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2018 MILITARY & AEROSPACE EMC GUIDE

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INTRODUCTION

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There some exciting technologies occurring within the military and aerospace sectors. Advances in millimeter wave communications and control, and especially autonomous vehicles, more advanced UAVs, drones, and robotics, are playing a greater role in military strategy. For example, drones now make up half the U.S. Air Force fleet and the next generation are already under development.

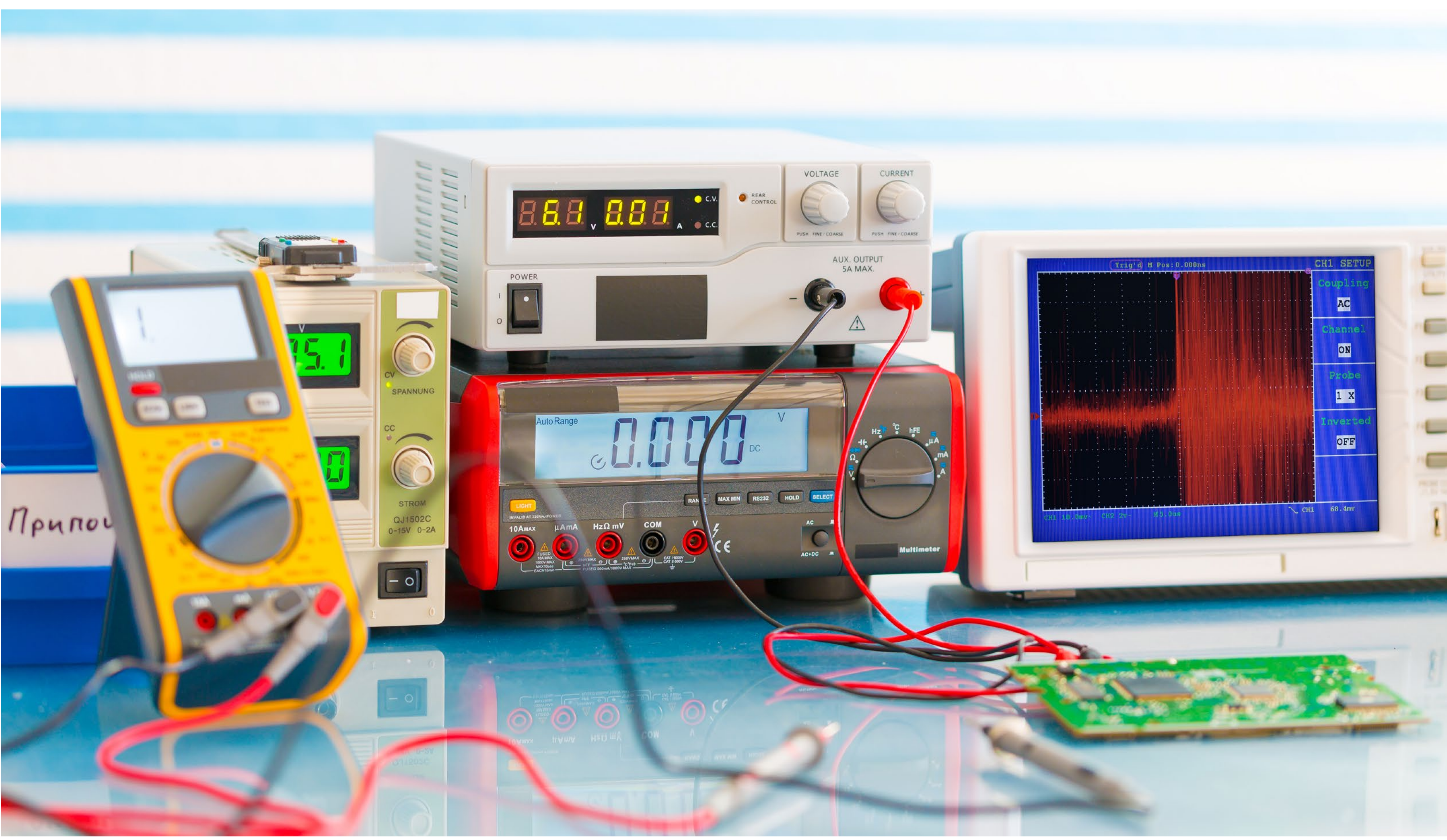
In addition, the aerospace sector is moving ahead with many exciting projects, including the James Webb Space Telescope with improved technology over the current Hubble Telescope. Commercial space launch platforms from Virgin Galactic, SpaceX, Scaled Composites, and the many "mini" launch companies, such as Sierra Nevada, Star Chaser, Venturer Aerospace, XCOR, Blue Origin, and others, are bringing more affordable alternatives to NASA and Arianne programs, as well as existing programs in Russia, China, Japan, and many other countries.

This new downloadable guide helps bring product designers and EMC engineers up to date on current DoD procurement policies and procedures. It also includes articles on MIL-STD and aerospace tests and standards, an introduction to the newly released MIL-STD-461G, a review of current MIL-STD-461G RE101 and 102 testing, dynamic spectrum allocation between military and commercial systems, electronic equipment grounding, and selecting the right filter for military and defense applications. Finally, we wrap up with some useful reference data on military and aerospace standards, a chart of EMC-related equipment suppliers, links to longer articles, and other valuable references.

EMC EQUIPMENT MANUFACTURERS

Introduction

The following chart is a quick reference guide of test equipment and includes everything you'll need from the bare minimum required for key evaluation testing, probing, and troubleshooting, to setting up a full in-house precompliance or full compliance test lab for military and aerospace testing. The list includes amplifiers, antennas, current probes, ESD simulators, LISNs, near field probes, RF signal generators, spectrum analyzers, EMI receivers, and TEM cells. Equipment rental companies are also listed. The products listed can help you evaluate radiated and conducted emissions, radiated and conducted immunity and a host of other immunity tests, such as the new ESD test for MIL-STD-461G.



EMC Equipment Manufacturers		Type of Product/Service															
Manufacturer	Contact Information - URL	Amplifiers	Antennas	Conducted Immunity	Current Probes	EMC Filters	EMC Testing	ESD Simulators	LISNs	Near Field Probes	Pre-Compliance Test	Radiated Immunity	Rental Companies	RF Signal Generators	Software	Spectrum Analyzers/EMI Receivers	TEM Cells
A.H. Systems	www.ahsystems.com	X	X		X						X						
Aaronia AG	www.aaronia.com	X	X								X					X	
Advanced Test Equipment Rentals	www.atecorp.com	X	X	X	X			X	X	X	X	X	X	X		X	X
ALTAIR	www.altair.com														X		
Amplifier Research (AR)	www.amplifiers.com	X	X	X					X		X	X		X		X	
Anritsu	www.anritsu.com										X			X		X	
Electro Rent	www.electrorent.com	X		X				X	X		X	X	X	X		X	
EM Test	www.emtest.com/home.php			X							X						X
EMC Partner	www.emc-partner.com			X				X									
Empower RF Systems	www.empowerrf.com	X										X					
Fischer Custom Communications	www.fischercc.com				X				X	X	X						
Gauss Instruments	www.gauss-instruments.com/en/															X	
Haefley-Hippotronics	www.haefely-hipotronics.com			X				X									
HV Technologies, Inc.	www.hvtechnologies.com	X		X								X		X		X	
Instrument Rental Labs	www.testequip.com	X		X				X	X		X	X	X	X		X	
Instruments For Industry (IFI)	www.ifi.com	X		X								X					
ITG Electronics	www.itg-electronics.com					X											
Keysight Technologies	www.keysight.com/main/home.jspx?cc=US&lc=eng								X	X	X			X	X	X	
Microlease	www.microlease.com/us/home	X		X				X	X		X	X	X	X		X	
Milmega	www.milmega.co.uk	X		X								X					
Narda/PMM	www.narda-sts.it/narda/default_en.asp	X	X	X					X		X	X				X	
Noiseken	www.noiseken.com			X				X			X						
Ophir RF	www.ophirrf.com	X		X													
Pearson Electronics	www.pearsonelectronics.com				X												
PPM Test	www.ppmtest.com		X								X	X			X	X	
R&B Laboratory	www.rblaboratory.com						X										
Rigol Technologies	www.rigolna.com				X					X	X			X	X	X	
Rohde & Schwarz	www.rohde-schwarz.com/us/home_48230.html	X	X	X	X				X	X	X	X		X	X	X	
Siglent Technologies	www.siglentamerica.com									X	X			X	X	X	
Signal Hound	www.signalhound.com									X	X			X	X	X	
TekBox Technologies	www.tekbox.net	X							X	X	X				X		X
Tektronix	www.tek.com									X	X				X	X	
Teseq	www.teseq.com/en/index.php	X		X	X			X			X	X					X
Test Equity	www.testequity.com/leasing/	X		X				X	X		X	X	X	X		X	
Thermo Keytek	www.thermofisher.com/us/en/home.html			X				X									
Thurlby Thandar (AIM-TTi)	www.aimtti.us										X			X		X	
Toyotech (Toyo)	www.toyotechus.com/emc-electromagnetic-compatibility/	X	X						X		X	X				X	
TPI	www.rf-consultant.com										X			X			
Transient Specialists	www.transientspecialists.com			X								X					X
TRSRenTelCo	www.trs-rentelco.com/SubCategory/EMC_Test_Equipment.aspx	X	X	X					X		X	X	X	X		X	
Vectawave Technology	www.vectawave.com	X															
Windfreak Technologies	www.windfreaktech.com										X			X			

INTRODUCTION TO DoD POLICY, GUIDANCE, & THE ACQUISITION PROCESS

Tony Keys
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Introduction
This article provides an introduction to DoD policy, guidance and the acquisition process. E3 is defined as the impact of the Electromagnetic Environment (EME) upon the operational capability of military forces, equipment, systems, and platforms. E3 encompasses all electromagnetic disciplines, including Electromagnetic Interference and Electromagnetic Compatibility (EMI/EMC); Electromagnetic Vulnerability (EMV); Electromagnetic Pulse (EMP); natural phenomena such as lightning, electrostatic discharge (ESD) and precipitation static; and Hazards of Electromagnetic Radiation to Personnel (HERP), Ordnance (HERO), and Fuel (HERF). In addition, Spectrum Supportability must be addressed in conjunction with E3 for Spectrum Dependent (S-D) systems.

INTRODUCTION TO DoD POLICY, GUIDANCE, & THE AQUISITION PROCESS

Early consideration of E3 and Spectrum Supportability (SS) in electronic and S-D systems is a fundamental criterion that must be satisfied before communications-electronics (CE) equipment and related weapons systems are developed and fielded. Development or acquisition of systems that meet operational requirements, but are not electromagnetically compatible or fail to obtain spectrum supportability, creates a potential for severe mutual interference between themselves and other spectrum users, squanders resources, and delays fielding warfighting capabilities to field units.

Equipment, subsystems and systems employed for military purposes are exposed to extreme EMEs. Providing the warfighter with systems that will operate within these extreme EMEs requires specific requirements, design and test considerations. This new mini guide from Interference Technology will review E3 related policies and requirements specific to military equipment, subsystems and systems, from a top down perspective, including overviews of MIL-STD-464C and MIL-STD-461G, a listing of relevant military E3 related documents and points of contact.

Real World Operational Impacts/Examples

There are many examples of EMC and spectrum supportability problems in military systems which have caused serious, and even catastrophic, operational and programmatic problems. Some examples include:

Between 1981 and 1987, several UH-60 Blackhawk helicopters nose-dived and crashed, killing 22 servicemen. The crashes were attributed to insufficient flight control immunity to high intensity radiated fields when flying past radio broadcast towers. This interference produced uncommanded control surface movements causing fatal dives.

The US Air Force has had to address a potential frequency-interference issue with their B-2 bombers. Analysis indicates a high probability of the Raytheon AN/APQ-181 radar system on the B-2As interfering with commercial satellite communications after 2007.

The B-2's radar would most likely disrupt their transmissions and could damage commercial communications satellites, for which the USAF likely would be liable, according to industry sources. The total estimated cost is expected to exceed $1.3B.

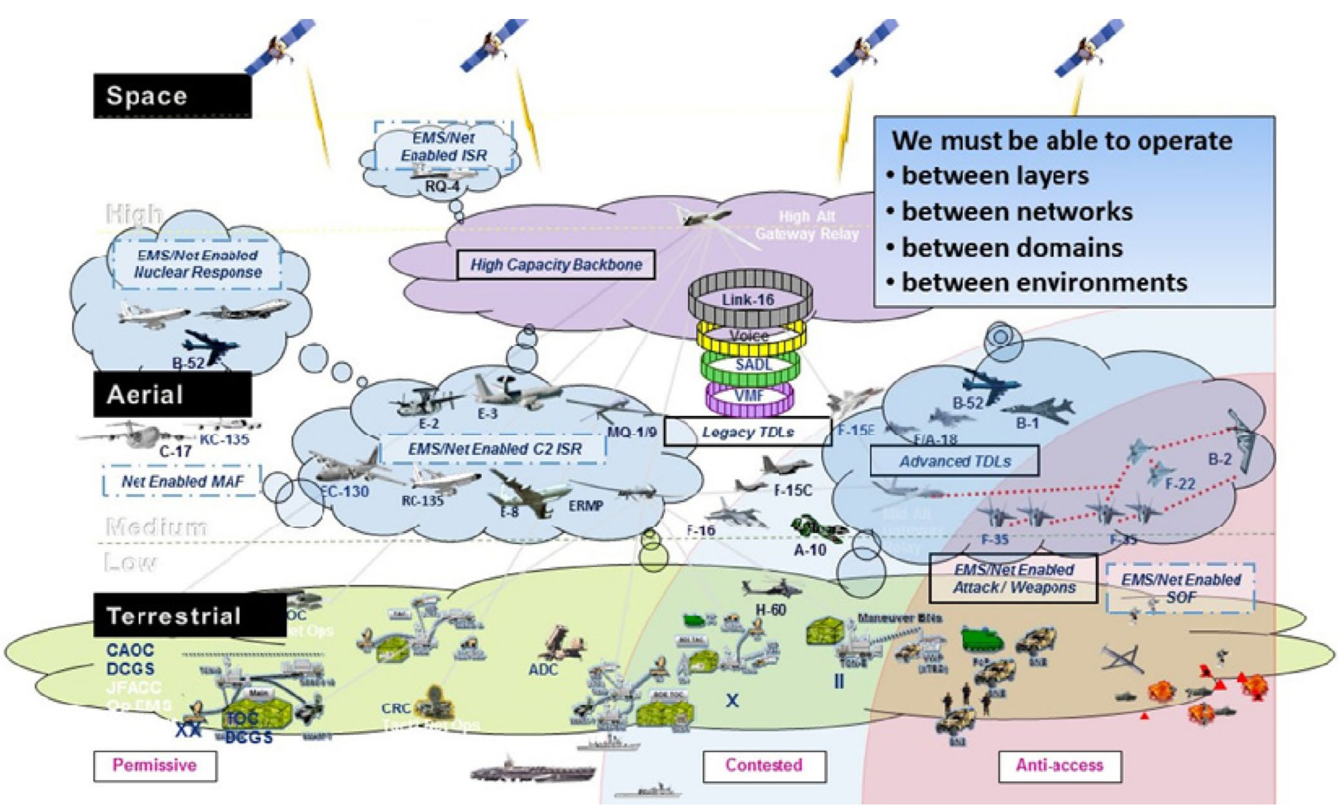


FIGURE 1: Spectrum Dominance Illustration

An AV-8B Harrier was lost and the pilot killed as a result of the indirect effects of a lightning strike. The lightning strike caused large internal electrical currents inside the wing. A coupler inside the wing fuel tank system was not designed to withstand such a current flowing across it and sparked, causing a fuel explosion.

While there have been these and other catastrophic examples, the vast majority are simply performance degradation problems that put our fighting forces at risk, delay fielding of important capabilities or stretch budgets beyond their limits.

DoD Policy and Perspective

The need for control of the electromagnetic spectrum and the EME is understood at the highest levels of DoD management and military operational directors, who must ensure that U.S. Forces have the ability to operate effectively in all domains: space, sea, land, air, information; and can conduct operations with a combination of forces tailored to different situations. Military success relies on Information Superiority: Obtaining, processing, distributing, and protecting accurate information while exploiting or denying the adversary's ability from doing the same. Much of the information superiority depends on access to the RF spectrum. The priority placed on force mobility, range, and speed dictates that much of the information technology be wireless. Again, the critical medium is the EM spectrum with EMI free operations.

Spectrum dominance is a cornerstone of the DoD's warfighting strategy. To maintain this spectrum dominance, the spectrum and system EMC within the spectrum must be carefully controlled.

While EMI (including interference caused by spectrum management problems) can cause catastrophic problems, the majority of interference problems render systems less than fully effective, which reduces operational readiness and increases costs. These may be hard to see, and more difficult to quantify in terms of return on investment; however, taking care of E3 and Spectrum Certification requirements early on in a program provides significant future cost savings. *Figure 1* illustrates the concept of spectrum dominance.

