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Historical Analysis of Electromagnetic Interference Limits

APRIL 1967

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AIR FORCE SYSTEMS COMMAND
LOS ANGELES AIR FORCE STATION
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HISTORICAL ANALYSIS OF ELECTROMAGNETIC INTERFERENCE LIMITS

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FOREWORD

This report is published by the Aerospace Corporation, El Segundo, California, under Air Force Contract No. AF04(695)-1001.

This report, which documents research carried out from October 1966 through January 1967, was submitted on 9 June 1967 to Capt Ronald J. Starbuck, SSD(SSTRT), for review and approval.

Approved

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Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

Ronald J. Starbuck, Capt, USAF
Chief, Space Environment and
Electronics Branch

ABSTRACT

Limits currently used by military specifications for control of electromagnetic interference and susceptibility are uniformly based on tests which were conducted many years ago on aircraft voice communication equipment in typical aircraft installations, and do not necessarily relate to present requirements of space systems.

This paper examines the development of interference and susceptibility limits in various military specifications indicating the technique by which the limits were derived, the rationale for such derivation, and the changes in various limits with time since their original formulation. It also discusses certain inconsistencies within and among the limits of the various specifications.

The evaluation of the status of this field practically dictates that a study should be initiated to realistically formulate a theoretically and empirically valid set of interference and susceptibility limits to fit the needs of modern, complex systems in crowded, electromagnetic environments.

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1. INTRODUCTION

Within the past few years, there has been a great deal of activity in the generation of new interference specifications which, to a certain extent, have made a break with their predecessors. This trend was started by Mil-Standard-826 in 1964 (and its subsequent revision in 1966) and by the issuance of the proposed Military Standards 461 and 462. The changes in these specifications are not merely ones of organization and methods of testing, but apply to the test limits themselves. Such changes in limits lead one to question why the changes were made and, further, how the original and present interference limits were generated. To provide answers to these questions, a study was conducted to compare the various military department's interference limits, determine the degree of commonality among these limits, and see whether a reasonable criterion might be established to evaluate particular interference limits. It was necessary to trace the formative steps of establishment of interference and susceptibility limits. A continuing picture is presented of the evolution of interference limits to meet the increasingly severe conditions of crowded, electromagnetic environments.

The following paragraphs present the historical development of interference and susceptibility limits, both conducted and radiated, and describe the empirical and theoretical rationale for formulation of such limits to meet electromagnetic compatibility requirements of present-day systems design.

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2. EARLY ELECTROMAGNETIC INTERFERENCE SPECIFICATIONS

One of the earliest electromagnetic interference specifications was the joint Army/Navy specification JAN-I-225 (Ref. 1) of June 1945. This specification set forth no interference limits, but merely prescribed methods of measurement over the frequency range of 150 kilohertz (kHz) to 20 megahertz (MHz).* It was used in conjunction with specification AN-I-27, which was established as an early criterion for control of interference in aircraft electrical systems.

These documents provided for measurements of conducted and radiated interference, the latter utilizing both a rod antenna and a loop probe. The rod antenna was to be located at a distance not greater than one foot from the nearest point of the test sample; the loop probe could be put in actual physical contact with the test sample, since the test consisted of probing the equipment and wiring to obtain the maximum indicated level of interference, which was then compared to a sine-wave signal injected into the receiver. Such measurements introduced many variables dependent upon the position of the probe and upon the noise versus sine-wave sensitivity of the receiver; the criterion of success or failure of a measurement was a function of the operator's skill in handling the probe.

AN-I-27 was superseded by AN-I-42 which was, in turn, superseded in June of 1950 by Mil-I-6181 (Ref 2). This last specification contained specific interference limits for the particular measurements required by JAN-I-225. In addition, susceptibility tests and limits were established. Radiated interference limits were defined in terms of equivalent input microvolts for particular measuring instruments over the applicable portions of the frequency range.

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*The hertz (Hz) is used as a supersession for the cycle(s) per second (cps)

In general, these limits appeared to be at the threshold of equipment sensitivity, i.e., the limit represents the minimum discernible signal of the particular receiver used to establish the limit. The limits were not differentiated for broadband or continuous wave (CW) measurements, and the instrument was merely operated in a wideband position when making broadband measurements.

In evaluating these specifications, the historical context must be kept in mind, as well as the intended use of the documents. They were to apply only to aeronautical equipment for the Army/Air Force and Navy, and were directed toward the control of interference to voice communication receivers operating in the frequency range of 2 to 30 MHz. Such receivers were connected to an aircraft long-wire antenna via an unshielded lead-in which was run within the fuselage of the aircraft. The receiver would thus be extremely susceptible to interference picked up via this lead-in, and all interference reduction efforts were directed toward reducing any radiated energy in this frequency range within the aircraft, which might be picked up by the affected receiver antenna lead-in. It should also be noted that little by-passing or filtering was provided on power leads to receivers, and, in many cases, as little as 10 to 20 millivolts (mV) of interference coupled to these power leads could cause undesired or unintentional responses in the receiver. The constant possibility of such responses furnished the rationale for conducted interference and susceptibility measurements on power leads and led to a further rationale for radiated interference measurements. The antenna lead-in represented a high impedance antenna and, as such, was primarily responsive to high impedance fields; it was for this reason that the rod antenna was chosen as the most realistic type of antenna to be used for radiated interference testing.

Early in 1950, one of the first Tri-Service Committee approaches to a unified interference specification was attempted. This Committee, reporting through the Interference Reduction Panel of the Research and Development Board to the Defense Supply Management Agency, was charged with developing a proposed Military Standard No. 225 to standardize interference measurement techniques among the three military agencies. In January of 1953, this Committee produced a draft of the proposed Mil-Std-225, but it was never officially approved by the three departments. The Bureau of Ships made some modifications to the content and issued it as Mil-I-16910, (Ref. 3), while Wright Air Development Center and the Navy Bureau of Aeronautics generated another version as the basis for revision of Mil-I-6181, which resulted in Mil-I-6181B (Ref. 4) in May of 1953.

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3. INTERFERENCE LIMITS

3.1 RADIATED INTERFERENCE LIMITS

The radiated interference limits in Mil-I-6181B reflected the awareness that suitable differentiation in terms of the bandwidth of the measurement instrument must be made between the limits for broadband and CW interference. Thus, while curves of the equivalent input microvolts (μV) and correction factor curves for pulse repetition rate were given for particular instruments; standard interference limits, in terms of microvolts and microvolts-per-kilohertz bandwidth of antenna-induced voltage for the standard 41-inch rod and dipole antennas, were also given.

Reference 5 discusses the derivation of the interference limits of Mil-I-6181B and describes the testing upon which the limits were based. Briefly, a BC-348Q airborne radio receiver, part of the AN/ARC-21 (with a sensitivity of 5 to 7 μV over the 200 kHz to 18.0 MHz frequency range), was installed inside a shielded room with a 24-inch lead to a 12-foot straight-wire antenna located outside the shielded room to simulate the aircraft set-up; it should be noted that the 24-inch lead was unshielded, as is typical of antenna lead-ins for aircraft at that time period. Various types of radio interference sources, such as dc motors, poorly shielded dynamotor cables, and adjustable output ignition sources, were installed at a distance of one foot from the lead-in. At those frequencies where the interference sources happened to produce an interference signal which was slightly above the background level of the receiver within the shielded room, a measurement was made by means of the newly developed AN/PRM-1 interference instrument (NM-20A) with a rod antenna located one foot from the noise source. The measurement was taken as an approximation of the desired broadband radio interference limit. Figure 1 shows these test values and the broadband limit itself, plotted in terms of the standard antenna-induced voltage in decibels (dB) above one microvolt per megahertz (μV/MHz) bandwidth. It is to be noted that the interference limit was taken to be from 5 to 17 dB less than the test values, except at the higher frequency where one test value actually appears at the test limit itself. Shown on this figure is the background level of the AN/PRM-1 receiver (NM-20A); this is contrasted with the earlier limit of Mil-I-6181, which was roughly at the level of receiver sensitivity.

Also shown in Figure 1 are the further extrapolations of the broadband limits in subsequent specifications. Mil-I-006181C, Mil-I-26600 (Ref. 6) and Mil-I-6181D (Ref. 7) refined the Mil-I-6181B curve by resolving it into two straight-line segments, which raised the limit from 3 to 6 dB and extended it to 25 MHz from its former 20-MHz end point. Based upon various test data which indicated that the particular limits might be too restrictive, Mil-Standard-826 (Ref. 8) relaxed the limits by as much as 30 dB across the frequency range and added the refinement of expressing the limit in units of field intensity, as had been done by Mil-I-16910 (Ref. 9); the value in Figure 1 is the correlated antenna-induced level.

To illustrate the evolution in thought, it might be mentioned that Reference 5 stated that pulsed CW signals were not to be considered as broadband interference but, rather, as associated with the CW limits. However, both Mil-I-6181B and its subsequent replacements treated pulsed CW as broadband interference. Mil-Std-826 reverted to the original concept of treating such signals as CW interference. The CW limits in the 0.15 to 20 MHz frequency range in Mil-I-6181B were taken to be numerically equal to the broadband input microvolt limits as corrected for the bandwidth of the AN/PRM-1 measuring instrument. Figure 2 shows these CW interference limits as determined for Mil-I-6181B, in contrast to the earlier limits of Mil-I-6181 and the later limits of Mil-I-26600, Mil-I-6181D, and Mil-Std-826.

An academic argument could be made, and often has been, that "field intensity" is not a proper term to use in describing the phenomenon being measured and that "antenna-induced voltage" is much more descriptive of that phenomenon. Field intensity is generally defined as a measure of the intensity of the electric

