Errata

Document Title: Modern EMI Measurements (AN 63E)

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HP References in this Application Note

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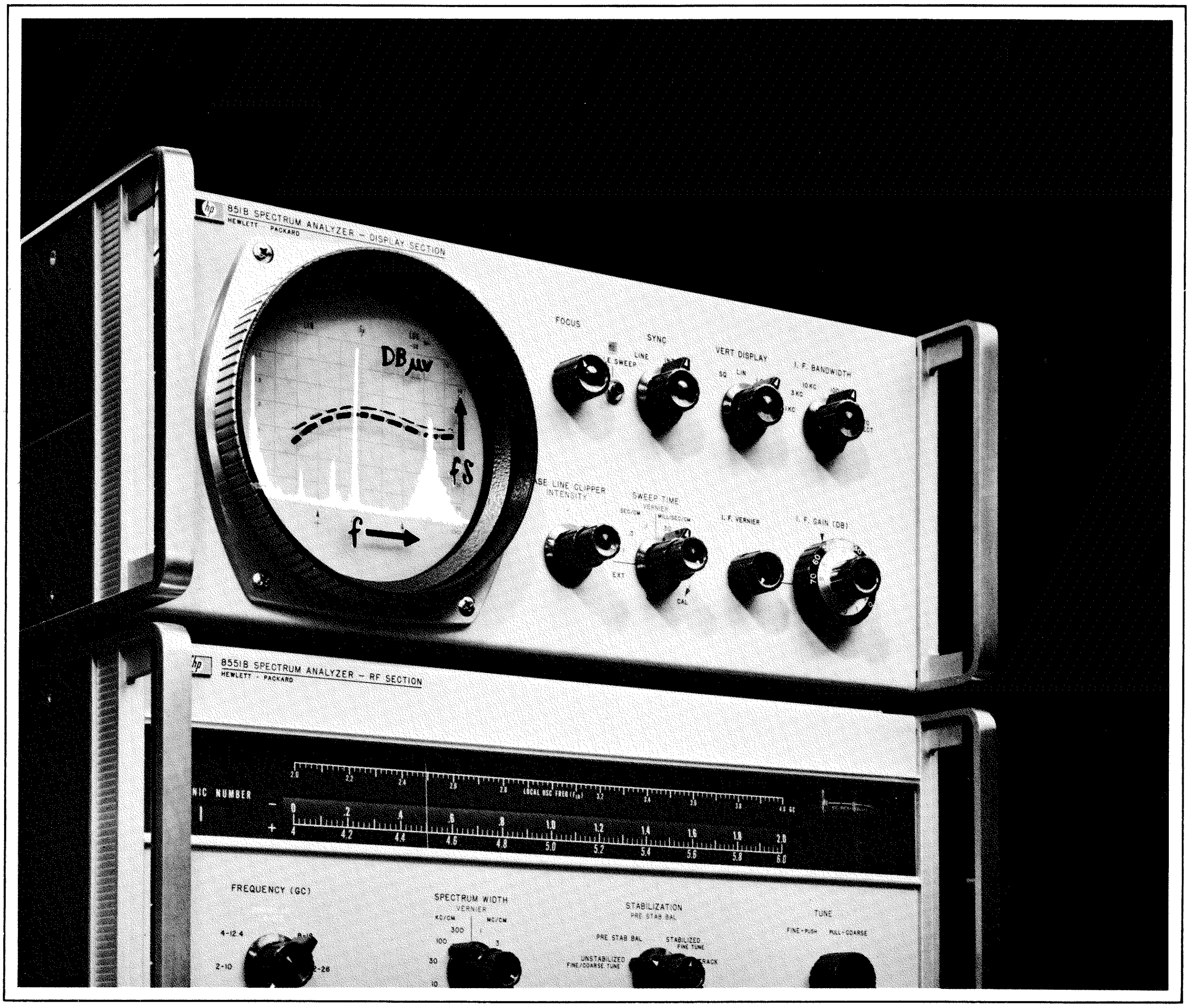
APPLICATION NOTE 63E

Modern EMI Measurements



AN APPLICATION OF SPECTRUM ANALYSIS——*HEWLETT hp PACKARD*

APPLICATION NOTE 63E
MODERN
EMI
MEASUREMENTS

AN APPLICATION OF SPECTRUM ANALYSIS

Revised: June 1979

HEWLETT hp PACKARD

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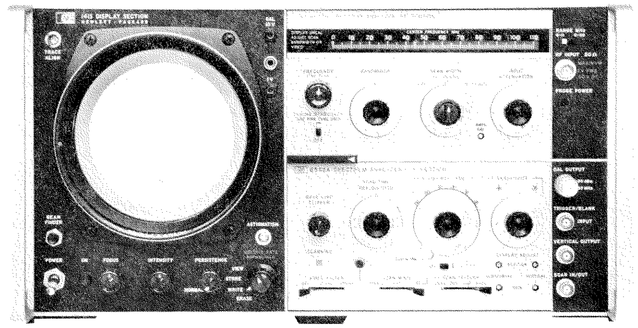

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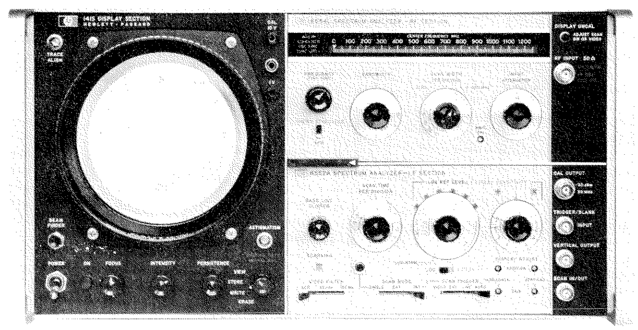
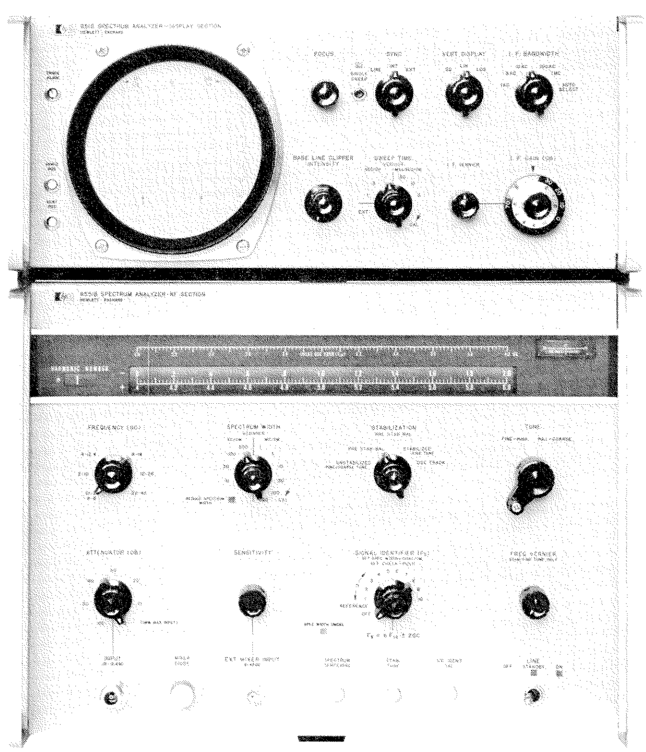
1 kHz to 110 MHz



141S/8554L/8552A
500 kHz to 1.25 GHz



851B/8551B
10.1 MHz to 40 GHz

Figure 1. HP Spectrum Analyzers

MODERN EMI MEASUREMENTS

INTRODUCTION

Electromagnetic compatability (EMC) and electromagnetic interference (EMI) are terms often discussed these days, for they deal with the ability of electronic devices to function simultaneously with other electronic devices without adverse effects. As more and more devices are developed and more of the electromagnetic spectrum is consumed, it becomes increasingly important for everyone in the electronics industry to be compatability-minded.

