E Pluribus Unum

A look back at fifty years of MIL-STD-461

Ken Javor, EMC Compliance, March 2018

(Author's introductory note: This review assumes general familiarity with MIL-STD-461 on the part of the reader. It is a historical retrospective and not a primer.[1] With MIL-STD-461 as a necessary background, this article provides insight into the evolution of EMI requirements and test methods, due to both changes in radio and EMI test technologies over the past half-century.)

2017 marked the golden anniversary of military Tri-Service EMI standardization in the United States of America, while 2018 marks the silver anniversary of the "D" updates to MIL-STD-461 and -462.

Prior to 1967 the United States Department of Defense had a variety of active EMI/EMC specifications and standards. Since they were all solving similar problems and using similar test equipment, they were all necessarily quite similar. Likewise, as is still true to the present day, the number of opinions on the right way to do something is proportional to the number of engineers, factorial (only exacerbated when they work for different Services). So all these standards were slightly different, as well. As a test engineer, imagine different antenna-equipment separation placements, different required receivers and antennas, some limits being in terms of field intensity, and others antenna-induced (more on that presently) and of course zero automation to assist in doing things correctly. And that is just the tip of the iceberg, which in its titanic totality is described herein.

As test engineers, everyone practicing today is blessed to be dealing with just one (USA DoD) military EMI standard. But very few people realize the extent of the blessing, having never experienced the alternative. Also, not that many practitioners today recall the sorry state of MIL-STD-461 prior to the "D" revisions in 1993.

This article will give the reader a better understanding of where we are, and a better appreciation for it, by recounting how we got here.

MIL-STD-461/-462 were released on 31 July 1967. It should be noted that the three Services got together somewhat under duress to hammer out a compromise standard using the committee process.[2] [3] Not at all what the "summer of love" was about, and neither conception nor delivery were idyllic. MIL-STD-461/2/3 were not very prepossessing babies, and even through young adulthood they were a bit on the ugly duckling side – three further MIL-STD-461 revisions ("A" – "C") doing nothing to improve the original impression. The degree of disenchantment with MIL-STD-461/2/3 in 1967 may be gauged by looking at the system-level EMC specification for airborne systems released that same year, MIL-E-6051D.

> 3.2.4.1 *Subsystems/equipments*. Unless otherwise specified in the contract, subsystems/ equipments shall be designed to meet the requirements of MIL-STD-461 and MIL-STD-462. <u>Since some of the limits in these standards are very severe, the impact of these limits on system effectiveness, cost, and weight shall be considered</u>.

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[1] Unless otherwise indicated, cited references are available for viewing/download from the author's Linked IN profile page, in addition to actual publisher. For a straight-up comparison of pre- and post-1993 MIL-STD-461 requirements, see: Javor, K. "Report on Draft Versions of Revisions to MIL-STD-461C and MIL-STD-462," EMC Test & Design magazine, July 1992.

[2] Preparing activity for MIL-STD-461 was the Navy, for MIL-STD-462, the Air Force, and MIL-STD-463, the Army. This was the reason for the split between limits and procedures, which was unprecedented before and after (MIL-STD-461E combined -461 & -462 back into one standard in 1999). Including and since MIL-STD-461E, USAF has been the preparing activity.

[3] Despite the forced marriage, by 1971 the Services had each gone their own separate ways with their own Service-unique Notices to MIL-STD-461 and -462; the Army Notices were larger than the original standards and included test equipment not found elsewhere in the standard. MIL-STD-461B/C reunited all Services under one requirement standard again, but with up to seven different sections each for different Services and applications. And the MIL-STD-462 notices remained Service-specific until superseded by MIL-STD-462D in 1993 (see timeline at article's end).

Proposed modifications to the limits shall be included in the EMC plans for the system and subsystems/equipments. (author-added emphasis)

Compare this to the corresponding paragraph in the predecessor MIL-E-6051C revision, released in 1960, when Service-unique EMI standards were in place.

3.4 *Susceptibility characteristics of electrical and electronic subsystem contractor-furnished airborne equipment*. The interference control requirement stated herein shall be considered in the design phases of the weapon system. All support systems and subsystems shall incorporate interference control requirements in accordance with MIL-I-6181 for Army and Navy requirements and for Air Force requirements for class Ia equipment as defined by MIL-I-26600, and in accordance with MIL-I-26600 for other Air Force requirements. Specific attention shall be given to the interference susceptibility characteristics of the subsystem in relation to the predicted electronic interference environment. Where additional requirements are necessary, it shall be the responsibility of the weapon system contractor to impose those requirements on the subsystem. Compliance with the requirements relating to subsystems shall not relieve the weapon system contractor of the overall responsibility of controlling the weapon systems electro-interference.

The difference is profound. With MIL-STD-461, the attitude is “try to meet all subsystem EMI requirements without weighing down the aircraft to where it can’t fly, and/or we can’t afford it,” vs. with predecessor requirements, it was “make sure subsystems meet all EMI requirements and make sure they all play together nicely, because just meeting subsystem EMI requirements doesn’t relieve the contractor of the responsibility of achieving overall system EMC.”

Twenty-five years ago, after being flagged as “problem standards,” MIL-STD-461/2/3 received a complete and utter makeover (“D” revision) and ever since, including three further revisions (“E” – “G”), they have blossomed from ugly duckling status into a beautiful swan, to pursue the metaphor to its logical conclusion.[4] [5]

2017 also marked a sad date – we lost Steve Caine, who presided over the MIL-STD-461D/-462D revision process. In 1989, when the “D” revision process began, Mr. Caine was the only still active military personnel of those associated with the original MIL-STD-461/2/3 project, and in his own words, “was punished for that transgression by being assigned to fix the mess he helped create,” or words to that effect.[6]

MIL-STD-461/2/3 was notable for many reasons. It was the first successful Tri-Service EMI standard(s) covering all procurements. MIL-STD-826 had been released in 1964 and was meant to function as did MIL-STD-461/2/3, but it was only adopted by the preparing activity, the Air Force (USAF). Much of what is in MIL-STD-461/2/3 that was not found in the earlier EMI specifications may be found in MIL-STD-826.[7] This includes 10 uF feedthrough capacitors, log-spiral antennas, standardized one-meter antenna-test sample separation, CS06 for ac and dc powered equipment, and other changes.

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[4] MIL-STD-463 (definitions) was a casualty of the “D” revision makeover that morphed the ugly ducklings into beautiful swans. MIL-STD-463 was replaced by its commercial equivalent, ANSI C63.14. Also in 1993 specifications on EMI receiver characteristics were dropped from MIL-STD-461/2 and since rely on ANSI C63.2, which in turn references CISPR 16-1-1.

[5] John Zentner of Wright Patterson Air Force Base was one of two Air Force representatives to the -461D/-462D TSWG. He spearheaded most of the changes that resulted in making the “D” version so much better than the previous versions. This required quite a bit of fortitude, as many of the changes were controversial at the time. The crowning glory of the “D” revisions, the addition of the bulk cable injection requirements, was so controversial (although business-as-usual today) that the author was still debating the topic at the end of the century under IEEE EMC Society sponsorship. Mr. Zentner also wrote the majority of the rationale appendices.

[6] Author’s recollection of Chairman Caine introducing the “D” revision process and Tri-Service Working Group (TSWG) members at a briefing at the 1989 IEEE EMC Symposium in Denver.

[7] Interestingly, history repeated itself when MIL-STD-464 became the Tri-Service top-level E3 standard, replacing Service-specific EMC standards. MIL-STD-1818 had been written for this very purpose by the USAF, but was rejected by the other Services. A side-by-side comparison of MIL-STD-464 with obsolete MIL-STD-1818 reveals a great deal of commonality.

There were a plethora of Service-specific EMI specifications prior to MIL-STD-461, as well as Tri-Service coordinated specifications, but the latter were for specific types of equipment, such as hand tools or internal combustion engines. The Air Force had MIL-I-26600 for aircraft, even though there was a Tri-Service coordinated specification, MIL-I-6181, for aircraft. The Army had MIL-E-55301. And the Navy had MIL-I-16910 for ships. And these are just the main players. There were hosts of others, all similar but not identical.[8] An abridged time line of military EMI specifications and standards is presented at the article's end.

Why a Tri-Service standard? Some sources have said that industry complained about a lack of common requirements/test methodologies between Services, requiring multiple qualifications of equipments. Also, that multiple kinds of near identical test equipment had to be kept on hand. For instance, Figure 1 EMI receivers were developed under Air Force and Navy sponsorship, or used by them. Equipment shown in Figure 2 was developed under the auspices of the US Army. A review of the forerunner specifications just prior to MIL-STD-461 shows that all of these machines were approved for use in the coordinated Tri-Service specifications, but some of the single-Service specifications required specific measurement receivers and antennas. Also, some requirements, such as hand tools, had requirements for radiated emissions at multiple distances, which makes sense for equipment not installed on platforms. But multiple set-ups, however technically justifiable, were ultimately deemed uneconomical.