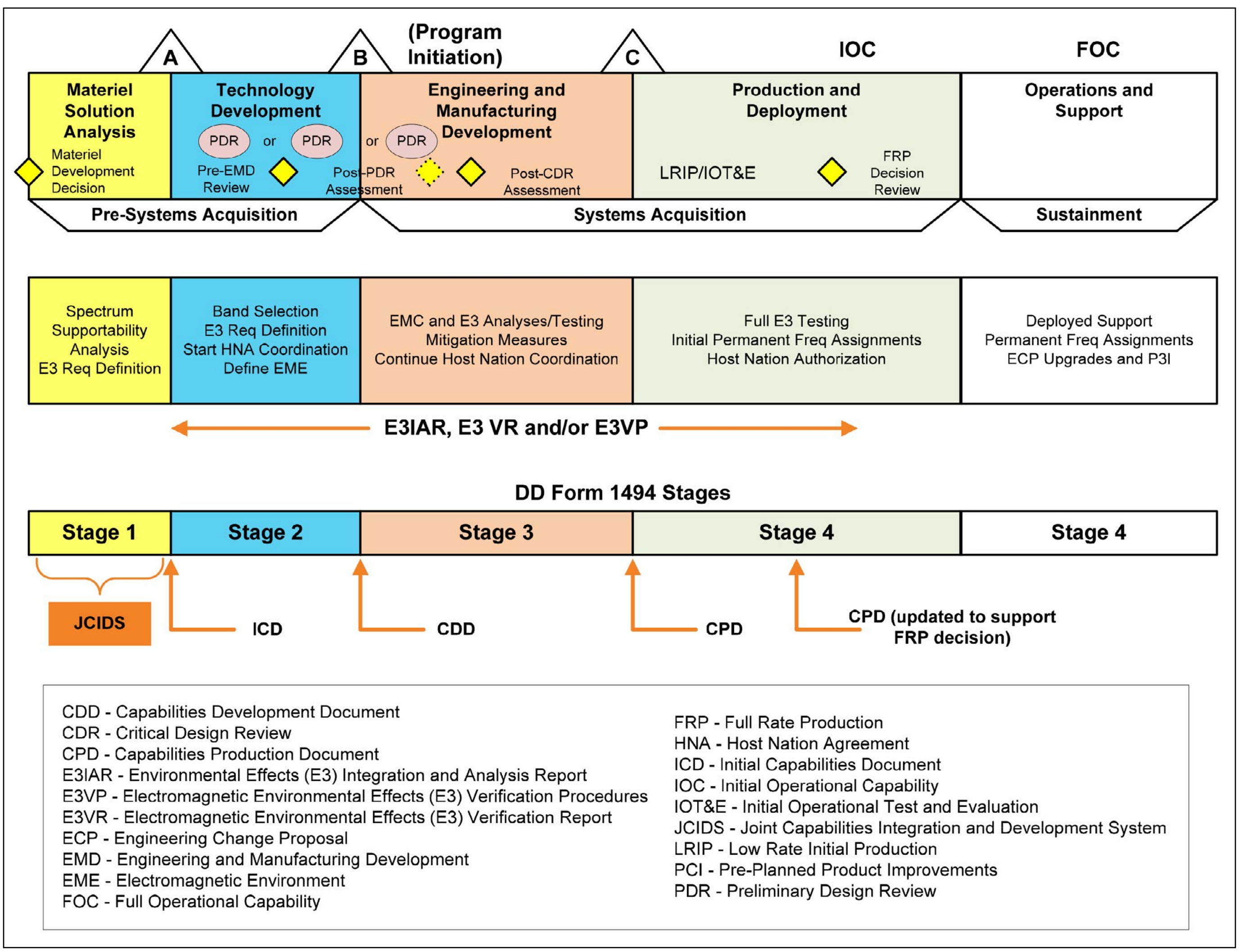


FIGURE 2: E3 and SS Processes

Acquisition Process
The military procurement system is driven by high level policies that flow down to processes and procedures covering anything that is considered a technical requirement. E3 and SS are no different.

There are high level policies that require programs to consider E3 and SS in system design, procurement and fielding as well as policies requiring that military systems follow the rules of frequency use. The two most significant top level directives that require spectrum management and E3 control in the acquisition cycle are:

DoD Instruction 3222.03 DoD Electromagnetic Environmental Effects (E3) Program, 24 Aug 2014
This Instruction drives the requirement that "All electrical and electronic systems, subsystems, and equipment, including ordnance containing electrically initiated devices, shall be mutually compatible in their intended EME without causing or suffering unacceptable mission degradation due to E3." It identifies many high level DoD organizations and outlines their responsibilities for E3 control within systems acquisition and operational communities.

DoD Instruction 4650.01, Policy and Procedures for Management and Use of the Electromagnetic Spectrum, 09 Jan 2009
This instruction outlines the requirements for DoD spectrum use to ensure that systems can operate without interference. Some requirements include:

Obtaining a written determination that there is reasonable assurance of Spectrum Supportability for DoD organizations developing or acquiring spectrum-dependent equipment.

Applicability of Spectrum Supportability determination requirements for "off-the-shelf" or other non-developmental systems (including commercial items).

The requirement to produce a Spectrum Supportability Risk Assessment (SSRA) to identify and assess an acquisition's potential to affect the required performance of the newly acquired system or other existing systems within the operational EME. SSRAs identify SS and E3 risks and the steps that need to be taken to mitigate the risks.

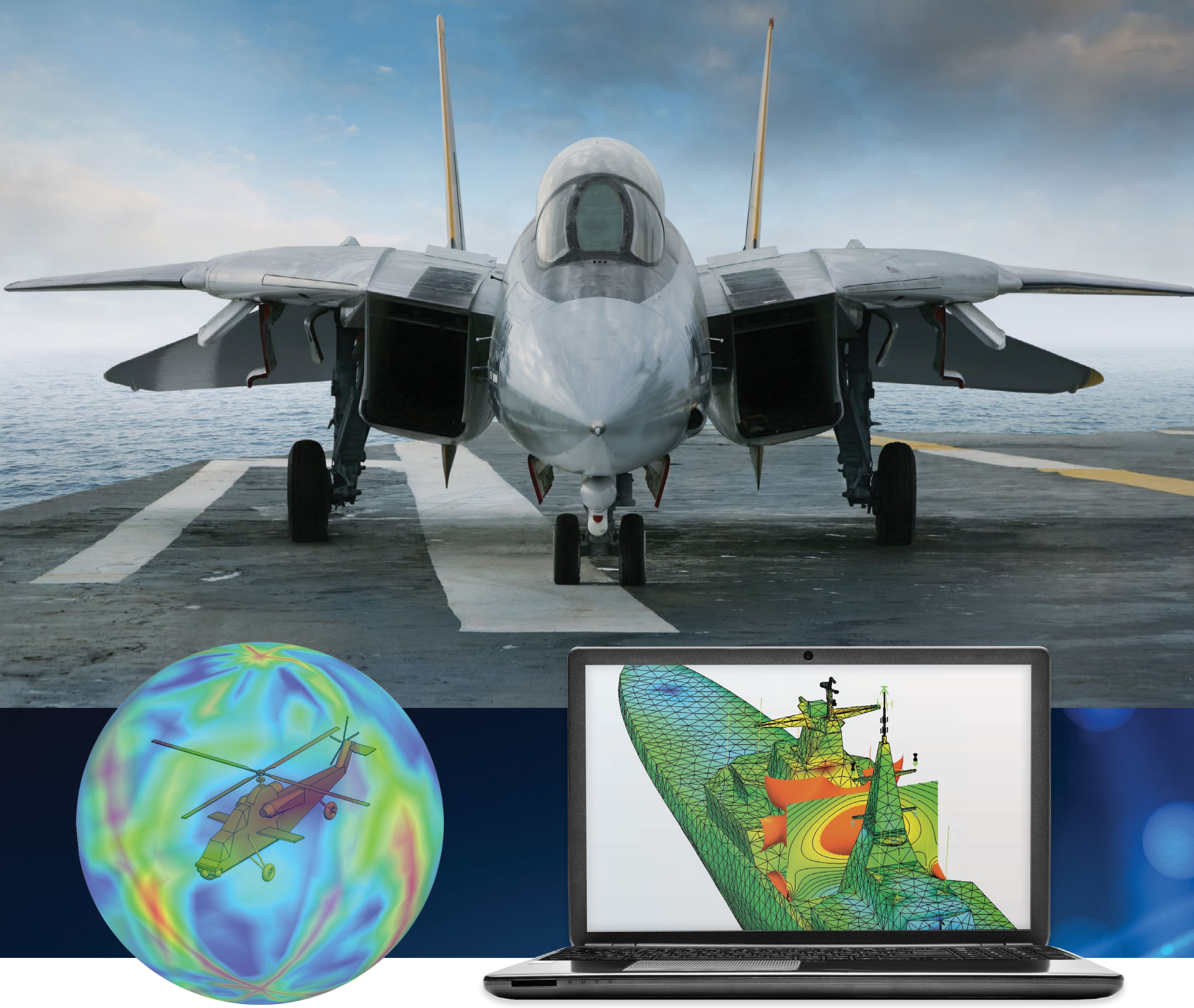
The fundamental E3 and SS related processes and tasks over the military system procurement cycle are shown in *Figure 2*.

About the Authors
Tony Keys is the President and Principal Consultant for EMC Analytical Services. Mr. Keys has over 20 years of experience in Electromagnetic Environmental Effects (E3) engineering. His experience covers a wide range of E3 specialty areas from a multitude of organizational aspects including E3 support contracting, DoD E3 service, and DoD system development. He can be reached at tony.keys@emcanalyticalservices.com.

The author would like to thank Brian Farmer for his significant contribution to the article.

Brian Farmer has a long career providing E3 and Spectrum Supportability systems engineering and program management services to the DoD, including the Naval Air Systems Command (NAVAIR), the Joint Spectrum Center (JSC) and the Naval Surface Warfare Center Dahlgren Division. After working for several companies in the E3 engineering business, Brian formed EMC Management Concepts in 2002.

In addition to being CEO of EMC Management Concepts, Brian still provides direct E3 program management support to several Navy offices and the JSC. He leads contract efforts to develop and deliver E3 and Spectrum Supportability training to the acquisition community.He can be reached at bdfarmer@emcmanagement.com



INTRODUCTION TO MIL-STD-461G

Tony Keys
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Introduction

Where MIL-STD-464C serves as a system/platform level set of requirements, MIL-STD-461G serves as an equipment/ subsystem level set of requirements. Similar to MIL-STD-464C, MIL-STD-461G was developed as an "Interface Standard" to allow usage without a waiver. The overall structure of the two documents is also the same in that both have a contractual main body and a very informative non-contractual rationale and lessons-learned appendix. However, unlike MIL-STD-464C, MIL-STD-461G provides pass/fail criteria, limits, test levels and detailed procedures. The purpose of MIL-STD-461G is to control EMI characteristics of equipment/ subsystems procured by the DoD to increase the likelihood of compatibility in its EME. It is not applicable for platforms/systems or modules/parts. Applicable items include enclosures no larger than an equipment rack, electrical interconnections that are discrete wiring harnesses between enclosures and electrical power derived from prime power sources. Requirements depend on equipment/ subsystem type and use and may be tailored. It is important to note that passing MIL-STD-461G testing does not ensure platform level EMC and failing MIL-STD-464G testing does not necessarily mean a platform EMI problem.

INTRODUCTION TO MIL-STD-461G

As background, MIL-STD-461 is officially prepared by the US Air Force, but it is the product of a Tri-Service Working Group (TSWG) made up, not surprisingly, of representatives from the Army and Navy as well. In addition to Service members there are industry representatives.

Since 1993, MIL-STD-461 has been on a five-year review cycle, to ensure that it remains current and useful. This does not mean a new revision has to be released every five years; just that a review must be performed on that cycle. It would be entirely acceptable to simply reaffirm the old version with no changes. To date, that hasn't happened.

MIL-STD-461D and MIL-STD-462D released in 1993 remain the major "revolution" in military EMI standards, with evolutionary changes following. MIL-STD-461E combined MIL-STD-461 and MIL-STD-462 into a single standard, obsoleting MIL-STD-462 in 1999. MIL-STD-461F was released on 10 December 2007 and provided a number of changes from MIL-STD-461E, but the changes were minor in nature when compared to the changes between revisions D and E. MIL-STD-461G, released 11 December 2015, makes the most structural changes since that time, adding two new requirements (lightning indirect effects, CS117, and personnel electrostatic discharge, CS118) while eliminating the CS106 requirement that was added the last time around in MIL-STD-461F.

This guide will focus on MIL-STD-461G, but given the recent revision change and the fact that most programs are contractually under MIL-STD-461F, major differences between the two revisions will be highlighted as required. MIL-STD-461G imposes requirements in only four major areas for equipment and subsystems: Conducted Emissions (CE), Conducted Susceptibility (CS), Radiated Emissions (RE) and Radiated Susceptibility (RS) and are identified by a 1XX, to differentiate them from the earlier MIL-STD-461A/B/C requirements that were numbered XX. The complete listing of test methods is shown in *Table 1*. CS106 in blue text was required in MIL-STD-461F, but was eliminated from MIL-STD-461G. CS117 and CS118 in red text were added to MIL-STD-461G. The following is not intended to serve as an all-inclusive tutorial on MIL-STD-461G, but rather an overview to illustrate how MIL-STD-461G is employed as a tool by the DoD to support the warfighter. The applicability of each test method is dependent on Service Branch and specific platform installation.

Table 2 illustrates the applicability of each test method.

Requirement	Description
CE101	Conducted Emissions, Audio Frequency Currents, Power Leads
CE102	Conducted Emissions, Radio Frequency Potentials, Power Leads
CE106	Conducted Emissions, Antenna Port
CS101	Conducted Susceptibility, Power Leads
CS103	Conducted Susceptibility, Antenna Port, Intermodulation
CS104	Conducted Susceptibility, Antenna Port, Rejection of Undesired Signals
CS105	Conducted Susceptibility, Antenna Port, Cross-Modulation
CS106	Conducted Susceptibility, Transients, Power Leads
CS109	Conducted Susceptibility, Structure Current
CS114	Conducted Susceptibility, Bulk Cable Injection
CS115	Conducted Susceptibility, Bulk Cable Injection, Impulse Excitation
CS116	Conducted Susceptibility, Damped Sinusoidal Transients, Cables and Power Leads
CS117	Conducted Susceptibility, Lightning Induced Transients, Cables and Power Leads
CS118	Conducted Susceptibility, Personnel Borne Electrostatic Discharge
RE101	Radiated Emissions, Magnetic Field
RE102	Radiated Emissions, Electric Field
RE103	Radiated Emissions, Antenna Spurious and Harmonic Outputs
RS101	Radiated Susceptibility, Magnetic Field
RS103	Radiated Susceptibility, Electric Field
RS105	Radiated Susceptibility, Transient Electromagnetic Field

Note: CS117 and CS118 were added for MIL-STD-461G (indicated in red).
Note: CS106 was a requirement in MIL-STD-461F, but has been removed from MIL-STD-461G (indicated in blue).

TABLE 1. MIL-STD-461G Test Methods

Equipment and Subsystems Installed In, On, or Launched From the Following Platforms or Installations	Requirement Applicability																		
	CE101	CE102	CE106	CS101	CS103	CS104	CS105	CS109	CS114	CS115	CS116	CS117	CS118	RE101	RE102	RE103	RS101	RS103	RS105
Surface Ships	A	A	L	A	S	L	S	L	A	S	A	L	S	A	A	L	L	A	L
Submarines	A	A	L	A	S	L	S	L	A	S	L	S	S	A	A	L	L	A	L
Aircraft, Army, Including Flight Line	A	A	L	A	S	S	S		A	A	A	L	A	A	A	L	A	A	L
Aircraft, Navy	L	A	L	A	S	S	S		A	A	A	L	A	L	A	L	L	A	L
Aircraft, Air Force		A	L	A	S	S	S		A	A	A	L	A		A	L		A	
Space Systems, Including Launch Vehicles		A	L	A	S	S	S		A	A	A	L			A	L		A	
Ground, Army		A	L	A	S	S	S		A	A	A	S	A		A	L	L	A	
Ground, Navy		A	L	A	S	S	S		A	A	A	S	A		A	L	L	A	L
Ground, Air Force		A	L	A	S	S	S		A	A	A		A		A	L		A	

A = Applicable (in green).
L = Limited as specified in the individual sections of MIL-STD-461G (in yellow).
S = Procuring activity must specify in procurement documentation (in red).

TABLE 2. MIL-STD-461G Requirements Matrix

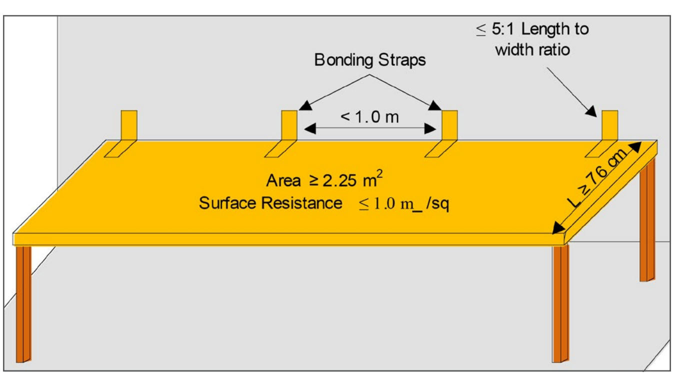

FIGURE 1: Test Ground Plane Configuration

MIL-STD-461G provides a set of general interface and verification requirements. The general interface requirements include motherhood style guidance on joint procurements, self-compatibility, non-developmental items (NDI), Government Furnished Equipment (GFE), switching transients and interchangeable modular equipment. They also include specific requirements on minimizing the use of line-to-ground filters for EMI control in Navy systems. The general verification requirements include detailed information for verification testing on topics including; measurement tolerances, shielded enclosures, ambient electromagnetic level, ground planes, power source impedance, general test precautions, EUT test configurations and operations, and the use and calibration of measurement equipment.

Measurement tolerances are specified for distance (±5%), frequency (±2%), amplitude of the measurement receiver (±2 dB), time waveforms (±5%), resistors (±5%), capacitors (±20%) and the overall amplitude of the complete measurement system (±3 dB). Shielded enclosures are normally required for MIL-STD-461G testing with RF absorber material placed above, behind, and on both sides of the EUT as well as behind the transmitting or receiving antenna. The RF absorber material is required to have a minimum absorption of 6 dB from 80 MHz to 250 MHz and 10 dB above 250 MHz. Controlling the ambient environment during testing is critical.

The ambient electromagnetic level measured with the EUT de-energized and all auxiliary equipment turned on must be at least 6 dB below the allowable specified limits when the tests are performed in a shielded enclosure. Ambient conducted levels on power leads should be measured with the leads disconnected from the EUT and connected to a resistive load, which draws the same rated current as the EUT. Testing must be performed with ground planes that simulate the actual installation if it is known. In cases where the specific installation is not known, or there will be various installations employed, then a metallic ground plane is used. For cases where the EUT does not employ a ground plane when installed, testing is performed on a non-conductive table. In some cases, conductive composite ground planes are used in the installed configuration. In these cases, the surface resistivity of the typical installation is used. *Figure 1* summarizes the ground plane requirements delineated in MIL-STD-461G.

