MIL-STD-461G: The Compleat Review

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The deleted old,
The brand-spanking new.
That which was borrowed,
And that, eschewed.

MIL-STD-461G WAS RELEASED ON 11 December 2015 and will become contractually obligatory on programs initiated after that date.

This account is more than a simple laundry list arrived at by performing a side-by-side "F" vs. "G" comparison. Instead, it is an insider account into the issues with which the Tri-Service Working Group (TSWG) was grappling, and the thought processes behind the changes, as well as, of course, the changes themselves. It also lists some of the issues brought to the table that were not incorporated in MIL-STD-461G, and why.

It will greatly assist the reader if a copy of MIL-STD-461G is available as this account unfolds.

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

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-461G 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. So we have a net increase of one requirement. There are also many other important changes, detailed herein.

One of the revolutionary aspects of MIL-STD-462D in 1993 was the inclusion of measurement system integrity checks that were performed prior to each emission measurement to ensure proper operation of the measurement system. To the author's knowledge, these checks have remained unique to MIL-STD-461 ever since.

The philosophy behind these checks gains its greatest expression in MIL-

STD-461G. The TSWG considers a real-time check of each set-up just prior to the actual measurement to be the best way to ensure an accurate measurement. To that end, several checks have been beefed up, but most importantly the regular calibration of transducers used in EMI testing has been de-emphasized. Section 4.3.11 *Calibration of measuring equipment* has been reduced in scope to devices such as EMI receivers and spectrum analyzers, oscilloscopes and (RS103) electric field sensors. The new text says, "After the initial calibration, passive devices such as measurement antennas, current probes, and LISNs, require no further formal calibration unless the device is repaired. The measurement system integrity check in the procedures is sufficient to determine acceptability of passive devices." A new SAE Aerospace Information Report, AIR 6236 has been written to support the verification of proper operation of such devices in the EMI test facility using only test equipment commonly available in an EMI test facility. The idea is that if a measurement system integrity check shows a problem, the AIR 6236 measurements will demonstrate whether or not there is a problem with a transducer. AIR 6236 is incorporated by reference only, and in the non-contractual appendix, at that. It is not part of any measurement system integrity check. Also the term "measurement system integrity check" globally replaces the inaccurate formerly used words, "calibration."

Another theme beginning with MIL-STD-461D through "G" is balancing what is technically correct vs. what it is possible to get the average test facility to do correctly. An example of this is the fixed distance for power wiring between test sample and LISNs. Since 1993, it has been a minimum of two meters, and a maximum of 2.5 meters, for all tests. Prior to 1993, under MIL-STD-462 back to 1967, the power wire length was one meter for CE/CS testing, and two meters for RE/RS testing. The idea was that for CE testing there would be better accuracy with less vswr-induced error with a shorter cable, but a longer cable was necessary for RE02 and RS03. But the sense of the TSWG was that too few people were doing that, so they compromised on one length for all tests under MIL-STD-462D and ever since. That is why CE102 only covers up to 10 MHz, instead of the previous CE03 running to 50 MHz.

Along these lines, MIL-STD-461G section 4.3.8.2 formalizes a requirement to check bond impedance between test sample and ground plane prior to EMI testing, and prior to cable-connection. It is disconcerting that this needs to be stated after a half-century of MIL-STD-461. Section 4.3.6 requires LISNs to be bonded to the ground plane with a resistance no greater than 2.5 milliohms. Section 4.3.7.2 says that the only antenna that can be in the shield room during a radiated test is the antenna in actual use. Translation: the shielded, anechoic-lined chamber is a test chamber, not a broom closet. It is distressing to see a chamber outfitted with expensive absorber, often exceeding MIL-STD-461 absorber treatment requirements, while at the same time every antenna used for RE102 and RS103 except the one in use is littered around the periphery of the chamber.

Similarly, sections 4.3.8.6.1 and 4.3.8.6.2 that describe cable layout in the test chamber now stipulate that the 5 cm above ground standoff is to be achieved using "non-conductive material such as wood or foam." And that the entire length of the cable, not just the two meters exposed to the antenna, be so-supported above the ground plane. Someone somewhere was using spare rf absorber to support cables…

A theme that began with MIL-STD-461F continues in "G", and that is responding to abuses of the standard by practitioners of EMC "law" as opposed to EMC engineering. Another way of saying this is that "lawyers" are misinterpreting the letter of the standard while ignoring the obvious intent. The use of shielded power cables where it wasn't justified resulted in a complete prohibition on the use of shielded power cables for EMI testing in MIL-STD-461F. This was described in an article on the MIL-STD-461F revision that appeared in the January 2008 issue of Conformity magazine:

> Prohibition of Use of Shielded Power Leads
>
> The wording in section 4.3.8.6 ("Construction and arrangement of EUT cables") is a little more definitive than in -461E, stating that shielded power conductors may not be used unless the platform on which the equipment is to be installed shields the power bus from point-of-origin to the load. There have been problems with equipment manufacturers asking for and receiving shielded power leads from the point-of-distribution (typically a breaker box) to the load, but with the power bus from the breaker box back to the generator being unshielded.
>
> Of course the fundamental rule is that test wiring simulate the intended installation. With a partially shielded power bus, the equipment manufacturer can claim that he gets a shielded feed on the platform while the integrator sees an unshielded main bus. MIL-STD-461E 4.3.8.6 wording was not conclusive on this subject: "Electrical cable assemblies shall simulate actual installation and usage. Shielded cables or shielded leads (including power leads and wire grounds) within cables shall be used only if they have been specified in installation requirements." This problem is alleviated in MIL-STD-461F, which states in plain language precisely the above quotation, but then adds, "Input (primary) power leads, returns, and wire grounds shall not be shielded."

Similarly, the alternative field intensity pre-calibration technique using an antenna above 1 GHz that existed from MIL-STD-462D through MIL-STD-461F has now been removed, requiring real time leveling using an electrically short broadband electric field sensor over the entire test frequency range. The original alternative two-antenna technique was a grandfather clause from 1993 when many EMI test facilities lacked an electric field sensor covering 1 – 18 GHz, which were new and expensive at the time. There was and is nothing wrong with this technique, but EMC lawyers were twisting the meaning of the standard to say they could precalibrate the field in the absence of the test sample at all frequencies. The "cure" for this abuse was to remove the grandfather clause, after an informal survey of USA EMI test facilities revealed that 100% of those polled had the equipment necessary to perform real-time leveling over all frequencies from 10 kHz to 18 GHz.

Another response to EMC lawyer abuse is very subtle, and is found in section 5.17.1 RE102 applicability. In the "F" version, this sentence is found:

> "… The requirement does not apply at the transmitter fundamental frequencies and the necessary occupied bandwidth of the signal."