Due to likely various motivations, MIL-STD-461/2/3 happened.

Figure 1*: Stoddart Aircraft Radio Company manually tuned receivers, 1950 – mid-'60s.*[9]

Figure 2: *Empire Devices NF-105 manually tuned receiver with plug-ins, 1950s – 60s.*

[8] For more than you ever wanted to know on this subject, see the author's book entitled "Introduction to the Control of Electromagnetic Interference, A Guide to Understanding, Applying, and Tailoring EMI Limits and Test Methods," published in 1993 – if you can find a copy. Much of the content in this article is a synopsis of what was written up in detail in that book, and since an author cannot be accused of plagiarizing himself, this footnote serves as the sole pointer towards the source of much of the article's content.

[9] All equipment images courtesy of the Museum of EMC Antiquities, located in Huntsville, AL. Dick Stoddart, founder of his eponymous company, previously worked for RCA/NBC, developing the radios used on Howard Hughes' aerial circumnavigation of the globe in 1938, and was also the radio operator on that journey.

Noteworthy innovations in the 1967 Tri-Service release of MIL-STD-461/2/3

- In retrospect, a very unfortunate result of the way MIL-STD-461 was implemented was to impose the total spectral usage of all the Services onto each individual Service. As opposed to the D – G revisions post-1993, where the test method remains the same but the limits tend to vary by Service and application. For example, prior to 1967 Army and Air Force CE and RE limits began at 150 kHz, the bottom of the automatic direction finding (ADF) band, whereas in contrast Navy ship and anti-submarine warfare (ASW) aircraft went all the way down to 14 kHz, on account of the AN/BRR-3 (Figure 3) vlf radio receiver and other related submarine ASW spectrum use 14 – 30 kHz. Adding in spectrum from 14 – 150 kHz to the controlled CE and RE limits imposed unnecessary burdens on the other Services.

Figure 3: *AN/BRR-3, Polaris class submarine vlf receiver. Polaris class submarines carried sea-launched, nuclear-tipped ballistic missiles. The AN/BRR-3 received instructions to launch Armageddon.*

- Control of radio frequency conducted emissions changed from rf potential measured across a LISN to a current-based conducted emission limits using a 10 uF feedthrough capacitor. Prior to MIL-STD-461 and MIL-STD-826, the 5 uH LISN was used by all three Services.[10] This sufficed above 150 kHz, the lowest radio frequency in use by any of the Services except the Navy. There was some criticism of the 5 uH LISN in that if one determined that the electrical power distribution system (PDS) impedance was different than that of the 5 uH LISN, it would be difficult to predict ripple in the actual installation. In a Tri-Service standard, this is more of a problem than in a Service-unique or single-application specification. The SAE ARP-936 10 uF feedthrough capacitor is basically an rf short to ground above 10 kHz. The idea was that over the entire range of frequencies in use by all three Services that the feedthrough cap-based measurement would provide a worst-case assessment of noise currents, which could then be applied analytically to any assumed bus impedance.
- Related to the change from a 5 uH LISN to a 10 uF feedthrough capacitor was a degradation in how CS02 was performed. With a LISN, the rf CS test is just the elegant mirror image of the rf CE test: injection at the LISN port instead of measuring EMI at the LISN port. With the advent of a capacitor, an inductor needed to be inserted in line so any capacitance on the power input wouldn't load the 50

[10] Al Parker, the late founder of Solar Electronics, related the pedigree of the 5 uH LISN in a presentation made at the1992 IEEE EMC Symposium in Anaheim, entitled, "A Brief History of EMI Specifications." He cited work by an Army Air Corps engineer named Alan Watton during WWII, who made impedance measurements on a DC-3 type aircraft (all aluminum, twin wing-mounted engines, 28 Vdc power distribution, and structure current return).

ohm signal source.[11] Also, a special injection network had to be used, instead of that inherent in the LISN EMI port. Finally, under this new set-up, the injection source impedance step changes from 0.5 ohm or less for CS01 to 50 ohms or thereabouts at 50 kHz. This is hardly realistic. With the LISN injection technique, the impedance rose smoothly: it was just the LISN impedance itself.

- Radiated emission (RE) and susceptibility (RS) measurements standardized a one-meter antenna – test sample separation.[12] Early military aerospace EMI standards based radiated measurements on a one-foot separation between culprit emitter and victim unshielded antenna lead-in.[13] By the mid-'60s, that technology was obsolete and the separation could be increased to one meter. There are many platforms/applications where a separation of greater than one meter would suffice, but in a Tri-Service standard including small ground and air vehicles, a one-meter separation as a worst case is reasonable. There was also a change in how radiated emission limits were presented. Prior to MIL-STD-826 and MIL-STD-461, RE limits imposed at one-foot separation were expressed in terms of dBuV induced at the antenna terminals.[14] The limit quantity was not field intensity, but the output of a specified transducer (antenna or probe) placed adjacent to the test sample in a prescribed manner. No one could mistake that an *antenna-induced* limit was purporting to be measuring radiation from the test sample. One-foot measurements, while not crosstalk, were of the mainly non-radiating quasi-static field, especially below 30 MHz, and likely closer to crosstalk than far field radiation. Backing up the antenna from one-foot to one-meter was accompanied by a change to a field intensity-denoted limit. It is arguable that the measurement is still near field, that the probe or antenna is still integrating a varying field gradient across its physical aperture, and that therefore an antenna-induced limit is still appropriate. Regardless, that change was made, and while the error antedates both MIL-STD-826 and MIL-STD-461, comparisons were made between RE and RS levels, as if the purpose were to control RE to avoid RS. This misunderstanding became so egregious and widespread, especially within the space industry, that MIL-STD-461D/-462D and all follow-on standards to this day clearly state in the RE102 and RS103 appendices that these are not complementary requirements: RE102 protects antenna-connected receiving devices from radio frequency interference (rfi), and RS103 assures that non-antenna connected electronics are compatible with the rf environment caused by high-powered rf transmitters.
- In the original release of MIL-STD-462, average detection was allowed for narrowband signals. That followed the precedent of antecedent single-Service EMI specifications. Average detection was deleted under a subsequent notice to MIL-STD-462 in the 1970s, by which time semi-automated sweeping was common, gradually superseding the manual tuning of a receiver while listening for signals. Until very recently, it was impractically time-intensive to perform sweeps using an average detector, but back in the days of manually tuned receivers, they were tuned looking for a signal, and when a signal was tuned in, and determined to be either NB or BB, the correct detector could be applied with little or no extra time required. Once semi-automated equipment capable of sweeping over large bands became available in the mid-1960s, the use of an average detector would have been very disadvantageous. It is only recently that detectors implemented not as actual circuits but

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[11] Required in MIL-STD-826, not required in MIL-STD-462, but highly desirable since the last stage of the typical EMI test facility EMI filter is capacitive. It was a significant defect that this was not included to prevent loading the 50 ohm CS02 signal source, but included to prevent loading the sub-ohm CS06 spike generator impedance!

[12] The use of a one-meter separation and field intensity-based RE limits came from MIL-STD-826 (1964). Previous aerospace specifications used one foot, but other specifications invoked a variety of separations for different applications.

[13] Javor, K. "Diamond Jubilee: The 60th Anniversary of the Use of the 41 Inch Rod Antenna in Military EMI Testing" IN Compliance magazine, August 2013.

[14] MIL-I-16910 (Navy ships) imposed requirements at three feet separation and limits were expressed both as antenna-induced and as field intensity. MIL-E-55301 (Army EMC) imposed measurements at various separations at and above five feet and used field intensity limits only.

firmware operating on digitized data became available. Now it is again possible to use multiple detectors with no impact on sweep time. This is particularly advantageous in the CISPR world, where they have multiple limits using multiple detectors.

- Receiver front-end protection requirements and detailed test methods CS03/04/05/07 were migrated from MIL-STD-826, but subsets of these existed in even earlier specifications. The CS08 test method (single source measurement of out-of-band rejection) looks like the receiver front-end rejection test method of MIL-I-6181D. These requirements protect receivers not from unintentional EMI as results from RE02 type emissions, but from strong signals emanating from intentional transmitters connected to antennas close to the victim antenna. They are very important whenever multiple antenna-connected systems must operate in close proximity, as is the case with many military platforms, most especially ships. On a platform with multiple transmit and receive rf subsystems operating simultaneously, their compatible operation is the biggest EMI problem to be solved.