To achieve compatibility, you must be able to make fast and reliable measurements of the interference characteristics of your devices. In the past, EMI measurements have been made on a point-by-point basis, a time-consuming and tedious process. However, this is no longer necessary due to technological advances in the art of spectrum analysis. This application note summarizes the present status of EMC measurement and shows the potential of calibrated Hewlett-Packard spectrum analyzers as efficient EMI measurement tools.

This note is intended for all interested in EMC. The design engineer just beginning to measure EMI will look first to the beginning sections for a survey of the field — a discussion of EMC in general and the problems of EMI measurement. For the EMC engineer, the last section describing how to use the spectrum analyzer as a calibrated, tuned microvoltmeter for EMI measurement will be important. The spectrum analyzer will greatly reduce the drudgery of EMI measurements, allowing time for more thorough investigation.

DEVELOPMENT OF THE EMC CONCEPT

The history of EMC is the story of engineers searching for a way to make quantitative measurements of a very complex quantity. Due to the many factors involved, test conditions and limits have often been arbitrarily set simply to achieve repeatable results. The time involved to make measurements and the inconvenient form of the rough data have often eclipsed the value of the actual results. However, at present the EMC community is stepping back and taking a broad look at the objectives and techniques of the field. The goals of a new direction in EMC have been stated in a recent Department of Defense (DOD) directive. These goals are clear from the definitions below.

EMC DEFINITIONS

EMC Definitions Quoted from DOD Directive No. 3222.3, Section III, July 21, 1967

A. Electromagnetic Compatibility (EMC) is the ability of communications-electronics (C-E) equipment, sub-systems and systems to operate in their intended operational environments without suffering or causing unacceptable degradation because of unintentional electromagnetic radiation or response. It does not involve a separate branch of engineering but directs attention to improvement of electrical and electronic engineering knowledge and techniques to include all aspects of electromagnetic effects.

B. Design Compatibility is EMC achieved by incorporation of engineering characteristics or features in all electromagnetic radiating and receiving equipments (including antennas) in order to eliminate or reject undesired signals, either self-generated or external, and enhance operating capabilities in the presence of natural or man-made electromagnetic noise.

C. Operational Compatibility is EMC achieved by the application of C-E equipment flexibility to ensure interference-free operation in homogeneous or hetrogeneous environments of C-E equipments. It involves the application of sound frequency management and clear concepts and doctrines to maximize operational effectiveness. It relies heavily on initial achievement of design compatibility.

The objectives of EMC programs have been revised several times since "static" was first used to describe annoying radio interference. As use of the radio spectrum developed to the point where "static" could not fully describe the various problems encountered, the term RFI (radio frequency interference) was adopted. RFI problems occurred mainly in RF communications systems, and RF communications equipment became the measurement standard. Specifications were developed around this equipment and then applied elsewhere as necessary. Problems were solved as they occurred. Eventually it was realized that the interference problem actually plagues the entire field of electromagnetics; it is not limited only to the RF frequencies and only to complex equipment. Every electronic and electrical device is a possible source and recipient of interference. Furthermore, there is only so much usable space in the electromagnetic spectrum. To make best use of this resource, much thought must be given to the compatibility of various systems and to multiple use of the spectrum. The term electromagnetic compatibility (EMC) has been adopted to describe the goal, and electromagnetic interference (EMI) is used to describe the phenomena. EMC is a positive approach - a design objective. This has been a significant change, for the science of EMC has evolved from problem-solving groups to a goal-directed discipline.

CASES OF INCOMPATABILITY

A few incidents will point out the types of problems incompatibility can cause. First, a classic that has been cited so often it might be considered folklore. One of the first missiles launched in this country was pulled from its course soon after lift-off and crashed. Subsequent research indicated that the missile's guidance system had received a false command from a metropolitan taxi dispatch radio. Now, at many launch sites, most radio equipment in the surrounding area is shut off during a space launch or missile test. The spectrum is constantly monitored, often by spectrum analyzers, to check whether possible interfering signals are present. Elaborate plans are made to locate missile tracking stations in "electromagnetically quiet" areas to prevent blocking of communication channels.

An incident which involved aircraft safety was recently reported by J. Lee Smith of the FCC.* Commercial aircraft communications at the Los Angeles airport were disrupted by local electronic garage door openers. The receivers on the door openers radiated energy around 243 MHz, the frequency used for airport emergency communications. The emergency receivers are designed to override all other receiving equipment aboard the aircraft. The signal from the door opener would activate the emergency receiver and noise would prevent contact with the control tower. The pilot could not get landing instructions. He was forced to shut off his emergency equipment to land and therefore would not have the protection he needed from the emergency channel. In the course of the investigation, spectrum analyzers were used to determine the frequency distribution of the radiation.

The compatibility problem, however, is not peculiar to telemetry or communications systems. The memory states in a computer can be altered by a switching transient within the system. A relay-operated fuel valve may generate a transient and inadvertently fire the position control rockets on an ICBM. And a sign often seen along highways during construction, "Caution, blasting -- turn off all radio equipment," has been placed there because of EMC problems.

The compatibility problem is known even to the design engineer at his bench. His circuits must work together to perform the function for which they were designed. A well-known troubleshooting technique is to attach a loop antenna to a spectrum analyzer and probe for unwanted signals.

In short, the entire environment, from intercircuit to intersystem to intrasystem must be compatible. Thus, every person working with electronics must be EMC-minded.

THE ASPECTS OF EMC

There are actually four aspects to the electromagnetic compatibility problem: (1) signals emitted from a device which may cause interference; (2) susceptibility of another device to such signals; (3) the transmission path by which signals get from one device to the other (there are two general paths by which the emitted energy may travel: transmission through space and conduction through any of the connecting cables - power lines, signal cables, control cables, etc.); and (4) the timing involved, that is, whether or not the signal is present during a time when the device is susceptible. EMC is a systems concept and each aspect of the problem suggests a possible cure. The compatibility question may be phrased: WILL THE ELECTROMAGNETIC ENERGY GENERATED BY ONE DEVICE AT A PARTICULAR FREQUENCY AND TIME CAUSE MALFUNCTION OF ANOTHER DEVICE? To answer this, we must determine what energy each device emits and to what energy each device is susceptible. The broad nature of the compatibility problem is diagrammed in Figure 2.