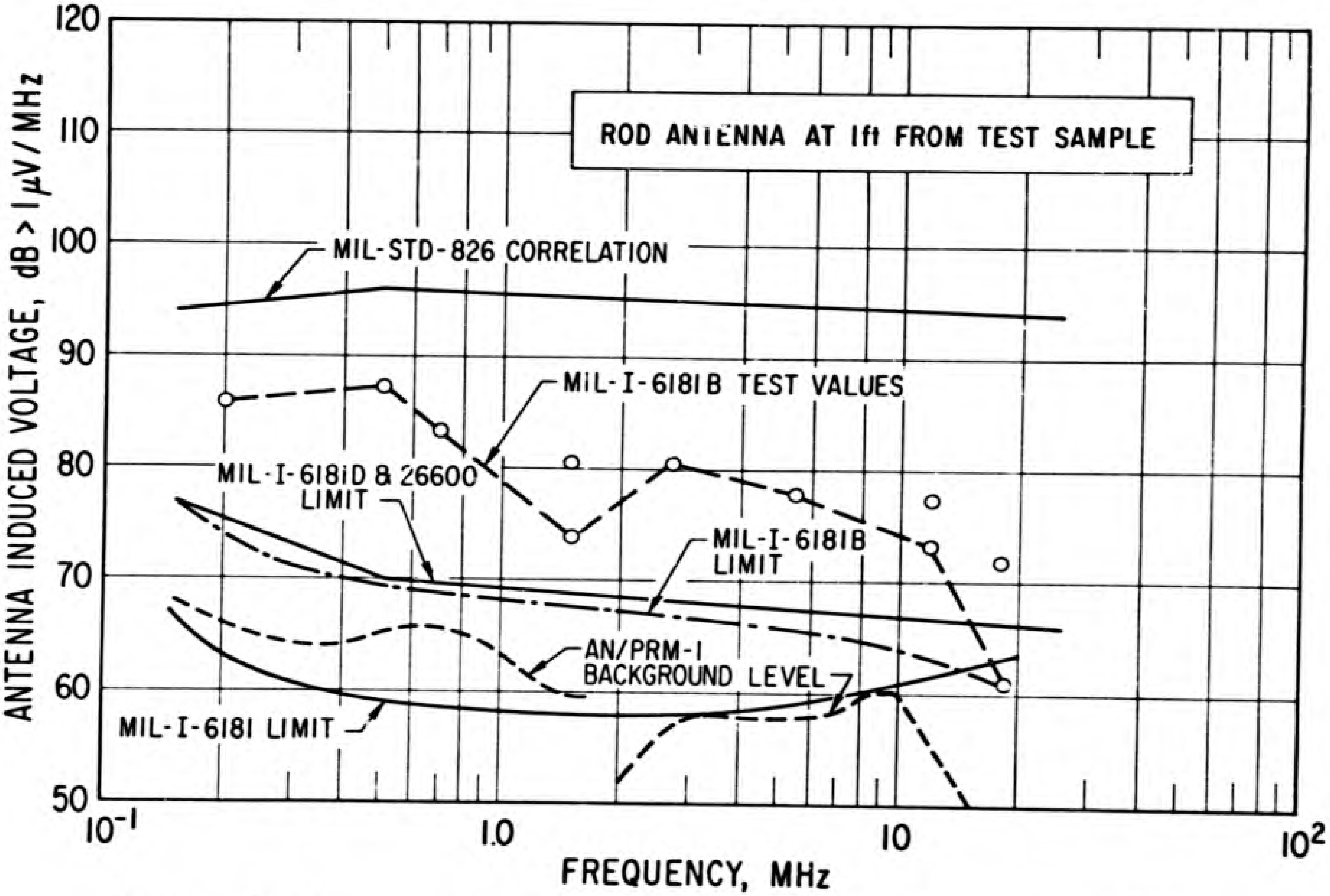

Figure 1. Development of Broadband Radiated Interference Limits (0.15 to 20 MHz)

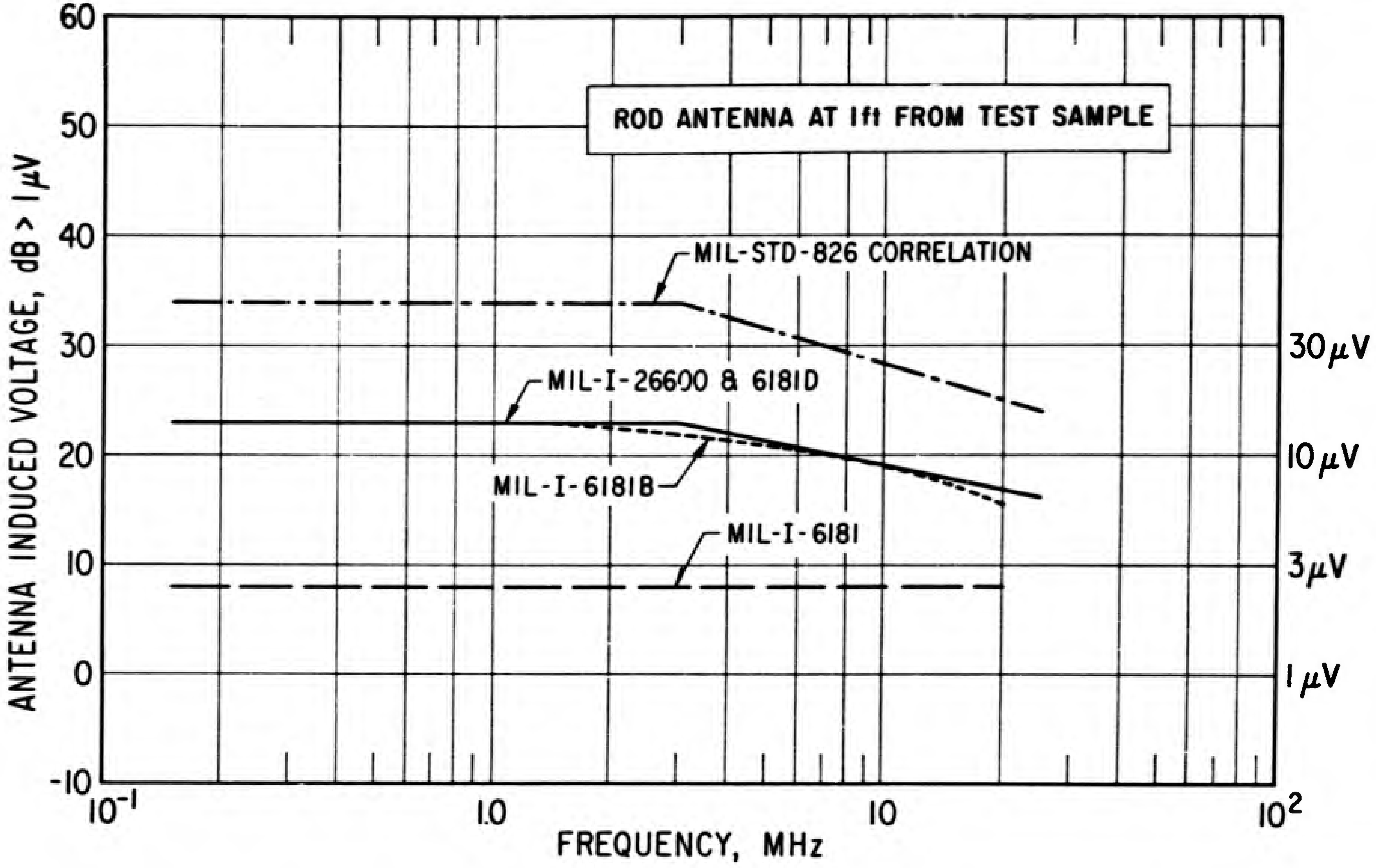

Figure 2. Development of CW Radiated Interference Limits (0.15 to 20 MHz)

field; the term implies that the measured electric field gives a valid indication of the power density in the wave front, and permits an estimate to be made of the power coupled into a receiving antenna. Such an estimate is valid only in the far field where the plane wave phase relationships of electric and magnetic fields are fixed. Thus, the measurement does not give a valid indication of power coupling.

Field intensity is also defined as the voltage induced in a conductor one meter long when held so that it lies in the direction of the electric field and at right angles to the direction of propagation and to the direction of the magnetic field. It can be argued that the equipment near-field does not have a uniphase front, and so the straight rod or dipole antenna will not necessarily be in the direction of the electric field. These near-field effects become even more marked at the higher frequencies where horn and parabolic reflectors are used.

The term field intensity should refer to a phenomenon which is independent of the measuring instrument rather than, as in the present case, being so highly dependent upon the particular antenna used. The phenomenon measured is not the actual electric field of the wave front, but consists of indications of partial components of that wave front in the near-field of the test sample. A better name for the phenomenon would be "apparent field intensity", but, as long as there is no confusion as to what is being measured, the name given to the phenomenon is not of great importance.

In Mil-I-6181B, the dipole antenna was used above 20 MHz, and the broadband limit represented the maximum allowable open-circuit voltage which could be induced in a resonant dipole from the broadband interference source under test. The levels were determined by adjusting the interference source to provide a threshold which was just equal to the old limits of Mil-I-6181 as read on the least sensitive instrument in use, and then measuring the interference on an instrument of known bandwidth which was capable of peak measurements. The measurements of broadband impulsive interference were required only to 150 MHz, since this was the upper frequency limit of the interference instruments utilized at the time, (typically, Measurements Corp. Model 58). By the time of the development of Mil-I-26600, interference problems with aircraft ignition systems had been encountered up to 400 MHz, and, since instrumentation was then available (AN/URM 7 or NF-105), the broadband limit was extended to that frequency.

The CW limits in this frequency range represent the conversion of the broadband limits in terms of the instrument bandwidth. Figures 3 and 4 illustrate the broadband and CW radiated interference limits above 20 MHz.

In Mil-I-26600, the frequency for CW and pulsed CW radiated interference was extended from 1 gigahertz (GHz) to 10 GHz, and a newly developed field intensity meter (FIM) was called out as the applicable measuring instrument. Initially, the limit was defined in terms of microvolts at the instrument input, but this was changed to be defined in terms of field intensity. As a rationale for development of the criterion, the limits of Mil-I-6181B for the dipole antenna at 1 GHz in terms of antenna-induced voltage (which were based upon the earlier limits of Mil-I-6181 and were essentially interference meter noise levels) were converted into terms of field intensity, assuming free-space propagation conditions. That level was then taken as a constant allowable limit of apparent field intensity over the range of 1 to 10 GHz, with the antenna positioned 3 feet from the test sample. Of course, the dipole antenna at 1 GHz was positioned only 1 foot from the test sample, which resulted in an inherent 9 to 10 dB error in the correlation between the two limits.

In 1959, the author presented a paper (Reference 10) on the development of interference limits on a system basis. A test was described in which a -90 dBm receiver mounted in a given multi-engine aircraft was used as a reference for an interference limit from 1 to 10 GHz. Based on that receiver with a given antenna and the measured/theoretical aircraft shielding

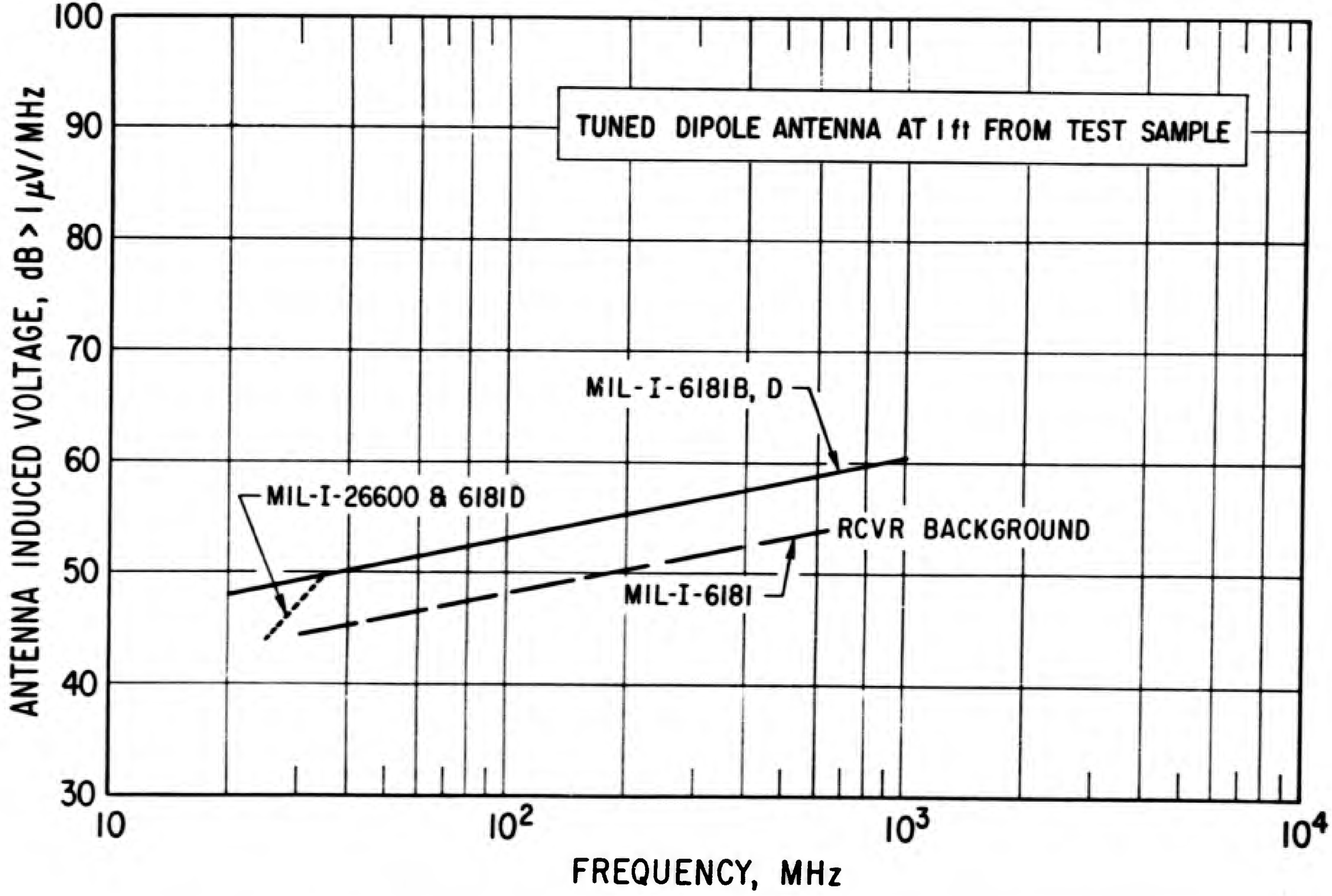

Figure 3. Development of Broadband Radiated Interference Limits (30 MHz to 1 GHz)

