether the EUT can operate as required during and/or after voltage spikes are applied to the AC and/or DC power input(s). Any method of generating the spike may be used, provided that the pulse produced has a duration of at least 10 microseconds, a rise-time of less than 2 microseconds, and a source impedance of 50 ohms. A minimum of 50 voltage spikes are applied within 1 minute. This test is very similar to MIL-STD-461F test method CS106 [3].

Equipment categories

There are two Equipment Categories. The Category B test level is twice the AC (rms) and/or DC line voltage (or 200 volts, whichever is less). The Category A test level is 600 volts.

What's new for DO-160G?

- Clarification that a minimum of 50 spikes in positive polarity, and 50 spikes in negative polarity, are required.

SECTION 18: AUDIO FREQUENCY CONDUCTED SUSCEPTIBILITY - POWER INPUTS

This test is performed to determine that the EUT will operate as specified when audio frequency interference is applied to the AC and/or DC power input. The test setup and procedure are nearly identical to MIL-STD 461F test method CS101, with the only difference being the actual test level and frequency range. The audio frequency interference is transformer coupled onto each power input lead, and the peak-to-peak voltage level of the interference signal is measured across the power input and return leads. Test levels are up to 8% of the nominal AC input voltage, and the frequency range is as broad as 10 Hz to 150 kHz.

The EUT must be tested while operating at both minimum and maximum current draw (if applicable), and at the AC power frequency extremes if designated for use with Variable Frequency systems. The frequency scan rate is 30 steps per decade, with a 1 minute dwell time at each frequency.

Equipment categories

There are three DC power Equipment Categories (R, B, and Z) that indicate the type of power used by the equipment and the type of DC power source with which the equipment is compatible.

Two AC power Equipment Categories are specified (R & K). Category R is used with an additional designation (a two character code), placed in parenthesis following the Category designator, indicating that the equipment has been tested for use with Constant Frequency (CF), Narrow Variable Frequency (NF), or Wide Variable Frequency (WF). Category K designates that the EUT has been tested for use with any type of AC power input, and tested to a higher level of voltage distortion than category R.

What's new for DO-160G?

- Users Guide has been added to the end of the section, resulting in many comments and remarks being moved from the requirements section to the new Users Guide.
- The allowance to limit applied power (of the test signal) to 100 watts has been removed and replaced by a 36 Amp peak-to-peak test current limit. Test setup figures have been modified to show the "Optional AC Current Monitor" in the proper location.
- The 0.6 ohm output impedance specification for the coupling transformer has been deleted.

SECTION 19: INDUCED SIGNAL SUSCEPTIBILITY

The tests in this section are performed to determine that the EUT can operate as required when the equipment and interconnecting cables are subjected to audio frequency electric fields, magnetic fields and transient voltage spikes.

The test levels for the interconnecting cable tests are determined by the length of wire that is exposed to the radiating wire. For the Inductive Switching Transients (induced spikes) test, the exposed length is either 1.2 or 3.0 meters, with the amplitude of the spikes applied to the radiating wire being at least 600 Volts peak-to-peak.

For the magnetic and electric fields induced into cables, the test level is defined as the product of the length of interconnecting cable that is exposed to the radiating wire and the rms voltage or current applied to the wire. This test level is given as "volts x meters" (V-m), or "amps x meters" (A-m). For example, category Z requires an electric field test level of 1800 V-m, which is typically obtained by exposing 3 meters of cable to a radiating wire with 600 volts rms applied to it. If less than 3 meters of cable is exposed to the radiating wire (due to space restrictions, for example), the voltage applied to the wire must be increased so that the test level of 1800 V-m is achieved. The exception to this requirement is when the actual length of the cable in the final installation is known to be less than 3 meters. In this case, the test level may be reduced in proportion to the ratio of the reduced coupling length.

The frequency ranges for the swept frequency tests are determined by the Equipment Category specified. The frequency scan rate is 30 steps per decade, with a 10 second dwell time at each frequency.

Equipment categories

The Equipment Categories are comprised of two characters. The first character (A, B, C, or Z) indicates the tests performed and severity level of the tests. The second character (C, N, or W) indicates the AC power system operating frequency (Constant, Narrow Variable, or Wide Variable) with which the EUT is compatible.

What's new for DO-160G?

- Clarification that these tests are not applicable to Power Input cables/leads.
- An "Electric Fields Induced Into the Equipment" test has been added. This test is very similar to the existing "Magnetic Fields Induced Into the Equipment" test, and a single test level of 170 Vrms (400 Hz) is used for all Equipment Categories. Corresponding Test Setup Figure also added.
- The requirement to sweep the radiating wire across the face of the equipment in both the Magnetic and Electric

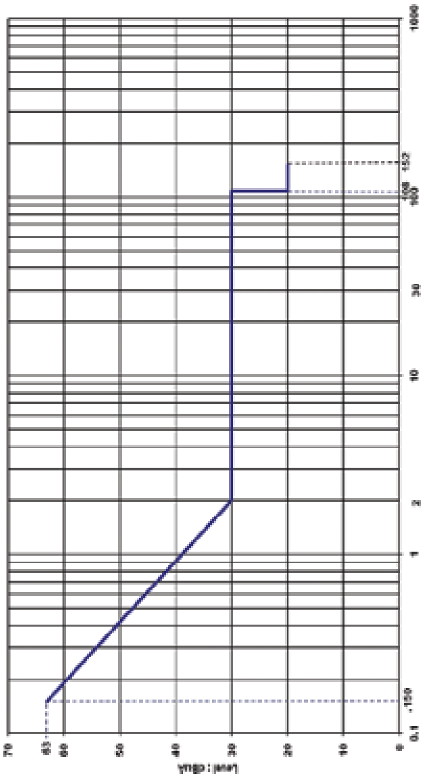

Figure 2. *Category Q conducted RF emissions limit - Interconnecting cables.*

Fields Induced Into the Equipment tests.

- Clarification added to the Inductive Switching Transients (Induced Spikes) figure, to allow for the fact that spikes of varying amplitude will be produced during the test, and that some spikes will be less than the indicated 600 Vpp amplitude.

SECTION 20: RADIO FREQUENCY SUSCEPTIBILITY (RADIATED AND CONDUCTED)

These tests are performed to determine that equipment will operate as specified when the EUT and its interconnecting cables are exposed to Radio Frequency interference. Continuous Wave (CW), Square Wave AM (SW), and Pulse Modulated (PM) RF signals are required. A Line Impedance Stabilization Network (LISN) must be inserted in series with each power lead and ungrounded power return lead, with a 10 uF capacitor connected between the power input of the LISN and the ground plane. Unless otherwise specified, interconnecting cables shall be at least 3.3 meters in length, and power leads will be no more than 1 meter in length for these tests.

Conducted susceptibility

The RF conducted susceptibility test procedure is similar to MIL-STD-461F test method CS114. RF interference is coupled into the EUT interconnecting cables and power leads using an injection probe that is calibrated (in a 50 ohm fixture) to the required test level prior to performing the test. The amount of RF power applied to the injection probe that is required to achieve the specified RF current in the fixture is recorded for each test frequency. This calibration table, showing RF power required at a given frequency, is then used during the actual test.

During testing, the RF current that is induced into the cable or lead under test is monitored with a calibrated RF current probe, and the RF power applied to the injection probe is increased until the appropriate current level (as defined by the applicable Equipment Category used) is reached. The amount of RF applied to the injection probe is limited to no more than 6 dB above the power level recorded during calibration in the 50 ohm calibration fixture. The test frequency range is 10 kHz to 400 MHz, and 2 scans are typically required for each test - once with a CW signal, and then again with a SW modulated signal.

Radiated susceptibility

The RF radiated susceptibility test procedure is similar to MIL-STD-461F test method RS103. The EUT and its interconnecting cables and power leads are exposed to RF radiated fields in the frequency range of 100 MHz to 18 GHz. There are two RF radiated susceptibility test methods specified in Section 20.

The first uses a standard semi-anechoic chamber as in MIL-STD-461F test method RS103. The chamber must be lined with RF absorber, and the minimum performance of the absorber is specified. The minimum antenna distance is normally 1 meter, and multiple antenna positions are required when the beamwidth of the antenna does not totally cover the system. If the EUT has apertures, connectors, seams, or other points of penetration in the EUT enclosure, all of these must be directly exposed to the test antenna, requiring multiple EUT positions during testing.

Calibration of the RF field prior to placement of the EUT is required. The RF power required to achieve the specified test level is applied to the antenna input and this power level is recorded at each calibration frequency, for each antenna used. During EUT testing, the calibrated power level for each test frequency is applied to the antenna.

The second method uses a Reverberation Chamber, which requires a Field Uniformity Validation and Maximum Chamber Loading Verification prior to the first use of the chamber, or after any modifications. Field Uniformity measurements are performed with a 3-axis E-Field probe at up to nine different positions within the chamber. In addition, a passive, linear, monitor antenna is moved to different positions within the chamber to calibrate the monitor antenna for use prior to each test. This calibration allows the monitor antenna to be used to measure Chamber Q, Time Constant, and Test Level determination, during EUT testing.

The RF power level required to achieve the desired test level for each test frequency is determined by injecting a known RF power level (typically 1 watt) into the chamber, and then measuring the field level inside the Reverb Chamber with the monitor antenna, after the EUT installed in the chamber.

Equipment categories

Equipment Category designation for Section 20 consists of two letters. Conducted susceptibility test levels are designated with the first category character and radiated susceptibility test levels with the second category character. There are 7 Equipment Categories for conducted susceptibility, and 10 Equipment Categories for radiated susceptibility. These categories indicate the severity level of the tests performed, and/or the type of modulation used. Category S is the least severe at 1 V/m, and Category L is the most severe, with test levels as high as 7200 V/m.

What's new for DO-160G?

- Users Guide added.
- Wording throughout the section has been revised or added to align Section 20 with the requirements of the new FAA HIRF Rule, FAA Advisory Circular 20-158, and SAE document ARP5583A (HIRF Users Guide).
- The requirement that when using the Anechoic Chamber method for Radiated Susceptibility, all faces of the EUT must be directly exposed to the test antenna, and if any face of the EUT is not directly exposed to the test antenna, the justification for this decision must be included in the Test Report.
- Clarification that the distance between the test antenna and the EUT must be the same for calibration and test.
- The Reverberation Chamber test method has been modified from a "Mode-Tuned" process to a "Mode-Stirred" process. This change has resulted in a major re-write of Section 20.6, to such an extent that it cannot be discussed in sufficient detail in this article, but a few highlights can be provided:

1. Field Uniformity determination using 3-axes E-Field probes is still required.
2. Test Level is determined by measuring the power received by a monitor antenna (with the EUT installed), and then calculating the field based on the maximum received level on the monitor antenna, over one tuner rotation.
3. Tuner speed is 4 rpm below 1 GHz, and 2 rpm above 1 GHz, or slower (usually a slower speed is needed).

SECTION 21: EMISSION OF RADIO FREQUENCY

The tests in this section are performed to determine that the EUT does not emit radio frequency interference in excess of the specified limits. Conducted RF emissions appearing on interconnecting cables and power leads are measured. Radiated RF emissions from the EUT, interconnecting cables, and power leads are also measured.

Measurements must be made with an instrument using a peak detector, and with IF bandwidths, frequency step size, and dwell time as specified in Section 21, Table 1, for the frequency range being scanned.

A LISN must be inserted in series with each power lead and ungrounded power return lead, with a 10 uF capacitor connected between the power input of the LISN and the ground plane. Unless otherwise specified, interconnecting cables shall be at least 3.3 meters in length, and power leads will be no more than 1 meter in length for these tests.

Ambient emission levels must be at least 6 dB below the applicable limit, and must be measured and recorded if any signals are found to be within 3 dB of the applicable limit.

Conducted emissions

Conducted RF currents on interconnecting cables and power leads are measured with a clamp-on current probe. The probe is positioned 5 centimeters from the EUT and measurements are made over the frequency range of 150 kHz to 152 MHz.

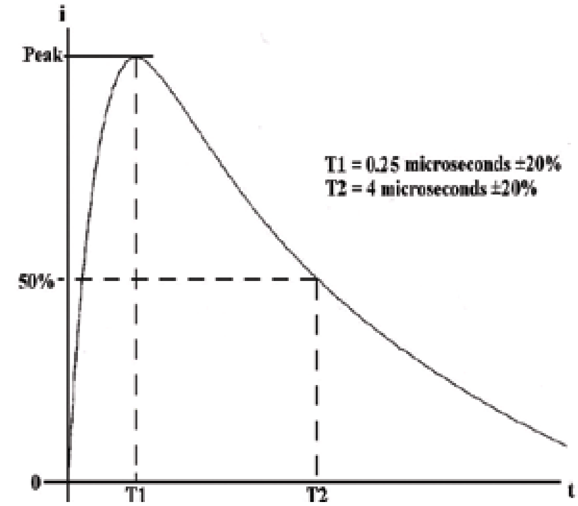

Figure 3. *Waveform 6.*

Radiated emissions

Radiated RF fields are measured with a linearly polarized antenna over the frequency range of 100 MHz to 6 GHz. As with RF radiated susceptibility testing in Section 20, there are two RF radiated emissions test methods allowed in Section

21: the Anechoic Chamber method, and the Reverberation Chamber method.

The Anechoic Chamber method requires a chamber lined with RF absorber, and the minimum performance of the absorber is specified. The measurement antenna distance is 1 meter, and multiple antenna positions are required when the beamwidth of the antenna does not totally cover the system. If the EUT has apertures, connectors, seams, or other points of penetration in the EUT enclosure, all of these must be directly exposed to the test antenna, requiring multiple EUT positions during testing.

The second method uses a Reverberation Chamber, which requires a Field Uniformity Validation from Section 20. EUT Loading is measured after the EUT is installed in the chamber, and this data is used as a correction factor for the radiated emissions measurement. A minimum of 200 sweeps of the analyzer or measurement receiver is required over one rotation of the tuner, for each measured frequency range.

Equipment categories

There are 6 Equipment Categories (B, L, M, H, P, and Q) that indicate the location of the equipment and the separation between the equipment and aircraft antennas. In general, the closer the equipment is to an aircraft antenna, and the more it approaches a "direct view" of an aircraft antenna, the tighter the emissions limits.

What's new for DO-160G?

- Users Guide.
- A new limit category has been added - Category Q - to provide added protection for VHF and GPS receivers, but without the Conducted Emissions "HF notch" used in Category P (see Figure 1 and Figure 2).
- Change in the frequency for the bandwidth step from 100 kHz to 1 MHz. Previous versions had this step at 1 GHz. DO-160G has the step at 960 MHz.
- Removal of the option to use a 10 kHz bandwidth to measure in the notches above 960 MHz, and instead, a note that a high-gain pre-amplifier may (will) be required.

SECTION 22: LIGHTNING INDUCED TRANSIENT SUSCEPTIBILITY

These tests determine whether the EUT can operate as specified during and/or after various lightning induced transient waveforms are injected into connector pins, interconnecting cables, and power leads using pin injection, and/or cable bundle tests. The pin injection method is normally used to show damage tolerance, while the cable bundle tests are normally used to show upset tolerance.

Change 3 to DO-160D, issued December 5, 2002, was a major revision of Section 22, primarily to add procedures, waveforms, and test levels for Multiple Burst and Multiple Stroke Cable Bundle test methods. New Waveform Set designators (G through K) were also added to cover the Multiple Burst and Multiple Stroke tests.

Pin injection

During pin injection testing, the EUT is normally powered, so that the circuits being tested are biased as they would be in normal operation. The test level is defined as an open circuit voltage (Voc) with a specified source impedance from the generator. For example, waveform 3, test level 2 specifies Voc as 250 volts, with a short circuit current (Isc) of 10 amps. The ratio of Voc to Isc yields a generator source impedance requirement of 25 ohms. The generator is adjusted to produce waveform 3 with these specified characteristics, and the transient waveform is then applied directly to the interface pins. After the pins have been tested, the EUT is evaluated to determine if its performance has been degraded.

Cable bundle tests

Cable Bundle Tests are performed using either Cable Induction or Ground Injection to couple the transient waveforms into the interconnecting cable bundles and power leads.

The cable induction test method uses an injection probe to induce the transient waveforms into interconnecting cables and power leads. The ground injection method is very similar to the cable induction method, except that the transient waveform is applied between the EUT case and the ground plane. The EUT is isolated from the ground plane by lifting all local grounds and returns, and insulating the case from the ground plane, which forces the injected transient into the cable shields and any other return paths back to the ground plane.

A Line Impedance Stabilization Network (LISN) must be inserted in series with each power lead and ungrounded power return lead, with a 10 uF capacitor connected between the power input of the LISN and the ground plane for AC powered equipment, or with a 33,000 uF capacitor connected across the power inputs of the LISNs for DC powered equipment. Unless otherwise specified, interconnecting cables shall be at least 3.3 meters in length, and power leads will be no more than 1 meter in length for these tests.

For each waveform, either a voltage or current test level is given, along with a current or voltage limit. For example, waveform 2, test level 3, specifies a voltage test level (VT) of 300 volts, and current limit (IL) of 600 amps. This means that during the test, the generator level is increased until the peak voltage measured on a single turn monitor loop placed thru the injection probe reaches 300 volts, or the monitored induced current in the cable or lead reaches the 600 amp limit.

Cable Bundle tests may be performed using the Single Stroke method only, or using a combination of the Single Stroke, Multiple Stroke, and Multiple Burst methods.

The Single Stroke test method is designed to represent the internal aircraft wiring response to the most severe external aircraft lightning strike. A single occurrence (stroke) of the specified test waveform is applied to the cable bundle or wire under test, and repeated for a total of 10 applications in each polarity.

The Multiple Stroke test method is designed to represent the induced effects to internal aircraft wiring in response to an external aircraft lightning strike that is composed of a first return stroke immediately followed by multiple return strokes (see Figure 5).

The Multiple Burst test method is

designed to represent the induced effects to internal aircraft wiring in response to an external aircraft lightning strike of a multiple burst nature (see Figure 6). The specified test waveform is applied to the cable bundle or wire under test, and repeated for at least 5 minutes in each polarity.

Equipment categories

Category designations consist of six characters that describe the pin and cable test Waveform Sets and test levels.

The 3 Pin Injection test waveforms are grouped together in two Waveform Sets (A & B). The 6 Cable Bundle test waveforms are grouped together in four Single Stroke Waveform Sets (C through F), and four combined Single Stroke and Multiple Stroke (G through K), and two Multiple Burst Waveform Sets (L& M).

What's new for DO-160G?

- Users Guide added, resulting in many notes and remarks being moved from the requirements section to the Users Guide. A vast amount of additional (helpful) information is included in the Section 22 Users Guide.
- The "resistor method" for determining the source impedance of the Pin-Injection test waveforms has been eliminated.
- Cable Bundle test Waveform 6 was added, for the Multiple-Burst test only. See Figure 3.
- Pin-Injection calibration and test setup figures were revised for clarity.

SECTION 23: LIGHTNING DIRECT EFFECTS

The tests in this section are performed to determine the ability of externally mounted electrical and electronic equipment to withstand the direct effects of a severe lightning strike. The equipment will not normally be powered during the test, and these tests usually cause damage (sometimes spectacular damage) to the EUT. High voltage and/or high current tests at levels of thousands of kilo-Volts and/or hundreds of kilo-Amps are required.

Equipment categories

Category designations consist of four characters that describe the nature and severity of the test waveforms applied. The first 2 characters designate the High Voltage Strike Attachment test category, and the last two characters designate the High Current Physical Damage test category. The designated test category for the EUT should correspond to the lightning strike zone in which the EUT will be installed on the aircraft.

What's new for DO-160G?

- No changes.

SECTION 25: ELECTROSTATIC DISCHARGE (ESD)

This test determines whether the EUT can operate as specified during and after being subjected to an electrostatic air discharge event. The test procedure and test generator used is similar to most other international ESD standards, except that the EUT is bonded to the ground plane and only air discharge is specified. Test points are chosen based on their accessibility to personnel, with 10 positive and 10 negative polarity discharges at 15 kV applied to each one.

Equipment categories

There is only one category (A), with a test level of 15 kV.

What's new for DO-160G?

- Clarification of applicability of test points, in particular, stating that connector pins are not to be tested.

THE LATEST FROM SC-135

At the most recent meeting of the RTCA Program Management Committee (which directs the activities of SC-135), where Revision G of DO-160 was approved, the decision was made to allow for a minimum of 5 years until another revision of DO-160 was released. The Program Management Committee revised the "Terms of Reference" for SC-135 to create a "stand-alone" document (possibly in the form of an appendix) that would contain all the Users Guide material for all sections of DO-160. Although no target date was given for the release of this new Users Guide, it is to be completed before the committee resumes work on the next revision of DO-160 (DO-160H).

SUMMARY

RTCA/DO-160, and its European twin, EUROCAE/ED-14, are truly the world standards for Electromagnetic Compatibility requirements for aircraft electronic equipment.

The test levels, requirements, and procedures are intended to reflect the "state-of-the-art" in aviation technology and EMC testing methodology.

Since both aviation technology and EMC testing methodology are evolving at a rapid rate, work is continuing on a comprehensive Users Guide covering all sections of RTCA/DO-160G and eventually, the next revision, DO-160H.

REFERENCES

- [1] RTCA/DO-160F, "Environmental Conditions and Test Procedures for Airborne Equipment," RTCA, Incorporated, December 2007.
- [2] RTCA/DO-160D, "Environmental Conditions and Test Procedures for Airborne Equipment," RTCA, Incorporated, July 1997.
- [3] MIL-STD-461F, "Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment," Dept. of Defense Interface Standard, December 2007.

Erik J. Borgstrom has worked in the EMC testing field for more than 24 years. He currently holds the position of EMC Operations Manager for Environ Laboratories LLC, and specializes in the EMC testing requirements for the Defense and Aerospace industries. Borgstrom is an active member of SAE Committees AE-2, where he leads the DO-160 Section 22 Task Group. He was also a member of the AE-4 (HIRF) Working Group, which worked on SAE document ARP5583 (HIRF Users Guide) Revision A, published in 2010. Borgstrom is one of Environ's representatives to RTCA, where he serves on Special Committee 135, as Change Coordinator for Section 22 (Lightning Induced Transient Susceptibility) and Section 25 (ESD) of DO-160. He can be reached at ejb@environlab.com

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On the Nature and Use of the 1.04 m Electric Field Probe

KEN JAVOR
EMC Compliance
Huntsville, Alabama USA

Repeatability problems have been noted with 1.04 m rod antenna measurements in the past (Jensen [1], Turnbull [2]). The problems noted center on resonances caused by the test set-up that result in erroneous measurements of field intensity with actual detected levels varying among test facilities. A complete history of the use of the 1.04 m rod antenna from the 1950s forward and test data showing the effects of different rod antenna use may be found in Javor [3].

Various vehicle-related standards utilize the 1.04 m rod antenna below 30 MHz. Military (MIL-STD-461 basic and all revisions), aerospace (RTCA/DO-160 basic through the E revision), and automotive EMI standards (CISPR 25-2002, among others) all make use of the rod antenna. To date, only MIL-STD-461F (2007) incorporates fixes to the resonance problem. And none of the other standards address the accuracy of the fundamental measurement, at frequencies where resonances are not a problem. Recently, Weston [4] criticized the MIL-STD-461F change. His main points are discussed herein.

Analytical modeling supported by experimental investigation shows that a floated counterpoise with transformer coupling between the rod antenna matching network and the test chamber ground provides the best performance at all frequencies. Experimental data shows the unacceptable perturbation caused by a grounded counterpoise. In addition to these particular issues, and as a means of making specific points, the general nature of the rod as an electric field probe, and the transfer function between field source and measured field intensity are explained.

INTRODUCTION

The 1.04 m rod "antenna" is electrically short at all test frequencies and does not function as a true antenna, which is a transducer that effectively radiates or receives "power" associated with electromagnetic fields. The rod is better understood as an electric field probe or sensor. The output impedance associated with the induced voltage in the rod is the reactance of 10 pF. Networks used with rod antennas are impedance matching devices which convert the rod's high impedance to a 50 Ohm output.

Use of the 1.04 m rod antenna has changed dramatically since its introduction in 1953 (MIL-I-6181B). Original use is shown in Figure 1, with the rod element connected directly to a battery-powered EMI receiver; the only ground connection being a very short bond strap to the tabletop ground plane. The first change allowed remote use of the EMI receiver from the antenna, which made EMI testing more practical, but introduced both a potential ground loop and also a difference in rf potential between the rod counterpoise and the EMI receiver. Another change increased the upper frequency at which the rod antenna was used from 25 to 30 MHz. This, coupled with a later change that increased separation between antenna and test sample from the original 12 inches to the present one meter

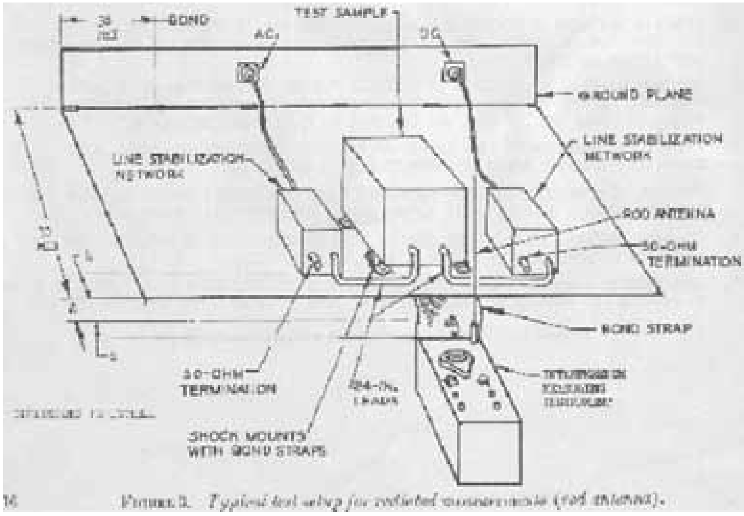


Figure 1a. *MIL-I-6181B use of 1.04 m rod antenna (ca. 1953).*

Figure 1b. *Recreation of Figure 1a.*

made the measurement more susceptible to test chamber resonances. There was good rationale for the changes, but measurement accuracy suffered. The counterpoise isolation proposed herein restores the integrity of the measurement set-up as originally configured.

The field sensing mechanism of the rod antenna is the effective potential difference between the rod base (counterpoise) and the rod tip. Since the rod's potential is measured relative to the counterpoise's potential, anything that affects the counterpoise's potential affects the measurement. This is the key point ignored by all present standards. Weston's critique [5] does not ignore the effect of the counterpoise, but that effort promotes the use of the grounded counterpoise, which references [1] – [3] as well as this effort show to be quite detrimental. Of all present standards, only MIL-STD-461F (2007) attempts to provide some control of the counterpoise potential. In so doing, MIL-STD-461F provides dampening of resonances occurring above 20 MHz.

Theoretical 1.04 m rod performance, actual performance of the traditional and the MIL-STD-461F implementation, and the proposed counterpoise isolation technique are compared herein. It is important to realize that "traditional" does not imply correct. In [3], evolution of the use of the 1.04 m rod antenna from the earliest days is explained and it is shown that what is now considered "traditional," due to common use since 1970, is in fact an aberration.

BACKGROUND

Analytical modeling and chamber testing described herein are based on a one meter long cable suspended 5 cm above a ground plane 10 cm back from the edge of the plane as shown in Figures 2 and 3. A level of -10 dBm was applied from 2 – 32 MHz driving a 50 Ohm termination. The -10 dBm level converts to 70.7 mV in a 50 ohm system. All data plots are 2-32 MHz. The test chamber size was 8' x 8' x 8', unlined. The lowest chamber resonance can be calculated from a commonly used equation to be 87 MHz, which is almost three times the highest measurement frequency of interest (30 MHz). Thus the fact that the measurements were made in a hybrid shield/screen room with no absorber lining does not affect measurement integrity. The rod antenna used was the Ailtech 95010-1, with a constant antenna factor of 8 dB/m from 10 kHz to 40 MHz. Data plots included herein are uncorrected raw antenna-induced potentials. The correlation of this data with analytical predictions is not obscured by any hidden factors. The rod antenna network was also used to measure counterpoise potentials with respect to the chamber floor. For this measurement, the network has 0 dB voltage gain and no correction factor is necessary for the actual voltage.

Figure 2. *Radiating structure, following common usage.*

EFFECTIVE FIELD STRENGTH MEASURED BY AN IDEAL 1.04 M ROD ANTENNA

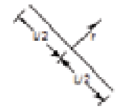
An analytical derivation is presented of the voltage developed on the 1.04 meter rod antenna due to radiation from a one meter long cable suspended 5 cm above a ground plane, spaced one meter away, as in Figures 2 and 3a. A separate but similar derivation is provided for the configuration of Figure 3b. The computed values will serve as targets

Figure 3a. *MIL-STD-462 Notice 2 through MIL-STD-461E, RTCA/DO-160 through -160E, CISPR 25-2002 rod antenna set-up.*

Figure 3b. *MIL-STD-461F rod antenna set-up.*

for the experimental measurements which follow. For those who wish to skip the derivation, here is an outline of what is involved. First the electric field from a line of charge and its image as described above is derived using Gauss' Law. Then the component of each field along the length of the rod antenna is developed, and then each of those fields is integrated along the length of the rod to get the induced potential. The end-to-end potentials due to the line and its image are summed and compared to the actual measurements and the results are captured in Table 1.

The derivation starts with the static (dc) equation for the electric field from a line of charge. The method of images is used to get the net electric field at any distance from a pair of positive and negative lines of charge. The vertical component of the net electric field is integrated over the line representing the 1.04 m rod antenna. The integration is the potential collected by the rod antenna. The static analysis is valid because the rod antenna measurement at one meter, below 30 MHz is a quasi-static measurement: both the radiating element and the receiving elements are electrically short (one-tenth wavelength or less), and the separation between radiator and pick-up is less than $\lambda/2\pi$, the accepted near field - far field boundary for a near isotropic radiator (λ being wavelength).



Drawing 1. *Radially directed electric field line from center of line of charge of length L.*

The radially symmetric electric field from the center of a line of charge of finite length L (drawing 1) is (Gauss' Law)

$$E = \frac{1}{2\pi\varepsilon_0}\frac{\rho_L}{r}\frac{1}{\sqrt{1+(2r/L)^2}} \qquad \textbf{Eqn. 1a}$$

where,
E is the radially directed electric field in Volts per meter,
ε_0 is the permittivity of free space (8.85 pF/m)
ρ_L is the linear charge density, Coulombs per meter
r is the radial separation from the line of charge, meters,
L is the length of the line of charge, 1 meter in our case.

In order to keep the math tractable, the first two terms of a binomial expansion of the radical term are retained.

$$\frac{1}{\sqrt{1+(2r/L)^2}} \quad \frac{L}{2r}\left[1-\frac{1}{2}\left(\frac{L}{2r}\right)^2\right]$$

This is accurate to within 4%. Equation 1a then reduces to

$$E \approx \frac{\rho_L L}{4\pi\varepsilon_0}\left[\frac{1}{r^2}-\frac{1}{8}\left(\frac{L^2}{r^4}\right)\right] \qquad \textbf{Eqn. 1b}$$

The only value not immediately available in equation 1b is the linear charge density. We can use the definition of capacitance to express the linear charge density in terms of the capacitance of the wire and the potential on it:

$\rho_L = q/L = CV/L$ **Eqn. 2**

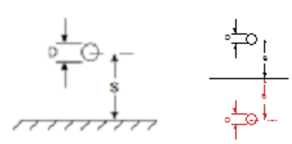
where,
q is charge, Coulombs,
C is capacitance in Farads, and
V is the potential on the line, in Volts

In the above, we have everything but the capacitance of the wire. In order to evaluate that, we have to evaluate the expression for the capacitance of a two wire line.

From Barnes [5], we have

$$C(pF/m) = \frac{\pi\varepsilon_0}{\ln\left[S/D+\sqrt{(S/D)^2-1}\right]} \qquad \textbf{Eqn. 3}$$

where S and D are as in drawing 2a.



Drawing 2a. *Geometry for wire above ground on left, geometry for capacitance calculation on right. Because separation between wire & image is twice that in actual set-up, the value plugged into equation 3 for S is 10, not 5 cm.*

For values of S = 5 cm, and D = 1mm (AWG 18), we get C = 5.25 pF/m. Actual cable length was 1.1 m.

Using equation 2, we compute the linear charge density, knowing that the line potential is -10 dBm, or 97 dBuV, or 70.7 mV.

ρ_L = 5.25 pF/m*1.1 m * 0.07 Volts = 0.4 pC/m

Substituting into equation 1b (and noting that L = 1.1 meter, we have the equation for the electric field from the wire of our test set-up, but ignoring the effect of the ground plane.

$$E^{+}(x) = 3.6\ mV\left[\frac{1}{r^2} - \frac{1.21}{8r^4}\right] \qquad \textbf{Eqn. 4}$$

Using the method of images (drawing 2b), we calculate the electric field from an identical line of opposite charge 5 cm below the ground plane. The symmetry of the situation is such that between –d/2 and d/2, the horizontal components of the two field lines cancel precisely, but the vertical components add, and they add in a negative sense. Above d/2 the contribution from the two wires are in opposite phase and tend to cancel.

Given the geometry of drawing 2b, the expression for the electric field from the above ground wire is

$$E^{+}(x) = 3.6\,mV\left[\frac{1}{x^2 + D^2} - \frac{1}{8}\frac{1.21}{(x^2 + D^2)^2}\right] \qquad \textbf{Eqn. 5a}$$

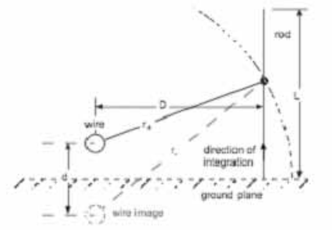
where x is vertical displacement from the point on the rod opposite the wire closest to the region of integration.

Equation 5a is the magnitude of the radially directed electric field; we desire the vertical component parallel to the rod. From the geometry of drawing 2b, the expression for the vertical component of the field is

$$E^{+}_{\smile,}(x) = 3.6\ mV\left|\frac{1}{x^2 + D^2} - \frac{1}{8}\frac{1.21}{(x^2 + D^2)^2}\right| * \frac{x}{\sqrt{x^2 + D^2}}$$

or

$$E^{+}_{\smile,}(x) = 3.6\ mV\left[\frac{x}{\sqrt{x^2 + D^2}^{3}} - \frac{1}{8}\frac{1.21x}{\sqrt{(x^2 + D^2)}^{5}}\right] \qquad \textbf{Eqn. 5b}$$



Drawing 2b. *Method of images geometry.*

We can similarly calculate the electric field from the line of charge below the ground plane, which is removed vertically by a separation of d.

$$E^{-}(x) = -3.6\ mV\left[\frac{1}{(x+d)^2 + D^2} - \frac{1}{8}\frac{1.21}{\{(x+d)^2 + D^2\}^2}\right]$$

when x≥ d/2, and **Eqn.5c**

$$E^{-}(x) = -3.6\ mV\left[\frac{1}{(x+d/2)^2 + D^2} - \frac{1}{8}\frac{1.21}{\{(x+d/2)^2 + D^2\}^2}\right]$$

when 0 < x < d/2 **Eqn.5d**

Just as above, this is the magnitude of the radially directed field; we desire the vertical component, which is (x≥d/2)

or

$$E^{-}(x) = -3.6\,mV\left[\frac{1}{(x+d)^2+D^2} - \frac{1}{8}\frac{1.21}{\{(x+d)^2+D^2\}^2}\right] * \frac{x+d}{\sqrt{(x+d)^2+D^2}}$$

$$E^{-}(x) = -3.6\,mV\left[\frac{x+d}{\sqrt{(x+d)^2+D^2}^{\,3}} - \frac{1}{8}\frac{1.21(x+d)}{\sqrt{(x+d)^2+D^2}^{\,5}}\right] \quad \textbf{Eqn. 5e}$$

and (when 0 < x < d/2)

$$E^{-}(x) = -3.6\,mV\left[\frac{x+d/2}{\sqrt{(x+d/2)^2+D^2}^{\,3}} - \frac{1}{8}\frac{1.21(x+d/2)}{\sqrt{(x+d/2)^2+D^2}^{\,5}}\right] \quad \textbf{Eqn. 5f}$$

The potential induced along any curve due to an electric field impinging upon it is given in general by

$$\mathrm{V} = \int_{rod\ base}^{rod\ tip} \underline{\mathbf{E}} \cdot d\underline{\mathbf{l}} \quad \textbf{Eqn. 6a}$$

where the integral is understood to be a line integral, with electric field in the direction of the curve at every point being summed over the length of the curve.

In the case of the rod antenna, we are integrating over its length, starting at the base and ending at the tip 1.04 meters above it. We can calculate the potential from the above ground wire, and then separately calculate the potential due to the image wire, and then, carefully taking into consideration the signs, combine the different contributions to arrive at the net potential induced in the rod. In order to perform the integration, the various expressions for the electric field from the above ground wire (equation 5b) and the image wire (equations 5e when x≥d/2 and equation 5f when 0 < x < d/2) are substituted for **E** in equation 6a, and dx substitutes for d**l**. Because the vertical components of the electric field are parallel to the rod, the dot product of equation 6a becomes a simple scalar multiplication.

In addition to separate expressions for the electric field from the image wire according to whether x is either less than or greater than d/2, the signs of the fields must be properly treated. From 0 to d/2, the contributions from the wire and its image add because the vertical component of each field is downwards. Above d/2, the vertical components are oppositely directed, and they subtract from each other. In the case of the MIL-STD-461F set up, with part of the rod below the ground plane, there is a short region below the ground plane where the field contributions from wire and image again subtract, but the signs of each contribution are opposite what they are when x > d/2 above the ground plane. It is also important to note that the range of integration is not based on the rod antenna as an absolute, but in relationship to where the radiating wire is. The radiating wire closest to the zone of integration is the zero point for integrating. Thus in some cases we integrate up from some point along the rod, and down the other direction from that point.

Between 0 and d/2 along the rod antenna, the electric field from the wire above the ground plane contributes a potential given by

$$V^{+} = -3.6\,mV\int\left[\frac{x}{\sqrt{x^2+D^2}^{\,3}} - \frac{1}{8}\frac{1.21x}{\sqrt{(x^2+D^2)}^{\,5}}\right]dx \quad \textbf{Eqn.6b}$$

Between d/2 (5 cm) and 1.04 meter along the rod antenna, the electric field from the wire above the ground plane contributes a potential given by

$$V^{+} = 3.6\,mV\int\left[\frac{x}{\sqrt{x^2+D^2}^{\,3}} - \frac{1}{8}\frac{1.21x}{\sqrt{(x^2+D^2)}^{\,5}}\right]dx \quad \textbf{Eqn. 6c}$$

Between 0 and d/2 along the rod antenna, the electric field from the image wire contributes a potential given by

$$V^{-} = -3.6\,mV\int\left[\frac{x+d/2}{\sqrt{(x+d/2)^2+D^2}^{\,3}} - \frac{1}{8}\frac{1.21(x+d/2)}{\sqrt{x+d/2)^2+D^2}^{\,5}}\right]dx \quad \textbf{Eqn. 6d}$$

Between d/2 (5 cm) and 1.04 meter along the rod antenna, the electric field from the image wire contributes a potential given by

$$V^{-} = -3.6\,mV\int\left[\frac{x+d}{\sqrt{(x+d)^2+D^2}^{\,3}} - \frac{1}{8}\frac{1.21(x+d)}{\sqrt{x+d)^2+D^2}^{\,5}}\right]dx \quad \textbf{Eqn. 6e}$$

Integrals of the form

$$\int\left[\frac{x+a}{\sqrt{(x+a)^2+D^2}^{\,3}}\right]dx = \frac{-1}{\sqrt{(x+a)^2+D^2}} \quad \text{and} \quad \int\left[\frac{x+a}{\sqrt{x+a)^2+D^2}^{\,5}}\right]dx = -\frac{1}{3}\frac{1}{\sqrt{x+a)^2+D^2}^{\,3}}$$

Equation 6b simplifies to

$$V^{+} = 3.6\,mV\left[\frac{1}{\sqrt{x^2+D^2}} - \frac{1}{24}\frac{1.21}{\sqrt{x^2+D^2}^{\,3}}\right]$$

with x running from 0 to d/2.

Eqn. 6f

Equation 6c simplifies to equation 6f with a change of sign out front.

$$V^{+} = -3.6\,mV\left[\frac{1}{\sqrt{x^2+D^2}} - \frac{1}{24}\frac{1.21}{\sqrt{x^2+D^2}^{\,3}}\right]$$

with x running from d/2 to 1.04 meters.

Eqn. 6g

Equation 6d simplifies to

$$V^{-} = 3.6\,mV\left[\frac{1}{\sqrt{(x+d/2)^2+D^2}} + \frac{1}{24}\frac{1.21}{\sqrt{(x+d/2)^2+D^2}^{\,3}}\right]$$

with x running from 0 to d/2.

Eqn. 6h

Equation 6e simplifies to

$$V^{-} = 3.6\,mV\left[\frac{1}{\sqrt{(x+d)^2+D^2}} + \frac{1}{24}\frac{1.21}{\sqrt{(x+d)^2+D^2}^{\,3}}\right]$$

with x running from d/2 to 1.04 meters.

Eqn. 6i

Three problems of interest are the "traditional" or MIL-STD-461E set-up, MIL-STD-461F, and a variation on the traditional approach where the antenna electronics box at the base of the rod sits on top of the counterpoise instead of below it. We use equations 6f – i to calculate all the various potentials from the wire above ground and its image. Then we sum all the contributions. This represents the open circuit potential between the rod base and tip and also the effective field intensity. Half this calculated potential is the open circuit potential on the rod, loaded and then amplified by the rod antenna base and presented into 50 Ohms.

"Traditional" or MIL-STD-461E calculation - Solve for the potential on the rod antenna from the radiating wire when the base of the rod antenna is the same height as the ground plane, and one meter away (Figure 3a).

Between 0 and d/2 along the rod antenna, the electric field from the wire above ground contributes an induced potential on the rod between 0 and d/2 of -3.6 uV (equation 6f).

Between 0 and d/2 along the rod antenna, the electric field from the image wire contributes a potential given by equation 6h of -15.4 uV (equation 6h).

Thus the total potential induced from 0 to 5 cm is -19 uV.

Equation 6g yields a potential of 938 uV induced between 5 cm and 1.04 meters due to the field from the wire above ground.

Equation 6i yields a potential of -1283 uV induced between 5 cm and 1.04 meters due to the field from the image wire.

The sum of the potentials over the whole rod is -364 uV, or 51.2 dBuV. Per above discussion, this means the effective field intensity is 51.2 dBuV/m and the unloaded potential appearing at the base of the rod to be amplified is 45.2 dBuV. Because the Ailtech 95010-1 rod antenna used in this effort loads the open-circuit potential by 2 dB, then provides 0 dB voltage gain, the output to an EMI receiver would be 43.2 dBuV, or -63.8 dBm.

This is what we expect to measure when configured as in Figure 3a. We also have independent verification that this value is in the right ballpark. The rationale appendix of MIL-STD-461D/E/F cites a relationship between rf potential on a 2.5 meter wire below 30 MHz and the radiated quasi-static electric field intensity. The transfer function is stated to be that the electric field intensity is 40 dB down from the rf potential. In the set-up used in this investigation, the wire is only 1.1 meter long, therefore we expect the transfer function to be 4.25 dB less efficient based on the wire length dependence of equation 1a, or 44.25 dB down. Starting with a wire potential of 97 dBuV, we expect a field intensity of 52.75 dBuV/m. The 51.2 dBuV/m calculation agrees within 1.55 dB.

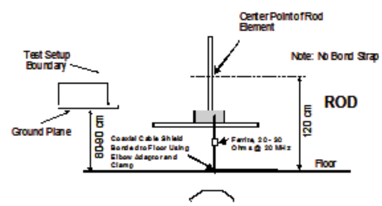
A similar calculation is performed when analyzing rod antenna performance for the Figure 3b MIL-STD-461F set-up. Only the limits of integration differ because of the relative position of the rod antenna and the radiating wire, per drawings 2c and d.

Referring to drawing 2d, the region 1 analysis is the same as that previously for x greater than d/2. Vertical components of the electric field from the wire and its image are opposite in sense and therefore subtract. In region 2, vertical components of the electric field from both wires are equal in magnitude and reinforce downwards. In region 3, the situation is as in region 1, but the sense of the vectors is reversed. Integration limits given with the rod base as zero, but to integrate properly, the closest radiating wire position is the zero point, as previously discussed.

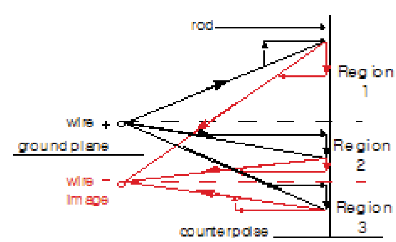
In region 1, limits of integration are d/2 to the rod tip (0.27 m to 1.04 m referenced to the base of the rod as ground). The contribution from the above ground wire evaluates equation 6g with these limits of integration to yield 657 uV. The contribution from the image wire evaluates equation 6i with these limits of integration to yield -966 uV. So the net potential induced in the rod from 5 cm above tabletop to the tip of the rod is -309 uV.

In region 2, the limits of integration are –d/2 to d/2, and there is symmetry making the problem easier to handle. The contribution from both the above ground wire and its image are equal and in the same sense, which is negative. So our computation is twice the result of the above ground wire equation 6f with limits of integration 17 to 27 cm and a change in sign. This comes to -30 uV.

In region 3, the limits of integration are x running from the rod base (68 cm above the floor) to -d/2 (85 cm above the floor), with the bench-top ground plane at 90 cm above ground. The sense of the contributions is opposite from region 1: the vertical electric field component from the above ground wire points downwards (negative), and the vertical electric field component from the image wire points up, positive. Further, equation 6g which was derived for the above ground wire now applies to the image wire, and equation 6i, which was derived for the image wire now applies to the above ground wire. The contribution from the above ground wire evaluates equation 6i with these limits of integration to yield -122 uV. The contribution from the image wire evaluates equation 6g with these limits of integration to yield 43 uV. These sum to yield -79 uV.



Drawing 2c. *MIL-STD-461F rod antenna set-up.*



Drawing 2d. *Geometry for limits of integration of drawing 2c.*

The sum of the potentials induced in regions 1 – 3 is -418 uV, or 52.4 dBuV, so the effective field intensity is 52.4 dBuV/m. That translates to -62.5 dBm at the EMI receiver. This is about 1 dB higher than that predicted for the MIL-STD-461E case where the rod antenna base is level with the ground plane, and is within 0.5 dB of the 40 dB relationship cited in the MIL-STD-461F RE102 appendix.

There is one final wrinkle to be analyzed. MIL-STD-461F precisely controls the height of the rod by stating its center point is 120 cm above the floor. But the earlier technique doesn't control the rod height, because some rod bases are designed to fit under the counterpoise, which is generally level with the tabletop ground plane, and some rod antenna bases, such as that used in this investigation, are designed to mount on top of the counterpoise, thus boosting the rod height by the height of the road antenna base. The rod antenna base used in this investigation was 12 cm tall, and in the author's experience, is about as tall as they come. The effect of using this base on top of the counterpoise is now

Figure 4a. *Rf potential on radiating wire loaded by 50 Ohms. Span is 2-32 MHz, reference is 10 dBm, 10 dB per division (-10 dBm = 97 dBuV).*

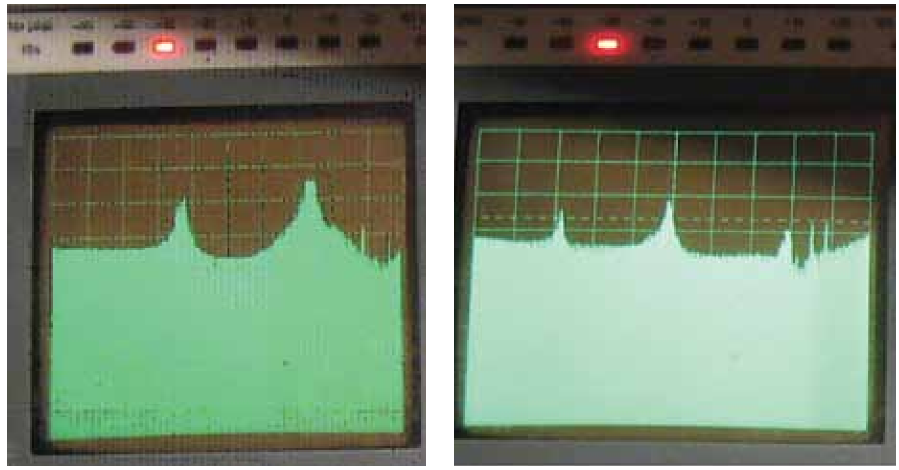
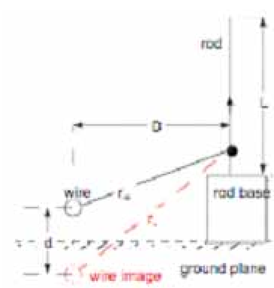


Figure 4b. *Radiated signature using Figure 3a antenna configuration, scanning 2-32 MHz, reference level is – 30 dBm. For picture on left, coax connection to chamber was 12 feet, on the right it was 24 feet. Uncorrected data; field intensity would be 8 dB higher than levels shown.*

analyzed. The analysis follows that for the traditional set-up, except that the limits of integration are from the base of the rod 12 cm above ground to 1.04 meter above that – there is no need to break the integral into different parts, because the vectors now all have the same sense with respect to each other over the entire rod length.

Per drawing 2e we integrate directly from the base at 12 cm above ground to the top of the rod at 1.04 meters plus 12 cm. Note that this makes the limits of integration 7 cm to 1.04 meters plus 7 cm, because our zero point is the wire above ground height of 5 cm.



Drawing 2e. *More exact simulation of Figure 3a.*

Equation 6g evaluates the contribution from the above ground wire as 938 uV. Equation 6i evaluates the contribution from the image wire as -1282 uV. The net result is -344 uV, or 50.7 dBuV. This means an effective field intensity of 50.7 dBuV/m, and the EMI receiver will read -64.3 dBm.

Analytical results for the three measurements of the same radiating wire are compared to measurements presented in section IV. Analytical and measured results for all methods agree well, except for resonances, which is why the MIL-STD-461F approach came about.

Method	Predicted E-field. dBuV/m	Predicted EMI Rcvr rd'g dBm	Meas'd dBm**	Agreement within (dB)
-461E:	51.2	-63.8	-63***	0.8
-461F	52.4	-62.5	-63	0.5
461E*	50.7	-64.3	-64.5	0.2

*antenna base on top of ground plane
**from section IV measurements section
*** absent resonances

Table 1. *Comparison of analytical and measured results.*

The analytical results make the following issues clear: the calculation of rod-coupled potential does not depend on counterpoise configuration. It was not discussed previously, but the only purpose of the counterpoise is to achieve the 10 pF source impedance of the 1.04 meter rod. Absent a counterpoise, that value decreases markedly. A counterpoise is a reference against which the rod antenna induced potential

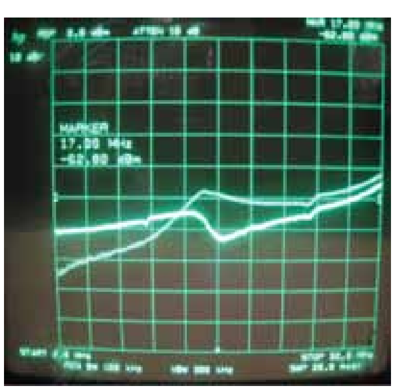


Figure 4c. *Counterpoise potential and rod antenna output super-imposed. Ground plane potential is the curve that is lower at the low end and higher after 14 MHz (2-32 MHz sweep, 17 MHz at center).*

Figure 4d. *Impedance between floor and counterpoise of MIL-STD-461F configuration w/o rf sleeve.*

is measured. *Since the potential at the base of the rod is taken with respect to the counterpoise, if the counterpoise potential is disturbed, the measurement will be off.* This is key in designing the proper set-up. The proper counterpoise configuration is the main subject of the following section.

EXPERIMENTAL VERIFICATION

First, the problem. The traditional Figure 3a set-up yields the cable length (and chamber size) dependent resonances of Figure 4b. Figure 4a is the rf potential on the radiating wire for comparison (stimulus vs. response).

Since the source potential is constant with frequency, we expect the measured radiated field to be likewise, based on the analytical section. Therefore we recognize that the Figure 4b performance is indicative of a problem with the test set-up. This observation and the description of the traditional set-up point out two problems with [4]. [4] doesn't show the radiating source potential, only the radiated fields. Departures from a flat response are observed over the entire 2-30 MHz band. It is not clear in [4] how much of the peaks are due to problems in the rod antenna set-up vs. problems in the radiating element. Secondly, Weston in [4] uses ferrite sleeve lining over the coax connection in both the -461E and -461F set-ups. None of the other the other standards besides MIL-STD-461F require such treatment. Weston displays a knowledge of the problems with MIL-STD-461E in so doing, but for the purposes of comparing and contrasting MIL-STD-461E and MIL-STD-461F methods, one cannot use ferrite sleeve lining in the MIL-STD-461E set-up because there is no requirement to do so.

The source of the resonance problem is the reactive impedance between counterpoise and chamber ground. This consists of the capacitance between the counterpoise and the chamber surfaces, as well as the parallel inductance of the coaxial transmission line shield acting as a ground strap between counterpoise and chamber. Both the capacitance and inductance will be chamber specific. The counterpoise is one plate of a capacitor working mainly against the floor; the effective plate size is the arithmetic average of the counterpoise area and the floor area. Since the size of chambers is uncontrolled (above some minimum), the capacitance will be larger than some minimum value, but otherwise unconstrained. Note that the capacitance depends mainly on the floor size; even if the counterpoise area approaches zero, the floor size sets the effective plate size. The length of coax cable interconnect is clearly dependent on room size and layout, and is even less controlled than the capacitance. Measurements made in the EMC Compliance chamber showed capacitance of 50 pF and inductance close to 0.5 uH. And that was using the MIL-STD-461F configuration less the rf sleeve; the inductance would have been much higher with a long length of coax. For the values measured, the

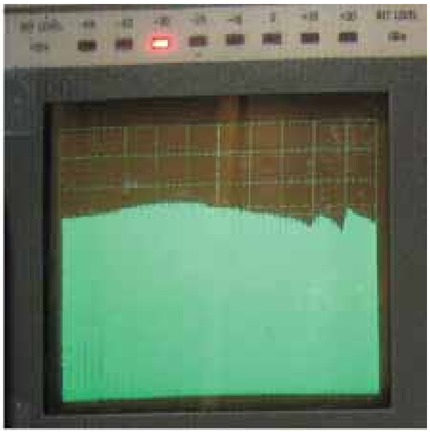


Figure 5a. *MIL-STD-461F-type rf sleeve resonance detuning. Analyzer settings same as for Figure 4b.*

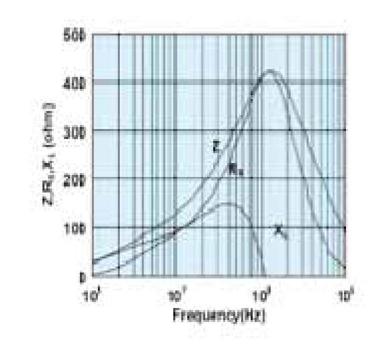


Figure 5b. *Impedance plots of Fair-Rite part 0431176451.*

parallel resonance (open-circuit) is at 31.8 MHz. This is just above the range of resonances seen at most facilities; a longer cable and larger floor area would have dropped the resonance below 30 MHz, where it is normally found. Figure 4c shows the actual potential on the MIL-STD-461F counterpoise with an rf sleeve to dampen the resonance. The potential measured out of the rod antenna base is also superimposed. Regardless of what the rod output is, it is measured with respect to the counterpoise, and the effect is very clear in Figure 4c. Figure 4d is a network analyzer measurement of the impedance between floor and counterpoise in a full-sized MIL-STD-461 test chamber. The inductive nature of the coax ground connection (less rf sleeve) and the resonance with capacitance is quite clear. Again, a longer coax connection to ground ("traditional") configuration, would have moved the resonance to a lower frequency.

In Figure 5a, the plot is for the MIL-STD-461F configuration, Figure 3b, using an rf sleeve solution that meets or exceeds MIL-STD-461F requirements. That solution, shown lying on the floor in Figure 6a, consists of four Fair-Rite 0431176451 sleeves, with a wire running through them that connects to a 270 Ohm resistor. The inductive reactance of these four sleeves (Figure 5b) in series is much greater than 270 Ohms, and the sleeves act as a transformer, with the 270 Ohm resistance being the impedance of the coaxial ground connection at and above 20 MHz. The total assembly is shown in Figure 6a.