Find the difference in the "G" version:

> "… this requirement does not apply at the transmitter fundamental frequency and the necessary occupied bandwidth of the signal."

The difference is in the use of the plural "frequencies" in "F," and the singular "frequency" in "G." Believe it or not, EMC lawyers were interpreting the plural to mean the requirement didn't apply at any frequency to which the radio could be tuned, as opposed to the intent, which is that it doesn't apply at the frequency to which the radio is tuned during the test.

Yet another theme, this one unique to MIL-STD-461G, is an added emphasis on the testing of large, floor standing test samples whose height approaches the horizontal extent of the test set-up. In previous versions ("D" through "F") there was plenty of information on how to set up RE102/RS103 antenna positions for test set-ups with extended horizontal dimensions, but no corresponding information for vertically large enclosures, such as 19" racks. The RE102 and RS103 sections of this version of the standard now require a sufficient number of antenna positions such that the entire *area* of the test set-up has been interrogated/illuminated.

A combination of these two themes leads to a conundrum. A comment against the draft for industry review correctly pointed out that a high gain antenna of the type often used at microwave frequencies won't be able to illuminate a large enclosure such as a 19" rack and an electric field sensor placed per standard guidelines, because the illumination spot size can't cover both the enclosure and a properly placed sensor with sufficient clearance from the enclosure to avoid undue influence from it. This sort of situation calls for a precalibrated field, but that is no longer available. Such cases will require tailoring with buy-in from the customer.

There is a global clarification to requirements CS114, CS115, and CS116. The requirement to monitor cable current within 5 cm of the equipment front face is relaxed if the EMI backshell (or braid sock) extends beyond that distance. In that case, the monitor probe should be placed as close as possible to the backshell end. The 5 cm requirement is somewhat of an anachronism ever since the "E" revision, which reduced the maximum CS114 frequency from 400 MHz to 200 MHz. The concept behind the 5 cm rule was to monitor the current that was flowing into the test sample. This needs to be done within a tenth wavelength of the test sample, which is 7.5 cm at 400 MHz, but 15 cm at 200 MHz. Note the spectrum of CS115 and CS116 is lower than that of CS114, so that probe placement instructions based on CS114 suffice for these latter two requirements.

Another global change to the measurement system integrity checks is to move specified test frequencies away from the very end of a requirement frequency range, and away from a bandwidth break point, in order that the data trace show the complete response, and not a truncated version thereof.

We'll get something out of the way first even though it is out-of-order, because it is likely the most pressing concern for EMI test facilities. The two new requirements CS117 and CS118 require no test equipment different from RTCA/DO-160 sections 22 and 25, with one exception. CS118 requires a contact discharge "target" as per EN 61000-4-2. If a test house has these test capabilities at present, they need buy no new test equipment. A summary table of equipment new to MIL-STD-461G is presented at the article end. It is presented at the end so that the reader can understand the context within which the new equipment is allowable and/or necessary. This table is not an endorsement, just a cross-reference of requirements, equipment and vendors.

There was a DoD input to include not only indirect effects of lightning, but also direct effects, as well. The TSWG rejected this on the basis that it doesn't belong in MIL-STD-461. Direct effects testing (RTCA/DO-160 section 23) doesn't naturally map into MIL-STD-461, because the pass/fail criterion is usually not proper operation, but lack of damage, or containment of damage so it doesn't propagate and cause an issue to other equipment/platform structure. Thus it more naturally falls within the purview of MIL-STD-810. It should be noted that RTCA/DO-160 "Environmental Conditions and Test Procedures for Aircraft" subsumes three different military standards: MIL-STD-810 for environmental qualification, MIL-STD-704 for electrical power quality, and MIL-STD-461 for EMI control. Lightning indirect effects is close enough to MIL-STD-461 to be a comfortable fit there, but direct effects evaluation most assuredly is not.

An editorial change is that frequency ranges are no longer listed in the individual requirement titles, but rather moved to the applicability subsection, where they more naturally belong. Many requirements have different start and stop frequencies depending on Service and application.

What follows is a list of what the author considers major changes of interest to the industry.

Section 1.2.2 tailoring of requirements now explicitly states that any tailoring must be approved by the procuring activity. This was always the case, but wasn't explicitly stated.

Most of the section 3 definitions have been tweaked. In particular, the definition of "Below deck" (section 3.4 in "F") has been expanded into two subsections in "G": 3.1.3 Below deck, and 3.1.5 Exposed below deck. Exposed below deck simply means not as much shielding as assumed for below deck, and equipment to be installed below deck gets the same RE102 limit as topside in Figure RE102-1, where the more stringent limit instead of being labeled "topside" as in "F," is now labeled "above deck and exposed below deck."

Supporting appendix material for section 4.2.2 Filtering (Navy only) adds extra rationale for the limits on line-to-ground capacitance. It all makes sense, but it doesn't have the urgency of the original explanation made to the author many moons (decades) ago. The original explanation stated that ship power was ungrounded so that in the event of battle damage, one phase could short to structure and continue to operate without degradation. Therefore it was necessary to limit line-to-ground capacitance to preserve a high impedance between phases in the event of such a short circuit. To the author, that is a much more satisfying (read strong) argument in the event someone wishes to violate it than more nebulous concepts (to program management) such as hull currents, ground loops and leakage current.

Section 4.3.5.1 (metallic ground plane), augmented by brand new Figure 5 requires 2.5 meters in any direction from the edge of the test set-up boundary to the edge of the ground plane, as compared to 1.5 meters in earlier versions of the standard. The change was based on the desire to have the ground plane underneath the entire set-up, antennas used in various tests, and distance beyond the backside of any such antenna still covered with ground plane. Also note Figure 5 replaces what looked like a truck or other wheeled vehicle (but wasn't supposed to) with something that looks like a test equipment rack. It is important to always reinforce that MIL-STD-461 applies to equipments and subsystems, not vehicles/platforms.

Figures 2 – 5 have two subtle changes. The first is that the test sample enclosures are oriented so that the connector side faces the way the cables are laid down the length of the tabletop, as opposed to in previous versions, where the connector side faces the front of the table. Actually Figure 5 has side-facing connectors in both "F" and "G;" the difference in Figure 5 is that the test sample evokes an electronic equipment rack instead of a wheeled vehicle (which was never intended), and the cables are laid out 5 cm above a tabletop ground plane, not 5 cm above the floor, as in "F." The second change is that all these figures are now titled "general." Complex enclosures with lots of cables and/or long EMI backshells with large cable bend radii will follow the new setup, but paragraph 4.3.8.5 Orientation of EUTs is unchanged and still requires surfaces which produce maximum radiation to face the measurement antenna. So nothing to fear here, EMC lawyers: there is still plenty of opportunity to ply your craft.