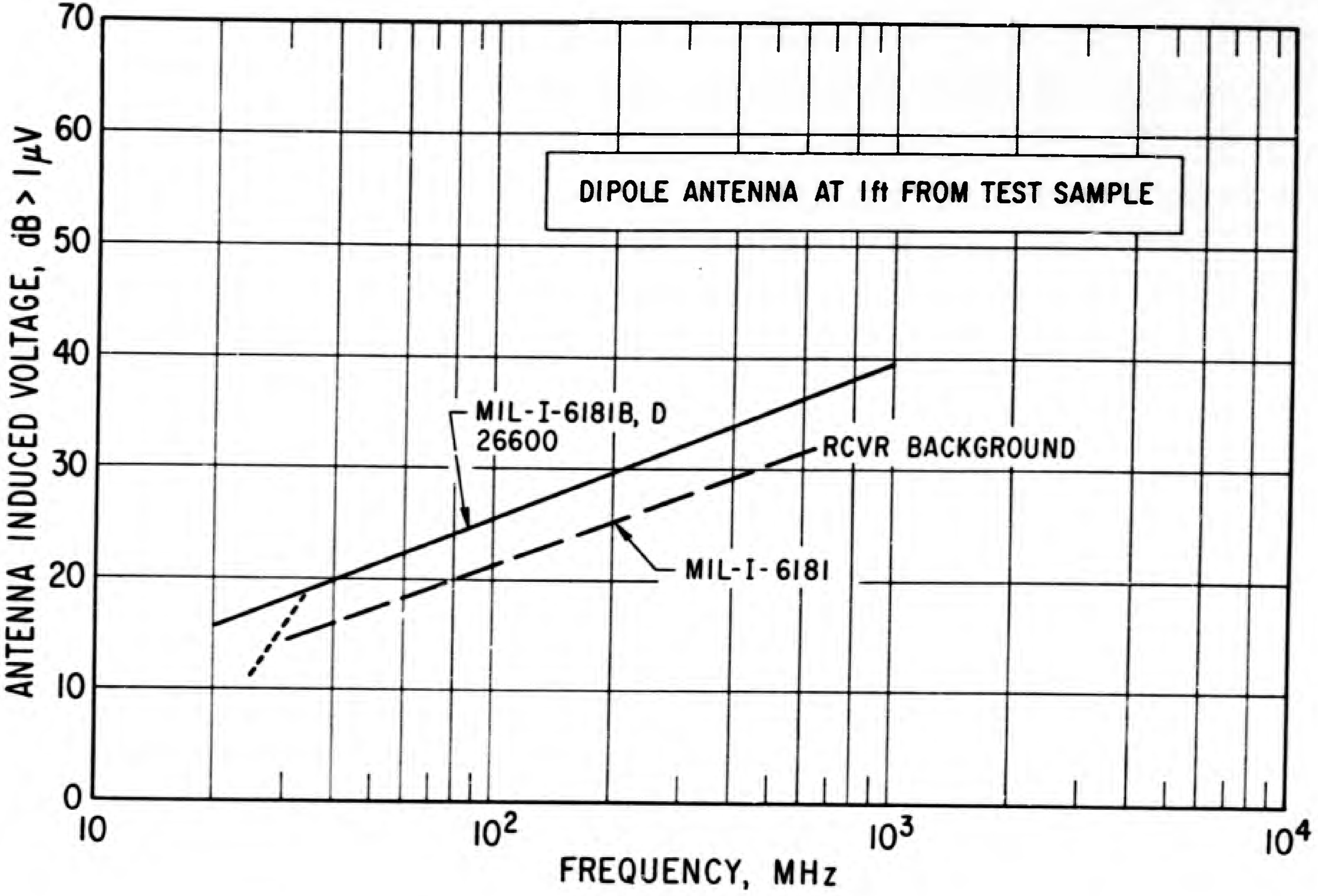

Figure 4. Development of CW Radiated Interference Limits (30 MHz to 1 GHz)

effectiveness, an interference limit was derived bearing a striking resemblance to that of Mil-I-26600, with a total variation of no more than 8 dB. The point is not that the limit of Mil-I-26600 is a "good" limit or necessarily valid, but that it is a reasonable limit for the condition of a typical -90 dBm receiver in an aircraft. It is not necessarily a "good" or valid limit for a -120 dBm or -150 dBm receiver in an aircraft or spacecraft nor for other receivers in different installations or environments.

Summarizing the information contained in the preceding figures and relying on the various conversion factors and curves presented in Reference 11, Figures 5 and 6 show the radiated interference limits of various military interference specifications in terms of apparent field intensity for broadband and narrowband interference corrected for a 3-foot measuring distance. These figures show the limits for the proposed Mil-Std-461 (Ref. 12), as well as those currently in use on some space programs (Ref. 22). It will be noted in Figure 5 that there is a sharp discontinuity of as much as 50 dB in the radiated interference limit at the 25-MHz crossover point for specifications such as Mil-Std-826 and Mil-I-618D. A similar discontinuity is shown on Figure 6 but the magnitude is far less, being on in the order of only 10 to 20 dB. If the quantity being measured is truly field intensity, which, as stated before, is a phenomenon of the field external to the antenna and not a function of the antenna itself, then no differential in field intensity should exist when the field is sampled by two different types of antenna. It has been said that the discontinuities in the interference limits are due to antenna polarization effects, since radiation from equipment in the lower frequencies is predominantly vertically polarized due to the relationship of the equipment with respect to the ground plane. For such vertical polarization, the rod antenna would provide very good coupling, while a horizontal dipole would have poor coupling. Such an approach may be admirable in theory, but, empirically, that portion of the interference limits most difficult to meet is in the area of the crossover between the rod and the dipole antenna, wherein the dipole limit appears unduly restrictive. Additionally, the discontinuity is, as mentioned before, only 10 dB for CW interference as opposed to 50 dB

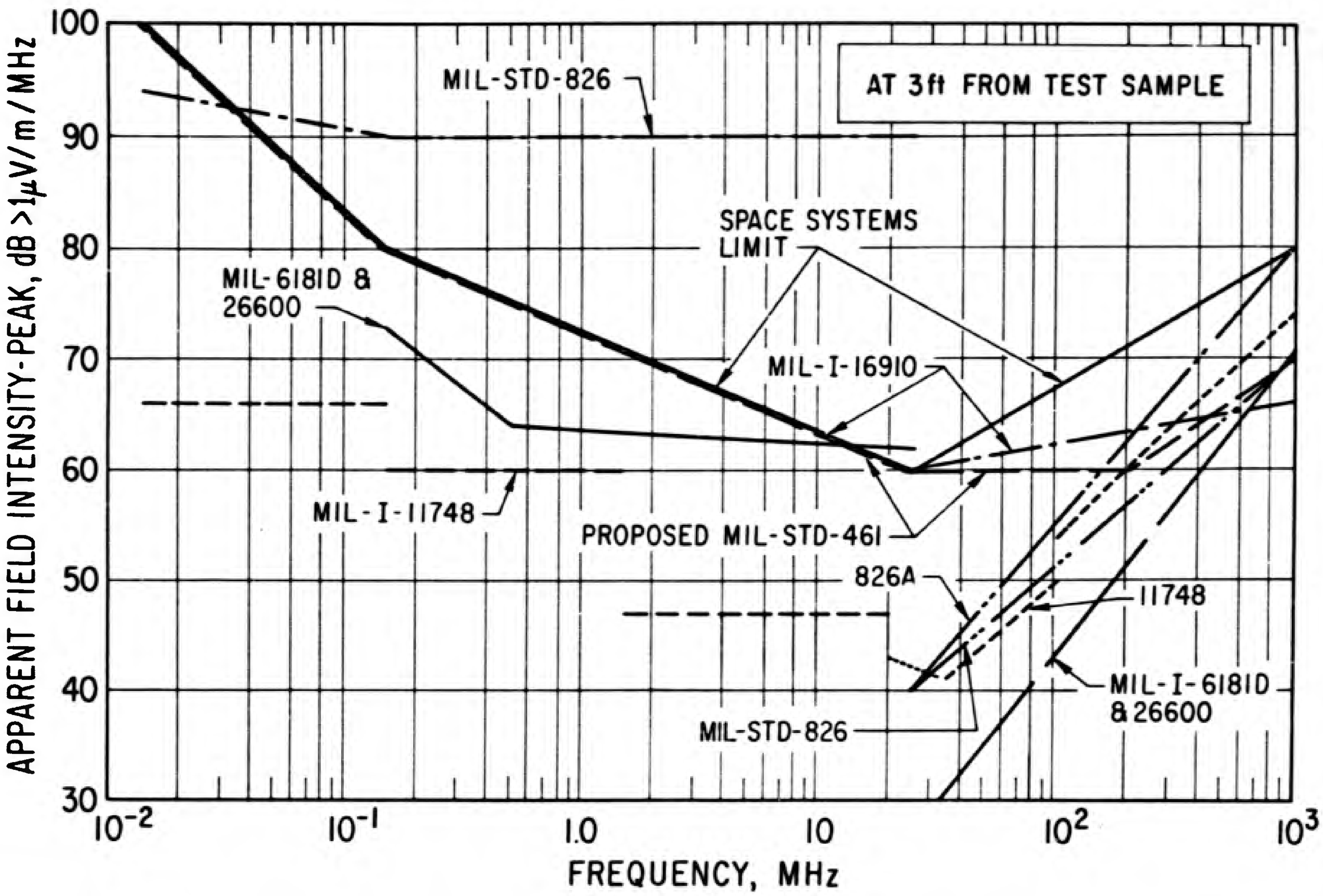

Figure 5. Comparison of Military Interference Specification Limits for Broadband Radiation