Finally, the optimal solution, which is a totally floated counterpoise. A Mini-Circuits FTB1-6 balun was used as an isolation transformer to isolate the counterpoise from chamber ground, as shown in Figure 6a. Figure 6b shows the rod antenna set-up. Figure 6c shows the resultant plot.

At this point it is reasonable to ask how Figure 6c results stack up against "reality." "Reality" defined as the set-up of Figure 7a, with all elements working against the floor of the chamber. Figure 7b shows the results which are about 2 dB lower than the Figure 6c results, for the reason that the rod starts off 12 cm above the floor, as detailed in the theory section. Agreement with theory is within 0.2 dB at the mid-point frequency.

THE EFFECT OF GROUNDING THE COUNTERPOISE

Imagine that instead of the typical EMI test set-up with a test sample and cables on a copper-top bench and a 1.04 meter rod antenna spaced a meter away, that the rod antenna is between the plates of a parallel plate transmission line or TEM cell that has enough separation between the plates to mount the rod antenna with room left over above the top of the rod. For specificity, imagine the plate to be 2.5 meters tall, with the base of the rod antenna resting on (ohmically attached to) the bottom (ground) plate. Such a plate should be well behaved at frequencies up to the 2.5 meter height representing a tenth wavelength, or 12 MHz. If an rf potential, V, is applied to the top plate relative to the bottom plate, then the electric field near the middle of the plate (ignoring fringing) will be [V/2.5] Volts per meter straight up and down perpendicular to the area of the plates. The rod antenna output, corrected for antenna factor, should yield this same electric field. Now imagine that the rod

Figure 6a. *Rf sleeves and resistor that place 270 Ohms between counterpoise and floor above 20 MHz, and isolation transformer that floats counterpoise.*

Figure 6b. *MIL-STD-461F configuration using isolation XFMR visible near floor ground point. Assembly to the right is the rf sleeve network that gave the plot of Figure 5a.*

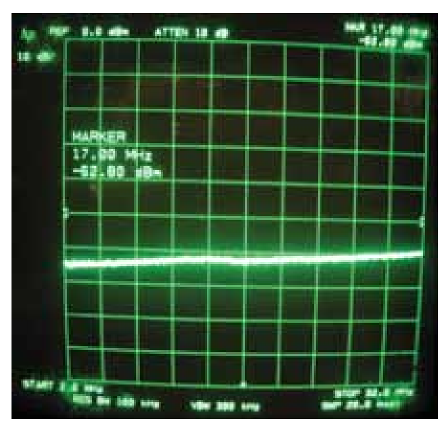


Figure 6c. *Resultant plot from set-up of Figure 6b. Note close agreement with theory (-62.5 dBm).*

Figure 7a. *"Reality" check configuration. Separation of radiating line from back wall the same as when on table-top ground plane.*

antenna base is raised off the bottom plate about 60 cm, the approximate height as required by MIL-STD-461F. What will the rod antenna indicate the field to be in this new position? We know the field is constant, so we should get the same answer. The integration along the rod will yield the same result, because the field is constant. If the rod antenna base and attached counterpoise is floated, then indeed we will ge t the same answer, because the rod potential is measured against its base, and all that has happened is that the rod top and base are at different potentials with respect to the ground plate, but the potential difference between top and base has not changed. But if we connect the antenna base/counterpoise to the ground plate, we are now creating a new ground 60 cm higher than previously, and that means the electric field is now the potential on the top plate divided by 2.5 meters less 60 cm, or [V/1.9] V/m. Clearly the electric field intensity has increased, and we will read this new value. Figure 3 of [4] includes supporting data. Measurements made above a floated counterpoise using a balanced antenna in lieu of a rod where the rod would normally be are much flatter and lower than with the counterpoise grounded.

It seems reasonable based on this model, that floating the counterpoise perturbs the field less than grounding it, and on this basis a floated counterpoise appears the best solution.

CONCLUSION

The 1.04 meter rod is an electric field probe, not an antenna. The analytical section demonstrates this by performing a static computation of the output of such a rod when exposed to a well-defined source field. Close correlation with experimental results establishes the probe-like nature of the rod "antenna." A key point is made that the measured potential induced in the rod is compared to the potential of the counterpoise. If the counterpoise potential is different than the ground of the measurement facility, errors ensue. Further, if the counterpoise ground connection disturbs the field being measured, the act of measuring then disturbs what is being measured. Three typical set-ups for measuring electric field intensity with a 1.04 meter rod antenna have been described. Of the three techniques discussed, a floated counterpoise is the best overall solution. The MIL-STD-461F solution comes in second, and indeed is very close if the rf sleeve makes the coaxial ground connection resistive rather than inductive. The "traditional" technique connecting the counterpoise to the table-top ground plane and using a ground connection of indeterminate length (coax connection) between the antenna base and chamber ground causes unacceptable resonances.

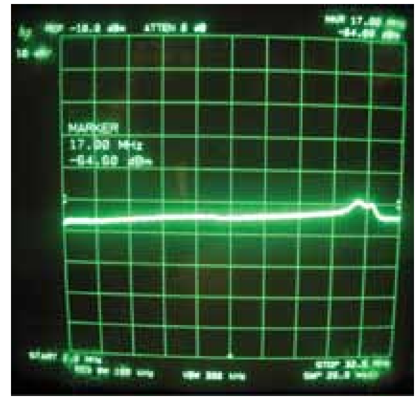


Figure 7b. *"Reality" check data plot. Level within 2 dB of the MIL-STD-461F configuration (Figure 6c).*

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KEN JAVOR has worked full time in the field of military and aerospace EMC since 1980. He is an industry representative to the DoD Tri-Service Working Groups that write MIL-STD-464 and MIL-STD-461. He founded EMC Compliance in 1992, providing EMC expertise to government and industry both in running EMC control programs, providing training on E3-related topics, and testing and solving problems.

Numerical Solution of Complex EMC Problems Involving Cables with Combined Field / Transmission Line Approach

MARLIZE SCHOEMAN
ULRICH JAKOBUS
EM Software & Systems – S.A. (Pty) Ltd
Stellenbosch, South Africa

Many problems of electromagnetic compatibility and interference involve cables, which either radiate through imperfect shields and cause coupling into other cables, devices or antennas, or which receive (irradiation) external electromagnetic fields (radiated from antennas or leaked through other devices) and then cause disturbance voltages and currents potentially resulting in a malfunctioning of the system.

From the background that in modern systems cables play such a dominant role (e.g. in the automotive environment a car these days has several kilometers of cables) it is crucial that already in the design process of electromagnetic systems such coupling / radiation / irradiation effects involving cables are taken into account from an EMC perspective. A simple example for this is shown in Figure 1 (cable bundle inside a car).

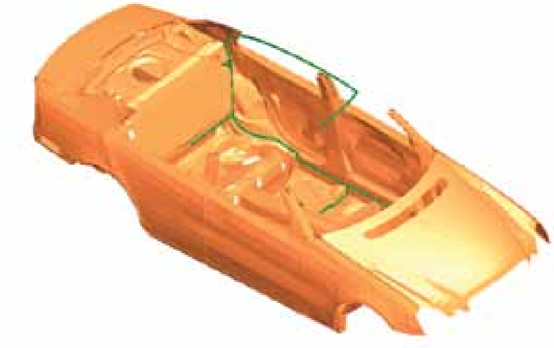

Figure 1. Generic car model including a cable path.

Shortened design cycles do not leave time to perform extensive measurements and correct the system, rather designs are done using CAD without physical models and only final verification / compliance measurements are done. To this end, we review in this article the solution of combined electromagnetic field / cable problems and their numerical solution with computer simulation techniques. All the formulations and examples presented in this paper are based on FEKO [1], which in its Suite 6.1 release provides such integrated cable modeling facilities in both the computational kernel and the user interface (traditionally FEKO has been a field computation package with interfaces to various other cable modeling codes).

COMPUTATION OF ELECTROMAGNETIC FIELDS

The central aspect of modeling both the radiation and irradiation of cables in a complex environment (e.g. Figure 1 cable in an automotive environment) is, besides the cable modeling as such, the ability to compute electromagnetic fields.

An example of such an electromagnetic field problem (without cable) is shown in Figure 2 where a log-per EMC measurement antenna is radiating and exciting electromagnetic fields which interact with the

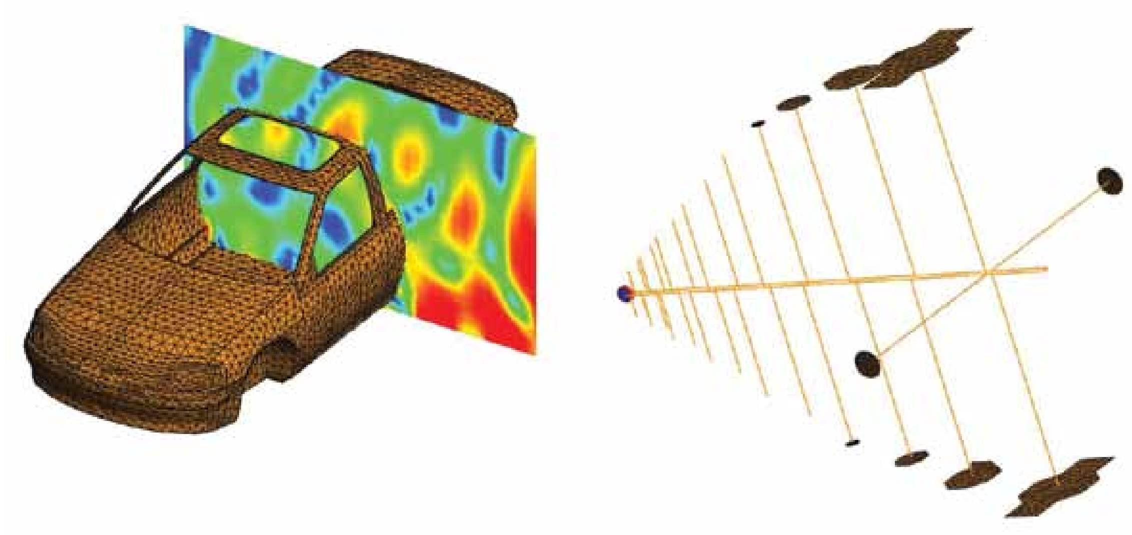

Figure 2. Log-per antenna radiating electromagnetic fields which interact with the device under test (here a car body) and cause an interference pattern.

device under test (here a car) and the near-field depicted in this figure shows the resulting interference pattern.

To solve such problems, FEKO is based on the Method of Moments (MoM) [2]. Metallic surfaces are discretized into triangular patch elements and wires are meshed into segments (with mesh elements being small compared to the wavelength), and then with certain basis functions the currents and charges are represented on this mesh with unknown complex coefficients. A procedure similar to the classic implementation of Rao, Wilton, and Glisson (RWG) in [3] is followed to obtain these unknown coefficients by solving a system of linear equations, which for open bodies (i.e. with holes / apertures) is derived from the electric field integral equation.

As compared to this traditional formulation (the RWG basis functions celebrate their 30th birthday this year), many improvements have been made over the years. For instance, in FEKO not only metallic but also dielectric bodies can be handled, special formulations for shielding from finite conducting material are available, a fast frequency sweep based on adaptive interpolation techniques, using current computer technologies like multi-core, parallel cluster processing or also GPU computing, or special solution techniques exist for integrated windscreen antennas [4] (common in many modern cars).

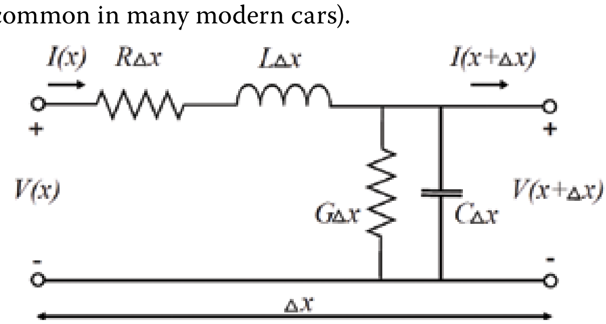

Figure 3. Distributed parameters for an incremental length of transmission line.

Despite this, one might find the solution of high frequency problems with the MoM is too challenging even on modern computers (due to memory and run-time constraints). To overcome this problem, we have hybridized the MoM with special high frequency techniques (such as Physical Optics or Diffraction Theory), and have accelerated the MoM leading to the Multilevel Fast Multiple Method (MLFMM) [5] or using Adaptive Cross Approximation (ACA) [6]. For complex problems involving multiple media also a full bi-directional FEM/MoM hybrid method is available [7] (FEM = Finite Element Method).

SOLUTION OF COMPLEX CABLE PROBLEMS

Multi-Conductor Transmission Line (MTL) Theory

In principle, the methods presented in the previous section (MoM, MLFMM, FEM etc.) can solve arbitrary problems, which also include cables. For such a solution, then all the details would have to be included in the model and discretized (e.g. multiple wires in a cable bundle, all the dielectric insulations, shields etc.). For practical problems, this is not possible (for simple problems it is possible and will be done later for some validation examples). In the following we give a review of the Multi-Conductor Transmission Line (MTL) Theory which can solve complex cable problems very efficiently.

In many ways transmission line theory bridges the gap between full wave solutions and basic circuit theory. As such, the phenomenon of wave propagation on transmission lines can be approached from an extension of circuit theory or from a specialization of Maxwell's equations.

As shown in Figure 3 an incremental length of a two-conductor transmission line can be described by the Telegrapher's equations [8]

$$\frac{dV(x)}{dx} + ZI(x) = 0$$
$$\frac{dI(x)}{dx} + YV(x) = 0$$

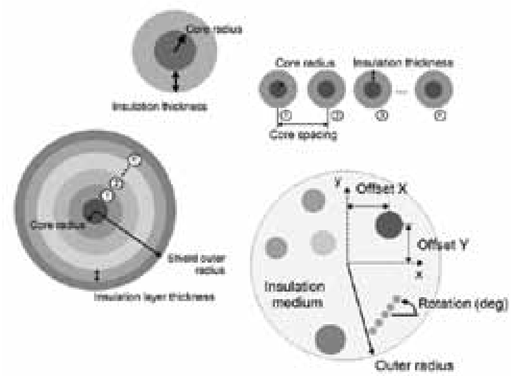

Figure 4. *Selection of some of the cable types supported in FEKO.*

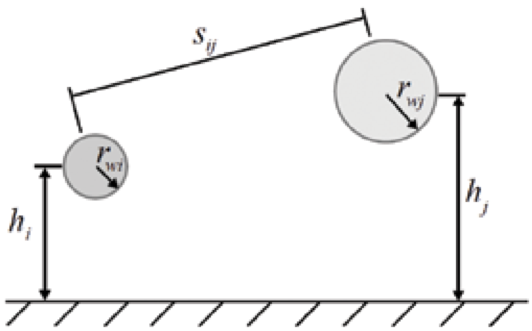

Figure 5. *Parameters for the computation of the per unit length inductances of widely separated wires above a ground plane.*

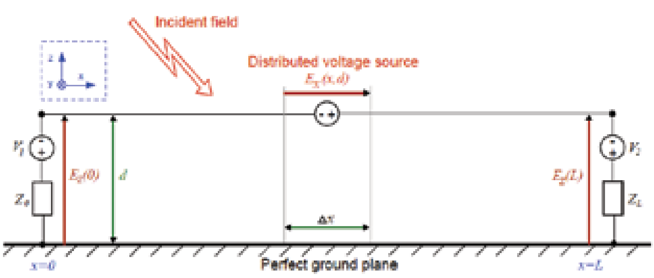

Figure 6. *Field excitation of a transmission line using only voltage sources (Agrawal method).*

where x denotes the longitudinal direction and parameters Z and Y are the per unit length impedance and admittance parameters of the line

$Z = j\omega L + R$

$Y = j\omega C + G.$

As a generalization to the two-conductor system, a multi-conductor transmission line model is simply a distributed parameter network for an arbitrary cable cross section (see Figure 4) where the voltages and currents can vary in magnitude and in phase over its length.

Per Unit Length Cable Parameters

The per unit length parameters of inductance, capacitance, resistance and conductance are essential ingredients in the determination of transmission line voltages and currents from the solution of the transmission line equations. All of

Entry	Analytical [pF/m]	FEM Solver [pF/m]	Relative Error [%]
C11	14.9395	14.9718	0.22
C12	-6.0894	-5.5062	9.58
C22	18.8111	18.7565	0.29
C13	-1.6117	-1.4734	8.58
C23	-6.0894	-5.5069	9.56
C33	14.9395	14.9710	0.21

Table 1. *Transmission line per unit length capacitance matrix entries for three widely spaced conductors above ground: Comparison of analytical values with the numerical static FEM solution.*

the cross sectional dimension information about a specific line is contained in these parameters.

Under the fundamental transverse electromagnetic field structure assumption, the per unit length parameters of inductance, capacitance, and conductance are determined as a static solution to Laplace's equation $\nabla^2 \phi(x,y)=0$ in the two-dimensional cross sectional (x,y) plane of the line. The determination of the per unit length parameters can be simple or very difficult depending on whether the cross sections of the conductors are circular or rectangular, and whether the conductors are surrounded by a homogeneous or an inhomogeneous dielectric medium.

In fact, there are very few transmission lines for which the cross sectional fields can be solved analytically to give simple formulas for the per unit length parameters. To illustrate, the self-inductance and mutual inductance terms of n widely spaced cores above an infinite ground (see Figure 5) can be derived as [9]

$$l_{ii} = \frac{\mu}{2\pi} \ln\left(\frac{2h_i}{r_{wi}}\right)$$

$$l_{ij} = \frac{\mu}{4\pi} \ln\left(1 + \frac{4h_i h_j}{s_{ij}^2}\right)$$

where r_{wi} is the wire radius, h_i is the wire height above ground and s_{ij} is the center to center spacing between wires. If however these cores are surrounded by an insulation medium or the separation is not wide, one has no alternative but to employ approximate, numerical methods. In FEKO a 2D static FEM solver to Laplace's equation is used. Table 1 compares the analytic to the numerical per unit length capacitance matrix entries for 3 wires above ground ($r_{w1}=r_{w3}=1.0$ mm, r_{w2} = 1.5 mm, $h_1=h_3=52$ mm, $h_2=50$ mm, $s_{12}=s_{23}=15.13$ mm, $s_{13}=30$ mm. The 2D FEM solution is based on minimizing the stored field energy per unit length. The self-capacitance matrix entries are a direct function of the total energy in the system, and hence these terms agree very well with those of the analytic prediction. The mutual capacitance matrix entries are derived from the FEM solution (integration over $-\nabla\phi$) and as such use a lower order approximation, also explaining the larger differences between the analytic and numerical solutions.

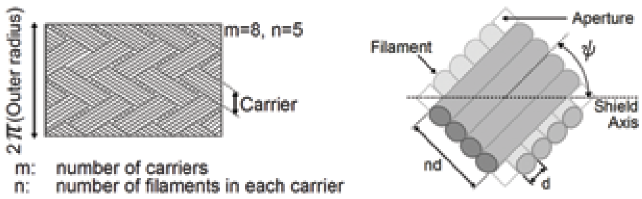

Figure 7. *Braided cable showing different weave parameters.*

Coupling of External Fields into Cables

Transmission lines can be excited by electromagnetic fields where their effect is to induce currents and voltages on the line and in the load impedances at the ends. There are three approaches for describing the coupling of an external field to a line using transmission line theory: the Taylor approach [10], the Agrawal method [11] and the Rashidi method [12]. Each of these coupling formulations gives the same response for the transmission line, although there are subtle differences in these techniques.

In FEKO the coupling of external fields into cables is considered with the scattered voltage formulation described by Agrawal. The problem can be considered to be an electromagnetic scattering process in which the tangential incident electric field along the conductors can be viewed as distributed voltage sources exciting the transmission line (see Figure 6).

Treatment of Cable Shields

In transmission line theory, the conductors in a cable bundle can be grouped into outer and inner circuits, each of which is coupled with a mutual conductor called a shield. The outer and inner circuits are completely separated by this shield, except that they are connected by current- and voltage-controlled sources (there should be no other connection between outer and inner circuits). The shield coupling parameters defining these controlled sources are termed transfer impedance Z_T and transfer admittance Y_T, which may be formally defined as follows

$$Z_T = \left.\frac{dV_i/dx}{I_s}\right]_{I_i=0} = \left.\frac{dV_s/dx}{I_i}\right]_{I_s=0}$$

$$Y_T = \left.\frac{dI_i/dx}{V_s}\right]_{V_i=0} = -\left.\frac{dI_s/dx}{V_i}\right]_{V_s=0}$$

where I_s, V_s and I_i, V_i are the currents and voltages on the outer shield and inner conductor of the separate circuits. Both Z_T and Y_T are basically dependent on the geometric and physical properties of the conductor system and as such are valid for both solid and braided shields.

For a solid tubular shield, the Schelkunoff model [13] is typically used

$$Z_T = \frac{1}{2\pi\sigma abD}$$

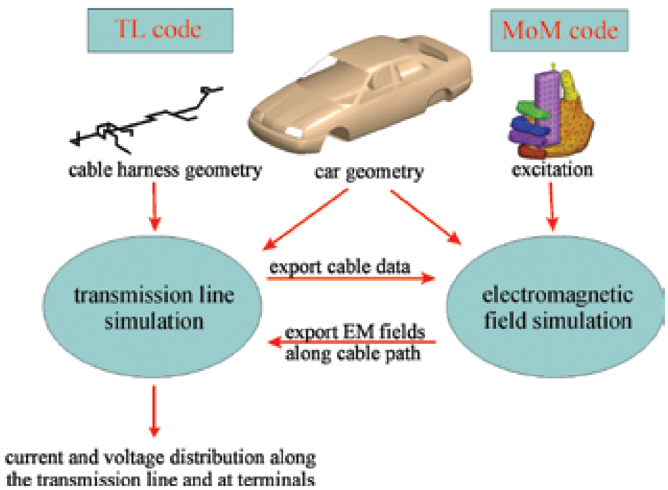

***Figure 8.** Combination of a transmission line (TL) and method of moments (MoM) code for solving the irradiation problem.*

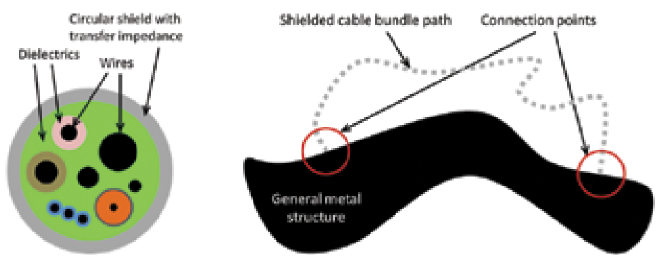

***Figure 9.** Example of permissible cross section and schematic cable path setup in the MoM/MTL combined approach (cable far away from ground).*

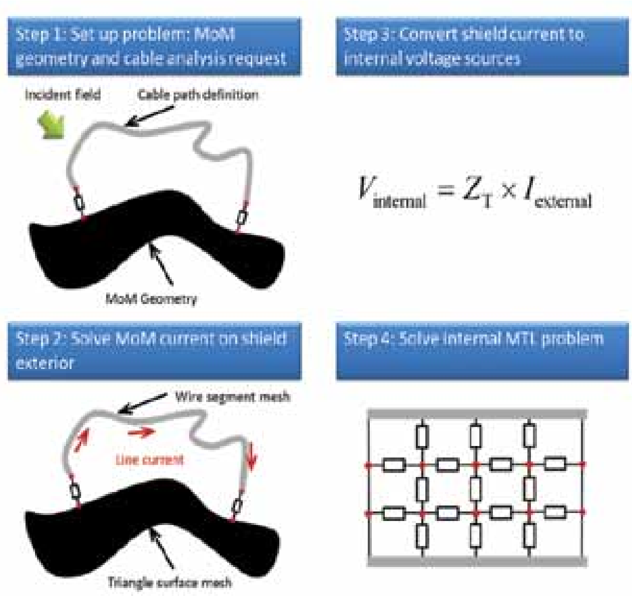

***Figure 10.** Step-by-step analysis method for shielded cable bundles following arbitrary paths, terminating on a metal structure.*

where $D=[I_1(\gamma b)K_1(\gamma a)-I_1(\gamma a)K_1(\gamma b)]$ and $\gamma=\sqrt{j\omega\mu(\sigma+j\omega\varepsilon)}$, while a and b are the inner and outer radius of the shield respectively. The electrostatic shielding is much greater than the magnetostatic shielding, and as a result, the transfer impedance term dominates at low frequencies. This fact has led many investigators to neglect the transfer admittance term in EMC coupling problems.

For braided shields as in Figure 7, the model proposed by Kley [14] is very popular. The coupling mechanism giving rise to the transfer impedance and admittance are enhanced, due to the field penetration through the shield apertures. At low frequencies, the electrostatic shielding of the braid is much better than the magnetic field shielding ($Y_T<<Z_T$). As the frequency increases, both the E and H fields are able to penetrate the braid apertures, and the induced effects on the inner conductor from both field components can be of the same order of magnitude, in which case the transfer admittance cannot be ignored.

COMBINING FIELD AND CABLE SIMULATION

The standard field-cable coupling formulation is a two-step procedure [11, 15].

For cable irradiation problems:

1. Solve the external problem with radiation sources and all structures except the cable bundles. Specifically, evaluate the electromagnetic near field along all cable bundle paths.
2. Use the calculated near field values as distributed sources together with multi-conductor transmission line theory, to solve the induced currents on the constituent wires in the bundles. Transmission line properties (L, C, R, G-matrices) used in the solution are evaluated numerically along the cable paths, based on local geometry. For shielded cables, near field values are used as distributed sources for the outside transmission line problem. The resulting current solution on the outside of the shield is then converted via the transfer impedance and admittance to distributed sources, which are then employed as excitation for the interior multi-conductor transmission line problem.

For cable radiation problems:

1. Based on specified circuit sources together with multi-conductor transmission line theory, solve the excited currents on the constituent wires in the bundles. Transmission line properties used in the solution are evaluated numerically along the cable paths, based on local geometry. For shielded cables, employ the transfer impedance and admittance bi-directionally similarly as in the irradiation case.
2. Solve the external problem with the excited cable bundle currents as impressed current sources replacing the cable bundles.

These two steps for radiation or irradiation can either be done by two codes which have an interface for the data exchange (e.g. interfaces between FEKO and CableMod

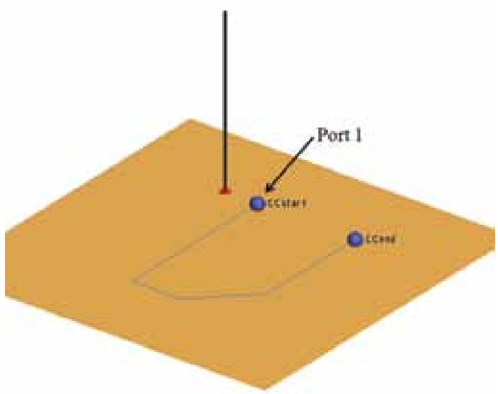

Figure 11. FEKO model of a monopole antenna close to an RG58 coaxial cable above ground.

or CRIPTE as cable modeling tools, see Figure 8 for a flow chart), or can also be integrated into one code (such as FEKO Suite 6.1) allowing for a better user experience (one common user interface, no data export / import).

This standard MTL approach does pose some challenges, e.g. that common mode currents and radiation loss cannot be modeled. One of the main limitations is that a cable bundle must run close to a conducting surface, typically with less than λ/5 spacing [16]. The reason for this restriction is that the formulation is derived assuming a TM field distribution in the vicinity of the bundle and conducting surface, which is valid only when the gap is small. Stated differently, when there is no external conducting surface close to the cable path the external problem cannot be solved using cable theory.

In FEKO a MoM/MTL combined approach was introduced to avoid this problem. As shown in Figure 9, a shielded cable bundle may now follow an arbitrary path, with the ends connected at two points on a metal structure. The method relies on the assumption that the exterior (structure and

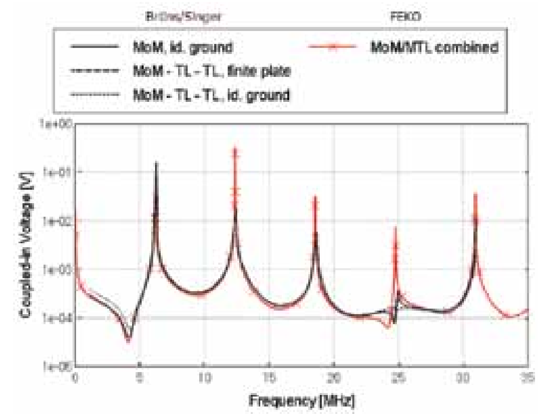

Figure 12. Magnitude of the induced voltages at the cable end closest to the antenna.

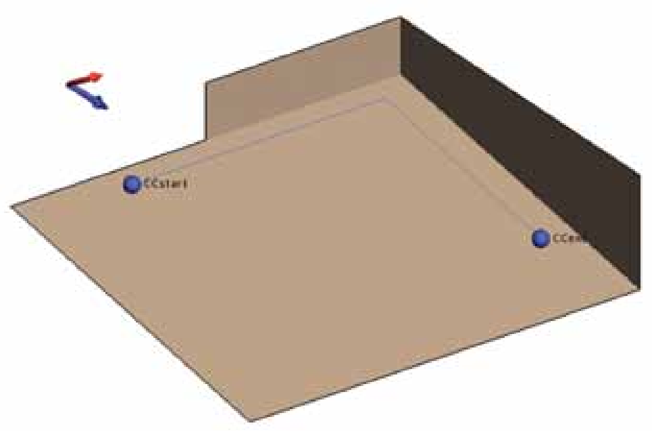

Figure 13. FEKO model for an L-shaped single conductor cable over a ground shape.

shield) and interior (cable bundle) problems only couple weakly through the transfer impedance. A very similar approach has been proposed in [17].

The steps of the irradiating case of the analysis method are shown in Figure 10 and are as follows:

1. Set up the problem geometry and cable analysis request. The metallic structure will be meshed with triangular elements. The exterior of the cable path will be included in the full-wave analysis with the MoM using thin shell wire segment elements of which the radius, thickness and material properties are the same as that of the shield.
2. Solve the external MoM system to obtain the shield (wire segment) exterior current. The MoM solution yields the total current flowing on the shield exterior.
3. Use the transfer impedance of the shield to convert the exterior shield current to a distributed voltage source exciting the multi-conductor transmission line interior problem.
4. Solve the internal problem using multi-conductor transmission line circuit analysis.

In a similar manner also the radiating case can be dealt with.

VALIDATION AND APPLICATION EXAMPLES

Although the techniques presented in this paper can be applied to complex real-world problems (e.g. cable harness running in a car), we present in the following rather simple validation and application examples. These examples have the advantage that full wave MoM solutions (i.e. discretizing the cable into MoM wire segments) exist as reference to compare to the combined MoM/MTL technique, or measurements / reference results from literature based on other techniques or other implementations available.

RG58 Coaxial Cable Close to Monopole Antenna (Irradiation)

A monopole antenna of 10 m height is fed by an input power of 10 W and is radiating in the neighborhood of an RG58 coaxial cable which forms a U-shaped loop of length 24.24 m. The axis of the cable is assumed to be 10 mm above a PEC ground with both shield ends short-circuited to ground. The coaxial core is terminated in 50 Ω to the shield and the shield transfer impedance is available from a measurement database. The frequency range extends from 1 MHz to 35 MHz. Figure 11 shows the configuration setup while Figure 12 compares the FEKO solution to reference results [18] for the voltage at the cable end closest to the antenna (Port 1). The results from [18] are based on a standard MTL / MoM combination which is only applicable to cables

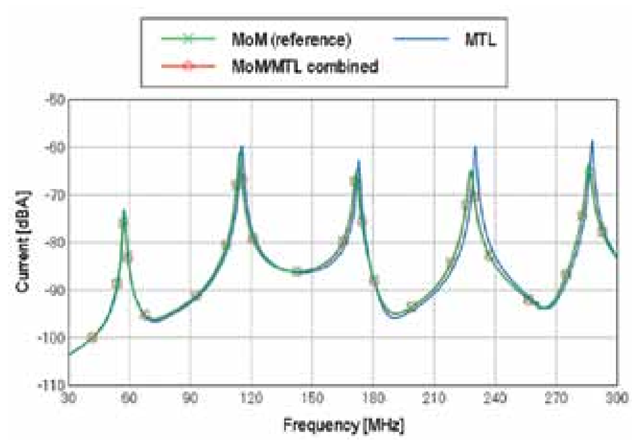

Figure 14. Magnitude of the induced current in the load at CCend.

running close to ground, which is the case here, thus one can consider [18] as independent reference here.

Single L-Shaped Conductor Line above Finite Ground (Irradiation)

In Figure 13, the geometry setup of a single wire cable (radius 2 mm) over a finite size ground plane with side walls is shown. Both ports are terminated in high impedance (15 kΩ). The excitation is by a right-hand circular polarized plane wave (magnitude 3 V/m; polarization angle 45º). Figure 14 compares the induced current in the load at CCend using different methods available in FEKO (full MoM reference solution in green, MoM for the plate and standard MTL for the cable in blue, and the combined MoM/MTL method where the outer cable problem is also solved with MoM in red). All these results agree very well. The two MTL results agree very well to the standalone MoM result, which can be considered a reference solution (see our comments above, such a full wave MoM solution is accurate, but can be obtained only for simple configurations due to the effort with regards to memory and run-time).

Shielded RG58 Cable above Ground Plane with Gap (Radiation)

In this example radiation from an RG58 C/U coaxial cable to a nearby antenna is computed. Two different ground plane arrangements were investigated (see Figure 15): (a) common ground between the cable source at *CC_Port1* and load at *CC_Last*; (b) separate grounds (2 cm apart) between the cable source and load leaving a gap.

The presence of separate ground structures for the configuration (b) restricts the usage of standard MTL techniques. The outer problem can no longer be solved using cable theory as there is no return path for the current to flow below the cable path. However, when using the unique MoM/MTL combined approach in FEKO, the current on the cable shield exterior is solved using MoM where there is no limitation regarding the cable path w.r.t. the surrounding geometry.

As this is not a single wire but a real

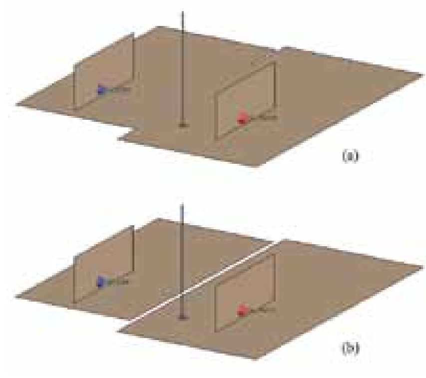

Figure 15. *FEKO model for the geometry setup of a shielded RG58 cable above different ground plane arrangements: (a) one single ground plane under the cable and (b) two separated ground planes with a slot in-between.*

RG 58 cable, a simple MoM reference solution without involving MTL is not possible here. Also as explained the standard MTL (without MoM combination) cannot be used, thus the only available validation here are measurement results (obtained independently from our calculations). Figures 16 and 17 compare the FEKO MoM/MTL combined approach to measurement results for the two different ground plane arrangements, and for both configurations (with and without gap in the ground plane) the agreement is again very good.

CONCLUSIONS

We gave an overview on how modern electromagnetic simulation techniques can handle combined field / cable problems, both for radiation and irradiation. The different approaches to handle such problems were summarized, and we introduced in particular a combination of MTL and MoM where the outer transmission line problem (shield and ground) is solved with MoM which enables one to solve cable problems where there is no distinct nearby ground plane (e.g. ground far

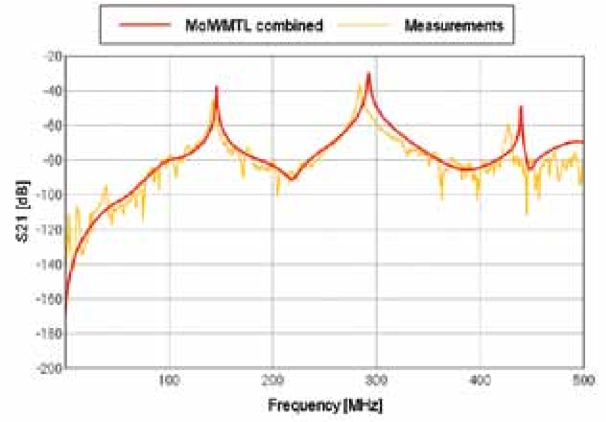

***Figure 16.** S-parameter comparison for shielded RG58 cable above common ground plane, configuration (a).*

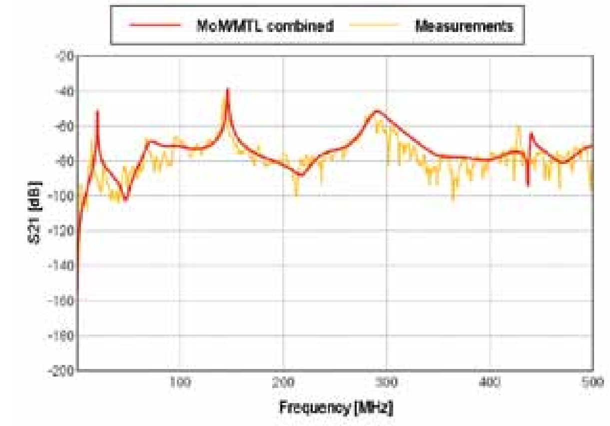

***Figure 17.** S-parameter comparison for shielded RG58 cable above ground plane with gap, configuration (b).*

away, or ground with holes / slots). Several examples were presented and solved with the computer code FEKO, demonstrating the successful application of these techniques.

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MARLIZE SCHOEMAN received the B.Eng-M. Sc.Eng and PhD degrees in Electronic and Computer Engineering from the University of Stellenbosch, South Africa, in 2003 and 2006, respectively. There she has been involved with research activities concerning computational electromagnetics and rational function interpolation and approximation techniques. Since July 2006 she has been with EM Software & Systems, Stellenbosch, South Africa, where she is doing research and development on the kernel of the FEKO code.

ULRICH JAKOBUS received the diploma, PhD and Habilitation (venia legendi) degrees in Electrical Engineering from the University of Stuttgart, Germany, in 1991, 1994, and 1997, respectively. There he has been actively involved in research on numerical techniques for the solution of electromagnetic problems with special emphasis on EMC, and this research lead to the computer code FEKO. Since October 2000 he is with EM Software & Systems, Stellenbosch, South Africa, with the roles of Director, FEKO Product Manager, and team leader of the FEKO kernel team.

Going from Analog to Digital

Radiated emissions performance of a nuclear plant control system from 10 kHz to 6 GHz

PHILIP F. KEEBLER
EMC Group, Electric Power Research Institute
Knoxville, Tennessee USA

STEPHEN BERGER
TEM Consulting, LLC
Georgetown, Texas USA

Nuclear power plants (NPPs) in the United States have been undergoing upgrades from analog instrumentation and control (I&C) equipment to digital equipment over the past several years. Upgrades have been occurring on the plant floor for systems such as generator controls, turbine supervisory controls, and chiller controls as well as control systems in the plant control room. Plant events involving electromagnetic interference (EMI) continue to occur with existing analog equipment and with some digital equipment. Because of the increased focus on safety and efforts to eliminate plant events, electromagnetic compatibility (EMC) is still a growing concern. The migration from analog I&C equipment to digital I&C equipment warrants the need to investigate the EMC characteristics of changing electromagnetic environments. These characteristics have been identified through Electric Power Research Institute (EPRI) research by conducting long-term emissions measurements before analog I&C systems are removed, and then again after new digital I&C systems were installed and operational. This paper presents the first-of-its-kind analysis of a complete set of radiated emissions measurement data from 100 Hertz to 6 GHz as part of an upgrade inside a control room to replace an analog control system with a digital control system for one operating unit of a nuclear plant in the United States.

Keywords- Digital upgrade, control room, radiated emissions, electromagnetic interference

INTRODUCTION

Electromagnetic characterization of spaces where electrical and electronic equipment must coexist is a necessary function of EMC for reasons discussed below. These spaces include areas inside and outside facilities that serve residential, commercial, industrial, and specialty needs such as healthcare and power plants. Operations of equipment in these spaces create the overall electromagnetic environment (EME).

Diverse Equipment Designs and Design Changes

About the only commonality between electronic equipment in today's modern world, including digital I&C equipment used to upgrade older analog I&C equipment in existing power plants, is the need for equipment to use AC or DC power to operate. With rapidly changing semiconductor technologies, the growing use of new digital devices, and the proliferation of software development and its embedded use to enhance the I&C functions of NPPs, I&C equipment manufacturers are developing new types of I&C equipment. The need for smaller more efficient equipment with faster processing speeds and increased network connectivity with higher reliability causes an increase in radiated and conducted emissions. Although filtering and shielding


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technologies are getting better, manufacturers still only use the amount of filtering and shielding needed to pass EMC regulatory tests. Designers are not keeping pace with the new mitigation technologies for controlling emissions. I&C designs are moving faster into digital than EMC mitigation devices are being used to control emissions generated by the digital devices. Regardless of which type of electronic device is brought into a plant, one can rest assured that the plant's EME will include its emissions characteristics. Moreover, emissions characteristics are more additive than subtractive, resulting in cumulative emissions increases over time as existing power plants continue to install new equipment. Manufacturers are focused on producing equipment designs that meet existing critical US Nuclear Regulatory Commission (NRC) requirements. In some cases where NRC requirements for digital I&C equipment have not yet been developed or are not yet mature, manufacturers are working with plant engineers, the NRC and EPRI to develop new requirements.

Changes in Equipment Shielding Characteristics

Shielding provides a two-way function for EMC performance—helping to protect equipment from external emissions (e.g., from cell phones and walkie-talkie radios) and helping to reduce emissions generated inside equipment (e.g., from power supplies and microprocessors). Shielding manufacturers and users have no formal method of determining the shielding effectiveness of shields smaller than a two-meter cube. Thus, small shields that are used in portable radio devices and digital I&C equipment, for example, may not be performing as manufacturers expect. However, the Institute of Electronic and Electrical Engineers (IEEE) is presently sponsoring a project (IEEE P299.1) to develop a new standard describing new test methods for measuring the shielding effectiveness of shields having dimensions between 0.1 and 2 meters. This standard will be published in 2011.

Changes in Design and Use of Portable Radio Devices

Rapid development of sophisticated devices (e.g., cell phones, wireless headsets, electronic book readers, etc.) has increased. Networks (i.e., the tower) can initiate changes in radio power to ensure connectivity resulting in increased power levels. The increased use of portable radios and radio applications results in the increased difficulty in controlling use.

Changes in Definition, Use, and Management of Electromagnetic (Radio) Spectrum

Increased use of stationary and portable electronic equipment combined with additional radio and television (digital) broadcast towers and wireless services results in more complex spectrum. Increased use of high-speed data communications in NPPs will also impact the spectrum. Changes in the use and management of spectrum will be seen in the future with new rulings by the US Federal Communications Commission (FCC). Changes in other countries may also occur that will affect use of the spectrum and it energy in NPPs abroad. Composite effects of each additive electromagnetic energy source needs to be identified as NPPs continue to change before NPPs reach a plateau where new EMI problems begin to surface.

Use of Spectral Data

It is a reasonable, standardized, and customary practice to collect spectral data from EMEs, especially when industries can report that EMI problems continue to occur, present serious plant operations, and that equipment environments are changing. In the NPP industry, this is a two-fold problem. First, in existing plants, digital upgrade projects continue in growing numbers as plants meet planned needs and identify new needs to replace older analog I&C equipment. For various reasons, some plants plan and request limited-scope surveys at the point-of-installation (POI). Surveys are carried out to gain additional knowledge regarding the EME prior to the upgrade and how the installation of the new equipment affected the EME. Of the surveys that EPRI has carried out between 2001 and 2010, unexpected knowledge regarding the EME was always learned after the survey. Utility customers reported after their review with the NRC regarding their digital upgrade projects that the initiative taken to do the survey and the information gained from doing it were positive steps in helping the plant, the NRC, and the NPP industry to understand more about EMC concerns and help achieve enhanced EMC for digital upgrade projects.

Secondly, utility engineers engaged in the design of advanced NPPs have expressed the importance of having POI surveys carried out prior to actually constructing new advanced plants. One might ask, "How can this be done?" As part of the design process, a pre-operational demonstration is built for the digital I&C equipment planned for use in new plants. Survey activities can be carried out in these areas for each utility planning an advanced plant. Measurements to characterize the low-frequency radiated magnetic fields and low- and high-frequency radiated electric fields can be made. Conducted emissions measurements of low- and high-frequency can also be made. In fact, there is technical benefit to making these measurements in these areas away from the cluttered EMEs of advanced plants after they are built. Data from such measurements will be useful in the development of an emissions analysis database and can be used to compare to the emissions captured during EMC certification of digital I&C equipment, emissions from analog I&C equipment, from historical surveys in existing plants, recent surveys in existing plants and emissions captured when advanced plants are completed as well as emissions captured during an EMI investigation.

ABOUT THE ORIGINAL SURVEY PROJECT FOR DCS UPGRADE

As a part of the digital control system (DCS) upgrade program for Units 1 and 2, a major US nuclear power plant requested that a survey for radiated magnetic and electric fields be conducted in three areas: 1) Control Room – near the system cabinets in the control room where the existing analog control system is to be retrofitted with the new digital control system for Units 1 and 2, 2) the Operator Assist Computer (OAC) Computer Room area for Units 1 and 2, and 3) the Testing and Training Facility (TTF) Facility where the DCS was set up for testing. A survey plan was designed to investigate the radiated EME in each areas. The investigation was carried out by conducting a partial EMC survey measuring the radiated emissions for Unit 1 and 2 for electric fields from 10 kHz to 6 GHz and for magnetic fields from 20 Hz to 100 kHz with the analog control system in place and operational. A full EMC survey would entail measuring both radiated and conducted emissions. If requested as a part of the survey, conducted emissions could have been measured along power and data cables on the existing analog control system. This in situ study on a DCS is the first of its kind. Only the electric field emissions from 10 kHz to 6 GHz are reported in this paper.

Once the DCS was set up for testing and training in the TTF facility, a second visit was made to the site. The same groups of measurements were made but with the DCS mounted only in wooden racks without any metallic system cabinets in place. (These measurements are not provided here.) After the DCS was installed and operational, the next visit was made to the site where emissions measurements (discussed in this paper) were again made in the control room at the same antenna positions. Measurements were also taken with selected system cabinet doors open for comparison but are also not included in this paper. A new automated emissions measurement system, developed by EPRI was used to capture the emissions data and is further described in Section III. B.

MEASUREMENT METHODS FOR COLLECTING RADIATED EMISSIONS DATA

The NRC NUREG 1.180 (Rev. 1) 2003 and the EPRI TR-102323 (Rev. 3) 2004 Documents

The document, "Guidelines for Evaluating Electromagnetic and Radio-Frequency Interference in Safety-Related Instrumentation and Control Systems", U.S. Nuclear Regulatory Commission (NRC) Regulatory Guide, NUREG 1.180 (October 2003) Rev. 1 was developed and published by the NRC. The purpose of this document is "to provide guidance to licensees and applicants on additional methods acceptable to the NRC staff for complying with the NRC's regulations on design, installation, and testing practices for addressing the effects of electromagnetic and radio-frequency interference (EMI/RFI) and power surges on safety-related instrumentation and control (I&C) systems." This guidance document focuses heavily on acceptable test methods to measure emissions generated by safety-related I&C equipment and to determine its immunity to man-made emissions and disturbances.

The survey presented in this article was not conducted to provide any guidance as to where the system cabinets or the DCS in the cabinets should be located in the control room as that information was already pre-determined by the customer as part of their upgrade program for the plant's control system. This survey was conducted to determine if any of the POI areas (without and with the DCS installed) have emissions characteristics that violate specific emissions envelopes currently in use by the NPP industry. These include the bounded envelope for plant emissions limits defined in the EPRI TR-102323-2004 (Rev 3) guidance document, "Guidelines for Electromagnetic Interference Testing in Power Plants" and the susceptibility line at 140 dBμV/m (10 V/m) defined in the NUREG 1.180 (Rev 1). These limits lines are included in the radiated emissions graphs presented later in this article for reference.

The NUREG 1.180 was also carefully reviewed along with the appropriate emissions measurement procedures included in MIL-STD-461E and the IEEE 473-1985 (R1991), "IEEE Recommended Practice for an Electromagnetic Site Survey (10 kHz to 10 GHz)." In addition, the research, data, and recommendations developed in published in EPRI TR-102323 were also carefully reviewed before this survey was carried out. Before the survey was conducted, two applicable survey methods—one based on MIL-STD-461E and the other based on IEEE 473—were reviewed. (For a comparative discussion on these methods, please see the article, "Measuring and managing electromagnetic interference: selecting the right antenna for your E3 program" which appeared in ITEM's EMC Directory and Design Guide 2006, pp. 36-51.)

In an effort to closely characterize the location area of interest in the Control Room of this major US nuclear power plant, the following EMC measurement equipment was used: two 461E antennae—one broadband discone antenna with a frequency range 100 Hz to 1 GHz for radiated electric field measurements and one large loop magnetic field antenna with a frequency range 20 Hz to 5 MHz for radiated magnetic field measurements, one mini directional antenna with a frequency range 1 GHz to 6 GHz for radiated electric fields above 1 GHz, and two measurement methods were employed. The use of a single broadband discone antenna was applied with the use of an automated emissions measurement system as a more appropriate technique to improve the measurement process for high-frequency radiated electric fields. The IEEE 473 method was also attractive given the use of an automated emissions measurement system discussed below in the next section of this paper.

Emissions Measurement and Data Storage System Used

The traditional measurement system used for conducting surveys in the past has been the spectrum analyzer with minimal on-board data storage. Although spectrum analyzers have continued to develop over the years to provide for hundreds of on-board functions necessary for radio and EMC engineering and spectral analysis, little has been done regarding their ability to program long-term scans for surveys and to provide for large amounts of data storage. Limitations associated with the use of a traditional spectrum

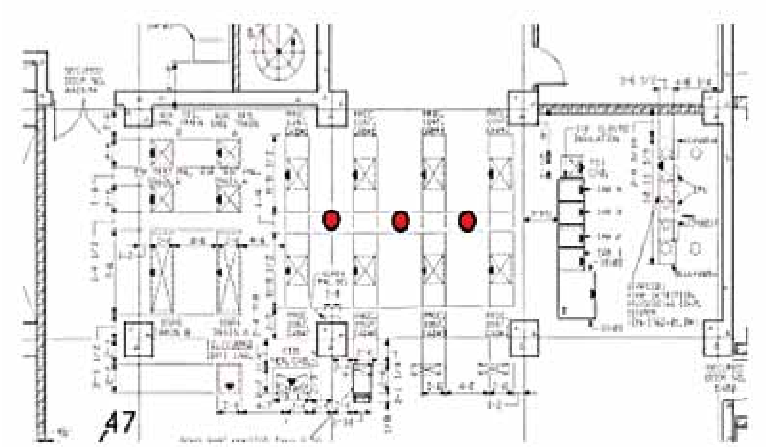

Figure 1. *Location of antenna positions adjacent to system cabinets for plant control system.*

analyzer include:

- Inability to program long-term cycling emissions tests across multiple frequency ranges
- Difficulty in capturing enough sweeps to properly represent the needed characteristics of an EME without having to dedicate a large number of man hours at the site
- Difficulty in capturing emissions sweeps associated with transients produced by the operation of devices such as relays, solenoids, valves, etc.
- Lack of proper data storage space on board the analyzer to store data from sweeps
- Inability to record sweeps in real-time and play them back on the screen if a review of emissions data is needed
- Difficulty associated with conducting mathematical operations on a limited set of emissions data to determine characteristics associated with a long-term recording of sweeps to support emissions analysis

To address the limitations listed above and several others, EPRI developed an automated emissions measurement system. This system utilizes a custom written program supporting a series of algorithms placed on a laptop computer that is interfaced to a spectrum analyzer through the IEEE 488 buss. Once activated, the computer program takes over the operation of the analyzer, allowing the EMI investigator to program exactly how the survey should be carried out. A total survey time of a few minutes up to a week can be selected. Once the survey emissions tests are simply programmed into the computer, the investigator clicks the "Start" button, closes up the access panel, locks the cabinet door, and walks away. The programmability and flexibility of this system allows the EMI investigator to set up emissions tests using a customer graphical user interface and determine when those tests would start and stop. The EMI investigator can also specify how much time would be spent on a specific frequency band and if emissions above a certain amplitude should be ignored among other custom settings. The system program also contains a data analysis package, which allows the investigator to conduct statistical analyses on the data, capture any trace or set of traces, and replace any range of traces or the whole data record upon command. Histogram analyses can also be carried out on the recorded data.

The system was built specifically for conducting surveys in critical areas where the location of emissions sources is unknown, where sources of transient emissions may be present and could cause severe malfunction of critical electronic equipment, where increasing the statistical confidence of the data would further improve the validity of the survey data, and where antenna size could possibly place constraints on the survey process thus limiting the amount of data collected. This system has already been used in other critical facilities including hospitals and com-

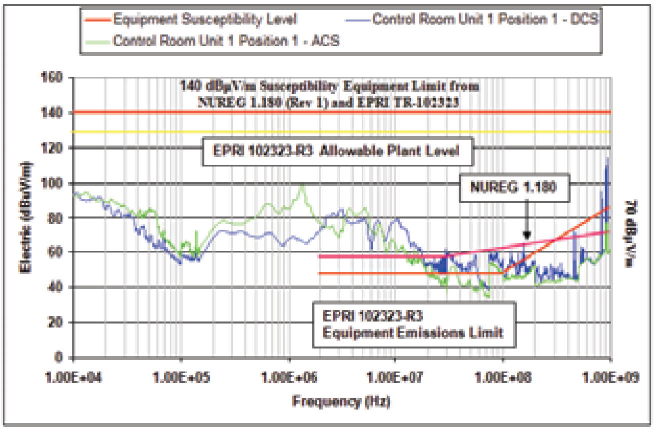

Figure 2. *Radiated electric field spectra, 10 kHz to 1 GHz, antenna position 1 in control room (Unit 1).*

munications facilities, and to date collected emissions data for more than ten digital upgrade projects in NPPs. Data gathered during this survey process furthered the understanding of the EMC for the DCS project at this major US nuclear power plant.

This automated system continues to be used to conduct POI surveys in NPPs and other types of facilities where surveys are needed or where EMI problems persist. One of the primary benefits of using this system is the permanent data record of emissions traces that the system creates when a survey or set of emissions measurements is carried out. This type of emissions record keeping will be beneficial when EPRI develops an on-line emissions database. Such a database can provide researchers and customers with access to historical and recent emissions data. Data from past surveys may even be converted to digital data which can be uploaded to the database.

MEASUREMENT DATA

Antenna Positions

Figure 1 illustrates the location of the three antenna positions near the system cabinets that now contain the new digital control system. These same cabinets previously contained the analog control system. All three antennae were used at these positions during the emissions measurements.

High-Frequency Radiated Emissions Data – Electric Fields: 10 kHz – 1 GHz

1) Antenna Position 1

Figure 2 illustrates the final radiated emissions trace (i.e., the maxima of each measurement point in this frequency band occurring among several thousand traces during the collection of data at this antenna position) for electric fields taken at Antenna Position 1 from 10 kHz to 1 GHz adjacent to one of the system cabinets for the plant control system. Figure 1 contains the data for both the analog control system (green trace) and the digital control system (blue trace). From the trace, one can see that a few characteristics of the analog control are that it peaks at 1.34 MHz at 99.2 dBμV/m and at the high-frequency end at 928 MHz at 76.6 dBμV/m.

The blue trace from digital control system has a similar signature starting from 10 kHz but lower amplitude and does not contain the 1.34 MHz peak. From 2.31 to 3.51 MHz, the radiated energy from the DCS is higher than that of the analog control system (ACS). From 6.71 MHz out to 1 GHz, the radiated energy from the DCS is just about always higher than that of the ACS. There are two distinctive peaks that are present on the DCS trace, which are not present on the ACS trace. These are at 468 MHz (71.6 dBμV/m) and 826 MHz (94.5 dBμV/m). One of the peaks at the higher frequency area at 928 MHz peaked at 113.5 dBμV/m, which is 36.9 dBμV/m higher when the DCS system was installed.

Two limit lines are placed on the plot as well. One is the 140 dBμV/m limit line (red line)—a susceptibility limit line defined in NUREG 1.180 (Rev 1) and also in EPRI TR-102323. The second limit line (yellow line) is the highest composite plant emissions envelope limit, originally defined in EPRI TR-102323 (Rev 1) in 1997. While there is more than an 8 dB safety margin between the peak of either trace and the 140 dBμV/m limit line, one will notice that the emissions from the DCS equipment at 928 MHz are near the allowable plant emissions limit line.