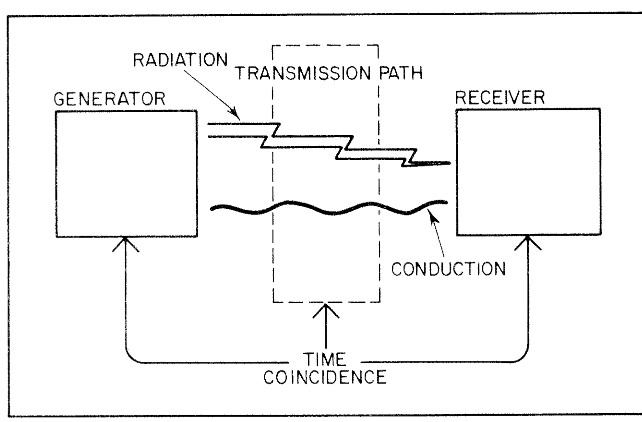


Figure 2. The EMC Problem

Will the electromagnetic energy generated by one device at a particular frequency and time cause malfunction of another device?

*J. Lee Smith, "Electromagnetic Radiation Problems Involving Safety of Life and Property," Technical Paper presented at the 8th IEEE Symposium on EMC, 1966.

THE METHOD OF EMI MEASUREMENT

The overall objective of EMI measurement is to characterize the emissions, susceptibility, coupling path and time relationship of the electromagnetic situation. Although each aspect of the EMC problem merits consideration by the design engineer, EMI measurement generally concentrates on emission and susceptibility problems. Data is already available for many coupling paths, and the time coincidence problem is peculiar to each system individually.

The characterization of emissions from, or the susceptibility of, electronic equipment is complicated by the wide range and the large number of system parameters which must be varied. All frequencies, whether outside or inside the normal operating range, must be considered; all modes of operation must be examined. All this is very involved and time-consuming on a point-by-point bases, but it is necessary to make complete measurement if the goal of EMC is to be realized.

EMC measurements are complicated by another problem — how good is good enough. For system compatibility, the answer is easy: if the system works under the required conditions, it is compatible with itself. But what about general and component EMI tests? Specifications and test limits provide one answer but this approach has its limitations. For instance, meeting a specification does not in itself guarantee compatibility. The test limits and conditions are chosen with consideration given to the EMI environment, with realization that measurements must be repeatable. Such factors as antenna polarization, instrument position, control settings of test sample, and positioning of objects in the screen room all influence the measurement and must be specified. Thus, operating conditions often cannot be duplicated during tests. To one used to working in other fields, EMI tests may seem over specified and arbitrary — and to some extent they are. However, these conditions and procedures are necessary to make tests repeatable.

Many documented standards for EMI measurements have been generated in attempts at repeatability. There are two kinds: those generated for specific systems and those generated for general EMI specifications. These standards have originated from several different sources for different purposes, but many have similar test limits and conditions.

Recently there has been an effort to unify the many military standards into one general-purpose standard. The MIL-STD-461, 462, and 463 series is the result of this effort. The methods and test limits specified in this standard are drawn from the experience of the past using modern technology and equipment. Most general-purpose EMI measurements in the future will probably be made as described in this standard. However, until present projects are completed, other standards will be used. A few of the important ones are described in Appendix III

Test procedures for EMI measurement may appear long and involved at first glance, but they can be generalized into three steps: 1) setup and calibration; 2) actual measurement and classification of signals; and, 3) evaluation of the results (see Figure 3). Measurements are made on both radiated and conducted interference since these are the two general signal paths for interference.

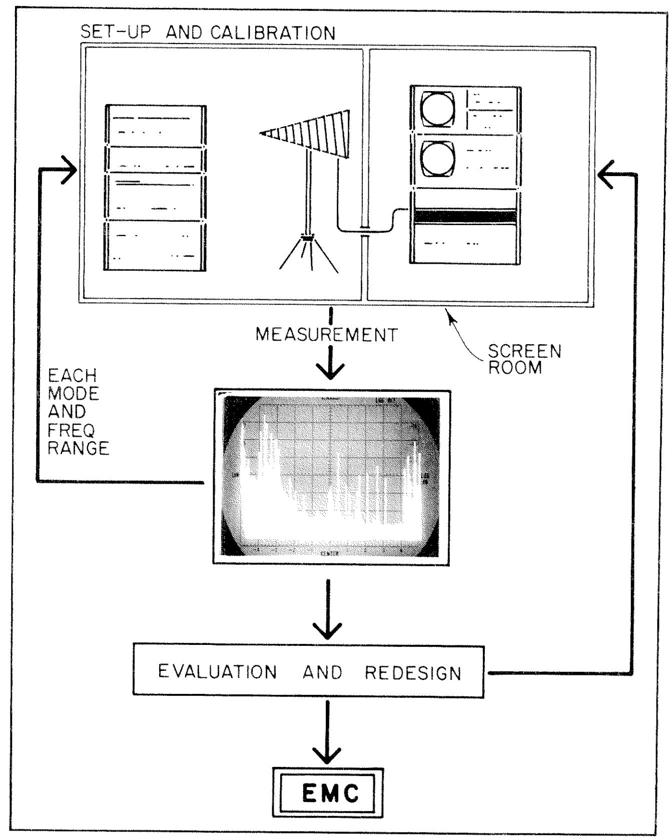


Figure 3. EMI Measurement Flow Chart

(Radiated emissions used as example)

EXAMPLE I

MAKING QUANTITATIVE EMI MEASUREMENTS WITH THE SPECTRUM ANALYZER

The spectrum analyzer may be easily calibrated for EMI measurements since its gain is constant over broad frequency ranges. The analyzer gain and the appropriate antenna factor or current probe factor may be combined and the specification limit marked across the front of the spectrum analyzer screen. A CRT photograph will show all signals within the band and the specification limit simultaneously.

Radiated Interference

Electronic counters have EMI problems similar to many other devices. With fast switching transients, high input signal levels, frequency converters, and pulse generators, they are a small system in themselves. It is to be expected that there will be quite a bit of radiation from these instruments unless EMC is designed into them from the start.

Figure a shows the radiated spectrum between 60 MHz to 140 MHz from a standard HP 5245L Counter. The line drawn on the CRT is the specification limit for MIL-STD-826A. (The curvature is due to the broadband antenna.) Even though this device emits energy above the specification limit, it will be compatible in most applications. However, an EMI-proof counter has been developed by HP, the H60-5245L. The results of testing this instrument to MIL-STD-826A appear in Figure b. All signals are below the specification limit.