The impedance of power sources providing primary input power to the EUT is controlled by specific (50 μH) Line Impedance Stabilization Networks (LISNs) for all measurement procedures. There are specific cases for CE101 and CE102, where the use of a 5 μH LISNs may be acceptable, but for the vast majority of applications, the 50 μH LISN is used. The specified LISN parameters are shown in *Figure 2*.

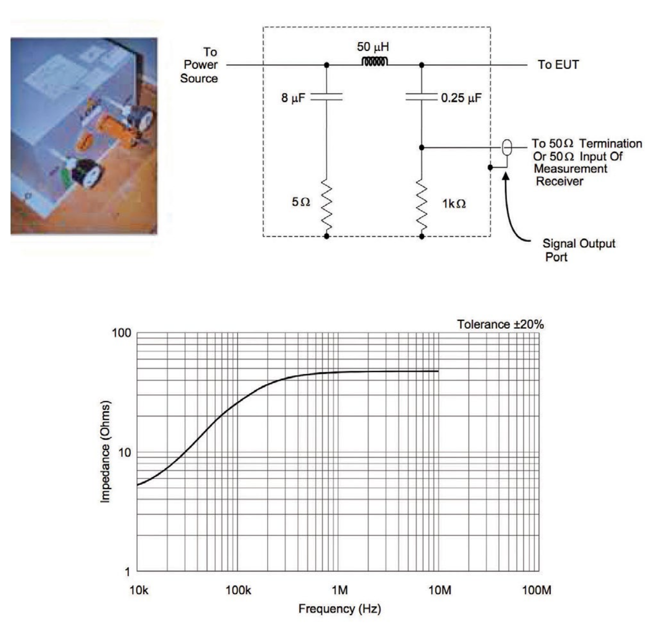

FIGURE 2: MIL-STD-461G 50 μH LISN

While it was always understood that LISNs must have an excellent RF bond to the ground plane for proper operation, it was not specifically stated until the MIL-STD-461G release.

One of the prime factors in MIL-STD-461G radiated (and conducted for that matter) test results is the arrangement and treatment of the electrical interfaces. Electrical cable assemblies are required to simulate actual installation and usage. The cable design and construction must be production representative (preferably actual production cables!). The cables used for testing must be fabricated identical to actual cables in terms of shielding and shield termination technique, wire size, twisting, etc. Shielded cables or shielded leads are only allowed if they have been specified in installation requirements. Input (primary) power leads, returns, and wire grounds shall not be shielded. Cables shall be checked against installation requirements to verify proper construction.

Individual leads are to be grouped into cables in the same manner as in the installation configuration with the lengths identical to the actual platform installation. In cases of cables longer than 10 meters, at least 10 meters must be included. The first 2 meters of cable length (except for cables less than 2 meters in the actual installation) must be run parallel to the front boundary of the setup. The remaining lengths are routed to the back of the setup and placed in a zigzagged arrangement, minimizing cable overlap or crossing. Individual cables are required to be separated by 2 cm measured from each other, but this can be become very difficult to achieve for systems employing a significant number of cables. The cable closest to the front boundary must be placed 10 cm from the front edge of the ground plane MIL-STD-461G now stipulates that the entire length of the cable, not just the two meters exposed to the antenna, be supported 5 cm above the ground plane using “non-conductive material such as wood or foam.” MIL-STD-4G1G addresses cable routing for floor standing units and requires that cables are routed from the top of the EUT then routed down to the bench ground plane with 2 meters run parallel to the front edge of the boundary. If the cables are routed from the bottom, then the cables must be routed up to the bench ground plane and then 2 meters run parallel to the front edge of the boundary.

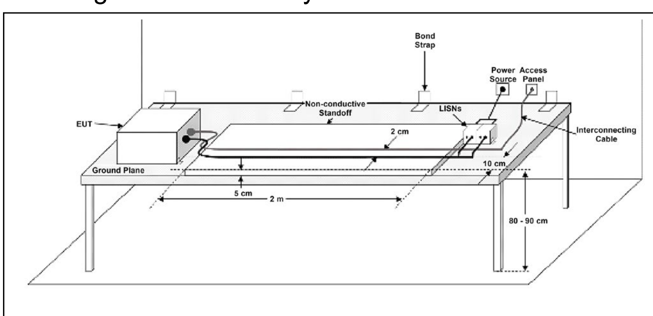

FIGURE 3: Ground Plane Mounted EUT Cable Routing

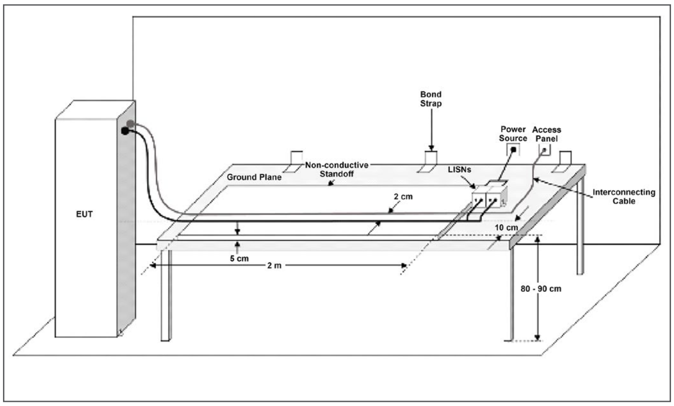

FIGURE 4: Floor Mounted EUT Cable Routing

Power leads are treated in a similar manner with regards to routing, but after the 2 meter exposed length, the power lead to LISN connection length must be as short as possible with a total length not to exceed 2.5 meters, except in cases of large EUTs. Cable routing requirements can be seen in *Figures 3* and *4*.

The operation of the EUT during testing should represent the mode producing the maximum emissions expected during emissions testing and mode which is most susceptible during susceptibility testing. This is very easy to state and attempt to require, but the reality is that engineering judgment is often needed to balance cost and technical aspects. In most cases, this will require a joint effort between systems engineers and EMI engineers to resolve, depending on the complexity and number of modes of operation.

Frequency Range	6 dB BW	Minimum Dwell Time		Minimum Measurement Time for Analog Measurement Receiver
		Stepped Receiver	FFT Receiver	
30 Hz – 1 kHz	10 Hz	0.15 sec	1	0.015 sec/Hz
1 kHz – 10 kHz	100 Hz	0.015 sec	1	0.15 sec/kHz
10 kHz - 150 kHz	1 kHz	0.015 sec	1	0.015 sec/kHz
150 kHz - 10 MHz	10 kHz	0.015 sec	1	1.5 sec/MHz
10 MHz – 30 MHz	10 kHz	0.015 sec	0.15	1.5 sec/MHz
30 MHz - 1 GHz	100 kHz	0.015 sec	0.15	0.15 sec/MHz
Above 1 GHz	1 MHz	0.015 sec	0.015	15 sec/GHz

TABLE 3: Emissions Bandwidth and Measurement Times

For emission measurements, a peak detector is required and measurement parameters are shown in *Table 3* with the changes for MIL-STD-461G highlighted in red. The use of FFT or time domain receivers, a new technology since the last release of the standard, is specifically addressed and *Table 3* below shows parameters for the use of such machines.

Frequency Range	Analog Scans Maximum Scan Rates	Stepped Scans Maximum Step Size
30 Hz – 1 MHz	0.0333 f_0/sec	0.05 f_0
1 MHz – 30 MHz	0.00667 f_0/sec	0.01 f_0
30 MHz – 1 GHz	0.00333 f_0/sec	0.005 f_0
1 GHz – 40 GHz	0.00167 f_0/sec	0.0025 f_0

TABLE 4: Susceptibility Scanning

FFT receivers differ from traditional EMI receivers. Traditional EMI receivers tune to a particular frequency, dwell for a time, then step to the next frequency. FFT receivers look at very large bands and use FFT algorithms to display signals as they would appear if measured traditionally. FFT receivers are much faster than traditional receivers. FFT operation must be in accordance with ANSI C63.2 and *Table II* parameters must be directly addressable, not as FFT quantities such as window type and percentage overlap. The appendix of MIL-STD-461G provides an excellent overview of the use of FFT receivers.

Specific guidance is provided for susceptibility testing on measurement scan rates, sweep times, dwell time and step size based on frequency range and is shown in *Table 3* or *4*.

The modulation of the CS114 and RS103 test stimulus is pulse modulated (on/off ratio of 40 dB minimum) at a 1 kHz rate with a 50% duty cycle. The dwell time of the susceptibility signal is often challenging. MIL-STD-461G requires a dwell time of 3 seconds or EUT response time, whichever is greater. However, when multiple modes of operation are required to be evaluated and the EUT response times are long, this requirement can be a larger cost and schedule driver due to the inherent length of RS103 and CS114 testing in general. This is another area where systems engineering and EMI engineering should work together for the best solution.

MIL-STD-461G includes 19 specific requirements and attendant test methods. *Figure 9* provides a generic military system with the applicability for each requirement. An overview of each requirement/method follows. It should be noted that each and every test method contains very specific details and nuances and the appendix of MIL-

STD-461G provides clarification on the requirements and applicability and detailed information on the test approach and procedures which are outside the scope of this mini guide.

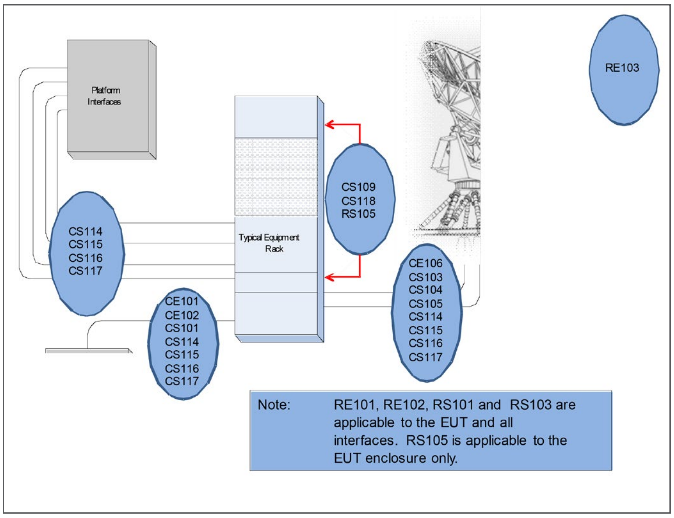

FIGURE 9: Test Method Applicability

CE101 Conducted Emissions, Audio Frequency Currents, Power Leads

CE101 is applicable from 30 Hz to 10 kHz for leads that obtain power from sources that are not part of the EUT. There is no requirement on output leads from power sources. Emission levels are determined by measuring the current present on each power lead.

For surface ships and submarines, the intent is to control the effects of conducted emissions peculiar to the shipboard power distribution system. For Army aircraft, the concern is to ensure that the EUT does not corrupt the power quality on platform power buses.

For Navy aircraft, CE101 is only applicable for installations using anti-submarine warfare (ASW) equipment, which operate between 30 Hz and 10 kHz. The specific limits are based on application, input voltage, frequency, power and current. One of the more common problem areas is rectifier noise at power line harmonic frequencies.

Changes made for MIL-STD-461G include clarification of the applicability to Navy aircraft in the following text: For equipment intended to be installed on Navy aircraft, this requirement is applicable only if the platform contains Anti-Submarine Warfare (ASW) equipment, which operate between 30 Hz and 10 kHz, such as Acoustic (Sonobouy) Receivers or Magnetic Anomaly Detectors (MAD).

Test changes include specific measurement system check frequencies at 1.1 kHz, 3 kHz and 9.9 kHz instead of 1.0 kHz, 3 kHz and 10.0 kHz and a change to *Figure CE101-1* which now specifies limits for both surface ship and submarine DC applications.

CE102 Conducted Emissions, Radio Frequency Potentials, Power Leads

CE102 is applicable from 10 kHz to 10 MHz for leads that obtain power from sources that are not part of the EUT. There is no requirement on output leads from power sources. The lower frequency portion is to ensure EUT does not corrupt the power quality (allowable voltage distortion) on platform power buses. Voltage distortion is the basis for power quality so CE102 limit is in terms of voltage. The emission levels are determined by measuring voltage present at the output port of the LISN. Unlike CE101, CE102 limits are based on voltage. The basic limit is relaxed for increasing source voltages, but independent of current. Failure to meet the CE102 limits can often be traced to switching regulators and their harmonics.

The major change to CE102 in MIL-STD-461G is verifying the LISN impedance at frequencies where it isn't 50 Ω, by recording how hard the signal generator must be driven at 10 and 100 kHz during the measurement system integrity test.

CE106 Conducted Emissions, Antenna Port

CE106 is applicable from as low as 10 kHz to as high as 40 GHz (depending on the operating frequency) for antenna terminals of transmitters, receivers, and amplifiers and is designed to protect receivers on and off the platform from being degraded by antenna radiation from the EUT. CE106 is not applicable for permanently mounted antennas. The upper test frequency requirement has been modified from MIL-STD-461F such that systems with the frequencies < 1 GHz, the upper frequency limit will be 20 times the highest frequency or 18 GHz whichever is greater. For systems with frequencies ≥ 1 GHz, the upper frequency limit will be 10 times the highest frequency or 40 GHz whichever is less. There is also a Navy shipboard specific frequency exclusion for transmitters with peak transmitter power greater than 1 kW. The standard 5% frequency exclusion will be increased by an additional 0.1% of the fundamental frequency for each dB above 1 kW of peak power.

The limits for receivers and transmitters and amplifiers in standby mode are 34 dBµV. For transmitters and amplifiers in transmit mode, harmonics, except the second and third, and all other spurious emissions shall be at least 80 dB down from the level at the fundamental. The second and third harmonics shall be suppressed to a level of -20 dBm or 80 dB below the fundamental, whichever requires less suppression. For Navy shipboard applications, the second and third harmonics will be suppressed to a level of -20 dBm and all other harmonics and spurious emissions shall be suppressed to -40 dBm, except if the duty cycle of the emissions are less than 0.2%, then the limit may be relaxed to 0 dBm.

CE106 limits for transmit mode operation may disagree with the system performance specification. Unfortunately, in many procurements, the transmitter performance specifications are developed independent of the CE106 requirements and suppression to meet requirements can result in significant design penalties if not identified early enough in the program.

Changes made to Mil-STD-461G include specific guidance given for Navy shipboard applications with peak transmitter power greater than 1 kW and the previously mentioned frequency exclusion. The upper test frequency is modified. For systems with intentional frequencies < 1 GHz, the upper test frequency is 20 times the highest intentional frequency or 18 GHz whichever is greater and for systems with intentional frequencies ≥ 1 GHz, the upper test frequency is 10 times the highest intentional frequency or 40 GHz whichever is less. The Navy shipboard applications limits are modified such that the 2nd and 3rd harmonics will be suppressed to a level of -20 dBm and all other harmonics and spurious emissions shall be suppressed to -40 dBm, except if the duty cycle of the emissions are less than 0.2%, then the limit may be relaxed to 0 dBm.

CS101 Conducted Susceptibility, Power Leads

CS101 is applicable from 30 Hz to 150 kHz for equipment and subsystem AC and DC power input leads. For DC powered equipment, CS101 is required over the entire 30 Hz to 150 kHz range. For AC powered equipment, CS101 is only required from the second harmonic of the equipment power frequency (120 Hz for 60 Hz equipment) to 150 kHz. In general, CS101 is not required for AC powered equipment when the current draw is greater than 30 amps per phase. The exception is when the equipment operates at 150 kHz or less and has an operating sensitivity of 1 μV or better.

The intent is to ensure that performance is not degraded from ripple voltages on power source waveforms. Two test voltage levels are defined. One for equipment operating at input voltages greater 28 Volts and one for equipment operating at 28 Volts and below. The requirement is also met when the power source is adjusted to dissipate the power level shown on *Figure CS101-2* of MIL-STD-461G in a 0.5 Ω load and the EUT is not susceptible.

Changes in MIL-STD-461G for CS101 include reducing applicability from a maximum load current of 100 Amps per phase to ≤ 30 Amps per phase, unless the system has an operating frequency 150 kHz or less and an operating sensitivity of 1 μV or better (such as 0.5 μV). Another change is allowing the use of Power Line Ripple Detectors (PRDs) to measure ripple induced on an AC power line in the frequency domain, which is very difficult to monitor in the time domain. The PRD functions as an interface between the power line and the 50 Ω input of a spectrum analyzer or EMI receiver, allowing the measurement to be made in the frequency domain so that the ripple component can be seen entirely separately from the power line frequency.

CS103, CS104 and CS105 Conducted Susceptibility, Antenna Port, Intermodulation, Rejection of Undesired Signals and Cross-Modulation

This series of receiver front-end tests include test methods for Intermodulation (CS103), Rejection of Undesired Signals (CS104) and Cross Modulation (CS105). They were designed for traditional tunable super-heterodyne type radio receivers. Due to the wide diversity of radio frequency subsystem designs being developed, the applicability of this type of requirement and appropriate limits need to be determined for each procurement. Also, requirements need to be specified that are consistent with the signal processing characteristics of the subsystem and the particular test procedures to be used to verify the requirement. These tests are particularly difficult to perform on modern channelized digital receiving systems and require a coordinated effort between systems engineering and EMI engineering. The reality of these tests is that they are most often used and perhaps best performed as characterization tests and not true qualification tests. There is very little guidance provided in MIL-STD-461G except for the original super-heterodyne type radio. The intent of CS103 is to control the response of antenna connected receiving subsystems to in-band intermodulation products of two signals outside of the intentional passband of the subsystem. CS103 is most applicable to fixed frequency, tunable, super-heterodyne receivers.

The intent of CS104 is to control response of antenna connected receiving subsystems to signals outside the intentional passband of the subsystem. CS104 is most applicable to fixed frequency, tunable, super-heterodyne receivers. CS104 has been used to characterize performance related to the EME tables defined in MIL-STD-464 for systems where the antenna characteristics were well-defined and direct injection was feasible.

The intent of CS105 is to control the response of antenna connected receiving subsystems to modulation being transferred from an out-of-band signal to an in-band signal. CS105 should be considered only for receivers, transceivers, amplifiers, and the like, which extract information from the amplitude modulation of a carrier.