Two other limits are also placed on the graph of Figure 2. These are equipment emissions limit lines. One is the limit line defined in NURED 1.180. The other is also an equipment emissions limit line defined in EPRI TR-102323 (Rev.

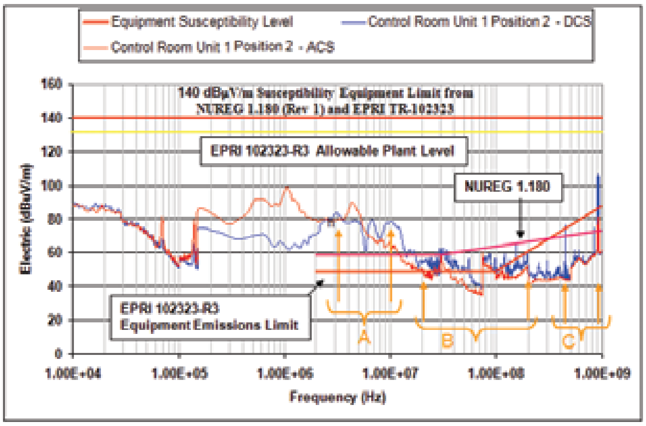

Figure 3. *Radiated electric field spectra, 10 kHz to 1 GHz, antenna position 2 in control room (Unit 1).*

3). Although these limit lines are intended to determine if the emissions from a single piece of equipment or system are too high, the emissions from both the ACS and the DCS equipment do exceed these limit lines.

2) Antenna Position 2

Figure 3 illustrates the final radiated emissions trace for electric fields taken at Antenna Position 2 from 10 kHz to 1 GHz adjacent to one of the system cabinets for the plant control system. This trace contains the data for both the analog control system (red trace) and the digital control system (blue trace). From Figure 2, one can see that a few characteristics of the analog control are that it peaks at 1.04 MHz at 99.3 dBμV/m and again at 4.55 MHz at 88.5 dBμV/m. Again, these two traces cross the NUREG 1.180 and EPRI TR-102323 equipment emissions limit lines for high frequency radiated emissions.

While the radiated emissions in the region between 139 kHz and 2.61 MHz have dropped as a result of converting the plant control system from analog to digital, there are other regions (e.g., A, B, and C) that have increased in amplitude. 132 These three example areas have experienced amplitude increases ranging from a few dB to as much as high as over 40 dB. With the nature of radiated emissions being cumulative with increasing digital devices in areas such as Control Rooms, areas such as A, B, and C will experience significant growth in amplitude more closely approaching the plant emissions limit line (yellow line) defined by EPRI TR-102323.

As additional digital control equipment is installed in the Control Room, these emissions levels will grow. Moreover, with the new advanced nuclear plants presently under design (some under early construction), I&C engineers can expect new concerns regarding higher emissions levels and new EMI problems as digital I&C controls are brought on line. This is an area that deserves careful consideration in efforts to lower the risk of allowing an EMI problem to occur in the fleet of advanced nuclear plants built and placed on the grid over the next ten years. Efforts put into place to gather emissions data for new digital I&C equipment slated for use in the new plants will provide much needed emissions guidance and aid in the prevention of future EMI problems.

High-Frequency Radiated Emissions – Electric Fields: 1 – 6 GHz

1) Antenna Position 1

Figure 4 illustrates the radiated emissions trace for electric fields taken at Antenna Position 1 from 1 to 6 GHz adjacent to one of the system cabinets for the plant control system. This trace contains the data for both the analog control system (red and blue traces) and the digital control system (purple trace only).

From red and blue (upper) traces, one can see that there are no significant peaks associated with the analog control system. However, with the digital control system there are peaks at 1.35 GHz at 49.9 dBμV/m, 1.88 GHz at 50.5 dBμV/m, 1.92 GHz at 53.4 dBμV/m, 2.41 GHz at 76.3, 2.46 GHz at 54.4 dBμV/m, and 5.82 GHz at 60.6 dBμV/m. Some of these spectral components are higher at Antenna Position 1 than at Antenna Position 2.

From increases in the usage of digital equipment in other mission-critical environments where surveys have been carried out, it is reasonable to predict that the above components will experience a growth in amplitude in addition to the development of new components with faster proces-

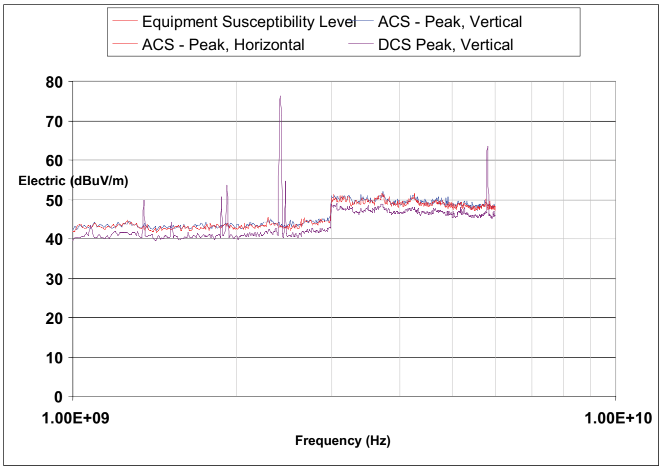

Figure 4. *Radiated electric field spectra, 1 - 6 GHz, antenna position 1 in control room (Unit 1).*

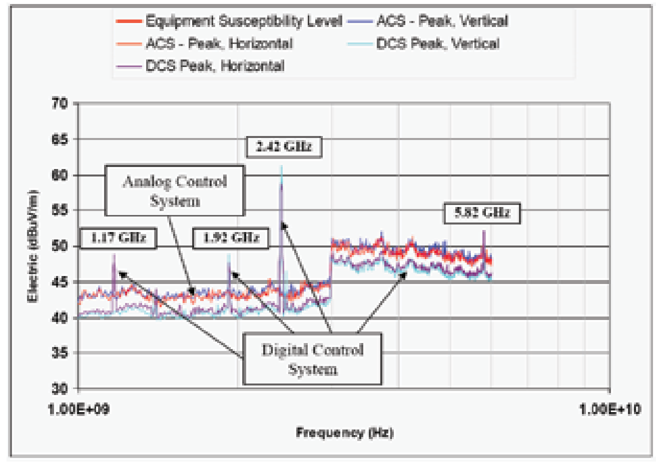

Figure 5. *Radiated electric field spectra, 1 - 6 GHz, antenna position 2 in control room (Unit 1).*

sors (and using more switch-mode power supplies) as more digital I&C systems are installed in the control room and other areas supporting the control room. The control rooms of the new advanced plants are, of course, no exception. They will also experience higher levels of radiated emissions in this frequency range and also extending up to 10 GHz.

2) Antenna Position 2

Figure 5 illustrates the radiated emissions trace for electric fields taken at Antenna Position 2 from 1 to 6 GHz adjacent to one of the system cabinets for the plant control system. This trace contains the data for both the analog control system (green trace) and the digital control system (blue trace). From the trace, one can see that there are no significant peaks associated with the analog control system. However, with the digital control system there are peaks at 1.17 GHz at 48.8 dBμV/m, 1.92 GHz at 48.9 dBμV/m, 2.42 GHz at 57.7 and 61.2 dBμV/m, and 5.82 GHz at 50.9 dBμV/m. Only data from Antenna Position 1 and 2 are included in this paper. Emissions data at Antenna Position 3 was similar to that of Antenna Position 1 and 2.

STANDARDS DEVELOPMENT

Presently, the nuclear power plant industry relies on the EPRI guidance document (TR-102323 (Rev. 3)) and the NUREG 1.180 to plan and conduct EMC qualifications testing for I&C equipment (analog and digital). EPRI is leading the effort in developing new standards for the NPP industry with the first standards project focusing on immunity testing of I&C equipment. An update on this standards development effort will also be presented at the conference as part of this presentation.

CONCLUSION

Project engineers responsible for digital I&C upgrades at the this major US nuclear power plant took the right step in having the two areas of concern—Control Room (near cabinets in Unit 1 where DCS was installed), OAC Computer Room, involving the completion of the digital control system (DCS) project—survey for radiated emissions. The DCS equipment is primarily digital (instead of analog) and its radiated emissions signatures were different than its analog counterparts. It is well known in the EMC industry that EMC surveys provide valuable insight as to the electromagnetic conditions of an environment in question, especially one as critical as a Control Room in a nuclear power plant. An analysis of the emissions and immunity test results and witness immunity testing of these proposed digital systems should be conducted prior to installation. Due to the critical nature of he DCS, simple proof of acceptable EMC compliance for this equipment should not be accepted as complete with regards to EMC. Further consideration of electromagnetic compatibility combined with a well-designed EMC installation practice and the results of this survey will further help to ensure that these systems are not interrupted by emissions from the electromagnetic environment in question. Digital I&C equipment slated for use in the advanced plants will also benefit from pre-op surveys in areas where some of the EME conditions can be controlled. These components can be integrated into an Electromagnetic Environmental Effects (E3) program should this power plant elect to establish such a program to maintain EMC throughout the plant. Further information regarding this type of program can be provided upon request.

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Philip F. Keebler *manages the Lighting and Electromagnetic Compatibility (EMC) Group at EPRI where EMC site surveys are conducted, end-use devices are tested for EMC, EMC audits are conducted and EMI solutions are identified. Keebler has conducted System Compatibility Research on personal computers, lighting, medical equipment, and Internet data center equipment. The lighting tasks were associated with characterizing electronic fluorescent and magnetic HID ballasts, electronic fluorescent and HID ballast interference, electronic fluorescent and HID ballast failures, and electronic fluorescent and HID lamp failures. Keebler has drafted test protocols and performance criteria for SCRP tasks relating to PQ and EMC. He served as editor developing a new EMC standard for power line filters, IEEE 1560.*

Stephen Berger *is president of TEM Consulting, an engineering services and consulting firm dealing in regulatory compliance, wireless, voting equipment and EMC. Berger was the convener and founding chair of IEEE SCC 41, Dynamic Spectrum Access Networks and immediate past chair of the IEEE EMC Society Standards Development Committee. He is a past president of the International Association of Radio and Telecommunications Engineers (iNARTE), a professional certification agency. Currently he works with ANSI ACLASS as a lab assessor and on issues of conformity assessment. Before forming TEM Consulting, Berger was a project manager at Siemens Information and Communication Mobile, in Austin, Texas, where he is responsible for standards and regulatory management. He has provided leadership in the development of engineering standards for 30 years, including five which have been adopted and incorporated into federal regulations by the FCC.*

A Risk Assessment for Lightning Protection System (LPS)

BRYAN COLE
Technology Research Council
Nichols, New York USA

Many articles, papers, and standards have been written and/or developed documenting proper application of surge protection devices (SPDs), identification of SPD performance characteristics, proper SPD safety requirements, etc. However, there are minimal articles on describing when an engineer should specify SPDs to be applied to an electrical distribution system.

SPDs are installed to protect against transient overvoltage and overcurrents from affecting the electrical systems and processes within a facility. Transients occur from environmental and human factors. Protection of the facility, the electrical system and the processes contained within the facility are the second most important item to be considered in the power quality pyramid; preceded only by grounding and bonding for the safety of personnel (Figure 1).

There are numerous environmental causes that can disrupt the facility, the electrical system, or the processes within the structure. These factors include hurricanes, tornados, floods, lightning, etc.

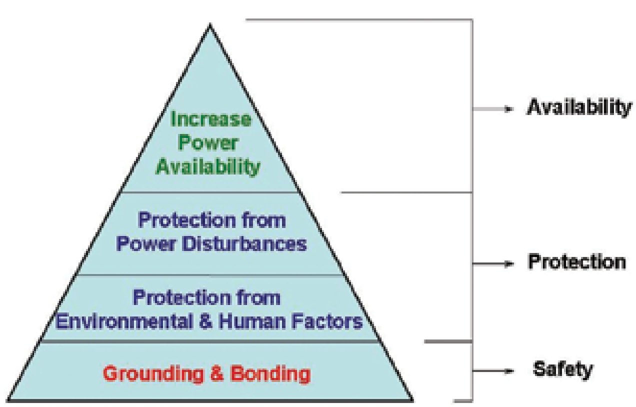

Figure 1. *Power quality pyramid.*

Transients from environmental causes include those from direct and indirect lightning strikes. To protect a facility from lightning induced transients, a lightning protection system is needed. When protecting a structure from direct lightning strikes, standards require that SPDs be installed whenever a lightning protection system is installed [1].

In the design of an optional, legally required standby, or emergency power system, a risk assessment of the interaction between environment and human factors is not mandated by the National Electric Code (NEC) [2]. In the design of a critical operating power system, the NEC requires that a risk assessment be conducted [2]. Even if not required by the NEC, a risk assessment of environment and human factors for all power systems should be considered in the design or redesign of every facility.

There are many factors to be considered in the risk assessment. Lightning risk assessments are described in US and international standards [2,3]. This article will focus on a risk assessment to determine if a lightning protection system and SPDs should be installed using the National Fire Protection Association standard on Lightning Protection Systems, NFPA 780. Annex L of NFPA 780 describes methods for simplistic and complex risk assessment. This article focuses on a simple risk assessment.

LIGHTNING RISK ASSESSMENT

Performing a risk assessment to determine if the facility needs a lightning protection

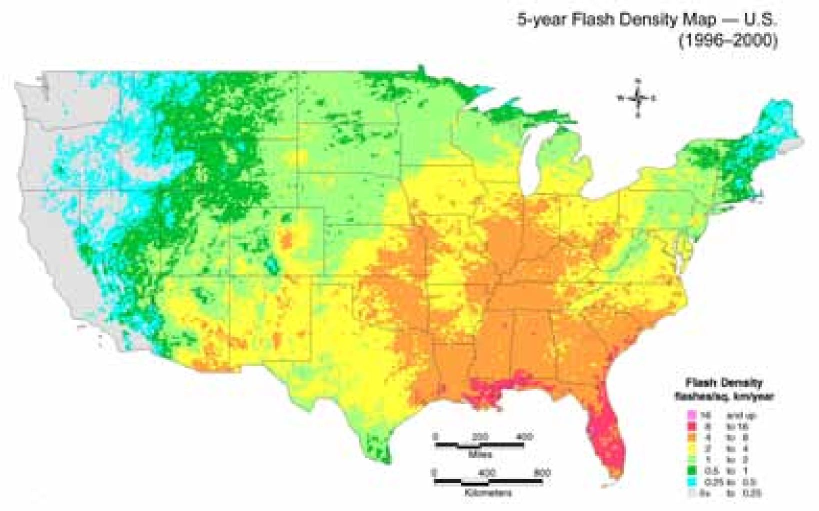

Figure 2. U.S. lightning flash density map. (Map provided by Vaisala-GAI. Lightning data provided by the U.S. National Lightning Detection Network.)

Surrounding Environment	Coefficient
Structure surrounded by similar sized structures	0.25
Structure surrounded by smaller sized structures	0.5
Isolated structure – level ground	1.0
Isolated structure – hilltop	3.0

***Table 1.** Coefficients of surrounding environment (C1).*

system requires the engineer to compare environmental factors (Nd) to the tolerable risk factors (Nc). Comparison is conducted by a ratio between the environmental factors and the tolerable risk. If the calculated ratio is 1.0 or greater, then a lightning protection system, which includes SPDs, is required. If the calculated ratio is less than 1.0, then a lightning protection system is not required.

The environmental factors are calculated using the equation of Eqn. 1.

$$N_d = N_g A_e C_1 (10^{-6})$$

Eqn. 1

The environmental factors consist of the collective area of the facility (Ae), its surrounding environment (C1) and the lightning flash density (Ng) of the area. There are different equations to determine the collective area of the facility based on the type of structure: standard rectangular structure, rectangular structure with prominent riser, rectangular structure with small riser. The collective area for a standard rectangular structure is calculated using equation Eqn. 2.

$$A_e = LW + 6H(L + W) + \pi 9H^2$$

Eqn. 2

Where L is the length of the structure, W is the width of the structure, and H is the height of the structure.

The surrounding environment of the facility has an integral affect on if and how lightning is going to strike a structure. Isolated structures located on a hilltop or mountain top are more vulnerable to lightning strikes than a structure located amongst similar sized structures. Determining the surrounding environment coefficient is done by choosing the appropriate values from Table 1.

The final parameter needed to calculate the environmental factors associated with the facility is the lightning flash density. The lightning flash density is the amount of lightning flashes that occur per year per kilometer. This value can be obtained through a variety of sources. However, it is important to understand that averages can change over time. Therefore, one should obtain not only the average of an extended period, e.g. ten years, but also maximum and minimal values over a short period of time, e.g. three months. A lightning flash density map is shown in Figure 2.

The tolerable risk of the facility (Nc) is determined by equation EQ3 and is dependent on the type of structure (C2), the contents within the structure (C3), the structure occupancy (C4), and the consequence of the loss of operations of the structure (C5).

$$N_c = \frac{(1.5)(10^{-3})}{C_2 C_3 C_4 C_5}$$

Eqn. 3

The type of structure is either metal with a non-metallic roof or metal with a metallic roof. Structures with other construction are not considered in this risk assessment. The coefficients for the type of structure are shown in Table 2.

The content of the structure is the second parameter to be determined. The structure contents range from low value, nonflammable contents to those of exceptional value, irreplaceable cultural items. The coefficients associated with each parameter are denoted in Table 3.

The occupancy of the structure is the third parameter that is determined. The definition of structure occupancies are: unoccupied; normally occupied; or difficult to evacuate. The coefficients associated with each parameter are denoted in Table 4.

The consequence of an interruption of service as a result of lightning is the fourth parameter to be determined. The definitions are: continuity of service is not required, no environmental impact; the continuity of service is required, no environmental impact; or the there are consequences to the environment. The coefficients associated with each

Structure Type	Coefficient
Metal with metallic roof	0.5
Metal with non-metallic roof	1.0

***Table 2.** Structure type.*

Structure Contents	Coefficient
Low value and nonflammable	0.5
Standard value and nonflammable	0.5
High value and moderate flammability	2.0
Exceptional value, flammable (electronics)	3.0
Exceptional value, irreplaceable cultural items	4.0

***Table 3.** Structure contents.*

Structure Occupancy	Coefficient
Unoccupied	0.5
Normally occupied	1.0
Difficult to evacuate or risk of panic	3.0

***Table 4.** Structure occupancy.*

parameter are denoted in Table 5.

The result of the lightning risk assessment will provide insight into whether a lighting protection system, which includes SPDs, should be installed. If the calculated value of the environmental factors is equal to or exceeds the calculated value of the tolerable risk, which results in a Nd/Nc ratio of 1.0 or greater, then a lightning protection system,

Structure Operations	Coefficient
Continuity of services not required, no environmental impact	1.0
Continuity of services required, no environmental impact	5.0
Consequences to the environment	10.0

Table 5. Consequence of interruption of service to the structure.

and SPDs, should be installed. If the Nd/Nc ratio is less than 1.0, then a lightning protection system is not required.

LIGHTNING RISK ASSESSMENT EXAMPLE

In this example, we need to determine if a new structure that we are designing should have a lightning protection system based on the following parameters:

1. Structure size – 100 meters long, 60 meters wide, 15 meters tall
2. The structure is the tallest structure in the vicinity
3. The location of the facility is in St. Petersburg, FL
4. The structure is metal with a metallic roof

Parameters	Coefficient
Collective area (A_e)	26,762 m2
Surrounding environment (C_1)	0.5
Lightning flash density (N_g)	16 flashes/yr/km
Structure type (C_2)	0.5
Structure contents (C_3)	3.0
Structure occupancy (C_4)	3.0

Table 6. Parameters and calculations for lightning risk assessment example.

5. The structure contains and data center for a regional bank
6. The structure is normal occupied with more than 300 people

Based on these conditions, the values and coefficients have been determined and are located in Table 6.

The environmental factor for the structure (Nd) is calculated as 0.42819. The tolerable risk factor (Nc) is calculated as 0.00017. Dividing the environmental factor by the tolerable risk factor returns a value of 2569. Any number of 1.0 or greater indicates that a lightning protection system should be installed, whereas a number less than 1.0 indicates that lightning protection system is not required.

CONCLUSION

A lightning protection system is an important component in protecting a structure, electrical systems and critical business processes. Surge protective devices (SPDs) are an important component of a lightning protection system and are required by U.S. and international standards to be installed if a lightning protection system is installed.

Knowing when to and when not to apply a lightning protection system is important analysis that an engineer must examine when design a new structure or updating an existing structure. Using a lightning risk assessment is a tool that an engineer can use to determine whether a lightning protection system and associated SPDs are required.

The lightning risk assessment should take into account parameters associated with the structure and its surrounds, the lightning flash density of the location, and the importance of the facility and its processes to the business, the community, and the environment. While the NEC only mandates that critical operating power systems be subjected to a lightning risk assessment, this requirement should be extended to all legally required and emergency power systems.

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Bryan Cole is the president/owner of Technology Research Council. Cole has more than 20 years experience in the design, development, application, and product safety of power quality equipment, aviation instrumentation, and various low-voltage distribution equipment. He is an IEEE member, a number of UL Standard Technical Panels, and has assisted in the development of more than 30 national and international standards related to Electrical Power Systems.

Accurate Feedthrough Capacitor Measurements at High Frequencies Critical for Component Evaluation and High Current Design

A shielded measurement chamber allows accurate assessment and modeling of low pass filters

GEORGE M. KAUFFMAN
NexTek, Inc.
Westford, Massachusetts USA

The shunt capacitor is the critical element in almost all low pass filters. Feed-through capacitors are configured as a center electrode passing through a grounded housing, which contains the desired capacitance from the electrode to the grounded housing, and practically eliminates lead inductance. This article will explain the importance of feedthrough capacitors, and provide improved methods for testing the high frequency performance of these critical components. Testing the insertion loss performance of feedthrough capacitors in a repeatable fixture is necessary to evaluate components for design, application qualification, and incoming inspection or quality audits. High current and high performance filters represent unique challenges for component testing. High current here refers to current ratings of significantly over 30 Amperes, up to and exceeding 400 Amperes. High performance generally refers to insertion losses of greater than 30dB at frequencies up to at least 1GHz.

Lower frequency performance may require series inductors with the shunt capacitor. For example, these components could be arranged according to Butterworth criteria to reduce the cut-off frequency and maximize slope of the insertion loss curve. For example, the ever popular π filter with a 16 kHz -3dB cutoff frequency, and 60dB per decade roll-off would consist of the components shown in Figure 2.

While the value of an inductor has a constant relationship of μH = 5 x μF for an optimized π filter; in many cases the inductor is a lower value than optimum during actual use due to weight, size, or cost constraints. The inductor can be susceptible to saturation at high current, thereby reducing the inductance value further. The other benefits of a series inductance is to increase the high frequency performance above the level achievable from a capacitor alone. The feedthrough capacitor is substantially immune from any effects of through current, and usually only has minor and predictable changes with applied voltage. For the lowest cost and size, and to eliminate through current performance variations, the feedthrough capacitor alone is the preferred, or initial, solution for high current and high frequency filtering requirements.

There have been several articles written regarding improved methods for measuring the low frequency performance of filters. A useful recommendation, particularly at frequencies below 100kHz, is to use current injection according to IEEE 1560 Method 10.5 at full current. Since high performance feedthroughs are functional well over 100MHz, measuring the component ac-

Figure 1. Typical feedthrough installation example.

curately is an important part of qualification. This article will address some of the concerns regarding measuring high frequency insertion loss of filters, particularly well above 30 MHz, while also accounting for high current levels.

An industry standard insertion loss measurement set-up is shown in Figure 3. This circuit has been successfully used in the bands from about 300kHz to over 30MHz. The challenge with this test set-up is the use at currents exceeding 30 amperes or greater, and at greater than 100MHz. Even though the test circuit is on a ground plane, the high frequency coupling across the power taps can have significant effects on the results. This high frequency coupling is shown in Figure 4.

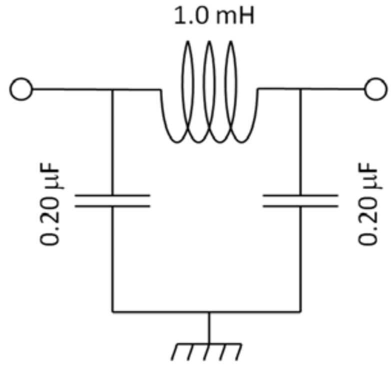

Figure 2. 16 kHz Pi filter.

The "open" DUT (Device Under Test) zone can cause measurement limitations at high frequencies. This is particularly true for high current filters, as the geometry of the end electrodes and attaching wiring can extend for 2.0" (50mm) or more on either side. As frequencies usually exceed 30MHz the parasitic capacitance across the filter (from one side of the capacitor to the other) can cause significant coupling around the filter. Consider that the feedthrough capacitor effectively shunts the center of the through conductor to ground, resulting in what are essentially opposing linear Beverage antennas.

The coupling around a filter can be modeled as either capacitance or antenna coupling. The parasitic capacitance shown in Figure 4 couples higher frequencies around the filter shown in the center of the figure. The parasitic capacitance is proportional to several factors, including exposed areas, and inversely related to separation of the two sides of the filter. Antenna-type coupling around the filter is related to several factors including, principally, separation and exposed length. The free path loss is inversely proportional to the square of the separation and frequency, which is the coupled signal reduction with distance. The antenna efficiency of the radiating surface is complex and improves to a maximum at $\lambda/4$ and harmonics thereof. This factor, and several others, can combine to produce a maximum value of coupling at an array of frequencies. In order to get an estimate of this coupling effect,

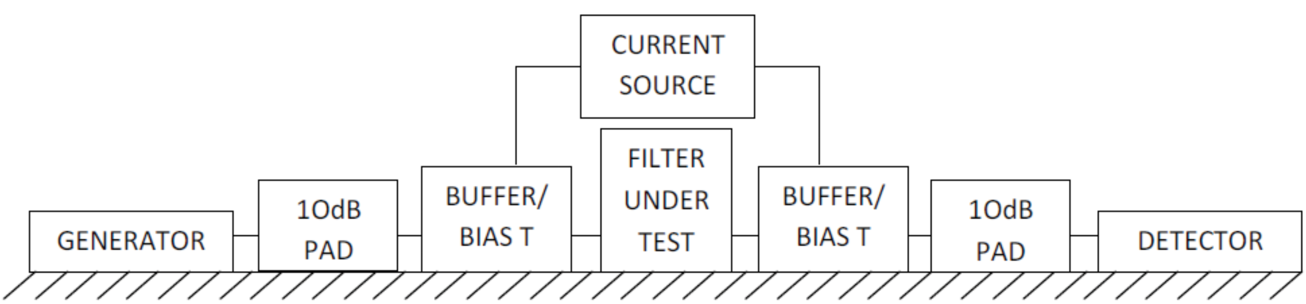

Figure 3. Insertion loss test set-up according to MIL-STD-220B with load current and buffer networks.

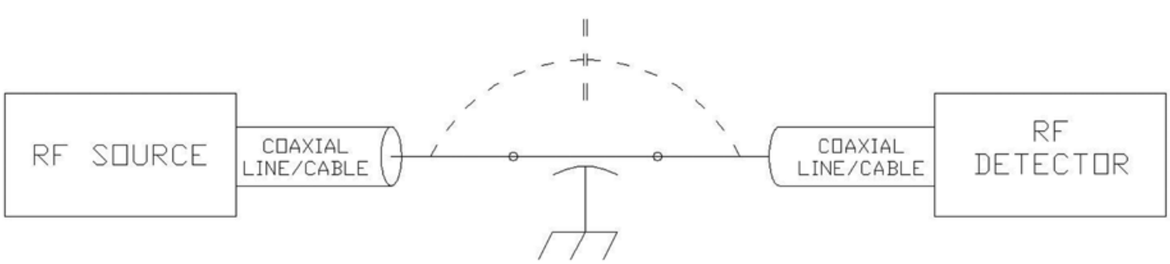

Figure 4. Coupling across a DUT, when measuring insertion loss.

Figure 5. *Grounded DUT hook-up test leads.*

the connection wires to a DUT shown in Figure 5 were measured for isolation. This figure shows two test leads, both coaxially aligned with shields and ends shorted to an aluminum ground plane. The exposed lengths are about 50mm (2.0") long, and the distance above the ground plane is about 13mm (½)". If we measure the isolation between these wires, we get a rough estimate of the lead-in and lead-out coupling around a feedthrough capacitor. Figure 6 shows the isolation for the grounded wires shown in Figure 5. Frequencies below 1 MHz have over 70 dB of isolation. Above 1 MHz a noticeable reduction in isolation occurs, with 50 dB indicated at 13 MHz. The isolation tends to reduce to about 30 dB at 100 MHz . The isolation maintains a value of about 30 dB up to 1Ghz, where a further drop in isolation occurs. This effectively means that "open leads" to the DUT could produce a noise floor at about 30 dB at high frequencies. MIL-STD-220B is effective at measuring the lower frequency performance including the effects of

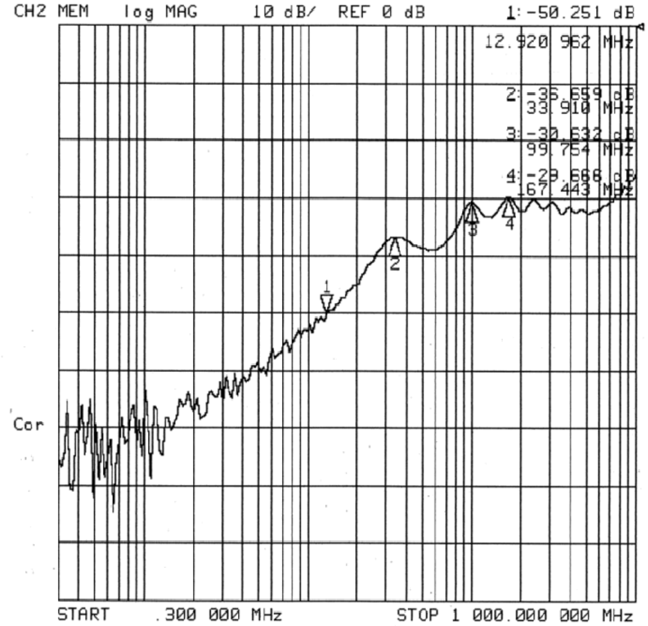

Figure 6. *Isolation between grounded DUT hook-up leads.*

voltage and current, but measurements at frequencies above 10MHz can be compromised by the "noise floor" due to this interlead coupling.

NexTek has developed a line of compact high current

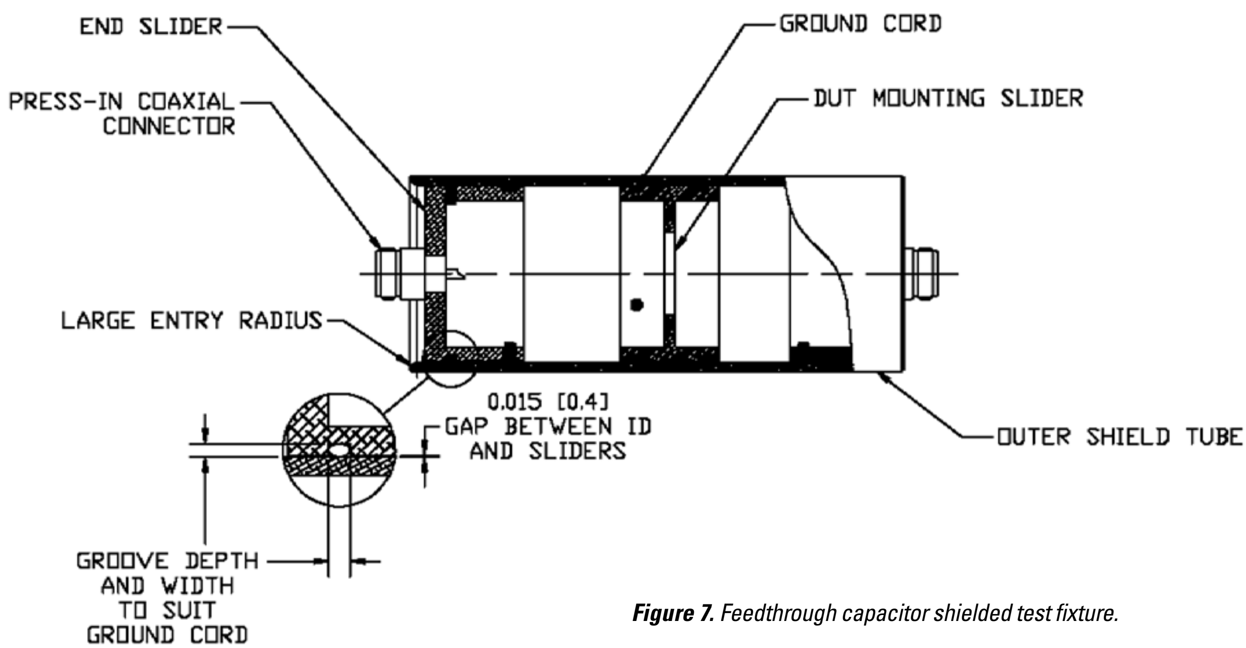

Figure 7. *Feedthrough capacitor shielded test fixture.*

feedthrough filter capacitors. Since the insertion loss of a C-type feedthrough is substantially unaffected by through current levels, it is advantageous to accurately evaluate the performance of a high current filter using less-than- full-scale test techniques. NexTek has also developed a method of accurately measuring the insertion loss at the component level with no load current being required and very accurate high frequency results.

The high frequency performance of capacitors requires a fully shielded enclosure for testing, including shielding of one side of the filter from the other. A fixture such as this is shown in Figure 7, and can be found at www.nexteklightning.com/FilterTestFixture.html).

The TEM cell inspired test fixture has an outer shield tube that is fashioned from a convenient diameter of metal pipe or tubing to fit around the largest expected filter. The inside will generally have to be precision turned and polished, and the inside entry edges should be well rounded. There are three internal sliders, which are piston shaped objects. Good results have been obtained with sliders and tubes made from nickel plated aluminum. The end sliders have coaxial connectors for connection to a network analyzer or source and detector. The coaxial connectors might have small springs, pogo pins or discs soldered onto the inner side of the center pins to make contact to the Device Under Test (DUT). The DUT slider should keep the capacitor centered by having a tapered face on one side, and/or a through hole which just fits the component. All three sliders have outer circumferential grooves, to hold ground cord in position, with holes through to the ID of the pistons, for securing the ends of the ground cord ends. With the adequate groove depth and width, and a small gap between the sliders and inside diameter of the shield tube, at least two complete circumferential shield grounds can be established between the sliders and the shield tube. Successful results have been obtained with both spiral and knit mesh type ground cord; however, silicone foam core with double layer SnCuFe mesh seems to work best. The ground cord effectively isolates left side from the right side of the middle slider, and the internal region of the test fixture from the external environment. The feedthrough capacitor is mounted on the middle slider, which is inserted near the midpoint of the shielding tube. The end sliders are inserted and advanced until contact is made with the end electrodes of the filter, when measurements can be taken.

Figure 8. *An HPR Filter being installed in test fixture.*

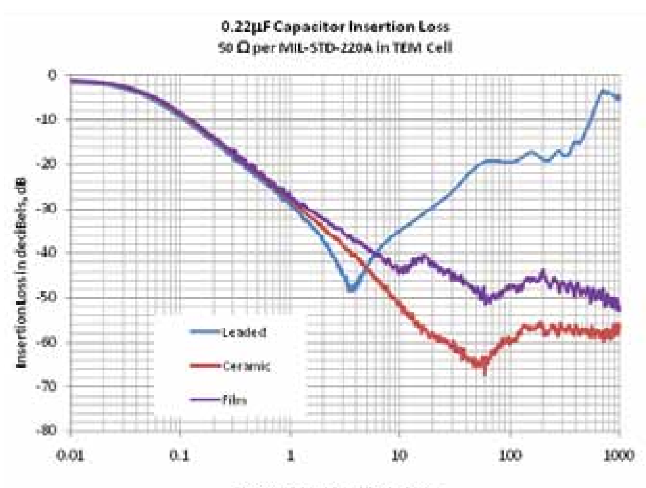

Figure 9. *Comparison of various filter capacitors.*

Figure 10. *Maximum insertion loss versus ESR.*

Figure 11. *.22µF/40µH/.22µF Filter Insertion Loss.*

Figure 8 shows an HPR 140 Ampere filter, which is secured to the DUT mounting slider, being slid into the outer shield tube. One ground mesh ring has passed into the outer shield tube, while a second mesh is close to entering. The end slider is shown with spiral ground cord, and would be installed after the DUT slider is inserted to approximately the midpoint of the outer shield tube. The N connector on each end would be connected into a through-calibrated network analyzer to measure the insertion loss of the filter with very high accuracy.

TIPS ON MEASURING FILTERING PERFORMANCE

A. The performance of different filtering technologies can be assessed. For example, a leaded capacitor can be compared to a ceramic or metalized plastic feedthrough. Figure 9 shows that the leaded component has a resonance

***Figure 12.** .22µF/160nH/.22µF filter insertion.*

at about 3.3MHz. This equates to an ESL of about 10nH. The metalized film capacitor has an insertion loss dip at about 20 MHz. This dip can be more pronounced for higher capacitance values.

B. Estimating capacitor parasitic properties. Feedthrough capacitors approach an insertion loss plateau at high frequencies. The Equivalent Series Resistance (ESR) of a capacitor limits the continued improvement of shunting performance of a real capacitor at ever higher frequencies. The level of the plateau relates strongly to the ESR of the capacitor, through the curve shown in figure 10. The metalized film capacitor has an ESR of about .075 Ohms. The ceramic feedthrough capacitor has an ESR of about 0.03 Ohms. This value of ESR can be used to assess dissipation or other parameters at high frequency.

C. Coordination of filtering with shielding. The same coupling effects across the filter that compromise filter performance measurement can also affect the measured application level isolation of an enclosure. A general rule of thumb is that coupling between axially aligned wires is about -30dB. Note that the level of coupling is frequency dependent, and -30dB begins to be a good estimate at wire lengths greater than $\lambda/20$. Therefore, the shielding effectiveness of the enclosure could be somewhat less than the values of the filter insertion loss and still preserve isolation. If the shielding is 30 dB less than the filter insertion loss, the resulting two equal value paths might have a reduction of isolation of about 3dB.

D. Modeling of filters with series inductors. Some applications require filter performance to be increased by use of series inductors. Accurately modeling the feedthrough capacitors and series inductors can yield predictable and accurate results. There are two commonly used inductors at high current; the wound type and the ferrite through-hole type. Wound type inductors generally have higher inductance and thus better low frequency performance; at the expense of size, weight and cost, and the electrical characteristics of self resonance. A simple but useful circuit analysis model of a wound inductor is a parallel inductor and capacitor. When the self resonance frequency is measured, the value of the capacitor can be estimated. In addition, the reduced inductance at full load current should be used, instead of the nominal. The parameters of the capacitor and inductor can be modeled quite accurately. Figure 11 shows the model of a 220nF/40uH/220nF filter. The characteristics of the capacitors are ceramic as shown in Figure 9; and the wound inductor self resonant frequency of 23 MHz corresponds to a shunt capacitance of 1.2pF, and the inductance drops to 30uH at peak current.

Ferrite bead inductors are compact, low cost, easier to install on high current conductors, and tend to be dissipaters of RF power. The dissipation can turn significant portions of the unwanted RF energy into heat, instead of reflecting or circulating the energy within the system. However, these benefits are at the expense of substantial inductance reduction at full current, due to saturation, and generally less inductance to start with. The saturation effects can be minimized by gapping techniques, but this makes a more stable but further reduced inductance. If the inductor is a ferrite bead type, then the circuit analysis model would be an inductor in parallel with a resistor. Figure 12 shows the modeled performance of a π filter with the same capacitors as in the previous example, and a ferrite bead 28A5131-0A2. This ferrite bead measures 160 nH with a 0.4mm (.016") gap at full load.

Not only does the accurate measurements of insertion loss allow better high frequency modeling, but lower frequency modeling is virtually error free, provided that full current inductance parameters are used.

E. It is always good to perform a through and isolated test for the test fixture. An example of these test results for a test fixture with an inside diameter of 51mm (2.0") and two 75mm (3.0") long chambers on either side of the middle DUT slider is shown in Figure 13.

Note that this curve covers from 3MHz to 6GHz. The top curve represents the insertion loss of a wire connection through a hole in the middle DUT slider. Since the impedance of a through wire is far higher than 50 , a departure from a very low insertion loss is expected at about 500 MHz, and harmonics thereof. The measured insertion loss may be overstated somewhat at about 500MHz. The first problematic resonance seems to occur at about 3.7GHz. The lower curve is isolation, with a solid middle slider. This insertion loss responds to the resonance of the chambers, the shielding of the sliders and attaching cables (and analyzer), and the length of the internal connection leads. The isolation with short leads, of approximately 25mm (1") in length, shows high levels of isolation to almost 2GHz, with reasonable isolation at 3.5 GHz. The first problematic isolation level is at about 4 GHz. This shows that the test fixture of this geometry is capable of accurately measuring insertion loss to more than 2GHz.

CONCLUSION

Accurate feedthrough insertion loss measurements, particularly at high frequency, are vital to understand component parameters, measure filtering performance, and/or design a filter. The shielded chamber presented has been used to over 1GHz, and is easy to fabricate and use.

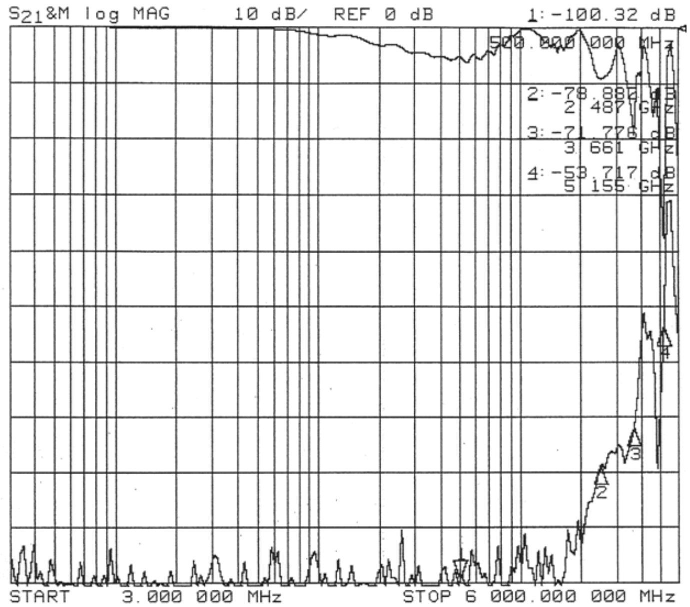

Figure 13. *Example of calibration results for test chamber.*

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- [2] Phipps, Keebler, and Connatser, "Improving the Way We Measure Insertion Loss" Item Publications Nov., 2008. Print.

George M. Kauffman, PE, holds a BSME and MS in Engineering Management from the University of Massachusetts at Amherst. He leads NexTeks design and engineering team. Kauffman has extensive EMC and microwave design experience. He holds several patents in RF protection and related technology. He can be reached at engineering@nexteklightning.com.

Measurements above 1 GHz in Time-Domain: Theory and Application

CHRISTIAN HOFFMANN
Technische Universität München, Lehrstuhl für Hochfrequenztechnik, Munich, Germany

STEPHAN BRAUN
GAUSS Instruments GmbH, Munich, Germany

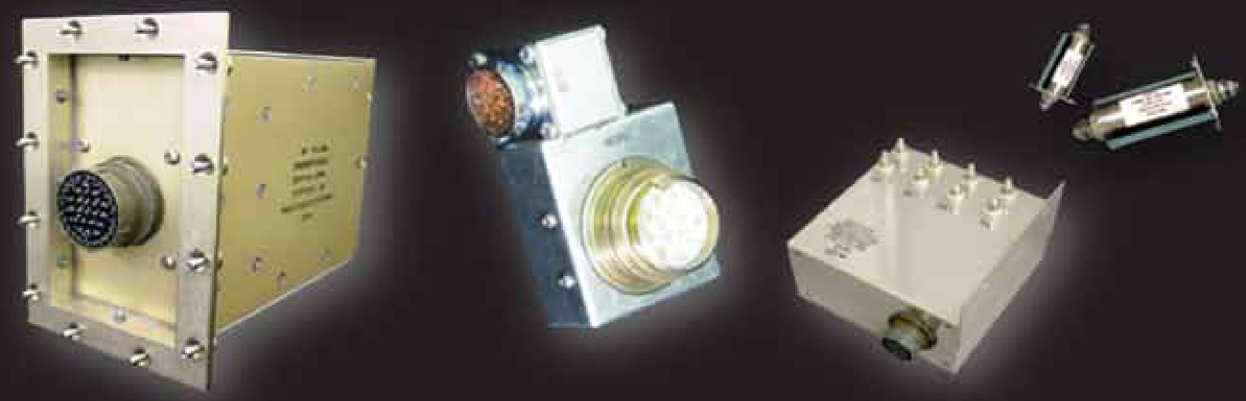
ARND FRECH
GAUSS Instruments GmbH, Munich, Germany

PETER RUSSER
Technische Universität München, Lehrstuhl für Nanoelektronik, Munich, Germany

Time-domain electromagnetic interference (EMI) measurement systems are widely used, especially for the measurement of non-stationary signals. The newest CISPR 16-1-1 Ed. 3 Am. 1 [1] adds specifications like gapless acquisition for such instruments. Such instruments are called FFT-based measuring instruments. Several publications focused on the frequency range up to 1 GHz exist on this topic e.g. [2]. Broadband emissions below 1 GHz are typically generated by switching processes caused by devices like household appliances or industrial equipment.

Above 1 GHz, there are devices that exhibit broadband non-stationary emissions. In order to protect modern communication systems above 1 GHz like Wi-Fi, such devices have to be measured, weighted and compared to limit lines. A particular point of interest in this respect is industrial, scientific and medical (ISM) equipment according to CISPR 11 [3]. Currently such measurements are carried out by using a spectrum analyzer in repetitive sweeps and applying the max hold function. If the peak level is above the limit line, the measurement is repeated with a video bandwidth of 10 Hz, which corresponds to a logarithmic average detector. Other discussions focus on the use of the amplitude probability density (APD) function for measurements of ISM equipment above 1 GHz. However, as the traditional EMI receivers can only observe the signal at one frequency at the same time, and the emission is changing over periods of several seconds, those receivers are not well suited to measure non-stationary EMI with reasonable scan times. Time-domain EMI measurements systems, using an FFT-based bank of receivers allow to make such measurements faster, and allow also to optimize the components of ISM equipment to obtain compliance according to CISPR 11.

In [4], a time-domain EMI measurement system up to 18 GHz is presented. In this paper, an overview of the theory of operation and the practical application of such a measurement system is shown. The system presented in this paper allows for EMI measurements, fully compliant to CISPR 16-1-1. Measurements have been carried out in the frequency range up to 18 GHz in a full anechoic room. These measurements show as an example the emission of a microwave oven in the ISM band at 2.45 GHz with real-time spectrograms of the fundamental and a subharmonic of the microwave oven's magnetron.



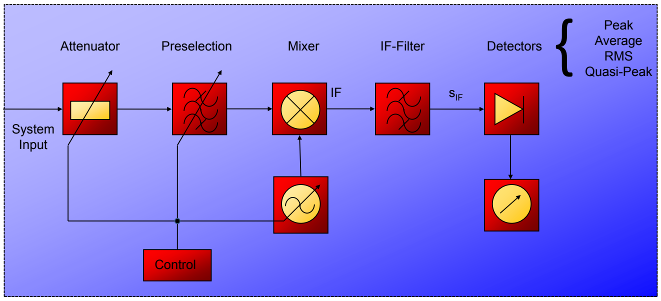


Figure 1. *Heterodyne EMI receiver.*

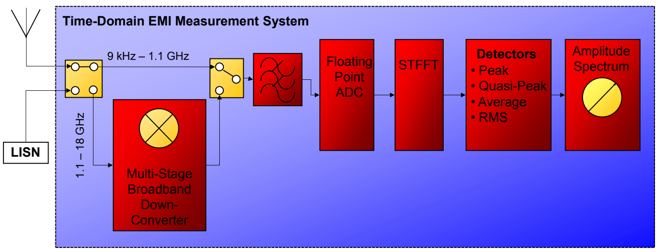


Figure 2. *Time-domain EMI measurement system.*

HETERODYNE MEASUREMENT RECEIVERS

Since the beginning of the 20th century, measurement receivers based on the heterodyne principle have been predominantly used to characterize EMI. As an example,

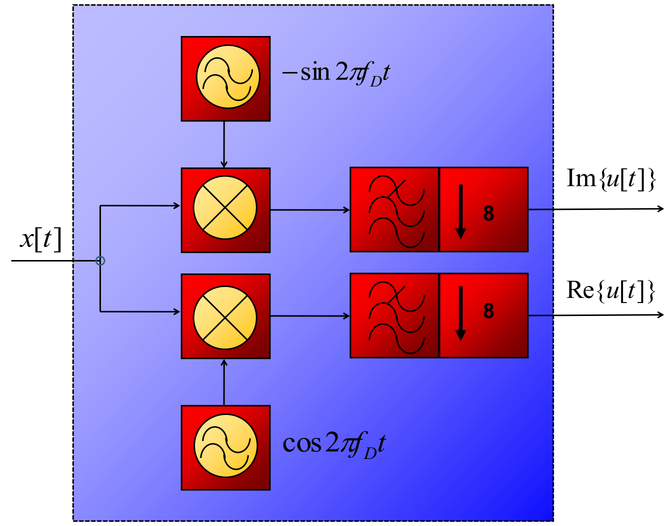


Figure 3. *Digital down-conversion.*

companies like General Electric and Siemens have started the development of such systems in the 1920s [5][6].

The block diagram of a heterodyne measurement receiver is shown in Figure 1. The EMI input signal is bandpass filtered by a variable preselection filter. Thus, the dynamic range is increased by attenuating out-of-band narrowband and transient broadband interference signals. The preselection typically consists of several selectable bandpass filters that are tunable within a certain frequency range. By means of a variable attenuator, the level of the input signal to the mixer is set in order not to overdrive the mixer and minimize distortion of the IF-signal. Every considered frequency is then consecutively down-converted to a fixed IF frequency. The IF-signal is filtered by the chosen IF-filter. Thereby it is assured, that only a specific band of the IF signal is reaching the detector input. CISPR 16-1-1 dictates the use of several IF-filters of different bandwidths that have to fulfill the given critical masks. The output signal is evaluated by a given set of detectors for the selected dwell-time. The average, CISPR-Average, peak, quasi-peak and rms detectors are used to measure EMI signals according to CISPR 16-1-1. The amplitude spectrum is displayed.

Heterodyne EMI receivers offer high dynamic range through a complex preselection, high sensitivity through low-noise preamplifiers and are commonly available up to millimeter wave frequencies. The major drawback of this technology are the long scan times. The scan time can easily reach hours or days, when wide measurement bands shall be measured with high frequency resolution and high sensitivity.

TIME-DOMAIN MEASUREMENT SYSTEM

The block diagram of the time-domain EMI measurement system is shown in Figure 2. The EMI input signal in the frequency range from 9 kHz-1.1 GHz is low-pass filtered to ensure Shannon's theorem is fulfilled. The filtered signal is sampled by a floating-point analog-to-digital converter (ADC) [2]. The spectrum is calculated by the Fast-Fourier-

Transform (FFT) and weighted by digital detectors like peak, quasi-peak, average or rms. The calculated amplitude spectrum is displayed.

Spectral Estimation

Discrete spectral estimation is performed by the Discrete-Fourier-Transform (DFT). A fast algorithm for the computation of the DFT is the FFT. The FFT exploits symmetry and repetition properties and is defined as [7]

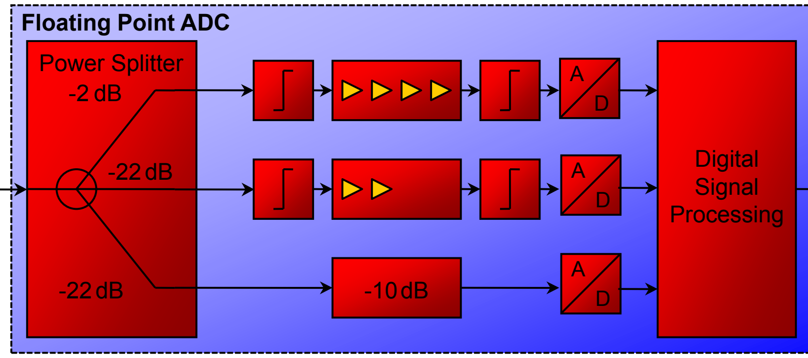


Figure 4. Floating-point analog-to-digital converter.

$$X[k] = \sum_{n=0}^{N-1} x[n] e^{\frac{-j2\pi kn}{N}}, \quad (1)$$

where *X[k]* is the discrete amplitude spectrum of the discrete time signal *x[n]*.

The Short-Time-Fast-Fourier-Transform (STFFT) is defined as an FFT over a limited time-interval. A Gaussian window function *w[n]* is applied, corresponding to the IF-filter of a conventional measurement receiver. By application of the STFFT, a spectrogram is calculated. The spectrogram is a FFT of a time-interval of the sampled time-domain signal. It depends on the discrete time coordinate of the window and the discrete frequency *k*. The STFFT is calculated by [7]

$$X[\tau, k] = \sum_{n=0}^{N-1} x[n+\tau] w[n] e^{\frac{-j2\pi kn}{N}}. \quad (2)$$

Digital Down-Conversion

In order to process the signal continuously and to enable the calculation of a real-time spectrogram, the frequency range from DC to 1.1 GHz is subdivided into eight subbands with a bandwidth of 162.5 MHz each. Every subband is digitally down-converted to the baseband and the subbands are processed sequentially [2]. The block diagram is shown in Figure 3. A polyphase decimation filter is used for the inphase and quadrature channel to reduce the sampling frequency and to fulfill the Nyquist criterion. The output sampling frequency is 325 MHz, while the bandwidth is 162.5 MHz.

Multiresolution Time-Domain EMI Measurement System

In Figure 4, the block diagram of the floating point ADC, which is comprised of several ADCs, is shown [2]. The input signal is distributed into three channels by an asymmetrical power splitter. Each channel consists of a limiter, a low-noise amplifier, and an ADC. While the first channel digitizes the amplitude range from 0 to 1.8 mV, the third channel digitizes the amplitude range from 0 to 5 V. The second channel is used to digitize the intermediate amplitude range from 0 to 200 mV. The signal is recorded in all three channels simultaneously.

A floating-point representation is calculated from the data of all three ADCs. The values are take in a way that the sample is taken from the ADC that shows the maximum not clipped value. By the multiresolution ADC-system, the necessary dynamic range is achieved to fulfill the requirements of CISPR 16-1-1. In comparison to the requirement for sinusoidal signals, for the measurement of transient signals, the input stage has to handle signals which require additionally 50 dB higher dynamic range, regarding the amplitude range. As an example the notch filter test, as described in CISPR 16-1-1 Section 4.6 has been carried out to verify the spurious-free dynamic range for pulses. A notch filter with an attenuation of at least 40 dB at around 300 MHz was connected to the system input and a pulse generator fed a pulse with a pulse width of 300 ps to the

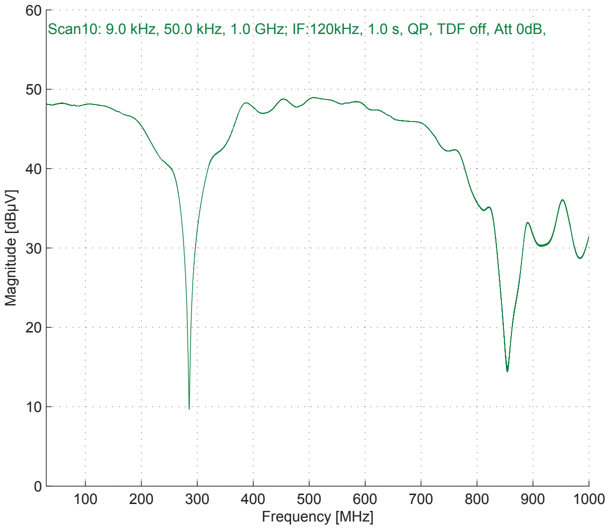


Figure 5. *Notch filter test.*

system. The required notch response is 36 dB. According to Figure 5, the time-domain measurement system shows a notch response of better then 38 dB.

MULTI-STAGE BROADBAND DOWN-CONVERTER

As illustrated in Figure 2, a multi-stage broadband down-converter was added to enable measurements above 1.1 GHz. For measurements from 1.1-6 GHz, the EMI input signal is down-converted to the range below 1.1 GHz, where it is sampled by the floating-point ADC. The amplitude spectrum is displayed.