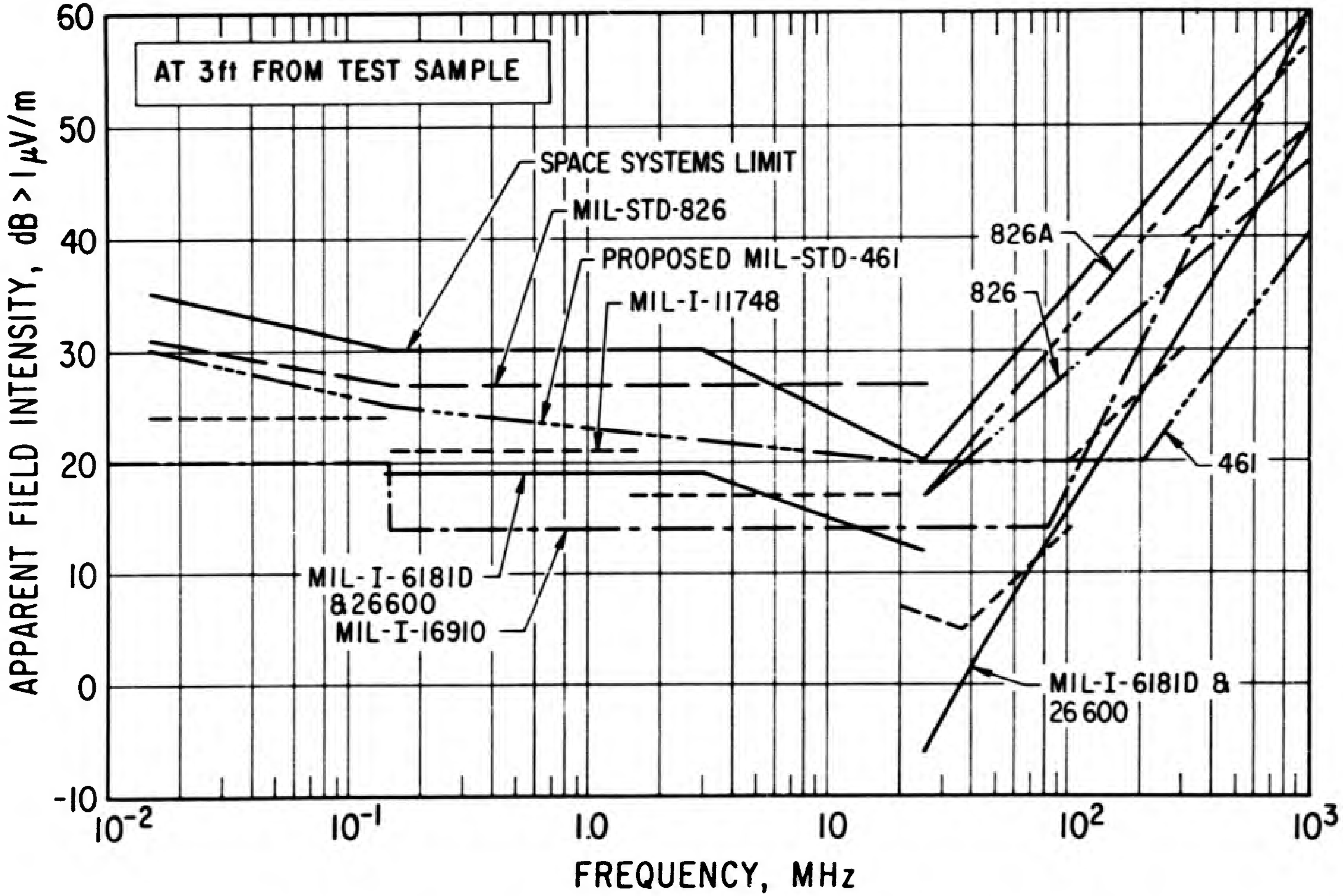

Figure 6. Comparison of Military Interference Specification Limits for CW Radiation

for broadband interference; if the differential is due only to polarization differences, it should be a constant differential regardless of the periodicity of the field being measured. Mil-I-16910 has never observed a discontinuity in limits, and the new Mil-Std-461 similarly uses a continuous curve for radiated interference limits.

Historically, there has been a steady upwards revision in the tolerable levels of radiated interference. The specification limits have been based on voice communication receivers with sensitivities in the range of -95 dBm in typical aircraft installations; the earliest limits were based on tests with VHF receivers and, from time to time, other tests have been done in UHF and in the S, C, and X bands. The limits thus derived are not necessarily applicable to the needs of space systems or highly sensitive receivers operating in other systems, but are largely arbitrary, even though following an historical evolutionary development. The relationship between successfully meeting this interference criterion and the achievement of system electromagnetic compatibility (EMC) has never been clear.

3.2 CONDUCTED INTERFERENCE LIMITS

The conducted interference measurements required by specification JAN-I-225 over the range of 150 kHz to 20 MHz utilized the test set-up illustrated in Figure 7. The test sample was mounted on a ground plane and connected by 10-foot leads to the power source whose positive side was bypassed to ground by two 4-microfarad (µf) capacitors; this had the effect of a line stabilization function and provided filtering of interference from the power source. The interference measuring instrument or meter was connected across the line at the test sample by 24-inch leads, and the test sample was connected to its load by 2-foot leads.

The limits for conducted interference specified in Mil-I-6181 were as shown in Figures 8 and 9 for broadband and CW interference; these figures also show the subsequent development of conducted interference limits for more

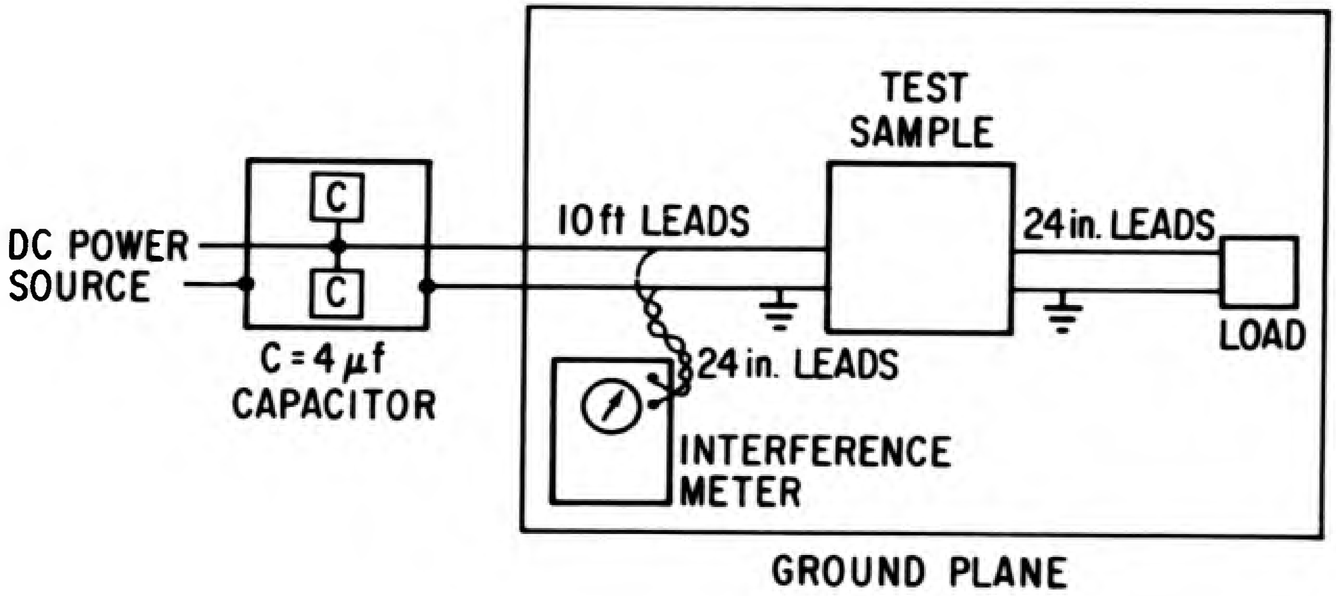

Figure 7. Test Setup for Conducted Interference Measurement per JAN-I-225

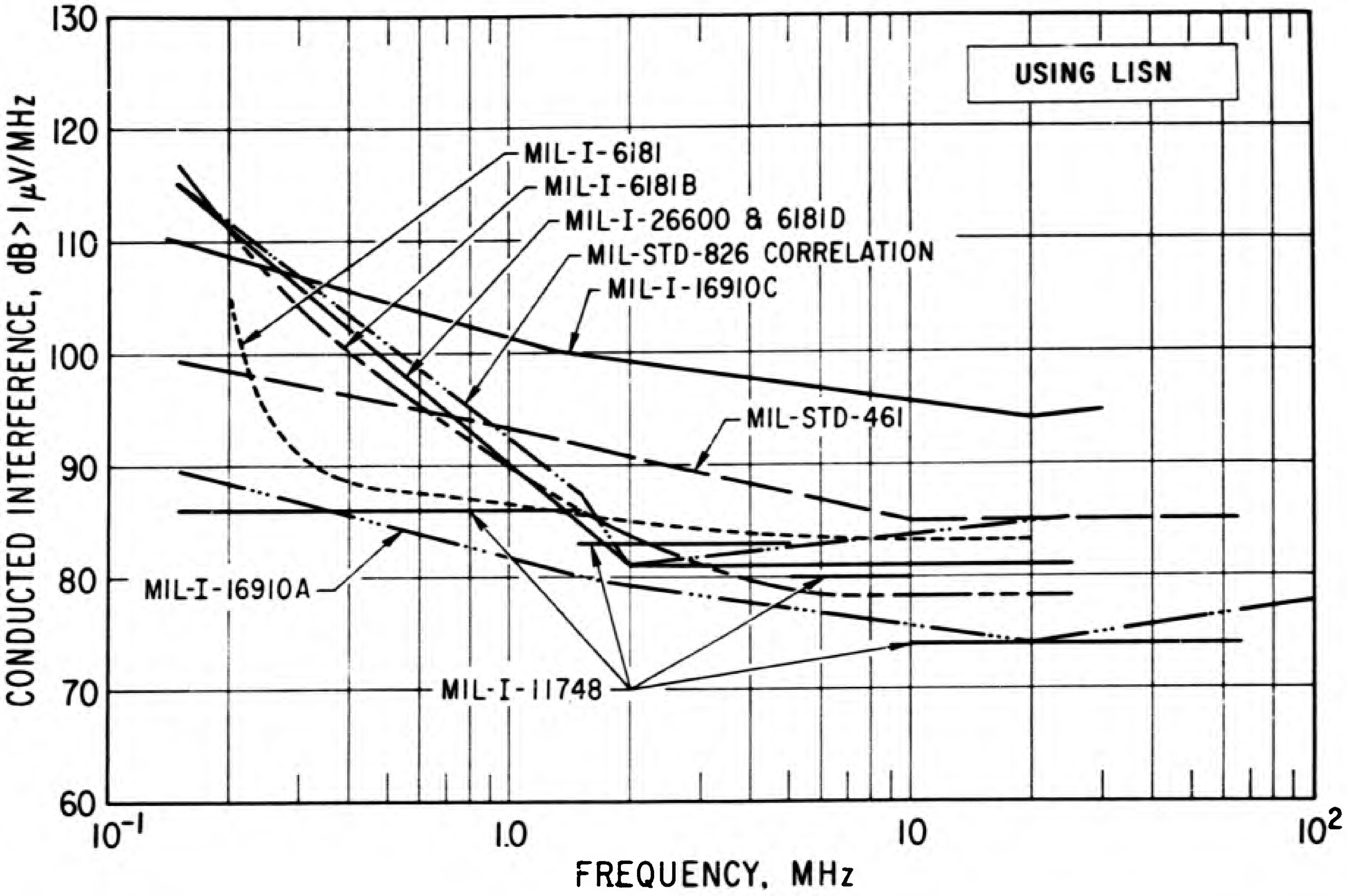

Figure 8. Development of Conducted Broadband Interference Limits (0. 15 to 25 MHz)