CS109 Conducted Susceptibility, Structure Current

CS109 is a highly specialized test applicable from 60 Hz to 100 kHz for very sensitive Navy shipboard equipment (1 μV or better) such as tuned receivers operating over the frequency range of the test. Handheld equipment is exempt from CS109. The intent is to ensure that equipment does not respond to magnetic fields caused by currents flowing in platform structure. The limit is derived from operational problems due to current conducted on equipment cabinets and laboratory measurements of response characteristics of selected receivers.

CS114 Conducted Susceptibility, Bulk Cable Injection
CS114 is applicable from 10 kHz to 200 MHz for all electrical cables interfacing with the EUT enclosures. There is also a common mode test applicable from 4 kHz to 1 MHz for shipboard and submarine installations with a test level of 77 dBµA for complete power cables. Multiple test levels are imposed based on application. The concept is to simulate currents developed on platform cabling from electromagnetic fields generated by antenna transmissions both on and off the platform. CS114 is not applicable for coaxial cables to antenna ports of antenna-connected receivers except for surface ships and submarines. Similar to CS101, protection against over-testing is accomplished by limiting both injected current and potential. Under MIL-STD-461D and G, the requirement is also met if the EUT is not susceptible at forward power levels sensed by the directional coupler that are below those determined during calibration provided that the actual current induced in the cable under test is Curve 5 = 115 dBµA, Curve 4 = 103 dBµA, Curve 3 = 95 dBµA, Curve 2 = 89 dBµA and Curve 1 = 83 dBµA across the frequency range. Due to impedance variations in the cable under test, the current injected may exceed the calibrated levels.

MIL-STD-461G introduces the requirement to insert a current probe and its fixture during the forward power pre-calibration in order to verify that the current probe's transfer impedance is properly taken into account by the measurement software, and that the current probe is functioning properly.

CS115 Conducted Susceptibility, Bulk Cable Injection, Impulse Excitation
CS115 is applicable to all electrical cables interfacing with EUT enclosures. The primary concern is to protect equipment from fast rise and fall time transients that may be present due to platform switching operations and external transient environments such as lightning and electromagnetic pulse. CS115 replaces "chattering relay" type requirements (RS06 in MIL-STD-461C). The excitation waveform from the generator is a trapezoidal pulse and a single pulse type is required for all applications. The pulse has a 2 ns rise time which is consistent with waveforms created by inductive devices interrupted by switching actions and the 30 ns pulse width standardizes each pulse energy and separates the rise and fall portions of the pulse so that each act independently. The 5 ampere amplitude covers most induced levels observed during aircraft testing. The 30 Hz pulse rate ensures that a sufficient number of pulses are applied to increase confidence that the EUT will satisfactorily operate.

CS116 Conducted Susceptibility, Damped Sinusoidal Transients, Cables and Power Leads
CS116 is applicable to electrical cables interfacing with each EUT enclosure and also on each power lead. The concept is to simulate electrical current and voltage waveforms occurring in platforms from excitation of natural resonances with a control damped sine waveform. Switching transients within the platform can also result in similar waveforms. At a minimum, testing is performed at 0.01 MHz (0.1 Amp peak), 0.1 MHz (1 Amp peak), 1 MHz (10 Amp peak), 10 MHz (10 Amp peak), 30 MHz (10 Amp peak), and 100 MHz (3 Amp peak).

Additionally, if there are other frequencies known to be critical to the equipment installation, such as platform resonances, testing should also be performed at those frequencies. The pulse repetition rate is not greater than one pulse per second and no less than one pulse every two seconds and is applied for a period of five minutes.

CS117 Conducted Susceptibility, Lightning Induced Transients, Cables and Power Leads
CS117 is one of two new test methods added to MIL-STD-461G. CS117 is applicable to safety-critical equipment interfacing cables and also on each power lead. Applicability for surface ship equipment is limited to equipment located above deck or which includes interconnecting cables, which are routed above deck. The concept is to address the equipment-level indirect effects of lightning as outlined in MIL-STD-464 and it is not intended to address direct effects or nearby lightning strikes. CS117 was borrowed from RTCA/DO-160 section 22, but many aspects of section 22 were left out of CS117. Two important simplifications are no pin testing, and just two levels, internal and external, mapping from RTCA/DO-160 section 22 levels 3 and 4, respectively. CS117 contains six waveforms borrowed from section 22. CS117 contains no separate table for a single stroke application. Instead, the single stroke levels of section 22 *Table 22-3* have been incorporated into the multiple stroke *Table VII* of CS117. *Table 22-3* levels 3 and 4 become the first stroke of the multiple stroke requirements in CS117 *Table VII*. Level 3 maps to internal, and level 4 maps to external. Subsequent strokes in CS117 *Table VII* are from section 22 *Table 22-4*, except that for Waveforms 4/5A, there was some mixing and matching from levels under Waveform 4/1 in section 22 *Table 22-4*.

Multiple bursts in the same CS117 *Table VII* are exactly the same as section 22 *Table 22-5* levels 3 & 4, again mapping to internal and external installations, respectively.

CS118 Conducted Susceptibility, Personnel Borne Electrostatic Discharge
CS118 is the other new test method added to MIL-STD-461G. CS118 is applicable to electrical, electronic, and electromechanical subsystems and equipment that have a man-machine interface. It should be noted that CS118 is not applicable to ordnance items. The concept is to simulate ESD caused by human contact and test points are chosen based on most likely human contact

locations. Multiple test locations based on points and surfaces which are easily accessible to operators during normal operations. Typical test points would be keyboard areas, switches, knobs, indicators, and connector shells as well as on each surface of the EUT. The limit and method is borrowed from RTCA/DO-160 Section 25 and IEC 61000-4-2. CS118 requires the EUT to be electrically bonded in accordance with the product installation requirements. Limits are 8 kV for contact, 15 kV for air discharge. Contact discharge is the preferred method unless the test item has nonconductive surfaces requiring an air discharge approach. Air discharges are performed not only at the 15 kV limit, as per RTCA/DO-160 section 25, but also at 2, 4, and 8 kV.

RE101 Radiated Emissions, Magnetic Field

RE101 is applicable from 30 Hz to 100 kHz and is used to identify radiated emissions from equipment and subsystem enclosures, including electrical cable interfaces. For Navy aircraft, this requirement is only applicable for ASW capability operating between 30 Hz and 10 kHz.

RE101 is a specialized requirement, intended to control magnetic fields for applications where equipment is present in the installation, which is potentially sensitive to magnetic induction at lower frequencies. Applicable for equipment intended for Navy ships and submarines, Navy ASW, or Army aircraft. RE101 and RS101 are complimentary, imposed to control magnetic EMI to sensitive low frequency (LF) equipment.

The Navy is concerned with the potential effects to LF, VLF, ELF and acoustic and communication systems and sensors with nano-volt sensitivities. The Army is concerned with potential effects to engine, flight, and weapon turret control systems and sensors with millivolt sensitivities. Limits are based on specific service applications with different limits for Navy and Army equipment. Common RE101 failures include equipment containing CRT yokes, transformers and switching power supplies.

Changes to MIL-STD-41G for RE101 include clarification for Navy aircraft applicability, specifically “Aircraft with ASW equipment which operates between 30 Hz and 10 kHz such as: Acoustic (Sonobouy) Receivers or Magnetic Anomaly Detectors (MAD).” Another subtle change is the specification that the loop winding resistance should be between 5 Ω and 10 Ω.

RE102 Radiated Emissions, Electric Field

RE102 is applicable from 10 kHz to 18 GHz and is used to identify radiated emissions from the EUT and associated cables. It is intended to protect sensitive receivers from interference coupled through the antennas associated with the receiver. Many tuned receivers have sensitivities on the order of 1 uV and are connected to intentional apertures (the antenna) that are constructed for efficient reception of energy in the operating range of the receiver. RE102 identifies specific antennas are specified for use in measurements. Antenna placement is defined including separation from the EUT and elevation from the floor. The number of antenna positions is determined based on size of the EUT and interfacing cables as well as beamwidth of the measurement antennas. Antenna placement is now based on EUT area and not just width. The RE102 limits vary with installation location, service branch and platform.

Changes to MIL-STD-41G for RE102 include setting the upper test frequency to 18 GHz for all applications versus 1 GHz or 10 times the highest intentionally generated frequency in previous versions. Another change is specifying the measurement system check frequencies as 10.5 kHz, 2.1 MHz, 12 MHz and 29.5 MHz for the active rod antenna instead of low mid and high frequencies, 197 MHz for the biconical antenna, 990 MHz for the large horn and 17.5 GHz for the small horn. However, the largest change in RE102 is a small change in wording regarding antenna positioning.

Previous versions required that the number of antenna positions used above 200 MHz be based on the width of the EUT and the first 35 cm of interfacing cables from 200 MHz to 1 GHz and the first 7 cm of interfacing cables from 1 GHz to 18 GHz as related to the 3 dB beamwidth of the measurement antenna. MIL-STD-461G changes the word “width” to “area” thus bringing the height of an EUT into the equation and thus potentially adding more positions. This was a much-needed change in order to more accurately test large vertical test objects such as shipboard racks. There are also minor changes to the 41” rod antenna set-up.

RE103 Radiated Emissions, Antenna Spurious and Harmonic Outputs

RE103 may be used as an alternative for CE106 when testing transmitters with their intended antennas. CE106 should be used whenever possible. However, for systems using active antenna or when the antenna is not removable or the transmit power is too high, RE103 should be invoked. RE103 is applicable essentially identical to CE106 for transmitters in the transmit mode in terms of frequency ranges and amplitude limits. The frequency range of test is based on the EUT operating frequency.

The test procedure is laborious and will require a large open area to meet antenna separation distances in many cases. The minimum acceptable antenna separations are calculated based on antenna size and operating frequency of the EUT and measurements in azimuth and elevation are required.

RS101 Radiated Susceptibility, Magnetic Field

RS101 is a specialized test applicable from 30 Hz to 100 kHz for Army and Navy ground equipment having a minesweeping or mine detection capability, for Navy ships and submarines, that have an operating frequency of 100 kHz or less and an operating sensitivity of 1 μV or better (such as 0.5 μV), for Navy aircraft equipment installed on ASW capable aircraft, and external equipment on aircraft that are capable of being launched by electromagnetic launch systems. The requirement is not applicable for electromagnetic coupling via antennas. RS101 is intended to ensure that performance of equipment susceptible to low frequency magnetic fields is not degraded. Two different limits are cited based on service branch.

The Navy RS101 limit was established by measurement of magnetic field radiation from power distribution components (transformers and cables), and the magnetic field environment of Navy platforms. The Army RS101 limit is based on 5 mV (independent of frequency) being induced in a 12.7 cm (5 inch) diameter loop.

An alternative test approach using Helmholtz coils is provided. Helmholtz coils generate a relatively uniform magnetic field that is more representative of the environment experienced on some platforms, particularly submarines. For this reason, the AC Helmholtz coil test option is preferred for submarine applications.

RS103 Radiated Susceptibility, Electric Field

RS103 is applicable from 2 MHz to 18 GHz in general, but the upper frequency can be as high as 40 GHz if specified by the procuring agency. It is applicable to both the EUT enclosures and EUT associated cabling. The primary concern is to ensure that equipment will operate without degradation in the presence of electromagnetic fields generated by antenna transmissions both onboard and external to the platform.

The limits are platform dependent and are based on levels expected to be encountered during the service life of the equipment. It should be noted that RS103 may not necessarily be the worst-case environment to which the equipment may be exposed.

For aircraft and ships, different limits are specified depending on whether the equipment receives protection from platform structure. Alternative method and procedures are provided for use in a mode-tuned reverberation chamber from 200 MHz to 40 GHz.

Changes to MIL-STD-41G for RS103 include requiring testing below 30 MHz for Army and Navy applications, but optional for all others. Additionally, receivers with permanently attached antennas, are allowed reduced performance over the intended receiver band of operation, but must meet its performance requirements after in-band exposure to the radiated field.

The major change for RS103 is identical to that of RE102 explained above – illumination of test set-up area, not just width.

RS105 Radiated Susceptibility, Transient Electromagnetic Field

RS105 is intended to demonstrate the ability of the EUT to withstand the fast rise time, free-field transient environment of EMP. RS105 applies for equipment enclosures which are directly exposed to the incident field outside of the platform structure or for equipment inside poorly shielded or unshielded platforms and the electrical interface cabling should be protected in shielded conduit.

The EMP field is simulated in the laboratory using bounded wave TEM radiators such as TEM cells and parallel plate transmission lines. Since the polarization of the incident EMP field in the installation is not known, the EUT must be tested in all orthogonal axes. Potential equipment responses due to cable coupling are controlled under CS116. Full RS105 testing capability is rare.

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DYNAMIC SPECTRUM ALLOCATION BETWEEN GOVERNMENT AND COMMERCIAL SYSTEMS

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MIL-STD-464C has provisions for Inter-system EMC that is primarily concerned with inter-force effectors. Emission limits, margins, and environments are given as reference to the levels of the expected transmitters (radio relays, radars, etc.), but guidance on the susceptibility to commercial wireless technology is largely ignored.

In the age of spectrum sharing and licensing of new communication bands adjacent to DoD infrastructure and communication systems, it becomes necessary to look at the potential impact of commercial systems on the receiver performance of critical systems like GPS and radars. A new focus on test and verification methodology must consider the impact on the receiver performance due the proliferation of wireless communication bands not just in the US, but also in any expected forward deployment environment.

DYNAMIC SPECTRUM ALLOCATION BETWEEN GOVERNMENT AND COMMERCIAL SYSTEMS

Smartphones are accelerating the pace of wireless communications around the world. The level of investment and regulation by each country has ensured that smartphones work properly wherever you go in the world. With base stations from various service providers often co-located, coexistence has been a critical part of their design. Not to mention that each phone contains many cellular frequency bands, as well as Wi-Fi, Bluetooth, and GPS.

Frequencies below 6 GHz offer excellent RF propagation performance and are ideal for the commercial wireless services (both terrestrial and satellite) and radiolocation services (radar). With the number of licensed fourth generation (4G) Long-Term Evolution (LTE) bands worldwide increasing from 11 to over 55 since 2011, several widely used radiolocation and geo-location service bands are now being encroached for use by commercial wireless services.

As radars tend to operate at higher power levels, recommendations and test methodology such as ITU-R M177-4 were created to minimize the impact on commercial wireless applications. These measurements focused on the radar spectrum and the potential interference of the radar on the wireless base station receiver. But what about the impact of millions of LTE phones and base stations on the radar and GPS receivers? GPS is a critical timing technology for COMSEC. Some traditional air traffic control (ATC), air surveillance radar (ASR) and maritime radar bands have existed long before the dawn of cellular communication (*Figure 1*).

In this article we will discuss some methodologies and techniques for benchmarking wireless government infrastructure receiver performance. This methodology will be useful for most applications, including first responder communication systems, radar and even GPS receivers. While the test methodologies for testing GPS receivers can largely be leveraged from international standards, to demonstrate the method for radars, we use an example of a commercial radar system in the presence of wireless systems and show preliminary measurement results.

Frequency Range	Example Service
1 – 2 GHz (NATO)	Global Positioning System carriers centered at 1176.45 MHz (L5), 1227.60 MHz (L2), 1381.05 MHz (L3), and 1575.42 MHz (L1) frequencies
2 – 4 GHz	ATC, maritime, weather radar: 2.7 – 3.1 GHz ASR: 3.1 – 3.5 GHz
4 – 8 GHZ	Magnetron/Klystron radar: 5.25 – 5.35 GHz SOTR – single object tracking radar: 5.45 – 5.825 GHz

Figure 1. Existing wireless government infrastructure application frequency bands.

Designing for Coexistence

Radar – Radar technologies have been deployed around the world for many decades. As commercial wireless applications have spread, numerous studies and ITU-R recommendations have focused on the impact of radar transmissions on these commercial receivers. These studies have resulted in measurement procedures and recommended practices focused on the prediction of mitigation distances between the systems. An enabling factor is the accepted methodology on measuring the power of the radar, ITU-R M1177-4 [1], and the 3GPP Technical and Test Specifications {5} to test the minimum acceptable immunity performance of the wireless base station and user equipment receivers. Radar receivers and wireless communication systems radio receivers have approximately the same sensitivity (~ -115 dBm). Logic would seem to dictate that since the power of the radar can be orders of magnitude higher than the typical 40 Watt base station carrier signal, it would make sense to focus just on the impact of the radar transmission on the victim wireless base station receiver.

For many years government agencies responsible for deployed wireless infrastructure have fought to keep sufficient guard bands between their defined spectrum and the encroachment of commercial spectrum use. As the spectrum has grown more crowded, the time to address these coexistence issues has arrived.

This is due to the fact that the performance of radar receivers are not subject to international or commercially assessed requirements. Guidelines on the frequency dependent rejection (FDR) of the radar systems are not standardized and need to be reassessed in consideration of the new frequency bands allocated for commercial wireless services. The lack of standard performance profiles limits the availability of data demonstrating the impact of the radar receiver from the transmission of a wireless communication system. The few standards that do exist on radars, for example IEC 62388, focus on the coexistence and interoperability of similar systems. The lack of standards on radar receivers does not prevent sovereign nationals from licensing spectrum in bands adjacent to radar infrastructure, or in adjacent spectrum to GPS services.

Long-Term Evolution (LTE) – Let's consider a modern commercial wireless application and see how its launch into a crowded spectrum has made coexistence an integral part of its design. For LTE, the 3GPP standards TS 25.104/25.141 define the technical specifications and performance requirements for international regulations. By means of these standards, base station receivers are designed to coexist on the same antenna tower (physically) a few feet apart with minimal frequency separation.

LTE base stations and other fixed communications systems are designed for co-siting and coexistence, with a substantial focus on blocking and selectivity immunity in the base station receiver as specified by the 3GPP (*Fig-*

ure 2). When the transmit mask of the LTE base station (ACLR) and the receiver performance are compared, there is relative reciprocity in the out-of-band emissions and the blocking and selectivity performance. Stated another way, the stringent emissions of the base station transmission is complemented by the stringent receiver requirements. The base station technical specifications along with rigorous conformance testing require demanding filter requirements for the receiver design. These performance requirements are set by channel bandwidths across 400 MHz to almost 6 GHz. Performance as a function of fractional bandwidth gets exceedingly more difficult at higher frequencies.