For measurements from 6-18 GHz, an additional mixer stage down-converts the input frequency band to the frequency range from 1.1-6 GHz. Subsequently, it is down-converted and processed like described above. A basic prototype of the time-domain EMI measurement system up to 18 GHz was presented in [4]. In comparison, the presented system is fully compliant to CISPR 16-1-1, enabling full compliance measurements from 9 kHz-18 GHz.

1.1 - 6 GHz Down-Converter

Because of the nonlinear characteristics of mixers, a large number of mixing products are generated at its output. These frequencies f_{IF} are determined by [8]

$$f_{\mathrm{IF}}^{m,\pm n} = |m \cdot f_{\mathrm{LO}} \pm n \cdot f_{\mathrm{RF}}| \ , \ m,n \in \mathbb{N}, \quad (3)$$

where f_{RF} is the RF input frequency and f_{LO} is the local oscillator frequency.

If only the fundamental frequencies of f_{LO} and f_{RF} are taken into consideration, i.e. m, n = 1, we obtain two frequency components f_{RF} 1,2 according to (3)

$$f_{\mathrm{RF}\ 1,2} = |f_{\mathrm{LO}} \pm f_{\mathrm{IF}}|. \quad (4)$$

The frequency conversion yields two sidebands. The image frequency signal is converted to the same intermediate frequency as the desired signal.

To avoid this, a two-stage mixer system is used in the 1.1 - 6 GHz down-converter [9]. The block diagram of the 1.1 - 6 GHz down-converter is shown in Figure 6. The input band is divided into 14 subbands with a bandwidth of 325 MHz each. Each of those bands is sequentially up-converted to a first high intermediate frequency band which is located above the input frequency band. A second mixer down-converts the IF-band to the range below 1.1 GHz, where it is sampled by the floating-point ADC. A fixed bandpass-filter is sufficiently suppressing the image band, because the input band and the image band do not overlap spectrally. This preselection filter also enhances the spurious-free dynamic range of the system by preventing the LNA and mixers being driven into saturation by high-level narrowband and broadband out-of-band EMI.

6 - 18 GHz Down-Converter

To extend the upper frequency limit of the time-domain-EMI measurement system to 18 GHz, a third mixer stage is added. The block diagram of the 6 - 18 GHz down-converter is shown in Figure 7. For measurements above 6 GHz, the preselection is dividing the input band into three ultra-broadband subbands: band 1 from 6 - 9 GHz, band 2 from 9 - 13 GHz and band 3 from 13 - 18 GHz. The switching between these bands is done via broadband, low-loss, single-input, triple-output (SP3T) PIN-diode switches. These ultra-

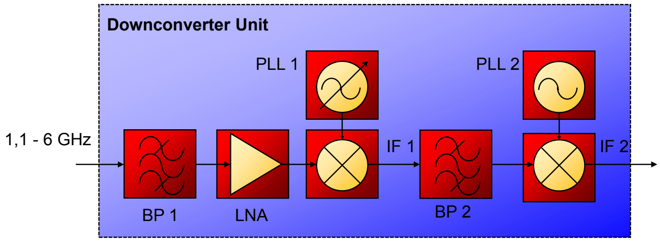


Figure 6. *1.1 - 6 GHz down-converter.*

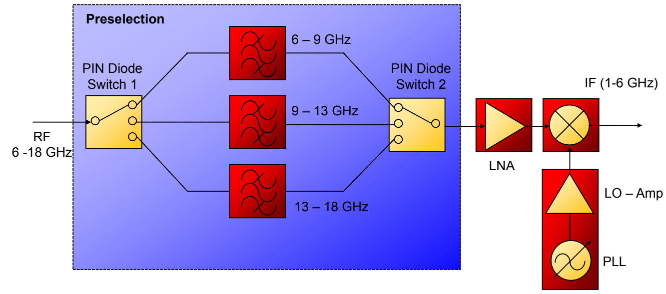


Figure 7. *6 - 18 GHz down-converter.*

broadband subbands are consecutively down-converted to the 1.1-6 GHz band via broadband, low-conversion loss mixer and fed to the input of the 1.1 - 6 GHz down-converter.

HARDWARE IMPLEMENTATION

As most of the EMI in the frequency range above 1 GHz, e.g. higher harmonics of communication systems, is low-level in nature, high sensitivity is mandatory for frequencies above 1 GHz. Increased attenuation of cable assemblies above 1 GHz in common test environments aggravates the problem. A low noise figure of the input stage is critical for high sensitivity. This correlates with a low attenuation of the first stages of the multi-stage broadband down-converter, as (5) for the calculation of the noise figure F of a cascaded system with N stages [10] implies

$$F = 1 + F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \ldots + \frac{F_N - 1}{\prod_{k=1}^{N-1} G_k}, \quad (5)$$

where G_i is the available power gain of stage i and F_i is the noise figure of stage i.

In the presented measurement system, high-gain, low-noise InGaP/GaAs MMIC preamplifiers yield a system noise figure of around 6-8 dB, rendering the use of external amplifiers unnecessary. To further increase the system's sensitivity and dynamic range, low-noise double balanced mixers with low conversion loss and high 1 dB compression point are used.

The switching between the bands from 6-18 GHz is accomplished by broadband low insertion loss, single-input, tripleoutput (SP3T) PIN-diode switches. The low diode junction capacitance in reverse polarity yields an excellent isolation of –55 dB to –35 dB in the OFF-state. The switches achieve a low insertion loss of –1.5 dB to –2 dB in the range from 6-18 GHz.

EMISSION MEASUREMENTS

Electric household appliances radiate considerable spectral energy density in the frequency range above 1 GHz. A commonly found example is the microwave oven. A magnetron generates high-power microwave energy at around 2.5 GHz. In order to characterize the radiated emission of a microwave oven, the oven was placed in a full anechoic chamber. An ultra-broadband quad-ridged horn antenna with a bandwidth from 1.7-20 GHz [11] was placed in a distance of 3 m to the device under test. To compensate for cable losses and to give the electric field strength of the EMI, the corresponding transducer factors and the antenna factor were applied.

In Figure 8, the measured emission spectrum from 2-18 GHz is presented. The spectrum shows the magnetron's strong fundamental at around 2.45 GHz and several higher harmonics up to 18 GHz. The scan time using an IF-filter bandwidth of 9 kHz and a frequency resolution of 50 kHz was around 120 s, while around 320 000 frequency points were calculated.

The emission of the microwave oven is not stationary. The amplitude spectrum cannot give any insights into the time-behavior of the radiated emission. The time-domain

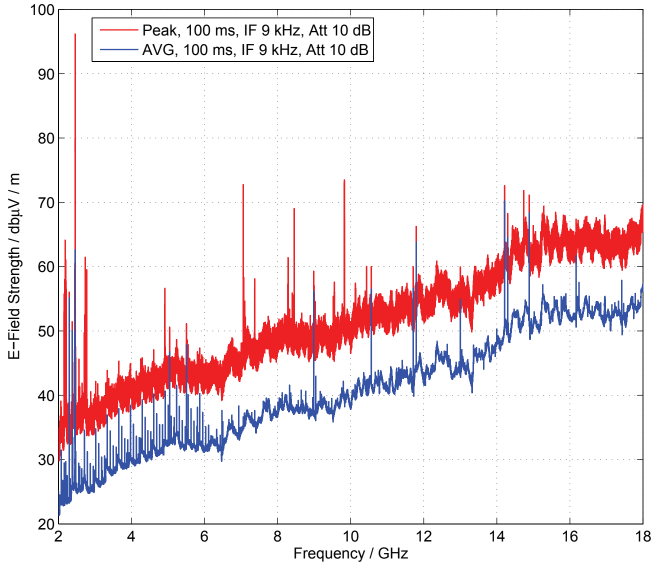


Figure 8. *Emission spectrum of a microwave oven.*

system's real-time capability allows for the examination of the time-behavior of the magnetron's fundamental. The spectrogram is shown in Figure 9. The microwave oven was set to a medium power level, where the magnetron is periodically turning on and off. After a short broadband switching pulse, the magnetron turns on at around 3 s in time and turns off at around 9 s. The magnetron's output frequency changes by about 10 MHz over this time-period, as the oscillator is freerunning.

The microwave oven's magnetron exhibits a non-linear transfer function and therefore, higher harmonics can be seen in the radiated emission spectrum. Figure 10 shows a spectrogram of the microwave oven's emission at the 6th harmonic, located at around 14.74 GHz. The maximum electric field strength of the microwave oven's radiated emission is about 70 dBµV/m at this frequency. With its ultra-low system noise floor and the corresponding high sensitivity, the time-domain EMI measurement system is able to measure this low-level emission in real-time.

The frequency shift of the free-running oscillator's 6th harmonic equals around 60 MHz. The microwave oven's magnetron can be described as a non-linear system [12]. Thus, the output signal *y(t)* contains harmonics of the sinusoidal input signal which can be described as

$$y(t) = A_n \cdot cos(n2\pi ft), n = 1, 2, \dots\ . \tag{6}$$

The frequency shift of the magnetron's fundamental resembles a frequency modulation of the output signal *y(t)* according to

$$y(t) = A \cdot cos[2\pi t(f + \delta f)]. \tag{7}$$

Thus, the frequency modulated magnetron's harmonics can be described as

$$y(t) = A_n \cdot cos[n2\pi t(f + \delta f)], n = 1, 2, \dots\ , \tag{8}$$

yielding a total frequency shift of

$$\delta f = 6 \cdot 10\ MHz = 60\ MHz \tag{9}$$

for the 6th harmonic.

CONCLUSION

The theory and application of time-domain EMI measurement systems according to CISPR 16-1-1 have been presented. Such measurement systems allow to reduce test time, and to perform investigations of the emission of ISM equipment above 1 GHz. As such emission measurement systems allow for real-time measurements over large frequency bands, the non-stationary behavior of the electromagnetic interference can be measured and weighted.

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CHRISTIAN HOFFMANN was born in Ulm/Donau, Germany. He received the Dipl.-Ing. degree in Electrical Engineering from the Technische Universität München (TUM), Munich, Germany, in 2008. He is currently working towards the Dr.-Ing. degree at the Institute for High-Frequency Engineering at TUM, Germany.

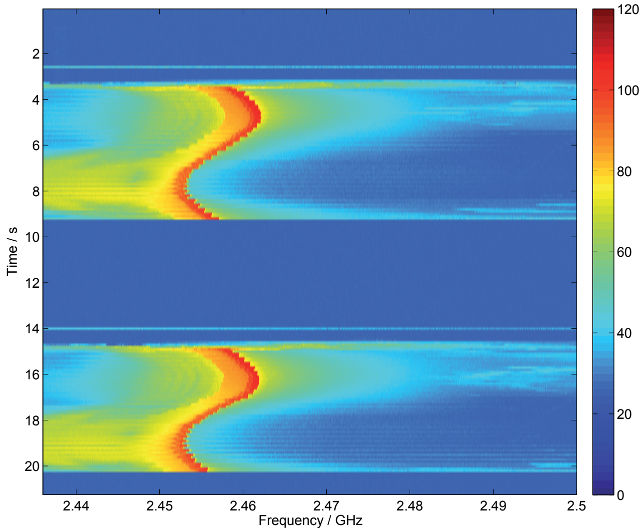

Figure 9. *Spectrogram of the fundamental of a microwave oven.*

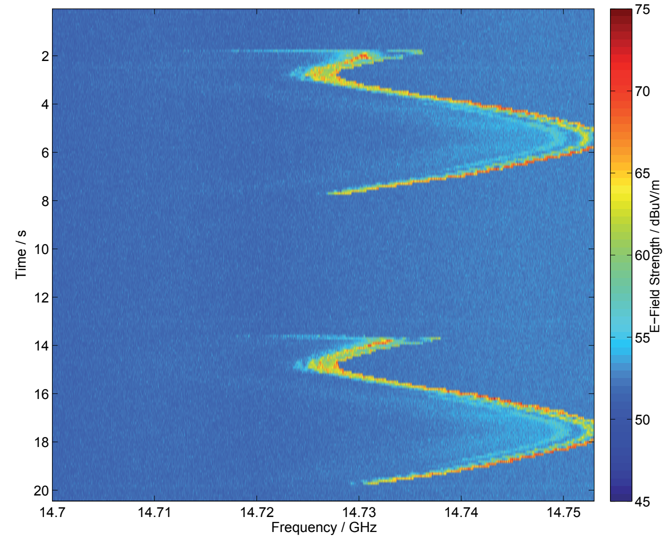

Figure 10. *Spectrogram of the 6th harmonic of a microwave oven.*

His research interests include measurement techniques in the microwave and millimeter wave regime, microwave and millimeter wave passive and active circuits and digital signal processing. His research is focused on the investigation of electromagnetic compatibility in time-domain above 1 GHz. Hoffmann is a member of the IEEE and VDE.

Stephan Braun *studied Electrical Engineering at Munich University of Technology (TUM), and received his Dipl.-Ing. Degree in 2003. From 2003-2009 he was research assistant at the Institute for High-Frequency Engineering, where he received his Dr.-Ing. degree in 2007. Dr. Braun is now managing director of GAUSS Instruments. His research interests are EMC and microwave measurement technology, as well as RF-circuits and digital signal processing. Further interests are fast digital circuits and configurable digital logic. Dr. Braun is Member of the VDE and IEEE. He is the author of more than 50 papers and inventor of several patents.*

Arnd Frech *was born in Bruchsal, Germany, in 1981. He studied electrical engineering at the Technische Universität München (TUM), Munich, Germany with focus on high-frequency engineering and electronic systems. He received the Bachelor of Science and the Dipl.-Ing. degree both from the Technische Universität München in 2005 and 2006, respectively. After finishing his diploma thesis in the field of near-infrared spectroscopy at the Swiss Federal Institute of Technology, Zurich, Switzerland, he joined the Institute for High-Frequency Engineering at the Technische Universität München as a research assistant working towards the Dr.-Ing. degree. He is co-founder and managing director of GAUSS INSTRUMENTS GmbH, working in the field of EMC and RF measurement instrumentation and high-speed digital signal processing.*

Peter Russer *received the Dipl.-Ing. (M.S.E.E.) degree in 1967 and the Dr. techn. (Ph.D.E.E.) degree in 1971, respectively, both from the Vienna University of Technology, Austria. In 1971 he joined the Research Institute of AEG-Telefunken in Ulm, Germany. With his research group he realized in 1978 the first optical fiber transmission link for 1 Gbit/s worldwide. From 1981 to 2008, Russer was professor and head of the Institute for High Frequency Engineering at the Technische Universität München, Germany. From October 1992 to March 1995, he was director of the Ferdinand-Braun-Institut für Höchstfrequenztechnik, Berlin. From 1997 to 1999, Russer was dean of the Department of Electrical Engineering and Information Technology of the Technische Universität München. In 1990, he was visiting professor at the University of Ottawa; in 1993 he was visiting professor at the University of Victoria and from August to October 2009 he was visiting scientist at the Institut Supérieur de l'Aéronautique et de l'Espace in Toulouse.*

Electromagnetic Interference Sources and Their Most Significant Effects

The increasing number of EMI sources is creating greater challenges for those responsible for maintaining the interoperability of products and systems

ANTHONY A. DIBIASE
Spec-Hardened Systems
Rochester, New York USA

As the density of the electromagnetic environment (EME) continues to increase the concern for its effects from sources producing EMI also increases. Advances in technology and the number of products produced, is having a significant effect on the efforts aimed at maintaining the required operation and inter operability of products and systems used in our society. These events have added challenges for those who are responsible for keeping pace with the effort required in maintaining the required level of electromagnetic compatibility (EMC) in these products and systems.

SOURCES

EMI sources both natural and man made that compose the EME can be categorized into several primary categories. Some of these classifications of sources are listed below.

(1) Ambient EME that is composed of numerous sources of which the most significant are:

- Television transmissions both analog and digital
- Radio AM, FM, and Satellite
- Solar Magnetic Storms which peak on a eleven year cycle
- Lightning which occurs as a very high voltage and high current event
- Utility power grid transmission lines which have high voltage, low current, and low frequency characteristics. In this category is also the new technology of Broadband over Power Lines (BPL) digital signals.
- Other ambient EME sources include airport port radar, telecom transmissions, electrostatic discharge (ESD), and white noise. Also in this category is the earth's magnetic field flux which has a value of about 500 milligauss.
- Some other major product and system's emissions sources include switching mode power supplies, arc welders, motor bushes, and electrical contacts

(2) High Powered Electromagnetic Pulse (HEMP) threats which are intended to disable electrical and electronic equipment. These sources are designed to be utilized by terrorist and military organizations. Currently existing HEMP devices include the following:

- Intentional Electromagnetic Interference (IEMI) source – a high powered pulse device utilized by combat, sabotage and terrorist organizations
- High Altitude Nuclear Electromagnetic Pulse (HNEMP) – produced by the detonation of a nuclear device high above the earth's atmosphere
- High Powered Microwave Weapon (HPM) – a device utilized by the military as a combat weapon
- E-Bomb – a HEMP weapon employed by

the military to disrupt an enemy's intra structure that is delivered by an aircraft.

- EMP Cannon – a military tactical weapon

(3) Power Quality degradation factors can effect the operation of equipment that is powered by a mains power source. These mains degradation factors include:

- Voltage surges, sages, dips, spikes, and high and low voltage
- Brownouts and blackouts
- Power line faults
- Electrical Fast Transitions (EFT)
- Electrical noise superimposed on the mains power line

These power quality degradation factors can occur simultaneously or independently, during any time interval.

(4) Railroad and Mass Transit Systems have some unique types of EMI source problems. These include:

- Propulsion system's high voltage and high current operational mode emissions
- Train signaling systems and their associated computer operating codes
- Third rail shoes arcing broadband emissions
- High voltage contact switching arcing broadband emissions
- Train control system's emissions
- Track train control circuits
- Right away emission sources

(5) Medical equipment utilized in medical facilities has numerous EMI sources. Some of the more prominent of these are listed below:

- Life support equipment such as ventilators, cardiac defibrillators, infusion pumps, etc.
- Patient telemetry and assistance equipment which includes electrocardiographs and motorized wheelchairs
- Electrical surgical units and their associated support equipment
- Magnetic Resonance Imagine (MRIs) systems
- X-ray units, both therapeutic and diagnostic
- Gamma Beam Electron Accelerators and Therapeutic equipment

SOURCES AND THEIR MOST SIGNIFICANT EFFECTS

(1) Ambient (EME) – Can affect sensitive electronic equipment in the vicinity of the EMI sources. The closer the sensitive electronic equipment is to the EMI source, the higher the source's radiated power level, and its in-band frequency the greater is the probability that the EMI will cause an interference problem.

In the case of the effects of ESD on sensitive electronic systems it can cause upsets, burn outs, and latch-ups in these units.

(2) High Powered Electromagnetic Pulse effects – High powered electromagnetic sources can totally destroy an electrical and electronic equipment's function.

As an example, an HNEMP device detonation above the earth's atmosphere of the United States can totally immobilize the whole of the continental United State's infrastructure. IEMI, HPM, E-Bombs, and EMP Cannons can be utilized to disable electronic systems at specific locations.

(3) Power Quality distortions and transits that are present on the power main systems can affect the normal operation of the equipment that it supplies power. Transits such as power surges are capable of destroying interface electronic circuits. EFTs can cause electronic circuit upset conditions.

(4) Railroad and Mass Transit Systems have one primary source of EMI and that is the transit and railroad engine's propulsion systems, which operates with high voltages, currents, and magnetic field levels. They have been known to affect other facilities that contain sensitive electrical equipment that are located near the railroad or mass transit systems right away. These propulsion systems have had EMI associated problems with other elements of their systems. Train control electronics can be affected by EMI sources such as third rail and other broadband frequency arcing sources if they are not adequate designed for EMC.

(5) Medical equipment and facilities sources include patient monitoring systems

Those are very susceptible to EMI interactions. The human body signals that they monitor are very weak. They are measured in unites of microvolts and micro-amps. Among other devices that are susceptible to EMI are hearing aids, wireless patient monitoring systems, magnetic resonance imaging systems, implantable cardiovascular devices, drug pumps, and portable diagnostic meters. As new technologies are developed and enter the marketplace at a fast pace the list will grow.

CONCLUSIONS

As new devices and new technologies enter the marketplace, many operating at lower power levels and higher frequencies that make will make these devices more susceptible to EMI effects. This will also increase the number of EMI sources in the EME. The Functional Safety of a product (a hazard resulting from an EMI induced failure in the operation of a product) becomes of increasing concern. EMI factors are important consideration that must be taken into account when evaluating the reliability and quality assurance status of electrical and electronic products and systems.

Fortunately the steady pace in the evolution of harmonized globally based EMC regulatory certification compliance requirements is resulting in the minimizing of the increase in the new generation of safety hazards and their associated safety risks as the density of the EME increases. EMC Engineers have the responsibility of insuring that electrical and electronic products placed on the market are safe and their EMC design requirements have been met.

***Anthony A. DiBiase** is the president of Spec-Hardened Systems, an EMC and Product Safety consulting company. He is a graduate of the Rochester Institute of Technology and holds a BSEE. He has presented seminars on EMC topics and has written several articles on that subject. He can be reached at SHSESC@aol.com*

Don HEIRMAN Consultants, L.L.C.

Donald N. Heirman, NCE
President

143 Jumping Brook Road
Lincroft, NJ 07738-1442 USA
+1 732-741-7723 (Voice)
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HOC ELECTROMAGNETIC COMPATIBILITY

standards recap

Compliance with standards makes or breaks the marketing of any new product. This section recaps new and revised national and international EMC standards. The information below has been featured in our weekly *Interference Technology eNews*. Just go to *InterferenceTechnology.com*, subscribe to the *eNews*, and you'll be updated on important changes in EMC standards weekly.

International Electrotechnical Commission (IEC)

IEC 61000-4-3-AM2 ED3.0 AMENDMENT 2

Publication Date: March 10, 2010

Electromagnetic compatibility (EMC) - Part 4-3: Testing and measurement techniques - Radiated, radio-frequency, electromagnetic field immunity test

IEC 60512-24-1 ED1.0 — CONNECTORS FOR ELECTRONIC EQUIPMENT

Publication Date: March 24, 2010

The International Electrotechnical Committee released IEC 60512-24-1, a new testing and measurement standard for electronic equipment connectors' residual magnetism. IEC 60512-24-1:2010 when required by the detail specification, is used for testing connectors within the scope of technical committee 48. It may also be used for similar devices when specified in a detail specification. The object of this standard is to detail a standard method to measure the residual magnetism of a connector after exposure to a specified magnetic field.

IEC 62132-2 ED1.0 — INTEGRATED CIRCUITS - MEASUREMENT OF ELECTROMAGNETIC IMMUNITY

Publication Date: March 30, 2010

The International Electrotechnical Committee released a TEM cell electromagnetic immunity standard, IEC 62132-2. This international standard specifies a method for measuring the immunity of an integrated circuit to radio frequency radiated electromagnetic disturbances. The frequency range of this method is from 150 kHz to 1 GHz, or as limited by the characteristics of the TEM cell.

IEC 61000-4-18-AM1 ED1.0 — TESTING AND MEASUREMENT TECHNIQUES

Publication Date: April 22, 2010

IEC 61000-4-18-am1 Amendment 1 - Electromagnetic compatibility (EMC) - Part 4-18: Testing and measurement techniques - Damped oscillatory wave immunity test, an EMC standard for damped oscillatory wave immunity testing and measurement techniques.

IEC 61000-4-3 ED3.2 CONSOL. WITH AM1&2 - TESTING AND MEASUREMENT TECHNIQUES

Publication Date: April 27, 2010

IEC 61000-4-3:2006+A1:2007+A2:2010 is applicable to the immunity requirements of electrical and electronic equipment to radiated electromagnetic energy. It establishes test levels and the required test procedures. The object of this standard is to establish a common reference for evaluating the immunity of electrical and electronic equipment when subjected to radiated, radio-frequency electromagnetic fields.

IEC/TR 62153-4-1 ED2.0 — METALLIC COMMUNICATION CABLE TEST METHODS

Publication Date: May 12, 2010

IEC/TR 62153-4-1:2010(E) gives a brief introduction to basic concepts and terms trying to reveal the common features of apparently different test methods. It should assist in correct interpretation of test data, and in the better understanding of screening (or shielding) and related specifications and standards. This second edition cancels and replaces the first edition published in 2007. The significant change is a new clause on the background of the shielded screening attenuation test method.

IEC 62599-2 ED1.0 — ALARM SYSTEMS

Publication Date: May 19, 2010

IEC 62599-2:2010 for immunity requirements applies to the components of the following alarm systems, intended for use in and around buildings in residential, commercial, light industrial and industrial environments:

- access control systems, for security applications;
- alarm transmission systems;
- CCTV systems, for security applications;
- fire detection and fire alarm systems;
- intruder and hold-up alarm systems;
- social alarm systems.

IEC 62615 ED1.0 — ELECTROSTATIC DISCHARGE SENSITIVITY TESTING

Publication Date: May 31, 2010

IEC 62615:2010 defines a method for pulse testing to evaluate the voltage current response of the component under test and to consider protection design parameters for electro-static discharge (ESD) human body model (HBM). This technique is known as transmission line pulse (TLP) testing. This document establishes a methodology for both testing and reporting information associated with transmission line pulse (TLP) testing. The scope and focus of this document pertains to TLP testing techniques of semiconductor components. This document should not become alternative method of HBM test standard such as IEC 60749-26. The purpose of the document is to establish guidelines of TLP methods that allow the extraction of HBM ESD parameters on semiconductor devices. This document provides the standard measurement and procedure for the correct extraction of

HBM ESD parameters by using TLP.

IEC 62479:2010 — LOW-POWER ELECTRONIC EQUIPMENT AND HUMAN EXPOSURE TO EM FIELDS

Publication Date: June 16, 2010

IEC 62479:2010 provides simple conformity assessment methods for low-power electronic and electrical equipment to an exposure limit relevant to electromagnetic fields (EMF). If such equipment cannot be shown to comply with the applicable EMF exposure requirements using the methods included in this standard for EMF assessment, then other standards, including IEC 62311 or other (EMF) product standards, may be used for conformity assessment.

IEC 60939-1 ED3.0 — PASSIVE FILTER UNITS FOR ELECTROMAGNETIC INTERFERENCE SUPPRESSION

Publication Date: July 29, 2010

IEC 60939-1:2010 relates to passive filter units for electromagnetic interference suppression for use within, or associated with, electronic or electrical equipment and machines. Both single and multi-channel filters within one enclosure are included within the scope of this generic specification. This generic specification establishes standard terms, inspection procedures and methods of test for use in sectional and detail specifications within the IECQ-CECC system for electronic components.

IEC 61000-4-15 ED2.0 — FLICKERMETER - FUNCTIONAL AND DESIGN SPECIFICATIONS

Publication Date: Aug. 24, 2010

IEC 61000-4-15:2010 gives a functional and design specification for flicker measuring apparatus intended to indicate the correct flicker perception level for all practical voltage fluctuation waveforms. Information is presented to enable such an instrument to be constructed. A method is given for the evaluation of flicker severity on the basis of the output of flickermeters complying with this standard. The flickermeter specifications in this part of IEC 61000 relate only to measurements of 120 V and 230 V, 50 Hz and 60 Hz inputs. Characteristics of some incandescent lamps for other voltages are sufficiently similar to the values in Table 1 and Table 2, that the use of a correction factor can be applied for those other voltages. Some of these correction factors are provided in the Annex B. Detailed specifications for voltages and frequencies other than those given above, remain under consideration.

IEC 62041 ED. 2.0 B:2010 — SAFETY OF TRANSFORMERS, REACTORS, POWER SUPPLY UNITS

Publication Date: Aug. 27, 2010

IEC 62041 Ed. 1.0 b:2003 has been replaced by by IEC 62041 Ed. 2.0 b:2010, Safety of transformers, reactors, power supply units and combinations thereof - EMC requirements. IEC 62041:2010 applies to transformers, reactors, power supply units and combinations thereof covered by the IEC 61558 series of standards. This standard deals with the electromagnetic compatibility requirements for emission and immunity within the frequency range 0 Hz - 400 GHz. No measurement needs to be performed at frequencies where no requirement is specified. This second edition cancels and replaces the first edition published in 2003. It constitutes a technical revision. This edition includes the following significant technical changes with respect to the previous edition:

- the frequency range for tests according to IEC 61000-4-3 has been extended above 1 GHz according to technologies used in this frequency area;
- the testing requirements according to IEC 61000-4-11 have been amended significantly;
- the inclusion of a clause on tests in series production;
- the inclusion of a new clause on measurement uncertainly, and
- the inclusion of requirements on DC power ports and telecommunication ports.

IEC 61000-4-20 ED2.0 — EMISSION AND IMMUNITY TESTING IN TRANSVERSE ELECTROMAGNETIC (TEM) WAVEGUIDES

Publication Date: Aug. 31, 2010

IEC 61000-4-20:2010 relates to emission and immunity test methods for electrical and electronic equipment using various types of transverse electromagnetic (TEM) waveguides. These types include open structures (for example, striplines and electromagnetic pulse simulators) and closed structures (for example, TEM cells). These structures can be further classified as one-, two-, or multi-port TEM waveguides. The frequency range depends on the specific testing requirements and the specific TEM waveguide type. The object of this standard is to describe:

- TEM waveguide characteristics, including typical frequency ranges and EUT-size limitations;
- TEM waveguide validation methods for EMC tests;
- the EUT (i.e. EUT cabinet and cabling) definition;
- test set-ups, procedures, and requirements for radiated emission testing in TEM waveguides and
- test set-ups, procedures, and requirements for radiated immunity testing in TEM waveguides.

IEC 61000-4-22 ED1.0 — RADIATED EMISSIONS AND IMMUNITY MEASUREMENTS IN FULLY ANECHOIC ROOMS

Publication Date: Oct. 27, 2010

IEC 61000-4-22:2010 considers immunity tests and emission measurements for electric and/or electronic equipment. Only radiated phenomena are considered. It establishes the required test procedures for using fully anechoic rooms for performing radiated immunity testing and radiated emission measurements. IEC 61000-4-22:2010 establishes a common validation procedure, equipment under test (EUT) set-up requirements, and measurement methods for fully anechoic rooms (FARs) when both radiated electromagnetic emission measurements and radiated electromagnetic immunity tests will be performed in the same FAR. As a basic measurement standard, this part of IEC 61000 does not intend to specify the test levels or emission limits to be applied to particular apparatus or system(s). Its main goal is to provide general measurement procedures to all concerned product committees of IEC or CISPR. Specific product requirements and test conditions are defined by the responsible product committees. The methods described in this standard are appropriate for radiated emission measurements and immunity tests in the frequency range of 30 MHz to 18 GHz. IEC 61000-4-22:2010 has the status of a basic EMC publication in accordance with IEC Guide 107, Electromagnetic compatibility - Guide to the drafting of electromagnetic compatibility publications.

IEC 61000-6-3-am1 ed2.0

IEC 61000-4-21 ED2.0 — REVERBERATION CHAMBER TEST METHODS

Publication Date: Jan. 27, 2011

IEC 61000-4-21:2011 considers tests of immunity and intentional or unintentional emissions for electric and/or electronic equipment and tests of screening effectiveness in reverberation chambers. It establishes the required test procedures for performing such tests. Only radiated phenomena are considered. The objective of IEC 61000-4-21:2011 is to establish a common reference for using reverberation chambers to evaluate the performance of electric and electronic equipment when subjected to radio-frequency electromagnetic fields and for determining the levels of radio-frequency radiation emitted from electric and electronic equipment. IEC 61000-4-21:2011 does not intend to specify the tests to be applied to a particular apparatus or system. Its main aim is to give a general basic reference to all concerned product committees of the IEC. The product committees should select emission limits and test methods in consultation with CISPR. The product committees remain responsible for the appropriate choice of the immunity tests and the immunity test limits to be applied to their equipment. Other methods, such as those covered in IEC 61000-4-3, CISPR 16-2-3 and CISPR 16-2-4 may be used. This second edition cancels and replaces the first edition published in 2003.

IEC 61000-6-3 ED2.1 CONSOL. WITH AM1 — EMISSION STANDARD

Publication Date: Feb. 17, 2011

IEC 61000-6-3:2006+A1:2010 This part of IEC 61000 for EMC emission requirements applies to electrical and electronic apparatus intended for use in residential, commercial and light-industrial environments. Emission requirements in the frequency range 0 Hz to 400 GHz are covered. No measurement needs to be performed at frequencies where no requirement is specified. This generic EMC emission standard is applicable if no relevant dedicated product or product-family EMC emission standard exists. This standard applies to apparatus intended to be directly connected to a low-voltage public mains network or connected to a dedicated DC source, which is intended to interface between the apparatus and the low-voltage public mains network. This standard applies also to apparatus which is battery operated or is powered by a non-public, but non-industrial, low-voltage power distribution system if this apparatus is intended to be used in the locations described below. The environments encompassed by this standard are residential, commercial and light-industrial locations, both indoor and outdoor.

IEC 61000-6-4 ED2.1 CONSOL. WITH AM1 — EMISSION STANDARD FOR INDUSTRIAL ENVIRONMENTS

Publication Date: Feb. 23, 2011

IEC 61000-6-4:2006+A1:2010 This part of IEC 61000 for EMC emission requirements applies to electrical and electronic apparatus intended for use in industrial environments as described below. Emission requirements in the frequency range 0 Hz to 400 GHz are covered. No measurement needs to be performed at frequencies where no requirement is specified. This generic EMC emission standard is applicable if no relevant dedicated product or product-family EMC emission standard exists.

IEC 61000-4-4 ED2.1 CONSOL. WITH AM1 — ELECTRICAL FAST TRANSIENT/BURST IMMUNITY TEST

Publication Date: March 30, 2011

IEC 61000-4-4:2004+A1:2010 Establishes a common and reproducible reference for evaluating the immunity of electrical and electronic equipment when subjected to electrical fast transient/bursts on supply, signal, control and earth ports. The test method documented in this part of IEC 61000-4 describes a consistent method to assess the immunity of an equipment or system against a defined phenomenon.

IEC 60118-13 ED3.0 - ELECTROACOUSTICS - HEARING AIDS - PART 13: EMC

Publication Date: April 11, 2011

IEC 60118-13:2011 in principle covers all relevant EMC phenomena for hearing aids. Hearing aid immunity to high frequency electromagnetic fields originating from digital wireless devices operating in the frequency ranges 0,8 GHz to 0,96 GHz and 1,4 GHz to 2,48 GHz is currently identified as the only relevant EMC phenomenon regarding hearing aids.

International Organization for Standardization (ISO) / IEC

ISO/IEC 17043: 2010, CONFORMITY ASSESSMENT — GENERAL REQUIREMENTS FOR PROFICIENCY TESTING

Publication Date: Jan. 29, 2010

ISO/IEC 17043 specifies general requirements for the competence of providers of proficiency testing schemes and for the development and operation of proficiency testing schemes. Proficiency testing involves use of interlaboratory comparisons in the determination of a laboratory's performance and, more specifically, in its on-going competence. Laboratories demonstrate their competence by complying with ISO/IEC 17025, General requirements for the competence of testing and calibration laboratories, and the need for additional confidence in their results is achieved through their participation in interlaboratory comparisons managed by proficiency testing provider operating in accordance with ISO/IEC 17043. The new standard addresses management, planning, design and personnel of the proficiency testing provider.

ISO/IEC TR 29125:2010 — INFORMATION TECHNOLOGY

Publication Date: Sept. 22, 2010

The International Organization for Standardization (ISO) / International Electrotechnical Commission (IEC) Technical Report, 29125:2010, targets the support of applications that provide remote power over balanced cabling to terminal equipment; covers the transmission and electrical parameters needed to support remote power over balanced cabling; covers various installation scenarios and how these may impact the capability of balanced cabling to support remote powering; specifies design and configuration of cabling as specified in International Standards ISO/IEC 11801, ISO/IEC 15018, ISO/IEC 24702 and ISO/IEC 24764; provides requirements and guidelines that will enable the support of a wide variety of extra low voltage (ELV) limited power source (LPS) applications using remote power supplied over balanced cabling.

ISO/IEC TR 18047-6:2011 — RADIO FREQUENCY IDENTIFICATION DEVICE CONFORMANCE TEST METHODS

Publication Date: Jan. 11, 2011

ISO/IEC TR 18047-6:2011 defines test methods for determining the conformance of radio frequency identification (RFID) devices (tags and interrogators) for item management with the specifications given in ISO/IEC 18000-6, but does not apply to the testing of conformity with regulatory or similar requirements.

The test methods require only that the mandatory functions, and any optional functions which are implemented, be verified. This can, in appropriate circumstances, be supplemented by further, application-specific functionality criteria that are not available in the general case.

The interrogator and tag conformance parameters in ISO/IEC TR 18047-6:2011 are the following:

* type-specific conformance parameters including nominal values and tolerances;
* parameters that apply directly affecting system functionality and inter-operability.

The following are not included in ISO/IEC TR 18047-6:2011:

* parameters that are already included in regulatory test requirements;
* high-level data encoding conformance test parameters (these are specified in ISO/IEC 15962).

International Special Committee on Radio Interference (CISPR)

IMPLICATIONS OF CISPR 16-1-1 UPDATE TO INCLUDE EMI

Publication Date: Jan. 28, 2010

Thanks to the release by the International Electrotechnical Commission of Edition 3 of the CISPR 16-1-1 standard, otherwise known as CISPR 16-1-1:2010, the world of electromagnetic interference measurement is undergoing a review. CISPR 16-1-1 specifies the characteristics and performance of equipment for measuring radio disturbance in the 9kHz to 18GHz frequency range, as well as providing requirements for specialized equipment for discontinuous disturbance measurements. The reason for the review is that the 2010 version of this standard now allows spectrum analyzers to be used to test EMI, in addition to dedicated, but more costly, EMI receivers.

IEC UPDATES CISPR 11 STANDARD

Publication Date: March 10, 2010

The International Electrotechnical Committee released an amendment to CISPR 11 – the radio-frequency EMC standard for industrial, scientific and medical equipment operating in the frequency range 0 Hz to 400 GHz and to domestic and similar appliances designed to generate and/or use locally radio-frequency energy. This consolidated version consists of the 2009 fifth edition and a 2010 amendment. This standard covers emission requirements related to radio-frequency (RF) disturbances in the frequency range of 9 kHz to 400 GHz. Measurements need only be performed in frequency ranges where limits are specified in Clause 6. For ISM RF applications in the meaning of the definition found in the ITU Radio Regulations, this standard covers emission requirements related to radio-frequency disturbances in the frequency range of 9 kHz to 18 GHz. Requirements for ISM RF lighting apparatus and UV irradiators operating at frequencies within the ISM frequency bands defined by the ITU Radio Regulations are contained in this standard. Equipment covered by other CISPR product and product family emission standards are excluded from the scope of this standard.

CISPR 22 ED6.0 CORRIGENDUM

Publication Date: April 22, 2010

Interpretation Sheet 2 - Information technology equipment - Radio disturbance characteristics - Limits and methods of measurement. At the CISPR SC I plenary, held on the 27th October 2007, a decision was taken to set the maintenance date for CISPR 22, Edition 6 to 2012. As a result the work identified within CISPR/I/279/MCR will not be started for the time being. At the subsequent meeting of CISPR SC I WG3 it was decided that 3 items within the MCR would benefit now from further clarification and an interpretation sheet would be helpful to users of the standard, with the intent of including this information in a future amendment to the standard.

CISPR 16-1-4 ED3.0 — SPECIFICATION FOR RADIO DISTURBANCE AND IMMUNITY MEASURING APPARATUS AND METHODS

Publication Date: April 27, 2010

CISPR 16-1-4:2010 specifies the characteristics and performance of equipment for the measurement of radiated disturbances in the frequency range 9 kHz to 18 GHz. Specifications for antennas and test sites are included. The requirements of this publication apply at all frequencies and for all levels of radiated disturbances within the CISPR indicating range of the measuring equipment. Methods of measurement are covered in Part 2-3, and further information on radio disturbance is given in Part 3 of CISPR 16.

CISPR 16-2-3 ED3.0 — SPECIFICATION FOR RADIO DISTURBANCE AND IMMUNITY MEASURING APPARATUS AND METHODS

Publication Date: April 27, 2010

CISPR 16-2-3:2010 specifies the methods of measurement of radiated disturbance phenomena in the frequency range of 9 kHz to 18 GHz. The aspects of measurement uncertainty are specified in CISPR 16-4-1 and CISPR 16-4-2. This third edition of CISPR 16-2-3 cancels and replaces the second edition published in 2006. It is a technical revision.

CISPR 11 ED5.1 CONSOL. WITH AM1 — INDUSTRIAL, SCIENTIFIC AND MEDICAL EQUIPMENT

Publication Date: May 19, 2010

CISPR 11:2009+A1:2010 applies to industrial, scientific and medical electrical equipment operating in the frequency range 0 Hz to 400 GHz and to domestic and similar appliances designed to generate and/or use locally radio-frequency energy. CISPR 11:2009 covers emission requirements related to radio-frequency (RF) disturbances in the frequency range of 9 kHz to 400 GHz. Measurements need only be performed in frequency ranges where limits are specified in Clause 6. For ISM RF applications in the meaning of the definition found in the ITU Radio Regulations (see Definition 3.1), this standard covers emission requirements related to radio-frequency disturbances in the frequency range of 9 kHz to 18 GHz. Requirements for ISM RF lighting apparatus and UV irradiators operating at frequencies within the ISM frequency bands defined by the ITU Radio Regulations are contained in this standard.

CISPR 16-2-3-AM1 ED3.0, AMENDMENT 1

Publication Date: June 21, 2010

Amendment 1 - Specification for radio disturbance and immunity measuring apparatus and methods - Part 2-3: Methods of measurement of disturbances and immunity - Radiated disturbance measurements

CISPR/TR 18-1 ED2.0 — RADIO INTERFERENCE CHARACTERISTICS OF OVERHEAD POWER LINES

Publication Date: June 24, 2010

CISPR 18-1:2010(E), which is a technical report, applies to radio noise from overhead power lines and high-voltage equipment which may cause interference to radio reception. The scope of this publication includes the causes, measurement and effects of radio interference, design aspects in relation to this interference, methods and examples for establishing limits and prediction of tolerable levels of interference from high voltage overhead power lines and associated equipment, to the reception of radio broadcast services. The frequency range covered is 0,15 MHz to 300 MHz. Radio frequency interference caused by the pantograph of overhead railway traction systems is not considered in this technical report. This second edition cancels and replaces the first edition published in 1982. It is a technical revision.

CISPR/TR 18-2 ED2.0 — METHODS OF MEASUREMENT AND PROCEDURE FOR DETERMINING LIMITS

Publication Date: June 24, 2010

A general procedure for establishing the limits of the radio noise field from the power lines and equipment is recommended, together with typical values as examples, and methods of measurement. The clause on limits concentrates on the low frequency and medium frequency bands and it is only in these bands where ample evidence, based on established practice, is available. No examples of limits to protect radio reception in the frequency band 30 MHz to 300 MHz have been given, as measuring methods and certain other aspects of the problems in this band have not yet been fully resolved. Site measurements and service experience have shown that levels of noise from power lines at frequencies higher than 300 MHz are so low that interference is unlikely to be caused to television reception. The values of limits given as examples are calculated to provide a reasonable degree of protection to the reception of broadcasting at the boundary of the recognized service areas of the appropriate transmitters in the radio frequency bands used for a.m. broadcasting, in the least favourable conditions likely to be generally encountered. These limits are intended to provide guidance at the planning stage of the line and national standards or other specifications against which the performance of the line may be checked after construction and during its useful life. The measuring apparatus and methods used for checking compliance with limits should comply with the respective CISPR specifications, as e.g. the basic standards series CISPR 16. This second edition cancels and replaces the first edition published in 1986. It is a technical revision.

CISPR/TR 18-3 ED2.0 — CODE OF PRACTICE FOR MINIMIZING THE GENERATION OF RADIO NOISE

Publication Date: June 24, 2010

CISPR 18-3:2010(E), which is a technical report, applies to radio noise from overhead power lines and high-voltage equipment which may cause interference to radio reception, excluding the fields from power line carrier signals. The frequency range covered is 0,15 MHz to 300 MHz. This second edition cancels and replaces the first edition published in 1986. It is a technical revision.

CISPR 16-2-2 ED2.0 — SPECIFICATION FOR RADIO DISTURBANCE AND IMMUNITY MEASURING APPARATUS AND METHODS

Publication Date: July 28, 2010

CISPR 16-2-2:2010 specifies the methods of measurement of disturbance power using the absorbing clamp in the frequency range 30 MHz to 1 000 MHz. This second edition cancels and replaces the first edition (2003), its Amendment 1 (2004) and Amendment 2 (2005). It constitutes a technical revision. It includes the following significant technical changes with respect to the previous edition: provisions for the use of spectrum analyzers for compliance measurements (Annex D) and the use of FFT-based test instrumentation (Clauses 3, 6 and 8) are now included. CISPR 16-2-2:2010 has the status of a basic EMC publication in accordance with IEC Guide 107, Electromagnetic compatibility - Guide to the drafting of electromagnetic compatibility publications.

CISPR 16-2-1-AM1 ED2.0 — SPECIFICATION FOR RADIO DISTURBANCE AND IMMUNITY MEASURING APPARATUS AND METHODS

Publication Date: July 28, 2010

The International Electrotechnical Commission recently launched the CISPR 16-2-1-am1 ed 2.0 specification covering the methods of measurement of disturbances and immunity - conducted disturbance measurements.

CISPR/TR 16-3 ED3.0 — SPECIFICATION FOR RADIO DISTURBANCE AND IMMUNITY MEASURING APPARATUS AND METHODS

Publication Date: Aug. 10, 2010

CISPR/TR 16-3:2010(E) is a collection of technical reports that serve as background and supporting information for the various other standards and technical reports in CISPR 16 series. In addition, background information is provided on the history of CISPR, as well as a historical reference on the measurement of interference power from household and similar appliances in the VHF range. Over the years, CISPR prepared a number of recommendations and reports that have significant technical merit but were not generally available. Reports and recommendations were for some time published in CISPR 7 and CISPR 8. At its meeting in Campinas, Brazil, in 1988, CISPR subcommittee A agreed on the table of contents of Part 3, and to publish the reports for posterity by giving the reports a permanent place in Part 3. With the reorganization of CISPR 16 in 2003, the significance of CISPR limits material was moved to CISPR 16-4-3, whereas recommendations on statistics of disturbance complaints and on the report on the determination of limits were moved to CISPR 16 4-4. The contents of Amendment 1 (2002) of CISPR 16-3 were moved to CISPR 16-4-1. This third edition of CISPR 16-3 cancels and replaces the second edition published in 2003, and its Amendments 1 (2005) and 2 (2006). It is a technical revision. The main technical change with respect to the previous edition consist of the addition of a new clause to provide background information on FFT instrumentation.

CISPR 24 ED2.0 — INFORMATION TECHNOLOGY EQUIPMENT

Publication Date: Aug. 24, 2010

CISPR 24:2010 applies to information technology equipment (ITE) as defined in CISPR 22. The object of this publication is to establish requirements that will provide an adequate level of intrinsic immunity so that the equipment will operate as intended in its environment. The publication defines the immunity test requirements for equipment within its scope in relation to continuous and transient conducted and radiated disturbances, including electrostatic discharges (ESD). Procedures are defined for the measurement of ITE and limits are specified which are developed for ITE within the frequency range from 0 Hz to 400 GHz. For exceptional environmental conditions, special mitigation measures may be required. Owing to testing and performance assessment considerations, some tests are specified in defined frequency bands or at selected frequencies. Equipment which fulfils the requirements at these frequencies is deemed to fulfil the requirements in the entire frequency range from 0 Hz to 400 GHz for electromagnetic phenomena. The test requirements are specified for each port considered. This second edition cancels and replaces the first edition published in 1997, and its Amendments 1(2001) and 2(2002). It is a technical revision.

CISPR 16-1-1 ED3.1 CONSOL. WITH AM1 — SPECIFICATION FOR RADIO DISTURBANCE AND IMMUNITY MEASURING APPARATUS AND METHODS

Publication Date: Nov. 10, 2010

CISPR 16-1-1:2010+A1:2010 specifies the characteristics and performance of equipment for the measurement of radio disturbance in the frequency range 9 kHz to 18 GHz. In addition, requirements are provided for specialized equipment for discontinuous disturbance measurements.

The specifications in this standard apply to EMI receivers and spectrum analyzers. This third edition cancels and replaces the second edition published in 2006, and its Amendments 1 (2006) and 2 (2007). It is a technical revision. This main technical change with respect to the previous edition consists of the addition of new provisions for the use of spectrum analyzers for compliance measurements. CISPR 16-1-1:2009 has the status of a basic EMC publication in accordance with IEC Guide 107, Electromagnetic compatibility - Guide to the drafting of electromagnetic compatibility publications.

CISPR 16-2-1 ED. 2.1 B:2010 — SPECIFICATION FOR RADIO DISTURBANCE AND IMMUNITY MEASURING APPARATUS

Publication Date: Dec. 16, 2010

CISPR 16-2-1:2008+A1:2010 specifies the methods of measurement of disturbance phenomena in general in the frequency range 9 kHz to 18 GHz and especially of conducted disturbance phenomena in the frequency range 9 kHz to 30 MHz.

This second edition of CISPR 16-2-1 cancels and replaces the first edition (2003) and its Amendment 1 (2005) and constitutes a technical revision. CISPR 16-2-1:2008 includes significant technical changes with respect to the previous edition. In general, this new edition aims at reducing compliance uncertainty in correspondence with findings in CISPR 16-4-1. Guidelines are given on

- resonance-free connection of the AMN to reference ground,
- avoidance of ground loops, and
- avoidance of ambiguities of the test setup of EUT and AMN with respect to the reference ground plane.

In addition, terms are clarified, a new type of ancillary equipment (CVP) is applied, and a clarification for the use of the AAN and AMN on the same EUT is provided.

European Telecommunications Standards Institute (ETSI)

NEW VERSIONS OF EMC AND RADIO SPECTRUM MATTERS STANDARDS

Publication Date: Feb. 12, 2010

ETSI EN 300 330-1 V1.7.1 and ETSI EN 300 330-2 V1.5.1, regarding radio equipment in the frequency range 9 kHz to 25 MHz and inductive loop systems in the frequency range 9 kHz to 30 MHz, discuss technical characteristics and test methods (Part 1) and harmonized EN covering the essential requirements of article 3.2 of the R&TTE Directive (Part 2).

ETSI EN 302 645 V1.1.1 — ELECTROMAGNETIC COMPATIBILITY AND RADIO SPECTRUM MATTERS

Publication Date: March 18, 2010

ETSI EN 302 645 V1.1.1 applies to GNSS repeaters. GNSS pseudolites as well as GNSS Receivers are not covered by the present document. GNSS repeaters are devices designed to re-transmit GNSS signals unchanged inside buildings in order to provide a usable signal for GNSS receivers that are out of sight of the GNSS satellite constellation or that they are unable to connect to GNSS signal simulators. A number of potential uses for such devices have been identified, such as the provision of a signal for test and development purposes and avoiding the need for receivers in emergency vehicles to re-acquire lock upon leaving a garage.

ETSI EN 301 025-1 V1.4.1 — ELECTROMAGNETIC COMPATIBILITY AND RADIO SPECTRUM MATTERS

Publication Date: March 30, 2010

ETSI EN 301 025-1 V1.4.1 covers the minimum requirements for general communication for shipborne fixed installations using a VHF radiotelephone operating in certain frequency bands allocated to the maritime mobile service using 25 kHz or 25 kHz and 12,5 kHz channels and associated equipment for DSC - class D. These requirements include the relevant provisions of the ITU Radio Regulations, appendix 18 [1], ITU-R Recommendations M.493-12 [3] (where class D is defined), M.825-3 [i.5] and incorporate the relevant guidelines of the IMO as detailed in IMO Circular MSC/Circ-803 [i.2]. The present document also specifies technical characteristics, methods of measurement and required test results.

ETSI TR 102 799 — ELECTROMAGNETIC COMPATIBILITY AND RADIO SPECTRUM MATTERS

Publication Date: June, 2010

ETSI TR 102 799 analyses the various possible techniques for spectrum access systems for PMSE technologies and for the guarantee of a high sound production quality on selected frequencies utilizing cognitive interference mitigation techniques and recommends a specific method.

ETSI EN 301 442 V1.2.1 — NEW ETSI STANDARD ON EMC AND RADIO SPECTRUM MATTERS

Publication Date: Aug. 5, 2010

The present document applies to the following Short Range Device major equipment types:

1) Generic Short Range Devices, including alarms, telecommand, telemetry, data transmission in general, etc.;

2) Radio Frequency Identification (RFID);

3) Radiodetermination, including detection, movement and alert applications. These radio equipment types are capable of operating in the permitted frequency bands within the 1 GHz to 40 GHz range:

- either with a Radio Frequency (RF) output connection and dedicated antenna or with an integral antenna;
- for all types of modulation;
- with or without speech.

ETSI STANDARD ON EMC AND RADIO SPECTRUM MATTERS

Publication Date: Sept. 2, 2010

The European Telecommunications Standards Institute released a six-part standard on electromagnetic compatibility and radio spectrum matters (ERM); peer-to-peer digital private mobile radio. They include:

ETSI TS 102 587-1 V1.3.1: Part 1: Conformance testing; Protocol Implementation Conformance Statement (PICS) proforma

ETSI TS 102 587-2 V1.3.1: Part 2: Conformance testing; Test Suite Structure and Test Purposes (TSS&TP) specification

ETSI TS 102 587-3 V1.3.1: Part 3: Requirements catalogue

ETSI TS 102 587-4 V1.2.1: Part 4: Conformance testing; Abstract Test Suite (ATS)

ETSI TS 102 587-5 V1.3.1: Part 5: Interoperability testing; Interoperability Test Suite Structure and Test Purposes (TSS&TP) specification

ETSI TS 102 587-6 V1.2.1: Part 6: Interoperability testing; Test Descriptions (TD)

ETSI TR 102 704 V1.1.1 - ELECTROMAGNETIC COMPATIBILITY AND RADIO SPECTRUM MATTERS

Publication Date: Dec. 2, 2010

The present document describes the spectrum requirements, technical characteristics and application scenarios for mobile and infrastructure radio location applications in the frequency range of 76 GHz to 77 GHz. The present document provides a proposal for the introduction of the planned applications for surveillance radar for operating in the 76 GHz to 77 GHz band and defines characteristics and operation modes for fixed or quasi fixed installation, industrial, airborne/space and for ground vehicular applications in order not to impair the operation of the existing automotive vehicle SRRs operating in the same frequency range as well as for applications in adjacent bands. The present document excludes radar sensor for level and tank level probing [i.8]. The present document also analyses the current ECC decision ECC(02)01 [i.2] and proposes to revise the ECC decision for sharing the new intended surveillance radar application with the EN 301 091 [i.1] type equipment in same frequency band.

Institute of Electrical and Electronics Engineers (IEEE)

DISTRIBUTED NETWORK PROTOCOL STANDARD SET TO BENEFIT SMART GRID

Publication Date: July 1 2010

IEEE ratified its IEEE 1815 Distributed Network Protocol (DNP3) standard for electric power systems communications. The new standard, which improves device interoperability and strengthens security protocols, was fast-tracked for completion and was delivered in only seven months. Scheduled for final publication in July 2010, IEEE 1815 is expected to play a significant role in the development and deployment of Smart Grid technologies.

NEW IEEE 802.11 AMENDMENT COVERS VEHICULAR ENVIRONMENTS

Publication Date: July 15, 2010

The latest IEEE 802.11 standard covers wireless LANs in vehicular environments. The standard is IEEE 802.11p™, "IEEE Standard for Information Technology — Telecommunications and information exchange between systems — Local and metropolitan area networks — Specific requirements---Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications---Amendment 6: Wireless Access in Vehicular Environments." IEEE 802.11p is the groundwork for Dedicated Short Range Communications (DSRC), a U.S. Department of Transportation project looking at vehicle-based communication networks, particularly for applications such as toll collection, vehicle safety services, and commerce transactions.

LATEST VERSION OF IEEE 1641 — SIGNAL AND TEST DEFINITION

Publication Date: Sept. 17, 2010

The latest revision to IEEE 1641™, "IEEE Standard for Signal and Test Definition," continues the trend of making the standard more rigorous, according to IEEE StandardsWire. IEEE 1641 provides the means to define and describe signals used in testing. It also provides a set of common basic signals, built upon formal mathematical specifications so that signals can be combined to form complex signals usable across all test platforms.