- The CS06 transient requirement was imported from MIL-STD-826, but existed in a simpler form in 1950s-era EMI requirements for 28 Vdc-powered equipment. The detailed spike source circuit diagram shown in these earlier standards was not imported, only the spike characteristics, because by 1962 Solar Electronics had commercialized the spike generator into a standard offering in their line of test equipment, the Model 6254-1. Honeywell also made a similar unit.[15] While the original unidirectional (positive) transient requirement was for equipment powered from 28 Vdc power, by the time of MIL-STD-826 and MIL-STD-461, it also applied to ac mains-powered equipments, and both polarities were required. While CS06 and all predecessor requirements cited a ~10 pps transient rate, CS06 additionally required that on ac mains-powered testing, the transient be synchronized to various phases of the ac line waveform. The Solar offering that provided this function, the -5 version of the Model 6254 transient generator, did not operate the way the standard intended. The standard requires 1 - 10 pps, synchronized to the ac line phase. The 6254-5 provided the required synchronization, but also provided a pulse for every half-cycle of the ac waveform, so 50/60 or 400 pps, depending on power type. This mistake, coupled with near universal adoption of the Model 6254 transient generator line, propagated itself not only through all the MIL-STD-461 tests that were performed at too high a rate, but also in derivative standards based on MIL-STD-461, requiring the CS06 transient at a 60 Hz rate even on dc-powered equipment![16]

- RS limits were expressed in terms of field intensity at the test sample as opposed to previously being instructions to apply a potential to an antenna terminal at a specified separation and orientation. This is similar to the change in how RE limits were specified.

- Biconical (30 – 200 MHz) and log-spiral antennas above 200 MHz replaced tuned dipoles, discones, and microwave horns. Tuned dipoles were not only required by some early EMI standards, it is obvious by inspection (and documentation) that many limits were based on the use of the 41" rod and tuned dipoles.[17] MIL-STD-461 referenced drawings describing the biconical and log-spirals or log-conical antennas.[18] There were two of the latter, one covering 200 – 1000 MHz, and another covering 1 – 10 GHz. The use of these broadband antennas eliminated the need to tune dipoles to each

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[15] Honeywell built very fine EMI test equipment back in the day: LISNs, current probes, the transient generator, antennas, including an excellent active rod antenna with front-end selectable attenuation to prevent overload.

[16] Solar Electronics fixed this problem in the next version, the 1982 Model 8282-1 transient generator, which supplied all the transients necessary in MIL-STD-461A/B/C, and at the correct rates.

[17] Prior to 1967, use of the 41" rod antenna below 30 MHz and tuned dipoles above 30 MHz meant that shield room sizes were informally standardized at about eight feet height (tuned dipoles were only deployed horizontally), 20 feet length and about 8 feet depth. After 1967, rooms had to be much deeper, although 8 feet still sufficed for height, and the long room dimension could be greatly shortened.

[18] Log-spirals had been previously required in MIL-STD-826 (1964). MIL-STD-461A (1968) defined construction of the prototype biconical within the standard with detailed instructions and drawings.

frequency of interest, saving a lot of test time – and measurement of vertically polarized fields became possible above 30 MHz.[19]

When Silver is Worth Its Weight in Gold[20]: Noteworthy changes between MIL-STD-461/2/3 basic and post-1993

- First and foremost, a rationale appendix was added. Right, wrong, or indifferent, we know why MIL-STD-461/-462 post-1993 says what it says. That is not true for earlier versions. The rationale appendix is a critical component of the standard, and aside from purely contractual issues, is the most important part.
- Replacement of 10 uF feedthrough capacitor by 50 uH LISN as the standard power source impedance. As noted in the 1967 discussion, the idea behind the 10 uF feedthrough capacitor was that over the entire range of frequencies in use by all three Services, the feedthrough cap-based measurement provides a worst-case assessment of noise currents, which could then be applied to any assumed bus impedance. While this point-of-view was accepted for over thirty years, the feedthrough cap came to be seen as driving EMI filter designs in a manner unproductive for real-world installations. That is, real world PDS impedance was inductive, and therefore filters designed looking into a 10 uF feedthrough capacitor using an inductor facing the capacitor were not going to be effective when the real world was an inductive PDS impedance. Hence, the "D" revision cycle reverted back to LISNs. In the initial "D" TSWG meetings, the 5 uH LISN was invoked, based on its use in similar industries, namely aerospace and automotive, but eventually a 50 uH LISN was adopted. The 50 uH LISN was adopted not based on similarity to installation PDS impedance but rather because it enabled an rf potential measurement down to 10 kHz, which mapped to the previous CE03 limit frequency range. Because the impedance of the 5 uH LISN is only defined above 150 kHz, use of it would have meant that CE102 could only start at 150 kHz, and that wasn't desired.
- The log-spiral antennas mentioned above were circularly polarized, as opposed to all the other antennas in use being linearly polarized. This caused some confusion, and they were replaced by double ridge guide horns in 1993. This doubled RE test time for these bands, because the log spirals didn't require two different orientations for horizontal and vertical polarizations. Another criticism of the log spirals was that at some frequencies the main lobe wasn't directly in front of the cone apex. This is a gratuitous critique for an antenna with very low gain and directivity. The entire concept of main lobe is lost when the antenna has better than 60 degrees beamwidth. Wide-angle, near-constant beamwidth coverage vs. frequency is exactly what is desirable when looking at a test set-up two or three meters long from just one meter away…[21]
- Another change in radiated testing, both emission and susceptibility, was a change in the placement of wide beamwidth (rod and biconical) antennas. In MIL-STD-462 basic and forerunner specifications, the antenna is placed opposite the test sample enclosure, which is at the center of the ground plane, lengthwise. In MIL-STD-462D and later, the test sample is near one end of the ground plane with loads at the opposite end, and the rod and biconical are placed in the center of the test set-up, which means in front of the cabling running between the test sample and loads, recognizing that the primary radiators in these lower frequency bands are cables.

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[19] Not all early specifications required tuned dipoles. Some used discones and at higher frequencies, horns. In these standards, vertically polarized electric fields were controlled.

[20] Regarding anniversaries…

[21] A real problem with log-spirals is the design relies on lossy coax so that the gain is much lower than the directivity. In effect, this means that only limited power can be transmitted, and also that the antenna pattern is not as broad as expected from the gain values (but still much wider beamwidth than horns, and constant).

- Part and parcel of the rigor imposed by having a rationale appendix is the need to justify each limit. Unjustifiable requirements were dropped. That doesn't mean there might not have been good rationale at one time for some deleted requirements, but since there was no rationale appendix prior to 1993, some requirements had no known basis for retention. CE02, CE04, CE07, CS02, CS06, RE04 and RS02 are examples. For instance, there are other standards that control common mode conducted emissions on power leads and signal lines, such as RTCA/DO-160, section 21, and various spacecraft EMC standards. But what to make of these apparently conflicting statements?

  MIL-STD-461 wording for CE02 and CE04: "Electromagnetic emissions ... shall not appear … in excess of values shown in Figures ... Intentional transmissions of electrical energy by conduction on their intended leads, at their specified power levels, and within their necessary information bandwidths are exempt from the requirements of this standard."

  MIL-STD-462 wording for CE02 and CE04: "In no case shall a group of leads be probed with both high and return leads in the test group, except for a twisted pair."

  It would appear the requirement was not intended to be exclusively common mode, but in that case it wasn't obvious what the intent was, and with no rationale appendix to explain/justify it, it was simply dropped.

  CE07 wasn't part of the original 1967 MIL-STD-461/2/3, but appeared in MIL-STD-461B (1980) and retained in MIL-STD-461C (1986). This was a poorly stated time-domain turn-on and turn-off requirement, coupled with a non-existent test method (i.e., what was labeled CE07 in MIL-STD-462 didn't correspond at all to the turn-on/off CE07 requirement in MIL-STD-461B/C). This requirement was dropped during the "D" revision process. MIL-STD-461D-G has no requirement limiting emissions at the moment of turn-on or off. And whereas there were various requirements providing frequency-domain broadband limit relaxations for various mode-switching events prior to 1993, post-1993 anything other than turn-on/off transients must meet steady-state limits.

  CS02 was replaced by CS114, one of a trio of new bulk cable injection (BCI) requirements, which get their own discussion below.

  CS06 was eliminated. Actual switching transients are much more severe in the various Service/application-specific power quality standards.[22] The crosstalk effects of switching transients are adequately handled by one of the new BCI requirements, CS115. The low impedance and duration of CS06 is quite problematical when injected in the same polarity as the power waveform.[23]

  The RE04 limit and test method was designed specifically around the performance of the EMCO 6640 magnetic field intensity meter, shown in Figure 4.[24] The MIL-STD-462 requirement that the magnetic field sensor and electronics be "capable of measuring 40 dB below nano tesla (sic) at 25 Hz" specifically refers to EMCO 6640 performance, specified at 10 dBpT per cycle.[25] Said device or ones like it not being in general use in 1989 (were they ever?) this requirement was tossed upon the ash heap of history.[26]

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[22] MIL-STD-704 for aircraft, MIL-STD-1275 for ground vehicles, and MIL-STD-1399, section 300 for ships.

[23] Javor, K. NASA/CR-1999-209574. Specification, Measurement and Control of Electrical Switching Transients. Downloadable here: https://see.msfc.nasa.gov/eepub

[24] Javor, K. "Low-level, Audio Frequency Conducted Emission Measurements: Motivation and Method." IN Compliance magazine, February 2012. Compare Figure RE04-2 in MIL-STD-462 to the sensor head shown in Figure 4.