A theme in MIL-STD-461G is to expand instructions on how to set-up and test when the test sample has large vertical extent. Previously, the instructions were based on avionics type equipment enclosures that mount on the tabletop ground plane. These could be large in horizontal extent and instructions have previously existed in how to lay this out and how to place antennas. Sections 4.3.8.6.1 (interconnecting leads and cables) and 4.3.6.8.2 (input primary power leads) expand on the routing of cables when the test sample is a large floor standing unit. Figures 4 and 5 also augment this topic.

Issues arise with proper antenna coverage of test samples with large vertical extent, and these are dealt with in RE102 and RS103 by requiring the entire surface *area* to be illuminated, not just the horizontal width. But another issue is cable length. There has always been a limit of 2.5 meters maximum between test sample and LISNs, in order to allow the LISN to control the line impedance (the reason why CE102 stops at 10 MHz). But with a large test sample like a floor-standing rack, especially if the cables exit near the top and a power strip runs down the height of the rack powering loads near the bottom, the 2.5 meters gets used up very quickly and a strict adherence to that limit would mount the LISNs very near the rack itself, limiting RE/RS interaction with power lines. Given the MIL-STD-462D decision to have a single power wire length for all tests, as opposed to short cables for CE testing and long cables for RE/RS as previously, it was decided to require two meters of power wiring exposed 5 cm above the tabletop ground plane regardless of where the wires emanate from the test sample, nor how long the cables are within the test sample.

Another theme in MIL-STD-461G is to expressly permit the use of certain types of test equipment that have appeared since the release of MIL-STD-461F. Perhaps the most important of these is the "time-domain" or Fast Fourier Transform (FFT) EMI receiver. Such receivers differ from the traditional in that instead of tuning to a particular frequency using the prescribed bandwidth and then stepping to the next frequency using a not-to-exceed half-bandwidth step, these receivers look at megahertz or tens of megahertz bands, and use FFT algorithms to recover the signals that would be measured using Table II prescribed bandwidths. Such receivers are much faster than traditional receivers. Section 4.3.10 (use of measurement equipment) expressly mentions and condones use of such receivers, and Table II is augmented to show dwell times required for time domain receivers. The appendix for this section and Table II explains why the FFT-specific dwell times are necessary, and shows test data for a broadband signal with much better performance than obtainable with a traditional receiver or spectrum analyzer when Table II dwell times are used. The appendix (pages 197 – 200) also shows what happens if Table II FFT-specific dwell times are not used, with the broadband signal completely missed. The FFT receiver properly or improperly used is like the little girl in the nursery rhyme:

"There was a little girl,
Who had a little curl,
Right in the middle of her forehead.
When she was good,
She was very, very good,
But when she was bad she was horrid."

The Table II modifications pertaining to FFT receivers are designed to make sure the little girl is always very, very good, and when she is bad, she is no worse than little girls used to be.

There are much greater advantages inherent in such receivers than simply getting a test done faster. The operation of some devices (a linear actuator, for example) come to the end of their travel much faster than a traditional CE102 or RE102 sweep. Or a helicopter rescue hoist cannot deploy as much line in a shield room as in flight, and thus cannot operate continuously through an emissions sweep. The ability to capture multiple megahertz bands during a few seconds of operation can actually provide better quality data for such devices. There are also devices designed with limited lifetimes, in which the ability to sweep faster may make testing possible that would have been impossible otherwise.

Section 4.3.10.4.2 (modulation of susceptibility signals) doesn't say so, but now both CS114 and RS103 both require demonstration that the required modulation has been applied. This is most easily done in zero-span mode and measuring the correct on-off timing and also the 40 dB on-to-off ratio.

Section 4.3.10.4.3 (thresholds of susceptibility) now requires "zeroing in" on the frequency of greatest susceptibility within the susceptibility band.

As mentioned earlier, Section 4.3.11 (calibration of measurement equipment) removes the need for routine calibration cycles on passive transducers.

Section 5.4.1 CE101 applicability adds a note explaining when the requirement is applicable to equipment installed on Navy aircraft.

Section 5.5.3.4.a.2 is the expansion on the basic CE102 measurement system integrity check that verifies the LISN impedance at 10.5 and 100 kHz. The previous ("D" through "F") technique verified the impedance at 2 and 10 MHz, but not at the lower frequencies, and with elimination of a requirement to regularly calibrate LISNs, the expanded measurement system integrity check fills that gap. There is little extra effort besides record keeping. Because the LISN is a low impedance relative to 50 Ohms, it is already the case that the signal source output amplitude must be increased above the actual level resulting across the LISN. The extra effort is simply to document the required increase (in dB) and compare that to what is theoretically required per the LISN impedance curve of Figure 7, including both the 20% tolerance of that figure, plus the losses associated with the LISN 0.25 uF blocking capacitor. This section says what the decibel difference is supposed to be at the measurement system integrity test frequencies of 10.5 and 100 kHz. SAE AIR 6236 shows the LISN insertion loss curve with tolerances over the entire 10 kHz to 10 MHz frequency range, and how to measure it.

Section 5.6.1 CE106 applicability has been modified by striking the following sentence from MIL-STD-461F:

> "RE102 is applicable for emissions from antennas in receive and standby modes for equipment designed with antennas permanently mounted to the EUT."

In the author's opinion, this is a big loss, and not only for receive and standby modes, but also for low power transmitters such as Wi-Fi. RE102 is much easier to perform than RE103, and where the device either transmitting or not can be shown to be in compliance with RE102 rather than RE103, that meets the overall intent of controlling interference. Also, the -80 dBc type requirement makes no sense for a milliwatt transmitter; RE102 is the only applicable requirement at harmonics of a low-power transmitter.

Section 5.6.1 CE106 has been modified for NAVSEA (surface ship) transmitter procurements. The traditional 5% exclusion zone surrounding the transmit frequency is increased according to a formula given in this section for transmitters operating above 1 kW (60 dBm).

There is also a modification of the criterion for the highest required test frequency. The effect of the change is that the test must always be run to at least 10 GHz, with a maximum frequency of 40 GHz. The modification is that under MIL-STD-461F, the upper frequency was stated to be:

> "The end frequency of the test is 40 GHz or twenty times the highest generated or received frequency within the EUT, whichever is less."

Under the "G" change, the end frequency criterion depends on whether the highest generated or received frequency is above or below 1 GHz. If the highest generated or received frequency is below 1 GHz, the end frequency is twenty times that frequency or 18 GHz, whichever is greater. If the highest generated or received frequency is equal to or above 1 GHz, then the end frequency is ten times the highest frequency, or 40 GHz, whichever is less.