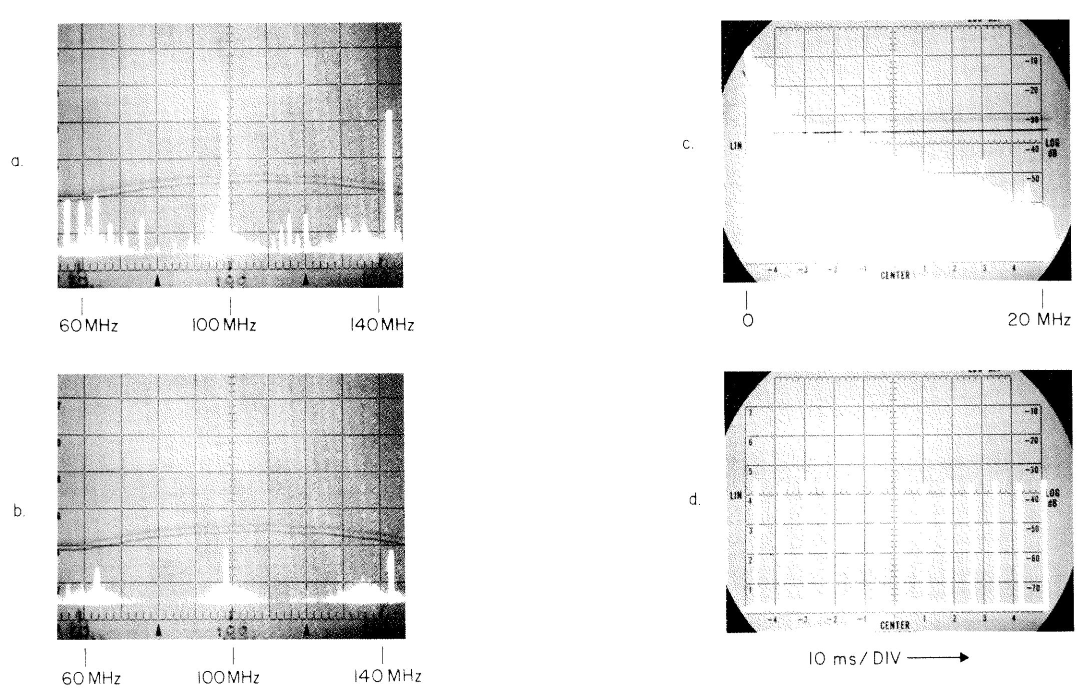
In both cases, the high level signals at 96 MHz and 144 MHz are re-radiated harmonics of the 48 MHz signal, measured by the counter. The regularly spaced signals originate in the counter's internal pulse generators.

Conducted Interference

Some silicon-controlled rectifiers circuits used in light dimmers or motor speed controls generate high level broadband interference. Conducted interference from one of these (0 - 20 MHz), is displayed on the spectrum analyzer variable persistence display in Figure c. The line on the CRT is the MIL-STD-461 specification limit, 50 dBμA/MHz (2 MHz to 50 MHz). The interference is above the allowed limit below 8 MHz.

To identify the source of the interference, the analyzer scan width is reduced to zero. The analyzer is now operating as a fixed-tuned receiver with a time-scanned IF. It is tuned to 5 MHz and the time scale is 10 ms/div; thus, the interference is occuring at 120 Hz, twice the line frequency. (Figure d)

Electric motors and switches generate the same sort of spectrum due to arcing at the armature or switch contacts. However with these, the pulse has a random nature and the spectrum is not well defined as above. The spectrum signature of an electric drill appears in Figure 9b.



RADIATED EMI MEASUREMENT

When making radiated EMI tests we wish to find how much radiated energy the device emits and is susceptible to. A calibrated receiver is used with an antenna to make these measurements. (See Figure 4). With other than system-level EMI measurements, we need to normalize the signal path. To do this, we would like to measure field intensity. Antenna factors are given for specific antennas to convert from field intensity to voltage, which is measured by the spectrum analyzer or other tuned voltmeter. The factors allow for different field patterns, size, mismatch, etc. They are added (in dB) to the measured voltage (in dBμV) at the input terminals of the measuring instrument. See Figures 5 and 6.

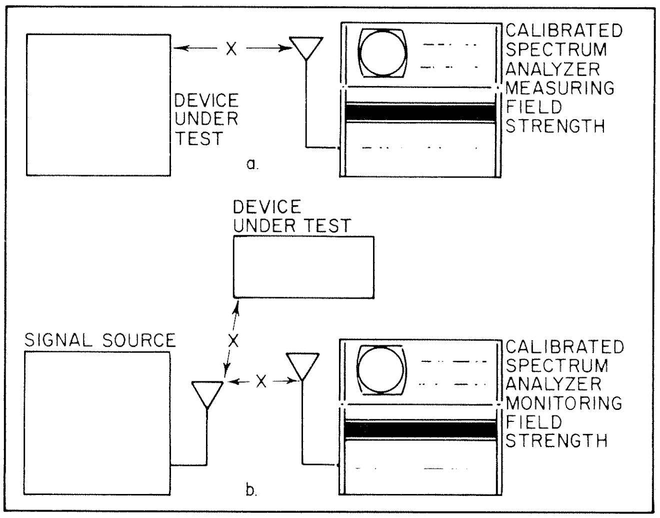


Figure 4. Radiated EMI Tests

a. Radiated emissions

b. Radiated susceptibility

X. Distance from device under test to antenna as specified in test procedure used.

MIL-STD-463 defines field strength as follows: "The term 'field strength' shall be applied only to measurements made in the far field. The measurement may be of either the electric or magnetic component of the field, and may be expressed as V/m, A/m, or W/m^2; and one of these may be converted to the others. It shall be abbreviated as FS. For measurements in the near field, the term 'electric field strength' (EFS) or 'magnetic field strength' (MFS) shall be used, according to whether the resultant electric or magnetic field, respectively is measured. The EFS shall be expressed as V/m, and the MFS as A/m. In this field region, the field measured will be the resultant of the radiation, induction and quasi static ($1/r$, $1/r^2$ and, if present, the $1/r^3$) components, respectively, of the field where r is the distance from the source. Inasmuch as it is not generally feasible to determine the time and space relationships of the various components of this complex field, the energy in the field is similarly indeterminate."

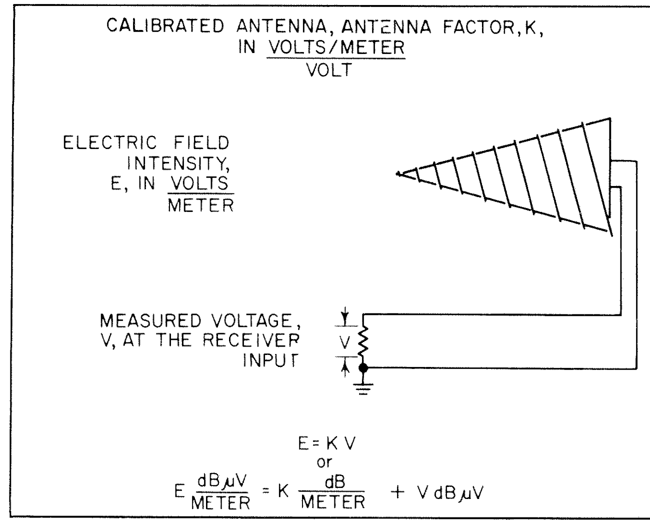


Figure 5. Antenna Factor

The antenna factor, K, is used to convert the measured voltage reading to the required field intensity. In the far field the magnetic field intensity, H, is related to the electric field intensity, E, by the impedance of free space, Z.