[25] EMCO 6640 data sheet, circa 1970

[26] Test method quite useful for spacecraft hosting magnetometers.

Figure 4: *EMCO 6640 magnetic field intensity meter, circa 1964*

CS115 replaces the pulsed part of RS02, and the power frequency part of RS02 was just deleted.

- Receiver front-end requirements in the 1967 release were reduced down to CS103 (intermodulation), CS104 (out-of-band rejection) and CS105 (cross-modulation). But the really big change reflects a change in radio technology over the twenty-five years between the original and "D" releases. The original requirements and test methods were all based on tunable narrowband super-heterodyne radio receivers. By 1993, radios in production and use included hoppers and spread spectrum (such as GPS). And now we have "software-defined" radios that can sample the spectrum and choose clean portions to use on an *ad hoc* basis. The 1967 limits and test methods cannot be directly applied to these newer technologies. The need to protect radios from out-of-band signals exists, but it's hard to define out-of-band when the "band" can be the entire spectrum allocation, or it can move around based on uncontrolled external stimuli. Therefore while the requirements still exist, the limits are "punted" to the individual procurement specification and test methods must be tailored on a case-by-case basis based on rationale appendix guidance.
- New requirements generically termed bulk cable or bulk current injection were added to replace and augment several of the individual requirements in earlier versions. CS114 and CS115 in particular were brand new in MIL-STD-461D/-462D, with no previous counterpart.

  CS114 is a low frequency, lumped-element model of electromagnetic field-to-wire coupling.[27] It replaces CS02, with the following advantages. While the antecedent to CS02 originated as a 1 millivolt level control on susceptibility to load-induced noise potentials on aircraft primary power in the 1950s, by the time it had evolved into the MIL-STD-461 requirement, it was hopped up on steroids and was 60 dB higher – 1 Vrms. At that level it could no longer be considered to be load-induced effects and could only be considered to be the coupling of high-power electromagnetic waves to power lines. However, if this were the case, then there were two problems. A limit flat from 50 kHz to 400 MHz is not an accurate model of electromagnetic field-to-wire coupling, and if high levels were coupling to power lines, would they not also couple to signal cables as well? CS114 addresses both these problems. And, as a lumped-element model of electromagnetic field-to-wire coupling, CS114 replaces and augments the low end of the former RS03. This is especially valuable when the installed cable is much longer than what can be tested in an EMI test facility. In the latter case, there is no way a radiated test can simulate what would couple to a longer-than-tested cable.

[27] Javor, K. "On Field-To-Wire Coupling Versus Conducted Injection Techniques," IEEE EMC Symposium Record 1997.

CS114 was not invented out of whole cloth for MIL-STD-461. Versions were already in use in RTCA/DO-160 section 20 and also DEF STAN 59-41 DCS02.

CS115 injects a 30 ns spike with 5 A amplitude at a 30 Hz rate. It simulates the coupling of transients from a culprit to a victim cable. The CS115 signal source is a 50 ohm charged line generator, operating on the same principle as an impulse generator used for calibrating EMI receivers, but using a longer piece of coax to yield the 30 ns duration.[28] CS115 replaces the pulsed part of RS02, and completely replaces RS06, the chattering relay test, which was not part of the 1967 MIL-STD-461/2/3, but added in MIL-STD-461C and MIL-STD-462 Notice 6 later.

CS116 is a simulation of the coupling of an electromagnetic pulse (EMP) to a cable. The EMP source is the atmospheric detonation of a thermonuclear device. It replaced four separate related MIL-STD-461 B/C requirements: CS10, CS11, CS12, and CS13. None of these requirements are found in the 1967 release of MIL-STD-461/-462. They appeared in the 1980 revision B of MIL-STD-461. CS116 is noteworthy in that the reason it replaces four previous requirements is that two of these were pin injection requirements. MIL-STD-461D/-462D eschewed all pin injection requirements.[29]

- Post-1993, Measurement System Integrity Checks for emission measurements provide confidence that measurements were properly performed. The response of the measurement system end-to-end to a known input at the limit is assessed (changed to 6 dB below the limit in later versions).
- It seems ancient history now, but prior to 1993 emissions data could be taken using fully manual equipment such as those shown in Figures 1 & 2. With this type of equipment there is no plot of emissions, just a table of individual measured frequencies and amplitudes. The "D" revisions mandated automatically generated Bode plots of emission data.[30]
- A very big problem solved in 1993 was the lack of a modulation requirement for the rf susceptibility requirements, CS02 and RS03. The Army Notice to MIL-STD-462 mentioned this, but nowhere else. In MIL-STD-462D, modulation is a requirement. The default value is described as 100% square wave 1 kHz pulse.
- The original MIL-STD-462 Appendix A was a list of approved test equipment. MIL-STD-462D post-1993 and follow-on MIL-STD-461E-G have no such list and cannot even suggest such or cite a manufacturer or part number.
- Shield rooms didn't require absorber in either forerunner specifications or MIL-STD-461 until 1993. This was a critical oversight in 1967. When they backed up the antenna from one foot to one meter, the measurement uncertainty due to reflections in a bare-walled shield or screen room became a much greater problem than when the separation was just one foot. This problem was partially remedied in 1993. While the present requirement is hardly the anechoic performance required for three-meter and larger separations in CISPR 22 and similar applications, the required treatment greatly reduces the maximum value of reflections in what is otherwise termed an electromagnetic hall-of-mirrors. The

[28] A CS115 forerunner was developed by the late Lothar "Bud" Hoeft in his days at BDM. The original motivation was an impulse generator to drive large aircraft so that a transfer function to cable induced currents could be developed to support EMP analysis.

[29] The "no pin injection" philosophy has been a common and robust thread ever since 1993. The 2015 release of MIL-STD-461G included lightning requirement CS117, borrowed mainly from RTCA/DO-160 section 22, but in keeping with the philosophy, only the cable injection waveforms were adopted; no pin injection. The other factor of two in the four-to-one reduction in requirements was from the Air Force and Navy agreeing on a single test method.

[30] While computer-controlled EMI receivers/spectrum analyzers were commonplace in the 1980s, attempts at automating older manually tuned receivers date back to the 1960s. Don White, another pillar of the EMC community we lost in 2017, was instrumental in developing the first semi-automated receiver system in the mid-'60s. His equipment was listed as approved for use in MIL-STD-826 dated 1964, and MIL-STD-462 in 1967.

present treatment is recognized imperfect; but is an economic compromise avoiding the cost of a full anechoic treatment.

- Table II. Minimum dwell times / maximum sweep rates. The issue of scan rate or dwell time based on equipment-under-test concerns was not an issue when EMI receivers had panel meters with needles and/or drove a plotter using a pen, as in Figure 5. Mechanical inertia of meters and pen plotters limited sweep rates in those days. With the advent of spectrum analyzers using CRT and then liquid crystal displays, limits on sweep speed based on equipment-under-test concerns had to be levied.

Figure 5: *Stoddart chart recorder to be used with Figure 1 receivers to generate plotted data.*

- Table II. Elimination of broadband emission limits accompanied by specified bandwidths. Prior to 1993, MIL-STD-461/2/3 (and all predecessor EMI standards) included both narrowband (NB) and broadband (BB) limits. Broadband limits were absolutely necessary at a time when most interference sources were broadband and there were no standards governing the bandwidths implemented in EMI receivers such as those shown in figures 1 & 2. With a broadband signal and different receivers with varying bandwidths, normalization to a standard bandwidth is required.[31] But by 1993 measurement bandwidths were largely agreed upon and standardized, at least in the CISPR world, and standardized bandwidths were required in Table II of MIL-STD-462D and MIL-STD-461E-G. Furthermore, many test facilities weren't performing NB/BB emissions measurements correctly, using one set of bandwidths for narrowband, and another set for broadband measurements (erroneously assuming that having separate NB/BB limits implied two different scans looking for two different kinds of signals). In 1980, Wright-Patterson Air Force Base released an application note authored by John Zentner that described the proper way to make these measurements.[32] The idea is that for a given radio bandwidth, there is a specific relationship between broad and narrowband limits that results in the same limit level being specified regardless of signal type, given by this equation:

  20 log (1 MHz/BW) = BB Limit (dB X/MHz) – NB Limit (dBX),

  where "X" is the quantity of interest, uV, uV/m, uA, etc.

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[31] The original substitution technique used an impulse generator calibrated in dBuV/MHz, depicted in the cover art pre-MIL-STD-461 image. This worked well both pre-1967 and after but modern techniques introduced when emissions measurements became computer-controlled were not as good and hastened the demise of broadband limits. But this is an involved topic – an article in itself. Stand by…

[32] MIL-STD-462 Application Note: Identification of Broadband and Narrowband Emissions dated 01 May 1980. Aeronautical Systems Division, WPAFB. Copy available from (article) author on request.