To illustrate how this can affect results, consider two devices, one with a highest generated or received frequency of 999 MHz, and the other with a 1 GHz highest frequency. Under MIL-STD-461F, the end frequencies are practically identical, at or near 20 GHz. Under MIL-STD-461G, the first device has a test stop frequency of 18 GHz, whereas the second device test stop frequency is only 10 GHz.

Of course the benefit of this approach is a lot of devices will only need to be tested to 18 GHz, instead of higher. Every test facility can test to 18 GHz because of RE102, but often testing beyond that requires the rental of a special receiver, so overall this modification is beneficial.

Section 5.6.2 CE106 has been modified for NAVSEA (surface ship) transmitter procurements. The relative limit in decibels below the carrier (e.g., -80 dBc) has been changed to a fixed level of -40 dBm. This was done to aid in co-location of high power transmitters and sensitive receivers. Note that for any transmitter power level above 10 Watts (40 dBm) this represents a more stringent limit than previously. There is a relaxation of this -40 dBm level to 0 dBm if the transmitter duty cycle is below 0.2%, which would take care of many radar systems.

Section 5.7.1 CS101 limits applicability to equipment drawing less than 30 Amps per phase, even though test equipment exists supporting testing to 100 Amps per phase. The rationale behind this is that usually such high current loads operate off high potential buses, and the CS101 ripple levels are smaller than the distortion on these buses, and the total CS101 ripple power is infinitesimal compared to the actual load power, and susceptibilities just aren't observed. However, it should be noted that CS101 limits are based on MIL-STD-704, which doesn't address bus potentials above 115 Vac or 270 Vdc. The large loads to which this 30 Amp limitation would usually apply would be upwards of 400 Vac. Note that the 6.3 Vrms ripple limit of Curve 1 is about 5% of a 115 Vac bus potential but only 1.5% of a 440 Vac bus. If the CS101 limit for a 440 Vac bus were raised to that same 5% (22 Vrms) then (in the author's opinion) it would be much more likely that issues would arise.

Section 5.7.3 CS101 test procedure allows for the use of a power line ripple detector (PRD) to measure ripple induced on an ac power line, which is very difficult to monitor. The PRD functions as an interface between the power line and the 50 Ohm 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. This was described in an article entitled "Fifty Year-Old EMI Testing Problems Solved," in the June 2012 issue of IN Compliance magazine. The electronic archive shows video of the ripple on the peak of the ac power waveform vs. the separate injected ripple component. Stills are shown below.

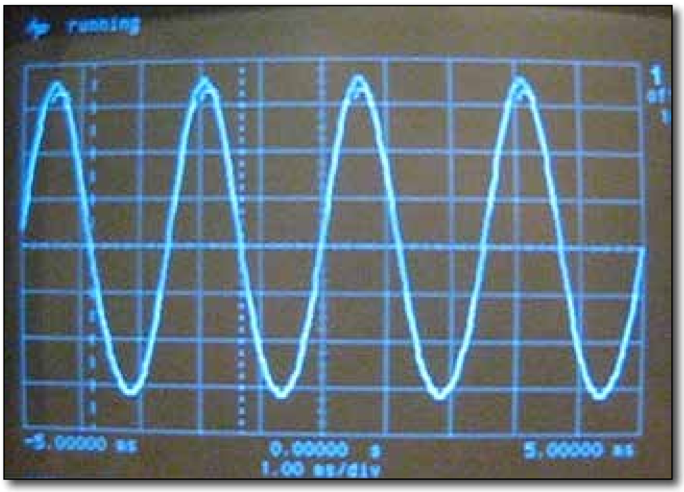

FIGURE 1: 800 Hz ripple riding on a 400 Hz ac power bus, traditional CS101 measurement.

FIGURE 2: 800 Hz ripple riding on a 400 Hz ac power bus, measured in the frequency domain. The PRD has a -66 dB transducer factor, so 66 dB has to be added to measured values to get to values on the power bus.

The PRD allows for monitoring and injecting ripple below the power frequency, a requirement prior to 1993 but the capability to do so was lost in 1993 when MIL-STD-462D prohibited use of the phase shift network method of eliminating the power frequency from the ripple measurement. In MIL-STD-461D and onward, because of that prohibition, the limit for ac ripple started at the second harmonic of the power frequency, instead of at 30 Hz. The PRD facilitates monitoring down to 30 Hz on any type of bus, as shown in Figure 3, but the TSWG was not interested in reviving the 30 Hz start frequency for ac buses after over twenty years of not having done so.

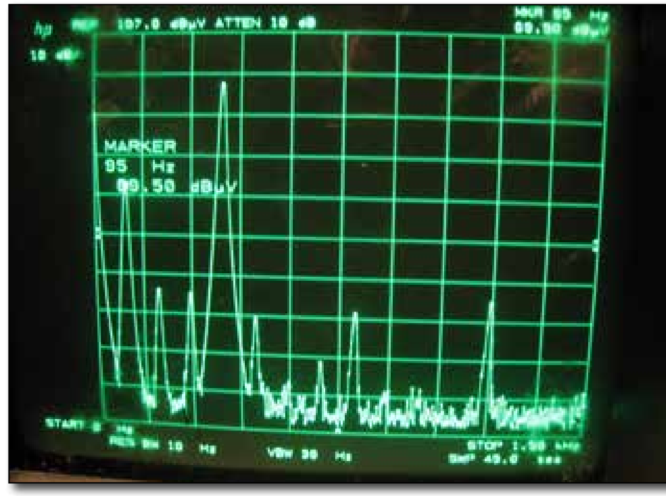

FIGURE 3: Injection of 100 Hz ripple on a 400 cycle ac bus.

The PRD as commercialized by Pearson Electronics contains an isolation transformer so that connection of the ac neutral to the PRD maintains isolation between the neutral and the grounded EMI receiver or spectrum analyzer chassis. That isolation is required by paragraph 5.7.3.1 of MIL-STD-461G.

CS101 figures are updated to show either the traditional measurement with floated oscilloscope or the new measurement with PRD and grounded receiver.

The CS101 supporting appendix material also includes this valuable information:

> "Below 10 kHz there is a possibility that a portion of the injected signal will drop across the power source rather than the test sample power input. Therefore, below 10 kHz when the specification limit potential cannot be developed across the test sample power input and the pre-calibrated power limit has been reached, it is incumbent on the tester to check that the missing signal level is not being dropped across the power source. If the missing potential is there (usually due to high impedance test facility EMI filters), then steps should be taken to lower the source impedance. This can be done on DC power by using a larger capacitor (~10,000 uF) in parallel with the 10 uF capacitor. With AC power that isn't possible and the best approach is to bypass facility EMI filters entirely, bringing unfiltered power into the room."