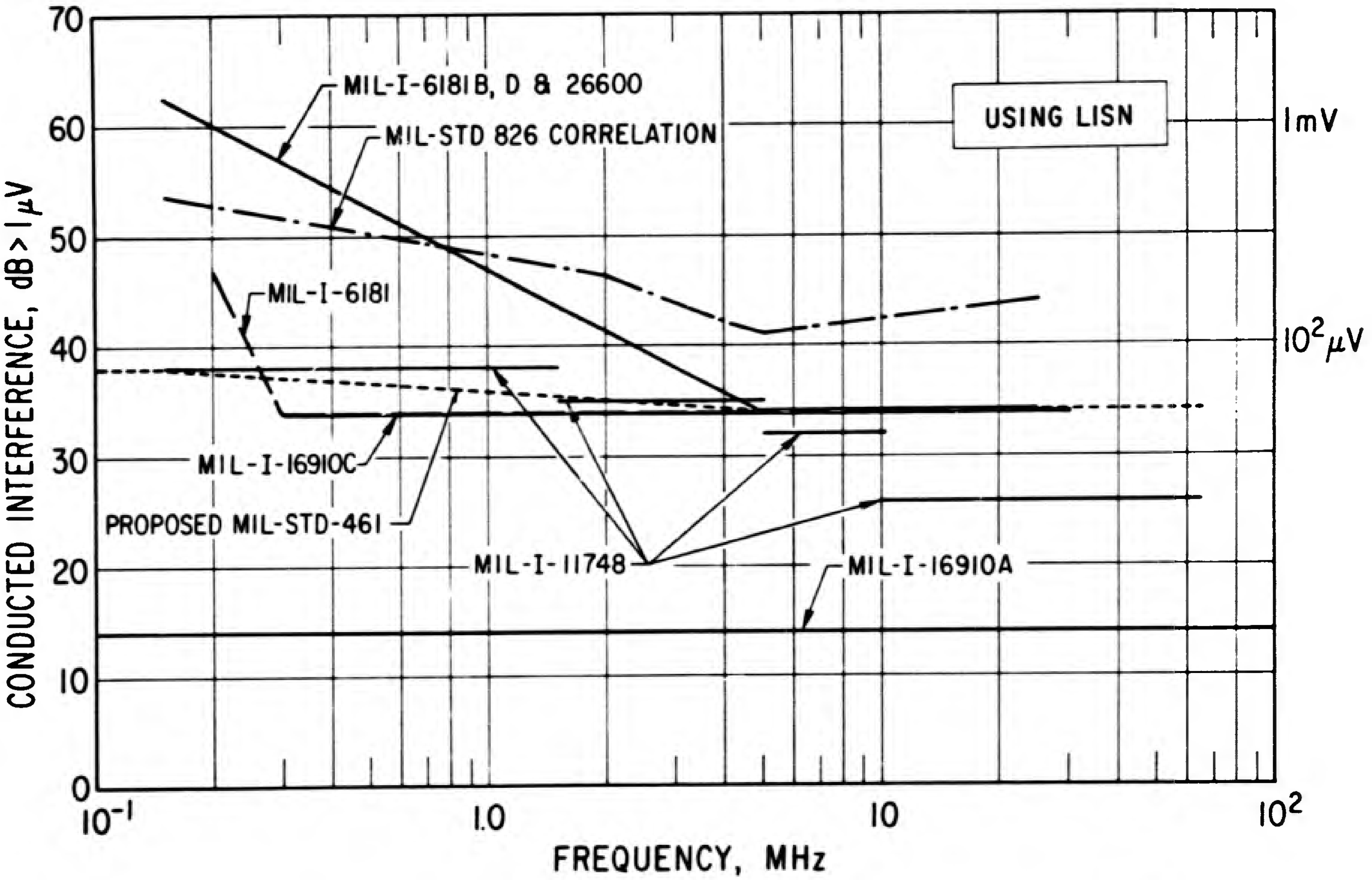

Figure 9. Development of Conducted CW Interference Limits (0.15 to 25 MHz)

recent specifications. The conducted interference limit was based (as was the radiated limit) on the rationale of an open-wire antenna lead-in to a voice communication radio-receiver. The test set-up used a radiating wire placed near the antenna lead-in; the level of signal in the radiating wire, just sufficient to cause an indication in the receiver, was indicated as the interference limit.

Early in 1950, the Line Impedance Stabilization Network (LISN) was developed, based on measurements of typical aircraft power lines indicating an impedance of a few ohms (Ω) in the area of 150 kHz, increasing to ~ 50 Ω at the higher frequencies. The network was developed with an impedance of 4.5 Ω at 150 kHz, increasing to 50Ω at 5 MHz. The previous 8 μf of capacitance from power line to ground of JAN-I-225 was replaced in the LISN with 1 μf in series with a 1Ωresistor, both in parallel with a 5-microhenry (μH) choke. At the higher frequencies, the 50-Ω impedance was supplied by the usual 50-Ω input circuit impedance of the measuring equipment. The characteristics of the LISN maintain the 50-Ω characteristic impedance relatively constant up to roughly 50 to 80 MHz; beyond this range, serious departures in the form of sharp peaks and valleys are encountered. Since conducted interference measurements in Mil-I-6181B were limited to 25 MHz, no problems were experi- with their use. However, many problems were experienced when these networks were utilized for conducted susceptibility testing.

Mil-I-6181B utilized the same conducted limit as Mil-I-6181, but, since the LISN higher impedance at the lower frequencies developed a higher interference voltage, the limit had to be raised to preserve the same interference-effect criterion. Mil-I-26600 and Mil-I-6181D changed the broadband interference limits slightly, but left the CW limit unchanged; this is shown in Figures 8 and 9. At that time, the use of the current-probe was introduced for measurements on interconnecting cables and high-current power conductors. Readings on the current-probe were correlated with those obtained utilizing the LISN to establish the current-probe limits. Mil-I-6181D did not utilize the current-probe for high-current lines, but reverted to the measurement technique utilized under JAN-I-225, except that the 8-μf capacitance was replaced by 1 μf. Since Mil-Std-826 utilizes only the current probe, the limits shown for it in Figures 8 and 9 represent an extrapolation of current probe limits as calculated for the LISN.

Also shown in Figures 8 and 9 are the limits of Mil-I-16910A and C (Shipboard) and Mil-I-11748B; the first is seen to be exceedingly restrictive compared with limits for airborne equipment. M l-I-16910C, issued in 1964, relaxed both its broadband and CW conducted interference limits by 20 dB, bringing the CW limit into accord with that of the original Mil-I-6181 and the proposed Mil-Std-461; the broadband limit is roughly 10 dB relaxed over that proposed for Mil-Std-461. The rationale for the limit relaxation has not been provided, but might have been the difficulty in suppressing equipment to meet the severe limits of Mil-I-16910A.

The Mil-I-11748B broadband limits follow closely those of Mil-I-16910A, while the CW limits are much more close to those of the newly proposed Mil-Std-461. That specification utilizes a broadband limit roughly 15 dB more restrictive than that of Mil-I-6181D at the lower frequencies and 4 to 10 dB more lenient at the higher frequencies; the CW limit has reverted to almost the original Mil-I-6181 limits, which represent a tightening up of some 20 dB at the lower frequencies.

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4. PROBLEMS OF LIMIT CORRELATION

Attempts to correlate the various interference limits (0.15 to 25.0 MHz) of the several interference specifications present especially elusive problems. As discussed earlier, most of the airborne interference limits trace back to the early limits of Mil-I-6181 and the efforts of the Tri-Service Committee in developing Mil-Std-225. Thus, one should expect to find some uniformity and standardization in certain parameters of the interference measurement. One such parameter would be the factor relating the interference effect of CW and broadband interference in terms of the affected or measuring receiver bandwidth. This factor would appear to be one on which all agencies would agree and which would be the same for radiated as well as for conducted interference. Neither expectation is realized, as is shown in Table 1. Listed in columns 1 and 2 are the range of dB differences between the broadband and CW limits for the various military interference specifications (for both conducted and radiated interference limits) over the frequency range of 0.15 to 25.0 MHz, as well as the mean value over that frequency range. While there is agreement on a mean of roughly 50 dB differential between the conducted broadband and CW limits among the various military specifications, the range of values extends over 28 dB. For the radiated limits, there is less agreement as to the mean value, and the variation increases to 38 dB over the frequency spectrum for the various specifications.

The ratio of differentials in column 3 of Table 1 for the conducted and radiated factors of columns 1 and 2 for CW and broadband interference runs from a minimum of 2 dB for Mil-I-6181D to as much as 24 dB for Mil-Std-826. When considering the mean values of columns 1 and 2, the ratios in column 4 between the conducted and radiated differentials show only a 1 dB mean variation for Mil-I-6181D and Mil-Std-461. Since the Mil-I-6181D limits are essentially those of Mil-I-6181B, in which the correlation between broadband and CW limits was provided by the bandwidth of the AN/PRM-1 measuring instruments used to establish the original limits, the close

Table 1. Differences Between Broadband and CW Limits (0.15 to 25 MHz)

	1		2		3	4
Specification	ΔdB Conducted		ΔdB Radiated		ΔdB (range) Conducted/ Radiated	ΔdB (mean) Conducted/ Radiated
	Range	Mean	Range	Mean		
Mil-I-6181 B & D Mil-I-26600	43 - 53	(48)	45 - 54	(49)	2	1
Mil-I-16910A	60 - 76	(68)	46 - 80	(63)	14	5
Mil-I-11748	48	(48)	30 - 42	(36)	18	12
Mil-Std-826	39-62	(50)	63	(63)	24	13
Mil-Std-461	51 - 61	(56)	40 - 70	(55)	11	1
	28 dB max.		38 dB max.		22 dB max.	12 dB max.

correlation seen in columns 3 and 4 of Table 1 for Mil-I-6181D is to be expected. Ideally, the differentials in columns 3 and 4 of Table 1 should be zero. However, for other military specifications (except for the mean of Mil-Std-461), no such close correlation appears, and a correlation factor different from the measuring instrument bandwidth has been used to relate broadband to CW interference.

The criterion for an interference limit should be the effect of that interference upon susceptible equipment. In the derivation of currently used interference limits, a standard airborne receiver was utilized as the reference whose bandwidth determined the tolerable level of broadband interference. When that affected equipment is replaced by sensitive equipment of wider bandwidth, the previously determined broadband interference limit may not offer sufficient protection since more interference energy will be coupled to the receiver; the CW sensitivity may not change, but the broadband sensitivity will. The early interference limits related CW to broadband interference effects by the bandwidth of a particular interference meter (AN/PRM-1), and present specifications largely continue to rely on the earlier correlation, with some deviations. It is important to recognize that an arbitrary receiver bandwidth has been utilized to establish a limit against which equipments of widely differing bandwidth characteristics are evaluated.

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5. LOW FREQUENCY CONDUCTED MEASUREMENTS

Interference measurements were not required below 0.15 MHz by the earlier interference specifications, but, with the development of large-scale complex systems such as Minuteman, the range of interference measurements was extended down to 30 Hz. Figure 10 shows interference limits from various specifications in this lower frequency region. The limit from BSD Exhibit 62-87 (Ref 13), which was the forerunner for the others, allows 100 amperes of interference current at 60 Hz and five amperes at 400 Hz. Mil-Std-826 imposes a one ampere limit out to 1 kHz, but exempts the first three harmonics of the power frequency from the measurement, as does Mil-Std-461. The NASA specification (Ref 14) differs from the foregoing approaches in that the curve pivots about the value at 15 kHz, and the lower limit is taken as the ac load at the particular fundamental frequency; several curves are shown on Figure 10 for varying values of load current and fundamental frequency. For dc loads, the curve follows that of the 60-Hz 10-amp rating, except that differing levels of dc load current will intercept the curve at various horizontal levels.