$$E/H = Z = 377\Omega.$$

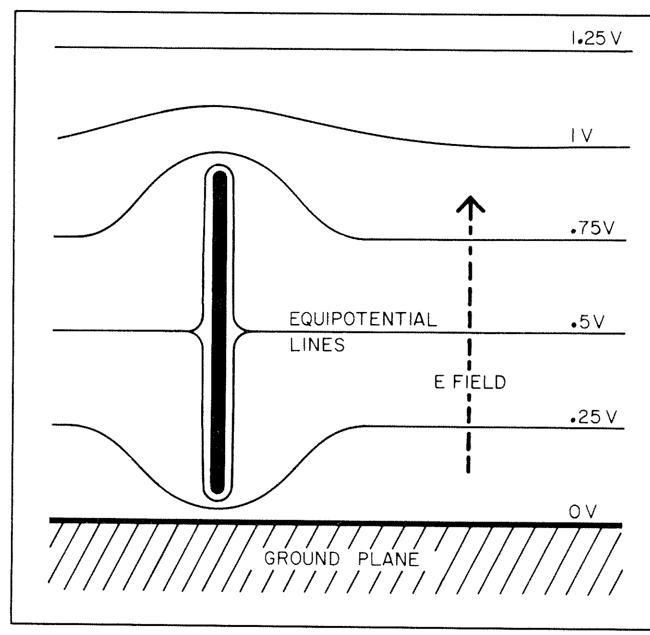


Figure 6. Derivation of Antenna Factor for 1 Meter Rod

A uniform electric field is warped (equipotential lines are shorted out) by a vertical conducting rod. Since the rod shorts the 1 volt/meter (normalized field) to the 0 volt/meter ground potential, the rod assumes the average, 1/2 volt/meter. Therefore, a high impedance voltmeter placed between the rod and ground would measure 1/2 volt. The antenna factor is 1/2 volt/meter/volt or 6 dB.

To measure field intensity, the antenna factor must be known and the environment must be nonreflective and void of interfering signals. This implies far-field measurement in a large anechoic chamber within a shielded room. However, these facilities are not generally available at this time. Measurements can sometimes be made outside if the environment is "quiet" enough. However, what is usually measured is the voltage induced at the antenna terminals in a near-field measurement within a shielded room. Near-field measurements and reflections off screen room walls, other instruments, and even the operator are situations that introduce ambiguities which are lived with. By specifying all conditions (antenna, position, distance, etc.), the measurements are reasonably repeatable and, with empirical knowledge, meaningful.

Antennas to be used for each test are usually specified. For example, Table 1 lists the antennas used above 14 kHz in MIL-STD-461. Antenna descriptions and typical antenna factors are given in the Standard. The antennas listed in 461 are useful in swept measurements, since they do not require adjustment over their frequency range.

Table 1. Antennas Specified in MIL-STD-461 for Emission and Susceptibility Measurements

Frequency	Description
14 kHz - 25 MHz	41" rod (electrical length 1/2 meter) and matching network.
20 - 200 MHz	Biconical antenna
200 - 1000 MHz	Conical logarithmic spiral antenna
1 - 10 GHz	Conical logarithmic spiral antenna

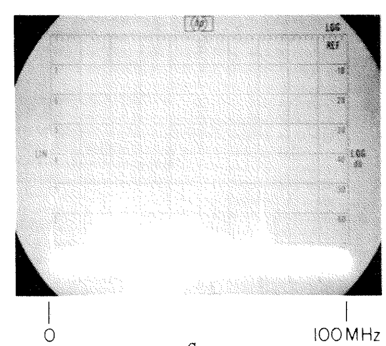
EXAMPLE II

INTERCIRCUIT EMI MEASUREMENTS

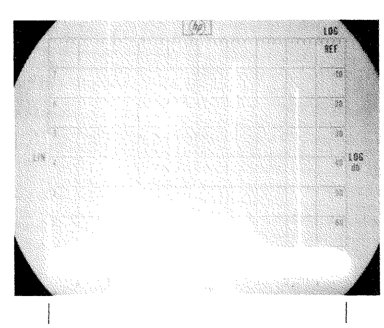
The design engineer must be EMI-conscious even at the circuit board level. Often he will probe among the circuit components with a small loop or connect directly to the device output looking for spurious oscillations.

In this example a potentially unstable common emitter amplifier is examined. At normal bias (Photograph a), the high noise peaks at 22 MHz and 72 MHz indicate potential oscillation. Bias is increased in Photograph b, and the amplifier oscillates at 21 MHz with a high harmonic content.

Whether or not these oscillations cause a problem is dependent on the other system components. If other circuits are sensitive to these frequencies, system problems could arise. Switching circuits generating broadband noise are notorious as sources of EMI problems due to the broad frequency spectrum generated.



a.



b.

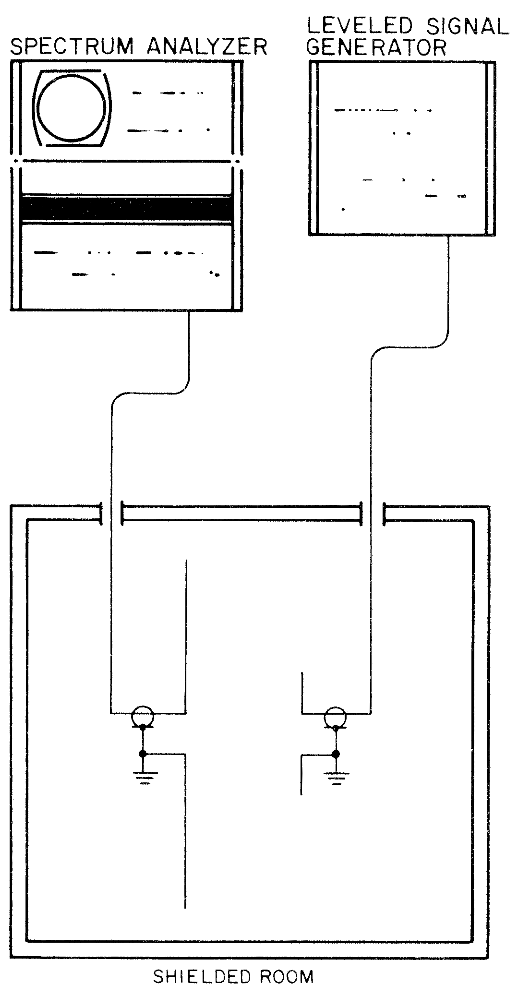
EXAMPLE III

SHIELDED ROOM MEASUREMENTS

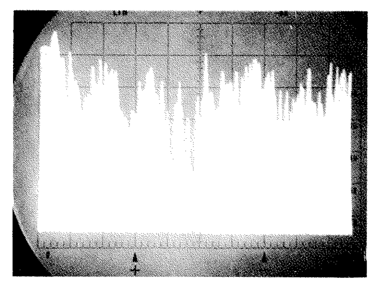
It is well known that radiated EMI measurements made in a shielded room are a poor compromise at best. The shielding does provide a clean electromagnetic environment, but causes internal reflections. As the shielded room has constant dimensions, it has resonant frequencies. To see just how reliable measurements in a shielded room are, an experiment was set up as in Figure a. The source antenna approximating a point radiator at 150 to 250 MHz was driven by a signal generator with a constant power output. A spectrum analyzer connected to the receiving antenna was tuned to 200 MHz and swept 10 MHz/cm. The screen room was set up as in an actual EMI test for the photograph of Figure b. The screen room characteristics from 150 to 250 MHz were recorded on the 842A Variable Persistence Spectrum Analyzer Display and photographed.