Table 7.3A: Adjacent channel selectivity

Parameter	Level Wide Area BS	Level Medium Range BS	Level Local Area / Home BS	Level Home BS[1]	Unit
Reference measurement channel data rate	12.2	12.2	12.2	12.2	kbps
Wanted signal mean power	-115	-105	-101	-91	dBm
Interfering signal mean power	-52	-42	-38	-28	dBm
Fuw (Modulated)	±5	±5	±5	±5	MHz
Note 1: For Home BS, this additional requirement ensures the performance is met over a large dynamic range.					

Table 7.4K: Blocking characteristics for Wide Area BS

Operating Band	Center Frequency of Interfering Signal	Interfering Signal mean power	Wanted Signal mean power	Minimum Offset of Interfering Signal	Type of Interfering Signal
I	1920 - 1980 MHz	-40 dBm	-115 dBm	±10 MHz	WCDMA signal*
	1900 - 1920 MHz 1980 - 2000 MHz	-40 dBm	-115 dBm	±10 MHz	WCDMA signal*
	1 MHz -1900 MHz 2000 MHz - 12750 MHz	-15 dBm	-115 dBm	—	CW carrier

Figure 2. The 3GPP standards TS 25.104/25.141 define the selectivity and blocking characteristics for LTE receivers.

Global Navigation Satellite System (GNSS)

The United States' Global Positioning System (GPS) was first launched in 1973 and has been fully operational since 1995. It is currently the world's most utilized satellite navigation system. Next generation satellites are being deployed to take advantage of new technologies, as well as adding immunity protections. In addition to the US system, many other countries are also launching similar navigation systems.

The Global Navigation Satellite System (GNSS) is the term used for satellite navigation systems that provide autonomous geo-spatial positioning with global coverage. This term includes the US's GPS as well as GLONASS, Galileo, Beidou and other regional systems. The advantage to having access to multiple satellites is accuracy, redundancy and availability. *Figure 3* highlights the spectrum usage for several of these systems. Some of the design and interference challenges have been well documented such as issues with L5/E5 in the Aeronautical Radio Navigation Service (ARNS) band and the issues with E2 signals from Galileo and the Amateur Radio band commonly used for Earth-Moon-Earth (EME) communication. In recent years in the US, LightSquared (now Ligado Networks) and the GPS community clashed on the policies of terrestrial communications systems in spectrum used by GPS. While this issue has remained unresolved in the US, it should be noted that the larger international communities and sovereign countries of Europe are going forward with plans to license spectrum for terrestrial communication networks (including LTE). Expected performance limits and test methods are in place to assure services are not interrupted.

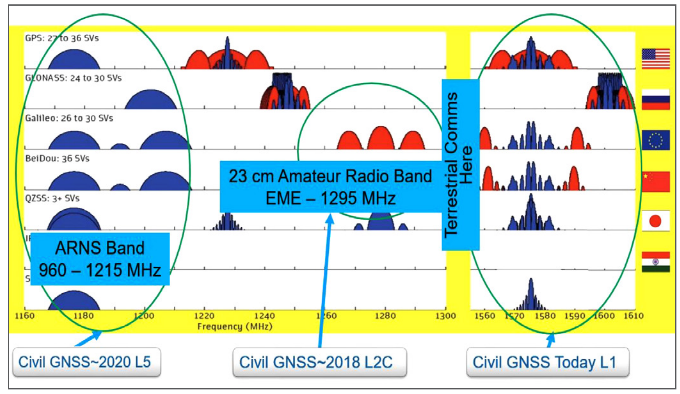

Figure 3. The trend in GNSS is more signals and more potential spectrum conflicts.

From the European Union, the recent EU RED Article 3.2 requirement places minimum performance standards on GNSS (geo-location) receivers as proof of this point. GNSS receivers in the EU are required to have minimum immunity performance such that adjacent spectrum can be licensed for terrestrial wireless services.

There are no such test methods or performance guidelines in MIL-STD-464C or guidance placed on most US DoD assets that may be used in Europe. The Radio Technical Commission for Aeronautics (RTCA) does address concerns in the avionics community and has attempted to harmonize some of the GPS receiver performance with specifications for minimum operational performance of GNSS system with standards such as RTCA DO-229; RTCA DO-301; and RTCA DO-368. These address both antenna performance requirements and receiver immunity performance.

The broadly applicable EU RED directive specifies that the carrier-to-noise density (C/No) is first reported by the GNSS user equipment without an interfering signal present. The C/No must then only be degraded by a maximum of 1 dB in the presence of the interferer (offsets, levels, bandwidth defined by standard).

Frequency band (MHz)	Test point centre frequency (MHz)	Adjacent frequency signal power level (dBm)	Comments
1 518 to 1 525	1 524	-65	MSS (space-to-Earth) band
1 525 to 1 549	1 548	-95	MSS (space-to-Earth) band
1 549 to 1 559	1 554	-105	MSS (space-to-Earth) band
1 559 to 1 610	GUE RNSS band under test		
1 610 to 1 626	1 615	-105	MSS (Earth-to-space) band
1 626 to 1 640	1 627	-85	MSS (Earth-to-space) band

Figure 4. Interferer Example for GPS L1: Source: table 4-2 in EN 303 413.

Let's consider a GPS L1 example with a center frequency of 1575.42 MHz, with 27 MHz bandwidth for worst case M-code, and a guard band of 1560 – 1610 MHz (*Figure 4*). The expected receive signal on earth would be -127 dBm. Based on RED Article 3.2 and test procedure in EN

303 413 the blocking performance of the GNSS receiver shall have the following performance capabilities:

- 1.5% fractional BW - +22 dB (21 MHz offset)
- 1.7% fractional BW - +32 dB (27 MHz offset – one channel BW)
- 3.2% fractional BW - +62 dB (52 MHz offset – second adjacent channel BW

Proposed Methodology – Radar Receivers

To evaluate the performance of radar systems, one needs to consider the functional performance of the radar system. For this reason, it makes sense to use Over-the-Air (OTA) measurement techniques. While in some cases it may be possible to test receivers directly on a test bench, the test signal must enter through the antenna to fully test the radar system.

MIL-STD-464C establishes electromagnetic environmental effects, interface requirements, and verification criteria for airborne, sea, space, and ground systems. MIL-STD-464C requires that the system shall be electromagnetically compatible among all subsystems and equipment within the system and with environments caused by electromagnetic effects external to the system. The consideration of commercial wireless systems in an international environment must be updated to include performance requirements of the radar receiver systems.

The figure of merit or measure of the radar's immunity to interference is defined as the frequency dependent rejection (FDR). The FDR is determined by the receiver IF selectivity and is a function of the performance of the low noise amplifier (LNA) and noise power through the down-conversion, filtering and signal processing. In a radar receiver, the two main interference parameters influencing the receiver sensitivity are blocking and selectivity.

Blocking is the measure of gain compression at the front-end LNA due to a strong signal forcing the LNA into nonlinear compression. In the interest of developing a standard method to assess the coexistence of radar and wireless communications systems, a CW tone can be used to represent the blocking signal (*Figure 5*). The CW source should have the ability to generate high-power with low phase noise and low harmonics, so the unintentional artifacts of the signal generator do not influence the test results. A standard practice is to determine the frequency and amplitude offsets that degrade the receiver performance. A standard practice is that a blocking problem would occur when the front-end LNA reaches a 2 dB compression point (the received signal level reduces by this amount due to the LNA gain compression).

Using the example of *Table 2* from the 3GPP standards on Table 7.4k, the performance of a cellular base station at 1980 MHz shall not degrade in performance from a CW interference signal 100 dB higher at a frequency of 2000 MHz. That is a fractional bandwidth offset of one percent! Imagine the performance of a radar receiver, such as an Air Traffic Control radar, at 2.7 GHz immunity to a base station in close enough proximity at 2680 MHz to create a signal 100 dB higher than the expected echo return of a distance aircraft.

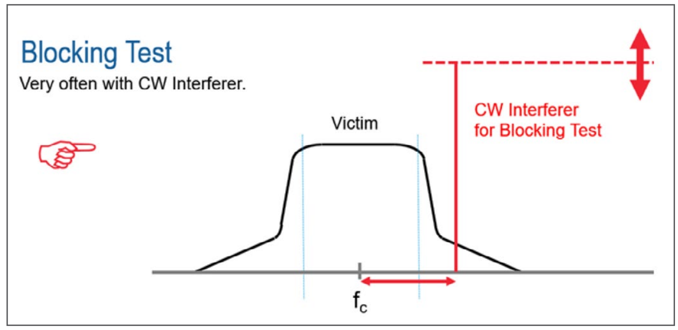

Figure 5. Blocking is the measure of gain compression at the front-end LNA due to a strong signal forcing the LNA into nonlinear compression.

Selectivity is the measure of the increase in noise introduced into the receiver front-end, while not in nonlinear compression, that will reduce the signal-to-noise ratio (SNR) of the receiver (*Figure 6*). For a selectivity test, a noise type signal is required. Since the challenge of coexistence in this case is primarily the mix of cellular and radar signals, the noise-like signal used to assess selectivity performance can be a 3GPP test model signal. For this methodology, a selectivity problem would occur when there is a 3dB increase in the SNR bleeding into IF due to adjacent channel noise. *Table 2* also shows the expected results of commercial base stations.

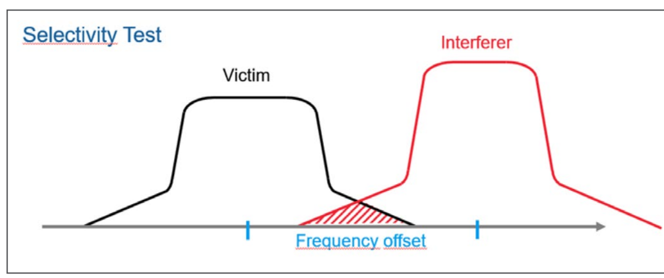

Figure 6. Selectivity is the measure of the increase in noise introduced into the receiver front-end that will reduce the signal-to-noise ratio (SNR) of the receiver.

To study the performance of the radar receiver in the presence of an LTE network, a standard method of assessing the FDR performance of the radar blocking and selectivity behavior needs to be defined. A cooperative radar system is a radar whose service duty will not be impaired while performing the testing assessment. The radar can be in a decommissioned state during the test, on a test range under emulated conditions or otherwise operating, while not expected to be in service during the test, yet fully functioning to allow observation of performance.

The functional performance of a cooperative radar should be assessed over-the-air (OTA) or in a test chamber. The importance is to assure that all the components of the radar performance, including the antenna and LNA, are part of the system. While the most common tool for assessing the functional performance of a radar is the use of a single dihedral corner reflector or an array of reflectors fixed at specific locations, this method is not as ideal as test tools that provide a scaled amplitude number of delayed echoes. Common tools with the ability to regenerate a set of scaled echoes in an OTA RF environment include the use of digital radio frequency memory (DRFM) systems or radar echo generators (REG).

Figure 7 shows how these tools have the advantage of a controlled delivery of a series of radar echoes utilizing digital delay taps that are representations of the transmitted radar signal delayed in time and at variable attenuations (representing radar cross sections). This is important for assessing the radar receiver performance such as delay time (range), signal amplitude, and even the Doppler rate of an echo.

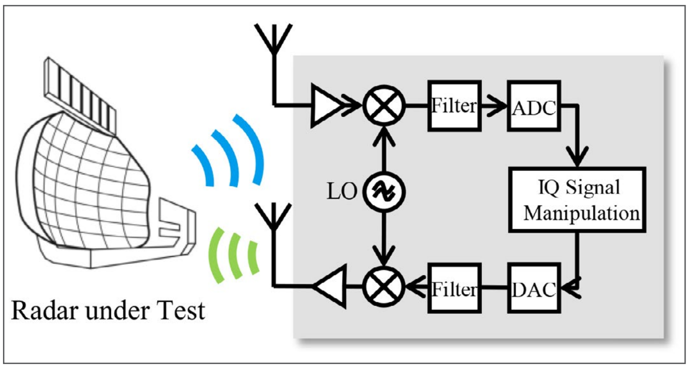

Figure 7. Example using a Radar Echo Generator (REG).

In a test lab, while it is common practice to test functioning radars with fiber optic delay lines (FODL) or coaxial delay lines (CDL), these may not have the flexibility to create multiple targets at different delays and attenuation levels. Further, these may bypass the critical RF components such as the antenna and LNA, which may skew the results.

The test method and results in this article use the REG[6] as the desired tool, constructed from commercially available test equipment with metrology grade instruments. With the added functionality, the REG can also create the additional RF interference signals required for testing, including CW, LTE or even arbitrary waveform signals. The baseline performance level for a selected mode of operation can be set with a REG to approximate a range of echo returns reliably detected on the radar system. The level and number of returns will depend on the quantitative thoroughness desired by the assessment. The baseline performance of the radar should provide a user interface that represents the actual operation expected by the end-user.

As the interference signals are introduced, the radar receiver will become impaired due to LNA compression (blocking) or increased noise into the IF (selectivity), and the number of echoes seen by the user will decrease. This is the method to determine the susceptibility of the radar. Some important considerations for the process and procedure for testing radar susceptibility are:

- **Occupied Channel** — Using ITU-R M.1177-4, it is necessary to determine the bandwidth of the occupied signal.
- **Frequency Dependent Rejection (FDR)** — The FDR is the measure of the rejection of an unwanted emission produced by the receiver's selectivity. Two important parameters of FDR are the on-tune rejection (OTR) and the off-frequency rejection (OFR).

Measurement Results

The performance of a maritime radar has been tested to provide an example for examining this test methodology. The results for selectivity demonstrate the frequency and amplitude offsets of the radar's FDR and is expressed as a function of the fractional bandwidth from the carrier frequency. In this example it was not possible to perform the measurements OTA due to licensing restrictions for OAT transmission, so the results largely demonstrate the selectivity of the radar receiver without the LNA. For the purposes of demonstration, the REG was connected directly to the RF input port, while the radar was set to scan mode. This enables the concentric circles to be represented on the radar display representing the radar echoes at different delay offsets. *Figure 8a* represents the baseline performance with three cascading echoes delayed in time and near the sensitivity of the radar. The SNR may be rather subjective if the echoes represented just a blip on the screen; therefore the REG is connected directly to the RF input port. In *Figures 8b* and *8c*, an interference signal is coupled to the radar echo return, offset in frequency and increasing in amplitude. The decreasing SNR due to the interference signal appears as increasing baseline noise. In *Figure 8c*, while the echoes in the development mode of the radar amplitude versus time display are still visible, a user would need to adjust the noise level of the radar to be able to discern any objects on the display.

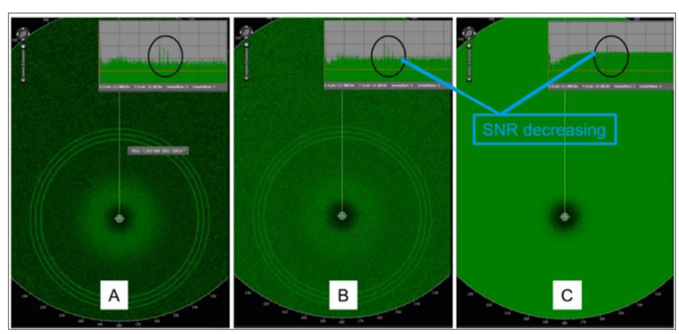

Figure 8. Radar selectivity with increasing interference.

To provide a reference of the radar's FDR, a set of tests was conducted to plot the selectivity versus offset frequency at a fixed amplitude signal of -50 dBm (*Figure 9*) and the selectivity versus amplitude at a fixed frequency offset (*Figure 10*). The results are expressed in fractional bandwidth offset from the center frequency and the interference level relative to the receiver sensitivity.

Three targets at range bins 270, 287 and 302 are shown in the "reference" measurement, where no interference was present. This shows that even at a modest interference level of -50 dBm at the receiver input, with a frequency offset between 2 to 3 percent fractional bandwidth, the echoes will not have enough SNR to be detected by the radar.

Compare these results to the standard performance of a wireless base station, where the base station can reject a +63 dB signal at a fractional bandwidth of 0.25 percent per *Table 2*. The radar had a much greater sensitivity at a much greater frequency offset. This affects the frequency allocation guard band between the radar and wireless services.

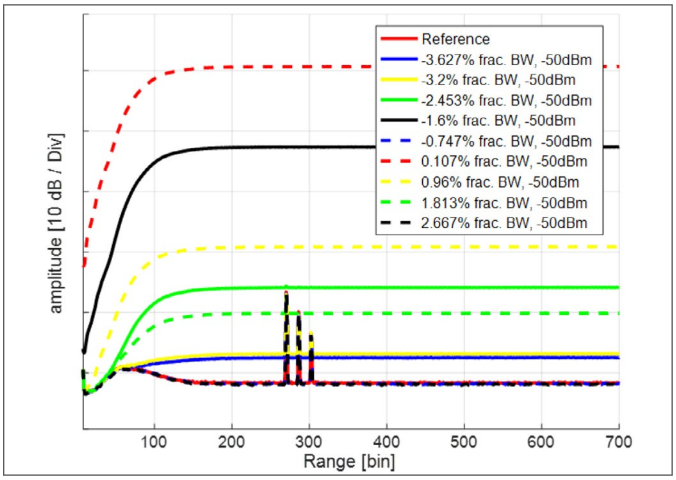

Figure 9. Plot of selectivity over amplitude at a fixed amplitude.