IEEE 802.22.1-2010 — INFORMATION TECHNOLOGY

Publication Date: Nov. 1, 2010

IEEE Standard for Information Technology--Telecommunications and information exchange between systems--Local and metropolitan area networks--Specific requirements Part 22.1: Standard to Enhance Harmful Interference Protection for Low-Power Licensed Devices Operating in TV Broadcast Bands defines the protocol and data formats for communication devices forming a beaconing network that are used to protect low-power, licensed devices operating in television broadcast bands from harmful interference generated by license-exempt devices, such as Wireless Regional Area Networks (WRAN), intended to operate in the same bands. The devices being protected are devices licensed as secondary under Title 47, Part 74, Subpart H in the USA and equivalent devices in other regulatory domains.

IEEE TO DEVELOP STANDARD FOR ENERGY STORAGE IN SMART GRIDS

Publication Date: Jan. 13, 2011

A new project from IEEE will develop guidelines to help facilitate the wide-scale and consistent implementation of energy storage systems to support the power infrastructure of the smart grid. The project, IEEE P2032.2™, "Guide for the Interoperability of Energy Storage Systems Integrated with the Electric Power Infrastructure," is being developed by the IEEE Standards Association Standards Board and its SCC21 - Fuel Cells, Photovoltaics, Dispersed Generation, and Energy Storage Committee.

UPDATED STANDARD COVERS ANALOG-TO-DIGITAL CONVERTERS

Publication Date: Jan. 14, 2011

The IEEE 1241 standard covering analog-to-digital converters has been updated to address conflicts with other standards. IEEE 1241-2010™, "IEEE Standard for Terminology and Test Methods for Analog-to-Digital Converters," incorporates many corrections and new information. It also contains revised language that is more consistent with IEEE 1057™ and other standards. IEEE 1241 provides common terminology and test methods for the testing and evaluation of analog-to-digital converters.

IEEE 1036 — FIRST REVISION TO SHUNT POWER CAPACITORS GUIDE

Publication Date: Jan. 17, 2011

IEEE has published a revision to IEEE 1036™, "IEEE Guide for Application of Shunt Power Capacitors." This is the first revision to the standard since 1992. IEEE 1036 applies to the use of 50 and 60 Hz shunt power capacitors rated 2400 Vac and above, and assemblies of capacitors. It includes guidelines for the application, protection, and ratings of equipment for the safe and reliable utilization of shunt power capacitors. The guide also covers applications that range from simple unit utilization to complex bank situations.

IEEE EMC SOCIETY WITHDRAWS FROM POWER LINE COMMUNICATIONS COMMITTEE

Citing concerns about parts of its technical content, the IEEE EMC Society Standards Development Committee (SDCom) voted to withdraw as the cosponsor of IEEE Standard for Power Line Communication Equipment -- Electromagnetic Compatibility (EMC) Requirements -- Testing and Measurement Methods (IEEE Standard 1775-2010).

VCCI Council

JAPAN VCCI: COMPLIANCE WITH LIMITS ON RADIATED DISTURBANCE ABOVE 1GHZ

VCCI Council will start enforcement of confor-mity with limits on radiated disturbance above 1GHz of products subject to conformity verification report filing on and after Oct. 1, 2010. However, it is up to each member to decide if he will opt in conformity assessment tests above 1GHz until September 2011.

Nevertheless, however, let us ask you to positively go ahead and ship products conforming to the 1GHz+ requirement by filing conformity verification reports on and after October 1, 2010 as if there were no 1-year grace period because VCCI runs its operation based on CISPR standards transposed to Japanese standard by the Information and Communication Committee, and July 2007 Japanese standard says implementation of 1GHz+ should start in 2010.

Other News

EUROPEAN COMMISSION URGES HARMONY ON RADIO SPECTRUM

The European Commission adopted in May har-monized technical rules for member states on the allocation of radio frequencies, aimed at avoiding interference and boosting its efforts to improve the deployment of high-speed wireless Internet services.

EUROPE WANTS UNIFIED SYSTEM FOR RECHARGING ELECTRIC CARS

European Union nations agreed on the need to develop a standardized system for recharging electric cars throughout Europe by next year. The union's 27 industry ministers, meeting in Brussels in May, said the standardization is important for a number of reasons, including to address safety risks and electromagnetic compatibility issues.

FCC ALLOWS ADDITIONAL 25 MHZ OF SPECTRUM FOR MOBILE BROADBAND USE

The Federal Communications Commission on May 20 adopted WT Docket No. 07-293, new rules allowing for an additional 25 megahertz of spectrum to be available for mobile broadband service in much of the United States, while protecting adjacent satellite radio and aeronautical mobile telemetry operations. The rules adopted amend the Wireless Communications Service (WCS) rules to immediately make 25 megahertz of spectrum available for mobile broadband services. The FCC also adopted enhanced build-out requirements for WCS licensees, to ensure that the promise of mobile broadband is realized. These requirements are designed to spur investment that will promote the deployment of innovative mobile broadband services across the country.

FCC OPENS ACCESS TO WHITE SPACES SPECTRUM

The U.S. Federal Communications Commission voted to open unused spectrum in the television band to unlicensed wireless broadband devices, a move that will give U.S. residents access to "super Wi-Fi." The five-member FCC voted unanimously to allow the use of so-called "white spaces" between TV stations to deliver broadband connections that can function as "super Wi-Fi," as the agency is calling the new technology. The agency is hoping to see devices with the technology start to appear within a year.

EUROPEAN UNION PUBLISHES NEW LIST OF HARMONIZED STANDARDS

Commission communication in the framework of the implementation of Directive 2004/108/EC of the European Parliament and of the Council of 15 December 2004 on the approximation of the laws of the Member States relating to electromagnetic compatibility and repealing Directive 89/336/EEC.

EUROPEAN STANDARDS GROUPS AGREE ON MICRO-USB

European standardization bodies CEN-CENELEC and ETSI have agreed to make micro-USB the standard interface port for smartphones in Europe. The standards allow for interoperability, i.e. the common charger is compatible with data-enabled mobile telephones of different brands. They also take account of safety risks and electro-magnetic emissions and ensure that common chargers have sufficient immunity to external interference. This is the most recent development in the process towards a global common mobile phone charger initiated by the European Commission. It follows the June 2009 agreement of 14 leading mobile phone producers to harmonize chargers for data-enabled mobile phones (i.e. that can be connected to a computer) sold in the European Union.

JEDEC TO CREATE STANDARDS FOR SMALLER SSDS

JEDEC Solid State Technology Association announced that its JC-64.8 Subcommittee for Solid State Drives will target the development of standards for SSDs in applications beyond conventional disk drive form factors. According to Jedec (Arlington, Va.), the interest in developing standards for unconventional form factor SSDs is being driven by rising demand for smaller consumer electronics devices.

INTERNATIONAL GROUPS ADVANCE GLOBAL ELECTRIC VEHICLE ROLL-OUT

The International Electrotechnical Commission (IEC) and e8, a global organization of 10 electricity companies, for the first time, brought together all major stakeholders that need to collaborate to accelerate the global roll-out of electric vehicles (EVs). At this international round table that took place on Jan. 19 in Washington D.C., USA, and which represents a milestone in the future growth of these vehicles, all participants confirmed that the IEC's existing and proposed International Standards for EV charging satisfy their global needs. The objective of the round table was to determine priorities for the development of EV-related standards, to define future needs, and to accelerate the broad adoption of the relevant international standards that will enable global interoperability and connectivity. Follow-up meetings are being planned.

FCC STEPS UP CELL PHONE, GPS JAMMING ENFORCEMENT EFFORTS

The FCC Enforcement Bureau announced new efforts to clamp down on the marketing, sale, and use of illegal cell phone and GPS jamming devices. Jamming devices are radio frequency transmitters that intentionally block, jam, or interfere with lawful communications, such as cell phone calls, text messages, GPS systems, and Wi-Fi networks. A single violation of the jamming prohibition can result in tens of thousands of dollars in monetary penalties, seizure of the illegal device, and imprisonment. The Bureau released two Enforcement Advisories and a downloadable poster on cellphone and GPS jamming that warn consumers, manufacturers, and retailers (including online and Web-only companies) that the marketing, sale, or use of cell, GPS, and other jamming devices is illegal. These steps highlight a new outreach phase of the Bureau's continuing effort to halt the distribution and proliferation of illegal jamming devices in the United States. In the last two weeks, the Bureau issued warnings to four well-known online retailers – including the company that markets the TxTStopperTM – directing them to cease marketing jamming devices to customers in the U.S. or face stiff fines.

IEEE Electromagnetic Compatibility Society (S-27)

Headquarters:
IEEE Operations Center
445 Hoes Lane, P.O. Box 1331
Piscataway, NJ 08855-1331
Phone: (732) 981-0060
www.ewh.ieee.org
President: Francesca Maradei, fr.maradei@ieee.org

The Institute of Electrical & Electronics Engineers (IEEE), the world's largest professional engineering society, is a global organization of individuals dedicated to improving the understanding of electrical and electronics engineering and its applications to the needs of society. The parent organization has over 360,000 members, approximately 70 percent of whom belong to technical groups such as the EMC Society.

Membership in the IEEE is on a qualified basis, with a basic annual fee of between $140.00 and $180.00 depending on the region of the world. The U.S. fee is $180.00. The Institute offers major medical and life insurance at low group rates, and each member receives a copy of the monthly publication, Spectrum. Affiliate, associate, and student memberships are available for those who do not qualify for regular membership; and special arrangements are provided for those temporarily out of work. Members may join one or more of the 39 technical societies by paying the additional individual society fee(s). The EMC Society has an annual fee of $25.00. Student memberships are $13.00.

The EMC Society, which enjoys a membership of over 5000, functions through a Board of Directors elected by the Society membership. The Board includes 20 members-at-large who serve staggered 3-year terms. The Executive Board consists of the President, President-Elect, Immediate Past President, Secretary, Treasurer, and five Vice Presidents, who oversee the activities of standing and technical committees. The officers are elected by the Board of Directors. The annual IEEE International Symposium on Electromagnetic Compatibility is sponsored by the Board of Directors, which also coordinates activities of standing technical and ad hoc committees.

EMC Society publications include Transactions on EMC, a quarterly journal which features state-of-the-art papers on interference technology and EMC, and the EMC Society Newsletter, a quarterly newsletter of society activities, industry developments, practical papers, and notices of meetings, regulations, and new publications.

The EMC Society also has a group of distinguished lecturers who are available to present talks to IEEE and other organizations. The Society subsidizes the lecturers' expenses, and organizations are encouraged to contact the society for further details.

Chairmen of these committees welcome assistance and indications of interest in committee activities from the EMC Society membership. EMC Society activities are provided by 54 chapters with members in 61 countries worldwide.

A Committee Directory, listing officer, board, committee, and chapter contacts' names, addresses, and telephone numbers, is available on the IEEE EMC Society website at www.emcs.org.

The EMC Society is also active in technical conferences and symposia through its sponsorship of the annual International Electromagnetic Compatibility Symposium and participation in other worldwide symposia. Symposia and conferences are announced in the EMC Society Newsletter.

The IEEE Symposium on Electromagnetic Compatibility will be held in Long Beach, Calif. USA from August 14-19, 2011. Visit the Symposium website at www.emc2011.org.

The EMC Society has published a number of standards. For information on EMC Society and other IEEE standards, contact the IEEE Operations Center, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331; Phone: (732) 981-0060.

IEEE Product Safety Engineering Society

While product safety had been addressed in various committees over the years, there was never a professional society or symposium solely devoted to product safety engineering as a discipline until recently. The IEEE Product Safety Engineering Society (PSES) began operation on 1 January 2004.

The field of interest of the Society is the theory, design, development and implementation of product safety engineering for electronic and electro-mechanical equipment and devices. This includes the theoretical study and practical application of analysis techniques, testing methodologies, conformity assessments, and hazard evaluations.

The Society's mission is to strive for the advancement of the theory and practice of applied electrical and electronic engineering as applied to product safety and of the allied arts and sciences.

The Society provides a focus for cooperative activities, both internal and external to IEEE, including the promotion and coordination of product safety engineering activities among IEEE entities. In addition, the Society will provide a forum for product safety engineering professionals and design engineers to discuss and disseminate technical information, to enhance personal product safety engineering skills, and to provide product safety engineering outreach to engineers, students and others with an interest in the field. The Society is accepting members at any time during the calendar year, both full IEEE members and affiliate members. Membership is available at www.ieee.org/services/join/.

The IEEE Product Safety Engineering Society works closely with various IEEE Societies and Councils that also include product safety engineering as a technical specialty. Currently there are 14 chapters with more in the formation process.

Every year, the PSES hosts a Symposium on Product Compliance Engineering. The next conference will be in San Diego, California, USA on 10-12 October 2011. The Symposium will consist of Technical Sessions, Workshops, Tutorials and Demonstrations specifically targeted to the compliance engineering professional. Attendees will have the opportunity to discuss problems with vendors displaying the latest regulatory compliance products and services. For more information, visit http://www.ieee-pses.org/symposium/. Past papers from the Symposia are available in IEEE Xplore or on CD (for a fee).

In addition to hosting an annual conference, the PSES provides the opportunity for product safety engineers to publish technical papers in a newsletter. See http://www.ieee-pses.org/newsletters.html. For further information and details on the Society, including becoming an author, please visit the website at www.ieee-pses.org.

dB Society

This unique, interesting, and exclusive fraternity of EMC engineers was founded in 1975 by 10 eminent EMC engineers. The purpose of the dB Society is to open doors within the EMC community. Its primary objectives are to greet and to welcome new engineers, suppliers, vendors, and manufacturers to the EMC community and to assist them in establishing contacts in the EMC field.

The following membership requirements are unique and rigidly enforced:

- Ten years of service to the EMC community,
- Five years of service to a recognized professional, EMC organization,
- Sponsorship by two Duo-Decade members,
- Favorable recommendations by three other recognized individuals in the EMC community, and
- Acceptance by the Admissions Board.

Business meetings and informal, relaxed get-togethers take place during major EMC functions. A formal evening social function is the highlight of each year and is usually conducted during the IEEE EMC Symposium. All meetings are for members only.

U.S. membership is limited to 100 EMC engineers. There are Society affiliates in the United Kingdom, India, and Israel. Qualified candidates are invited to write to:

The dB Society
22117 NE 10th Place
Sammamish, WA 98074
FAX: (425) 868-0547
E-mail: j.n.oneil@ieee.org

ESD Association

Headquarters:
ESD Association
7900 Turin Road, Building 3
Rome, NY 13440-2069
phone: 315-339-6937
fax: 315-339-6793
email: info@esda.org
website: www.esda.org

Founded in 1982, the ESD Association is a pro-fessional voluntary association dedicated to advancing the theory and practice of electrostatic discharge (ESD) avoidance. From fewer than 100 members, the Association has grown to more than 2,000 members throughout the world. From an initial emphasis on the effects of ESD on electronic components, the Association has broadened its horizons to include areas such as textiles, plastics, web processing, cleanrooms, and graphic arts. To meet the needs of a continually changing environment, the Association is chartered to expand ESD awareness through standards development, educational programs, local chapters, publications, tutorials, certification, and symposia.

ELECTROSTATIC DISCHARGE (ESD) TECHNOLOGY ROADMAP

In the late 1970s, electrostatic discharge, or ESD, became a problem in the electronics industry. Low-level ESD events from people were causing device failures and yield losses. As the industry learned about this phenomenon, both device design improvements and process changes were made to make the devices more robust and processes more capable of handling these devices. With devices becoming more sensitive through the year 2010, it is imperative that companies begin to determine the ESD capabilities of their handling processes. The ESD Technology Roadmap can be downloaded at: www.esda.org

ANSI/ESD S20.20 CONTROL PROGRAM STANDARD AND CERTIFICATION

A primary direction for the association is the continued implementation of a facility certification program in conjunction with ISO registrars. With the association's ESD control program standard, ANSI/ESD S20.20: Protection of Electrical and Electronic Parts, Assemblies and Equipment (Excluding Electrically Initiated Explosive Devices), the Association offers a means of independently assessing a company's ESD control program and of issuing a formal ANSI/ESD S20.20 certification.

The ANSI/ESD S20.20 standard covers the requirements necessary to design, establish, implement, and maintain an ESD control program to protect electrical or electronic parts, assemblies and equipment susceptible to ESD damage from Human Body Model (HBM) discharges greater than or equal to 100 volts. Developed in response to the Military

Standardization Reform Act, ANSI/ESD S20.20 has been formally adopted for use by the U.S. Department of Defense.

Although ESD programs have been part of some ISO 9000 audits in the past, the assessment frequently has been cursory and actual judgment of the program has been left to the individual auditor. ANSI/ESD S20.20 provides a formal, consistent process standard that can be audited. It provides a single, auditable ESD standard for OEM's, suppliers, and contractors. To date, there are approximately 132 facilities in 13 countries that have become ANSI/ESD S20.20 certified.

Accredited registrars conduct the actual assessments of the companies. The association has developed a training program for the registrars and supervises registrar witness audits. This independent assessment of a company's ESD control program could be performed as part of the company's ISO 9000 surveillance audit or as a separate audit. Currently, there are 161 trained auditors in 13 countries who have been certified to conduct ANSI/ESD S20.20 audits.

In addition, the ESD Association offers an ESD program documentation review service. For a fee of $1,500 (US), members of the ESD Association's Facility Certification committee will review your ESD program documentation and will compare it to the requirements listed in ANSI/ESD S20.20-2007. Facilities that choose to become certified will use the ANSI/ESD S20.20-2007 standard as the basis for their certification. A report will be provided that describes the areas that need to be improved for documentation to be compliant with ANSI/ESD S20.20-2007. This service should be considered a MUST for any company that is preparing for facility certification based on ANSI/ESD S20.20-2007.

SYMPOSIA, TUTORIALS, AND PUBLICATIONS

As part of its commitment to education and technology, the association holds the annual EOS/ESD Symposium, which places major emphasis on providing the knowledge and tools needed to meet the challenges of ESD. Scheduled for Sept. 11-16, 2011, at the Disneyland Hotel, in Anaheim, Calif., USA, the annual Symposium attracts attendees and contributors from around the world. Technical sessions, workshops, authors' corners, seminars, tutorials, and technical exhibits provide a myriad of opportunities for attendees to expand their knowledge of ESD.

In addition to tutorials and seminars, the association offers a number of publications and reference materials for sale. These range from proceedings of past EOS/ESD Symposia to textbooks written by experts in the field of ESD.

TechAmerica

Electromagnetic Compatibility Committee (G-46) Headquarters

TechAmerica
1401 Wilson Blvd., Suite 1100
Arlington, VA 22209
Phone: (703) 248-5326
www.TechAmerica.org

TechAmerica is the association that was created by the merger of AeA and ITAA. Earlier in 2008, ITAA and GEIA merged. The result of these mergers is an organization that is the leading voice for the U.S. technology industry, which is the driving force behind productivity growth and jobs creation in the United States. TechAmerica is the technology industry's only grassroots-to-global advocacy network. With nearly 1200 member companies, 20 regional councils and offices in Beijing and Brussels, the association represents the full spectrum of the technology industry.

TechAmerica is the technology industry's only grassroots-to-global advocacy network. The organization has expanded initiatives in areas such as: information Assurance / Information Security, Identity Management, Cloud Computing, Global Sourcing / Globalization, Intelligence agencies, Department of Defense & NASA, and State & Local programs and public policy advocacy.

TechAmerica provides programs for business development, networking and market intelligence in the Federal arena, dealing with government entities such as Department of Defense, Homeland Security, Federal Communications Commission, Federal Trade Commission,, Congress, as well as with state and local governments.

TechAmerica has a team of public policy professionals at state, federal and international levels, that allow the organization to successfully influence legislative and regulatory issues that affect member companies.

In addition, TechAmerica offers an active standards development program to provide industry with proven solutions to business process challenges. The program is nationally and internationally recognized for its leadership and expertise in the development of standards. Configuration Management, Systems Engineering, Systems Safety, Earned Value Management, Logistics, Reliability and Electromagnetic Compatibility (EMC) area where TechAmerica is involved in standard.

The Electromagentic Compatibility (EMC) Committee (formally known as G-46) deals with the system-oriented discipline that ensures electromagnetic compatibility in electronics design. The Committee develops technical criteria and procedures to guide the design engineer. Its work also includes spectrum management and conservation; secure communications; and electromagnetic emissions, susceptibility, control, and characterization.

The EMC Committee was established to provide an industry/user position on government specifications, regulations, and standards. Participation has expanded to include G-46 representation on the various committees drafting government specifications and standards. For example, G-46 participated on the working committees for MIL-STD-464A and MIL-STD-461E and provided update recommendations to MIL-STD-461F. The scope of G-46 activities has expanded to foster and facilitate the EMC discipline for the benefit of TechAmerica member companies.

Committee activities include spectrum management and conservation; personnel safety; and health care electronics design, usage and installation in terms of regulated and non-regulated electromagnetic (EM) emissions and immunity. Inter- and intra-environmental areas as they affect systems, subsystems and equipment, subassemblies, and components are also areas of concern. In addition to other activities, committees:

- Review, assess, advise, and coordinate related activities of organizations/individuals in government, industry, and technical societies.
- Assure that EMC legislation, regulations, specifications, standards, requirements, and evaluation procedures are adequate for procurement and application.
- Assure that EMC legislation, regulations, specifications, standards, requirements, and evaluation procedures are harmonized with their commercial counterparts to the maximum extent practical for procurement and application.
- Propose and recommend action and provide support to other organizations, as deemed desirable.
- Coordinate and promulgate information to facilitate advancement of the state-of-the-art.

Additional information on TechAmerica and the EMC Committee (G-46) can be obtained from Phyllis Call at (703) 284-5315, phyllis.call@techamerica.org, or via the GEIA website at http://www.geia.org.

Society of Automotive Engineers

Committee AE-4, Committee Headquarters:

Society of Automotive Engineers
400 Commonwealth Drive
Warrendale, PA 15096-0001
Phone: (724) 776-4841

SAE International is a professional society of engineers dedicated to a broad spectrum of engineering disciplines within the aerospace and automotive fields. Under the SAE Aerospace Council, technical standards committees address disciplines ranging from electrical power to multiplex signal characteristics—and from fiber optic data transmission to electromagnetic compatibility. The many elements of EMC are handled by SAE Committee AE-4, Electromagnetic Compatibility, which was organized in 1942 under the Aerospace Council. The committee is composed of technically qualified members, liaison members, and consultants—all of whom are responsible for writing standards on electromagnetic compatibility.

Committee AE-4 provides assistance to the technical community through standardization, improved design and testing methodology, and technical forums for the resolution of mutual problems. Engineering standards, specifications, and technical reports are developed by the Committee and are issued by the Society for industry and governments worldwide. Objectives of Committee AE-4 are to advance the state of technology, to stabilize existing technology, to obtain a uniformity of EMC requirements among government agencies, and to further the interests of the EMC technical community. The theme of "design before the fact" for EMC is a guiding concept. Special attention is given to maintenance of EMI control requirements consistent with the rapidly advancing state-of-the-art.

The following is a partial list of documents that have been issued to assist in implementing SAE objectives. For a complete list, visit the SAE website at www.sae.org or call SAE Customer Service at (724) 776-4841.

AEROSPACE RECOMMENDED PRACTICES (ARPS)

ARP 935A	Control Plan/Technical Construction File
ARP 936A	Capacitor, 10 mF for EMI Measurements
ARP 958C	Electromagnetic Interference Measurement Antennas, Standard Calibration Method
ARP 958D	Electromagnetic Interference Measurement Antennas, Standard Calibration Method
ARP 1172	Filters, Conventional, EMI Reduction, Specifications for
ARP 1173	Test Methods for EMI Gasketing
ARP 1267	EMI Measurement of Impulse Generators, Standard Calibration Requirements and Techniques
ARP 1481A	Corrosion Control and Electrical Conductivity in Enclosure Design
ARP 1705	Coaxial Test Procedure to Measure the RF Shielding Characteristics of EMC Gasket Materials
ARP 1870	Aerospace Systems Electrical Bonding and Grounding for Electromagnetic Compatibility and Safety
ARP 1972	Recommended Practices and Procedures for EMC Testing
ARP 4043A	Flightline Bonding and Grounding of Aircraft
ARP 4242	Electromagnetic Compatibility Control Requirements, Systems
ARP 4244	Recommended Insertion Loss Test Methods for EMI Power Line Filters

AEROSPACE INFORMATION REPORTS (AIRS)

AIR 1147	EMI on Aircraft from Jet Engine Charging
AIR 1209	Construction and Calibration of Parallel-Plate Transmission Lines for EMI Susceptibility Testing
AIR 1221	EMC System Design Checklist
AIR 1255	Spectrum Analyzers for EMI Measurements
AIR 1394A	Cabling Guidelines for Electromagnetic Compatibility
AIR 1404	DC Resistivity vs. RF Impedance of EMI Gaskets
AIR 1423	EMC on Gas Turbine Engines for Aircraft Propulsion
AIR 1425A	Methods of Achieving EMC of Gas Turbine Engine Accessories, for Self-Propelled Vehicles
AIR 1499	Recommendations for Commercial EMC Susceptibility Requirements
AIR 1662	Minimization of Electrostatic Hazards in Aircraft Fuel Systems

AIR	1700A	Upper Frequency Measurement Boundary for Evaluation of Shielding Effectiveness in Cylindrical Systems
AIR	4079	Procedure for Digitized Method of Spark Energy Measurement

SAE AE-4 ELECTROMAGNETIC ENVIRONMENTAL EFFECTS (E3 OR EMC) COMMITTEE

The SAE AE-4 E3 Committee provides a technical, coordinating, and advisory function in the field of E3. The focus is on problem areas in which committee expertise can be effectively applied at the national and international levels. Electrical and electronic accessories are studied for compatibility within systems and with various communications media. Engineering standards, specifications, and technical reports are developed and are issued for the general information of industry and government.

In the past, subcommittees have included AE-4R, Aircraft Radiated Environments, and AE-4H, High Power RF Simulators and Effects. AE-4 E3 holds national meetings in conjunction with the IEEE EMC Society Symposium, usually held in August at various locations. Additional information about meetings or more specific information on the activities of the Committee can be obtained by contacting:

Dorothy Lloyd
Aerospace Standards Specialist
Society of Automotive Engineers
400 Commonwealth Drive
Warrendale, PA 15096-0001
Phone: (724) 776-4841
dlloyd@sae.org

or the Chairman, Gary Fenical, gfenical@lairdtech.com.

Visit the SAE's Technical Standards Committee Forum website at http://forums@sae.org.

iNARTE

iNARTE, Inc. (The International Association for Radio, and Telecommunications and Electromagnetics, Inc.) was founded as a non-profit membership/certification organization in 1982. With the advent of deregulation and the Federal Communications Commission's "encouragement/urging" private industry to establish certification standards to fill the licensing void, iNARTE initiated and developed a comprehensive certification program for telecommunications engineers and technicians.

In 1988, a Command of the United States Navy, seeking a credible and respected certification entity, selected iNARTE as the administrative agent for the certification of engineers and technicians in the field of electromagnetic compatibility (EMC).

In 1993, iNARTE, certified by the Federal Communications Commission (FCC) as a Commercial Operators License Examination Manager (COLE Manager), was authorized to administer all examination elements for FCC licensure (formally an FCC responsibility).

In 1994, the ESD Association selected NARTE to implement and administer a certification program for Electrostatic Discharge Control Engineers and Technicians.

During 1997, two nations, China and Japan, requested iNARTE assistance in the establishment of specific in-country certification programs comparable to and able to meet iNARTE certification standards.

In 2000, iNARTE established the Unlicensed Wireless Systems Installer certification to identify fully qualified design and installation personnel. This certification accredits professionals who design and install wireless systems that do not require a license from the FCC—including information systems, security systems, and transportation systems.

In 2001, iNARTE developed an Agreement with the IEEE EMC Society for the co-promotion of awareness and education in EMC/EMI fields. Today the EMC Society is the keeper of the body of knowledge from which the iNARTE examinations are derived.

In 2003 iNARTE, together with specialist partners, developed the Product Safety certification program. The Product Safety program accredits professionals who use hazard-based analysis to identify and develop solutions to eliminate or minimize safety hazards. In 2004 iNARTE signed an Agreement with the IEEE Product Safety Engineering Society, PSES, to co-promote awareness and education in Product Safety. Today, technical experts within the PSES assist iNARTE in the development of the examination question pools.

In 2006 iNARTE executed Agreement with ANSI ASC 63, the Accredited Standards Committee on EMC, for the purposes of joint cooperation and promotion in education and technical achievement in EMC engineering.

By 2007, the global interest and participation in iNARTE Certification programs had resulted in almost one quarter of members being from overseas countries. In recognition of this, the iNARTE Board of Directors voted unanimously to change the Association name to the, "International Association for Radio. Telecommunications and Electromagnetics, iNARTE."

As iNARTE, an agreement of mutual support and cooperation was signed with the ESD Association in 2007. The ESDA will assist iNARTE in formulating and maintaining the question pools from which certification examinations are derived.

ACIL—The American Council of Independent Laboratories

The American Council of Independent Laboratories (ACIL) is the trade association representing independent, commercial engineering, and scientific laboratory, testing, consulting, product certifying, and R&D firms; manufacturers' laboratories; related non-profit organizations; and consultants and suppliers to the industry. The organization was founded in 1937. All ACIL activities focus on its mission: to enhance members' success by providing advocacy, education, services, and mutual support and by promoting ethics, objectivity, independence, and free enterprise.

ACIL is a voluntary, non-profit membership organization. Programs are determined by members, administered by an elected Board of Directors, and supported by a professional staff operating from headquarters in Washington, D.C.

ACIL'S CONFORMITY ASSESSMENT SECTION

ACIL's Conformity Assessment Section consists of firms with wide and varied interests, all performing testing, listing, or labeling in accordance with applicable safety and performance standards, and/or materials testing and resolution of product and structural problems. Several committees have evolved within the Section to meet the needs of its diverse membership, including the EMC Committee, the U.S. Council of EMC Laboratories, and the Third-Party Product Certifiers Committee. In January 2005, the Section sponsored a booth at the Consumer Electronics Show that advocated the advantages of independent third-party testing and the capabilities of ACIL member EMC laboratories.

ACIL'S EMC COMMITTEE

ACIL's EMC Committee was established in 1996 to address the common concerns of the ACIL EMC community. The Committee sponsors educational sessions at ACIL meetings that include both technical and policy issues such as mutual recognition agreements (MRAs). The Committee updates members on the latest developments, upcoming requirements, and activities in the field—both domestic and international.

In January 2002, ACIL published a 143-page document, Technical Criteria for the Accreditation of Electromagnetic Compatibility (EMC) and Radio Testing Laboratories, a checklist to assist both assessors and laboratories.

The Committee also formed the U.S. Council of EMC Laboratories (USCEL) in an effort to aid U.S. laboratories in addressing technical issues arising from the U.S./EU MRA and other global concerns. As the USCEL Secretariat, ACIL provides staff and supports volunteers active in this important area.

Over the past several years, ACIL has administered round robin proficiency testing programs with two artifacts allowing laboratories to make both AC line conducted and radiated emissions measurements over the frequency range of 0.15–30 MHz and 30 MHz–1 GHz, respectively. While continuing the round robins in the frequencies noted above, ACIL has launched another round robin with a new test artifact. This artifact will allow participating laboratories to demonstrate proficiency for radiated emissions measurements in the frequency range of 1–18 GHz. Emissions measurements above 1 GHz are becoming increasingly common with the advent of fast processors and wireless devices in the 2.4- and 5-GHz bands.

ACIL also was instrumental in the formation of the Telecommunication Certification Body Council (TCBC). New rules establishing TCBs were adopted by the FCC in December 1998, providing more options for manufacturers—they can now choose to have their product certified by either the FCC or a private certification body (TCB). A TCB may approve equipment subject to certification (e.g., transmitters, telecom terminal equipment, or scanning receivers). The TCB Council addresses the specific concerns of the TCB community and all constituent bodies are permitted to participate.

U.S. PRODUCT CERTIFIERS

Key U.S. product certifiers are ACIL members and are reaping many benefits, such as participation in the ACIL Third-Party Product Certifiers Committee ($3P^2C^2$). This Committee provides a forum for members to discuss and to act upon various issues of common interest. This committee formed the American Council for Electrical Safety to serve as a forum among testing laboratories, regulators, and electrical inspectors. ■

directory of government personnel involved in EMI/EMC

The following is a list of the principal U.S., NATO and Canadian Government personnel known to be involved in the interference technology field. This list is based upon best available data at the time of publication. Additions, deletions and corrections for any facility may be updated at any time by e-mailing your changes to slong@interferencetechnology.com.

DEPARTMENT OF DEFENSE

Defense Spectrum Organization

DSO Director: Ms. Paige R. Atkins........(703) 325-2567
Paige.Atkins@disa.mil
DSO Dep Dir: Mr. Ralph Puckett........... (703) 325-2874
Ralph.Puckett@disa.mil

Strategic Planning Office (SPO)

SPO Director: Mr. Steven A. Molina .... (703) 325-0435
Steven.Molin@disa.mil
Internat'l Team Lead: Mr. Chris Hofer ..(703) 325-2876
EST Team Lead: Ms. Mary Lin...............(703) 325-0136
National Team Lead: Mr. Dan O'Neill ...(703) 325-2606

Joint Spectrum Center (JSC)

2004 Turbot Landing
Annapolis, MD 21402-5064
Tel: (410) 293-4957
Fax: (410) 293-2631

Commander, JSC (J00):
COL John J. HICKEY Jr., USA .... (410) 293-2450
John.Hickey@jsc.mil
Commander's Group: commander@jsc.mil

Technical Director (J01):
Mr. Mike Williams .... (410) 293-2457
mike.williams@jsc.mil

Executive Officer (J02):
CDR Robert "Jeff" Lamont, USN .... (410) 293-2452
Jeff.Lamont@jsc.mil

Operations Division (J3):
Chief: LTC Kevin T. Laughlin................... (410) 293-9813
Kevin.Laughlin@jsc.mil
Senior Engineer: Mr. Robert Lynch .... (410) 293-9816
robert.lynch@jsc.mil

RD&A Division (J5):
Mr. Robert Schneider.............................(410) 293-4958
robert.schneider@jsc.mil
Senior Engineer: Mr. Marcus Shellman, Jr.....................
....(410) 293-4959
marcus.shellman@jsc.mil
Team Lead: Mr. Matthew Grenis ....(410) 293-9264
matthew.grenis@jsc.mil
R&D Team Lead: Mr. Serey Thai...........(410) 293-9263
Serey.Thai@jsc.mil

Spectrum Management Information Technology Division (J6):
Acting Chief: Mr. Joseph R. Whitworth.........................
....(410) 293-9822

Plans and Resources Division (J7):
Chief: Mrs. Joanne F. Sykes .... (410) 293-2356
joanne.sykes@jsc.mil

Applied Engineering Division (J8):
Chief: Aaron Leong, Lt Col, USAF.......... (410) 293-2682
Aaron.Leong@jsc.mil
Senior Engineer: Mr. Irving Mager, Jr. (J8) ....
.... (410) 293-2103
irving.mager@jsc.mil
Chief, DSRMA: Mr. Ted Grove...............(410) 293-2222

Joint Frequency Management and Spectrum Engineering Office, Atlantic (JFMO LANT)

Director JFMO LANT (USJFCOM/J63)
1562 Mitscher Ave., Ste. 200
Norfolk, VA 23551-2488
Tel.: (757) 836-8006
Fax: (757) 836-8022

UNITED STATES AIR FORCE

Aeronautical Systems Center (ASC)

ASC/ENAD
2145 Monahan Way
Wright-Patterson Air Force Base, OH 45433-7101
Fax: (937) 255-5305
E3 Technical Advisor
Mr. Manny Rodriguez .... (937) 255-8928
manuel.rodriguez@wpafb.af.mil
EMI/EMC Tech Specialist
Mr. Joseph M. DeBoy, (937) 255-9293
joseph.deboy@wpafb.af.mil
EMI/EMC Engineer
Mr. Brian M. Lezanic ....(937) 255-9051
brian.lezanic@wpafb.af.mil
Electromagnetic Environmental Effects (E3) Engineer
Mr. Jose Pabon Soto..............................(937) 255-0139
jose.pabon-soto@wpafb.af.mil

Aeronautical Systems Center (ASC)

312/326 AE SW (Fighter Bomber Wing)
702 AE SG (B-2)
2690 C St., B556
Wright-Patterson AFB, OH 45433-7424
Fax: (937) 255-9450
Mr. Joe Harrington................................ (937) 255-0844
joseph.harrington@wpafb.af.mil

Aeronautical Systems Center (ASC)

312/326 AE SW (Fighter Bomber Wing)
702 AE SG (B-2)
2690 C St., B556
Wright-Patterson AFB, OH 45433-7424
Dr. Phil Beccue..(937) 255-6881
Philip.Beccue@wpafb.af.mil

Aeronautical Systems Center (ASC)

312/326 AE SW (Fighter Bomber Wing)
651 AE SS (B-52)
2690 C St., B556
Wright-Patterson AFB, OH 45433-7424
FAX (937) 656-4621
Mr. Jeremy Burns...................................(937) 255-7025
jeremy.burns@wpafb.af.mil

HQ Air Force Material Command (AFMC)

AFMC/EN P
Bldg. 262/Rm N145/Post116D
Wright-Patterson AFB, Ohio 45433
Fax: (937) 656-4183
Mr. John S. Welch..................................(937) 255-0651
john.welch@wpafb.af.mil

Aeronautical Systems Center (ASC)

516 AE SW (Mobility)
836 AE SG (Tankers)
2530 Loop Road West,
Wright-Patterson AFB, Ohio 45433
Mr. Robert Rosengarten ....(937) 255-3451
Robert.Rosengarten@wpafb.af.mil

Aeronautical Systems Center

Special Operations Forces Systems Group
667 AE SS/EN
1895 5th St.
Wright-Patterson Air Force Base, OH 45433-7200
Fax: (937) 255-4018
Mr. Steven Coffman...............................(937) 255-2860
steven.coffman@wpafb.af.mil

Aeronautical Systems Center

Reconnaissance Systems Wing
303 AE SG (Global Hawk)
2640 Loop Road West
Wright-Patterson Air Force Base, OH 45433-7106
Mr. Dave Osborn.....................................(937) 255-7437
david.osborn@wpafb.af.mil

Air Force Research Laboratory, Sensors Directorate

AFRL/ RYRA
2241 Avionics Circle
Bldg 620, Rm 1DG106
Wright-Patterson Air Force Base 45433-7318
EMI Laboratory
Mr. John Zentner....................................(937) 904-9024
john.zentner@wpafb.af.mil

Air Combat Command (ACC)

85 Engineering Installation Squadron
85 EI S/SCYM
670 Maltby Hall Drive, Ste.234
Keesler AFB, MS 39534-2633
85.eis.scym@keesler.af.mil
Specialized Engineering Flight:
Mr. George R. McNeer, SCY.................. (228) 377-1037
Electromagnetics Section Chief:
Mr. Frederick G. Blache, SCYM.............(228) 377-3926
frederick.blache@us.af.mil
E3 Engineers:
Mr. Randal Blanchard, SCYT .... (228) 377-1068
randal.blanchard@us.af.mil
Captain Micah Coplan............................ (228) 377-1035
micah.coplan@us.af.mil
Ms. Kristen M. Corrigan .... (228) 377-1073
kristen.corrigan@us.af.mil
Mr. Edward Crum, SCYM....................... (228) 377-1096
edward.crum@us.af.mil
Mr. Stephen L. Dabney ....(228) 377-1074
stephen.dabney@us.af.mil
Mr. Tim O. Hillman.................................. (228) 377-1278
timothy.hillman@us.af.mil
Mr. Justin L. Johnston ....(228) 377-3041
justin.johnston@us.af.mil
Mr. Carlton L. Jones............................... (228) 377-1088
carlton.jones@us.af.mil
Mr. James W Laycock............................ (288) 377-1035
james.laycock@us.af.mil
Mr. Tom Lipski .... (228) 377-1084
thomas.lipski@us.af.mil
Captain Arris Pineda ....(228) 377-1126
arris.pineda@us.af.mil
Mr. Alton J. Richards III .... (228) 377-1079
alton.richards@us.af.mil
Captain Jason R. Seyba.......................... (228) 377-1085
jason.seyba@us.af.mil
Mr. Gregory P. Smith .... (228) 377-1083
gregory.smith.7@us.af.mil
Mr. Jesse L. Thomas III...........................(228) 377-1126
jesse.thomas@us.af.mil
Mr. Phi D. Tran .... (228) 377-1062
phi.tran@us.af.mil
Mr. Truong X. Vu..................................... (228) 377-1866
truong.vu@us.af.mil
Mr. Brandon Walker .... (228) 377-1048
brandon.walker.1@us.af.mil

Mr. Robert (Nick) Wilson, Sr. Electronics Engineer .... (228) 377-1047
robert.wilson.6@us.af.mil

UNITED STATES ARMY

U. S. Army Research, Development and Engineering Command (RDECOM)
Attn.: AMSRD-AAR-AEP-F
Bldg. 3208
Picatinny Arsenal, NJ 07806-5000
Fax: (973) 724-3025
Mr. Tom Crowley, Supvr. ....(973) 724-5678
thomas.m.crowley@us.army.mil
Mr. Derrick Coppin, Proj. Engr. ....(973) 724-4871
derrick.coppin@us.army.mil
Mr. Daniel Gutierrez, Sr. Proj. Engr. ......(973) 724-4667
daniel.gutierrez@us.army.mil
Mr. Paul Lee, Proj. Engr............... (973) 724-4584/4667
paul.m.lee@us.army.mil

Army Research, Development, and Engineering Command (RDECOM)
Attn: RDMR-AES-E3
Building 4488
Redstone Arsenal, AL 35898-5000
Fax: (256) 313-3194
E3 for Army Aircraft Airworthiness
E3 Branch Chief:
Mr. Dave Lewey.....................................(256) 313-8464
dave.lewey@us.army.mil
E3 Team Lead, Attack/Recon/Cargo Team:
Ms. Karen Compton ....(256) 313-8437
karen.compton@us.army.mil
E3 Team Lead, Utility/Fixed Wing/SOA Team:
Mr. Duane Driver ....(256) 313-8447
duane.driver@us.army.mil
Mr. Dale Heber .... (256) 313-2229
dale.heber@us.army.mil
Mr. Bruce Hildebrandt........................... (256) 313-8457
bruce.hildebrandt@us.army.mil
Mr. Elliot Croom.................................... (256)842-5387
Elliot.croom@amrdec.army.mil
Mr. Abner Merriweather ....(256) 313-8470
abner.merriweather@us.army.mil
Mr. Brian Smith,iNCE, iNCT...................(256) 313-8484
brian.smith42@us.army.mil
Mr. John Trp... (256) 313-3148
john.trp@us.army.mil
Mr. Mike Dreyer ....(256) 313-6384
michael.dreyer@us.army.mil
Mr. Dan Hinton ....(256) 313-8497
daniel.w.hinton@us.army.mil
Mr. David Alan Landrith..........................(256)313-9102
david.landrith@amrdec.army.mil
Mr. Roy Lawson......................................(256) 313-8454
roy.lawson@us.army.mil
Attn.: AMSAM-RD-MG-SD
SC Functions
Mr. Dave Smith.......................................(256) 876-1688
wayne.d.smith2@us.army.mil

Army Test and Evaluation Command (ATEC) Redstone Technical Test Center (RTTC)
E3 Test Branch
Attn.: CSTE-DTC-RT-E-EM
Redstone Arsenal, AL 35898-8052
Supervisor: Mr. James L. Zimmerman ....(256) 876-6386
jzimmerman@us.army.mil
Mr. Jeff Craven .... (256) 842-2952
jeffery.d.craven@us.army.mil
Mr. David Anconetani ....(256) 876-0981
danconetani@us.army.mil
Mr. David Elkins......................................(256) 876-3965
delkins@us.army.mil
Mr. Jarrod Fortinberry ....(256) 876-3505
jfortinberry@ us.army.mil
Ms. Jennifer Oberle ....(256) 955-6140
joberle@us.army.mil
Mr. Joe Reyenga ....(850) 833-2837
gerald.reyenga@eglin.af.mil
Dr. Tom Shumpert...................................(256) 876-9974
tshumpert@us.army.mil
Mr. Andrew Smilie ....(256) 876-9512
asmilie@us.army.mil
Mr. Lee Stucker ....(256) 876-1790
lstucker@us.army.mil
Dr. Mark Waller ....(256) 313-6970
mwaller@us.army.mil
Dr. Ken Whigham ....(256) 313-0257
kwhigham@us.army.mil

Army Center for Health Promotion & Preventive Medicine (CDR USACHPPM)
Radiofrequency/Ultrasound Program
Attn.: MCHB-TS-ORF
5158 Blackhawk Road
Aberdeen Proving Ground, MD 21010-5403
Mr. John J. DeFrank...............................(410) 436-3353
Bureau of Medicine and Surgery (M3F72)
2300 E. St., N.W.
Washington, DC 20372-5300
Fax: (202) 762-0931
LTJG Jamaal Whitmore ....(202) 762-3448
jawhitmore@us.med.navy.mil

Army Engineer Research and Development Center
Construction Engineering Research Laboratory
Attn.: CEERD-CF-F
P.O. Box 9005
Champaign, IL 61826-9005
Dr. William J. Croisant...........................(217) 373-3496
william.j.croisant@erdc.usace.army.mil

Army Electronic Proving Ground Test Engineering Directorate
Laboratory Division
Attn.: TEDT-EP-TEL
Fort Huachuca, AZ 85613-7110
Div. Chief Mr. Rafael Anton..................(520) 538- 4916
rafael.anton@us.army.mil
E3 Test Facility/Blacktail Canyon
Technical Lead: Mr. Johnny Douglas ... (520) 533-5819
johnny.douglas@us.army.mil
Mr. James Smith ....(520) 538-5188
james.a.smith4@us.army.mil
Ms. Rachel Blake................................... (520) 538-2818
rachel.m.blake@us.army.mil
Mr. David Seitz .... (520) 533-5819
david.seitz3@us.army.mil
Antenna Test Facility
Technical Lead: Mr. Doug Kremer........ (520) 533-8170
douglas.kremer@us.army.mil

Army Intelligence and Security Command G-4, Technical Support Division
Attn.: IALO-T
8825 Beulah St.
Ft. Belvoir, VA 22060-5246
Tel.: (703) 428-4479
Fax: (703) 428-4911
Ms. Anne Bilgihan
ambilgi@mi.army.mil

Army Nuclear and Chemical Agency (USANCA)
7150 Heller Loop, Ste. 101
Springfield, VA 22150-3198
Mr. R. Pfeffer... (703) 806-7862

Army Test and Evaluation Command (ATEC)
United States Army Aberdeen Test Center (ATC)
Electromagnetic Interference Test Facility (EMITF)
Attn.: CSTE-DTC-AT-SL-V-EMI
400 Colleran Road, Building 456
Aberdeen Proving Ground, MD 21005-5059
Fax: (410) 278-0579
EMITF Supervisor:
Mr. Michael C. Geiger .... (410) 278-2598
michael.c.geiger@us.army.mil
Electrical Engineer:
Mr. Clinton Sienkiewicz ....(410) 278-9340
cliftin.sienkiewicz@us.army.mil
Electronic Technicians:
Mr. Duane Buono....................................(410) 278-9340
duane.buono@us.army.mil
Mr. Keith Deitz...................................... (410) 278-9339
keith.deitz@us.army.mil
Mr. Christopher Dennison..................... (410) 278-9340
c.dennison@us.army.mil
Mr. JR Gildeleon.....................................(410) 278-9339
john.gildeleon@us.army.mil
Mr. Todd Holman .... (410) 278-9340
richard.t.holman@us.army.mil
Mr. Tom Martin...................................... (410) 278-9340
thomas.j.martin@us.army.mil
Mr. Brian Savage................................... (410) 278-4851
brian.c.savage@us.army.mil
Mr. Gary Stotts...................................... (410) 278-9340
gary.stotts@us.army.mil
Mr. Dennis Wanzer.................................(410) 278-4832
dennis.wanzer@us.army.mil

Army Test and Evaluation Command (ATEC)
Survivability Division
Attn.: TEAE-SZN
Bldg. 1660
1660 Jeb Stuart Road
Ft. Bliss, TX 79916-6812
Fax: (915) 568-4404
Mr. Joe Reza...(915) 568-6539
jose.reza@us.army.mil

White Sands Test Center
Attn.: TEDT-WSV-E (S Jesson)
Building 21225
White Sands Missile Range, NM 88002-5158
Ms. Stephanie Jesson ....(575) 678-6107
Stephanie.jesson@us.army.mil
Ms. Janet Danneman ....(575) 678-6307
Janet.danneman@us.army.mil
Mr. John Chavarria.................................(575) 678-1993
John.chavarria@us.army.mil

UNITED STATES MARINE CORPS

Marine Corps Operational Test and Evaluation Activity (MCOTEA)
3035 Barnett Ave.
Quantico, VA 22134
Chief of Test... (703) 432-0927

Marine Corps Systems Command (MCSC)
Attn.: Mr. Praful Bharucha (C4II/ACENG)
2000 Lester Street
Quantico, VA 22134-5010
E3 Control Program Sponsor
Mr. Praful Bharucha ....(703) 432-3806
praful.bharucha@usmc.mil

UNITED STATES NAVY

MID-LANT Area Frequency Coordination Office

Naval Air Warfare Center Aircraft Division
Code 5.2.2.2
23013 Cedar Point Road, Unit 4, Building 2118
Patuxent River, MD 20670-1183
Fax: (301) 342-1200
Mr. Mikel R. Ryan .... (301) 342-1532
mikel.ryan@navy.mil

Naval Air Systems Command (NAVAIR)

Electromagnetic Environmental Effects (E3) Division
AIR 4.1.13
48142 Shaw Road, Building 3197, Suite 1040
Patuxent River, MD 20670
E3 Div. Hd.: Mr. Mike Squires .... (301) 342-1660
michael.squires@navy.mil
Naval Air Systems Command (NAVAIR)
Air Systems EMI Corrective Action Program (ASEMICAP)
Ms. Angela Partin .... (301) 342-7813
angela.partin@navy.mil
Mr. Steve Rhoten .... (301) 995-2712
steven.rhoten@navy.mil
E3 Aircraft Engineering Branch AIR 4.1.13.1
Br. Head: Mr. Ted Rothman .... (301) 342- 9223
theodore.rothman@navy.mil
Ms. Carrol Basanez .... (301) 757-2451
carrol.basanez@navy.mil
Mr. Paul Belusko .... (301) 757-2446
paul.belusko@navy.mil
Mr. Jon Bergmann .... (301) 995-3832
jon.bergmann@navy.mil
Mr. John Besanceney .... (301) 757-2445
john.besanceney@navy.mil

Ms. Pamela Crispell .... (301) 342-8629
pamela.crispell@navy.mil
Mr. Ken Deans .... (301) 757-2447
kenneth.deans@navy.mil
Mr. William DePasquale .... (301) 757-6961
william.depasquale@navy.mil
Mr. Travis Flanagan .... (301) 342-7771
travis.flanagan@navy.mil
Mr. Frederick Heather .... (301) 342-6975
frederick.heather@navy.mil
Mr. Reggie Hope .... (301) 342-6975
lionel.hope@navy.mil
Mr. DJ Jardine .... (301) 757-2451
david.jardine@navy.mil
Mr. Joe Kmetz .... (301) 757-2361
joseph.kmetz@navy.mil
Mr. Gene Kuhn .... (301) 757-6545
gene.kuhn@navy.mil
Mr. Jay Lees .... (301) 342-0350
jay.lees@navy.mil
Mr. Jason Mackowiak .... (301) 342-8344
jason.mackowiak@navy.mil
Mr. Felipe Nazario .... (301) 342-1662
felipe.nazario@navy.mil
Ms. Jennifer Nguyen .... (301) 995-7671
jennifer.nguyen@navy.mil
Mr. Luke Onachila .... (301) 757-2420
luke.onachila@navy.mil
Mr. Steve Salisbury .... (301) 342-2255
steven.salisbury@navy.mil
Mr. John Schultz .... (301) 757-2456
john.schultz@navy.mil
Mr. Craig Simmons .... (301)342-4907
craig.simmons@navy.mil
Mr. Michael Skrabacz .... (301) 342-5805
michael.skrabacz@navy.mil
Mr. Robert Tate .... (301) 342-8632
robert.d.tate1@navy.mil
Mr. John Tonello .... (301) 342-2158
john.tonello@navy.mil
Mr. Thierry Wandji .... (301) 342-3297
ketchiozo.wandji@navy.mil

NAVAL AIR WARFARE CENTER AIRCRAFT DIVISION

Electromagnetic Interference Lab, 5.4.4.9
Patuxent River, MD
Fax: (301) 342-5390
EMI Lab
Branch Hd.: Mr. Lance Pearce .... (301) 342-0851
lance.pearce@navy.mil
Mr. Kenneth Brezinski .... (301) 342-0848
kenneth.brezinski@navy.mil
Mr. Tom Dennehey .... (301) 342-0832
thomas.dennehey@navy.mil
Mr. Richard Harvan .... (301) 342-0847
richard.harvan@navy.mil
Ms. Diane Kempf .... (301) 342-0850
diane.kempf@navy.mil
Ms. Pam Lumsden .... (301) 342-0852
pamela.lumsden@navy.mil
Mr. Patrick Mills .... (301) 995-4148
patrick.n.mills@navy.mil

NAVAIR Aircraft Division, Lakehurst

AIR 4.1.13.1
Hwy. 547, Bldg. 355-2
Lakehurst, NJ 08733-5112
Fax: (732) 323-1844
EMI Lab
Mr. Richard Del Conte .... (732) 323-2085
richard.delconte@navy.mil
Mr. David Fetzer .... (732) 323-2085
david.fetzer@navy.mil

NAVAIR Weapons E3 Engineering

China Lake Site
41M200D
1900 Knox Road, Stop 6622
China Lake, CA 93555-6001
Fax: (760) 939-1065
Br. Head: Mr. John Brandt .... (760) 939-1625
john.brandt@navy.mil
Mr. Chinh Dang .... (760) 939-9435
chinh.dang@navy.mil
Mr. Luke Dawson .... (760) 939-7565
luke.dawson@navy.mil
Mr. Fernando Garcia .... (760) 495-2622
fernando.m.garcia1@navy.mil
Ms. Patricia Siegel .... (760) 939-4637
patricia.siegel@navy.mil
Mr. Stephen Tanner .... (760) 939-4669
stephen.tanner@navy.mil
Mr. Gabriel Waliser .... (760) 939-8997
gabriel.waliser@navy.mil

NAVAIR Weapons Targets Division

Point Mugu Site
41M200E
575 I Ave., Ste. 1
Point Mugu, CA 93042-5049
Fax: (805) 989-3826
Ld. Engr.: Mr. Les Jue .... (805) 989-7884
leslie.jue@navy.mil

Naval Air Systems Command (NAVAIR)

Orlando 4.1.M
12350 Research Parkway
Bldg Deflorez Floor 3 Rm 3C6H
Orlando, FL 32826
Mr. John Mock .... (407) 380-4476
john.mock@navy.mil

NAVAIR, Aircraft Division

48202 Standley Rd.
Unit 5,Ste. 3B
Patuxent River, MD 20670-1910
Integrated Battlespace Simulation & Test Department
AIR 5.4.4 ICE
Fax: (301) 342-6982
Div. Head: Mr. Kurt Sebacher .... (301) 342-1664
Kurt.Sebacher@navy.mil
Dep. Div. Head: Mr. Brian Woode .... (301) 995-2331
brian.woode@navy.mil
Mr. Vern Panei .... (301) 342-6150
vern.panei@navy.mil
Electromagnetic Compatibility Branch (5.4.4.5 EMC)
Hd.: Mr. Mark Mallory .... (301) 342-1663
mark.mallory@navy.mil
Mr. Paul Achtellik .... (301) 342-7820
paul.achtellik@navy.mil
Mr. Omar Ali .... (301) 342-7814
omar.ali@navy.mil
Mr. Rich Andrusko .... (301) 342-7810
richard.andrusko@navy.mil
Mr. Mike Clelland .... (301) 342-8605
michael.clelland@navy.mil
Mr. Russ Danaher .... (301) 342-0020
russell.danaher@navy.mil
Mr. John Finley .... (301) 342-4855
john.finley@navy.mil
Mr. Xuyun Gan .... (301) 342-8725
xuyun.gan@navy.mil
Mr. Scott Graham .... (301) 342-7809
scott.graham@navy.mil
Mr. Matt Griffith .... (301) 757-9414
matt.griffith@navy.mil
Mr. Remash Guyah .... (301) 342-8681
remash.guyah@navy.mil
Mr. Scott Halt .... (301) 342-7575
scott.halt@navy.mil
Mr. Ryan Hanks .... (301) 342-7785
ryan.hanks@navy.mil
Mr. Danny Johnson .... (301) 342-7811
daniel.r.johnson@navy.mil
Mr. James Lewis .... (301) 342-5845
james.g.lewis@navy.mil
Ms. Alexis Martin .... (301) 342-0199
alexis.martin@navy.mil
Mr. Jeffrey Miller .... (301) 757-0019
jeffrey.c.miller@navy.mil
Mr. Tim Moynihan .... (301) 342-7846
timothy.moynihan@navy.mil
Mr. Mike Nahaj .... (301) 342-3554
michael.nahaj@navy.mil
Mr. Sam Niebauer .... (301) 757-0016
samuel.niebauer@navy.mil
Mr. Donn Rushing .... (301) 342-7848
donn.rushing@navy.mil
Mr. Chris Theofolis .... (301) 342-1667
chris.theofolis@navy.mil
Ms. Virginia Wines (Sec.) .... (301)757-2507
virginia.wines@navy.mil
Electromagnetic Environments (EME) Branch
AIR 5.4.4.6 EME
Fax: (301)757-3611 (Bldg. 2105)
(301) 342-3786 (Bldg. 2100)
Branch Hd.: Mr.Alan Mazuc .... (301) 757-3609
alan.mazuc@navy.mil
Mr. Dave Brown .... (301) 342-4597
dave.a.brown@navy.mil
Mr. John Crim .... (301) 757-3612
john.crim@navy.mil
Mr. Fabrizio Donis .... (301) 757-3604
fabrizio.donis@navy.mil
Mr. Jack Farren .... (301) 342-0507
jack.farren@navy.mil