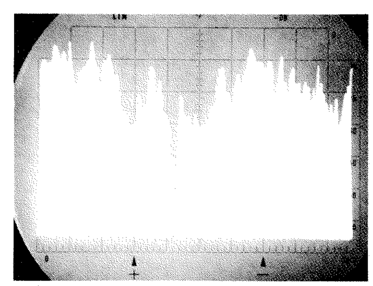
Then conditions inside the room were varied. A large (3 ft x 6 ft) aluminum plate was moved to alter the room characteristics and antenna positions were varied. Some of the results obtained appear in Figures c and d. These results show the necessity of strict adherence to test setup procedures and an uncluttered screen room to achieve repeatable results. Note that since variations up to 40 dB are possible, test conditions not specified in the standard (instrument orientation, operator and test equipment location, etc.) must be altered and measurements repeated to find maximum response.

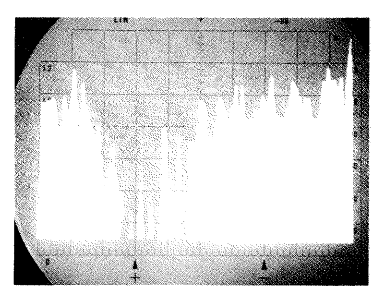
Use of the spectrum analyzer makes such experiments practical, since frequency bands are swept in a very short time and present essentially a continuous display. The effects of variations are immediately evident to the operator and he may take more reliable data.



a.


150 MHz b. 250 MHz


150 MHz c. 250 MHz


150 MHz d. 250 MHz

CONDUCTED EMI MEASUREMENT

Conducted EMI tests are made to determine how much interference is emitted by a device through connecting cables and how much interference can be conducted to a device before it malfunctions (See Figure 7). Conducted emission measurements are made using a current probe or other standard network, or by direct connection.

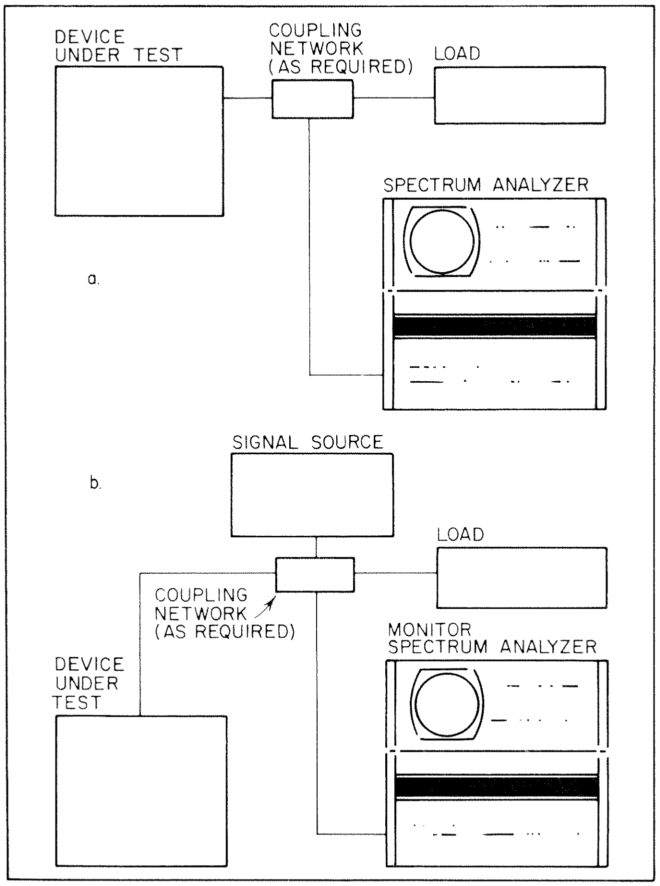


Figure 7. Conducted EMI Tests

a. Conducted emissions

b. Conducted susceptibility

These tests are made on each conductor associated with the device under test. The load is as close as possible to that used in actual operation. The coupling network may be a current probe, transformer resistive T, or a direct connection, depending on the particular conductor.

Current probes are simply transformers with the power line under test as the primary winding and the probe itself the secondary. Calibration factors (transfer impedance) converting from line current (RF) to output voltage are usually given in dB above 1 ohm (dBΩ). See Figure 8. Current probes to measure conducted EMI to military standards are readily available commercially.

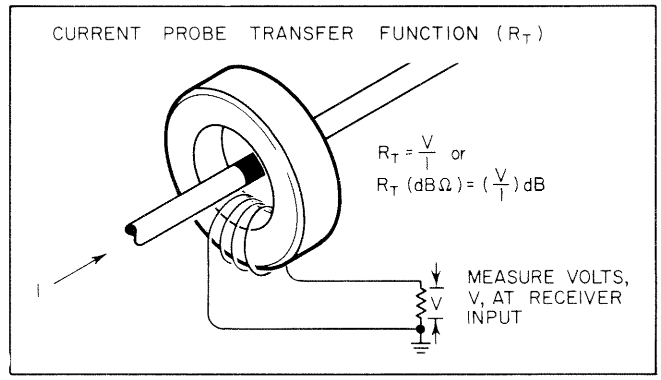


Figure 8. Current Probe Transfer Function

The current probe transfer function (R_t) is used to convert the voltage (V_t) read at the probe output to the current (I) flowing in the conductor.

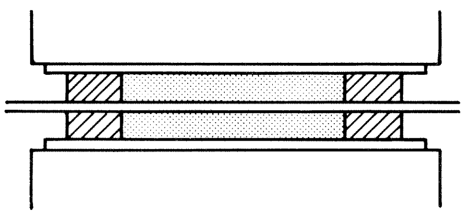
In measuring conducted emissions, some thought must be given to the load the signal sees, both in operation and under test. The load is generally known and can be simulated for system components, but this is not the case for general purpose equipment. Therefore, to provide a repeatable but useful standard, a particular load is specified. Generally, this is one of two types, a line stabilization network (LSN) or a 10 microfarad capacitor. Both attempt to present a low impedance load so that maximum current will flow and be picked up by the current probe.

The LSN is a filter network put in series with the power leads. The filter impedance is approximately 50 ohms over much of its frequency range and is useful to 25 MHz. The 10 microfarad capacitor has more recently been specified for use for power line measurements (MIL-STD-826A and MIL-STD-462). It is placed in parallel with the line to ground. Generally, the capacitor presents a better load because it is a better short circuit at RF frequencies; furthermore, the capacitor's impedance function is easily predictable. Use of this capacitor anticipates source impedance measurements for complete characterization of conducted interference.