The original limit for conducted interference in the lower frequency range was derived by Boeing in its document D2-2444 (Ref 15) in February of 1959. In that document, the peak-to-peak ripple on the dc bus was restricted to 5% of the nominal dc bus voltage when measured with a wideband (20 Hz to 150 kHz) vacuum tube voltmeter (VTVM) directly connected across the dc leads. For the nominal 28-volt dc power system then common to aircraft, the 5% limitation would yield 1.4 volts peak-to-peak or 0.7 volt peak over the frequency range of 20 Hz to 150 kHz. This limitation was, in turn, based on the requirement of Mil-E-7894A (ASG), (Ref 16) which was the applicable requirement for aircraft power systems. This specification required the dc peak ripple not to exceed 2.1 volts as measured by a peak-reading VTVM in a series with a 4-μf capacitor across the power lead. Applying a 10-dB safety factor to the 2.1 volt peak limit yields the 0.7 volt requirement on allowable ripple generated by any individual equipment in the lower frequency region.

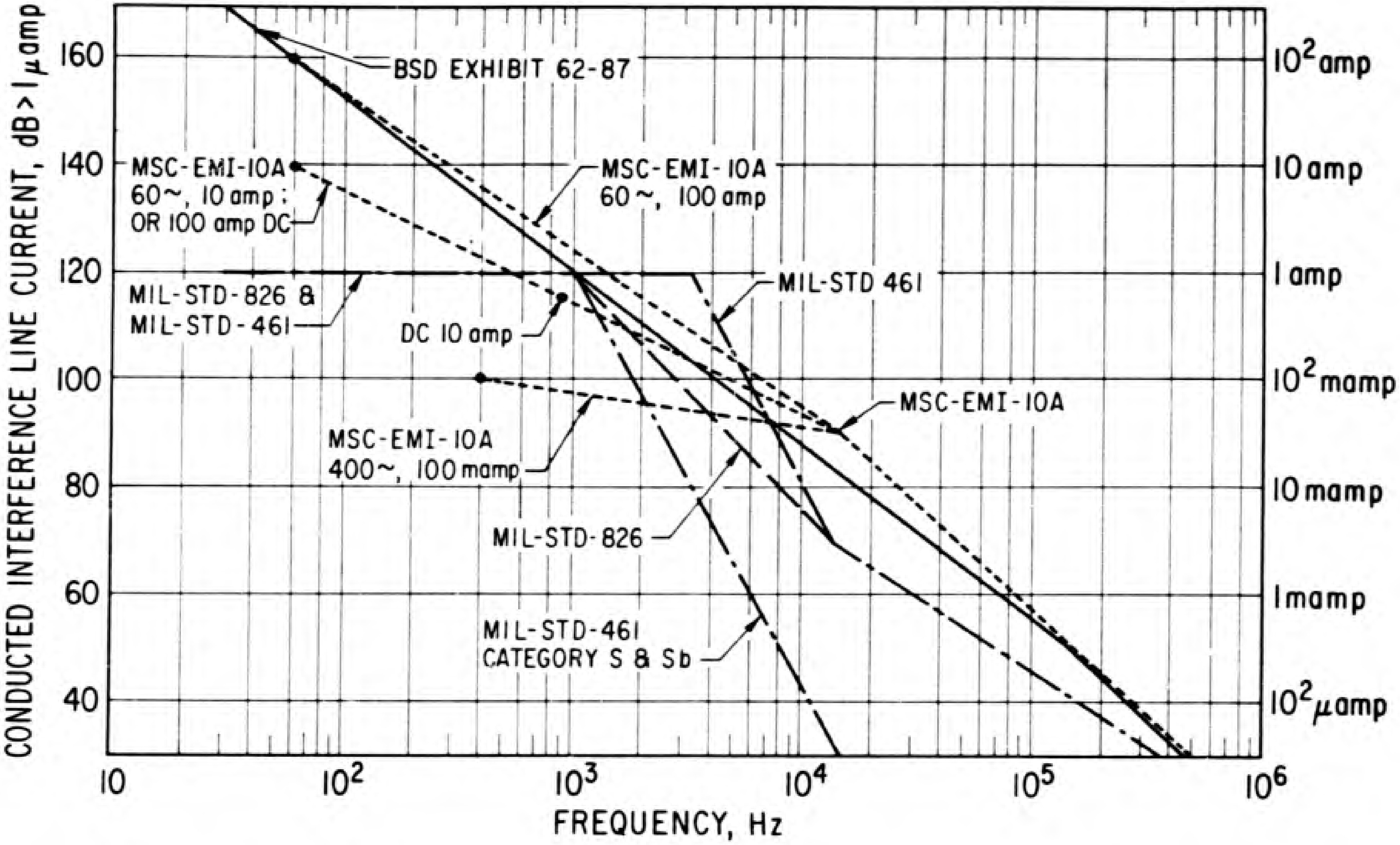

Figure 10. CW Conducted Interference, Current Probe (30Hz to 150 kHz)

The Boeing document was used as the basis for the Minuteman interference specification (Ref 17) in which the original broadband measurement was converted into both narrowband and broadband measurements utilizing the NM40 and NM10 instruments. To make this transformation, interference current in a line was monitored by a current probe as well as by the required VTVM; the 700-millivolt (mV) peak reading on the VTVM was translated into current in the line over a range of simulated source and load impedances for a typical aircraft bus system over the range of 30 Hz to 15 kHz. As mentioned earlier, the CW limit coincidentally passes through 100 amperes at 60 Hz and 5 amperes at 400 Hz. Also, perhaps coincidentally, the 700-mV peak limit over the range of 20 Hz to 150 kHz yields a limit in broadband terminology of 133.4 dB above one microvolt per MHz. Assuming a one-ohm aircraft power system bus impedance, this would be only 6/10 of a dB from the currently specified limit of 134 dB above one microampere per MHz.

Mil-E-7894A was superseded in 1960 by Mil-Std-704 for Aircraft Power Systems (Ref 18), and the limit on ac ripple was reduced from 2.1 volts to 1.5 volts, with a recommendation (Ref 19) that further reduction be made to one volt. Frequency characteristics of the ripple were also included in Mil-Std-704 and no individual frequency component exceeded 1.1 volts peak. It was estimated that, if the limit were reduced to one volt, the maximum peak ripple would be 575 millivolts at harmonic frequencies of the 400-MHz fundamental. If the low frequency limits are to be based on the requirements of a power quality specification, then further revision needs to be made to the limits.

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6. SUSCEPTIBILITY

6.1 CONDUCTED SUSCEPTIBILITY

6.1.1 Audio Frequency Limits

Conducted susceptibility testing in the audio frequency range was introduced in Mil-I-6181B, wherein a 2-volt rms signal was introduced across the test sample power leads over the range of 60 Hz to 10 kHz. The test was done only on dc power leads and was measured under closed circuit conditions. The interference limit was based upon the requirement of Mil-E-7894A (ASG), which established a peak ripple voltage limit of 2.1 volts for aircraft dc power systems. Testing equipment to the 2-volt rms limit provided a safety margin of 2.6 dB relative to the ripple on the dc power bus. Mil-I-26600 (and Mil-I-6181D) extended the test to ac power lines and raised the limit to 3 volts rms, but later stipulated that the voltage was to be measured open-circuit before application to the test sample. If the 3-volt limit were directly compared with the criterion of Mil-E-7894A, then a 6-dB safety margin would result; however, no such correlation can be made since the measurement is open circuit, and the safety margin would depend upon the particular test sample impedance.

Due to the indeterminate nature of an open-circuit voltage test, Mil-Std-826 specified closed-circuit conditions and required a test voltage of 10% of the line voltage (2.8 volts rms for 28 vdc line). Concurrently, Mil-Std-704 replaced Mil-E-7894A as the requirement for aircraft power systems; the criterion for dc bus ripple-voltage was reduced to 1.5 volts peak. Thus, the susceptibility test of Mil-Std-826 provides an 8.5 dB safety-margin over the allowable bus ripple-voltage of Mil-Std 704. The authors of Mil-Std-704 considered one-volt ripple as a reasonable goal for future aircraft electric systems (Ref 19), thus providing a 12-dB safety margin in relationship to the 2.8 volt test limit of Mil-Std-826. Both the 8.5- and 12-dB margin figures are higher than the requirement for only a 6-dB safety margin in Mil-E-6051C (Ref 20).

Figure 11 illustrates the foregoing test limits for Mil-I-6181B&D, MIL-I-26600, and Mil-Std-826, as well as those for Mil-Std-461. This latter is similar to that of Mil-Std-826 except that cutoff is at 1.5 kHz rather than 15 kHz, which is probably due to recognition of the excessive stress being placed on the tantalum capacitors utilized in many low-frequency filters. Also shown in Figure 11 is a limit utilized for various space systems, based on 5% of the line voltage as a susceptibility limit. This yields 1.4 volts rms as opposed to the 2.8 volts of Mil-Std-826; it provides only a 2.5-dB margin with reference to the 1.5-volt ripple requirement of Mil-Std-704, but a 6-dB margin for the one-volt peak limit mentioned as a reasonable goal for ripple by the authors of Mil-Std-704. However, few space systems actually have bus ripple-voltages in excess of 200 to 500 millivolts, thus usually providing a margin of at least 12 dB for all equipment using the lowered susceptibility test limit.

It should also be possible to correlate the susceptibility test limits with those for conducted interference. It was previously stated that the limit for BSD Exhibit 62-87 (Ref 13) was based on the conversion of a 700-millivolt peak signal on the line into terms of line current. The limit of Mil-Std-826 is a constant one ampere of line current from 30 Hz to 1 kHz. As seen in Figure 10, the high current at the lower frequencies implies an extremely low bus impedance. If it is assumed that the impedance of the line is as much as 0.500 ohm, this would allow only 0.5 volt to be developed as conducted interference in this frequency range. When this is compared to the 2.8 volt susceptibility test requirement, a 15-dB safety margin results. If the line impedance were as much as one ohm, a 10 dB safety factor would be provided. Both of these figures are in excess of the 6-dB system safety margin required by Mil-E-6051C. Naturally, such a margin is purchased with weight, money, space, and time; if it is not absolutely required, it represents an unnecessary expense. It may be that the higher equipment safety margin ensures the achievement of the system safety margin, but this is by no means clear or certain.