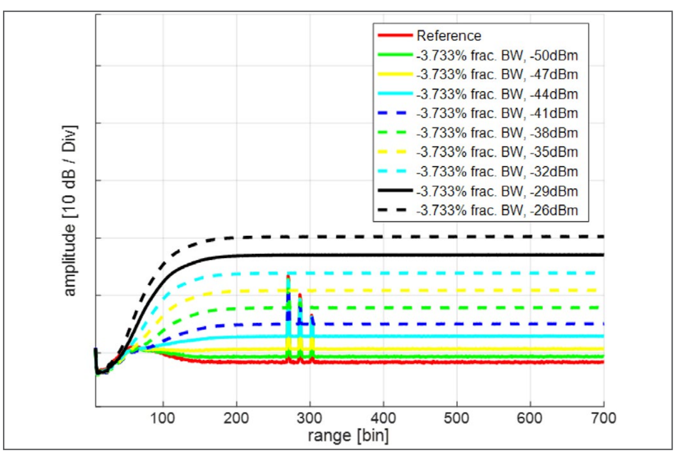

Figure 10. Plot of selectivity over amplitude at a fixed frequency offset

Using the values in *Figure 9* and calculating a free space loss, the potential impact on a victim radar can be assessed. Assuming a cellular base station power in LTE frequency Band 41 (2496 MHz to 2690 MHz operation in Time Division Duplex Mode – TDD) at 40 W (+46 dBm), the cellular base station would have a free space attenuation of approximately -116 dB at a distance of 6 km. A possible Band 41 downlink signal at 2690 MHz represents a -0.37 percent offset for a radar with a center frequency of 2.7 GHz. Knowing the FDR behavior of the victim radar, a 3 percent fractional bandwidth would dictate the radar should not be operated at a frequency below 2780 MHz at this 6 km distance.

The results of the performance of radar transmit mask and the radar receiver frequency dependent rejection (FDR) curves demonstrate a substantial difference in performance for out-of-band signal behavior. The radar receiver used in this study clearly has an FDR that would make it highly susceptible to interference from a wireless network at a close-in frequency.

Summary

In this article we discussed a methodology and technique for benchmarking wireless government infrastructure receiver performance. To demonstrate the method, we used an example of a commercial radar system and simulated the presence of a wireless LTE system. We showed that since the radar receiver and a wireless base station receiver have very similar levels of performance, both applications need similar standards for ensuring their performance.

For this study it was difficult to get information on the blocking sensitivity when not testing in an OTA environment. Gaining access to most of these deployed systems is difficult and staging them in a proper OTA setting will require coordination with the relevant government agency. Further testing would be beneficial in defining and refining a procedure based on occupied bandwidth and evaluating immunity based on fractional bandwidth.

Studies and mitigation distances for all wireless government infrastructure systems and receivers need to be considered. A standard methodology and approach will enable a baseline performance measure, so these issues can get the necessary attention and potential guidelines on design constraints or frequency allocations can be determined.

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IS THE ELECTRIC EQUIPMENT GROUNDING THE BASIC PROTECTION MEANS AGAINST HEMP?

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Abstract
The article discusses the differences between the electromagnetic pulses at lightning (LEMP) and at high altitude nuclear explosion (NEMP or HEMP). The article also shows that these differences do not allow to transfer LEMP experience on to NEMP. The author questions the effectiveness of grounding of electronic equipment as the main protection principle against NEMP, even though this method of protection is stipulated by all the regulatory documents and standards.

Keywords: *grounding, electronic equipment, electromagnetic interferences, EMP, NEMP, LEMP, filters*

IS THE ELECTRIC EQUIPMENT GROUNDING THE BASIC PROTECTION MEANS AGAINST HEMP?

Introduction
Electromagnetic pulse (EMP) occurring when lightning (LEMP) hits grounded facilities (either a tree, tower, building or a lightning rod) is a natural phenomenon that has been known for as long as mankind exists. During the last century, this phenomenon was well studied and this allowed to adopt some methods and techniques, which are widely used as protection from EMP.

As for electromagnetic pulse of high altitude nuclear explosion (NEMP), which occurs near the ground surface upon nuclear weapon detonation at high altitudes (30 – 400 km), the situation is different. The first trials to study NEMP were held in USA in the summer of 1962. During these trials, powerful electro-magnetic pulses were registered, which could vastly affect electronic equipment, communication and power supply lines, radio- and radar stations. They even knocked out street lighting in Hawaii, which is located about 1,500 km from the center of explosion.

In the fall of 1962, the Soviet Union also conducted three high altitude nuclear explosions, (each with a capacity of 300 kt) under the project called “Project-K” above the military fire range Sary-Shagan (Karaganda region, Kazakhstan) in order to study NEMP phenomenon.

During these trials, an impulse current of up to 3400 A was registered in aerial telephone line cables, which resulted in the emergence of a pulse voltage with an amplitude of up to 28 kV; actuation of all the arresters installed in the equipment and blowing of all the fuses accompanied by shutdown of communication system; damage of radio communication systems located 600 km away from the center of explosion; outage of a radio location unit located 1000 km away; damage of transformers and power generators at power plants; insulator punctures of overhead transmission lines.

Serious damage of equipment was also reported at Baikonur Cosmodrome. It should be noted that this refers to equipment manufactured in the 1960s, i.e. the one using electromechanical elements and vacuum tubes, which is much more resistant to EMP than modern digital and micro-processor based equipment.

The destructive impact of both types of EMP on the objects is alike and is stipulated by two factors: very high amplitude of voltage pulse applied to the object and high pulse current flowing through this object, as well as other secondary EMP outcomes related to these two factors, which are dangerous and damaging for electronic and electrical equipment.

This similarity of destructive impact resulted in the fact that the lightning protection methods and techniques, which have been properly researched and tested, started to be applied to NEMP. An example would be the fundamental principle of protection against the lightning: compulsory grounding of objects through the minimum possible resistance and the use of gas discharge tubes and filters that divert the pulse’s energy to the ground.

Is it really true? Are the specifications of LEMP and NEMP so similar to allow identical methods and techniques of protection?

Main Differences Between LEMP and NEMP
In fact, LEMP is a local electric breakdown of gas space (air) between two electrodes featuring high potential difference between them: a cloud and the earth (or an object located on the earth and featuring the earth’s potential), *Fig. 1*.

However, NEMP is a distributed electric field, which covers a large area and affects the objects located hundreds and thousands of kilometers away from the explosion epicenter due to spatial relocation of charged particles, e.g. electrons and ions that appeared as a result of complex physical processes, which occur upon the nuclear explosion in the atmosphere, *Fig. 1*.

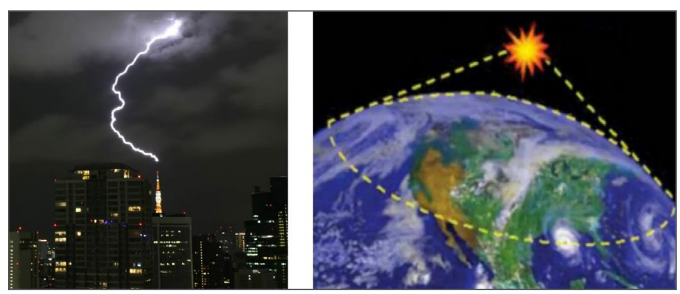

Fig. 1. The area of lightning and high altitude nuclear explosion impact.

Moreover, the structure of this field is not uniform and can be conditionally split into three component parts: E1, E2 and E3. E1 is a very short pulse of electric field shaped as 2/25 ns with the field gradient of 50 kV/m near the ground surface. E2 is a weaker electric field’s pulse with duration from several to dozens milliseconds. E3 is a very long low voltage pulse of electric field, which has to do with various processes in ionospheric medium. This can last up to several minutes and stipulates occurrence of significant quasi-DC currents in long-distance conductive media, such as rails, pipes, cables and wires. E1 is the most powerful, destructive and complex pulse (from the standpoint of protection) with vertical and horizontal polarized parts. Thus, when saying NEMP in this article, it will mean E1 as its main component.

Compared to LEMP, NEMP is less powerful (*Fig. 2*) and significantly shorter (*Fig. 3*), but as it covers a large area and affects thousands of facilities simultaneously; it is more dangerous than LEMP.

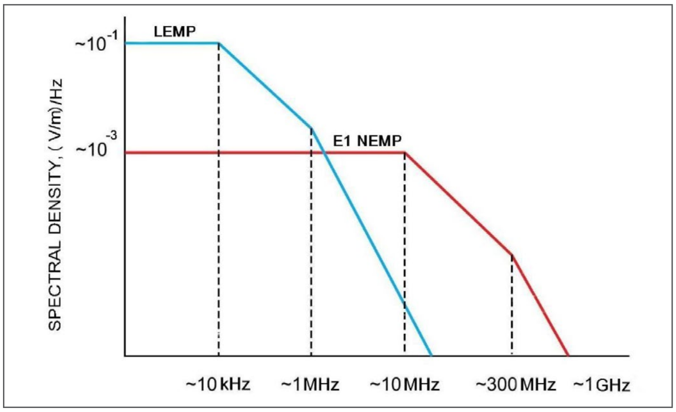

Fig. 2. Spectral density of LEMP and NEMP energy.

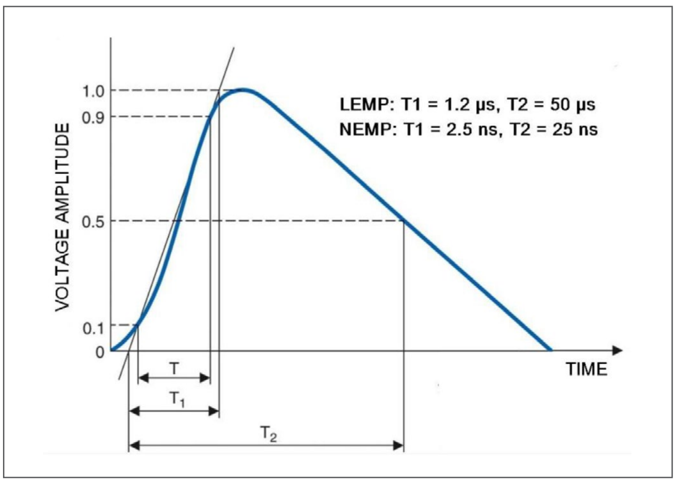

Fig. 3. Differences in time parameters of LEMP and NEMP

As stated above, both LEMP and NEMP can relocate over a distance and reach the ground surface in different ways. In case of LEMP's relocation through the ionized channel represented by a single or even branched cord, the situation is more or less clear. However, in case of NEMP the situation is much more complicated. First, the shape of NEMP's electric field near the ground surface is developed subject to the Earth's magnetic field; it is rather uneven. Second, the electromagnetic wave reaches the ground surface at a specific angle and thus, the electric field near the ground surface possesses both vertical and horizontal components. Third, part of electromagnetic energy, falling onto the ground surface at an angle, will be reflected and can consolidate with the energy falling onto the ground.

These differences between LEMP and NEMP make it possible to assume that they are different in their effect on the objects located on the ground surface.

Indeed, if we take a 10-meter metal rod, push one of its ends into the soil (vertically) and attach to it a current sensor, when lightning hits the open end of the rod, the sensor will register high amplitude current flowing through the rod as its grounded end has got zero (conditionally) potential, while the upper end takes up high (relative to ground) potential of the lightning.

When we have the bottom end of the rod well insulated from the ground surface and install it vertically, then there will be no current in the rod, even if we assume that lightning hits it, as there is no potential difference between the rod's ends (different capacitance values of the rod's ends relative the ground can be neglected due to their low level).

If NEMP impacts the same insulated rod, there will be high potential difference between its ends (theoretically, dozens of kilovolts) and the current sensor will register the relatively high amplitude current pulse flowing through it. Moreover, high potential difference occurs between the rod's ends, even if it is located horizontally relative to the ground surface.

What happens if we ground one of the ends of this horizontal rod? It is a much more complex case because NEMP penetrates in the soil and induces gradients directly in the soil. This effect takes into consideration the model of a power transmission line with grounded neutral to study the NEMP affect. In such a model, the voltage on the open second end of the line to the ground will depend on the transmission line height above ground, its length and soil conductivity [1]. But this model is not our case with insulated ends of the rod, and in our case the grounding of one of its ends does not affect the voltage gradient between the ends.

The same effect will occur at a single electronic device installed in a cabinet in a control room with fully electrical insulated (without considering capacity to ground) control cables connected to its inputs. The electric field affecting these cables has nothing to do with the ground and its potential. In other words, such cables with potential difference induced on its ends by NEMP acts as a EMP source insulated from the ground for electronic devices. It works as a charged accumulator battery in an insulated body.

What happens, when only one pole of the accumulator battery is grounded? Just nothing! Neither with the accumulator battery, nor with the insulated load, that receives power from this accumulator.

So, why would something happen if we ground the NEMP affected small local object as a control cabinet with electronic devices inside? This question is very important and highly relevant as it directly affects efficiency of equipment intended to ensure protection against NEMP. According to [2]: "The early-time E1 HEMP waveform also couples efficiently to short lines (1-10 meter) connected to equipment (power, signal lines, etc.) and can induce large voltages and currents that can be conducted to the inside of the equipment". In this sentence there is no relation to ground.

Unfortunately, it is a very difficult to study this phenomenon in an open area test site simulator (OATS) suitable for simultaneous testing the group of electrical control cabinets with cable connection between them, because most such simulators contain a Marx generator and two electrodes: one grounded mesh and another one – an insulated mesh placed above the grounded mesh at a height 5 – 20 m, *Fig. 4* (so-called "single port open wave-guide simulators"

Fig. 4. Single port open area guided-wave simulators, produce a vertical electric field.

A simulated electrical pulse field is applied directly between these two electrodes, between the upper electrode and the ground. In such a simulator, well grounding the equipment under test (that is a low impedance connection the shields and metal shells of equipment to the down electrode) will always play the role of effective protection means as at lightning testing.

The grounding of down electrode is due to necessity simulating influence of ground reflection on the field in the test volume. However, in contrast, in small radiated test facilities equipment under test (EUT) shall be placed on dielectric stand above the ground plane within the test volume, according to IEC 61000-4-20 standard [7]. In our opinion, to study aforementioned phenomenon in a large OATS also can be use dielectric plate between EUT and down electrode without EUT grounding.

Grounding of Electric Equipment as the Main Protection Means Against NEM

Various standards, (both civil and military) as well as different guidelines and recommendations, justify the necessity of compulsory grounding of all types of electronic and electrical equipment as the main protection means against NEMP. But why, if the grounding system does not act as an opposite electrode with an opposite charge for NEMP (unlike a lightning strike)?

According to [3] "In general, the reason for grounding are varied, and it would be presumptuous to attempt to specify grounding procedures without first establishing the reasons for grounding and the goals that the grounding system should achieve. These reasons and goals are usually based on system functional, safety and RF interference considerations as a consideration in the ground-system design, at least one more goal has been added (EMP hardness), but the reason for grounding may remain unchanged. The basic reason for providing a "ground" in electronic equipment is to establish a firm reference potential against which signal and supply voltage are measured (or established)".

Such considerations are a reason for standard recommendation about standard grounding methods in all documents related to NEMP, despite the grounding is not a clear and proven protection means against NEMP. But the functional and safety considerations and reference potential necessity for electronic equipment have also another direct grounding solution [4 - 6]. At the same time, it is obvious that the branched and spatially distributed grounding system acts as a huge antenna for NEMP, absorbing energy from a large area and delivering it directly to sensitive electronic equipment via the grounding circuits. Of course, the energy level will be partially lowered by the conductive soil. However, the part that finds its way into the system will be enough to result in a dangerous potential rise directly in electronic circuits of highly sensitive microprocessor-based equipment (such as digital protection relays - DPR):

- *"Many elements of a facility can act as efficient collectors and provide propagation paths for EMP energy. EMP can couple to structures such as power and telephone lines, antenna towers, buried conduits, and the facility grounding system* [8]*;*

- *"Based upon coupling calculations it is appears that levels up to 10 kV may be coupled to horizontal buried lines in a substation yard (although 20 kV is possible under some scenarios)"* [2]*;*

- *"A "ground" is commonly thought of as a part of a circuit that has relatively low impedance to the local earth surface. A particular ground arrangement that satisfies this definition may, however, not be optimum and may be worse than no ground for EMP protection"* [9]*.*

- *"For HEMP protection, however, the grounding system is considered a potential path for transient penetration into the system and a means of distributing transients throughout the interior* [10]*.*

There are two contradictory ideas about grounding appears in many engineering books and documents, for example:

> *"The primary effect of the HEMP is, therefore, the production of large voltages or currents in large structures and conductors such power lines, buried cables, and antennas, as well as in facility grounding systems" (page 935)…. And in the same page: "The goal of all grounding and bounding techniques is to redirect the HEMP-induced currents to the earth"* [11].
>
> *"Grounding does not directly provide protection against EMP…" (page 5-3) and*
>
> *"The grounding required for EMP protection... (page 5-5)"* [8].

What conclusion may appear from such ideas?

In fact, many individual printed circuit boards of this equipment have got their own "ground", i.e. a system of conductor strips with a so called "zero" or "reference" potential; all the other potentials necessary for equipment operation will emerge relative to the former. As a rule, this internal ground is connected to a metal body, which, in turn, is connected to an external grounding system. The potential of the grounding system is known to increase under the common lightning strike. At the same time, it is considered that if all the electronic devices will share the potential of a grounding system, i.e. there will be no difference of potentials between the circuits of "zero potential" of various devices, this increase of common potential and its difference from zero, that takes place in all the devices simultaneously, cannot cause malfunctioning of these devices.

The whole theory of grounding is based on this assumption prescribing to maintain minimum resistance of grounding system's elements, using equipotential planes, etc., in other words, the measures aimed at prevention of a difference of potentials between "zero potential" circuits, distanced from each other and hence grounded at different locations, but at the same time they stay in electric and informational contact. Furthermore, the issue of what happens in a single electronic device during the rise of its "zero potential" circuit is not addressed. The fact is that any electronic circuit contains a lot of non-linear elements and those that possess capacitance and inductance and connected to "zero potential" circuit. As a consequence, voltage and current will not rise simultaneously at different points of the circuit during the potential rise in it.

You can visualize it as a plate supporting weights of different mass that are attached to this plate by means of springs of various rigidity. If we start raising this plate gradually (i.e. during the gradual increase of potential energy), the potential energy of all the elements resting on this plate will increase simultaneously. However, if we raise the plate abruptly, the elements will not change their position and potential energy simultaneously. Additionally, if they were mechanically united, perhaps this would even result in breakages of those connections. Thus, availability of equipotential plane and maintaining zero difference between the circuits of "zero potential" of different devices does not guarantee the absence of malfunctioning of highly sensitive electronic equipment.

In real life, when using electronic equipment located at spatial facilities, it is very difficult and sometimes even impossible to maintain zero difference of potentials between the circuits of "zero potential, especially when the grounding system is working as an antenna, *Fig. 5*.