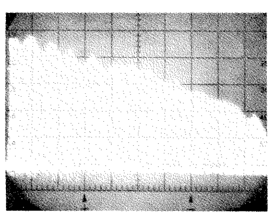
EXAMPLE IV

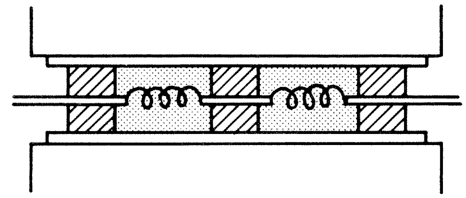
EVALUATION OF EMI DESIGN

In the design of electronic components, EMI problems must often be substantially reduced without particular regard to specification limits. In this case, the spectrum analyzer can be used profitably without vertical calibration. These figures are a quick-look evaluation of attempts to shield the leads of a backward-wave oscillator tube for conducted interference. EMI filters were constructed for the leads as shown in the diagrams, and the photographs show the amount of conducted broadband leakage for the frequency range between 1 and 2 GHz. In this case, it is easy to conclude that a little polyiron material applied at the proper places does a better job than solid polyiron around the leads.

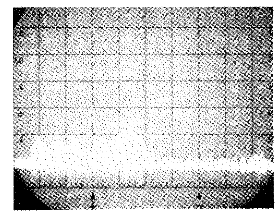


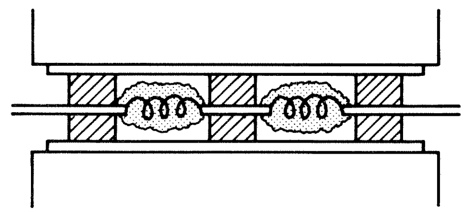
(a.) STRAIGHT WIRE SOLID POLYIRON



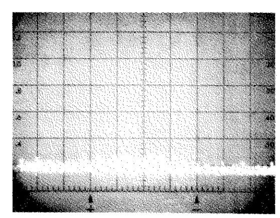


(b.) INDUCTORS IMBEDDED IN POLYIRON





(c.) INDUCTORS COATED WITH THIN LAYER OF POLYIRON



SIGNAL CHARACTERIZATION

To characterize a signal, measurement is made in either the time or frequency domain, depending on the expected environment.* For instance, if nearby electronic equipment can be triggered only by a certain rise-time pulse, EMI measurements, as they apply to that equipment, are best made in the time domain. On the other hand, if the susceptible device is frequency-selective, measurements are best made in the frequency domain. Whenever the operating environment is unknown, as in general EMI tests, the frequency domain is the best choice due to the greater sensitivity of "tuned voltmeters."

Since the signal levels in many EMI measurements are very small, measurement is made relative to one microvolt. Expressed in decibels, levels are dB above (or below) one microvolt (dBμV). In a 50Ω system, 1μV (0 dBμV) = -107 dBm. Current measurements are made relative to one microamp (dBμA).

When attempting to predict the effect of the electromagnetic energy on a general electronic device, we encounter difficulty in some cases. For CW, single-tone AM, and low-modulation FM, the signals are easily described by giving their power and frequency. But we cannot do this with noise or impulse signals; energy is spread over too broad a frequency range. (See Figure 9). Furthermore, the susceptible device may be frequency-selective and, therefore, not sensitive to the total energy of the signal. Consequently, our measurements on broadband signals are normalized with respect to frequency.

*Theoretically, measurements could be made in either the time or the frequency domain and could be converted to the other through the Fourier transform, but phase information must be available in the frequency domain.

Broadband signals are often generated by narrow, low-repetition-rate or random rate pulses. (See Figure 10). They are measured in terms of spectral intensity, which is the total voltage within a 1-MHz impulse bandwidth (dBμV/MHz) (White or random noise is measured as a power density since the rms voltage must be added.) At any one frequency the measured voltage is proportional to the spectral intensity and the impulse bandwidth (BW_i). The impulse bandwidth is derived from the ratio of the peak value of the voltmeter transient (V_p) divided by the spectral intensity of the impulse signal (S).

$$BW_i = V_p/S$$

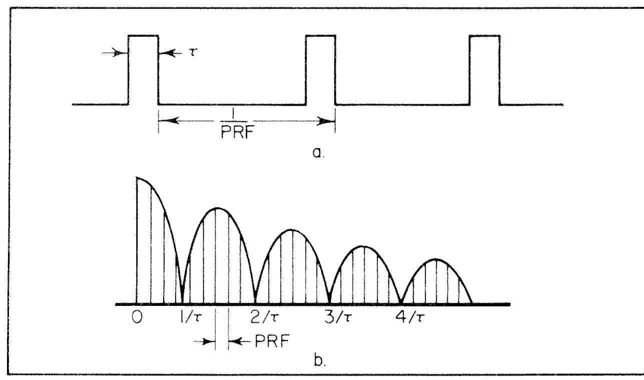


Figure 10. Pulse Spectrum

The spectrum of a pulse in (a) the time domain and (b) the frequency domain. The frequency spectrum consists of lines spaced at intervals of the repetition frequency (PRF). The magnitude of these lines follows a (sin x)/x function. A single pulse, such as a switching transient, would not have any spectral lines since it has an infinite repetition rate.

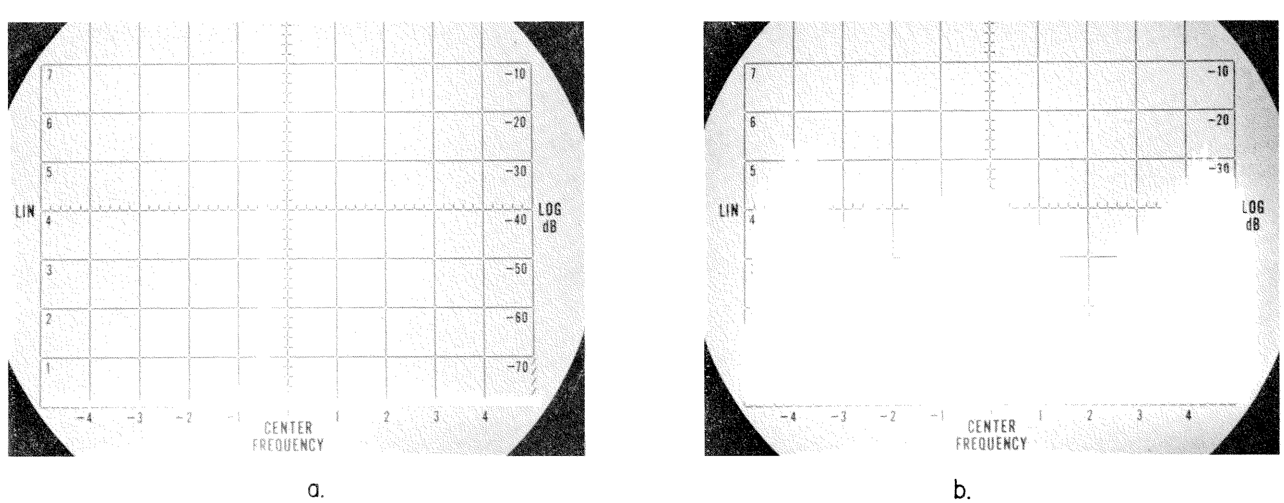


Figure 9. Narrow-band and Broadband Signals

Signals are separated into two classes, narrow-band and broadband, because of their different effect on frequency-selective susceptible devices. A CW signal (a) produces energy at only one frequency and is, therefore, narrow-band. Energy is distributed across a wide frequency range by impulse noise (b) which is a broadband signal.