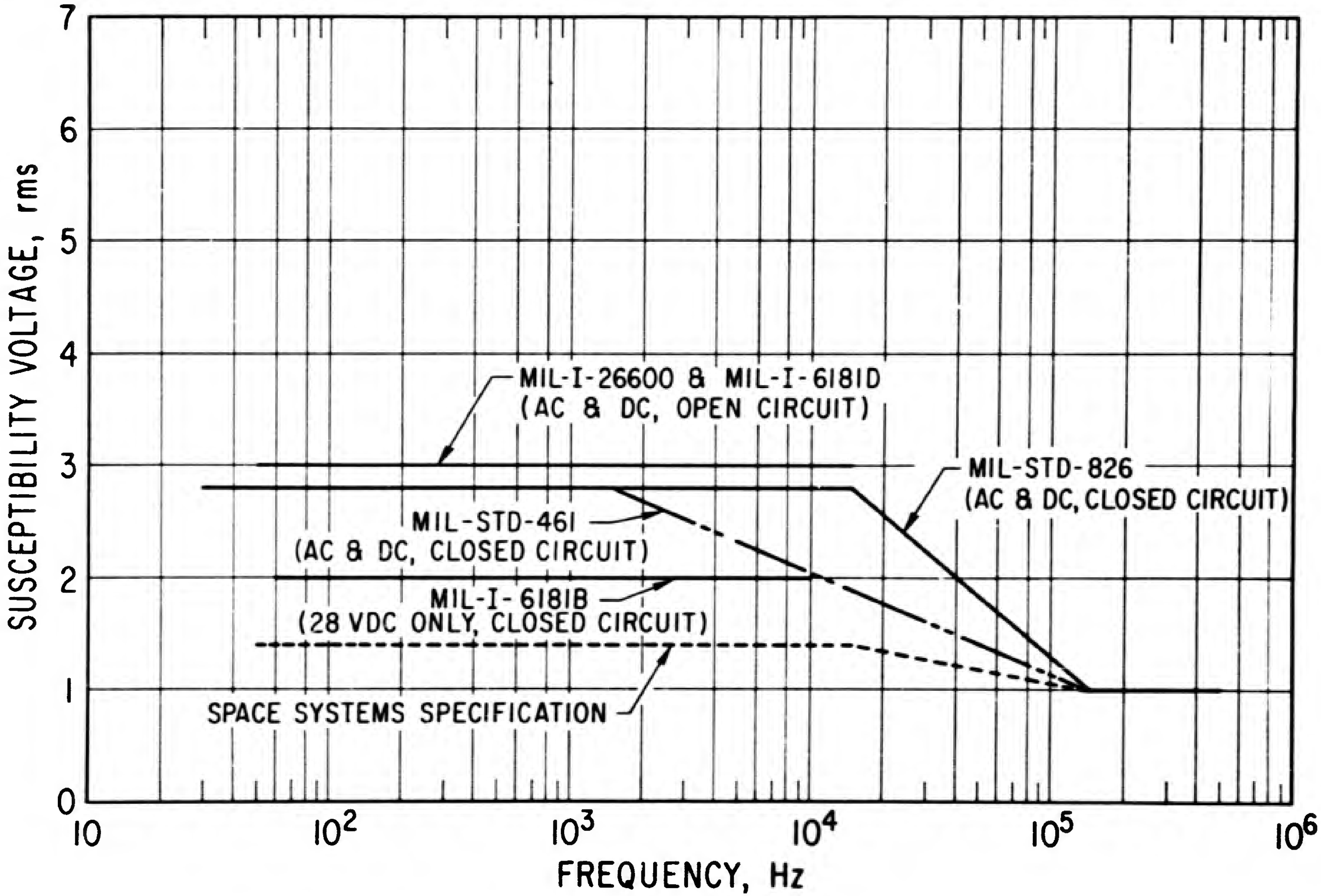

Figure 11. Audio Conducted Susceptibility Limit (30Hz to 150 kHz)

In the earlier specifications, audio conducted susceptibility testing extended only to 15 kHz, and the region between 15 and 150 kHz was not tested. Mil-Std-826 extended the frequency coverage to include this previously untouched range. In the audio conducted susceptibility test, 50 watts are available to deliver power to the test sample; this will deliver ~10 amps into a short circuit for the 3-volt test criterion. At 150 kHz and above, test generators of far less power capability are normally used, delivering rarely more than one ampere into a short circuit. This discontinuity in test equipment capability results in either over- or under-stressing of the test sample at the 150-kHz cross-over frequency. A more judicious melding of the two curves should be provided, preferably by reducing the current delivery to the test sample at the higher frequencies.

6.1.2 RF Conducted Limits

As shown in Figure 12, Mil-I-6181, the earliest of the interference specifications under consideration, utilized a susceptibility limit of one millivolt directly applied to the test sample leads over the frequency range of 150 MHz. When this level of susceptibility voltage is compared to the appropriate conducted interference limits above 150 kHz, a 26-dB margin of safety existed. Mil-I-6181B increased the susceptibility test voltage by an order of magnitude to 10 millivolts, but also changed the method of coupling so that the test voltage was now applied through the LISN. The LISN is not an ideal coupling mechanism, since signals measured at the test sample can be one to two orders of magnitude less than that injected into the LISN. Thus, while the 20-dB increase in susceptibility voltage yielded a nominal 20-dB increase in safety margin, there was actually little more test voltage delivered to the test sample than under Mil-I-6181. This was especially true at the higher frequencies, since the impedance of the LISN underwent wild gyrations above 100 MHz.

Mil-I-6181D and Mil-I-26600 further extended the frequency range to 10 GHz, again coupling the signal through the LISN, while the susceptibility test voltage was raised another order of magnitude to 100 millivolts. Little, if any, signal was actually transmitted through the LISN to the test sample at the higher frequencies. Mil-Std-826 added yet another order of magnitude increase to the test voltage, eliminated the LISN coupling mechanism, and

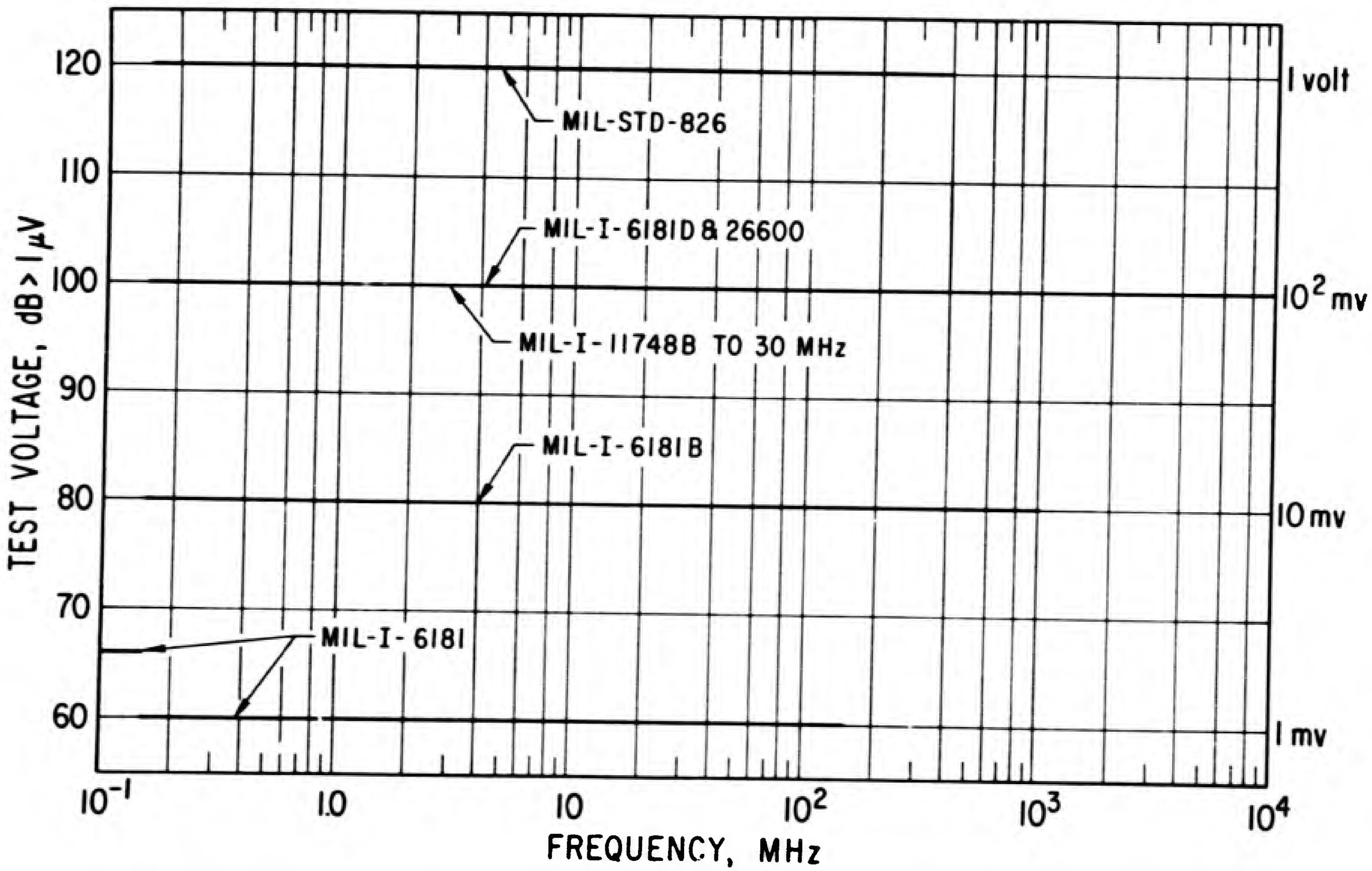

Figure 12. RF Conducted Susceptibility Limits (150 kHz to 1 GHz)

relied on a coupling capacitor; the test was limited to 400 MHz. If this susceptibility test voltage is considered with relation to the interference limit over this frequency region, a safety margin of some 70 dB results. This equipment EMISM (electromagnetic interference safety margin) must be considered in light of the 6-dB system requirement of Mil-E-6051C, again indicating the problem of correlating equipment interference control with system EMC.

6.2 RADIATED SUSCEPTIBILITY

Radiated susceptibility testing was initiated with Mil-I-6181B, in which stub antennas ranging from 20 to 3 inches were mounted on a ground plane and connected to a signal generator via a 5-ohm terminating resistor. RF voltages from 0.1 volt to 5 millivolts were applied over the frequency range of 15 kHz to one GHz. Relying on certain theoretical assumptions regarding propagation conditions, the field produced at the test sample (located one foot from the radiating antenna) can be calculated, and is illustrated in Figure 13. As shown, this field varies from ~30 microvolts per meter at 15 kHz to a maximum of ~50 millivolts per meter around 300 MHz, with a nominal value of 10 millivolts per meter over the frequency range of 10 MHz to 1 GHz. Since the field was produced utilizing a rod antenna, the radiation was primarily high-impedance in nature, and protective shielding could be relatively easily provided. Mil-I-26600 and Mil-I-6181D abandoned the use of the special rod test antenna, utilizing instead the antennas employed for radiated interference testing. Measurements were not required below 150 kHz, but the range was expanded above 1 GHz; Mil-I-26600 specified a non-directive antenna while Mil-I-6181D called for directive horn antennas in this higher frequency range. As before, the field can be calculated utilizing certain theoretical assumptions regarding propagation, and the resultant values are plotted in Figure 13. The levels of the newer specifications yield higher field susceptibility values than those of Mil-I-6181B. Additionally, the field produced by the dipole was not predominantly electric in nature, but was, rather, a complex electromagnetic field. The maximum field value was 500 millivolts per meter at 4 GHz, while, over the major portion of the