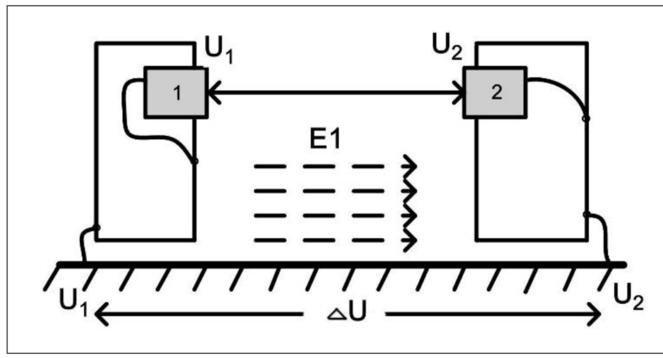

Fig. 5. The impact of high voltage on the inputs of electronic equipment remotely located from each other in grounded bodies upon the impact of E1 component of NEMP onto the grounding system.

This situation is true for large energy producers and industrial enterprises, such as power plants and substations, oil refineries, etc.

Protection Devices Against NEMP

Usually, devices designed for protecting equipment from NEMP overvoltage, are connected between the circuits to be protected and the grounding system (common mode protection), *Fig. 6*.

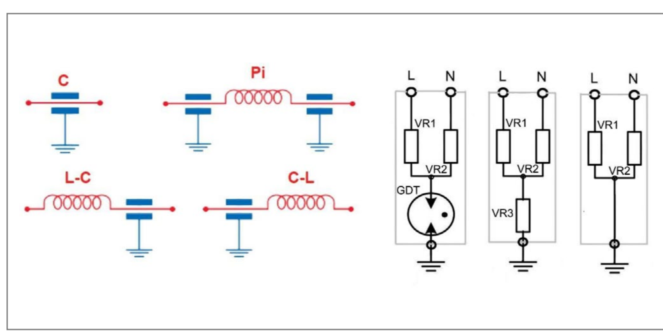

Fig. 6. Simplified design of various LC-filters against NEMP and devices protecting from pulse overvoltage with parallel elements that divert impulse energy from the input to the ground. VR – varistors, GDT – gas discharge tube.

Special filters intended for NEMP protection include non-linear elements that divert impulse energy from the filter inputs to the ground, *Fig. 7*.

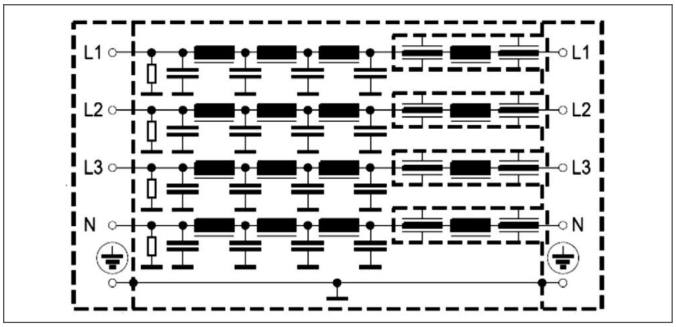

Fig. 7. Real design of 3-phase NEMP filter that contains non-linear resistors connected between each input of the filter and the ground (in addition to capacitors that divert energy to the ground).

Another problem is the difference in parameters of such filters for a pulse applied between the input and the ground compared to the pulse, applied between individual inputs, *Fig. 7*. At the same time, main protection is designed between each input and the ground. Many filters have been designed with only one input terminal, one output terminal and the grounded body (*Fig. 8*). Thus, they are intended to protect sensitive inputs of equipment solely from pulses featuring higher amplitude relative to the ground and divert energy from the input to the ground.

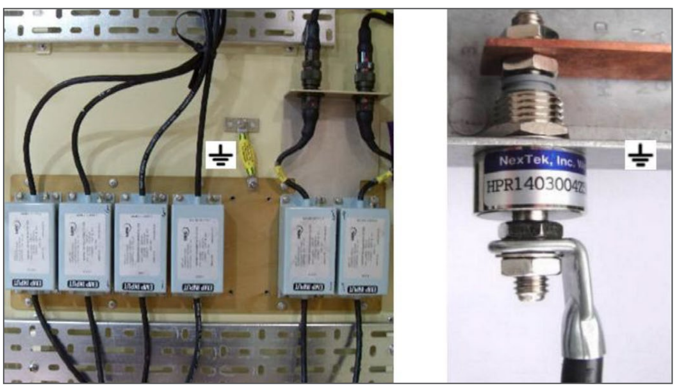

Fig. 8. Filters protecting from NEMP pulse applied to equipment input terminals relative to the ground.

However, when the grounding system does not represent the area of reverse potential or zero potential for NEMP, where will the pulse energy be diverted? And when a similar pulse occurs on the grounding electrode simultaneously with high voltage pulse occurring on the input of a filter or a device protecting from overvoltage, how will this filter weaken NEMP?

These questions are still waiting to be answered. Thus, the specialists invite active discussions concerning this problem because "grounding may not be a solution; rather it could be part of the problem" [11].

Conclusions

Use of grounding of electronic and electric equipment as the main NEMP protection is not only questionable, but also may be dangerous, as instead of NEMP weakening, it can enhance its destructive impact on equipment. However, since this grounding is stipulated in all the regulatory documents, this problem needs to be further discussed with the relevant specialists.

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REVIEW OF MIL-STD 461 RE101– RADIATED EMISSIONS, MAGNETIC FIELD AND RE102 RADIATED EMISSIONS, ELECTRIC FIELD

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Introduction

This article discusses RE101 and RE102, including the updates contained in MIL-STD-461 revision "G", the current version. These tests quantify undesired signals being radiated into the air from a device and the associated cables. If unchecked, these signals couple onto other equipment cables or may enter into the other equipment chassis and onto internal conductors. The received field has the potential to induce current in other equipment conductors and may cause harmful interference from either field.

Both of these test methods have been a part of the MIL-STD-461 test program from the onset using RE04 (Magnetic Field) and RE02 (Electric Field) numbering. Release of MIL-STD-461C changed the RE04 number to RE01 for the magnetic field radiation test method but MIL-STD-462 continued to refer to RE04 even with issued notices updating the standard.

REVIEW OF MIL-STD 461 RE101– RADIATED EMISSIONS, MAGNETIC FIELD AND RE102 RADIATED EMISSIONS, ELECTRIC FIELD

Introduction

RE01 (RE04) covered the frequency range of 30 Hz to 50 kHz with the magnetic loop antenna located 1-meter from the Equipment Under Test (EUT). The limit was in dBpT (dB referenced to 1 picotesla) terms indicating a flux density measurement. RE02 covered the frequency range of 14 kHz to 10 GHz for narrowband (NB) emissions and limited the upper frequency to 1 GHz for broadband (BB) emissions with the antenna located 1-meter from the EUT. The limit was in dBmV/m for NB emissions and dBmV/m/MHz for BB emissions.

As noted above, RE02 called for tests to determine if the emissions were classified as narrowband (NB) or broadband (BB). The limits would allow broadband emissions to be higher in amplitude since this kind of noise tended to have a more benign impact to human senses. Compare the sound of wind blowing through trees creating many sound frequencies (BB) to a siren with a single frequency (NB). The wind would permit audio speech and the siren would provide a greater interference to speech reception. In the early days, interference to radio communications was a dominate problem so the separation of NB and BB had a significant impact on product qualification.

While we are on the BB subject a review on making the decision seems timely. MIL-STD-462 provided two tests to support the decision.

Test One:

1. Tune the receiver to the peak signal frequency.
2. Adjust the frequency ±2 IBW (IBWNote 1 is impulsive bandwidth part of the receiver calibration).
3. If the amplitude changed by <3 dB the signal was classified as BB.
   Note 1: *IBW is a measure of how the receiver reacts to an impulse signal. An impulse generator (IG) signal with the impulse peak calibrated for a 1 MHz bandwidth is applied to the receiver. If the receiver bandwidth is set for 10 kHz, the impulse should measure 40 dB lower than the IG amplitude setting. Assume that the IG output is set for 80 dBmV/MHz and the receiver measurement is 42 dBmV for a 38 dB impulse restriction indicating an IBW of 12.6 kHz. Calibration of the IBW is only necessary if measuring BB signals and converting to the /MHz units.*

Test Two:

1. Measure the pulse repetition frequency of the emission
2. If the pulse repetition frequency was less than or equal to the IBW of the receiver the emission was classified as BB.

If either of these two tests resulted in a BB classification, the emission was BB and was compared to the limit to determine acceptance. Let's not forget that the limit measurement units for BB is dBmA/MHz, so the measurement had to be normalized to the /MHz units by applying a -20logBW in MHz conversion factor. For example if your measurement was using a 10 kHz bandwidth (BW), then -20log(0.01) would provide a 40 dB conversion to conform the measurement to dBmA/MHz units. *Note 1* above provides more detail on the conversion.

Back in the day when these measurements were common, a spectrum analyzer with custom proprietary software to make the NB/BB determination was used and the measurements were plotted on the applicable chart. Today, this process is manual and can be somewhat time consuming, so when this is applicable to your test program, allow sufficient time for the manual interaction needed.

For a quick assessment, tune receiver to the emission frequency and change the receiver BW by a factor of ten. If the measurement did not change the emission is NB, if the measurement changed by 10 dB the emission is random noise and if the measurement changed by 20 dB the emission is BB. Note that this technique doesn't follow the standard, so for official measurements use the standard approach.

In 1993 the release of MIL-STD-461D and MIL-STD-462D, changed the testing to RE101 for the 30 Hz to 100 kHz frequency range measured with a 13.3 cm loop sensor located 7 cm and 50 cm from the EUT. The two distances were specified to determine if the magnetic field attenuation would allow the item to be accepted for use if the 7 cm test showed non-compliance and the application did not jeopardize other equipment in the vicinity. RE102, the electric field test method, changed the frequency range to 10 kHz to 18 GHz (actually 1 GHz or 10-times the highest intentionally generated frequency up to 18 GHz) and called out particular antennae for various frequency ranges. This revision also deleted the NB / BB determination requirement and prescribed specific BWs for selected test frequency ranges. This version required that cables were exposed during test, so cable radiation could be measured during the radiated portion of the test program.

MIL-STD-461D specified that an anechoic test chamber be used for RE102 testing to reduce the effect of reverberation causing very large measurement errors. The anechoic room required that the RF absorber minimum absorption be 6 dB (80 MHz – 250 MHz) and 10 dB (above 250 MHz).

MIL-STD-461E removed the 50 cm testing distance calling for compliance at the 7 cm test distance. This took away having measurements at another distance making the decision to grant a waiver more difficult. I want to expand on this a bit because reducing magnetic field emissions can be challenging. Let's consider a laptop computer where the current associated with a bright screen produces an over limit at 7 cm. Moving the receiving loop to a distance of 15 cm reduces the field below the limit with the 15 cm distance from the front or rear of the display. If the laptop is used on a desk, it is unlikely that a susceptible device will be located within the 15 cm distance especially the front where the operator will be located during operation. If by some remote chance, the rear causes an issue, placing a ferrous metal sheet between the laptop and the susceptible device should redirect the flux lines and resolve the problem.

MIL-STD-461F added a distance measurement to the RE101 test method. If the device was non-compliant at the 7 cm distance, the procedure calls for increasing the distance to meet the limit and provide that distance information in the test report for assessment by the procuring agency. RE102 implemented a significant change in positioning and configuring the rod antenna for measurements below 30 MHz. The standard of connecting the base counterpoise to the ground plane was deleted. The rod antenna base also connected the cable connector to the base instead of using an isolated coaxial connector. A ferrite was installed on the cable to the receiver. The changes brought about a lot of concern from the EMC community, but several studies demonstrated that the MIL-STD-461F configuration obtained more consistent results from one facility to another.

MIL-STD-461G brought forth a few minor changes to the RE101 test method. RE102 also had minor changes but one that is significant. The test frequency range 10 kHz to 18 GHz, eliminating the option to end the test at 1 GHz or 10-times the highest intentionally generated frequency up to 18 GHz. This can be a significant impact in test time for large devices where the antenna beam-width demands multiple antenna positions in the 1-18 GHz frequency range, especially when using a tuning receiver (time is low when using a FFT receiver because you can measure 100 MHz or more at the same dwell time instead of ½ bandwidth per dwell time interval).

Our discussion on the detailed requirements is based on MIL-STD-461G, the current standard.

RE101 Radiated Emissions, Magnetic Field
Let's delve into RE101 first with the signal integrity verification where we check the measurement system by creating a known signal frequency and amplitude. We then measure the signal to ensure we obtain the correct values using the measurement system we have selected for test. Adding to the check, the target amplitude should be 6 dB below the applicable limit to demonstrate measurement system sensitivity to detect emissions at that level.

Assemble the signal source for measurement as shown in *Figure 1* part A using the coaxial cable selected for EUT testing. Set the signal generator frequency to 50 kHz and amplitude to the limit minus 6 dB minus the loop conversion factor. The loop is not present for this signal check, but the measurement system will include the factor as part of the data reduction. Operate the measurement receiver to capture the 50 kHz signal and verify that the measurement is 6 dB below the limit (±3 dB).

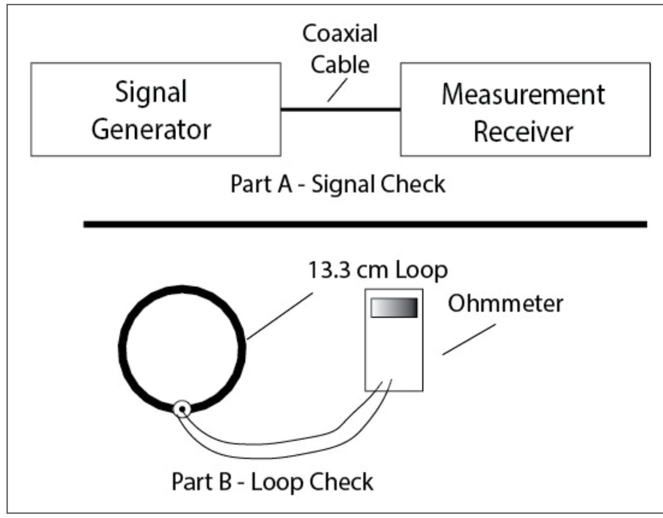

Figure 1: RE101 Signal Integrity Check Configuration

Now we can configure the test item as shown in *Figure 2* for testing after successful completion of the signal integrity check. The loop antenna is placed 7 cm from the EUT with the loop parallel to the EUT and perpendicular to the ground plane. Move the loop antenna into position after the EUT is operating and stabilized to avoid capture of inrush current effects. Set the receiver to capture a segment of the test frequency range, normally the range for one of the bandwidth settings. Set the receiver to max hold to capture worst case emissions. While observing the receiver display, move the loop antenna over the EUT face maintaining the 7 cm spacing.

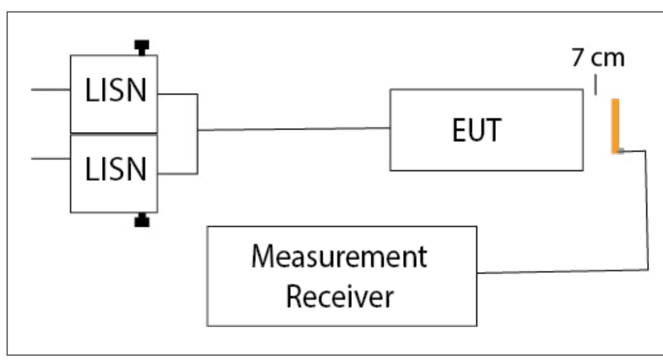

Figure 2: RE101 Test Configuration

At the location where the worst-case emissions were detected, orient the loop to perpendicular to the EUT and perpendicular to the ground plane to verify maximum emissions. The third orientation, perpendicular to the EUT and parallel to the ground plane will be used to complete that segment of the test. Repeat the testing for each frequency range segment and each face of the EUT. The standard discusses measuring worst-case emission and a number of frequency points, but this method described above captures all frequency points instead of a select few.

It is common on large test items to discover that different antenna locations show different emissions as indicated in *Figure 3*. In a case like this each point would need to be captured separately. If the results show over-limit emission, measure the distance from the EUT where the limit is met to support review by the procuring agency as we discussed earlier.

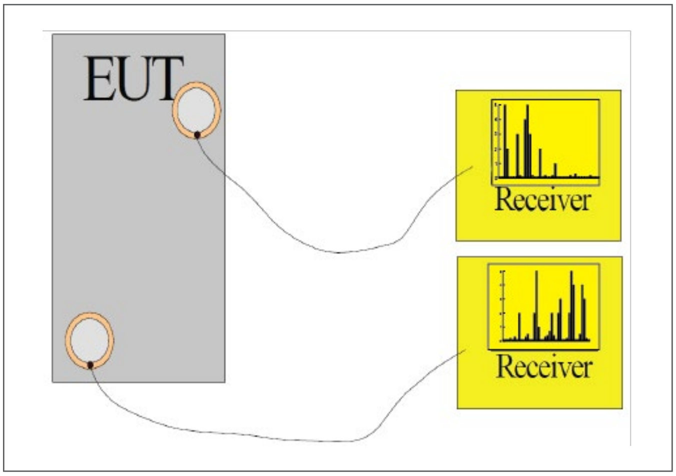

Figure 3: RE101 Results Example

RE102 Radiated Emissions, Electric Field

We begin the RE102 procedure with the system integrity verification. Recall that revision "G" permitted removing several passive test equipment items from periodic calibration including passive antennas.

Assemble the signal source for measurement as shown in *Figure 4* using the coaxial cable selected for EUT testing. Include attenuators, filter or pre-amplifiers as required for testing. The rod antenna amplifier section is connected to the coaxial cable by a calibrator providing termination and capacitive coupling to the antenna input replacing the rod portion of the antenna. Refer to MIL-STD-461G for more detail on the rod calibrator configuration. Other antennae are not included in the signal integrity check. Set the signal generator frequency to 10 kHz (2 MHz if test range is not below 2 MHz).and amplitude to the limit minus 6 dB minus the antenna conversion factor. The antenna is not present for this signal check, but the measurement system will include the factor as part of the data reduction. Operate the measurement receiver to capture the signal and verify that the measurement is 6 dB below the limit (±3 dB). Repeat the checks for the specified check frequencies. Repeat the check for each measurement path configuration change such as addition or removal of a filter or other element of the path.