Given a specific NB and BB limit, one can use the above equation to pick a bandwidth that makes both limits coincide numerically, and this is the ideal single bandwidth to be used (in a given frequency range).[33]

But this was largely to no avail, and by 1989 DoD was tired of reviewing bad test procedures, witnessing bad tests and reviewing flawed test data.[34]

While broadband limits are now obsolete in military EMC practice, that does not mean the concept is also obsolete. The original problem of different EMI receivers having different bandwidths is solved, but the problem of different victims having different bandwidths is very real. So for instance we use 100 kHz bandwidth from 30 – 1000 MHz, and that is a reasonable bandwidth for many victims out there, but what happens to reception of a signal that is many MHz wide? A real world example of that is the CISPR 120 kHz bandwidth employed over the same frequency range, modeled on the FM broadcast band. But broadcast television operates above the FM band, each channel occupying 6 MHz, so that dithered clocks designed to spread the clock spectrum outside the 120 kHz and effectively create a broadband signal are not doing so in the television bands. While measured EMI is reduced, the TVI effect is not reduced at all.

- Table III. In 1967, susceptibility signal sources were manually tuned, as shown in Figure 6. The "bandwidth" of the human operator was so much smaller (slower) than the response time of (relatively) simple electronics that no controls were placed on sweep rate or dwell time. Fast-forward to 1989, and sweeping synthesized signal sources had completely replaced the manually tuned cavity oscillators and butterfly capacitors. Now it was possible to sweep too fast or dwell too short a time to get a response from many of the equipments-under-test. Hence we have Table III with maximum sweep rates/step sizes, and minimum dwell times.

Figure 6: *Susceptibility signal sources using cavity-tuned oscillators, mainframe and separate plug-ins. Plug-ins show that tuning and coupling was all done mechanically. At the end of a long day of CS02 and RS03, the technician's hands were callused and cramped.*

[33] That this sometimes results in computed bandwidths too large for practical use is a condemnation of the limits themselves. The purpose of separate NB/BB limits is to ensure that in the appropriate bandwidth, a BB signal at the BB limit yields the same potential or power level as a NB signal at the NB limit.

[34] Aside from whether broadband requirements are still needed, the inability to perform these measurements correctly did not cast the test industry in a good light.

- Radiated susceptibility limits increased by orders-of-magnitude (1 V/m in 1967 up to 200 V/m post-1993). This had a pronounced effect on the test method. Not just the obvious in terms of high power amplifiers and antennas capable of handling the power, but also in how the field is calibrated. In 1967, precalibration was the order of the day, using two identical antennas and recording power required to establish the required field intensity. Precalibration was done in the center of the chamber, whereas the field during testing was aimed at the test sample installed on a tabletop ground plane – see MIL-STD-462 Figure 2. In 1993, this method was replaced by a requirement to use electrically short field monitoring probes that are broadband devices capable of being placed in the immediate vicinity of the test sample, relieving the concern about inaccuracies inherent in the older method.
- A change beginning in MIL-STD-461D that should have occurred in the 1967 release was to differentiate radiated emission limits based on equipment location relative to ship and fixed-wing aircraft-installed antennas.[35] When the antenna-test sample separation was increased from one foot to one meter, that was because an rf coupling problem interior to platforms had been solved by replacing unshielded antenna lead-ins with coax.[36] At that point, the problem of rfi coupling interior to platforms moved to the outside, with rfi only occurring via coupling to antennas, typically mounted external to the platform. Ship limits are delineated topside and below deck, and aircraft limits are based on location inside or outside the fuselage.[37]
- Requirement CS101 differs from predecessor CS01 for ac mains-powered equipment. It is no longer acceptable to use a "phase-shift network" to eliminate the mains potential when measuring injected ripple potential. The phase-shift network was introduced conceptually in MIL-STD-826, was specifically mentioned as useful in MIL-STD-462 CS01 and a commercial version became available from Solar Electronics circa 1970 (see Figure 7). MIL-STD-462D and follow-on MIL-STD-461E – G forbid its use because the theory of operation assumes that all injected ripple drops across the test sample power input, and none across the power source. If some ripple does drop across the power source, use of the phase-shift network overestimates injected ripple at the test sample, thus potentially under-testing. Lack of the phase-shift network impacts the ability to measure ripple riding on the ac power waveform. Due to this change, the low end of the CS101 frequency range was changed for ac mains-powered equipments from the previous 30 Hz to twice the mains frequency. Various frequency domain techniques have since been developed that allow ripple to be observed separate from the power waveform.[38] These techniques "give back" the lost frequency range between 30 Hz and 120 or 800 Hz. However, in the intervening years between the adoption of the "D" revisions and the advent of the frequency domain techniques, no platform compatibility issues had been noted, so that the CS101 start frequency for ac mains-powered equipment remains the mains frequency second harmonic.

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[35] Ground vehicles, helicopters and spacecraft have only one limit; no isolation is assumed between equipment complement and antennas.

[36] Reference footnote 13.

[37] This change wasn't fully accomplished for ships until MIL-STD-461F in 2007.

[38] One method is the use of oscilloscopes with built-in FFT capability. Another is described here: Javor, K. "Fifty-Year Old EMI Testing Problems Solved!" IN Compliance magazine, June 2012.

Figure 7: *Solar Electronics test equipment specifically designed for CS01. All equipment shown is still valid and useful for CS101, except the phase-shift network on the right.*[39]

- RS04 was eliminated. CS114 replaces RS04.[40] RS04 was a test based on using a parallel plate to illuminate the test sample and attached cables underneath it. This method is still valid but not required. Post-1993, MIL-STD-461 doesn't specify how fields are generated, except that both horizontal and vertical polarizations are required above 30 MHz.
- A 5-year review cycle was established so EMI standards would not get obsolete as they did in the period between 1967 and 1989.

Some Interesting Details of MIL-STD-461 and MIL-STD-462 from 1967

- A problem with RE02 was that the original NB and BB limits (Figures 8a & b) didn't line up. The apex was 25 MHz for narrowband, and 200 MHz for broadband. This never made sense, and no one the author polled could ever explain it. Looking at the draft MIL-STD-461 from 1966 reveals that the problem arises from Bode plot engineering/specsmanship. Figures 9a & b show what these limits looked like before they were simplified into the actual release version. The breakpoints all coincide in the draft version.

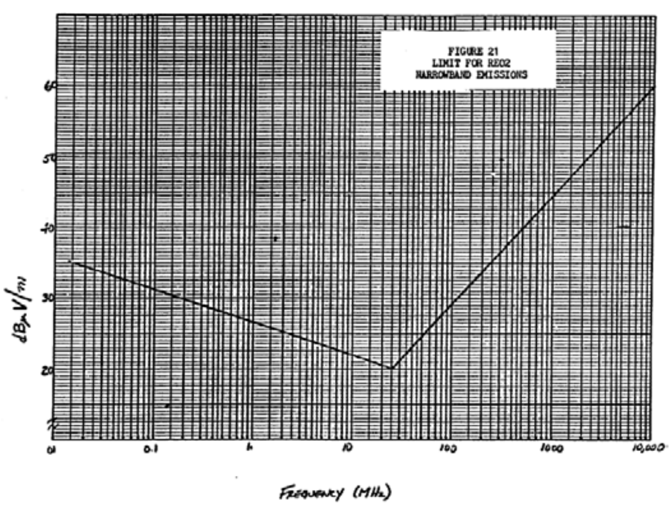

Figure 8a: *MIL-STD-461 RE02 NB limit*

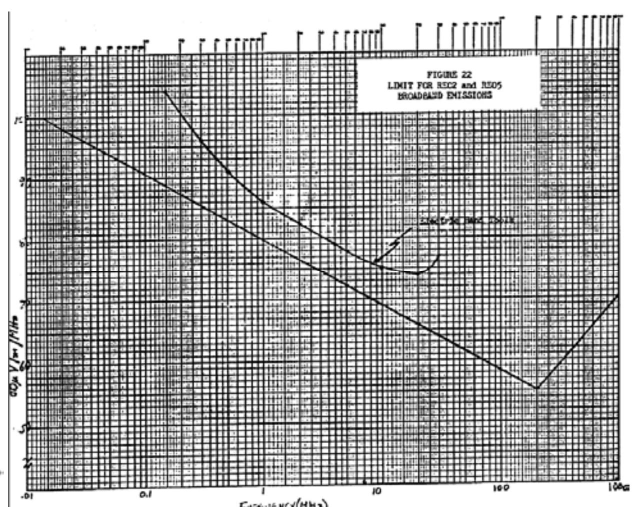

Figure 8b: MIL-STD-461 RE02 BB limit

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39 The amplifier and power oscillator remain (to the author's knowledge) the only sources providing specifically 0.5-ohm output impedance when coupled through the injection transformer, just what is necessary, no more and no less. That is, this equipment will never over-test a low impedance test sample.