The PRD facilitates that measurement by having two sets of jacks for simultaneously connecting to both test sample power input and across the power source and being able to read either of these values at the flip of a switch.

CS106 was added in MIL-STD-461F and is deleted in MIL-STD-461G. The rationale for adding it was included in the MIL-STD-461F rationale appendix and is repeated here:

> "The primary concern is to ensure that equipment performance is not degraded from voltage transients experienced on shipboard power systems coupling to interface wiring inside enclosures.
>
> Electrical transients occur on all electrical distribution systems and can cause problems in circuitry which tend to be sensitive to voltage transients, such as latching circuits expecting a single trigger signal. On submarines and surface ships, these transients can be caused by switching of inductive loads, circuit breaker (or relay) bounce, and load feedback onto the power distribution system.
>
> The 400 volt peak, 5 microsecond pulse defined in Figure CS106-1 is a suitable representation of the typical transient observed on Navy platforms. Measurements of transients on Navy platforms have shown the transient durations (widths) are predominantly in the 1 – 10 microsecond range. The large majority (> 90%) of the transients measured on both the 115 volt and 440 volt ac power distribution systems were between 50 and 500 volts peak."

The underlying issue was not the response of the power supply to the transient, but crosstalk within an equipment between the transient on the power wiring and signals carried on wiring adjacent to the power wires without adequate protection. The very purpose of the requirement was to force adequate segregation between power and signal circuitry.

However, CS115 was designed specifically to represent the coupling of transients on a power bus into cables run adjacent to it. The very short 30 ns duration and even shorter 2 ns rise and fall times represent the leading edge of a waveform such as CS106 on a power bus inductively coupling into an adjacent cable. Measurements on a one foot section of ribbon cable modeling an unprotected connection between a connector and motherboard revealed that injecting CS115 on the simulated signal wires looked very similar to the cross-coupling from injecting CS106 on the simulated power wires.

It was concluded that CS115 already meets the intent behind the reintroduction of CS106.

There are two changes to CS114. One affects the limit, the other is procedural.

The limit reverts back to that of MIL-STD-461D, where the primary limit is the forward power recorded in the calibration fixture when the appropriate specification limit (Curve 1 – 5) is induced in the fixture, with the only current limit being 6 dB higher than the current in the plateau region of the curve. This is as opposed to the "E" and "F" versions, where the current limit is the actual current at the specific test frequency. The reason behind the reversion to MIL-STD-461D is explained in "(More) On Field-To-Wire Coupling Versus Conducted Injection Techniques," in the October 2014 issue of IN Compliance magazine. This change will make it important to tailor the breakpoint frequency of the limit (nominally 1 MHz) for platform or actual cable dimension, in order to avoid over-testing. In order to perform that tailoring, it is necessary to understand that the breakpoint represents the frequency at which a platform or cable is one-half wavelength long. A 1 MHz break point is a physical length of 150 meters. So if a platform is instead about 15 meters long, the breakpoint would shift to 10 MHz.

The procedural change is that in addition to the traditional measurement of the forward power required to induce the specification limit current in the calibration fixture, the current in the fixture must be measured using the current probe that will be used to monitor current on the cable-under-test. This is an augmentation of the measurement system integrity check, because again a current probe will not require periodic calibration.

CS117 (lightning induced transients on cables and power leads) is one of the two new requirements in MIL-STD-461G. It was borrowed from RTCA/DO-160 section 22, and it is subset of RTCA/DO-160 section 22. There is nothing in CS117 that doesn't exist in section 22, but many aspects of section 22 were left out of CS117. There was a desire to simplify, but the simplification was not performed for its own sake, but rather in keeping with two philosophical tenets of MIL-STD-461 since the "D" revisions in 1993. These are that cable-related tests are performed at the bulk cable level, no pin injection, and second that platform installations are divided into two categories, internal and external (relative to a metallic platform).

MIL-STD-461B/C had requirements EMP-like damped sine injection requirements CS10/11/12/13 two of which injected on the entire bundle, and two of which were injected at the pin level. These were all subsumed into bulk cable injection (BCI) requirement CS116 in 1993. Likewise CS114 and CS115 began as BCI requirements and have stayed that way. CS117 is adopted as a BCI requirement only, eschewing the pin injection requirements in section 22. This greatly simplifies the test campaign on the types of equipment to which CS117 applies, such as flight and engine controls that have multiple cables with lots of pins. Pin injection is important with shielded cables where the installed length is greater than the ten meters required in MIL-STD-461. For this small subset of cables, some thought will need to be given to possibly boosting the injected current to make up for the lower shield transfer impedance of the set-up vs. installation.

CS117 has six waveforms borrowed from section 22, but only two levels, internal and external. In addition to that simplification vs. five different levels in RTCA/DO160 G section 22, another simplification is that there is 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 requirement 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.

One other wrinkle is that RTCA/DO-160 uses the 5 uH LISN, vs. the MIL-STD-461 default to 50 uH. This means that the same waveform applied in a CS117 set-up will apply less potential to the load than if the test were performed to section 22, because the power source impedance is higher with CS117. This was considered by the TSWG and accepted as part of maintaining consistency with the default 50 uH LISN used throughout the standard.

CS118 (personnel borne electrostatic discharge) is the second new requirement in MIL-STD-461G. Before getting into requirement and test details, some background is in order. In the run-up to the MIL-STD-461G revision process, proponents of including an ESD requirement discussed failures in the field and how those could be tied to ESD problems. Such damage would most likely occur during remove-and-replace operations, not during powered up use, else the failures would be much more dramatic and noticeable (i.e., hardware working during a mission and suddenly failing, as opposed to installing hardware and running a built-in test - BIT - and with a BIT failure, installing a different box). The application of ESD pulses to an unpowered box and then subsequently running BIT or some other acceptance test procedure (ATP) was argued to not fit within MIL-STD-461, just like lightning direct effects doesn't, but rather to belong in MIL-STD-810. But this argument didn't fly, not least because the candidate test methods were based on RTCA/DO-160 section 25 and IEC 61000-4-2, which apply ESD pulses to fully operational hardware and look for *malfunction.*

The test set-up and "gun" are based largely on RTCA/DO-160 Section 25, with the addition of a "target" borrowed from IEC 61000-4-2 for calibrating the current discharge waveform, and a contact discharge electrode design not found in RTCA/DO-160 because it only requires air discharge. The section 25 set-up was chosen over IEC 61000-4-2 because of the obvious similarities in a metal vehicle application, with the test sample enclosure directly grounded to structure, as opposed to the 61000-4-2 approach with a nonconductive table top 80 cm removed from ground, with at most a green wire ground connection. The use of the 61000-4-2 target prior to each test is part of the measurement system integrity check philosophy, rather than relying solely on a "gun" calibration sticker. Likewise CS118 requires an electrostatic assessment of the gun potential prior to the discharge. Contrast these two measurements with RTCA/DO-160G section 25.5.2: "…The ESD generator shall be calibrated to produce a positive and negative 15,000 volt (+10%, -0%) peak output pulse. The generator setting required to produce this output shall be recorded."