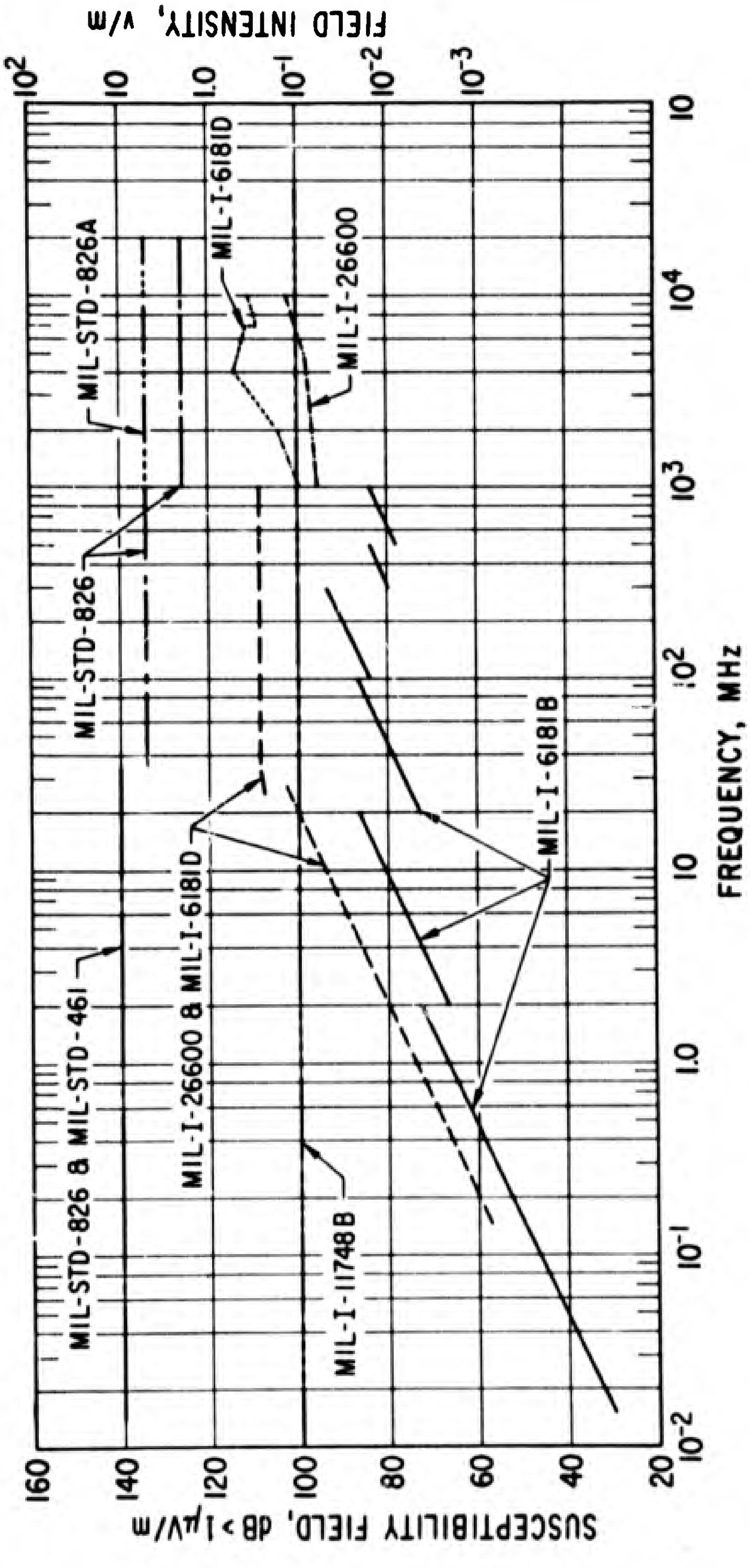

Figure 13. RF Radiated Susceptibility Limits (150 Hz to 1 GHz)

frequency range, field values ranged between 200 and 300 millivolts per meter.

It is constructive to compare the levels herein discussed with those of Figure 6 (interference limits for CW radiation expressed in terms of field intensity). When the allowable radiation at 3 feet from the test sample is compared to the susceptibility field at the test sample for Mil-I-6181D, it is seen that the susceptibility field exceeds the radiated field by a minimum of 113 dB at 25 MHz, thereafter declining to 59 dB at one GHz. The radiated interference field will increase for lesser distances to the test sample, but utilizing the theoretical factors on which the present limits are based would only diminish these safety margins by perhaps 10 dB at one foot from the test sample.

Mil-I-11748B (Ref 21) requires susceptibility field testing to be done over the range of 10 kHz to 36 GHz at a constant field intensity of 100 millivolts per meter, which, compared with its radiated interference fields, yields a safety margin ranging from 50 to 105 dB. Mil-Std-826 and the proposed Mil-Std-461 require radiated susceptibility fields of 10 volts per meter from 15 kHz to 35 MHz and five volts per meter from 35 MHz to 20 GHz. When these are compared with the appropriate radiated interference limits, safety margins ranging from 77 to 117 dB result.

If the radiated interference from the test equipment is to be so stringently limited, what item of equipment is going to be generating the intense field required by the susceptibility test limit? Conversly, if equipment is required to survive in such extremely severe fields, why must the radiation from the equipment be limited to such extremely low levels? In this regard, the power density level of 100 watts per square meter is frequently utilized as a criterion for survivability of electro-explosive devices; this corresponds to a plane-wave field intensity of 194 volts per meter, which is ~26 dB above the radiated susceptibility limit of Mil-Std-826A. The justification for these high level susceptibility fields is that fundamental and harmonic emissions from various transmitters, including radars, can produce extremely high field intensities in the area of particular equipment. Some reliance can be placed on the shielding efficiency of the fuselage of an aircraft or missile, but structural requirements and weight saving advantages for many space vehicles dispense with a contiguous metal covering over the vehicle framework, thus providing little shielding efficiency. Such radiation, of course, usually occurs at the launch site and not in orbit; an area of possibly fruitful inquiry is the degree to which high levels of radiation need to be imposed on each equipment within the satellite, as opposed to the complete satellite vehicle.

The intent of the foregoing discussion is not to indict or eliminate high level susceptibility testing as unnecessary, but merely to indicate that there does not seem to be a correlation between the susceptibility and interference limits of any of the current military interference specifications. There is a seeming trend toward increasingly severe requirements as far as fields in which equipments are required to operate, with a corresponding increase in the limitation on the amount of radiation which the equipment is allowed to emit. This works a great hardship on the equipment designer and, inevitably, on the purchaser of the equipment. The steps which are taken to render the equipment non-susceptible to the high intensity radiated fields are in large part the same steps that are taken to reduce the amount of radiation from the equipment; therefore, perhaps the two limits are indeed complementary, the one merely serving as a check on the other. It would appear, however, that a thorough study needs to be made with regard to the rationale and correlation for interference and susceptibility testing limits, basing them on operational systems experience of today.

6.3 TRANSIENT TESTING

As a result of transistor failures in intercommunications equipment in aircraft, the previously mentioned Boeing specification D2-2444 required a transient conducted test to be performed on 28-volt dc supply leads. The pulse applied was a positive 50-volt, 10-μsec pulse at a rate of two per second. This test requirement was later incorporated into BSD Exhibit 62-87.

Mil-Std-286 incorporated this test with two significant extensions in coverage: the test was applied to ac as well as dc lines, and the 50-volt pulse was applied in negative as well as positive polarity. Mil-Std-826A, on the basis that a 50-volt pulse may not be a rigorous test on a line whose peak amplitude may be 160 volts, requires that the pulse be twice the line voltage or 100 volts, whichever is less. When the test is performed on 28-volt bus, a transient is superimposed in both positive and negative polarities, whose peak amplitude is 56 volts, resulting in a positive stressing of 84 volts and a negative excursion to -28 volts. On a 115 volt rms ac line, a peak transient of ± 100 volts would be applied, causing an excursion between 63 and 263 volts, considering both positive and negative polarities. Proposed Mil-Std-461 retains the feature of positive and negative polarity pulses, but maintains the pulse amplitude at 50 volts, which reduces the ac line excursion to the range of 113 to 213 volts peak.

The fundamental problem with the transient susceptibility test as it is presently constituted is the amount of energy transferred to the tested equipment. In the original test, a 1-μf capacitor charged to 150 volts was used to store the test transient; it had a maximum energy capability of ~10 millijoules. Coincident with the inception of Mil-Std-826, a commercial transient generator became available and was listed as acceptable in Mil-Std-826. It utilized a one -microfarad charging capacitor, but the voltage charging limit was increased to 250 volts, thus yielding an energy storage capability of ~ 30 millijoules. Because of difficulty in obtaining the necessary 50-volt transient across the test sample terminals, the charging capacitor was increased to four microfarads, thus raising the energy potential to 120 millijoules. This is the maximum amount of energy which can be stored by the transient generator and does not imply that it all can be delivered to the test sample;

it represents an upper limit on the possibility of energy transfer. Mil-Std-826A recognized the problem of energy transfer by requiring the transient to be developed across a 5-ohm load before being applied to the test sample. However, if the 50-volt transient is developed across a 5-ohm load for 10 microseconds, only five millijoules of energy are delivered to the test sample, as opposed to the basic capability of 30 to 120 millijoules of the test equipment. Some upper limit on energy must be set, or testing and design engineers will be at constant cross purposes, providing still greater protection for still higher transient energy levels. Since a 5-ohm resistor provides too low an energy coupling, it is suggested that a 100 millijoule figure be used as an appropriate limit on energy transfer to the tested equipment, and that further study be done of actual energies involved in typical system switching actions.

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7. CONCLUSIONS

The historical road from first formulation of interference limits to their present state is one which is long in time but rather short in technological advancement. The limits presently in use are, upon close examination, little different from those of almost two decades ago, and those were based on environmental/ operational considerations far different from those of today.

A serious study is needed to develop or validate realistic equipment interference limits in light of present and planned systems. Undoubtedly, a laboratory development program could be instituted to determine a scientifically valid set of interference limits, based on certain statistical assumptions regarding: susceptibility and measuring equipment characteristics; shielding effectiveness of spacecraft panels or aircraft fuselage; the utilization of the given equipment; and information concerning equipment integration into given systems. A multiplicity of interferring sources would need to be utilized, both broadband and CW, as well as many different types of susceptible devices. In this fashion, a realistic and empirically and theoretically valid set of interference limits, both conducted and radiated, might be developed. Such has not been done, as is shown by the present arbitrary, and perhaps irrelevant, interference limits.

Additionally, further study is needed in gaining a deeper understanding of the phenomena being measured and of the measurement techniques utilized. These are unresolved questions as to the utility, validity, and appropriateness of some measurements and instrumentation and their further correlation with significant system parameters.

Underlying the entire problem of interference limits is the basic unresolved question of the relationship between equipment interference criteria and successful system operation. By what percentage is system electromagnetic compatibility (EMC) enhanced if all equipment comprising that system meet the applicable interference criteria? What is the cost effectiveness of equipment interference tests versus system testing? While this study did not directly address itself to these questions, it inevitably was confronted with them and concluded that such questions need to be seriously asked, and answers must be forthcoming if EMC is to be engineered into future systems.

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13 ABSTRACT

Limits currently used by military specifications for control of Electromagnetic interference and susceptibility are uniformly based on tests which were conducted many years ago on aircraft voice communication equipment in typical aircraft installations, and do not necessarily relate to present requirements of space systems.

This paper examines the development of interference and susceptibility limits in various military specifications indicating the technique by which the limits were derived, the rationale for such derivation, and the changes in various limits with time since their original formulation. It also discusses certain inconsistencies within and between the limits of the various specifications.

The evaluation of the status of this field practically dictates that a study should be initiated to realistically formulate a theoretically and empirically valid set of interference and susceptibility limits to fit the needs of modern, complex systems in crowded, electromagnetic environments.

14. KEY WORDS

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Electromagnetic Interference Control
Interference
Radio Interference
Radio Frequency Interference
Susceptibility
Radiation
Interference Limits
Specification

Abstract (Continued)