40 RS04 improperly handled in MIL-STD-461, fixed in "A" revision a year later. Was correct in original MIL-STD-462.

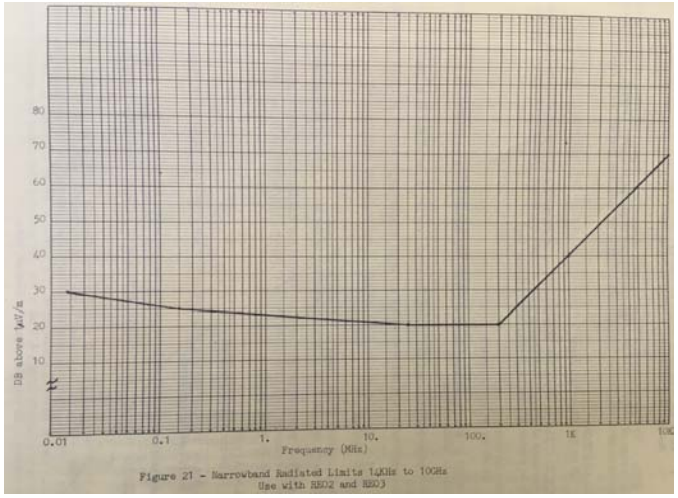


Figure 9a: *(1966 draft) MIL-STD-461 RE02 NB limit*

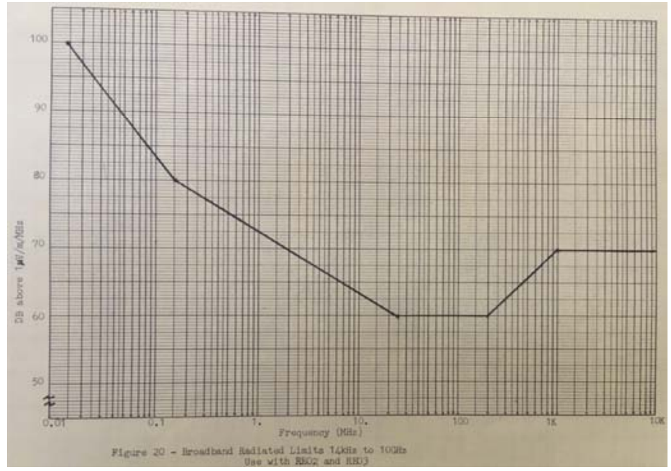


Figure 9b: *(1966 draft) MIL-STD-461 RE02 BB limit*

One can back out the victim radio bandwidths protected by the levying of these limits comparing the numerical values of Figures 9a & b using the method John Zentner explained in the Air Force application note about how to choose bandwidths:

Frequency	RE02 BW
14 kHz	300 Hz[41]
200 kHz	2 kHz
25 MHz	10 kHz
200 MHz	10 kHz
1 GHz	30 kHz
10 GHz	1 MHz

The Figure 8a & b finished products in the released 1967 MIL-STD-461 look like one person smoothed out the draft NB limit, while another smoothed out the draft BB limit, or if it was one person, the left hand didn't know what the right hand was doing.[42]

- MIL-STD-462 in 1967 required one-meter long power cables for CE testing, two-meter minimum for radiated. This was to enhance accuracy on conducted emission measurements and reasonable radiation efficiency for radiated measurements. It was easily accomplished using two sets of feedthrough capacitors, one set placed a meter from the test sample, and one set two meters away, and using two one-meter sections of power wiring that connected/disconnected using some manner of quick disconnects. However, this requirement of one set of wires for conducted and another for radiated was one of the most violated, and after a quarter century of repeatedly flagging such violations, the members of the TSWG opted for a single length of power wires, effectively dumbing down the standard to what the industry could reliably perform.[43] This had significant ramifications on the frequency range of the conducted emissions requirement CE102, resulting in the frequency range

[41] Comparison of this bandwidth to those available on AN/BRR-3 in Figure 3 shows that it is commensurate. These receivers were not voice, but data only, having not enough bandwidth for voice.

[42] As previously noted, the author was not able to get this seeming mystery answered, until he happened upon a copy of the draft MIL-STD-461 while rummaging through old file cabinets. This is called "EMC archaeology." The author asked Steve Caine about the changes between draft and final released version just after the turn of the century, and his response was something like, "A lot of horse-trading went on…" but his body language was on the order of, "Seriously – you expect me to remember a detail like that forty years out?" Entirely natural response, and also the rationale for a rationale appendix.

[43] Another black mark for the EMI test industry…

being truncated at 10 MHz, whereas everyone else controls CE to 30 MHz, and the predecessor 1967 CE03 controlled CE to 50 MHz.

- There is one MIL-STD-462 change between 1967 and 1993 that at first glance seems to be a 180° change in direction, but on further inspection is more nuanced. In 1967 cables were laid out in the first 10 cm from the edge of the ground plane, which was no change from predecessor standards. Post-1993, the minimum separation between ground plane edge and forward-most cable is 10 cm. On the face of it, this is a complete reversal in philosophy. The issue is radiation efficiency and efficiency of coupling to cables from a radiated field. The closer the conductors are to the edge of the ground plane to which they run parallel, the more they radiate and the more they capture incident radiation. However, in the case of a very simple equipment with only a power cable, there is no difference at all. Standard practice in either case places the cable 10 cm back from the front edge of the ground plane. If there were a second cable there is a slight difference in placement, and with each succeeding extra cable the two standards diverge more. However, once it gets to the point that the cables can't fit in the first 10 cm, then as the number of cables increases still further, the implementation of each standard begins to converge again.

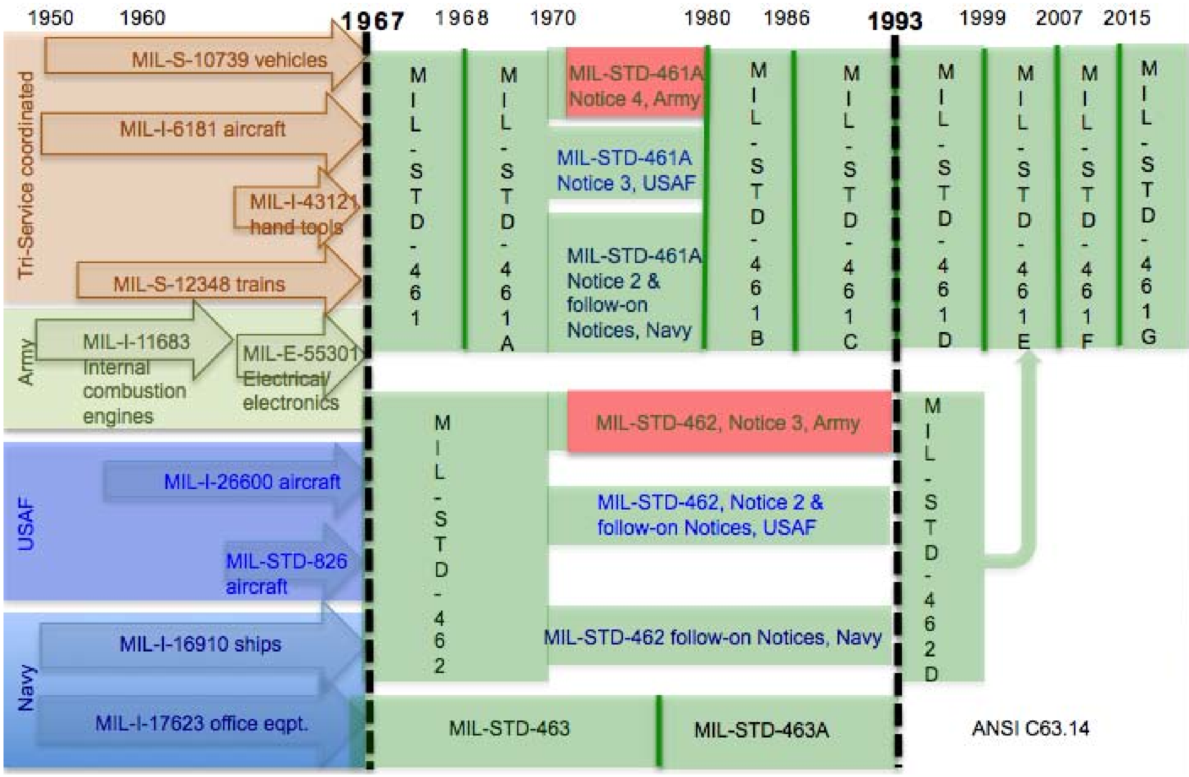
Conclusion

The purpose of this article was to chronicle changes in military EMI requirements over the past fifty years. But some things never change. In the reference cited in footnote 10, Solar Electronics founder and ex-Stoddart Aircraft Radio Company employee Al Parker provided the following description of early practitioners in the field of measuring EMI: "In those early days … the technicians involved were often described as misfits and malcontents." That description remains apt.