Applicability is limited to non-ordnance connected electronics; ordnance response to ESD is covered elsewhere, but not in MIL-STD-461G. 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. This is because air discharge current waveforms can have higher amplitudes at lower potentials, due to smaller arc distances and hence lower arc resistance. It is most often the coupling from the radiated field of the ESD event that causes upset, and the higher the waveform di/dt, the large the transient coupled to (potential) victim circuits.

Section 5.18.1 RE102 applicability removes the conditional limit on the upper test frequency and makes it 18 GHz, regardless of test sample clock speeds. It was deemed that the time saved not testing to 18 GHz was insignificant.

The most notable RE102 changes relate to illuminating/interrogating the entire test set-up area, as opposed to width, as already noted. A change in the RE102 measurement system integrity check for the 41" rod antenna acknowledges that the assumed Thevenin model output impedance of a 41" rod is not always 10 pF, because some large diameter rods have larger output capacitance. The standard now invokes the manufacturer's suggested value. But there is another much more subtle change, and it is important in the same way that the tip of an iceberg is important to a ship at sea.

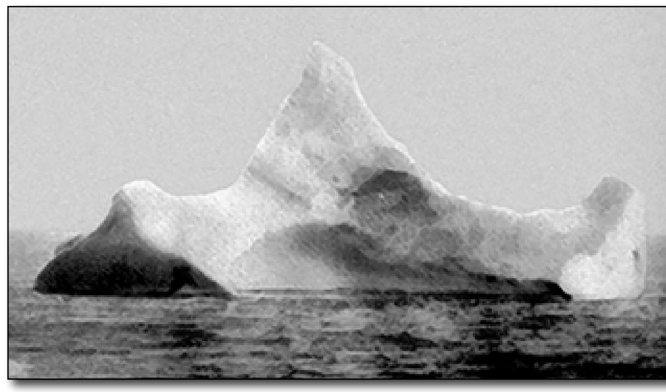

FIGURE 4: Some say this is a photo of the iceberg that sank the Titanic.

MIL-STD-461F introduced a change in how the rod antenna is configured. The purpose of that change was to detune an observed resonance that occurs between 20 – 30 MHz. Part of the change included clamping a ferrite sleeve around the coaxial transmission line between rod antenna base and EMI receiver. MIL-STD-461 cannot specify a manufacturer or part number, but the previously referenced MIL-STD-461F update article identified one candidate as a Fair-Rite Part Number 431176451. The salient feature of that bead as shown in Figure 5 is that its impedance is mainly resistive/absorptive in the 20 – 30 MHz frequency range of interest, as is appropriate for detuning a resonance. But that information never made it into the standard; the only description other than the actual impedance range cited in Figure RE102-6 was in the MIL-STD-461F RE102 appendix stating that, "Floating the counterpoise with the coaxial cable electrically bonded at the floor with a weak ferrite sleeve (lossy with minimum inductance) on the cable produced the best overall results." That description was routinely ignored by many test engineers, which resulted in said engineers criticizing the MIL-STD-461F technique as flawed. Of course, attempting to detune a resonance by adding a largely reactive component isn't going to help matters any, only shift the resonance downwards in frequency. MIL-STD-461G moves that impedance description to the main body section 5.18.3.3.c(1): "…A ferrite sleeve with 20 to 30

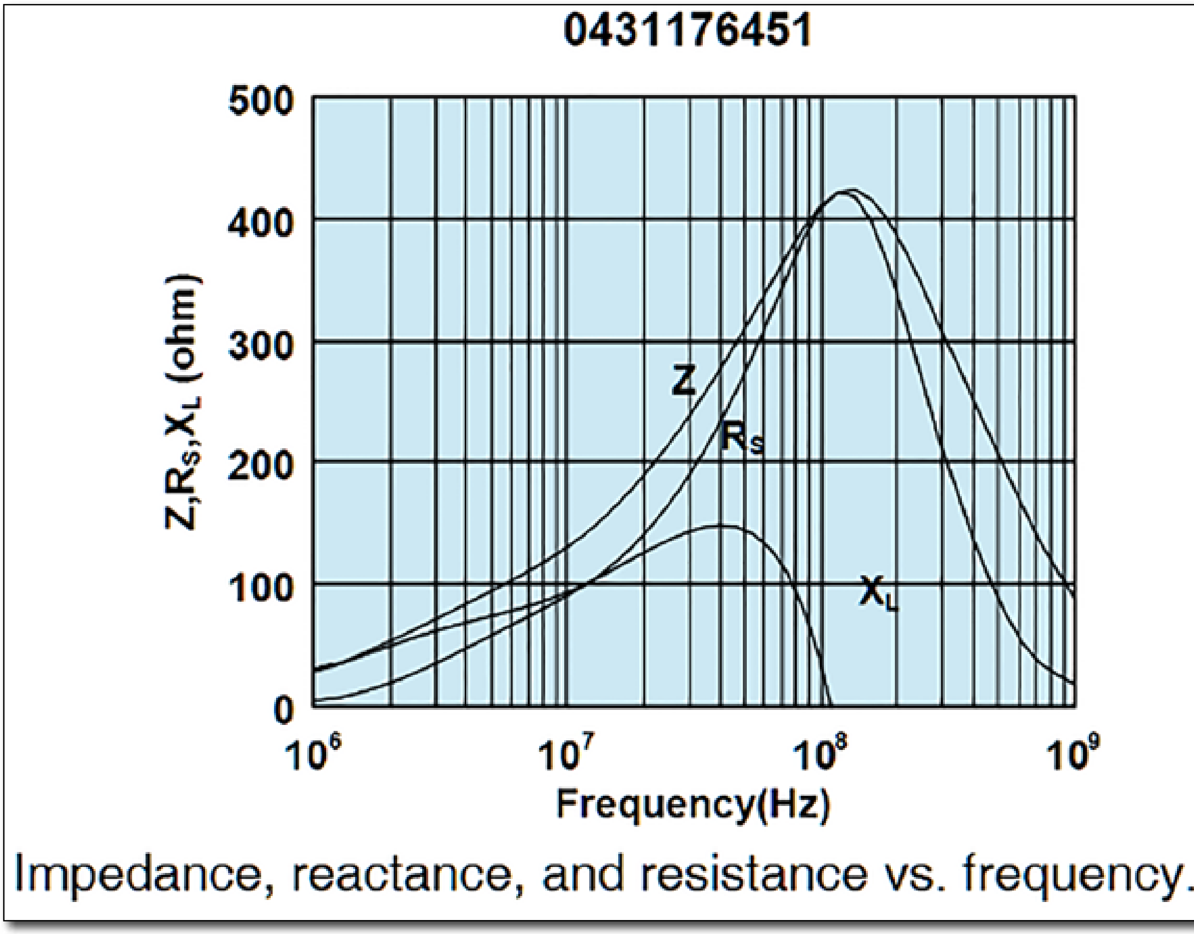

FIGURE 5: Characteristics of MIL-STD-461F rod detuning rf sleeve (from Fair-Rite catalog)