Note that during the check the passive antennae were not present. A physical inspection of each antenna should be accomplished and repaired if found damaged. After a repair the antenna should be calibrated. Using a stub radiator *Note 2*, radiate a signal in the reception band for each antenna to confirm that the antenna is receiving the radiated signal. Note that accurate measurement of the stub radiation is not required but if the stub radiator and receiving antenna are consistently placed, measurements should be very close from one test to another.

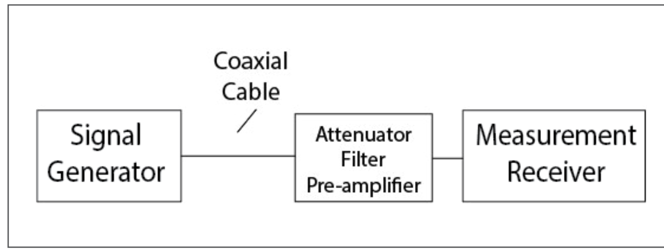

Figure 4: RE102 Signal Integrity Check Configuration

Note 2: Stub radiator is typically a coaxial cable with the outer braid removed on one end that will act like a monopole antenna providing a radiated signal to check the measurement system antenna for function.

Once all measurement path and antennae have been checked you are ready to establish the test configuration as shown in *Figure 5*. The antenna replaced the signal generator used in the integrity check.

The antenna is positioned 1-meter from the test boundary. The test boundary is the area that encompasses the EUT, cables and LISNs – not the ground plane. If the cables are 10 cm from the ground plane front edge, then the antenna is 0.9-meter from the ground plane. The rod and biconical antennae are normally located near the center of the test boundary. The doubled ridge horn antenna is positioned so that the EUT plus 35 cm of cable is within the antenna beam-width for the 200 MHz to 1 GHz range. The double ridge horn for the 1 GHz to 18 GHz antenna is positioned to place the EUT plus 7 cm of cable in the antenna beam-width. For large test articles, multiple antenna positions may be necessary to examine the EUT. Horizontal and vertical antenna polarizations present different beam-widths so one polarization may require more positions that the other polarization.

The standard indicates that testing should be accomplished on the EUT face with maximum emissions. Prior to test, a probing process may be used to look at all faces to determine worst-case orientations. Frequently, the cable interface side is worst at lower frequencies and an operator display face or open panels are worse at higher frequencies. Testing of more than one face may be necessary.

Establish operation of the EUT and operate the measurement receiver system to collect and record emission measurements. Normally a separate chart is provided for each antenna, each antenna polarization and each antenna position.

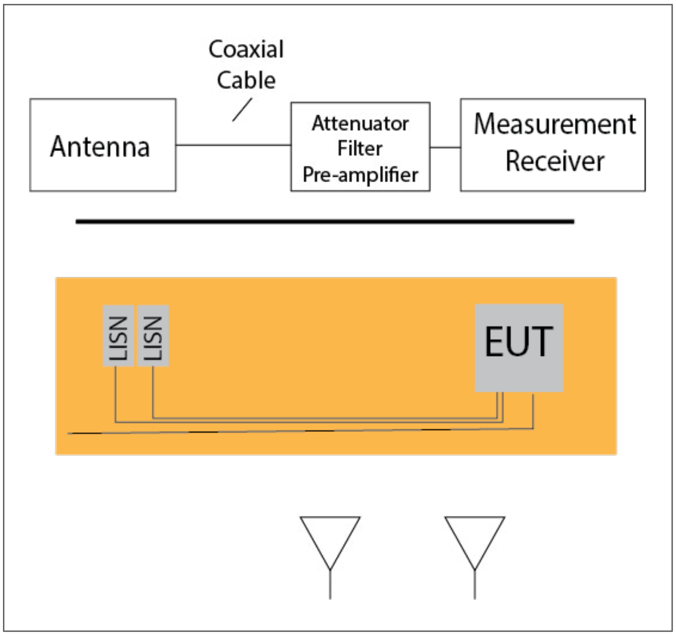

Figure 5: RE102 Test Configuration

Summary

The RE testing is not difficult, but there are many items that can cause flawed data. Consider the results and ask yourself "does this data make sense" and if you doubt the validity, examine for mistakes or simply redo things in question. At an antenna change point, the emissions should not suddenly disappear. A bandwidth change should see a noise floor change and a broadband signal would change by 20 dB for a decade of bandwidth change.

The signal integrity checks should not be taken lightly – lots of things are checked in this process from the hardware operation to selecting the correct file for applying correction and conversion factors. Measurement system cables are part of the integrity checks so don't ignore their influence.

As with any emission testing, make sure that the EUT cycle time is considered. If the EUT takes longer than the minimum dwell time of the measurement receiver, the dwell time will need to be set for the EUT cycle time.

TABLE OF NEW EQUIPMENT ALLOWED/REQUIRED IN MIL-STD-461G

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The following table was compiled by Ken Javor, of EMC Compliance. The updated changes to MIL-STD-461G require some new equipment. One of these changes allows the use of time domain EMI receivers, which will help speed up the testing, due to their fast FFT-based signal acquisition. Following is a list of some specific changes and equipment requirements:

CS101 *(Conducted Susceptibility, Power Leads) - There is now a requirement to measure induced AC power line ripple. This requires a new "*power ripple detector", which is a specially designed isolation transformer that matches the power line to 50 ohms.

CS114 *(Conducted Susceptibility, Bulk Cable Injection) - This injection probe test now requires the use of a current probe calibration fixture to validate the test level duri*ng pre-calibration.

CS117 *(Conducted Susceptibility, Lightning Induced Transients, Cables and Power Leads) - This* is a new test added to MIL-STD-461G and requires a lightning transient simulator.

CS118 *(Conducted Susceptibility, Personnel Borne Electrostatic Discharge) - This* is a new test added to MIL-STD-461G and requires a standard electrostatic discharge simulator.

RS103 *(Radiated Susceptibility, Electric Field) - This test requires an E-field antenna that can go down to 2 MHz.*

Table of New Equipment Required for Latest Updates to MIL-STD-461G

Requirement	Equipment Type	Vendor(s)	Websites
General	Time Domain EMI receivers*	Amplifier Research	http://www.arworld.us/html/dsp-receiver-multistar.asp
		Gauss Instruments	http://www.gauss-instruments.com/en/products/tdemi
		Keysight	http://www.keysight.com/en/pdx-x201870-pn-N9038A/mxe-emi-receiver-3-hz-to-44-ghz?cc=UG&lc=eng
		Rohde & Schwarz	https://www.rohde-schwarz.com/us/products/test-measurement/emc-field-strength-test-solutions/emc-field-strength-test-solutions_105344.html
CS101	Frequency domain ripple monitoring transducer*	Pearson Electronics	http://www.pearsonelectronics.com/news/179
	High-voltage differential probe, 100 MHz, 1k V(RMS)	Rohde & Schwarz	https://www.rohde-schwarz.com/us/product/rtzd01-productstartpage_63493-34629.html
	Digital Oscilloscopes (200 MHz - 4 GHZ, 5/10 GSa/s)	Rohde & Schwarz	https://www.rohde-schwarz.com/us/product/rto-productstartpage_63493-10790.html or https://www.rohde-schwarz.com/vn/product/rte-productstartpage_63493-54848.html (with Option RTO-K17)
CS114	Current probe calibration fixture	ETS/Lindgren	http://www.ets-lindgren.com/EMC (fixture not listed on web site but should be part of current probe/injection clamp line-up)
		Fischer Custom Communications	http://www.fischercc.com/ViewProductGroup.aspx?productgroupid=141
		Pearson Electronics	http://www.pearsonelectronics.com/news/180 (fixture holds both injection clamp and current probe)
		Solar Electronics	http://www.solar-emc.com/RFI-EMI.html (scroll to bottom of page)
CS117	Indirect lightning test systems	HV Technologies	http://www.hvtechnologies.com/TestsTrack/Lightning/tabid/408/Default
		Thermo Scientific	http://www.thermoscientific.com/en/product/ecat-lightning-test-system-lts.html
		Solar Electronics	http://www.solar-emc.com/2654-2.html
CS118	ESD gun	EMC Partner	https://www.emc-partner.com/products/immunity/esd/esd-generator
		EM Test	http://www.emtest.com/products/productGroups/ESD_generators.php
		Haefely	http://www.haefely-hipotronics.com/product/product-category/electrostatic-discharge-test-systems-esd/
		Kikusui	http://www.kikusui.co.jp/en/product/detail.php?IdFamily=0020
		LISUN Group	http://www.lisungroup.com/product-id-318.html
		Noiseken	http://www.noiseken.com/modules/products/index.php?cat_id=1
		Thermo Scientific	http://www.thermoscientific.com/en/product/minizap-15-esd-simulator.html
		TESEQ	http://www.teseq.com/product-categories/esd-simulators.php
RS103	1 – 18 GHz electric field probe (most test facilities already have one)	Amplifier Research	http://www.arworld.us/html/field-analyzers-field-monitoring.asp
		ETS/Lindgren	http://www.ets-lindgren.com/EMCProbes
		NARDA	http://www.narda-sts.us/products_highfreq_bband.php

* Specified as acceptable for use, but not required.

MILITARY RELATED DOCUMENTS AND STANDARDS

The following references are not intended to be all inclusive, but rather a representation of available sources of additional information and point of contacts.

MIL-HDBK-235-1C Military Operational Electromagnetic Environment Profiles Part 1C General Guidance, 1 Oct 2010.

MIL-HDBK-237D Electromagnetic Environmental Effects and Spectrum Certification Guidance for the Acquisition Process, 20 May 2005.

MIL-HDBK-240A Hazards of Electromagnetic Radiation to Ordnance (HERO) Test Guide, 10 Mar 2011.

MIL-HDBK-263B Electrostatic Discharge Control Handbook for Protection of Electrical and Electronic Parts, Assemblies and Equipment (Excluding Electrically Initiated Explosive Devices), 31 Jul 1994.

MIL-HDBK-274A Electrical Grounding for Aircraft Safety, 14 Nov 2011.

MIL-HDBK-335 Management and Design Guidance Electromagnetic Radiation Hardness for Air Launched Ordnance Systems, Notice 4, 08 Jul 2008.

MIL-HDBK-419A Grounding, Bonding, and Shielding for Electronic Equipment and Facilities, 29 Dec 1987.

MIL-HDBK-454B General Guidelines for Electronic Equipment, 15 Apr 2007.

MIL-HDBK-1004-6 Lightning Protection, 30 May 1988.

MIL-HDBK-1195, Radio Frequency Shielded Enclosures, 30 Sep 1988.

MIL-HDBK-1512 Electroexplosive Subsystems, Electrically Initiated, Design Requirements and Test Methods, 30 Sep 1997.

MIL-HDBK-1857 Grounding, Bonding and Shielding Design Practices, 27 Mar 1998.

MIL-STD-188-124B Grounding, Bonding, and Shielding for Common Long Haul/Tactical Communications-Electronics Facilities and Equipment, 18 Dec 2000.

MIL-STD-188-125-1 High-Altitude Electromagnetic Pulse (HEMP) Protection for Ground-Based C41 Facilities Performing Critical, Time-Urgent Missions Part 1 Fixed Facilities, 17 Jul 1998.

MIL-STD-220C Test Method Standard Method of Insertion Loss Measurement, 14 May 2009.

MIL-STD-331C Fuze and Fuze Components, Environmental and Performance Tests for, 22 Jun 2009.

MIL-STD-449D Radio Frequency Spectrum Characteristics, Measurement of, 22 Feb 1973.

MIL-STD-461F Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment, 10 Dec 2007.

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MIL-STD-464C Electromagnetic Environmental Effects Requirements for Systems, 01 Dec 2010.

MIL-STD-704E Aircraft Electric Power Characteristics, 12 Mar 2004.

MIL-STD-1310H Standard Practice for Shipboard Bonding, Grounding, and Other Techniques for Electromagnetic Compatibility Electromagnetic Pulse (EMP) Mitigation and Safety, 17 Sep 2009.

MIL-STD-1377 Effectiveness of Cable, Connector, and Weapon Enclosure Shielding and Filters in Precluding Hazards of EM Radiation to Ordnance; Measurement of, 20 Aug 1971.

MIL-STD-1399 Section 300B Interface Standard for Shipboard Systems, Electric Power, Alternating Current, 24 Apr 2008.

MIL-STD-1541A Electromagnetic Compatibility Requirements for Space Systems, 30 Dec 1987.

MIL-STD-1542B Electromagnetic Compatibility and Grounding Requirements for Space System Facilities,

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15 Nov 1991. MIL-STD-1605 Procedures for Conducting a Shipboard Electromagnetic Interference (EMI) Survey (Surface Ships), 08 Oct 2009.

MIL-STD-1686C Electrostatic Discharge Control Program for Protection of Electrical and Electronic Parts, Assemblies, and Equipment (Excluding Electrically Initiated Explosive Devices). 25 Oct 1995.

ADS-37A-PRF Electromagnetic Environmental Effects (E3) Performance and Verification Requirements, 28 May 1996.

DOD-STD-1399 Section 070 Part 1 D.C. Magnetic Field Environment, Notice 1, 30 Nov 1989.

DoDI 3222.03 DoD Electromagnetic Environmental Effects (E3) Program, 24 Aug 2014.

DoDD 4650.01 Policy and Procedures for Management and Use of the Electromagnetic Spectrum, 09 Jan 2009.

DoDI 6055.11 Protecting Personnel from Electromagnetic Fields, 19 Aug 2009.

AEROSPACE STANDARDS

AIAA Standards
http://www.aiaa.org/default.aspx

S-121-2009, Electromagnetic Compatibility Requirements for Space Equipment and Systems

RTCA Standards
https://www.rtca.org/

DO-160G, Environmental Conditions and Test Procedures for Airborne Equipment

DO-160G Change 1, Environmental Conditions and Test Procedures for Airborne Equipment

DO-233, Portable Electronic Devices Carried on Board Aircraft

DO-235B, Assessment of Radio Frequency Interference Relevant to the GNSS L1 Frequency Band

DO-292, Assessment of Radio Frequency Interference Relevant to the GNSS L5/E5A Frequency Band

DO-294C, Guidance on Allowing Transmitting Portable Electronic Devices (T-PEDs) on Aircraft

DO-307, Aircraft Design and Certification for Portable Electronic Device (PED) Tolerance

DO-307A, Aircraft Design and Certification for Portable Electronic Device (PED) Tolerance

DO-357, User Guide: Supplement to DO-160G

DO-363, Guidance for the Development of Portable Electronic Devices (PED) Tolerance for Civil Aircraft

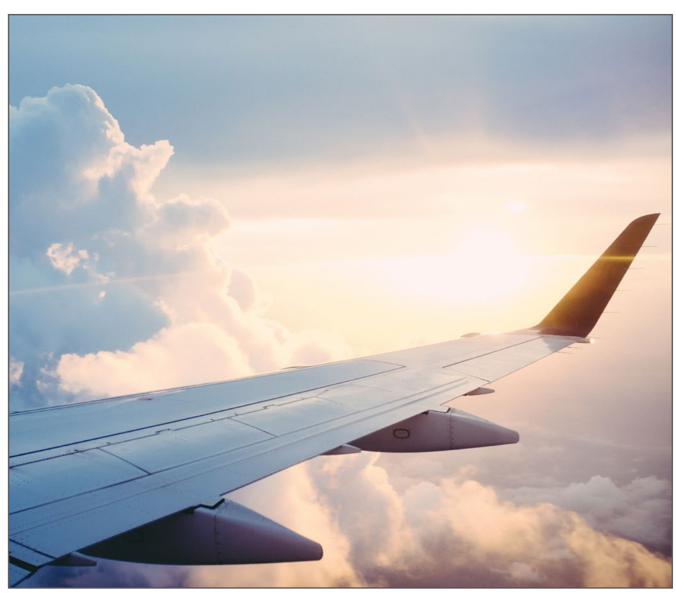
DO-364, Minimum Aviation System Performance Standards (MASPS) for Aeronautical Information/Meteorological Data Link Services

DO-363, Guidance for the Development of Portable Electronic Devices (PED) Tolerance for Civil Aircraft

DO-307A, Aircraft Design and Certification for Portable Electronic Device (PED) Tolerance

SAE Standards
http://www.sae.org/

ARP 5583 – Guide to Certification of Aircraft in a High Intensity Radiation (HIRF) Environment http://standards.sae.org/arp5583/



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(ARTICLE LINKS, DIRECTORIES, CONFERENCES, & LINKEDIN GROUPS)

LINKS TO LONGER ARTICLES

"MIL-STD-461G – The Compleat Review"
https://interferencetechnology.com/mil-std-461g-compleat-review/

"Selecting the Proper EMI Filter Circuit For Military and Defense Applications"
https://interferencetechnology.com/selecting-proper-emi-filter-circuit-military-defense-applications/

"Why is there AIR (In MIL-STD-461G)?"
https://interferencetechnology.com/air-mil-std-461g/

TEST HOUSE DIRECTORY

Test House Directory – 2016 Test and Design Guide
http://learn.interferencetechnology.com/2016-emc-test-and-design-guide/

2018 CONFERENCE DIRECTORIES

AFCEA Events:
www.afcea.org/site/

ASCE Events:
www.asce.org/aerospace-engineering/aerospace-conferences-and-events/

ASD Events:
www.asdevents.com/shopcontent.asp?type=aerospace_defence

Aviation Week Event Calendar:
www.events.aviationweek.com/current/Public/Enter.aspx

Defense Conferences:
www.defenseconference.com/

Global Edge (MSU):
www.globaledge.msu.edu/industries/aerospace-and-defense/events/

ICMST Events (PDF):
www.drdo.gov.in/drdo/egate/FICMST_Vol_12_No_03_January_2017.pdf

IEEE AESS Events:
www.ieee-aess.org/conferences/home

Jane's Events:
www.janes.com/events

LINKEDIN GROUPS

Aerospace and Defense Subcontractor and Suppliers

Aerospace and Security and Defence Technology and Business (Defence spelled correctly)

Defense and Aerospace

EMP Defense Council

High Intensity RF (HIRF) Professionals

Radio, Microwave, Satellite, and Optical Communications

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