Even though the original MIL-STD-461/2/3 wasn't optimal, having one standard versus several was/is a huge advantage. That being said, in 1980, when the author got involved with military aerospace EMC, if an equipment failed MIL-STD-461, especially emissions below 150 kHz, it was difficult to explain to program management the need for expensive rework and retest, except that "we have to meet the contractual requirement."

For the last twenty-five years, we have been blessed with a single standard which we can stand behind or tailor intelligently, knowing why it is written as it is. Is it perfect? The five-year review cycle, which requires no revisions – only review – has resulted in a new revision each cycle, so the question of perfection must be answered in the negative. But the revisions have been minor evolutionary "tweaks" compared to the major revolution of 1989.

In 1993, after the release of MIL-STD-461D/-462D, the author was able to tell John Zentner, "For the first time, I am proud to work in the world of military EMC."



A brief timeline of military EMI specifications and standards. Pre-1967 information is limited to those specifications/standards superseded by MIL-STD-461 and is greatly abridged.

Acknowledgement

The author gratefully acknowledges review comments from several experienced EMC engineers, in the trenches since at least the MIL-STD-461A days. Any errors of omission or commission are solely the author's responsibility.

Bio: Ken Javor has worked in the field of military and aerospace EMC for close to forty years. For the last twenty years, he has been an industry representative to the DoD Tri-Service Working Groups writing MIL-STD-461 and MIL-STD-464. He has his own consulting and testing business, and may be contacted at ken.javor@emccompliance.com.

Full size figures/photos on following pages:

Figure 1*:* *Stoddart Aircraft Radio Company manually tuned receivers, 1950 – mid-'60s.*

Figure 2: *Empire Devices NF-105 manually tuned receiver with plug-ins, 1950s – 60s*

Figure 3: *AN/BRR-3, Polaris class submarine vlf receiver. Polaris class submarines carried sea-launched, nuclear-tipped ballistic missiles. The AN/BRR-3 received instructions to launch Armageddon.*

Figure 4: *EMCO 6640 magnetic field intensity meter, circa 1964*

Figure 5: *Stoddart chart recorder to be used with Figure 1 receivers to generate plotted data.*

Figure 6: *Susceptibility signal sources using cavity-tuned oscillators, mainframe and separate plug-ins. Plug-ins show that tuning and coupling was all done mechanically. At the end of a long day of CS02 and RS03, the technician's hands were callused and cramped.*

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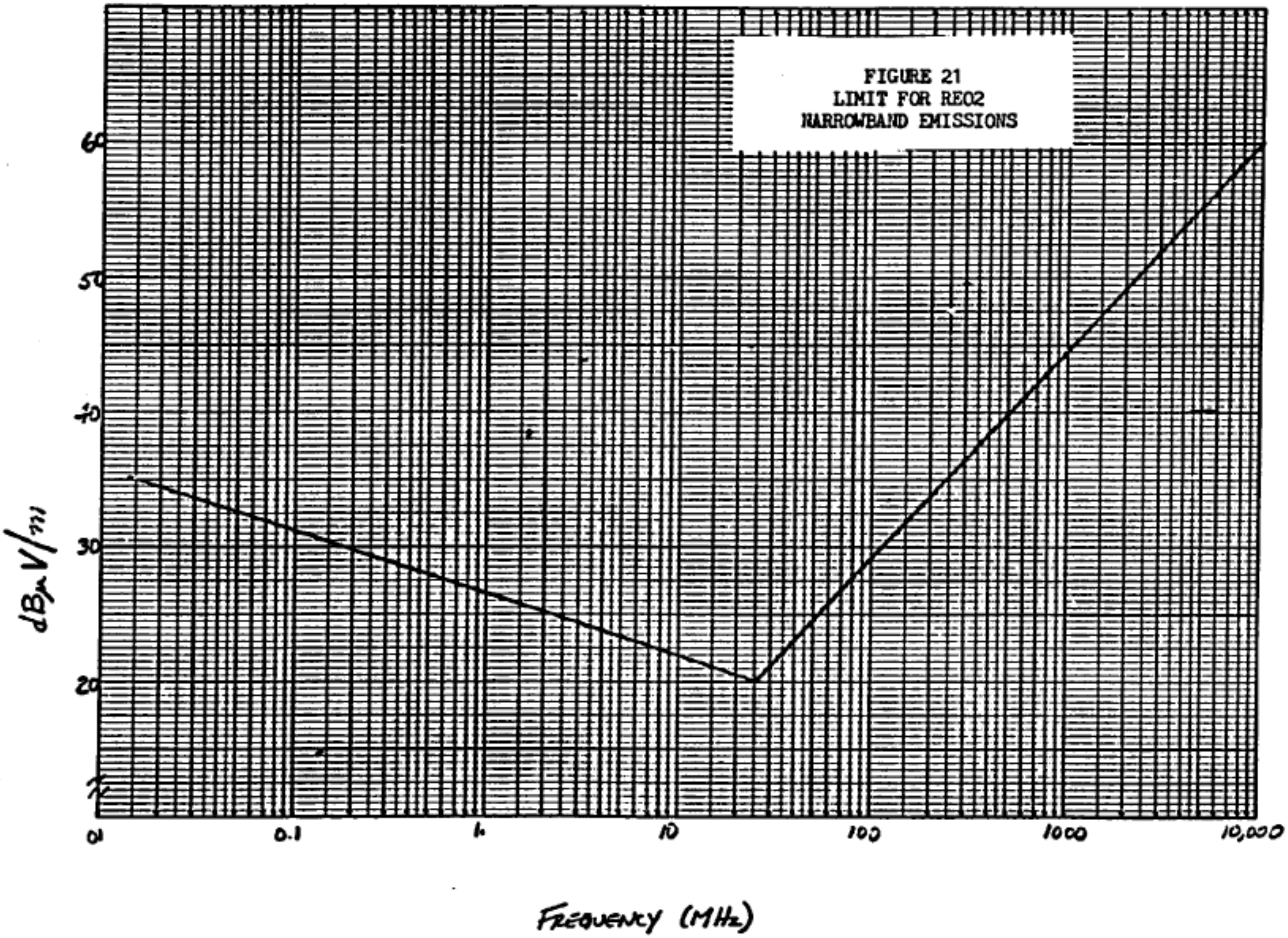