ohms impedance (lossy with minimal inductance) at 20 MHz shall be placed near the center of the coaxial cable length between the antenna matching network and the floor."

But this subtle change of moving a recommendation from the appendix to the main body is just the tip of the rod antenna configuration iceberg. Much work remains to be done which will have to wait for MIL-STD-461H. This work is now described.

An article published in the 2011 ITEM entitled, "On the Nature and Use of the 1.04 m Electric Field Probe," explained in its conclusion that the only way to make an accurate field intensity measurement with a rod antenna was to either use the floor for a ground plane, or if the counterpoise was elevated above ground, then it must be totally floated above ground. The recommended technique was the insertion of an isolation transformer in the coaxial cable connection between the rod antenna base and the EMI receiver. Another separate suggestion from another researcher recommended a fiber optic link. Both these suggestions were evaluated during the MIL-STD-461G revision process, but both came up short for reasons described presently. Also, a test equipment vendor introduced a rod antenna that was inherently floated using a fiber-optic link to a laptop computer controller. Unfortunately, they were unable to make one available to the TSWG for evaluation during the MIL-STD-461G revision process.

Inserting a fiber optic link in the connection to a conventional rod antenna failed due to what appeared to be parasitic capacity between the green wire ground in the laboratory power and the bias potentials fed to the opto-electronic converters. The plan was to replace the power supply with batteries to see if that eliminated the problem, but time ran out. The problem with isolation transformers is there is always some degree of inter-winding capacitance between winding banks, and at these frequencies it cannot be ignored. While the original problem dealt with by MIL-STD-461F was a parallel L-C trap with capacitance between the counterpoise and floor and the inductance supplied by the coaxial shield connection, when an isolation transformer is inserted a new series L-C trap is formed from the inter-winding capacitance and the coaxial shield inductance. The combination of capacitance and inductance have to be limited such that the resultant resonance (which cannot be eliminated, only moved around) is above 30 MHz. Given that different models of transformers have different and unspecified inter-winding capacitance, it would have to be measured by the test facility and then a maximum length cable would need to be specified to work with it to keep the resonance above 30 MHz. This is difficult to write into a standard. We hope that all this will be ironed out in time for routine incorporation into MIL-STD-461H. Stay tuned for progress updates in the form of articles on the subject either in future editions of ITEM or IN Compliance magazine.

Another RE102 change that was slated to happen but didn't was wording that would allow the use of the new ETS/Lindgren Model 3117 antenna to be used above 1 GHz in addition to the original double ridge guide horn as presently specified in MIL-STD-461 via its physical aperture of 24.2 by 13.6 cm opening. As can be seen from Figure 6 showing both antennas side-by-side, the newer antenna doesn't have any sides as does the more traditional looking horn, and therefore specifying it via its physical aperture would be quite ambiguous. MIL-STD-461 cannot specify test equipment by manufacturer and model, so a generic description that nevertheless conveys the desired characteristics is required. We didn't get a satisfactory description from the manufacturer, and discussed including salient performance characteristics instead such as beamwidth, which was where the new antenna was much better than the old one. But in the end it was decided that would be too complicated because we would have physical apertures for all other antennas, but performance characteristics of the new one, and no one wanted to change to performance characteristics for all antennas.

And finally, there was quite a bit of interest in adding a reverberation chamber alternative test procedure to RE102, much as for RS103, which was added in MIL-STD-461E. There are several advantages to a reverb RE test method, and none of the drawbacks of RS reverb, namely the schedule hit.

Reverb RE testing captures all test sample emissions, rather than those emanating from the front face. A reverb technique removes test chamber resonance issues due to the partial absorber liming coverage allowed by MIL-STD-461. The test chamber is much less expensive. There is the potential for making more sensitive measurements than in an absorber-lined chamber because we are capturing constructive interference of all the emanations at once. The degree of improvement is based on the room "Q," offset by the difference in gain between the traditionally required antennas and the biconicals that would be necessary. Reverb purists who believe antenna gain doesn't factor into a reverb measurement hang on until you have read the next paragraph, which outlines a reverb technique for making near field measurements.

RE reverberation techniques exist, such as in RTCA/DO-160 section 21, but these all work on an assumption that the collected power is available to radiate from a dipole antenna using a far field equation to analytically determine the field strength limit. It was felt that this might not be the optimal approach, and an investigation based on the work of Norm Wehling, retired chief engineer at Elite Electronic Engineering Company as published in the 1993 issue of ITEM is underway.[1] Although that effort was aimed at RS testing, the author realized it was eminently better suited for RE testing. The basic idea is to use biconical antennas all the way from 30 – 1000 MHz and position them close to the normal placement for RE102 measurements, but put a paddle behind the antenna. In an unlined chamber and the paddle stopped, this would be equivalent to the MIL-STD-462 test method prior to 1993, where unlined test chambers were the norm, and any RE measurement was in fact a mode-tuned measurement, except a single mode. The paddle allows multiple modes, and the spectrum analyzer/EMI receiver performs multiple fast sweeps in max hold mode during a single revolution of the paddle, which sweeps continuously at 6 – 7 rpm. This means that a single frequency domain sweep over in milliseconds represents a single mode because the paddle is nearly motionless in that time period. If an unlined chamber were the basis of RE measurements, as they were prior to 1993, there would be nothing to add to the method, because basically the paddle just captured the peaks of the constructive interferences instead of recording peaks and valleys (destructive interference), as in Figures 7 from Wehling. But since the last twenty years have used an absorber-lined chamber, it is now necessary to back out the "boost" factor of the unlined chamber, which is evaluated by performing an ARP-958 antenna calibration in the stirred chamber and comparing the

FIGURE 6: Traditional microwave DRG horn as specified in MIL-STD-461E/F and newer version not specified in MIL-STD-461

[1] Wehling, Norman. Repeatable Low-cost Radiated Susceptibility Test in a Standard Shielded Enclosure. ITEM 1993, p16ff.