Ms. Jack Faulkner ....(301) 995-2350
jack.faulkner@navy.mil
Mr. Miikka Holso .... (301) 757-3604
miikka.holso@navy.mil
Mr. Charles Joseph ....(301) 757-3608
charles.joseph@navy.mil
Mr. Bruce McClure .... (301) 342-0511
bruce.mcclure1@navy.mil
Mr. Mike Orloske .... (301) 757-3604
mark.orloske@navy.mil
Mr. Fulton Preston ....(301) 342-6979
fulton.l.preston@navy.mil
Mr. Mike Whitaker ....(301) 757-3604
mike.whitaker@navy.mil
Aircraft Information Security (TEMPEST) Branch
AIR 5.4.4.7 TEMPEST
Fax: (301)342-4593
Branch Hd.: Ms. Margaret Orr............. (301) 995-2433
margaret.orr@navy.mil
Mr. Scott Anderson ....(301) 342-6066
scott.t.anderson@navy.mil
Mr. Tom Dorrie...................................... (301) 342-6065
thomas.dorrie@navy.mil
Mr. Dan Lemanski ....(301) 342-6086
daniel.lemanski@navy.mil
Mr. Jimmy Lyon .... (301) 342-6129
james.lyon@navy.mil
Ms. Kim Wooden................................... (301) 342-2194
kimberly.wooden@navy.mil

Naval Air Warfare Center Training Systems Division (NAWCTSD)
Code 6.7.2.3
12350 Research Parkway
Orlando, FL 32826-3275
Mr. Allen D. Parker, NCE...................... (407) 380-4920
allen.parker@navy.mil

Space and Naval Warfare Systems Center, Charleston
(SPAWAR SYSCEN, Charleston)
P.O. Box 190022
North Charleston, SC 29419-9022
Fax: (843) 218-4238
Electromagnetic Environmental Effects (E3)
Branch, Code 5610
Branch Hd.: Mr. Wayne Lutzen............ (843) 218-5723
Wayne.lutzen@navy.mil
E3 Engineers
Reco Baker.. (843) 218-3988
Reco.baker@navy.mil
Mr. Frederic Duffy ....(843) 218-4363
Frederic.duffy@navy.mil
Mr. Michael Hanna ....(843) 218-4039
Michael.a.hanna@navy.mil
Mr. Guillermo Leiva .... (843) 218-7129
Guillermo.leiva@navy.mil
Mr. Thomas Sessions ....(843) 218-6331
Thomas.sessions@navy.mil

Space and Naval Warfare Systems Center Pacific, Pacific C4ISR Department
(SSC PAC, PAC C4ISR DEPT)
2293 Victor Wharf Access Road
Pearl City, HI 96782-3356
Fax: (808) 474-5511
Ms. Candice Saka................................. (808) 471-4028
Candice.saka@navy.mil
Mr. Jack Munechika.............................. (808) 471-1976
Jack.munechika@navy.mil
Mr. Randy Yamada .... (808) 474-6061
Randy.yamada@navy.mil
Mr. Lloyd Hayashida............................. (808) 474-1967
Lloyd.hayashida@navy.mil
Mr. Laine Murakami .... (808) 471-0366
laine.murakami@navy.mil

SPAWAR Systems Center - Pacific
(SSC-Pacific)
53560 Hull St.
San Diego, CA 92152-5001
Fax: (619) 553-3791
Applied Electromagnetics Branch, Code 5541
Branch Hd.: Dr. John Meloling .... (619) 553-2134
john.meloling@navy.mil
Mr. Jeffrey C. Allen ....(619) 553-6566
jeffrey.allen@navy.mil
Ms. Carol Becker .... (619) 553-1033
carol.becker@navy.mil
Mr. David C. Dawson ....(619) 553-4075
david.c.dawson@navy.mil
Mr. David Hurdsman .... (619) 553-4261
david.hurdsman@navy.mil
Mr. Lance Koyama.................................(619) 553-3784
lance.koyama@navy.mil
Mr. Ahn Lee .... (619) 553-3426
ahn.lee@navy.mil
Mr. P. Michael McGinnis...................... (619) 553-5092
mike.mcginnis@navy.mil
Ms. Nazia Mozaffar .... (619) 553-2593
nazia.mozaffar@navy.mil
Mr. Rick Nielsen .... (619) 553-6015
rick.nielsen@navy.mil
Ms. Jeanne Rockway ....(619) 553-3886
jeanne.rockway@navy.mil
Mr. Kianoush Rouzbehani ....(619) 553-3134
kian.rouzbehani@navy.mil
Raquel Sanchez-Karem.........................(619) 553-5876
raquel.sanchez-karem@navy.mil
Ricardo Santoyo-Mejia .... (619) 553-6139
ricardo.santoyomejia@navy.mil
Anirudha Siripuram .... (619) 553-8749
anirudha.siripuram@navy.mil
Ron Thompson.......................................(619) 553-0457
ron.thompson@navy.mil
Electromagnetics Technology Branch, Code 5542
Branch Head: Matt Osburn ....(619) 553-5941
matthew.osburn@navy.mil
Dr. Rich Adams .... (619) 553-4313
rich.adams@navy.mil
Mr. Jim Birkett...................................... (619) 553-3586
jim.birkett@navy.mil
Mr. Jose L. Chavez ....(619) 553-5075
jose.chavez@navy.mil
Dr. Will Cronyn .... (619) 553-5084
will.cronyn@navy.mil
Mr. Chris Dilay .... (619) 553-3794
chris.dilay@navy.mil
Mr. Vincent V. Dinh ....(619) 553-7255
vincent.v.dinh@navy.mil
Ms. Silvia Goodman, Secretary ....(619) 226-5953
silvia.goodman@navy.mil
Mr. David Hilton .... (619) 553-2666
david.r.hilton@navy.mil
Mr. Carl P. Kugel .... (619) 553-3066
carl.kugel@navy.mil
Ms. Wendy Massey .... (619) 553-9711
wendy.massey@navy.mil
Mr. Daniel Meeks.................................. (619) 553-6753
daniel.meeks@navy.mil
Dr. John D. Rockway ....(619) 553-5438
john.rockway@navy.mil
Mr. Alberto Rodriguez.......................... (619) 553-5697
alberto.rodriguez2@navy.mil
Advanced Electromagnetic Technology Branch, Code 5546
Branch Hd.: Jodi McGee ....(619) 553-3778
jodi.mcgee@navy.mil
Diana Arceo .... (619) 553-6344
diana.arceo@navy.mil
Lam T. Bui.. (619) 553-6038
lam.bui@navy.mil
Jennifer Edwards ....(619) 553-5428
jennifer.edwards@navy.mil
Daniel R. Gaytan................................... (619) 553-7461
daniel.gaytan@navy.mil
John L. Hunter .... (619) 553-5086
john.hunter@navy.mil
Lillie Jackson, Secretary ....(619) 553-5076
lillie.jackson@navy.mil
Dr. Burt Markham..................................(619) 553-6082
burt.markham@navy.mil
Mr. Marcus Maurer ....(619) 553-3797
marcus.maurer@navy.mil
Mr. Aldo Monges................................... (619) 553-6129
aldo.monges@navy.mil
Mr. Filemon Peralta...............................(619) 553-3043
filemon.peralta@navy.mil
Mr. Hoa Phan .... (619) 553-0148
hoa.phan@navy.mil
Mr. Randall Reeves .... (619) 553-1032
randall.reeves@navy.mil
Mr. Anthony Ton .... (619) 553-5428
anthony.ton@navy.mil
Mr. Daryl W. Von Mueller ....(619) 553-6527
daryl.vonmueller@navy.mil
Mr. Benton Wong .... (619) 553-3043
benton.wong@navy.mil

Chief of Naval Operations
Code NC-1, PT-5451, N6F13
2000-Navy Pentagon
Washington, DC 20350-2000
Fax: (703) 601-1323
Spectrum Electromagnetic Environmental Effects (E3) & EMP Policy & Programs
Head: Mr. Dave D. Harris.......................(703) 601-3968
dave.harris@navy.mil

Naval Ordnance Safety and Security Activity (NOSSA)
NAVORDSAFSECACT INDIAN HEAD
Electrical Explosives Safety
Code N84
Farragut Hall, Bldg. D323
23 Strauss Ave.
Indian Head, MD 20640-5035
Fax: (301) 744-6088
Weapons Assessment (N8)
Director: Charles Denham ....(301) 744-4447
charles.denham@navy.mil

Naval Research Laboratory
Code 5348
4555 Overlook Ave., S.W.
Washington, D.C. 20375-5320
Tel.: (202) 404-7726
Mr. Larry Cohen
Lawrence.Cohen@nrl.navy.mil

Naval SeaSystems Command (NAVSEA)
Force Electromagnetic Environmental Effects (E3) and Spectrum Management Warfare Systems Engineering Directorate (SEA 06)
1333 Isaac Hull Ave., S.E., Stop 5011
Washington Navy Yard, DC 20376-5011
Fax: (202) 781-4568
Force E3 and Spectrum Management Branch
Branch Head: Mr. J. Don Pierce .... (202) 781-4214
james.d.pierce@navy.mil

Naval Surface Warfare Center, Crane Division (NSWC Crane)
Code GXS
300 Highway 361, Bldg. 3287E
Crane, IN 47522
Fax: (812) 854-3589

Mr. Larry McKibben .... (812) 854-5107
Lawrence.McKibben@navy.mil

Naval Surface Warfare Center Dahlgren Division

5493 Marple Road, Suite 156
Dahlgren, VA 22448-5153
Electromagnetic Effects Division, Code Q50
Div. Hd: Mr. Marshall Baugher..............(540) 653-3416
marshall.baugher@navy.mil
Electromagnetic Effects Division
Chief Engineer: Mr. Jason Bardine ...... (540) 653-7450
Jason.bardine@navy.mil
NAVSEA E3 Technical Warrant Holder:
Mr. Kurt Mikoleit .... (540) 653-3425
Kurt.mikoleit@navy.mil
E3 Spectrum Supportability Branch, Code Q51
Branch Head: Mrs. Amy Sunshine Smith-Carroll...........
....(540) 653-1694
amy.smith-carroll@navy.mil
E3 Spectrum Supportability Branch, Code Q51
Operations and Spectrum Support Group Lead: Mr. Mark Flenner ....(540) 653-7892
Mark.l.fleener@navy.mil
E3 Spectrum Supportability Branch, Code Q51
Spectrum Engineering Group Lead: Ms. Margaret Neel... (540) 653-8021
Margaret.neel@navy.mil
E3 Spectrum Supportability Branch, Code Q51
Electromagnetic Pulse Group Lead: Mr. Blaise Corbett
....(540) 653-2104
Blaise.corbett@navy.mil
E3 Assessment & Evaluation Branch (Q52)
Branch Head: Mr. William T. Lenzi...... (540) 653-3444
william.lenzi@navy.mil
E3 Assessment & Evaluation Branch (Q52)
EMC/EMV Evaluation Group Lead: Mr. James McGinniss ....(540) 653-0489
james.mcginniss@navy.mil
E3 Assessment & Evaluation Branch (Q52)
RADHAZ Program Manager: Mr. Richard Magrogan ....
.... (540) 653-3445
richard.magrogan@navy.mil
E3 Assessment & Evaluation Branch (Q52)
Weapons System E3 Group Lead: Mr. Michael Miller
....(540) 653-3460
michael.d.miller4@navy.mil
E3 Assessment & Evaluation Branch (Q52)
HERO Systems Certification Group Lead: Mr. Andrew Rash.. (540) 653-1368
andrew.a.rash@navy.mil
E3 Assessment & Evaluation Branch (Q52)
EMI/461 Lab Group Lead:Mr. Carl Hager.......................
.... (540) 653-9501
carl.hager@navy.mil
E3 Assessment & Evaluation Branch (Q52)
Test Operations Group Lead: Mr. Matthew Curtis ....
....(540) 653-3439
matthew.a.curtis@navy.mil
E3 Assessment & Evaluation Branch (Q52)
Science & Technology Applications Group Lead: Mr. Michael Slocum..................................... (540) 653-2212
michael.slocum@navy.mil
E3 Assessment & Evaluation Branch (Q52)
RADHAZ Environment Characterization Group Lead: Ms. Tamera Hay ....(540) 653-1419
tamera.hay@navy.mil
E3 Assessment & Evaluation Branch (Q52)
Surface Maritime Sensors Group Lead: Mr. Michael Workman .... (540) 653-4646
michael.l.workman@navy.mil
E3 Platform Integration Branch (Q53)
Branch Head: Mr. Kenneth D. Larsen ....
....(540) 653-3476
kenneth.d.larsen@navy.mil
E3 Platform Integration Branch (Q53)
Senior Scientist: Dr. Greg Balchin...................................
.... (540) 653-6037
gregory.a.balchin@navy.mil
E3 Platform Integration Branch (Q53)
MAAC Group Lead: Mr. Greg Brobjorg ....
....(540) 653-7075
greg.brobjorg@navy.mil
E3 Platform Integration Branch (Q53)
Combatant Group Lead:Mr. Reza Biazaran ....
.... (540) 284-0595
reza.biazaran1@navy.mil
E3 Platform Integration Branch (Q53)
CVN Group Lead: Mr. Tim Baseler .... (540) 653-0741
timothy.baseler@navy.mil
E3 Platform Integration Branch (Q53)
Computational Electromagnetics Group Lead: Mr. Bryan Wagaman.................................. (540) 653-3430
bryan.wagaman@navy.mil
E3 Systems Interoperability Branch, Code Q54
Branch Head: Mr. Rich Link ....(540) 653-8907
rich.link@navy.mil
E3 Systems Interoperability Branch, Code Q54
Shipboard EMC Improvement Program Lead: Mr. Mark Hamer..(540) 284-0711
mark.hamer@navy.mil
E3 Systems Interoperability Branch, Code Q54
Force E3 Interoperability Group Lead: Mr. John "Bart" Barbee... (540) 653-3483
john.s.barbee@navy.mil
E3 Systems Interoperability Branch, Code Q54
Communication Systems E3 Interoperability Group Lead:Mr. Cris Lake ....(540) 653-5087
cristopher.lake@navy.mil
E3 Systems Interoperability Branch, Code Q54
Radar Systems E3 Interoperability Group Lead:Mr. Al Pitts... (540) 653-6268
albert.pitts@navy.mil
E3 Systems Interoperability Branch, Code Q54
Electronic Warfare Systems E3 Interoperability Group Lead:Mr. Brad Conner...........................(540) 653-0610
bradley.conner@navy.mil

Naval Undersea Warfare Center (NUWC)

1176 Howell St.
Newport, RI 02841-1708
Fax: (401) 832-7423
Submarine Electromagnetic Environmental Effects (E3) Branch, Code 3431
Branch Head: Mr. Craig F. Derewiany...(401) 832-5542
craig.derewiany@navy.mil
Mr. Scott Albert .... (401) 832-4122
scott.albert@navy.mil
Mr. Jon Bond .... (401) 832-6480
jon.bond@navy.mil
Mr. Michael J. Carpenter.......................(401) 832-5540
michael.j.carpenter@navy.mil
Mr. Douglas L. DeAngelis .... (401) 832-5872
douglas.deangelis@navy.mil
Mr. Jamie A. Donais.............................. (401) 832-3603
jamie.donais@navy.mil
Mr. Anthony Francis.............................. (401) 832-5493
anthony.francis1@navy.mil
Mr. Edward R. Javor.............................. (401) 832-5546
edward.javor@navy.mil
Mr. Alan T. McHale .... (401) 832-5635
alan.mchale@navy.mil
Mr. Michael P. Martin .... (401) 832-5630
michael.p.martin@navy.mil
Mr. Paul D. Opperman........................... (401) 832-4092
paul.opperman@navy.mil
Mr. Fredric A. Stawarz.......................... (401) 832-5550
fredric.stawarz@navy.mil
Mr. John L. Thibeault............................ (401) 832-5551
john.thibeault@navy.mil
Mr. Richard L. Thibeault........................ (401) 832-5552
richard.thibeault@navy.mil
Mr. Oleg Volchansky .... (401) 832-5399
oleg.volchansky@navy.mil
Mr. Oscar R. Zelaya............................... (401) 832-5597
oscar.zelaya@navy.mil
EMC Laboratory .... (401) 832-5554

OPNAV N2N6F1221

Spectrum Management and Electromagnetic Environmental Effects Office Net-Centric Capabilities/Strategic and Tactical Communications Branch Information Dominance Directorate
2511 Jefferson Davis Highway
Arlington, VA 22244-0001
Tel: (703) 601-1414; Fax: (703) 601-1323
Director: Mr. D. Mark Johnson ....(703) 601-1414
david.m.johnson4@navy.mil

OTHER UNITED STATES AGENCIES

Dept. of Health & Human Services

Food and Drug Administration
Center for Devices and Radiological Health
12725 Twinbrook Pkwy. (HFZ 133)
Rockville, MD 20852
Tel.: (301) 827-4944
Electrophysics Branch, Div. Physical Sciences
Mr. Howard I. Bassen, Chief
Mr. Paul S. Ruggera
Mr. Donald Witters

U.S. Environmental Protection Agency (EPA)

Office of Radiation and Indoor Air (ORIA)
Radiation Protection Division (6608J)
1200 Pennsylvania Ave., N.W.
Washington, DC 20460
Fax: (202) 343-3204
Director: Mr. Jonathan Edwards.......... (202) 343-9437
edwards.jonathan@epa.gov
Mr. Norbert Hankin .... (202) 343-9235
hankin.norbert@epa.gov

HQ, Federal Aviation Administration

ATC Spectrum Engineering Services, AJW-6
800 Independence Avenue, S.W.
Washington, DC 20591
Dir.: VACANT
Spectrum Assignment & Engineering Office, AJW-932
Manager: Mr. Jerrold B. Sandors......... (202) 267-9720
Jerrold.Sandors@faa.gov
Spectrum Planning & International Office, AJW-933
Manager: Mr. Robert A. Frazier .... (202) 267-9722
Robert.Frazier@faa.gov

Federal Aviation Administration

FAA Aviation Safety (AMN-110N)
1601 Lind Ave. S.W.
Renton, WA 98057
Fax: (425) 917-6590
Chief Scientific & Technical Advisor, EMI & Lightning:
Mr. David Walen.....................................(425) 917-6586
dave.walen@faa.gov

Federal Communications Commission

445 12th Street, SW
Washington, DC 20554
Office of Engineering & Technology
Tel.: (202) 418-2470
Chief: Julius P. Knapp
Deputy Chief.: Mr. Ira Keltz
Deputy Chief: Ronald Repasi
Deputy Chief: Alan Stillwell
Associate Chief: Bruce Romano
Policy & Rules Division
Tel.: (202) 418-2472

Chief: Geraldine Matise
Deputy Chief: Mark Settle
Spectrum Policy Branch
Chief: Mr. Jamison Prime
Technical Rules Branch
Chief: Ms. Karen Ansari
Spectrum Coordination Branch
Chief: VACANT
Electromagnetic Compatibility Division
Tel: (202) 418-2475
Chief: Walter Johnston
Technical Analysis Branch
Chief: Mr. Robert Weller
Experimental Licensing Branch
Chief: Mr.James Burtle

Federal Communications Commission Laboratory

7435 Oakland Mills Rd.
Columbia, MD 21046
FCC Laboratory Division
Dr. Rashmi Doshi, Chief .... (301) 362-3011
Mr. Jim Szeliga .... (301) 362-3051
Mrs. Pat Wright .... (301) 362-3001
Equipment Authorization Branch
Mr. Joe Dichosco, Chief .... (301) 362-3024
Ms. Evelyn Cherry .... (301) 362-3022
Mr. Steve Dayhoff .... (301) 362-3027
Mr. Tim Harrington .... (301) 362-3039
Mr. Andrew Leimer .... (301) 362-3049
Mr. Stanley Lyles .... (301) 362-3047
Ms. Diane Poole .... (301) 362-3034
Audits and Compliance Branch
Mr. Raymond Laforge, Chief .... (301) 362-3041
Mr. David Galosky .... (301) 362-3290
Ms. Katie Hawkins .... (301) 362-3030
Ms. Phyllis Parrish .... (301) 362-3045
Mr.Martin Perrine .... (301) 362-3025
Mr. Richard Tseng .... (301) 362-3054
Mr.Samuel Uganzenwoko .... (301) 362-3033
Technical Research Branch
Mr. William Hurst, Chief .... (301) 362-3031
Mr. Kwok Chan .... (301) 362-3055
Mr. James Drasher .... (301) 362-3047
Mr. Steve Jones .... (301) 362-3056
Mr. Steve Martin .... (301) 362-3052
Mr. Tom Phillips .... (301) 362-3044
Mr. George Tannahill .... (301) 362-3026
Customer Service Branch
Mrs. Sandy Haase, Chief .... (301) 362-3013
Ms. Bessie Bordenave .... (301) 362-3046
Ms. Linda Elliott .... (301) 362-3032
Mr. Tim Jamerson .... (301) 362-3014
Mr. Ken Reitzel .... (301) 362-3015
Ms. Bette Taube .... (301) 362-3028
Mrs. Joycelyn Walls .... (301) 362-3017

Goddard Space Flight Center

Greenbelt, MD 20771
Code 565 Electrical Systems Branch
Mr. Steven Graham, EMC Engr. .... (301) 286-3248
Steven.M.Graham.1@nasa.gov
Code 549.0, Electromagnetic Systems Engineering
Mr. Todd Bonalsky, PhD, lead engineer ....
.... (301) 286-1008
Todd.M.Bonalsky@nasa.gov

National Aeronautics and Space Administration

Kennedy Space Center
Kennedy Space Center, FL 32899
EMC Engineers
Team Lead: Ms. Dawn Trout (VA-F3),... (321) 867-5366
dawn.h.trout@nasa.gov
Mr. Ron Brewer (Analex) .... (321) 867-5329
ronald.w.brewer-1@nasa.gov
Mr. Kevin Clinton (VA-F3) .... (321) 867-5314
kevin.j.clinton@nasa.gov
Mr. Tung Doan .... (321) 867-5330
tung.m.doan@nasa.gov
Mr. Paul Edwards .... (321) 867-8927
paul.edwards@nasa.gov
Ms. Catherine C. Lewis........................... 216-433-3806
Catherine.c.lewis@nasa.gov
Mr. Noel Sargent (Analex).................... (216) 433-3395
noel.b.sargent@nasa.gov
Mr. James Stanley .... (321) 867-1991
james.e.stanley@nasa.gov
Mr. Jarek Tracz .... (321) 867-2780
jarek.a.tracz@nasa.gov
EMC Test Engineer Manager:Mr. Jack Cowras (VB-E1)
.... (321) 867-2914
john.cowras-1@nasa.gov

National Aeronautics and Space Administration
Langley Research Center

5 North Dryden St., Bldg. 1202
Hampton, VA 23665
Fax: (757) 864-9884
EMC Test Facility (MS 130)
Ms. Courtney Rollins .... (757) 864-7814
c.h.rollins@larc.nasa.gov
HIRF Laboratory (MS 130)
Mr. Jay J. Ely .... (757) 864-1868
j.j.ely@nasa.gov
Mr. Truong X. Nguyen .... (757) 864-7528
t.x.nguyen@larc.nasa.gov
EMI/EMC Analysis and Troubleshooting (MS 488)
Dr. Arthur T. Bradley .... (757) 864-7343
arthur.t.bradley@nasa.gov

National Aeronautics and Space Administration
John H. Glenn Research Center

21000 Brookpark Road
Cleveland, OH 44135
EMC Engineer
Mr. Tesfahunei T. Tecle .... (216) 433-6620
tesfahunei.t.tecle@grc.nasa.gov

National Aeronautics and Space Administration
Lyndon B. Johnson Space Center

2101 NASA Rd.
Houston, TX 77058-3696
Avionics Systems Test Branch (EV4)
Branch Chf.: Ms. Linda Bromley .... (281) 483-0129
Analysis Grp. Ldr.: Ms. C. Sham .... (281) 483-0124
EMC Grp. Ldr.: Mr. Robert Scully .... (281) 483-1499
robert.c.scully@nasa.gov
EMC Test Laboratory
Facility Mgr: Mr. Rod Robinson .... (281) 483-1465
Electronic Systems Test Laboratory
Facility Mgr: Mr. Ned Robinson .... (281) 483-0130

National Aeronautics and Space Administration
George C. Marshall Space Flight Center

Marshall Space Flight Center, AL 35812
Spectrum Manager: Terry Luttrell .... (256)544-0130
Terry.Luttrell@nasa.gov
EMC Engineers (M/S ES42/4708)
Division Chief: Mr. Tony Clark .... (256) 544-2394
Tony.Clark@nasa.gov
Branch Chief: Mr. Jeff Wesley .... (256) 544-3393
Jeff.Wesley@nasa.gov
Team Lead: Mr. Mark Krome .... (256) 544-5635
Mark.Krome@nasa.gov
Mr. Michael Crane (ERC) .... (256) 544-7259
Michael.G.Crane@nasa.gov
Mr. Tim Dew (ERC)................................ (256) 544-3718
Timothy.M.Dew@nasa.gov
Mr. Ross Evans (Dynetics) .... (256) 961-2305
Ross.W.Evans@nasa.gov
Ms. Tammy Flowers .... (256) 961-0508
Tammy.D.Flowers@nasa.gov
Mr. Truman Glasscock (Triumph).......... (256) 544-5318
Truman.G.Glasscock@nasa.gov
Mr. Kenneth Gonzalez (Qualis) .... (256) 544-1658
Kenneth.P.Gonzalez@nasa.gov
Mr. Steve R Jones .... (256) 544-4373
Steve.Jones@nasa.gov
Mr. Steve Linthicum (Dynetics) .... (256) 544-5312
Steven.E.Linthicum@nasa.gov
Mr. Jonathan Mack .... (256) 544-3599
Jonathan.D.Mack@nasa.gov
Mr. Matthew McCollum .... (256) 544-2351
Matt.Mccollum@nasa.gov
Mr. Matthew McGrath (Dynetics) .... (256) 544-3051
Matthew.M.McGrath@nasa.gov
Mr. Tom Perry (Jacobs) .... (256) 544-0744
Thomas.A.Perry@nasa.gov
Mr. Glenn Shelby .... (256) 544-0694
Glenn.Shelby@nasa.gov
EMI Test Facility .... (256) 544-8121

National Institute of Standards and Technology

Electromagnetics Division
Boulder, CO 80305
Div. Chief: Dr. Perry Wilson .... (303) 497-3406
pfw@boulder.nist.gov
Secretary: Ms. Willa Mayns .... (303) 497-3132
RF Fields Group 818.02
Group Leader: Mike Francis.................. (303) 497-5873
francis@boulder.nist.gov
Secretary: Mr. Gian Aparicio................ (303) 497-3321
aparicio@boulder.nist.gov
Antenna Metrology (818.02 project)
Mr. Jeffrey Guerrieri .... (303) 497-3863
guerrieri@boulder.nist.gov
Reference Fields & Probes
Mr. Dennis Camell .... (303) 497-3214
dennis.camell@boulder.nist.gov
Field Parameters and EMC Applications (818.02 project)
Galen Koepke... (303) 497-5766
koepke@boulder.nist.gov
Metrology for Wireless Systems, Project Leader
Kate Remley... (303) 497-3652
kate.remley@nist.gov
Quantum Electrical Metrology Division, 817
Gaithersburg, MD 20899
Div. Chief: Dr. Michael H. Kelley .... (303) 497-4736
michael.kelley@nist.gov

National Telecommunications and Information Administration (NTIA)

U.S. Department of Commerce
1401 Constitution Ave., N.W.
Washington, DC 20230
(202) 482-1850
Emergency Planning Subcommittee Chairman
Chief: Mr. Stephen R. Veader .... (202) 482-4417
sveader@ntia.doc.gov
Spectrum Planning Subcommittee Chairman
Chief: Mr. Stephen Butcher .... (202) 482-4163
sbutcher@ntia.doc.gov

Institute for Telecommunications Sciences (ITS)

325 Broadway
Boulder, CO 80305-3328
Exec. Officer: Mr. Brian Lane................. (303) 497-3484
blane@its.bldrdoc.gov
Director: Mr. Al Vincent .... (303) 497-3500
avincent@its.bldrdoc.gov
Spectrum & Propagation Measurements Division

Mr. Eric D. Nelson .... (303) 497-7410
enelson@its.bldrdoc.gov
Telecommunications & Information Technology Planning Division
Mr. Jeffrey R. Bratcher .... (303) 497-5132
jbratcher@its.bldrdoc.gov
Telecommunications Engineering, Analysis & Modeling Division
Ms. Patricia Raush .... (303) 497-3568
praush@its.bldrdoc.gov
Telecommunications Theory Division
Mr. Frank Sanders .... (303) 497-7600
fsanders@its.bldrdoc.gov

TEMPEST CONTACTS

Army Electronic Proving Ground Test Engineering Directorate
RF Test Division
Attn.: CSTE-DTC-EP-TR
Electromagnetic Environmental Effects/TEMPEST & Antenna Division
Attn.: TEDT-EP-SEA
2000 Arizona Street, Fort Huachuca, AZ 85613-7110
Div. Chief:Mr. Johnny Douglas .... (520) 533-5819
johnny.douglas@us.army.mil
E3 Test Facility/Blacktail Canyon
Technical Lead: Mr. Johnny Douglas .... (520) 533-5819
johnny.douglas@us.army.mil
Mr. James Smith .... (520) 538-5188
james.a.smith4@us.army.mil
Mr. David Seitz .... (520) 533-5819
david.seitz3@us.army.mil
Mr. Garrett Rude .... (520) 533-2818
Garrett.rude@us.army.mil
Mr. Fulton Woo .... (520) 533-5819
Fulton.woo@us.army.mil
Antenna Test Facility
Technical Lead: Mr. Doug Kremer .... (520) 533-8170
douglas.kremer@us.army.mil
Mr Anthony Sanchez .... (520) 533-9874
anthony.c.sanchez@us.army.mil

BELGIUM

Belgian Naval Headquarters
Project Office, Kwartier Koningin Elisabeth
1 Everestraat, 1140 Brussels, Belgium
Tel.: +32-2-7013334, Fax: +32-2-7014786

CANADA

Aerospace Engineering Test Establishment (DND)
PO Box 6550, Cold Lake, AB T9M 2C6, Canada
Tel.: (780) 840-8000
Mr. Serge Couture .... ext. 7511
serge.couture@forces.gc.ca

ITALY

Ministry of Defense
Centro Interforze Studi per le Applicazioni Militari (CISAM)
Via della Bigattiera 10, San Piero a Grado, 56010 San Piero a Grado (Pisa), Italy
Fax: +39 050-961001
Director:Amm. Isp. Giordano Cottini .... +39 050-964200
Scientific Coordinator:Silvio Zotti Martelli .... +39 050-964200
silvio.zotti@cisam.it

MARITELERADAR
Instituto per le Telecomunicazioni e l'Elettronica della Marina Militare
"Giancarlo Vallauri", Viale Italia, 72-57126 Livorno, Italy
E-mail: mariteleradar@marina.difesa.it
EMC Dept.
Ric. Ing. Giancarlo Misuri .... + 00-39-0586-238208
EMC Section/Laboratory
Cdr. Roberto Desideri .... +00-39-0586-238153
C.T.E.R. Salvatore Trovato .... +00-39-0586-238153

products & services index

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ETS-Lindgren
Panashield, Inc.

ANECHOIC CHAMBER TESTING
D.A.R.E!! Calibrations
DNB Engineering, Inc.
Electronics Test Centre (Kanata)
ETS-Lindgren
F-Squared Laboratories
MET Laboratories, Inc.
National Technical Systems
Radiometrics Midwest Corp.
Retlif Testing Laboratories
TUV SUD America Inc.

ANECHOIC CHAMBERS
Advanced Test Equipment Rentals
Albatross Projects GmbH
Braden Shielding Systems
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F-Squared Laboratories

ANECHOIC CHAMBERS – FIRE PROTECTION
ETS-Lindgren
Panashield, Inc.

ANECHOIC MATERIALS
ETS-Lindgren
Fair-Rite Products Corp.
Panashield, Inc.

ANTENNA FILTERS
Captor Corporation
Fotofab
ETS-Lindgren
Spectrum Advanced Specialty Products
ETS-Lindgren
WEMS Electronics

ANTENNAS
Advanced Test Equipment Rentals
A.H. Systems, Inc.
Applied Electromagnetic Technology (AET) LLC
AR RF/ Microwave Instrumentation
ARA Technologies
ASR Technologies, Inc.
Beehive Electronics
Captor Corporation
Com-Power Corp.
Dynamic Sciences International, Inc.
ETS-Lindgren
Fotofab
Instruments For Industry (IFI)
Liberty Labs, Inc.
Lubrizol Conductive Polymers
Macton
Noise Laboratory Co., Ltd.
Q-par Angus Ltd
Spectrum Advanced Specialty Products
Sunol Sciences Corporation
TDK Corp.
TDK RF Solutions, Inc.
Teseq
TMD Technologies Ltd.

ANTISTATIC COATINGS
Dontech Incorporated
Lamart Corporation
Swift Textile Metalizing LLC

ANTISTATIC MATERIALS
ACL, Inc.
Seal Science
Swift Textile Metalizing LLC

ARCHITECTURAL SHIELDING PRODUCTS
Alco Technologies, Inc.
Kemtron Limited
Metal Textiles Corp.
Swift Textile Metalizing LLC

AUDIO BAND POWER AMPLIFIERS
AE Techron, Inc.

AUTOMOTIVE TESTING
D.L.S. Electronic Systems, Inc.
Elite Electronic Engineering, Inc.
Eurofins Product Service GmbH
MET Laboratories, Inc.
National Technical Systems
Radiometrics Midwest Corp.
Teseq

BACKSHELLS, SHIELDED ASSEMBLIES, TERMINATIONS
Metal Textiles Corp.
Northern Technologies Corp.

BELLCORE TESTING (SEE TELCORDIA)
D.L.S. Electronic Systems, Inc.
MET Laboratories, Inc.
National Technical Systems
TUV SUD America Inc.

BICONICAL ANTENNAS
A.H. Systems, Inc.
ETS-Lindgren
Instruments For Industry (IFI)
Liberty Labs, Inc.
Noise Laboratory Co., Ltd.
Teseq
TMD Technologies Ltd

BIDIRECTIONAL COUPLERS
Instruments For Industry (IFI)

BOARD LEVEL SHIELDS
3Gmetalworx World
Device Technologies, Inc.
Kemtron Limited
Mech-Tronics
Photofabrication Engineering Inc.
Precision Photo-Fab, Inc.
Schlegel Electronic Materials
Swift Textile Metalizing LLC
Tech-Etch, Inc.
W. L. Gore & Associates, Inc.

BOOKS
D.L.S. Electronic Systems, Inc.
Henry Ott Consultants
ITEM Publications
Kimmel Gerke Associates, Ltd. - AZ
Lightning Technologies, Inc
Montrose Compliance Service, Inc.

BRAID
Alco Technologies, Inc.
Calmont Wire & Cable, Inc.
Device Technologies, Inc.
Kemtron Limited
Swift Textile Metalizing LLC
Zero Ground LLC

BROADBAND EMI DETECTORS
Advanced Test Equipment Rentals
Agilent Technologies, Inc.
ETS-Lindgren

CABINETRY & HARDWARE
FIBOX Enclosures
Fotofab

CABLES & CONNECTORS
Alco Technologies, Inc.
Amphenol Industrial Operations
CONEC Corporation - USA
Electri-Flex Company
Fotofab
GTN Kommunikations- und Sicherungssysteme GmbH & Co. KG
Hi-Tech Controls
Hi-Voltage & EMI Corp
ITT Interconnect Solutions
Ja-Bar Silicone Corp
Laird Technologies
Lamart Corp.
PennEngineering
Positronic Industries
PSC Electronics
Qualtek Electronics Corp.
RIA CONNECT
Schurter Inc.
Sealcon
Spectrum Advanced Specialty Products
Swift Textile Metalizing LLC
Synergistic Technology Group, Inc.
Teledyne Reynolds
Wilicoxon Research
Wurth Electronics Midcom Inc

CALIBRATION SERVICES
A.H. Systems, Inc.
Austest Laboratories
D.A.R.E!! Calibrations
ETS-Lindgren
Fischer Custom Communications
Instruments For Industry (IFI)
LTI Metrology
National Technical Systems
Pearson Electronics, Inc.

Teseq
TUV SUD America Inc.

CALIBRATION TESTING

D.A.R.E!! Calibrations
F-Squared Laboratories
Liberty Labs, Inc.

CERTIFICATION SERVICES

Braco Compliance Ltd
D.L.S. Electronic Systems, Inc.
DNB Engineering, Inc.
Electronics Test Centre (Kanata)
Elite Electronic Engineering, Inc.
F-Squared Laboratories
ITEM Publications
MET Laboratories
National Technical Systems
Panashield, Inc.
Radiometrics Midwest Corp.
TUV SUD America Inc.

COAXIAL FILTER CONNECTORS

Curtis Industries/ Filter Networks
EMC Eupen, A Div. of I2R Corp.
LCR Electronics, Inc.
Soshin Electronics Europe GmbH
Spectrum Advanced Specialty Products

COMPETENT/CERTIFIED ACCREDITING BODIES TESTING

D.L.S. Electronic Systems, Inc.
Elite Electronic Engineering, Inc.
F-Squared Laboratories
MET Laboratories
National Technical Systems

COMPUTER-AIDED ANALYSIS SERVICES

Apache Design Solutions
Electronics Test Centre (Kanata)
ETS-Lindgren
National Technical Systems
TUV SUD America Inc.
Visron Design, Inc.

CONDUCTIVE ADHESIVES, CAULKS, EPOXIES, & ELASTOMERS

Alco Technologies, Inc.
ARC Technologies, Inc.
Creative Materials, Inc.
Device Technologies, Inc.
Dontech Incorporated
Ja-Bar Silicone Corp.
Kemtron Limited
Lamart Corporation
Leader Tech, Inc.
Master Bond Inc.
Metal Textiles Corp.
Seal Science
Silicone Solutions
Sunkyoung S.T.
Tech-Etch, Inc.

CONDUCTIVE CLOTH

Alco Technologies, Inc.
ARC Technologies, Inc.
Device Technologies, Inc.
Dontech Incorporated
Intermark (USA) Inc.
Ja-Bar Silicone Corp.
Kemtron Limited
Leader Tech, Inc.
Metal Textiles Corp.
Schlegel Electronic Materials
Swift Textile Metalizing LLC

CONDUCTIVE COATINGS

Alco Technologies, Inc.
ALX Technical
Conductive Compounds Inc.
Dontech Incorporated
Ja-Bar Silicone Corp.
Lamart Corporation
Schlegel Electronic Materials
Swift Textile Metalizing LLC

CONDUCTIVE CONTAINERS

LCR Electronics, Inc.
MuShield Company, Inc.
Panashield, Inc.
Schlegel Electronic Materials
Swift Textile Metalizing LLC

CONDUCTIVE LAMINATES

Device Technologies, Inc.
Dontech Incorporated
Ja-Bar Silicone Corp.
Kemtron Limited
Metal Textiles Corp.
Schlegel Electronic Materials
Swift Textile Metalizing LLC

CONDUCTIVE MATERIALS

3M Electrical Markets Division
Adhesives Research, Inc.
Alchemetal
Alco Technologies, Inc.
Antistatic Industries of Delaware
ARC Technologies, Inc.
Caprock Mfg.
Desco Industries Inc.
Device Technologies, Inc.
Dontech Incorporated
Eeonyx Corp.
Intermark (USA) Inc.
Ja-Bar Silicone Corp
Kemtron Limited
Leader Tech, Inc.
LGS Technologies
Marktek
MTI - Microsorb Technologies
Mueller Corporation
Oak-Mitsui Technologies
Potters Industries, Inc.
Progressive Fillers International
Schlegel Electronic Materials
Seal Science
Sealing Devices Inc.
Sulzer Metco (Canada) Inc.
Swift Textile Metalizing LLC
Syscom Advanced Materials
Tech-Etch, Inc.
THEMIX Plastics, Inc.
Venture Tape Corp

CONDUCTIVE PAINT

Alco Technologies, Inc.
Dontech Incorporated
Schlegel Electronic Materials
Swift Textile Metalizing LLC

CONDUCTIVEPARTICLES

Ja-Bar Silicone Corp.

CONDUCTIVE PLASTICS

CAPLINQ Corporation
Dexmet Corp.
Dontech Incorporated
Lamart Corporation

CONDUCTIVE PLATING

Device Technologies, Inc.
Dontech Incorporated
Ja-Bar Silicone Corp.
Kemtron Limited
Swift Textile Metalizing LLC

CONDUCTIVE TAPES

Alco Technologies, Inc.
Bystat International Inc.
Device Technologies, Inc.
Dontech Incorporated
Intermark (USA) Inc.
ITW/Pressure Sensitive Adhesives & Components
Ja-Bar Silicone Corp.
Kemtron Limited
Lamart Corporation
Leader Tech, Inc.
Metal Textiles Corp.
Swift Textile Metalizing LLC

CONDUIT, ELECTRICAL, SHIELDED, MAGNETIC & RF

Device Technologies, Inc.
Electri-Flex Company
Ja-Bar Silicone Corp.
Kemtron Limited
Seal Science
Zero Ground LLC

CONSULTANTS

BorderWatch Compliance Services LLC
D.L.S. Electronic Systems, Inc.
DNB Engineering, Inc.
Don HEIRMAN Consultants
Elite Electronic Engineering, Inc.
EMC Compliance
EMC Management Concepts
EMCCons Dr. Rasek GmbH
EMITEMC
EM Software & Systems-SA Pty. Ltd
Equipment Reliability Institute
ERA Technology Ltd trading as Cobham Technical Services
ETS-Lindgren
F-Squared Laboratories
Gaddon Ltd.
Henry Ott Consultants
Hoolihan EMC Consulting
ITEM Publications
Kimmel Gerke Associates, Ltd. - AZ
LCR Electronics, Inc.
Lightning Technologies, Inc.
MET Laboratories, Inc.
Montrose Compliance Service, Inc.
Mooser Consulting GmbH
NewPath Research L.L.C.
Power & Controls engineering Ltd.
Power Standards Lab (PSL)
Radiometrics Midwest Corp.
Retlif Testing Laboratories
TUV SUD America Inc.

COUPLING-DECOUPLING NETWORKS

Haefely EMC

CRT ELECTRO-OPTICAL SHIELDS

Dontech Incorporated
MuShield Company, Inc.

CURRENT PROBES

A.H. Systems, Inc.
ETS-Lindgren
Fischer Custom Communications
Ion Physics Corporation
Pearson Electronics, Inc.

DESIGN SOFTWARE

AR RF/ Microwave Instrumentation
EM Software & Systems-SA Pty. Ltd.
ETS-Lindgren
FEKO
Moss Bay EDA
Sonnet Software, Inc.

DIE CUT SHIELDING MATERIAL

APEX Die & Gasket Inc.
Dontech Incorporated
Identification Products Corp
Insul-Fab, A Division of Concote Corp.
Ja-Bar Silicone Corp.
Kemtron Limited
M&C Specialties Co.
Metal Textiles Corp.
Orion Industries Inc.
Seal Science
Spira Manufacturing Corporation
Swift Textile Metalizing LLC
Tech-Etch, Inc.
W. L. Gore & Associates, Inc.

DIRECT LIGHTNING TESTING

DNB Engineering, Inc.
Lightning Technologies, Inc.
National Technical Systems
TUV SUD America Inc.

E-FIELD ANTENNAS

A.H. Systems, Inc.
Advanced Test Equipment Rentals
AR RF/ Microwave Instrumentation
ETS-Lindgren
Instruments For Industry (IFI)
Noise Laboratory Co., Ltd.

ELECTROSTATIC DISCHARGE (ESD) GENERATORS

Advanced Test Equipment Rentals
EMC Partner
EM Test USA
Haefely EMC
Lightning Technologies, Inc.
Noise Laboratory Co., Ltd.

ELECTROSTATIC DISCHARGE (ESD) SIMULATORS

Advanced Test Equipment Rentals
EMC Partner
EM Test USA
Fischer Custom Communications
Haefely EMC
HV Technologies, Inc.
Liberty Labs, Inc.
Lightning Technologies, Inc.
National Technical Systems
Noise Laboratory Co., Ltd.

ELECTROSTATIC DISCHARGE (ESD) TESTING

D.L.S. Electronic Systems, Inc.
DNB Engineering, Inc.
Elite Electronic Engineering, Inc.
F-Squared Laboratories
L-3 Communications Cincinnati
Lightning Technologies, Inc.
Radiometrics Midwest Corp.
Retlif Testing Laboratories
TUV SUD America Inc.

EMI GASKETS

ACS Industries, Inc.
Boyd Corporation
CGS Technologies
China EMI Shielding Materials Co., LTD
GETELEC
Intermark (USA) Inc.
Ja-Bar Silicone Corp.
Kemtron Limited
Metal Textiles Corp.
Plastic-Metals Technology Inc.
Seal Science
Spira Manufacturing Corporation
Stockwell Elastomerics, Inc.
United Seal and Rubber Co., Inc.
Swift Textile Metalizing LLC
Tech-Etch, Inc.
W. L. Gore & Associates, Inc.

EMI RECEIVERS

Agilent Technologies, Inc.
AR RF/ Microwave Instrumentation
ETS-Lindgren

EMI TEST ANTENNAS

A.H. Systems, Inc.
Advanced Test Equipment Rentals
AR RF/ Microwave Instrumentation
ETS-Lindgren
Fotofab
Instruments For Industry (IFI)
Macton
TMD Technologies Ltd

EMISSIONS TESTING

D.L.S. Electronic Systems, Inc.
DNB Engineering, Inc.
Don HEIRMAN Consultants
Elite Electronic Engineering, Inc.
F-Squared Laboratories
L-3 Communications Cincinnati
LCR Electronics, Inc.
maturo GmbH
Mitsubishi Digital Electronics America Inc
Montrose Compliance Service, Inc.
National Technical Systems
Partnership for Defense Innovation (PDI)
Radiometrics Midwest Corp.
Retlif Testing Laboratories
TUV SUD America Inc.
V-COMM, LLC

EMP GENERATORS

EM Test USA
EMC Partner
Fischer Custom Communications
HV Technologies, Inc.
Montena EMC

EMP SIMULATORS

Advanced Test Equipment Rentals
EM Test USA
EMC Partner
Fischer Custom Communications
HV Technologies, Inc.
National Technical Systems

EMP, SGEMP SYSTEM ASSESSMENT

DNB Engineering, Inc.
Kimmel Gerke Associates, Ltd. - AZ
MET Laboratories, Inc.
National Technical Systems

EMP/LIGHTNING EFFECTS TESTING

D.L.S. Electronic Systems, Inc.
DNB Engineering, Inc.
Elite Electronic Engineering, Inc.
L-3 Communications Cincinnati
Lightning Technologies, Inc.
MET Laboratories, Inc.
National Technical Systems
Radiometrics Midwest Corp.
Retlif Testing Laboratories
Teseq
TUV SUD America Inc.

ENVIRONMENTAL TESTING

D.L.S. Electronic Systems, Inc.
Elite Electronic Engineering, Inc.
L-3 Communications Cincinnati
Partnership for Defense Innovation (PDI)
TUV SUD America Inc.
WEMS Electronics

EUROPEAN CERTIFICATION TESTING

D.L.S. Electronic Systems, Inc.
DNB Engineering, Inc.
Elite Electronic Engineering, Inc.
EU Compliance Services, Inc.
F-Squared Laboratories
INTERTest Systems, Inc.
ITL Israel
L-3 Communications Cincinnati
LCR Electronics, Inc.
Montrose Compliance Service, Inc.
National Technical Systems
Radiometrics Midwest Corp.
Retlif Testing Laboratories
TUV SUD America Inc.

FACILITIES & SHIELDED ENCLOSURE SERVICES

Compac Development Corp
DNB Engineering, Inc.
ETS-Lindgren
Rittal Corporation

FCC PART 15 & 18 TESTING

D.L.S. Electronic Systems, Inc.
DNB Engineering, Inc.
Don HEIRMAN Consultants
Elite Electronic Engineering, Inc.
F-Squared Laboratories
LCR Electronics, Inc.
Montrose Compliance Service, Inc.
National Technical Systems
Radiometrics Midwest Corp.
Retlif Testing Laboratories
TUV SUD America Inc.

FCC PART 68 TEST EQUIPMENT

DNB Engineering, Inc.
EM Test USA
EMC Partner
HV Technologies, Inc.
Retlif Testing Laboratories

FCC PART 68 TESTING

D.L.S. Electronic Systems, Inc.
DNB Engineering, Inc.
Elite Electronic Engineering, Inc.
Haefely EMC
LCR Electronics, Inc.
National Technical Systems

FEED-THROUGH FILTERS

Captor Corporation
Curtis Industries/ Filter Networks
EMI Filter Company
Genisco Filter Corp
LCR Electronics, Inc.
Radius Power, Inc.
RF Immunity Ltd.
Schaffner EMC, Inc.
Spectrum Advanced Specialty Products
Syfer Technology Limited
Tri-Mag, Inc.
WEMS Electronics

FERRITE BEADS & CORES

Cosmo Ferrites Limited
Fair-Rite Products Corp.
Ferronics Inc.
Intermark (USA) Inc.
Kemtron Limited
Leader Tech, Inc.
LCR Electronics, Inc.
National Magnetics Group, Inc.
THORA Elektronik GmbH
Würth Elektronik eiSos GmbH & Co. KG

FERRITE SUPPRESSION COMPONENTS

ARC Technologies, Inc.
Fair-Rite Products Corp.
Intermark (USA) Inc.
Kemtron Limited
LCR Electronics, Inc.
Leader Tech, Inc.
Spectrum Advanced Specialty Products

FERRITES

Adams Magnetic Products Co.
ARC Technologies, Inc.
Dexter Magnetic Technologies
EMC Component Group, Inc.
Fair-Rite Products Corp.
Intermark (USA) Inc.
Kemtron Limited
Leader Tech, Inc.
Spectrum Advanced Specialty Products
Taiyo Yuden (U.S.A.) Inc.

FIBER OPTIC CABLES

ETS-Lindgren
Lamart Corp.

FIBER OPTIC SYSTEMS

Accurate Controls Ltd.
D.A.R.E!! Instruments
Fischer Custom Communications

FIELD INTENSITY METERS

EMC Test Design
ETS-Lindgren
Instruments For Industry (IFI)
SRICO, Inc.

FILTER ARRAYS

Curtis Industries/ Filter Networks
Fotofab
LCR Electronics, Inc.
RF Immunity Ltd.
Spectrum Advanced Specialty Products
Syfer Technology Limited
WEMS Electronics

FILTER CAPACITORS

Beijing Tempest Electronics Technologies Co. Ltd.
Captor Corporation
Curtis Industries/ Filter Networks
EMI Filter Company
Fotofab
Genisco Filter Corp
LCR Electronics, Inc.
Radius Power, Inc.
Schaffner EMC, Inc.
Spectrum Advanced Specialty Products

Syfer Technology Limited
WEMS Electronics
X2Y Attenuators LLC

FILTER CHOKES

Captor Corporation
Curtis Industries/ Filter Networks
Datatronics
Fair-Rite Products Corp.
Genisco Filter Corp
LCR Electronics, Inc.
Radius Power, Inc.
Schaffner EMC, Inc
Schurter Inc.
WEMS Electronics

FILTER COILS

Captor Corporation
Communication Coil, Inc.
Curtis Industries/ Filter Networks
Genisco Filter Corp
LCR Electronics, Inc.
Radius Power, Inc.
Schaffner EMC, Inc
Schurter Inc.
WEMS Electronics

FILTER CONNECTORS

AEF Solutions
Filter Networks
Glenair Inc.
Heilind Electronics
RF Immunity Ltd.
Schurter Inc.
Spectrum Advanced Specialty Products
WEMS Electronics

FILTER MODULES

Curtis Industries/ Filter Networks
LCR Electronics, Inc.
RF Immunity Ltd.
Schaffner EMC, Inc
Schurter Inc.
Spectrum Advanced Specialty Products
WEMS Electronics

FILTER PIN CONNECTORS

Filter Networks
LCR Electronics, Inc.
RF Immunity Ltd.
Spectrum Advanced Specialty Products

FILTER PINS

Filter Networks
EMI Filter Company
Spectrum Advanced Specialty Products
Syfer Technology Limited

FILTER SEAL INSERTS

Lamart Corp.

FILTERED POWER ENTRY MODULES

Americor Electronics Ltd.
Curtis Industries/ Filter Networks
Genisco Filter Corp
LCR Electronics, Inc.
Radius Power, Inc.
Schaffner EMC, Inc
Schurter Inc.
Spectrum Advanced Specialty Products
Tri-Mag, Inc.

FILTERS

Advanced Monolythic Ceramics, Inc.
Aerodev Electronmagnetic Tech
Alco Technologies, Inc.
Amphenol Canada Corp.
API Delevan
Arcotronics, Inc.
Aries Electronics
Capcon International, Inc.
Captor Corporation
Cre8 Associates Ltd.
Curtis Industries/ Filter Networks
EEMCCOIMEX
EESeal
Electrocube, Inc.
EMI Filter Company
EMI Solutions
EPCOS, Inc.
Fil-Coil
Filtronica, Inc.
Fotofab
Fuss-EMV
Genisco Filter Corp
Gowanda Electronics
High & Low Corp.
Instruments For Industry (IFI)
Integrated Microwave Corp.
Intermark (USA) Inc.
JiangSu WEMC Technology., Ltd.
Johanson Dielectrics, Inc.
Kemtron Limited
LCR Electronics, Inc.
MPE
Murata Electronics North
Oxley Developments Company Ltd
Pacific Aerospace & Electronics, Inc.
Panasonic Electronic Components
Quell Corporation
Radius Power, Inc.
RF Immunity Ltd.
RFI Corporation
Roxburgh EMC
Sabritec
Schaffner EMC, Inc.
Schurter Inc.
Souriau PA&E
Spectrum Advanced Specialty Products
Supression Devices
Syfer Technology Limited
Texas Spectrum Electronics
Tyco Electronics
View Thru Technologies, Inc.
Vishay Intertechnology, Inc.
VPT, Inc.
V Technical Textiles, Inc.
WEMS Electronics

FINGERSTOCK

Ja-Bar Silicone Corp.
Kemtron Limited
Metal Textiles Corp.
Tech-Etch, Inc.

GROUND RESISTANCE TESTERS

AEMC Instruments

GROUNDING RODS

Intermark (USA) Inc.
Zero Ground LLC

GROUNDING SERVICES

Intermark (USA) Inc.
Zero Ground LLC

GROUNDING SYSTEMS

Intermark (USA) Inc.
Lightning Eliminators & Consultants, Inc.
Zero Ground LLC

GTEM CELLS

ETS-Lindgren
Fischer Custom Communications
Instruments For Industry (IFI)
Noise Laboratory Co., Ltd.

H-FIELD ANTENNAS

A.H. Systems, Inc.
AR RF/ Microwave Instrumentation
ETS-Lindgren
Instruments For Industry (IFI)
Noise Laboratory Co., Ltd.