Figure 8a: *MIL-STD-461 RE02 NB limit*

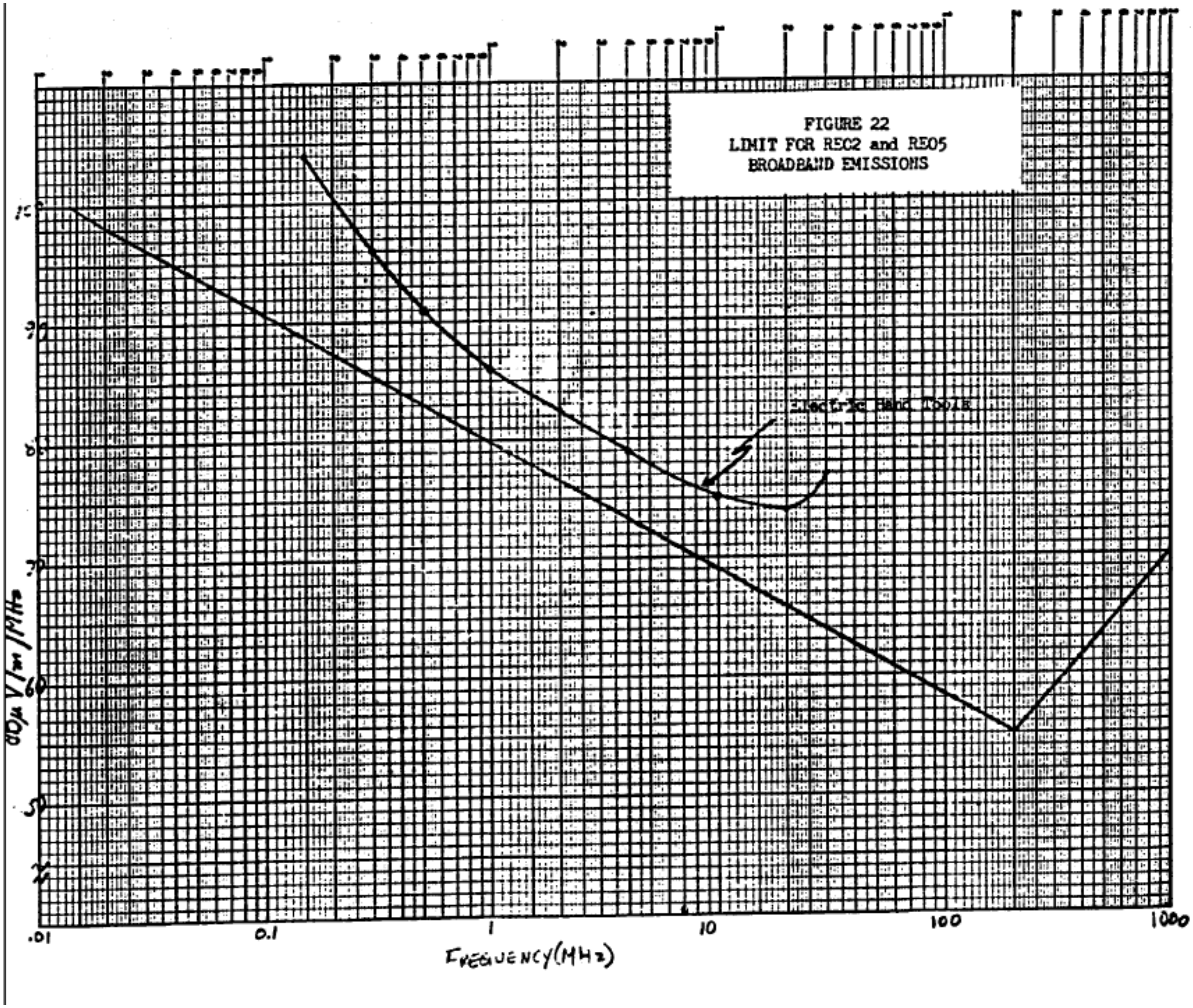
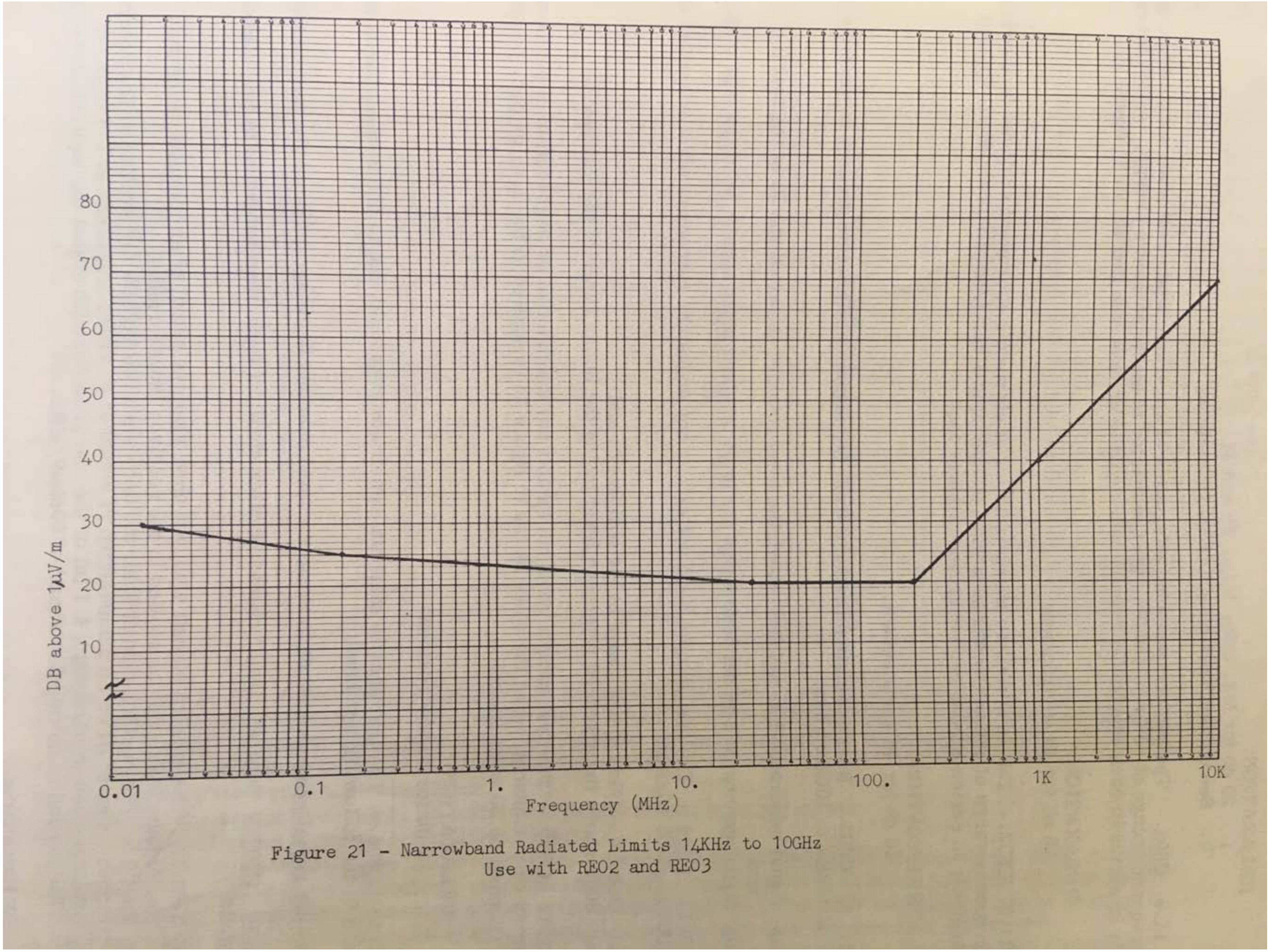


Figure 8b: MIL-STD-461 RE02 BB limit



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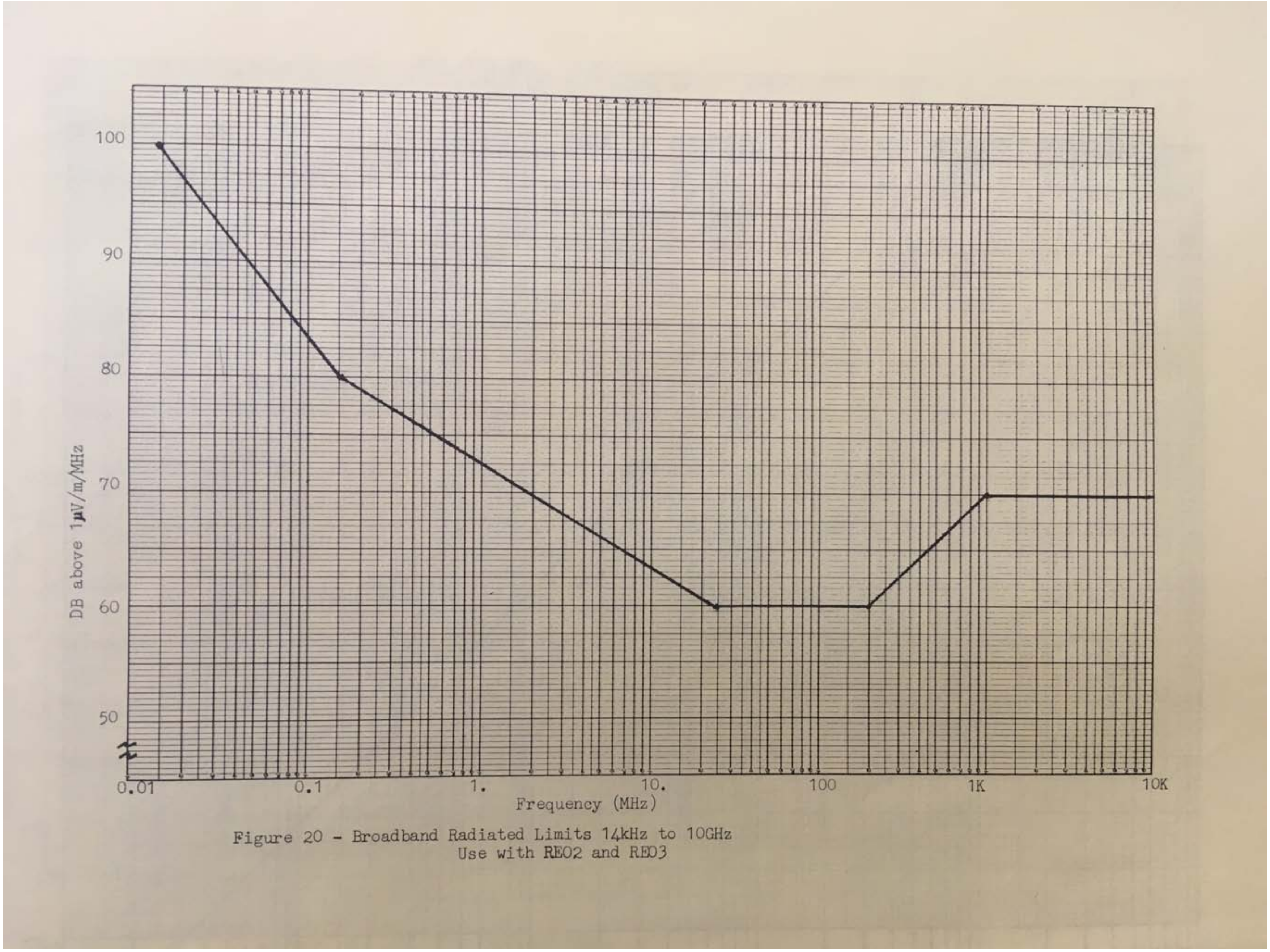

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