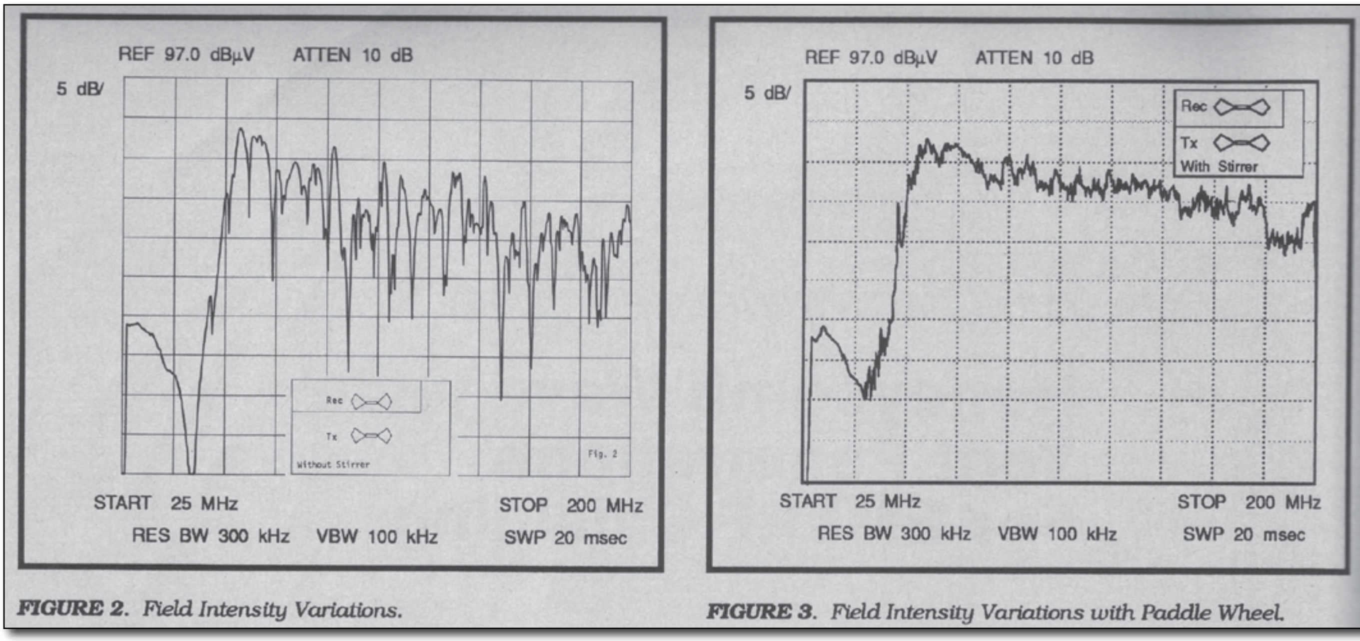

FIGURE 7: Field uniformity without and with stirring in a typical MIL-STD-461-sized test chamber from 30 – 200 MHz, from Wehling.

measured antenna factor to the normal calibration. The difference is the "Q" of the room, and that must be backed out of the measured field intensity in the chamber in order to make the reverb measurement no more stringent than that in a lined chamber. At least, that is the author's theory and plan.

The author's investigation was nowhere near complete during the "G" revision process, but might bear fruit for the next revision cycle.

Section 5.19 RE103 has the same sort of changes in it as already described for CE106.

Section 5.20.1 RS101 applicability adds a note explaining when the requirement is applicable to equipment installed on Navy aircraft. "For Navy aircraft, this requirement is applicable only to equipment installed on ASW capable aircraft, *and external equipment on aircraft that are capable of being launched by electromagnetic launch systems*." The italicized clause is new in "G."

In addition to the RS103 changes already cited, there is a subtle change in the applicability of the requirement at the tuned frequency of a radio receiver. A little historical background.

MIL-STD-461D and previous versions of MIL-STD-461 did not require RS103 testing at the tuned frequency of a radio receiver. The reason for this is that the radio electronics are less exposed to the external electromagnetic environment (EME) than the antenna, and the radio receiver is tested with antenna port dummy loaded, so that it was clear that the antenna would conduct much more signal into the electronics than through the platform and through the radio enclosure. During the revision process culminating in "E", a case of two radios mounted side-by-side interfering with each other was brought forth. One radio was tuned to the local oscillator (LO) of the other radio, and the LO leaked enough to couple into the victim radio. This case resulted in a change where the RS103 requirement at the tuned frequency of a radio was the appropriate RE102 limit relaxed by 20 dB. The limit basis was that the culprit would meet RE102, but the intensity a few centimeters away would be higher than the limit at one meter. Under MIL-STD-461F, this interaction was de-emphasized, but NAVSEA (surface ships) had a concern for radio receivers mounted below decks far from their topside antennas but exposed to wireless networks and adjacent used handheld radio transmitters. So there was no exception whatsoever at the tuned frequency of a radio for this Service and application. MIL-STD-461G builds on this with further explanation (from the appendix):

> "Revision G of this standard has further changed the applicability of RS103 for tuned receivers. The exemption at the tuned frequency to meet RS103 is in place for Air Force and Army equipment. For Navy equipment, RS103 is applicable at the tuned frequency unless the antenna is permanently attached to the equipment being tested. The reason for this is that on Navy installations, the antenna may be situated a far distance from the receiver, so these services want the test to apply to a receiver. Since the exemption at the tuned frequency is installation dependent, it may be extended to other systems as tailoring to this standard with procuring activity approval. For equipment where the antenna is permanently attached to the equipment, such as portable equipment or WiFi transmitters, the expectation is that there will be interference at the tuned frequency that is a "front door" event. In those cases, the requirement is that the antenna/receiver work after application of the E-field. Therefore, during the test, responses when RS103 is at the tuned frequency are allowed."

MIL-STD-461G RS103 Section 5.21.3.3.d. Placement of electric field sensors has slightly different wording than MIL-STD-461F RS103 section 5.20.3.3.d.1 on the same subject, but the change is only to make position information clearer; there is no change to the positioning requirement.

Section 5.22.1 RS105 applicability adds a note explaining when the requirement is applicable to equipment installed on surface ships. And the oscilloscope single-event bandwidth is updated to 700 MHz from the previous 500 MHz, even though the limit itself is unchanged.

Table of New Equipment Allowed/Required in MIL-STD-461G

Requirement	Equipment Type	Vendor(s)	Websites
General	Time Domain EMI receivers*	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
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/product/135120100000010183.php
		Haefly	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.