HARNESSES

Zero Ground LLC

HELMHOLTZ COILS

ETS-Lindgren
Fischer Custom Communications

HIGH VOLTAGE PULSE TRANSFORMERS

Pearson Electronics, Inc.

HONEYCOMB SHIELDING

ETS-Lindgren
Intermark (USA) Inc.
Ja-Bar Silicone Corp.
Kemtron Limited
Metal Textiles Corp.
Spira Manufacturing Corporation
Tech-Etch, Inc.

HORN ANTENNAS

A.H. Systems, Inc.
Advanced Test Equipment Rentals
AR RF/ Microwave Instrumentation
ETS-Lindgren
Instruments For Industry (IFI)
Liberty Labs, Inc.
Teseq
TMD Technologies Ltd

IMMUNITY TESTING

A.H. Systems, Inc.
D.L.S. Electronic Systems, Inc.
DNB Engineering, Inc.
Elite Electronic Engineering, Inc.
F-Squared Laboratories
L-3 Communications Cincinnati
LCR Electronics, Inc.
LEDE-SIECIT
National Technical Systems
Radiometrics Midwest Corp.
Retlif Testing Laboratories
Teseq
TUV SUD America Inc.

IMPULSE GENERATORS

AR RF/ Microwave Instrumentation
EM Test USA
EMC Partner
Haefely EMC
HV Technologies, Inc.
Ion Physics Corporation
National Technical Systems

INDUCED CURRENT METERS & PROBES

AR RF/ Microwave Instrumentation
EMC Partner
ETS-Lindgren

INDUCTORS

BI Technologies
Captor Corporation
Curtis Industries/ Filter Networks
Frontier Electronics, Corp.
Kemtron Limited
Micrometals, Inc.
Schaffner EMC, Inc.
Schurter Inc.

INSERTION LOSS TEST NETWORKS

WEMS Electronics

INTERFERENCE GENERATORS

EMC Partner
HV Technologies, Inc.

IRON CORE POWDERED MAGNETIC MATERIALS

Fair-Rite Products Corp.

ISO 9000 TESTING

National Technical Systems
Swift Textile Metalizing LLC
TUV SUD America Inc.

ISOTROPIC FIELD SENSORS

D.A.R.E!! Instruments
ETS-Lindgren
Instruments For Industry (IFI)

LIGHTNING GENERATORS

EM Test USA
EMC Partner
Fischer Custom Communications
Haefely EMC
HV Technologies, Inc.

Lightning Technologies, Inc.
Noise Laboratory Co., Ltd.

LIGHTNING SIMULATORS

EM Test USA
EMC Partner
Fischer Custom Communications
Haefely EMC
HV Technologies, Inc.
Lightning Technologies, Inc.
Noise Laboratory Co., Ltd.

LIGHTNING STRIKE TESTING

D.L.S. Electronic Systems, Inc.
DNB Engineering, Inc.
Elite Electronic Engineering, Inc.
National Technical Systems
Radiometrics Midwest Corp.
Retlif Testing Laboratories
TUV SUD America Inc.

LOG PERIODIC ANTENNAS

A.H. Systems, Inc.
Advanced Test Equipment Rentals
AR RF/ Microwave Instrumentation
ETS-Lindgren
Instruments For Industry (IFI)
Liberty Labs, Inc.
Noise Laboratory Co., Ltd.
TMD Technologies Ltd

MAGNETIC FIELD METERS

Combinova AB
Fischer Custom Communications

MAGNETIC FIELD PROBES

AR RF/ Microwave Instrumentation
ETS-Lindgren
Fischer Custom Communications
Langer EMV –Technik GmbH

MAGNETIC SHIELDING GASKETS

Kemtron Limited
Spira Manufacturing Corporation

MICROWAVE ABSORBERS

ARC Technologies, Inc.
ETS-Lindgren
Intermark (USA) Inc.
Kemtron Limited
Seal Science

MICROWAVE FILTERS

Cobham Microwave
EMI Filter Company
Fotofab
Instruments For Industry (IFI)
Spectrum Advanced Specialty Products
Syfer Technology Limited

MICROWAVE POWER AMPLIFIER

Advanced Test Equipment Rentals
AR RF/ Microwave Instrumentation
Giga-tronics/Ascor Incorporated
Instruments For Industry (IFI)
TMD Technologies Ltd

MIL-STD 188/125 TESTING

DNB Engineering, Inc.
Elite Electronic Engineering, Inc.
MET Laboratories, Inc.
National Technical Systems

MIL-STD 461 / 462 TESTING

D.L.S. Electronic Systems, Inc.
DNB Engineering, Inc.
Elite Electronic Engineering, Inc.
Harris GCSD EMI EMC TEMPEST Test Lab
L-3 Communications Cincinnati
National Technical Systems
Partnership for Defense Innovation (PDI)
Radiometrics Midwest Corp.
Retlif Testing Laboratories
TUV SUD America Inc.

MOBILE SHIELDED ROOMS

Select Fabricators, Inc.
Swift Textile Metalizing LLC

MONOPOLE ANTENNAS

ETS-Lindgren
Instruments For Industry (IFI)
Liberty Labs, Inc.
Noise Laboratory Co., Ltd.

MRI SHIELDING

Dontech Incorporated
ETS-Lindgren
Leader Tech, Inc.
MuShield Company, Inc.
Select Fabricators Inc.

NAVLAP / A2LA APPROVED TESTING

Bay Area Compliance Labs Corp.
D.L.S. Electronic Systems, Inc.
DNB Engineering, Inc.
Elite Electronic Engineering, Inc.
F-Squared Laboratories
L-3 Communications Cincinnati
Liberty Labs, Inc.
Lightning Technologies, Inc.
National Technical Systems
Radiometrics Midwest Corp.
Retlif Testing Laboratories
TUV SUD America Inc.

NETWORK ANALYZERS

Agilent Technologies, Inc.

PARALLEL PLATE LINE TEST SET

ETS-Lindgren
Fischer Custom Communications

PORTABLE TEST EQUIPMENT

A.H. Systems, Inc.
ETS-Lindgren
Haefely EMC
HV Technologies, Inc.
Instruments For Industry (IFI)
Prostat Corporation

POWER LINE DISTURBANCE MONITOR

Voltech Instruments Ltd.

POWER LINE FILTERS

Curtis Industries/ Filter Networks
Delta Electronics
Delta Products Corp.
DNB Engineering, Inc.
Emission Control, Ltd.
Filter Concepts Inc.
JINAN Filtemc Electronic Equipment Co., Ltd.
Radius Power, Inc.
RF Immunity Ltd.
Schaffner EMC, Inc.
Schurter Inc.
Syfer Technology Limited
Tri-Mag, Inc.
WEMS Electronics

PRINTED CIRCUIT BOARD (PCB) FILTERS

Captor Corporation
Curtis Industries/ Filter Networks
LCR Electronics, Inc.
Radius Power, Inc.
Schurter Inc.
Spectrum Advanced Specialty Products
Syfer Technology Limited
Tri-Mag, Inc.
WEMS Electronics

PRODUCT SAFETY TESTING

D.L.S. Electronic Systems, Inc.
DNB Engineering, Inc.
Elite Electronic Engineering, Inc.
F-Squared Laboratories
LCR Electronics, Inc.
National Technical Systems
Retlif Testing Laboratories
TUV SUD America Inc.

RADHAZ TESTING

DNB Engineering, Inc.
Retlif Testing Laboratories

RADIATION HAZARD METERS

ETS-Lindgren

RADIATION HAZARD PROBES

ETS-Lindgren
Instruments For Industry (IFI)

RETROFIT FILTERS & CONNECTORS

Curtis Industries/ Filter Networks
RF Immunity Ltd.
Schaffner EMC, Inc.
Schurter Inc.
WEMS Electronics

RF POWER AMPLIFIERS

Advanced Test Equipment Rentals
AR RF/ Microwave Instrumentation
D.A.R.E!! Instruments
Instruments For Industry (IFI)
Noise Laboratory Co., Ltd.
Teseq
TMD Technologies Ltd

RF POWER COMPONENTS

EM Test USA
MKS Instruments

RF POWER METERS

AR RF/ Microwave Instrumentation
ETS-Lindgren

RF SHIELDING GASKETS

ARC Technologies, Inc.
Ja-Bar Silicone Corp.
Kemtron Limited
Metal Textiles Corp.
Schlegel Electronic Materials
Seal Science
Spira Manufacturing Corporation
Swift Textile Metalizing LLC
Tech-Etch, Inc.
W. L. Gore & Associates, Inc.

RF SHIELDING MATERIAL

Cybershield
Dexmet Corp.
Intermark (USA) Inc.
Ja-Bar Silicone Corp.
Kemtron Limited
Metal Textiles Corp.
Seal Science
Spira Manufacturing Corporation
Swift Textile Metalizing LLC
Tech-Etch, Inc.
TWP Inc
W. L. Gore & Associates, Inc.
Zero Ground LLC

RS03 > 200 V / METER TESTING

D.L.S. Electronic Systems, Inc.
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Elite Electronic Engineering, Inc.
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Radiometrics Midwest Corp.
Retlif Testing Laboratories
TUV SUD America Inc.

RTCA DO-160 TESTING

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L-3 Communications Cincinnati
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Lightning Technologies, Inc.
National Technical Systems
Partnership for Defense Innovation (PDI)
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TUV SUD America Inc.

SCIF DESIGN CONSTRUCTION & MAINTENANCE

ETS-Lindgren

SHIELDED AIR FILTERS

ETS-Lindgren
Ja-Bar Silicone Corp.
Kemtron Limited
Metal Textiles Corp.
Spira Manufacturing Corporation
Swift Textile Metalizing LLC
Tech-Etch, Inc.

SHIELDED BUILDINGS

ETS-Lindgren

SHIELDED BUS BARS

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Swift Textile Metalizing LLC

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Fotofab
Lamart Corp.
Lapp USA
LCR Electronics, Inc.
MegaPhase LLC
Swift Textile Metalizing LLC
The Phoenix Company of Chicago
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Zero Ground LLC

SHIELDED COMPONENTS

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Schurter Inc.
Spira Manufacturing Corporation
Tech-Etch, Inc.
Zero Ground LLC

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Electri-Flex Company
Lamart Corp.
Zero Ground LLC

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Zero Ground LLC

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ETS-Lindgren
Swift Textile Metalizing LLC

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AR Tech
ClickFold Plastics
Electrorack Enclosure Products
IMS/AMCO Engineered Products
MuShield Company, Inc.
Modpak, Inc.
Select Fabricators, Inc.

SHIELDED FANS

ETS-Lindgren
Spira Manufacturing Corporation
Swift Textile Metalizing LLC

SHIELDED FUSE HOLDERS

Schurter Inc.

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Curtis Industries/ Filter Networks
Dontech Incorporated
ETS-Lindgren
Fotofab
Genisco Filter Corp
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WEMS Electronics

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EMP-tronic
ETS-Lindgren
I. Thomas GmbH
Select Fabricators Inc.

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Leader Tech, Inc.
Lightning Technologies, Inc.
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Seal Science
Shielding Resources Group, Inc.
Swift Textile Metalizing LLC
Zero Ground LLC

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Braden Shielding Systems
Bud Industries
Captor Corporation
Comtest Eng.
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Fotofab
Frankonia
F-Squared Laboratories
Global EMC Ltd
Instruments For Industry (IFI)
Kform, Inc.
Leader Tech, Inc.
Lightning Technologies, Inc.
Noise Laboratory Co., Ltd.
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Rainford EMC Systems Ltd.
Seal Science
Select Fabricators Inc.
Spira Manufacturing Corporation
Stahlin Non-Metallic Enclosures
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ETS-Lindgren

SHIELDED SCANS, MONITORS & CRTS

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Radiometrics Midwest Corp.
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Stork Garwood Laboratories Inc.
World Cal, Inc.
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company directory

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A

A&R Tarpaulins, Inc. ....
16246 Valley Blvd., Fontana, CA 92335 USA; 909-829-4444; jessica@artech2000.com; www.artarps.com

A.H. Systems, Inc. 7, 41
9710 Cozycroft Ave., Chatsworth, CA 91311 USA; 818-998-0223; Fax: 818-998-6892; sales@ahsystems.com; www.AHSystems.com; Arthur C. Cohen, Pres.; Travis Samuels, Ops. Dir.

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TX	Richardson, Southwest Electronics Ind.	972-523-0017

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	Beijing, Compliance Direction Systems, Inc.	86-10-6846-0592
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CRI	Alianza S.E.T.	305-767-4000
DEU	Ludwigsburg, Pro Nova Elektronik GmbH	49-7141-2858-20
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	Druento, Teseo S.p.A.	011-39-99-41-911
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Gewerbegebiet Aaronia AG, Strickscheid, DE-54597 Euscheid, Germany; +49 (0) 6556 93033; Fax: +49 (0) 6556 93034; www.aaronia.de

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25 Cowley Road, Nuffield Industrial Estate, Poole, Dorset, United Kingdom; +44 (0) 1202 678108; mspreadbury@accurate-controls.ltd.uk; www.accurate-controls.ltd.uk

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5015 B.U. Bowman Drive, Buford, GA 30518 USA; 770-831-8048; 770-831-8598; sproffitt@acstestlab.com; www.acstestlab.com

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Advanced Testing Services ....
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14-29 112 St., College Point, NY 11356 USA; 718-939-4422; 800-680-6608; Fax: 718-539-3719; SLevine_sales@aeronavlabs.com; www.aeronavlabs.com

Aerodev Electronmagnetic Tech..........................
19525 Talavera Lane, Edmond, OK 73012 USA; 405-760-6064; Fax: 405-285-6572; usa@aerodev.com; www.aerodev.com

Aeroflex ....
35 South Service Road, P.O. Box 6022, Plainview, NY 11803 USA; 516-694-6700; 800-843-1553; Fax: 516-694-2562; info-test@aeroflex.com; www.aeroflex.com

Agilent Technologies, Inc. 31
5301 Stevens Creek Blvd., Santa Clara, CA 95051 USA 800-829-4444; Jim McCord, jim_mccord@agilent.com; www.agilent.com

AHD EMC Lab / Amber Helm Development L.C. ....
92723 Michigan Hwy 152, Sister Lakes, MI 49047 USA; 269-429-8352; 888-847-8027; Fax: 269-429-9016; ghelm@ahde.com; www.ahde.com

Albatross Projects GmbH ....
Daimlerstraße 17, 89564 Nattheim, Germany; +49 7321 730510; Fax: +49 7321 730590; info@albatross-projects.com; www.albatross-projects.com

Alchemetal ....
3327 80 St., Suite 2, New York, NY 11372 USA; 917-297-3560; egreenwood@alchemetal.com; www.alchemetal.com

ALCO TECHNOLOGIES

Alco Technologies, Inc. ....
1815 W. 213th St. #175, Torrance, CA 90501 USA; 310-328-4770; Fax: 310-328-1262; Susan Lea Lopez, susie@alcotech.com; www.alcotech.com

Alion Science & Technology R&B Laboratory ....
20 Clipper Road, West Conshohocken, PA 19428 USA; 610-825-1960; Fax: 610-825-1684; splastino@alionscience.com; http://rb.alionscience.com

All-Spec Industries ....
5228 US Hwy 421 N, Wilmington, NC 28401 USA; 800-537-0351; 910-763-5664; sales@allspec.com; www.all-spec.com

Allied Moulded Products, Inc. ....
222 North Union St., Bryan, OH 43506 USA; 419-636-4217; sales@alliedmoulded.com; www.alliedmoulded.com

Alltec Corp. ....
64 Catalyst Drive, Canton, NC 28716 USA; 828-646-9290; Fax: 828-646-9527; ift@allteccorp.com; www.allteccorp.com

Alltest Instrument, Inc. ....
1310 S. Roller Road, Ocean, NJ 07712 USA; 732-695-0800; 800-251-0706; Fax: 732-695-0801; harvey@alltest.us; www.alltest.us

ALX Technical ....
630 Rivermede Road, Unit 9, Concord, Ontario, L4K 2H7 Canada; 905-761-0370; www.alxtechnical.com

Amber Technologies ....
4 Oxford Las, Smithtown, NY 11787 USA; 631-724-4619; Fax: 631-361-4836; rsjaniec@aol.com

American Environments Co., Inc. ....
17 Commercial Blvd., Medford, NY 11763 USA; 631-736-5883; Fax: 631-736-5272; wmiller49@optonline.net; www.aeco.com

Americor Electronics, Ltd. ....
675 S. Lively Blvd., Elk Grove Village, IL 60007 USA; 800-830-5337; Fax: 847-956-0300; info@americor-usa.com; www.americor-usa.com

Amphenol Canada Corp. ....
20 Melford Drive, Scarborough, Ontario M1B 2X6, Canada; 416-291-4401; Fax: 416-292-0647; sales@amphenolcanada.com; www.amphenolcanada.com

Amphenol Industrial Operations ....
40-60 Delaware Ave., Sidney, NY 13838 USA; 800-678-0141; Fax: 607-563-5157; www.amphenol-industrial.com

AMS ....
9119 Cross Park Drive, Knoxville, TN 37923 USA; 865-691-1756; Fax: 865-691-9344; brad@ams-corp.com; www.ams-corp.com

Amstat Industries, Inc. ....
3012 N. Lake Terrace, Glenview, IL 60026 USA; 847-998-6210; Fax: 948-998-6218; larry@amstat.com; www.amstat.com

Amuneal Manufacturing Corp. ....
4737 Darrah St., Philadelphia, PA 19124 USA; 215-535-3000; 800-755-9843; Fax: 215-743-1715; info@amuneal.com; www.amuneal.com

Andre Consulting, Inc. ....
12812 NE 185th Court, Bothell, WA 98011-3121 USA; 206-406-8371; pat@andreconsulting.com; http://andreconsulting.com

ANDRO Computational Solutions, LLC ....
Beeches Professional Campus, Bldg 2 Suite 1, 7902 Turin Road, Rome, NY 13440-2067 USA; 315-334-1163; Fax: 315-334-1397; androcs@androcs.com; www.androcs.com

Anritsu Company ....
1155 East Collins Blvd., Suite 100, Richardson, TX 75081 USA; 972-644-1777; 800-267-4878; Fax: 972-671-1877; gina.varela@anritsu.com; www.us.anritsu.com

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11 Deerpark Drive, Suite 102 B, Monmouth Junction, NJ 08852-1923 USA; 732-274-0001; 800-214-7900; Fax: 732-438-9152; aexstatic@aol.com; www.antistaticindustries.com

Apache Design Solutions ....
2645 Zanker Road, San Jose, CA 95134 USA; 408-457-2000; Fax: 408-428-9569; apache_sales@apache-da.com; www.apache-da.com

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132 Fairgrounds Road, W. Kingston, RI 02892 USA; 800-788-1704; www.apc.com

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P.O. Box 1442, Tempe, AZ 85280-1442 USA; 480-894-1112; 888-937-3907; dave@apexdc.com; www.dieandgasket.com

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270 Quaker Road, East Aurora, NY 14052 USA; 716-652-3600; Fax: 716-652-4814; apisales@delevan.com; www.delevan.com

Apogee Labs Inc. ....
210 S. Third St., North Wales, PA 19454 USA; 215-699-2060; dhendricks@apogeelabs.com; www.apogeelabs.com

Applied Electromagnetic Technology LLC ....
P.O. Box 1437, H.G. Trueman Road, Solomons, MD 20688 USA; 410-326-6728; info@appliedemtech.com; www.appliedemtech.com

Applied Physical Electronics, L.C. ....
P.O. Box 341149, Austin, TX 78734 USA; 512-264-1804; Fax: 512-264-1784; rschreib@apelc.com; www.apelc.com

Applied Systems Engineering ....
7510 Benbrook Parkway, Fort Worth, TX 76126 USA; 817-249-4180; Fax: 817-249-3413; bjostrand@applsys.com; www.applsys.com

APREL Laboratories ....
17 Bentley Ave., Nepean, Ontario K2E 6T7, Canada; 613-820-2730; Fax: 613-820-4161; info@aprel.com; www.aprel.com

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AR/RF Microwave Instrumentation 3, 29, 57
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DC	Delmarva Engineering	410-990-9000
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ME	R.J. Sickles Associates	781-862-5100
MI	Delta Technology Solutions	419-394-6766
MN	Electronic Instrument Associates Inc.	612-695-4055
MO	KJS Marketing	816-578-4751
MS	Brennan Associates	727-446-5006
MT	Syntek	425-822-7777
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OH	Delta Technology Solutions	419-394-6766
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PA	Advanced Technical Marketing	800-310-8805
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16246 Valley Blvd., Fontana, CA 92335; 909-829-4444; Fax: 909-829-0564; www.artech2000.com

ARA Technologies...
P.O. Box 226, Smithtown, NY 11787 USA; 631-724-4619; Fax: 631-361-8691; emc@aratech-inc.com

ARC Technologies, Inc. 9
11 Chestnut St., Amesbury, MA 01913 USA; 978-388-2993; Fax: 978-388-6866; sales@arc-tech.com; www.arc-tech.com

Arcotronics, Inc. ....
20-1 Jules Court, Bohemia, NY 11716 USA; 631-563-9568; Fax: 631-563-9569; rich@arcotronics.net; www.arcotronics.net

Aries Electronics ....
2609 Bartram Road, Bristol, PA 19007 USA; 215-781-9956; Fax: 215-781-9845; www.arieselec.com

ASR Technologies, Inc. ....
332 Crestview Road, Ottawa, Ontario K1H 5G6, Canada; 613-737-2026; Fax: 613-737-3098; a.podgorski@ieee.org; www.asrtechnologiesinc.com

AT4 Wireless...
C/ Severo Ochoa, 2 PTA Campanillas, Malaga 29590, Spain; +34 95 261 91 00; jcasini@at4wireless.com; www.at4wireless.com

ATLAS Compliance & Engineering.....................
1792 Little Orchard St., San Jose, CA 95125 USA; 408-971-9743; Fax: 408-971-9783; info@atlasce.com; www.atlasce.com/

Austest Laboratories...
33-35 Alleyne St., ground floor, Chatswood, Sydney NSW 2067, Australia; +61 (0)2 9882 6500; Fax: +61 (0)2 9882 6600; martin@austest.com.au; www.austest.com.au

Autosplice, Inc. ....
10121 Barnes Canyon Road, San Diego, CA 92121 USA; 858-678-3181; Fax: 858-535-0130; cmiller@autosplice.com; www.autosplice.com

Averna ....
87 Prince St., Suite 140, Montreal Quebec, Canada H3C 2M7; 514-842-7577; Fax: 514-842-7573; www.averna.com/urt/

Axonics, Inc. ....
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19650 Pauling, Foothill Ranch, CA 92610 USA; 800-366-1006; Fax: 949-460-2300; sales@balseal.com; www.balseal.com

Barth Electronics, Inc. ....
1589 Foothill Drive, Boulder City, NV 89005 USA; 702-293-1576; Fax: 702-293-7024; debbie@barthelectronics.com; www.barthelectronics.com

Bay Area Compliance Labs Corp. ....
1274 Anvilwood Ave., Sunnyvale, CA 94089 USA; 408-732-9162, ext. 3106; Fax: 408-732-9164; www.baclcorp.com

BEC Inc. ....
970 East High St., Pottstown, PA 19464 USA; 610-970-6880; Fax: 610-970-8381; sales@bec-ccl.com; www.bec-ccl.com

Beehive Electronics ....
8555 Lawrence Lane, Sebastopol, CA 95472 USA; 707-824-9206; Fax: 707-581-1955; sales@beehive-electronics.com; www.beehive-electronics.com

Beijing Tempest Electronics Technologies Co. Ltd. ....
Room 321, Zhuanxiu Building No.83, Fuxing Road, Beijing, China; 010-66697852; Fax: 010-66699041; tempest@public.bta.net.cn; www.chinatpst.com

BI Technologies ....
4200 Bonita Place, Fullerton, CA 92835 USA; 714-447-2345; Fax: 714-447-2400; sales@bitechnologies.com; www.bitechnologies.com

Binder-USA...
3903 Calle Tecate, Camarillo, CA 93012 USA; 805-437-9925; greg.harter@binder-usa.com; www.binder-usa.com

Bird Technologies Group / TX RX Systems ......
30303 Aurora Road, Solon, OH 44139 USA; 440-248-1200; 866-695-4569; Fax: 440-248-5426; sales@bird-technologies.com; www.bird-technologies.com

Blackwood Labs ....
8 Woodfieldside Business Park, Pontllanfraith, Blackwood, South Wales NP12 2DG, United Kingdom; + 44 (0) 1495 229219; test@blackwood-labs.co.uk; www.blackwood-labs.co.uk

Blue Guide EMC Lab..
Joseph Cardijnstraat 21, B-9420 Erpe-Mere, Belgium; +32 (0) 53 60 16 52; Fax: +32 (0) 53 70 78 99; info@bgemc.com; www.bgemc.com

Bourns Inc...
1200 Columbia Ave., Riverside, CA 92507-2129 USA; 951-781-5500; www.bourns.com

Boyd Corporation...
600 So McClure Road, Modesto,CA 95357 USA; 209-236-1111; 800-554-0200; www.boydcorp.com

Braco Compliance Ltd. ....
P.O. Box 31188, Ilam, Christchurch, Canterbury 8444, New Zealand; +64 21 208 4303; admin@bracocompliance.com; www.bracocompliance.com

Braden Shielding Systems................................ 81
9260 Broken Arrow Expressway, Tulsa, OK 74145 USA; 918-624-2888, ext. 102; Fax: 918-624-2886; Glen Pierandri, Manager of Gov't. / Commercial Products, gpierandri@bradenshielding.com; www.bradenshielding.com

Brim Electronics, Inc. ....
120 Home Place, Lodi, NJ 07644 USA; 201-796-2886; danziba@gmail.com; www.brimelectronics.com

Bud Industries ....
4605 E. 355th St., Willoughby, OH 44094 USA; 440-946-3200; Fax: 440-951-4015; saleseast@budind.com; www.budind.com

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Littleton Distribution Center, One Distribution Center Circle, Suite #1, Littleton, MA 01460 USA; 978-486-8880; 877-277-8880; Fax: 978-486-8828; craig.lazinsky@us.bureauveritas.com; www.BureauVeritas.com/EE

Bystat International Inc. ....
2630, rue Sabourin, Ville Saint-Laurent Québec, Canada, H4S 1M2; 514-333-8880; 800-361-6777; Fax: 514-333-8885; static@bystat.com; www.Bystat.com

C

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420 East Alton Ave., Santa Ana, CA 92707; 714-549-0336; www.calmont.com

CAP Wireless...
3235 Grande Vista Drive, Newbury Park, CA 91320 USA; 805-499-1818; Fax: 805-499-6649; info@capwireless.com; www.capwireless.com

Capcon International, Inc. ....
120 Craft Ave., Inwood, NY 11096-1708 USA; 516-371-5600; Fax: 516-239-5481; turab@capconemi.com; www.capconemi.com

CAPLINQ Corp. ....
957 Snowshoe Crescent, Orléans (Ottawa) Ontario, K1C 2Y3, Canada; 613-482-2215; Fax: 702-995-1235; info@caplinq.com; www.caplinq.com

Caprock Mfg. ....
2303 120th St., Lubbock, TX 79423 USA; 806-745-6454; Fax: 806-745-5963; caprock@caprock-mfg.com; www.caprock-mfg.com

Captor Corp. 115
5040 South County Road 25A, Tipp City, OH 45371 USA; 937-667-8484; Fax: 937-667-5133; Scott Timms, stimms@captorcorp.com; www.CaptorCorp.com; Bob Jenks, Sales/Design Engineer; Nathan Miller, Sales/Design Engineer; Joe Otto, Sales/Design Engineer; Brian Monnin, Sales/Design Engineer; Scott Timms, BP/GM; Ryan Sollmann, Sales/Design Engineer

CA	Fremont, R C Products LLC/Bruce Creedy	510-656-8490
	Palm Desert, Ramsgate Tech Sls/Don Hosmer	760-779-5600
FL	Tampa, CBC Electronics/Seth Brock	813-969-1901
IN	CRP Technical Solutions/Chris Platt	317-841-7273
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Cascade TEK ....
5245-A NE Elam Young Parkway, Hillsboro, OR 97124 USA; 503-648-1818; 888-835-9250; Fax: 503-648-1798; www.cascadetek.com

Central Coating Company.......................................
165 Shrewsbury St., West Boylston, MA 01583 USA; 508-835-6225; Fax: 508-835-6228; aaccettullo@centralcoating.com; www.centralcoating.com

CertifiGroup ....
901 Sheldon Drive, Cary, NC 27513 USA; 800-422-1651; info@ certifigroup.com; www.certifigroup.com

CETECOM Inc. ....
411 Dixon Landing Road, Milpitas, CA 95035 USA; 408-586-6200; sales@cetecomusa.com; www.cetecomusa.com

CGS Technologies...
1801 W. Parkside Lane, Phoenix, AZ 85027 USA; 623-869-0600; Fax: 623-582-4813; info@cgstech.com; www.cgstech.com

Cherry Clough Consultants Ltd. ....
9 Bracken View, Brocton, Staffordshire ST17 0TF, Great Britain; +44 (0) 1785 660 247; Fax: +44 (0) 1785 660 247; Keith Armstrong, keith.armstrong@cherryclough.com; www.cherryclough.com

Chomerics, Div. of Parker Hannifin Corp. ....
77 Dragon Court, Woburn, MA 01888 USA; 781-935-4850; Fax: 781-933-4318; chomailbox@parker.com; www.chomerics.com; 100 Indigo Creek Drive, Rochester, NY 14626-5101 USA; 781-939-4158; Fax: 781-935-2758; pterilli@parker.com; www.chomericstest.com

Cima NanoTech, Inc. ....
1000 Westgate Drive, St. Paul, MN 55114-1067 USA; 651-646-6266; Fax: 651-646-4161; egranstrom@cimananotech.com; www.cimananotech.com

Circuit Insights LLC ....
3744 Valley Lights Drive, Pasadena, CA 91107 USA; 626-201-0488; Fax: 626-466-4448; circuit-insights@charter.net; www.LoopSlooth.com

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1515 NW 167th St., Suite 6-303, Miami, FL 33169 USA; 305-621-0022; Fax: 305-621-0766; citel@citelprotection.com; www.citelprotection.com

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5046 Sierra Pines Drive, Mariposa, CA 95338 USA; 209-966-5240; 800-500-4362; Fax: 866-779-9776; ckclabs@ckc.com; www.ckc.com

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2900 Westinghouse Blvd., Ste. 118, Charlotte, NC 28273 USA; 866-649-8665, ext. 701; Fax: 866-649-8665; info@clickfold.com; www.clickfoldplastics.com

Cobham Microwave ....
Stocks Lane,Bracklesham Bay, Chichester, West Sussex, United Kingdom; +44 (0) 1243 670711; Fax: +44 (0) 1243 672907; www.cobham.com/microwave

Combinova AB ....
Domkraftsvägen 1,S-197 40, Bro, Sweden; +46-8-627 93 10; Fax: +46-8-29 59 85; sales@combinova.se; www.combinova.se

Communication Certification Laboratory ....
1940 W. Alexander St., Salt Lake City, UT 84119 USA; 801-972-6146; Fax: 801-972-8432; info@cclab.com; www.cclab.com

Communication Coil, Inc.......................................
9601 Soreng Ave., Schiller Park, IL. 60176 USA; 847-671-1333; Fax: 847-671-9191; info@communicationcoil.com; www.communicationcoil.com

Compac Development Corp. ....
1460 North Clinton Ave., Suite O-15, Bay Shore, NY 11706 USA; 631-585-3400; Fax: 631-585-3534; prao@compac-rf.com; www.compac-rf.com

Compatible Electronics, Inc. ....
114 Olinda Drive, Brea, CA 92823 USA; 714-579-0500; ruby@celectronics.com; www.celectronics.com

Compliance Certification Services....................
47173 Benicia St., Fremont, CA 94538 USA; 510-771-1000; Fax: 510-661-0888

Compliance Engineering Ireland Ltd. ....
Raystown, Ratoath Road, Ashbourne, Co. Meath, Ireland; + 353 1 8256722; john.mcauley@cei.ie; www.cei.ie/

Compliance Testing, LLC..
3356 N. San Marcos Place, Suite 107, Chandler, AZ 85225 USA; 480-926-3100; Fax: 480-926-3598; www.compliancetesting.com

Compliance Worldwide ....
357 Main St., Sandown, NH 03873 USA; 603-887-3903; Fax: 603-887-6445; Larry@cw-inc.com; http://cw-inc.com

Com-Power Corp. ....
114 Olinda Drive, Brea, CA 92823 USA; 714-528-8800; Fax: 714-579-1850; sales@com-power.com; www.com-power.com

Comtech PST Corp. ....
105 Baylis Road, Melville, NY 11757 USA; 631-777-8900; Fax: 631-777-8877; sales@comtechpst.com; www.comtechpst.com

Comtest Eng. ....
Industrieweg 12, 2382NV, Zoeterwoude, Netherlands; + 31 71 5417531; Fax: + 31 71 5420375; engineering@comtestnl.com; www.comtestnl.com

Conductive Compounds Inc. . ...
17 Hampshire Drive, Unit 8, Hudson, NH 03051 USA; 603-595-6221; Fax: 603-595-6228; sales@conductivecompounds.com; www.conductivecompounds.com

CONEC Corp. - USA ....
343 Technology Drive #1101, Garner, NC 27529 USA; 919-460-8800; Fax: 919-460-0141; info@conec.com; www.conec.com

Connors Company ....
P.O. Box 807 Carver, MA 02330 USA; 508-272-1500; Fax: 508-866-5393; brian@connorsrep.com; www.ConnorsRep.com

Core Compliance Testing Services ....
79 River Road, Hudson, NH 03051 USA; 603-889-5545; khcmacgrath@aol.com; www.corecompliancetesting.com

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Solan, Himachal Pradesh, India; 911792 277231-36; www.cosmoferrites.com

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CPI (Communications & Power Industries) Satcom Div. ....
811 Hansen Way, Palo Alto, CA 94304-1031; USA; 650-846-3803; doug.slaton@cpii.com; www.cpii.com/product.cfm/4/11

Cranage EMC Testing Ltd. ....
Stable Court, Oakley, Market Drayton, Shropshire TF9 4AG, United Kingdom; +44 1630 658568; Fax: +44 1630 65821; keith.rich@cranage.co.uk; www.cranage.co.uk

Cre8 Associates Ltd. ....
Bruntingthorpe Proving Ground, Bath Lane, Lutterworth, Leicestershire, LE17 5QS, United Kingdom; +44 (0)1162 479787; davidh@cre8-Associates.com; www.cre8-associates.com

Creative Materials, Inc. ....
141 Middlesex Road, Tyngsboro, MA 01879 USA; 978-649-4700; Fax: 978-649-2040; info@creativematerials.com; www.creativematerials.com

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1350 Tolland Road, P.O. Box 489, Rollinsville, CO 80474 USA; 303-258-0100; Fax: 303-258-0775; critech@earthlink.net; www.criteriontech.com

CSA International ....
178 Rexdale Blvd., Toronto M9W 1R3, Canada; 866-797-4272; Fax: 416-747-4149; cert.info@csa-international.org; www.csa-international.org

CST - Computer Simulation Technology AG.....
Bad Nauheimer Str. 19, 64289 Darmstadt, Germany; +49 6151 73030; Fax: + 49 6151 7303100; info@cst.com; www.cst.com

CST

CST of America, Inc. 59
492 Old Connecticut Path, Suite 505, Framingham, MA 01701; USA; 508-665-4400; Fax: 508-665-4401; info@cst.com; www.cst.com

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CZE	CST AG, Prague	420 257 219 488

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2400 S. 43rd St., Milwaukee, WI 53219; 414-649-4200; Fax: 414-649-4279; sales@curtisind.com; www.curtisind.com; Steven Powers, Pres.; Al Hungsberg, Sales Director; Glenn Cummings, Regional Sales Manager

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600 Wheat Lane, Wood Dale, IL 60191 USA; 630-595-4855; 800-323-9562; Fax: 630-595-1666; mschuck@phoenixofchicago.com; www.customassemblyllc.com

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DARE!! Instruments
Vijzelmolenlaan 7, NL3447GX Woerden , Netherlands; +31 (0)348 41 65 92; Fax: +31 (0)348 49 97 32; instruments@dare.nl; www.emc-instruments.com

Datatronics
28151 Highway 74, Romoland, CA; 951-928-7700; Fax: 951-928-7701; www.datatronics.com

Dayton T. Brown, Inc.
1175 Church St., Bohemia, NY 11716-5031 USA; 631-589-6300; Fax: 631-589-3648; test@dtbtest.com; www.dtbtest.com

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1120 Auburn St., Fremont,CA 94538 USA; 510-656-2325; Fax: 510-656-3214; solson@dbcontrol.com; www.dBControl.com

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216 Hillsboro Ave., Lexington, KY 40511 USA; 859-253-1178; Fax: 859-252-6128; www.dbicorporation.com

Delta Electronics
Amphur Bangpakong, Chachoengsao, Thailand; +66 (0)38522480; www.deltaww.com

Delta Products Corp.
4405 Cushing Parkway, Fremont, CA; 919-767-3860; www.deltaww.com

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3651 Walnut Ave., Chino, CA 91710 USA; 909-627-8178; Fax: 909-627-7449; Dave.Bermani@Desco.com; www.DescoIndustries.com

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155 Northboro Road, Unit 8, Southborough, MA 01772 USA; 508-229-2000; Fax: 508-229-2622; Nick Petri, Director of Sales & Marketing, npetri@devicetech.com; www.devicetech.com/shielding/default.asp

Dexmet Corp. 97
22 Barnes Industrial Road South, Wallingford, CT 06492 USA; 203-294-4440; Fax: 203-294-7899; sales@dexmet.com; www.dexmet.com

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1050 Morse Ave., Elk Grove Village, IL 60007 USA; 847-956-1140; 800-775-3829; Fax: 877-221-5052; info@dextermag.com; www.dextermag.com/soft-magnetics.aspx

Diversified T.E.S.T. Technologies
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CA Riverside, Tony Piraino, Sls & Mktg Manager 951-637-2630
UT Coalville, Les Payne Manager 435-336-4433

Don HEIRMAN Consultants 126
143 Jumping Brook Road, Lincroft, NJ 07738 USA; 732-741-7723; Fax: 732-530-5695; Don Heirman, d.heirman@ieee.org; www.DonHeirman.com

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700 Airport Blvd., Doylestown, PA 18902; 215-348-5010; Fax: 215-348-9959; info@dontech.com; www.dontech.com; Jeff Blake, Vice President - Business Development;John Wahl, Director - Engineering; Bill Cusack, Eastern Regional Sales Manager; John Vecchione, Western Regional Sales Manager

Dynamic Sciences International, Inc.
6130 Variel Av., Woodland Hills, CA 91367 USA; 818-226-6262; 800-966-3713; Fax: 818-226-6247; market@dynamicsciences.com; www.dynamicsciences.com

E

E&C Anechoic Chambers Asia Ltd.
Flat/Rm 303, 3/F St. George's Bldg, 2 Ice House St., Central Hong Kong; +852 397 221 73; Fax: + 852 397 222 11; jtsang@ecanechoicchambers.com; www.ecanechoicchambers.com

E.F. Electronics Co.
217 W. Mill St., Montgomery, IL 60538 USA; 630-897-1950; EFEMCTEST@aol.com

East Coast Shielding
1914 Rt 57, Hackettstown, NJ 07840 USA; 908-227-6857; Fax: 908-852-9163; mike@eastcoastshielding.com; www.eastcoastshielding.com

Ecliptek Corp.
3545-B Cadillac Ave., Costa Mesa, CA; 714-433-1200; Fax: 714-433-1234; customersupport@ecliptek.com; www.ecliptek.com

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769 Susquehanna Ave., Franklin Lakes, NJ 07417 USA; 201-891-4003; 800-348-6268; Fax: 201-891-3207; sales@edfagan.com; www.edfagan.com

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Appoloweg 80, Leylstad, Flevoland 8239DA, Netherlands; +31 32 295 395; Fax: +31 32 413 133; info@eemc.nl; www.eemccoimex.nl

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750 Belmont Way, Pinole, CA 94564 USA; 510-741-3632; Fax: 510-741-3657; info@marktek-inc.com; www.eeonyx.com

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5639 B Jefferson NE, Albuquerque, NM 87109 USA; 505-243-1423; Fax: 505-243-9772; eeseal@aol.com; www.eeseal.com

E-Labs Inc.
4007 Leonard Drive, Fredericksburg, VA 22408 USA; 540-834-0372; Fax: 540-834-0373; info@e-labsinc.com; www.e-labsinc.com

Electri-Flex Company 83
222 W. Central Ave., P.O. Box 72260, Roselle, IL 60172 USA; 1-630-529-2920; Fax: 1-630-529-0388; Janelle Jones, Marketing Manager, jjones@electriflex.com www.electriflex.com

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3366 Pomona Blvd., Pomona, CA 91768 USA; 909-595-4037; 800-515-1112; Fax: 909-595-0186; esales@electrocube.com; www.electrocube.com

ElectroMagnetic Investigations, LLC
20811 NW Cornell Road, Suite 600, Hillsboro, OR 97124 USA; 503-466-1160; 888-466-1160; Fax: 503-466-1170; support@emicomply.com; www.emicomply.com

Electro-Metrics Corp.
231 Enterprise Road, Johnstown, NY; 518-762-2600; Fax: 518-762-2812; sales@emihq.com; www.electro-metrics.com

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P.O. Box 6487, Bloomingdale, IL 60108-6487 USA; 630-924-1600; Fax: 630-477-0321; frank@electronicinstrument.com; www.electronicinstrument.com

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302 Legget Drive, Suite 100, Kanata K2K 1Y5, Canada; 613-599-6800; Fax: 613-599-7614; Lynn Diggins, Director Business Development, lynn.diggins@etc-mpb.com; 27 East Lake Hill, Airdrie, Alberta T4A 2K3, Canada; 403-912-0037; Fax: 403-912-0083; Mala Mediboina, General Manager, mmediboina@etc-mpbtech.com; www.etc-mpb.com

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EM Software & Systems-SA (Pty) Ltd. 79
P.O. Box 1354, Stellenbosch, 7599, South Africa; +27 (0)21 880 1880; Fax: +27 (0)21 880 1936; Celeste Mockey, info@emss.co.za; www.feko.info
VA Hampton, EM Software & Systems (USA) Inc. 866-419-FEKO
INTERNATIONAL
DEU Böblingen, EM Software & Systems GmbH .... +49 (0)7031 714 5203

EM Test
Sternenhofstrasse 15, Reinach (BL) 4153, Switzerland; +41 (0)61 717 91 91; Fax: +41 (0)61 717 91 99; g.taddio@emtest.ch; www.emtest.com

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EM Test USA 37
3 Northern Blvd., Unit A-4, Amherst, NH 03031 USA; 603-769-3477; Fax: 603-769-3499; Michael Hopkins, General Manager, m.hopkins@emtest.com; www.emtest.com

EMC Compliance ....
P.O. Box 14161, Huntsville, AL 35815 USA; 256-650-5261; ken.javor@emccompliance.com; www.emccompliance.com

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2901 Tasman Drive, Suite 211, Santa Clara, CA 95054 USA; 408-330-9216; Fax: 408-330-0012; sales@emccomponent.com; www.emccomponent.com

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EMC Engineering and Safety.................................
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EMC MCC Bv...
Sedanlaan 13a, Eindhoven, N. Br. 5627MS, Netherlands; +31-40-53811242; +31-40-2927490; mart.coenen@emcmcc.nl; www.emcmcc.nl

EMC Partner AG...**53**
Baselstrasse 160, Laufen 4242, Switzerland; +41 61 775 2030; Fax: +41 61 775 2059; Nicholas Wright, International Sales Manager, sales@emc-partner.ch; www.emc-partner.com

INTERNATIONAL

AU	Sydney, Test & Measurement	+61 2 4739 9523
AR	Buenos Aires, Mannos	+54 11 4373 25 85
BE	Berchem-Ste-Agathe, Decatel	+32 2 469 00 90
BR	Sao Paulo, Test & Measurement	+55 11 5092 5229
CA	Manassas, HV Technologies	+1 703 365 2330
CN	Shanghai, Precision International	+86 21 6211 5111
CZ	Prague, Tectra	+420 281 921 650
DE	Iserlohn, H+H	+49 2371 7853-0
EG	Ramadan City, Horus	+20 15 379416
ES	Barcelona, Wavecontrol	+34 933 20 80 55
FI	Helsinki, INEL	+358 10 423 7570
FR	Cosnac, EMC Partner	+33 5 55 74 31 68
GB	High Wycombe, EMC Partner	+44 1494 44 42 55
GR	Athens, ACTA	+30 210 600 33 02
HU	Budapest, EL Test	+36 1 202 18 73
IL	Petach Tikva, Dan-El	+97 2 3 927 1888
IT	Milan, AFJ Instruments	+39 02 91 43 48 50
JP	Tokyo, Nippon Automatic Control	+81 3 5434 1600
KR	Seoul, Kwang Wha Trading	+82 2 2679 39 96
MX	Manassas, HV Technologies	+1 703 365 2330
NL	Oosterleek, Rimarck	+31 229 503 478
PL	Poznan, ASTAT	+48 61 849 80 61
SE	Vellinge, ERDE	+46 40 42 46 10
SG	Singapore, Precision Tech	+65 6273 4573
TR	Istanbul, Aktif Neser	+90 216 577 6999
TW	Taipei, Precision International	+886 2 8512 4888
US	Manassas, HV Technologies	+1 703 365 2330
ZA	Sandton, Protea Electronics	+27 11 719 57 00

EMC Technologies Pty Ltd. ....
176 Harrick Road, Keilor Park, Victoria 3042, Australia; +613 9365 1000; Fax: +613 9331 7455; melb@emctech.com.au; www.emctech.com.au

EMC Tempest Engineering ....
2190 East Winston Road, Anaheim, CA 92806 USA; 714-778-1726; www.emctempest.com

EMC Test Design..
PO Box 600532, Newton, MA; 508-292-1833; exid@emctd.com; www.emctd.com

EMC Testing Laboratories, Inc. ....
2100 Brandon Trail, Alpharetta, GA 30004 USA; 770-475-8819; gbailey@emctesting.com

EMCO Elektronik GmbH ....
Bunsenstraße 582152, Planegg, Germany; +49-89-8955650; Fax: +49-89 -895 90 376; www.emco-elektronik.de

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EMI Solutions Inc. ....
15 Hammond, Suite 304, Irvine, CA 92618 USA; 949-206-9960; Fax: 949-206-9983; bob@4emi.com; www.4emi.com

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2200 North Telshor Blvd., Las Cruces, NM 88011 USA; 575-532-9190; Fax: 575-532-0884; tezak.d@emitechnologies.com; www.emitechnologies.com

Emission Control, Ltd. ....
12704 W. Arden Place, Butler, WI ; 262-790-0092; Fax: 262-790-0095 ; sales@emissioncontrol.com; www.emissioncontrol.com

EMITECH ....
Rue des Coudriers, ZA de l'Observatoire, Montigny le BX, Ile de France 78180, France; +33 1 30 57 55 55; Fax: 33 1 30 43 74 48; jm.rogi@emitech.fr; www.emitech.fr

EMITEMC ....
Arroyo de la China 3510 Rio Negro, Bariloche, Argentina; +542944527498; hsineiro@emitemc.com; Hernan Sineiro

EMP-tronic..
EMP-tronic AB, Box 130 60,250 13, Helsingborg, Sweden; 464-223-5060; Fax: 042 23 51 82; info@emp-tronic.se ;www.emp-tronic.se

EMSCAN Corp. ....
#1, 1715-27 Ave., NE Calgary, Alberta T2E 7E1, Canada; 403-291 0313; 877-367-2261; Fax: 403-250 8786; etickam@emscan.com; www.emscan.com

emscreen GmbH ....
Wallbergstraße 7, Taufkirchen , Bavaria 82024, Germany; +49 89 614171-0; Fax: +49 89 61471-71; info@emscreen.de; www.emscreen.de

EMSS Consulting Pty (Ltd.) ....
32 Techno Ave., Technopark, Stellenbosch, Western Cape 7600, South Africa; +27 21 880 1880; bbosch@emss.co.za; www.emssixus.com

emv - Elektronische Meßgeräte Vertriebs GmbH ....
Wallbergstraße 7, Taufkirchen, 82024, Germany; +49 (0) 89614243; Fax: +49 (0) 89614282; awahrmann@emvgmbh.de; www.emvgmbh.de

Enerdoor Inc. ....
75 Industrial Way, Portland, ME 04103 USA; 207-210-6511; 877-778-2875; Fax: 207-210-6512; stefano.medved@enerdoor.com; www.enerdoor.com

Engineered Testing Systems ....
1711 West 15th St., Indianapolis, IN 46202 USA; 317-396-0573; Fax: 317-536-8006; golten@engineered-testing.com; www.engineered-testing.com

Environ Laboratories, LLC ....
9725 Girard Ave., South Minneapolis, MN 55431 USA; 952-567-2302; 800-826-3710; www.environlab.com

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186 Wood Ave. S, Iselin, NJ 08830 USA; 732-906-4374; Fax: 732-632-5927; inductors-emc.usa@epcos.com; www.epcos.com/emc

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1520 Santa Rosa Ave., Santa Barbara, CA 93109 USA; 805-564-1260; tustin@equipment-reliability.com; www.equipment-reliability.com

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CA	Altamont Technical Services	925-294-9774
GA	dBm Marketing	678-690-5258
IN	Electronic Instrument Associates	317-770-3689
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TX	CF Scientific Systems	817-467-0970
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INTERNATIONAL

ARG	Precision Electronica SRL	+54 11 4735 8814, +54 11 4708-9384
ARG	Vimelec S.A.	+54 11 4912 3998
AUS	Faraday Pty Ltd	+61 0 3 9729 5000
AUT	MEM	+43 1 943 4254
AUT	Universal Elektronik-Import GmbH	+43 1545 1588
BOL	CONATEL	+598 2902 0314
BGR	Giga Electronics	+359 2 731 498
BGR	Martec Ltd.	+359 898 418 900
BRA	AK Telemedia	55-11-38150594
CAN	Interfax Systems, Inc	416-674-8970 x121
CHE	Emitec AG	+41 41 7486010
CHL	Dymeq Ltda	+56 2 3392000
CHL	Sistemas de Instrumentacion Ltda	+52 0 2 696 0031
COL	High Tec Environmental Ltda	+57 1 671 3700
COL	Technical Marketing Specialists	303 488-0220, ext. 303
CZE	Testovaci Technika s.r.o	+420 274 782 237
DEU	EMCO Elektronik GmbH	+49 89 895 569-23
DEU	Pischzan Technologies	+49 6109 771948

DNK Metric A/S +45 43 71 64 44
ECU Caprotecsa +593 59342231875
EGY Omega Integrated Systems +20 2 3370501
ESP ALAVA Ingenieros, S.A. +34915679720
ESP Nusim SA +1 3491 535 9640
EST Arpen Elekter +372 671 1947
FRA M2S Sarl +33 4 6881 4952
GRC Netscope Solutins S.A. +30 210 27 24 207
HKG Euro Tech (Far East) LTD +852 2 814 0311
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HKG PTC International, LTD +852 2 827 9977
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IND Complus Systems Pvt. Ltd. +91 80 23146683
INA PT Berca Hardayaperkasa +62 21 3800902
ISR R.D.T. Equipment & Systems Ltd +972 36450745
ISR Safe-Tech Ltd. +972 4 958 5789
ITA ASEA SISTEMI S.R.L. +39 011 9963071
KOR Crezon Corporation 82 31 777 8949
KOR Will Technology Co Ltd 82 31 3226100
KSA AMICO (medical only) +0119 662 660 1149
Latin America Lumur International, Inc +1 787 781-9833
LAT Moduls Riga +371 7070101
LIB Computer Information Systems +961 4 410410
LTU Satela UAB +370 699 90743
MEX Sistemas e Ingenieria de EMC (SI-EMC) +52 55 2163 2148
NED ar Benelux B.V. +31 172 423000
NZL Vicom (NZ) Ltd +64 9 379 4596
NOR Nortelco Electronics AS +47 22 57 6100
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PHL Ark One Solutions Inc +63-2-8429090 or 91
POL Urzadzenia Elektroniczne Import (UIE) +48 22 313 1735
RSA Protea Electronics (PTY) Ltd +27 11 719 5700
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RSA H.A.S.S. Industrial Pty. Ltd. 011 966 2660 1149
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SWE Ce-Bit Elektronik AB +46 87 35 75-50
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TUR Spark Measurement Technologies +90 312 466 8212
TWN Lintek Corporation +886 2 2709 0387
TWN Burgeon Instrument Co, Ltd +886 3 328 0531 (15 L)
UKR Unitest Ltd +380 44 272 6094
UAE Al-Hayat Pharmaceuticals +971 +011-6-559-2481
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COL High Tec Environmental Ltda +57 1 671 3700
COL Technical Marketing Specialists 303 488-0220, ext. 303
CZE Testovaci Technika s.r.o. +420 274 782 237
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DEU Pischzan Technologies +49 6109 771948
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ISR R.D.T. Equipment & Systems Ltd +972 36450745
ISR Safe-Tech Ltd. +972 4 958 5789
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Latin America Lumur International, Inc +1 787 781-9833
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LIB Computer Information Systems +961 4 410410
LTU Satela UAB +370 699 90743
MEX Sistemas e Ingenieria de EMC (SI-EMC) +52 55 2163 2148
NED ar Benelux B.V. +31 172 423000
NZL Vicom (NZ) Ltd +64 9 379 4596
NOR Nortelco Electronics AS +47 22 57 6100
PAK Telec Electronics & Machinery PVT Ltd. +92 21 5217201
PAR CONATEL +598 2902 0314
PER Instrumentos y Complementos S.A.C. +51 1 2604 926
PHL Ark One Solutions Inc +63-2-8429090 or 91
POL Urzadzenia Elektroniczne Import (UIE) +48 22 313 1735
RSA Protea Electronics (PTY) Ltd +27 11 719 5700
RSA Envirocon Instrumentation +27 11 476 7323
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SWE Proxitron AB +1 46 141 580 00
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TWN Lintek Corporation +886 2 2709 0387
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UAE Tamra Electrocom +971 4 2233 259
URU CONATEL +598 2902 0314
VEN Optipro 58 212 257 4434
VIE Victory Co, LTD +84 4 9761586

EU Compliance Services, Inc.
7580 St. Clair Ave., Mentor, OH 44060 USA; 440-918-1425; Fax: 440-918-1476; emcjanki@aol.com; www.eucs.com

Eurofins Product Service GmbH
Storkower Str. 38C Reichenwalde 15526 Germany; +49 33631 8880; Fax: +49 33631 888 660; jenszimmermann@eurofins.com; http://pt.eurofins.com

F

F-Squared Laboratories
26501 Ridge Road, Damascus, MD 20872 USA; 301-253-4500; 877-405-1580; Fax: 301-253-5179; Ken DeVore, kdevore@f2labs.com; www.f2labs.com
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OH Middlefield. 440-632-5541

Fabreeka International, Inc.
1023 Turnpike St., P.O. Box 210, Stoughton, MA 02072 USA; 781-341-3655; Fax: 781-341-3983; info@fabreeka.com; www.fabreeka.com

Fair-Rite Products Corp. 113
1 Commercial Row, P. O. Box 288, Wallkill NY, 12589; 845-895-2055; Fax: 845-895-2629; ferrites@fair-rite.com; www.fair-rite.com; James Montgomery, Applications Engineer; Paul Zdanowicz, Dir. Sales and Marketing; Jerry Barbaro, Area Sales Manager (Western US/Mexico); Bob Polhamus, Area Sales Manager (Eastern U.S./Canada)
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CO Littleton, Chinook Tech. Sls. 303-933-9007
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FEKO PO
Box 1354, Stellenbosch 7599, South Africa; +27 21 8801880; Fax: +27 21 8801936; celestem@emss.co.za; www.feko.info

Ferronics, Inc.
45 O'Connor Road, Fairport, NY 14450; 585-388-1020; Fax: 585-388-0036; odavies@ferronics.com; www.ferronics.com

Feuerherdt GmbH
Motzener Str. 26 b, 12277 Berlin, Germany; +49 30 710 96 45 51; Fax: +49 30 710 96 45 99; clemens.euerherdt@feuerherdt.de; www.shielding-online.com

FIBOX Enclosures
810 Cromwell Park Drive, Suite R, Glen Burnie, MD 21061; 410-760-9696; Fax: 410-760-8686; sales@fiboxusa.com; www.fiboxusa.com

Field Management Services
123 N. Laurel Ave., Los Angeles, CA 90048 USA; 323-937-1562, ext. 7; Fax: 323-934-2101; james.tidwell@fms-corp.com; www.fms-corp.com

Fil-coil
77-18 Windsor Place, Central Islip, NY 11766 USA; 631-467-5328; Fax: 631-467-5066; sales@custompowersystems.us; www.CustomPowerSystem.com

Filter Concepts Inc.
2624 Rousselle St., Santa Ana, CA 92707 USA; 714-545-7003; Fax: 714-545-4607; info@filterconcepts.com; www.filterconcepts.com

Filtronica, Inc. ....
607 Brazos St., Suite U, Ramona,CA 92065 USA; 760-788-4975; 1-888-FILTRONICA; Fax: 760-788-4356; peter@filtronica.com; www.filtronica.com

Fischer Custom Communications 11
20603 Earl St., Torrance, CA 90503 USA; 310-303-3300; Fax: 310-371-6268; sales@fischercc.com; www.fischercc.com; Allen Fischer, Vice President

INTERNATIONAL

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FRA	emv, s.a.r.l. (FRANCE)	33-1-6461-6329
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NLD	Comtest Instrumentation, B.V.	31-71-541-7531
SWE	Stockholm, CE-BIT	46-8-735-7550

Fotofab 75
3758 Belmont Ave., Chicago, IL 60618 USA; 773-463-6211; Fax: 773-463-3387; sales@fotofab.com; www.fotofab.com; James Tankersley, Inside Technical Sales Representative; Dan Sima, Sales & Marketing Manager

Frankonia EMC ....
Industrie Strasse, 16, Heideck, D-91180, Germany; 49 91 77-98 500; www.frankonia-emc.com

Frontier Electronics, Corp. ....
667 E. Cochran St., Simi Valley, CA; 805-522-9998; Fax: 805-522-9989; frontiersales@frontierusa.com; www.frontierusa.com

Fuss-EMV ....
Johann-Hittorf-Strasse 6, 12489 Berlin, Germany; +49 30-4044004; stefan.weber@fuss-emv.de; www.fuss-emv.de

G

Gaddon Ltd. ....
18 New Royd Millhouse Green , Sheffield, South Yorkshire S36 9NW, United Kingdom; +44 1226766999; ian.white@gaddon.co.uk; www.gaddon.co.uk

Gaven Industries Inc ....
6655 North Noah Drive, Saxonburg, PA ; 724-352-8100; Fax: 724-352-8121; www.gavenindustries.com

Genisco Filter Corp 119
5466 Complex St. #207, San Diego, CA 92123 USA; 858-565-7405; Fax: 858-565-7415; Dick Guerena, sales@genisco.com; www.genisco.com

GETELEC ....
375, rue Morane Saulnier, 78530, Buc, France; (33) 1 39 20 42 42; Fax: (33) 01.39.20.42.43; info@getelec.com; www.getelec.com

Giga-tronics/Ascor Inc. ....
4650 Norris Canyon Road, San Ramon, CA 94583 USA; 925-328-4650; Fax: 925-328-4700; dkwok@gigatronics.com; www.gigatronics.com

Glenair Inc. ....
1211 Air Way, Glendale, CA 91201-2497 USA; 818-247-6000; Fax: 818-500-9912; mKaufman@glenair.com; www.glenair.com

Global Advantage ....
180 Brodie Drive, Richmond Hill, ON L4B 3K8, Canada; 905-883-3919; larry.cook@globaladvantage.ca; www.globaladvantage.ca

Global Certification Laboratories, Ltd. ....
4 Matthews Drive, East Haddam, CT 06423 USA; 860-873-1451; Fax: 860-873-1947; janice@globaltestlabs.com; www.globaltestlabs.com

Global EMC Ltd. ....
Prospect Close, Lowmoor Road Ind., Est Kirkby-in-Ashfield, Nottinghamshire NG17 7LF, United Kingdom; +44 (0)1623 755539; Fax: +44 (0)1623 755719; information@globalemc.co.uk; www.globalemc.co.uk

Global Testing ....
4183 Riverview Drive, Riverside, CA 92509 USA; 951-781-4540; Fax: 951-781-4544; www.global-testing.com/

W. L. Gore & Associates, Inc. 94, 95
380 Starr Road, Landenberg, PA 19350-9221 USA; electronics.usa@wlgore.com; www.gore.com

Gowanda Electronics ....
One Magnetics Parkway, Gowanda, NY 14070 USA; 716-532-2234; Fax: 716-532-2702; sales@gowanda.com; www.gowanda.com

Green Mountain Electromagnetics, Inc. ....
219 Blake Roy Road, Middlebury, VT 05753 USA; 802-388-3390; Fax: 802-388-6279; gme@gmelectro.com; www.gmelectro.com

GTN Kommunikations- und Sicherungssysteme GmbH & Co. KG ....
Lindener Bergsfeld 9, D - 31188 Holle / OT Grasdorf; +49 (0)5062/8991-0; Fax: +49 (0)5062/8991-99; b.siebke@gtn-germany.de; http://www.gtn-germany.de

H

Haefely EMC 63
1650 Route 22, Brewster , NY 10509 USA; 845-279-8091; emcsales@hubbell-haefely.com; www.haefelyemc.com; www.hipotronics.com

Harris Corp. - EMI/TEMPEST Lab ....
P.O. Box 37, Melbourne, FL 32902 USA; 321-727-6209; Fax: 321-727-4335; jboorde@harris.com; www.govcomm.harris.com

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IN	New Albany	812-542-2540

INTERNATIONAL

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Heilind Electronics ....
58 Jonspin Road, Wilmington, MA 01887 USA; 800-555-8027; Fax: 440-473-9330; connect2@heilind.com; www.heilind.com

Henry Ott Consultants 126
48 Baker Road Livingston, NJ 07039 USA; 973-992-1793; Fax: 973-533-1442; h.ott@verizon.net; www.hottconsultants.com; Henry W. Ott, Pres.

Hermon Laboratories ....
Hatachana Street, P.O. Box 23, Binyamina 30500, Israel; +972-4-6268450; sales-tca@hermonlabs.com; www.hermonlabs.com

HFC Shielding Prod. Co. Ltd. ....
515 Valley St., Maplewood, NJ USA; 973-928-7769; emigasket@hotmail.com; www.emigasket.com

High & Low Corp. ....
4F-2, No. 129, Lane 235 ,Pao-Chiao Road, Hsin Tien City, Taipei Hsien 231, Taiwan; +886 2 89191800; Fax: +886 2 89191900; daniel@hal.com.tw; www.hal.com.tw

Hi-Tech Controls ....
14853 E. Hinsdale Ave., Suite D, Centennial, CO 80112-4240 USA; 303-680-5159; info@hitechcontrols.com; www.hitechcontrols.com

Hi-Voltage & EMI Corp. ....
93 Stone Lane, Levittown, NY 11756 USA; 516-644-5486; Fax: 516-735-3585; rfhivoltage2@aol.com; www.hivoltage.li

Holland Shielding Systems BV ....
Jacobus lipsweg 124, 3316BP Dordrecht, the Netherlands; +31 (0)78 - 613 13 66; Fax: +31 (0)78 - 614 95 85; info@hollandshielding.com; www.hollandshielding.com

Holaday Industries, Inc., ETS-Lindgren ....
1301 Arrow Point Drive, Cedar Park, TX; 512-531-6400; Fax: 512-531-6500; www.ets-lindgren.com

Hoolihan EMC Consulting 126
32515 Nottingham Court, P.O. Box 367 Lindstrom MN 55045 USA; 651-213-0966; Fax: 651-213-0977; Daniel D. Hoolihan, danhoolihanemc@aol.com; www.emcxpert.com

HV Technologies, Inc. 5
8526 Virginia Meadows Drive, Manassas, VA 20109 USA; 703-365-2330; Fax: 703-365-2331; emcsales@hvtechnologies.com; www.hvtechnologies.com; Tom Revesz, EMC Sales Manager

I

I. Thomas GmbH ....
An der B73 - 200a,D-21684 Stade, Germany; +49 4141 82920; Fax: +49 04141 84461; Vertrieb@Schirmkabinen.de; www.schirmkabinen.com

Identification Products Corp ....
104 Silliman Ave., Bridgeport, CT; 203-334-5969; info@idproducts.com; www.idproducts.com

IMS/AMCO Engineered Products ....
1 Innovation Drive, DesPlaines, IL; 847-391-8203; Fax: 847-391-8354; sales@imsmfg.com; www.imsep.com

iNARTE, Inc. ....
840 Queen St., New Bern, NC 28560 USA; 252-672-0111; 800-89-NARTE; Fax: 252-672-0111; Lawrence@inarte.us

Ingenium Testing, LLC. ....
3761 South Central Ave., Rockford, IL 61102 USA; 815-315-9250; Fax: 815-489-9561; michael.caruso@ingeniumtesting.com

Instrument Plastics Ltd. ....
Unit 35, Kings Grove Industrial Est., Maidenhead, Berkshire SL6 4DP, United Kingdom; +44 01628 770018; Fax: +44 01628 773295; rad@instrumentplastics.co.uk; www.instrumentplastics.co.uk

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903 South Second St., Ronkonkoma, NY 11779 USA; 631-467-8400; Fax: 631-467-8558; www.ifi.com; Mark Swanson, President; Mike Yantz, Sr. VP Sales; Catherine Schlie, Sales/Marketing; Leon Benatar, VP Engineering; Abe Jaffe, Director of Operations

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INTERNATIONAL

AUS	Mt. Riverview, Test & Measurement Australia Pty Ltd.	+61247399523
AUT	EMCO Elektronik	+49898955650
BEL	Air-parts B.V.	+31172422455
BRA	LUNUS	+551239418001
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CHE	Planegg, Pischzan Technologies	+49(0)6109771948
CHN	Shenzhen, Everjet Science & Technology Co	+8675526864487
DEU	Planegg-Martinsried, EMCO Elektronik	+49898955650
DEU	Maintal, Pischzan Technologies	+49 (0) 61 09 77 19 48
DNK	Hovik, Saven Hitech	+4767120512
ESP	Madrid, Adler Instrumentos	+34-91-3584046
FIN	Alphen aan den Rijn, Air-Parts B.V.	+31172422455
FRA	EMC Partner France	+33(0)5 55 74 31 68
GBR	Hertfordshire, Dowding & Mills	+44-462-421234
GRC	Athens, M.J.PRINIOTAKIS SA	+302107227719 or +30
IND	Mesa MW Corporation	+480 890-1612
IND	Secunderabad (Hyderabad), Kaytronics	+914027847924
ISR	Petah Tikva, RCM Ltd.	+972-3-9229006
ITA	Rome, LP Instruments	+390640800491
ITA	Trezzano, LP Instruments	39-02-48401713
JPN	Tokyo, Techno Science Japan Corp. (TSJ)	+81357993160
KOR	Kyonggi, InfoTech Co.	+ 82 32 612 8252
MYS	Singapore Technologies Electronics Ltd.	+6564131727
NLD	DA Lelystad, EEMC Coimex	+31 0320295395
NOR	Hovik, Saven Hitech	+4767120512
POL	Unitronex Corporation.	+4822 631 2643
RUS	Moscow, Radiocomp	+7(095)361-0904
SGP	Singapore Technologies Electronics Ltd (STEE)	+65 64133119
SWE	Stockholm, Ingenjörsfirman Gunnar Petterson AB	+46-8-930280
THA	Singapore Technologies Electronics LTF	+6564131727
TWN	Honova Resources Ltd.	+ 88 6282286089

Insul-Fab, Div of Concote Corp. ....
600 Freeport Parkway, Suite 150, Coppell, TX 75019 USA; 214-956-0055; Fax: 214-956-0848; andyw@insulfab.net; www.insulfab.net

Integrated Engineering Software........................
220-1821 Wellington Ave., Winnipeg, Manitoba, R3H 0G4 Canada; 204-632-5636; Fax: 204-633-7780; info@integratedsoft.com; www.integratedsoft.com

Integrated Microwave Corp. ....
11353 Sorrento Valley Road, San Diego, CA 92121 USA; 858-259-2600; Fax: 858-755-8679; dclark@imcsd.com; www.imcsd.com

Intermark (USA) Inc. 86
1310 Tully Road #117, San Jose, CA 95122 USA; 408-971-2055; Fax: 408-971-6033; sales@intermark-usa.com; www.intermark-usa.com; Masa Hatakeyama, VP

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70 Codman Hill Road, Boxborough, MA 01719 USA; 978 263 2662; 1-800-WORLDLAB; Fax: 978 264 9403; hope.mascott@intertek.com; www.intertek.com

INTERTest Systems, Inc. ....
303 Route 94, Colorado Springs, CO; 719-522-9667; Fax: 908-496-8004; info@intertestinc.com; www.intertest.com

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373 Main St., P.O. Box 165, Fremont, NH 03044 USA; 603-895-5100; 800-223-0466; Fax: 603-895-5101; sales@ionphysics.com; www.ionphysics.com; Leslie Faunce, Marketing Manager; Helmut Milde, President

IQS, a Div. of The Compliance Management Group ....
257 Simarano Drive, Marlboro, MA 01752 USA; 508-460-1400; Fax: 508-460-7979; rdunne@cmgcorp.net; www.iqscorp.com

ITC Engineering Services, Inc. ....
9959 Calaveras Road, Sunol. CA 94586 USA; 925-862-2944; Fax: 925-862-9013; sales@itcemc.com; www.itcemc.com

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ITL Israel ....
Bat-Sheva St. 1, POB 87, Lod, Israel; 972 8 9153100; Fax: 972-8-9153101; standard@itl.co.il; www.itl.co.il

ITT Interconnect Solutions ....
666 East Dyer Road, Santa Ana, CA 92705 USA; 714-628-8277; Fax: 714-628-8470; christine.stieglitz@btbmarketing.com; www.ittcannon.com

ITW/Pressure Sensitive Adhesinves & Components..
90 James Way, Southapmton, PA 18966; 215-322-1600; Fax: 215-322-1620; info@mcspecialties.com; www.mcspecialties.com

J

Ja-Bar Silicone Corp. ....
252 Brighton Ave., P.O. Box 1249, Andover, NJ 07821 USA; 973-786-5000; Fax: 973-786-5546; Maria Cruz, Customer Service Manager, mcruz@ja-bar.com; www.ja-bar.com

Jacobs Technology Inc. ....
3300 General Motors Road, Milford, MI 48380 USA; 248-676-1123; www.jacobstechnology.com

Jastech EMC Consulting, LLC ....
P.O. Box 3332, Farmington Hills, MI; 248-876-4810; info@jastech-emc.com; www.Jastech-EMC.com

JEMIC Shielding Technologies.............................
1160 S. Cameron St., Harrisburg, PA 17104 USA; 717-232-1030; dietrich@jemic.com; www.jemic.com

JiangSu WEMC Technology Co., Ltd. ....
No. 8, JianYe Road, TianMu Industrial Park, LiYang, JiangSu 213300, China; +86 519 8746 7888; Fax: +86 519 8746 5666; weiyl@wemctech.com; www.wemctech.com

JINAN Filtemc Electronic Equipment Co.,Ltd.
9 Lanxiang Road, Jinan ID 250032, China; +86 531 85738859; Fax: + 86 531 85717366; lwl@filtemc.com; www.filtemc.com

Johanson Dielectrics, Inc. ....
15191 Bledsoe St., Sylmay, CA 91342 USA; 818-364-9800; scole@johansondielectrics.com; www.johansondielectrics.com

JRE Test, LLC. ....
1350 Pittsford-Mendon Road, Mendon, NY 14506 USA; 585-298-9736; 888-430-3332; Fax: 585-919-6586; brian@jretest.com; www.jretest.com

JS TOYO Corporation (Shenzhen) Ltd.................
2-25G, China Phoenix Building Futian CBD, Shenzhen,, 518026 China; www.jstoyo.cn

K

Kemtron Limited...
19-21 Finch Drive, Braintree, Essex CM7 2SF, United Kingdom; +44 1376 348115; Fax: +44 1376 345885; David Wall, Managing Director, dbw@kemtron.co.uk; www.kemtron.co.uk

Keystone Compliance ....
2861 W. State St., New Castle, PA 16101 USA; 724-657-9940; Fax: 724-657-9920; tony@keystonecompliance.com; www.keystonecompliance.com

K-Form, Inc. ....
9A Acacia Lane, Sterling, VA 20166 USA; 703-450-4401; Fax: 703-894-4914; kform@kform.com; http://manufacturing.kform.com

Kikusui America Inc. ....
1633 Bayshore Hwy., Suite 331, Burlingame, CA 94010 USA; 650-259-5900; Fax: 650-259-5904; itoko@kikusuiamerica.us; www.kikusuiamerica.us

Kimmel Gerke Associates, Ltd.......................126
2538 West Monterey Ave., Mesa, AZ 85202 USA; 888-EMI-GURU; Daryl Gerke, dgerke@emiguru.com; www.emiguru.com
MN St. Paul 888-EMI-GURU
Bill Kimmel, bkimmel@emiguru.com

Kycon ....
11810 Little Orchard St., San Jose, CA 95125 USA; 408-494-0330; jill_scarnecchia@kycon.com; www.kycon.com

L

L. Gordon Packaging ....
22 W. Padonia Road, Suite 304A, Timonium, MD 21093 USA; 410-308-2202; Fax: 410-308-2207; lgordonpkg@verizon.net; www.lgordonpackaging.com

L.S. Research ....
W66 N220 Commerce Court, Cedarburg, WI 53012 USA; 262-375-4400; Fax: 262-375-4248; www.lsr.com

L-3 Communications Cincinnati Electronics.... 49
7500 Innovation Way, Mason, OH 45040-9699 USA; 513-573-6809; Fax: 513-573-6499; Steven Davis, Business Development Manager, Steven.Davis@L-3Com.com; www.L-3Com.com/ce

Laboratory Testing Inc. ....
2331 Topaz Drive, Hatfield, PA 19440 USA; 800-219-9095; Fax: 800-219-9096; sales@labtesting.com; www.labtesting.com

Laird Technologies ....
World Headquarters: 3481 Rider Trail, South St. Louis, MO 63045 USA; 1-800-843-4556; Fax 314-344-9333; matt.judkins@lairdtech.com;www.lairdtech.com

Lamart Corp. ....
16 Richmond St., Clifton, NJ 07011 USA; 973-772-6262; Steve Reidenbach, Product Manager - Industrial Tapes, sreidenbach@lamartcorp.com; www.lamartcorp.com

Langer EMV-Technik GmbH..............................52
Noethnitzer Hang 31, Bannewitz, 01728, DE, 0351-430093-23; michak@langer-emv.de; www.langer-emv.de

Laplace Instruments Ltd. ....
3B, Middlebrook Way, Holt Road, Cromer, Norfolk, NR27 9JR, UK; +44 (0) 12 63 51 51 60; Fax: +44 (0) 12 63 51 25 32; tech@laplace.co.uk; www.laplaceinstruments.com

Lapp USA...
29 Hanover Road, Florham Park, NJ 07932 USA; 973-660-9700; 800-774-3539; Fax: 973-660-9330; mbroe@lappusa.com; www.lappusa.com

LCR Electronics, Inc. 121
9 S. Forest Ave., Norristown, PA 19401 USA; 610-278-0840; Fax: 610-278-0935; Eric A. Kessler, Director of Commercial Sales, ekessler@lcr-inc.com; www.lcr-inc.com

Leader Tech, Inc. 71
12420 Race Track Road, Tampa, FL 33626 USA; 813-855-6921; 866-832-4364; Fax: 813-855-3291; Tim Black, Director - Sales & Marketing, tblack@leadertechinc.com; www.leadertechinc.com

LEDE-SIECIT..
48 & 116 St., La Plata, Buenos Aires 1900, Argentina; +54 11 221 4250877; lede@ing.unlp.edu.ar

Less EMF Inc. ....
809 Madison Ave., Albany, NY 12208; 518-432-1550; Fax: 309-422 - 4355; lessemf@lessemf.com; www.lessemf.com

L F Research EMC...
12790 Route 76, Poplar Grove, IL 61065; info@lfresearch.com; www.lfresearch.com; 815-566-5655; FAX: 815-547-3467

LGS Technologies ....
2950 W. Wintergreen, P.O Box 763039, Lancaster, TX 75134 USA; 972-224-9201; 1-800-441-5470; Fax: 972-228-0652; crobles@lgsco.com; www.lgstechnologies.com

Liberty Labs, Inc. 13
1346 Yellowwood Road, P.O. Box 230, Kimballton, IA 51543 USA; 712-773-2199; Fax: 712-773-2299; Tamie Fahn, Administrative Assistant, tfahn@libertylabs.com; www.libertylabs.com
INTERNATIONAL
JPN Yokohoma, Mitsunobu Samoto............................ 81-45-500-1280

Lightning Eliminators & Consultants, Inc..........
6687 Arapahoe Road, Boulder, CO 80303; 303-447-2828; Fax: 303-447-8122; www.lecglobal.com

Lightning Technologies, Inc. 61
10 Downing Industrial Parkway, Pittsfield, MA 01201-3890 USA; 413-499-2135; Fax: 413-499-2503; Mary Cancilla, cancilla@lightningtech.com; www.lightningtech.com

Little Mountain Test Facility..................................
12000 W.12th St., Ogden, UT 84404 USA; 801-315-2320

Littlefuse Inc. ....
8755 W. Higgins Road, Suite 500, Chicago, IL; 773-628-1000; Fax: 847 759 0272; www.littlefuse.com

LTI Metrology...
2331 Topaz Drive, Hatfield, PA 19440; 800-784-2882; Fax: 800.219.9096; sales@labtesting.com; www.labtesting.com

Lubrizol Conductive Polymers
9911 Brecksville Road, Brecksville, OH 44141 USA; 888-234-2436; Fax: 216-447-6232; kew@lubrizol.com; www.statrite.com

Lutze Inc. ....
13330 South Ridge Drive, Charlotte, NC 28273 USA; 704-504-0222; 1-800-447-2371; Fax: 704-504-0223; sgregson@lutze.com; www.lutze.com

M

Macton Corporation 50
116 Willenbrock Road, Oxford, CT 06478 USA; 203-267-1500x14; Fax: 203-267-1555; Jack Shepherd, Product Manager, 203-267-1500 x31, jshepherd@macton.com; www.macton.com

Magnetic Radiation Laboratories........................
690 Hilltop Drive, Itasca, IL 60143 USA; 630-285-0800; 888-251-5942; Fax: 630-285-0807; admin@magrad.com; www.magrad.com

Magnetic Shield Corp. ....
740 N. Thomas Drive, Bensenville, IL 60106-1643 USA; 630-766-7800; Fax: 630-766-2813; shields@magnetic-shield.com; www.magnetic-shield.com

MAJR Products Corp. ....
17540 State Highway 198, Saegertown, PA 16433 USA; 814-763-3211; 877-625-7776; Fax: 814-763-2952; terry@majr.com; www.majr.com

Marktek Inc. ....
13621 Riverway Drive, Suite H, Chesterfield, MO 63017 USA; 314-878-9190; 866-364-6285; Fax: 314-878-9558; Pres. arhenn@marktek-inc.com; www.marktek-inc.com

Master Bond Inc. ....
154 Hobart St., Hackensack, NJ 07601 USA; 201-343-8983; Fax: 201-343-2132; rruchama@masterbond.com; www.masterbond.com

maturo GmbH..
Bahnhofstr. 26,92536 Pfreimd, Germany; +49 9606 9239130; Fax: +49 (0) 9606 923913-29; info@maturo-gmbh.de; www.maturo-gmbh.de

MCL, Inc., A MITEQ Company...............................
501 S. Woodcreek Drive, Bolingbrook, IL 60440 USA; 630-759-9500; Fax: 630-759-5018; sales@mcl.com; www.mcl.com

Mech-Tronics...
1635 N. 25th Ave., Melrose Park, IL 60160 USA; 708-344-9823 ext.638; 1-800-989-9823; Fax: 708-344-0067; bob.feiler@mech-tronics.com; www.mech-tronics.com

MegaPhase LLC ....
2080 Hamilton Road East, Stroudsburg, PA 18360; 570-424-8400; Fax: 570-424-6031; www.megaphase.com

Mekoprint A/S Chemigraphics.............................
Mercurvej 1, DK-9530 Støvring, Denmark; +45 9936 5618; Fax: + 45 9936 5603; sk@mekoprint.dk; www.mekoprint.dk

Mercury United Electronics Inc. ....
9299 9th St., Rancho Cucamonga, CA 91730; 909-466-0427; Fax: 909-466-0762; sales-us@mercury-crystal.com; www.MercuryUnited.com

Mesago Messe Frankfurt GmbH..........................
Rotebuehlstrasse 83-85, Stuttgart, D-70178, Germany; www.mesago-online.de/en; 49 711 61946 26

MET Laboratories, Inc. 25
914 W. Patapsco Ave., Baltimore, MD 21230 USA; 410-354-3300;800-638-6057;Fax: 410-354-3313; info@metlabs.com; www.metlabs.com

Metal Textiles Corp. ....
970 New Durham Road, Edison, NJ 08818 USA; 732-287-0800; Fax: 732-287-8546; John Soltis, jsoltis@metexcorp.com; www.metexcorp.com

Metatech Corporation ....
358 South Fairview Avenue Suite E, Goleta, CA; 805-683-5681; Fax: 805-683-3023; info@metatechcorp.com; www.metatechcorp.com

MH&W International Corp. ....
14 Leighton Place, Mahwah, NJ 07430 USA; 201-891-8800; 866-MHW-CORE; Fax: 201-891-0625; garyv@mhw-intl.com; www.mhw-intl.com

Micrometals, Inc. ....
5615 E. La Palma Ave., Anaheim, CA 92807; 714-970-9400; Fax: 714-970-0400; sales@micrometals.com; www.micrometals.com

Michigan Scientific Corp. ....
321 East Huron St., Milford, MI 48381 USA; 248-685-3939 ext. 111; Fax: 248-684-5406; pjmorand@michscimfd.com; www.michsci.com

Micronor, Inc. ....
750 Mitchell Road, Newbury Park, CA 91320; 805-499-0114; Fax: 805-499-6585; sales@micronor.com; www.micronor.com

MILMEGA Ltd. ....
Ryde Business Park, Park Road, Ryde Isle of Wight PO33 2BE, United Kingdom; +44 (0)1983 618004; Fax: +44 (0)1983 811521; joeley@milmega.co.uk; www.milmega.com

MIRA Ltd. ....
Watling St., Nuneaton, Warwickshire CV10 0TU, United Kingdom; +44 (0) 2476 355 5000; Fax: +44 (0)2476 355 8000; matthew.farmer@mira.co.uk; www.mira.co.uk

Mitsubishi Digital Electronics America Inc. ...
9351 Jeronimo Road, Irvine, CA 92618-1904 USA; 949-465-6206

MKS Instruments ....
2 Tech Drive, Suite 201, Andover, MA 01810 USA; 978-645-5500; mks@mksinst.com; www.mksinst.com

Modpak, Inc. ....
97 Mudgett Road, Kenduskeag, ME 04450 USA; 207-884-8285; Fax: 207-884-8712; modpak@roadrunner.com; www.modpak.com

Montena EMC ....
Route de Montena 75, Rossens 1728, Switzerland; +41 26 411 93 33; Fax: +41 26 411 93 30; francois.volery@montena.com; www.montena.com

Montrose Compliance Service, Inc. **126**
2353 Mission Glen Drive, Santa Clara, CA 95051-1214 USA; 408-247-5715; mark@montrosecompliance.com; www.montrosecompliance.com

MOOSER Consulting GmbH ....
Amtmannstrabe 5, Egling/Thanning, 82544 Germany; 49-8176 92250; http://mooser-consulting.de/en_index.php?lang=english

Moss Bay EDA ....
23889 NE 112th Circle #2, Redmond ,WA 98053 USA; 206-779-5345; Fax: 484-730-5345; gene@mossbayeda.com; www.mossbayeda.com

MPE Ltd. ....
Hammond Road, Knowsley Industrial Park, Liverpool Merseyside L33 7UL, United Kingdom; +44(0)151 632 9100; Fax: +44(0)151 632 9112; sales@mpe.co.uk; www.mpe.co.uk

MTI - Microsorb Technologies, Inc. ....
32 Mechanic Ave., Unit 211, Woonsocket, RI 02895-0089 USA; 401-767-2269; 401-767-2255; engineer@microsorbtech.com; www.microsorbtech.com

Mueller Corp. ....
530 Spring St., East Bridgewater, MA 02333 USA; 508-583-2800; Fax: 508-378-4744; glenn@muellercorp.com; www.muellercorp.com

Murata Electronics North America ....
2200 Lake Park Drive, Smyrna, GA 30080-7604 USA; 770-436-1300; 800-241-6574; Fax: 770-805-3192; nrosenfeld@murata.com; www.murata.com

MμShield Company, Inc. **85**
9 Ricker Ave., Londonderry, NH 03053 USA; P.O. Box 5045, Manchester, NH 03108-5045; 603-666-4433 ext. 21; 888-669-3539; Fax: 603-666-4013; (800)666-4013; lukeg@mushield.com; www.mushield.com

N

Narda Safety Test Solutions, s.r.l. ....
Via Leonardo da Vinci, 21/23 – 20090, Segrate, Italy; 39-022699871; Fax: +39 02 26998700; support@narda-sts.it; www.narda-sts.it

National Magnetics Group, Inc. ....
1210 Win Drive, Bethlehem, PA; 610-761-7600; Fax: 610-867-0200; sales@magneticsgroup.com; www.magneticsgroup.com

National Technical Systems **1**
Headquarters: 24007 Ventura Blvd., Suite 200, Calabasas, CA 91302 USA; 800-270-2516; Fax: 818-591-0899; info@ntscorp.com; www.ntscorp.com; Nia Carignan, Marketing Supervisor

AR	Camden, NTS Camden	870-574-0031
AZ	Tempe, NTS Tempe	480-966-5517
CA	Culver City, NTS Culver City	310-641-7700
	Fremont, Elliott Labs	408-245-7800
	Fullerton, NTS Fullerton	714-879-6110
	Santa Clarita, NTS Santa Clarita	661-259-8184
	Santa Rosa, NTS Santa Rosa/Phase Seven	707-284-5875
	Sunnyvale, Elliott Labs	408-245-7800
KS	Wichita, NTS-USTL	316-832-1600
MA	Acton, NTS Acton	978-263-2933
MA	Boxborough, NTS Boxborough	978-266-1001
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NJ	Tinton Falls, NTS New Jersey	732-936-0800
TX	Plano, NTS Plano	972-509-2566
VA	Rustburg, NTS Rustburg/DTI	414-846-0244
	INTERNATIONAL	
CAN	NTS Calgary	403-568-6605

NAVAIR Advanced Warfare Technologies.. **47**
NAWCAD E3 DIVISION - Code 4.4.5, 48202 Standley Road, Hangar 144, Suite 3B Unit 5,Patuxent River, MD 20670-1910; 301-342-1663; Fax 301-342-6982; Mark.Mallory@navy.mil; Kurt.Sebacher@navy.mil; www.nawcad.navy.mil

NAWC AIRCRAFT DIVISION - E3 Branch Code 5.4.4.5 ....
48202 Standley Road, Hangar 144, Suite 3B, Unit 5, Patuxent River, MD 20670-1910 USA; 301-342-1663; Fax: 301-342-6982; raymond.hammett@navy.mil; www.navair.navy.mil/nawcad/

NCEE Labs ....
4740 Discovery Drive, Lincoln, NE 68521-5376 USA; 402-472-5880; 888-567-6860; Fax: 402-472-5881; dkramer@nceelabs.com; www.nceelabs.com

NEDC Fabricating Solutions ....
42 Newark St., Haverhill, MA 01832; (978)374-0789; www.nedc.com

Nemko USA ....
802 North Kealy Ave., Lewisville, TX 75057 USA; 972-436-9600; bruce.ketterling@nemko.com; www.nemko.com

NewPath Research L.L.C. ....
2880 S. Main St., Salt Lake City, UT 84115 USA; 801-573-9853; mahagmann@newpathresearch.com; www.newpathresearch.com

NEXIO ....
46 Avenue du General de Croutte, Toulouse 31100, France; +33 (0)5 61 44 02 47; Fax: +33 (0)5 61 44 05 67; sales@nexio.fr; www.nexio.frr

Nextek ....
439 Littleton Road, Westford, MA 01886 USA; 978-486-0582; Fax: 978-486-0583; araymond@nexteklightning.com; www.nexteklightning.com

Noise Laboratory Co., Ltd. **12**
1-4-4, Chiyoda, Chuo-ku, Sagamihara City, Kanagawa Pref 252-0237, Japan; +81-42-712-2051; Fax: +81-42-712-2050; Yuji Kimizuka, Senior Manager, sales@noiseken.com; www.noiseken.com

NY	New York, Shinyei Corp. of America	917-484-7893
	INTERNATIONAL	
AUS	DHS Elmea Tools GmbH	41-1-813-5380-0
BRA	Sao Paulo, T&M Instruments	55-11-5092-5229
CHN	Shenzhen, Shenzhen HaoGu Technology Co., Ltd.	86 0755 8398 8565
	Shenzhen, Rico Tools Trading Limited	86-755- 83600838
	Shenzhen,Nihon Denkei Co., Ltd.	86-755-8209-6179
	Shanghai, Rico Kohki (Shanghai) Co., Ltd.	86-21-63537223
	Shanghai, Shanghai Sanki Electronics Industries Co., Ltd.	86-21-6257-4333
	Shanghai,Nihon Denkei Co., Ltd.	86-21-5820-9710
	Dalian ,Nihon Denkei Co., Ltd.	86 -411-8762-2136
	Tianjin, Nihon Denkei Co., Ltd.	86-22-8386-5887
	Beijing, Nihon Denkei Co., Ltd.	86-10-5131-1181
	Dongguan, Nihon Denkei Co., Ltd.	86-769-2202-6986
DEU	Rodemark, DHS Elmea Tools GmbH	49-6074-9199080
IDN	Jakarta, Nihon Denkei Co. Ltd.	62-21 8087-1621
IND	Chennnai, MEL Systems and Services Ltd.	91-44-2496-1903
	Bangalore, Complus Systems Pvt. Ltd.	91-80-4168-3883
	Bangalore, Nihon Denkei India Private Limited	91-80-4093-5381
ISR	Ramat Gan, IES Electronics Agencies (1986) Ltd.	972-3-7530751
ITA	Druento, TESEO SpA	39-11-994 1911
KOR	Seoul, Noise Technology Co. Ltd.	82-31-781-7816
MYS	Kuala Lumpur,Nihon Denkei (Malaysia) Sdn Bhd.	60-3-2283-5702
	Selangor Daurl Ehsan, AMPTRONIC (M) SDN.BHD.	60-3-5632-8411
PHL	Makati City, Nihon Denkei Co., Ltd.	63-2-8452638
SGP	NihonDenkei Co. Ltd.	65-6355-0851
THA	Bangkok, Nihon Denkei Co. Ltd.	66-2-675-5688
	Bangkok, Industrial Electrical Co., Ltd.	66-2-642-6700
TWN	Taipei, Precision International Corp.	886-2-8512-4888
VNM	Hanoi, Nihon Denkei(Vietnam) Co., Ltd	84-4-951-6505

Nolato Silikonteknik ....
Bergmansv 4, Hallsberg 702 16, Sweden; +46 582 88900; magnus.johansson@nolato.se; www.nolato.se/silikonteknik

Northern Technologies Corp. ....
95 Konrad Crescent, Markham, Ontario L3R 8T8, Canada; 905-475-9320; 800-456-1875; Fax: 905-475-5719; chrismarshall@northerntech.com; www.northerntech.com

Northwest EMC, Inc. ....
41 Tesla, Irvine, CA 92618 USA; 888-364-2378; www.nwemc.com

NP Technologies, Inc. ....
2393 Teller Road #108, Newbury Park, CA 91320 USA; 805 376-9299; Fax: 805 376-9288; sales@nptrf.com; www.nptrf.com

Nu Laboratories, Inc....
312 Old Allerton Road, Annandale, NJ; 908-713-9300; Fax: 908-713-9001; webmaster@nulabs.com; www.nulabs.com

O

Oak-Mitsui Technologies ....
80 1st St., Hoosick Falls, NY 12090 USA; 518-686-8088; Fax: 518-686-8080; john.andresakis@oakmitsui.com; www.oakmitsui.com

Okaya Electric America, Inc. ....
52 Marks Road, Suite 1, Valparaiso, IN 46383 USA; 800-852-0122; Fax: 219-477-4856; ross@okaya.com; www.okaya.com

OPHIR RF...
5300 Beethoven St., Los Angeles, CA 90066 USA; 310-306-5556; Fax: 310-577-9887; pvirga@ophirrf.com; www.ophirrf.com

Orbel Corp. ....
2 Danforth Drive, Easton, PA 18045 USA; 610-829-5000; Fax: 610-829-5050; lgiralico@orbel.com; www.orbel.com

ORBIT Advanced Electromagnetics, Inc. (AEMI) ....
P. O. Box 711719, Santee, CA 92072-1719 USA; 619-449-9492; Fax: 619-449-1553; Isaac@mc-tech.com; www.aemi-inc.com

Orion Industries Inc....
One Orion Park Drive, Ayer, MA; 978-772-6000; Fax: 978-772-0021; www.orionindustries.com

Oxley Developments Company Ltd. ....
Priory Park, Cumbria, Ulverston LA12 9QG, United Kingdom; +44 0 1229 840519; Fax: +44 0 1229 870451; m.blows@oxley.co.uk; www.oxleygroup.com

P

P & P Technology Ltd....
Finch Drive, Springwood, Braintree, Essex, CM7 2SF United Kingdom; +44 (0) 1376 550525; Fax: +44 (0) 1376 552389; info@p-p-t.co.uk; www.p-p-t.co.uk

Pacific Aerospace & Electronics, Inc. ....
434 Olds Station Road, Wenatchee, WA 98801 USA; 509-665-8000; Fax: 509-663-5039; rkalkowski@pacaero.com; www.pacaero.com

Paladin EMC..
65 Buckwheat Ave., Portsmouth, RI 02871 USA; 401-924-3700; spence@paladinemc.com; www.paladinemc.com

Panashield, Inc. **67**
185R West Norwalk Road, Norwalk, CT 06850-4312 USA; 203-866-5888; Fax: 203-866-6162; Peggy Girard, VP/GM, girard@panashield.com; www.panashield.com

Panasonic Electronic Components....................
Three Panasonic Way, 7H-2 Secaucus, NJ 07094 USA; 1-800-344-2112; Fax: 201-348-7393; piccomponentsmarketing@us.panasonic.com; www.panasonic.com/industrial/electronic-components/

Parker EMC Engineering..
15246 Daphne Ave., Gardena, CA 90249-4122 USA; 310-323-4188; Fax: 310-323-4188; parkeremc@worldnet.att.net; http://parkeremc.mustbehere.com

RESEARCH & DEVELOPMENT LAB
PARTNERSHIP FOR DEFENSE INNOVATION

Partnership for Defense Innovation.............. **43**
455 Ramsey St., Fayetteville, NC 28301 USA; 910-307-3060; Fax: 910-307-3007; info@ncpdi.org; www.ncpdilab.org

Pasternack Enterprises ....
P.O. Box 16759, Irvine, CA 92623 USA; 1-866-727-8376; Fax: 949-261-7451; shaun@pasternack.com; www.pasternack.com

Peak Electromagnetics Ltd. ....
139 Bank St., Macclesfield,Cheshire SK11 7 AY, United Kingdom; +44 01625 2698080; ian.pocock@peak-em.co.uk; www.peak-em.co.uk

Pearson Electronics, Inc. **55**
4009 Transport St., Palo Alto, CA 94303 USA; 650-494-6444; Fax: 650-494-6716; Sherri Morfin, Sherri@pearsonelectronics.com; www.pearsonelectronics.com

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PennEngineering ....
5190 Old Easton Road, Danboro, PA 18916 USA; 215-766-8853; Fax: 215-766-0143; gkelly@penn-eng.com; www.pemnet.com

Percept Technology Labs, Inc. ....
4888 Pearl East Circle, #110, Boulder, CO 80301 USA; 303-444-7480; www.percept.com

Philips Applied Technologies - EMC center ....
5190 Old Easton Road, Danboro, PA 18916 USA; 215-766-8853; Fax: 215-766-0143; gkelly@penn-eng.com; www.pemnet.com

Philips Innovation Services-EMC center
High Tech Campus 26, PO box 80036, Eindhoven, Noord Brabant 5656AE The Netherland; +31-40-2746771; Fax: +31-40-2742233; emc.testlab@philips.com; www.emc.philips.com

Phoenix Contact...
586 Fulling Mill Road, Middletown, PA 17057 USA; 717-944-1300; Fax: 717-944-1625; info@phoenixcon.com; www.phoenixcontact.com/usa_home

Photofabrication Engineering Inc. ....
500 Fortune Drive, Milford, MA 01757 USA; 508-478-2025; Fax: 508-478-3582; clehrer@photofabrication.com; www.photofabrication.com

Pioneer Automotive Technologies, Inc. - EMC Lab ....
100 S. Pioneer Blvd., Springboro, OH 45066 USA; 937-746-6600 ext. 363; Fax: 937-746-6828; mark.condon@pioneer-usa.com; www.pioneeremc.com

Plastic-Metals Technology Inc. ....
7051 SW Sandburg Road, Ste. 200, Tigard, OR; 503-684-0725; Fax: 503-684-0735; www.p-mtinc.com

Positronic Industries...
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Power & Controls engineering Ltd. ....
4 Foothills Drive, Ottawa, Ontario K2H 6K3, Canada; 613-829-0820; Fax: 613-829-8127; mail@pcel.ca; www.pcel.ca

Power Products International Ltd. ....
Commerce Way, Edenbridge, Kent TN8 6ED, United Kingdom; + 44 (0) 1732 866424; Fax: + 44 (0) 1732 866399; gkrobinson@ppi-uk.com; www.ppi-uk.com

Power-Electronics Consulting ....
4 Tyler Road, Lexington, MA 02420-2404 USA; 781-862-8998; nathansokal@gmail.com

Power Standards Lab (PSL)..................................
2020 Challenger Drive #100, Alameda, CA; 510-919-4369; Fax: -510-522-4455; Sales@PowerStandards.com; www.powerstandards.com

PPM (Pulse Power & Measurement) Ltd. ....
65 Shrivenham, Hundred Business Park, Watchfield, Swindon SN6 8TY, United Kingdom; +44 1793 784389; Fax: +44 1793 784391; sales@ppm.co.uk; www.point2point.co.uk

Praxsym, Inc. ....
120 S. Third St., P.O. Box 369, Fisher, IL 61843 USA; 217-897-1744; Fax: 217-897-6388; jmeissen@praxsym.com; www.praxsym.com

Precision Photo-Fab, Inc. ....
4020 Jeffrey Blvd., Buffalo, NY 14219; 716-821-9393; Fax: 716-821-9399; www.precisionphotofab.com

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12955 Bellamy Brothers Blvd., Dade City, FL 33525 USA; 352-588-2209; Fax: 352-588-2544; arobbins@pseinc.com; www.pseinc.com

Professional Testing (EMI), Inc. ....
1601 N. A.W. Grimes, Suite B, Round Rock, TX 78665 USA; 512-244-3371; www.ptitest.com

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2404 East 28th St., P.O. Box 72709, Chattanooga, TN 37407 USA; 1-423-629-0007; 1-888-988-0007; Fax: 1-423-629-0444; kevin@pfillers.com; www.progressivefillers.com

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1072 Tower Lane, Bensenville, IL 60106; 630-238-8883; Fax: 630-238-9717; www.prostatcorp.com

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Pulver Laboratories Inc.
320 North Santa Cruz Ave., Los Gatos, CA 95030-7243 USA; 408-399-7000; 800-635-3050; Fax: 408-399-7001; Lee.Pulver@PulverLabs.com; www.PulverLabs.com

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QEMC
Rio de Janeiro, Brazil; (+55.21) 8111 6661; www.QEMC.com.br

QinetiQ
Cody Technology Park, Ively Road, Farnborough, Hants GU14 0LX, United Kingdom; +44 1252 393437; Fax: +44 1252 397058; emcfocus@qinetiq.com; www.QinetiQ.com/emc

Q-par Angus Ltd.
Barons Cross Laboratories, Leominster, Herefordshire HR6 8RS, United Kingdom; +44 (0)1568 612138; Fax: +44 (0)1568 616373; julian.robbins@q-par.com; www.q-par.com

Qualtek Electronics Corp.
7675 Jenther Drive, Mentor, OH 44060 USA; 440-951-3300; Fax: 440-951-7252; bgrubb@qualtekusa.com; www.qualtekusa.com

Qualtest Inc.
5325 Old Winter Garden Road, Orlando, FL 32811 USA; 407-313-4230; Fax: 407-313-4234; chebda@qualtest.com; www.qualtest.com

Quarterwave Corp.
1300 Valley House Drive, Suite 130, Rohnert Park, CA 94928 USA; 707-793-9105; Fax: 707-793-9245; paul@quarterwave.com; www.quarterwave.com

Quell Corp.
5639 B Jefferson, NE Albuquerque, NM 87109 USA; 505-243-1423; Fax: 505-243-9772; eeseal@aol.com; www.eeseal.com

R

Radiometrics Midwest Corp. 26
12 E. Devonwood, Romeoville, IL 60446 USA; 815-293-0772; Fax: 815-293-0820; Dennis Rollinger, CEO, info@radiomet.com; www.radiomet.com

RADIUS POWER

Radius Power, Inc. 104
1751 N. Batavia St., Orange, CA 92865 USA; 714-289-0055; Fax: 714-289-2149; George Wells, Sales Manager, georgew@radiuspower.com; www.radiuspower.com

Rainford EMC Systems Ltd.
North Florida Road, Haydock St., Helens, Merseyside GA WA11 9TN, United Kingdom; +44 1942 296 190; Fax: + 44 1942 275 202; bill.mcfadden@rainfordemc.com; www.rainfordemc.com

Ramsey Electronics
590 Fishers Station Drive, Victor, NY 14564 USA; 585-924-4560; Fax: 585-924-4555; brian@ramseyelectronics.com; www.ramseytest.com

Remcom Inc.
315 S. Allen St., Suite 222, State College, PA 1680 USA; 814-861-1299; 888-773-6266; slucas@remcom.com; www.remcom.com

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921 Venture Ave., Leesburg, FL 34748 USA; 877-220-5554; 888-886-0585; eric.egler@restormetrology.com; www.restormetrology.com

RETLIF TESTING LABORATORIES

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795 Marconi Ave., Ronkonkoma, NY 11779 USA; 631-737-1500; Fax: 631-737-1497; sales@retlif.com; www.retlif.com; Walter A. Poggi, Pres.; William K. Hayes, Exec. V.P.; Scott Wentworth, NH Branch Mgr.; Joseph Maiello, PA Branch Mgr.

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RFI Global Services Ltd.
Pavilion A, Ashwood Park, Ashwood Way, Basingstoke, Hampshire, RG23 8BG United Kingdom; +44 (0)1256 312000; Fax: +44 (0)1256 312001; www.rfi-global.com

RF Immunity Ltd. 118
2.Prat St., Yavne 81227, Israel; 972-73-2331300; Fax: 972-73-2331325; Haim Kalfon, Managing Director, haimk@rfimmunity.co.il; www.rfimmunity.com

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340 Village Lane, Los Gatos, CA 95030 USA; 408-399-7007; Fax: 408-399-7011; jessica.hayes@rficontrols.com; www.rficontrols.com

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100 Pine Aire Drive, Bay Shore, NY 11706-1107 USA; 631-234-6400; Fax: 631-234-6465; ilashinsky@rficorp.com; www.rficorp.com

RFTEK
5103 Duntrune Court, Raleigh, NC 27606 USA; 919-622-4088; dguzman@rftek.net; www.rftek.net

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360 Herndon Parkway, Suite 1400, Herndon, VA 20170 USA; 703-689-0368; Fax: 703-689-2056; sgrandy@rheintech.com; www.rheintech.com

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200 Tornillo Way, Tinton Falls, NJ 07712 USA; 732-389-1300; 888-722-5625; Fax: 732-389-9066; donna@riaconnect.com; www.riaconnect.com

Rittal Corp.
1 Rittal Place, Urbana, OH 43078 USA; 937-399-0500; 1-800-477-4000; Fax: 937-390-5599; mcorcoran@rittal-corp.com; www.rittal-corp.com

RMV Technology Group, LLC
NASA Research Park Bldg. 19, Suite 2030, MS 19-46C, Moffett Field, CA 94517 USA; 650-964-4792 650-964-1268; bob@esdrmv.com; www.esdrmv.com

Rogers Labs, Inc.
4405 West 259th Terrace, Louisburg, KS 66053 USA; 913 837-3214; Fax: 913 837-3214; rogers@pixius.net; www.rogerslabs.com

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8661A Robert Fulton Drive, Columbia, MD 21046-2265 USA; 888-837-8772; Fax: 410-910-7801; Achim.Gerstner@rsa.rohde-schwarz.com; www.rohde-schwarz.com/usa

Roxburgh EMC
Deltron Emcon House, Hargreaves Way, Sawcliffe Industrial Park, Scunthorpe, North Lincolnshire, DN15 8RF, United Kingdom; +44 1724 273205; Fax: +44 1724 280353; dkilminster@dem-uk.com; www.dem-uk.com/roxburgh

Roxtec
10127 E. Admiral Place, Tulsa, OK 74116 USA; 918-254-9872; 800-520-4769; Fax: 918-254-2544; michael.budde@us.roxtec.com; www.roxtec.com

RTP Company
580 E. Front St., Winona, MN 55987 USA; 507-454-6900; Fax: 507-454-2041; Kirk Fratzke, Advtg and Promotions, rtp@rtpcompany.com; www.rtpcompany.com/

Rubbercraft
15627 South Broadway, Gardena ,CA 90248 USA; 310-328-5402; Fax: 310-618-1832; mchian@rubbercraft.com; www.rubbercraft.com

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284 West Drive, Melbourne, FL 32904 USA; 321-951-1710; jgerke@rubicomtestlab.com; www.rubicomtestlab.com

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Safety Test Technology Co., Ltd
Pu Tian Science Park B415, 28 Xin Jie Kou Wai Da Jie, Xicheng District, Beijing, 100088 P.R. China; 86-10-51654077; FAX: 86-10-82051730; overseas@instrument.com.cn; www.instrument.com.cn

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939 Wading River Manor Road, Manorville, NY 11949 USA; 631-727-1441 ext. 302; Fax: 631-727-1387; msteckis@sasindustries.com; www.sasindustries.com

schaffner

Schaffner EMC, Inc. 105
52 Mayfield Ave., Edison, NJ 08837 USA; 800-367-5566; Fax: 732-225-4789; Ken Bellero, ken.bellero@schaffner.com; www.schaffnerusa.com

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IN Allied Enterprises, Inc......................................440-808-8760
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KY Allied Enterprises, Inc......................................440-808-8760
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ME Norris Associates Inc....................................... 781-749-5088
MI Allied Enterprises, Inc......................................440-808-8760
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MO Connector Technology LLC (CTEC) 636-561-3543
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Schlegel Electronic Materials ....Inside Back Cover
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447 Aviation Blvd., Santa Rosa, CA 95403 USA; 707-636-3000; Fax: 707-636-3033; Marjorie Tibbs, Marcom Coordinator, mtibbs@schurterinc.com; www.schurterinc.com
SWI Lucerne ....+41 41 369 33 82

Seal Science 96
Seal Science West: 17131 Daimler St., Irvine, CA 92614 USA; 949-253-3130; Fax: 949-253-3141; westernsales@sealscience.com; Seal Science East: 1160 Win Drive, Bethlehem, PA 18017-0759; 610-868-2800; Fax: 610-868-2144; easternsales@sealscience.com; www.sealscience.com

Sealcon ....
14853 E. Hinsdale Ave., Suite D, Centennial, CO 80112-4240 USA; 303-699-1135; info@sealconusa.com; www.sealconusa.com

Sealing Devices Inc. ....
4400 Walden Ave., Lancaster, NY 14228 USA; 716-684-7600; 800-727-3257; Fax: 716-684-0760; deberhardt@sealingdevices.com; www.sealingdevices.com

Seibersdorf Laboratories......................................
Seibersdorf Labor GmbH, Seibersdorf 2444, Austria; +43 50550 2500; Fax: +43 50550 2502; www.seibersdorf-laboratories.at

Select Fabricators Inc. 99
5310 North Str. Bldg. 5, P.O. Box 119, Canandaigua, NY 14424-0119 USA; 585-393-0650; 888-599-6113; Dan Ramich & Brian Smith; contactus@select-fabricators.com; www.select-fabricators.com

Sensor Products Inc. ....
300 Madison Ave., Madison, NJ 07940 USA; 973-884-1755; 800-755-2201; Fax: 973-884-1699; dlandau@sensorprod.com; www.sensorprod.com

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913 Tressler St., P.O. Box 650, Boalsburg, PA 16827 USA; 814-466-6559; Fax: 814-466-2777; tom@7ms.com

SDP Engineering Inc. ....
17 Spectrum Pointe, P.O. Box #508, Lake Forest, CA 92630 USA; 949-588-7568; Fax: 949-588-8871; don@sdpengineering.com; www.sdpengineering.com

SGS...
201 Route 17, North Rutherford, NJ 07070 USA; 201-508-3188; Fax: 201-935-4555; maureen.plowman@sgs.com; www.ee.sgs.com

Shanghai Empek Electromagnetic Technology Ltd. ....
No.78 Caobao Road, Shanghai, China; +86 21 62477218 62477258; Fax: +86 21 62475839; vtexpo@online.sh.cn; www.emcexpo.com

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9512 E. 55th St., Tulsa, OK 74145; 918-663-1985; Fax: 918-663-1986; www.shieldingresources.com

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Silicon Labs...
400 W. Cesar Chavez, Austin, TX 78701 USA; 512-416-8500; Fax: 512-416-9669; susan.nayak@silabs.com; www.silabs.com

Silicone Solutions...
1670-C Enterprise Pkwy., Twinsburg, OH 44087; 330-405-4595; Fax: 330-405-4596; www.siliconesolutions.com

SILENT Solutions ....
10 Northern Blvd., Suite 1, Amherst, NH 03031 USA; 603-578-1842; LeeHillSilent@gmail.com; www.silent-solutions.com

Simberian Inc. ....
2326 E. Denny Way, Seattle, WA 98122 USA; -2029; Yuriy Shlepnev, President, shlepnev@simberian.com; www.simberian.com

SimLab Software GmbH..
Bad Nauheimer Str. 19, 64289 Darmstadt,Germany; 49 6151 7303-0; Fax: +49 6151 7303-100; schrack@simlab.de; www.cst.com

SiTime Corp. ....
990 Almanor Ave., Sunnyvale, CA 94085 USA; 408-331-9138; Fax: 408-328-4439; psevalia@sitime.com; www.sitime.com

Solar Electronics Co. ....
10866 Chandler Blvd., North Hollywood, CA 91601 USA; 818 755-1700; 800-952-5302; Fax: 818 755-0078; tom@theparkerpress.com; www.solar-emc.com

Soliani EMC SRL ....
Via Varesina 122, 22100 Como Lombardia, Italy; +39-031-5001112; Fax: + 39-031-505467; info@solianiemc.com; www.solianiemc.com

Sonnet Software, Inc. ....
100 Elwood Davis Road, N. Syracuse, NY 13212 USA; 315-453-3096; 1-877-7SONNET; Fax: 315-451-1694; calton@sonnetsoftware.com; www.sonnetsoftware.com

Soshin Electronics Europe GmbH ....
Westerbachstrasse 32, c/o NGK Europe GmbH, Kronbergim, Taunus D-61476, Germany; 49-6173-993108; Fax: +49-6173-993206; tkhayashi@soshin.co.jp; www.soshin-ele.com/

Southwest Microwave, Inc. ....
9055 South McKemy St., Tempe, AZ 85284; 480-783-0201; www.southwestmicrowave.com

Southwest Research Institute ....
6220 Culebra Road, P.O. Drawer 28510, San Antonio, TX 78228; 210-684-5111; www.swri.com

Spec-Hardened Systems ....
110 Larkwood Drive, Rochester, NY 14625-4270 USA; 585-225-2857; Fax: 585-225-2857; shsesc@aol.com; members.aol.com/shsec.myhomepage/index.html

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4675 Burr Drive, Liverpool, NY 13088 USA; 315-730-5667; Fax: 315-457-0428; source1.sf@gmail.com; www.source1compliance.com

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434 Olds Station Road, Wenatchee, WA 98801 USA; 509-664-8000; Fax: 509-663-5039; rkalkowski@pacaero.com; www.pacaero.com

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3 McCrea Hill Road, Ballston Spa, NY 12020 USA; 518-885-8826; 800-437-1442; Fax: 518-885-4682; astiles@sspinc.com; www.sspinc.com

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Spira Manufacturing Corp. 91
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