Broadband signals are distinguished from narrow band signals in MIL-STD-463 as follows: Broadband emission is "that which has a spectral distribution sufficiently broad, uniform, and continuous so that the response of the measuring receiver in use does not vary significantly when tuned over a specified number of receiver impulse bandwidths." Narrow-band emission is defined as "that which has its principal spectral energy lying within the bandpass of the measuring receiver in use."

It is evident from the definitions that classification of these signals depends on the impulse bandwidth of the receiver used. What we really want to know, however, is if the interference energy will degrade performance of a susceptible device. Thus, we would like to classify broadband or narrow-band signals in terms of the bandwidth of expected susceptible instruments. Unfortunately, for general EMI measurements, we do not know these bandwidths in advance and thus are restricted to the above definitions.

Although the boundary between the broadband and narrow-band signals is somewhat hazy, we can make some useful generalizations. Signals that can be represented on a frequency-amplitude plot as a single line or group of single lines spaced at wide intervals are classed as narrow-band signals. Signals that appear as continuous bands of energy are broadband signals. Consideration of the response of a tuned voltmeter to impulse signals of various repetition frequencies will illustrate the difference between broad band and narrow band signals. (See Figure 11).

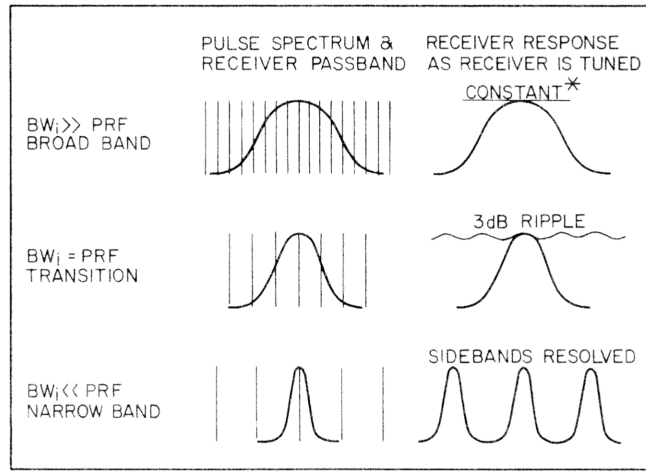


Figure 11. Receiver Response to a Pulse

The ratio of the receiver impulse bandwidth (BW_i) to the pulse repetition frequency (PRF) determines whether a signal is broadband or narrow band.

**If the receiver bandwidth is wide enough to contain a sufficient number of spectrum lines, the receiver response will vary with time.*

EMI INSTRUMENTATION

The spectrum analyzer and many other instruments for measuring the output voltage of the pickup transducer (antenna or current probe) are superhetrodyne receivers, operating as calibrated, tunable RF microvoltmeters. These other instruments, known by several names – RI/FI meters (radio interference/field intensity), NFI meters (noise and field intensity), and FIM (field intensity meters) – are essentially the same. They are mechanically tuned receivers with a meter readout. Often plug-in RF tuning heads are used to cover the tuning range desired. These receivers are very sensitive, but do not have flat frequency response. Therefore they must be calibrated at each frequency. (Calibration charts or internal calibration signals are usually provided.) With suitable input attenuation and preselection, these instruments can measure over a wide amplitude range. Their only real disadvantage is lack of speed. Modern EMC requirements demand that measurements be performed quickly and accurately so that evaluation and modification may be expedited.

The requirements for modern EMI instrumentation are stated in DOD directive No. 3222.3 as follows: "the future of electronic design and electromagnetic analysis depends directly upon the use of the best instruments and techniques. These are the basic tools of electronics and electrical engineering: not special EMC instruments and techniques."

THE SPECTRUM ANALYZER

Using a spectrum analyzer (Figure 12) the EMC engineer will be able to expand his measurement capability and save him invaluable time. EMC engineers are often frustrated by radiated emission specifications and procedures because these often specify that the antenna position, polarization, instrument mode, etc. be adjusted for maximum reading. This is very time-consuming if you are looking at each frequency individually. Furthermore, there is always the chance that signals may be overlooked. With a specific antenna orientation and instrument control setting, an instrument may appear to be clean; but significant signals may be detected by changing conditions slightly. However, with the spectrum analyzer displaying a wide frequency range at once, monitoring the effects of continuous adjustment of device controls, antenna position, and reflective devices in the room is possible. Although changing test conditions in a searching fashion as suggested may not lead to completely repeatable results, chances are very good that all significant emissions will be observed. These emissions can then be measured under controlled conditions. This is a very significant point in view of the recent increased emphasis on EMC. It is no longer sufficient to just measure "by the book"; a thorough and fast investigation is necessary if the goal of EMC is to be realized.

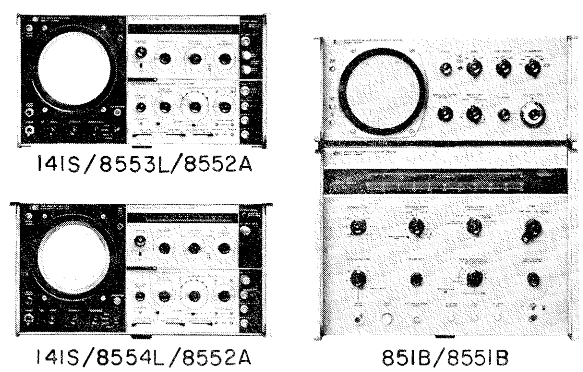


Figure 12. HP Spectrum Analyzers

EXAMPLE V

COMPARISON OF EMI RECEIVER OPERATION

Hand-tuned RFI Receiver

As the operator carefully hand-tunes the receiver through each band looking for signals, he adjusts the device under test to create these interference signals. He must be extremely careful to observe all important control combinations at all frequencies. If a signal is found, the device controls and antenna are adjusted to maximize this signal. The signal strength is measured, evaluated, and recorded point by point. Correction factors are added to the raw data and the results are recorded on graphs to present the information in a meaningful form. Hand-tuned receivers can be converted for automated measurements by the addition of servo motors. Then a complete sweep is made for each operating mode of the device under test.

Spectrum Analyzer

The analyzer is tuned and set for the desired frequency display. Entire frequency bands are evaluated at once. The device under test and the antennas are adjusted to maximize the signals. Effects of these adjustments on all frequencies within the band can be noted at once. The type of signal is determined (broadband, narrow band, AM, FM, pulse, etc.) and checked against specification limits. The entire spectrum is recorded with photographs showing the effects of changes on all signals simultaneously. The time saved using the spectrum analyzer can be used for more detailed evaluation or for problem solving.

The spectrum analyzer is a superheterodyne receiver, as are conventional field intensity meters, but the analyzer has two important differences — the input is swept and the response is constant with frequency. The block diagram of the spectrum analyzer appears in Figure 13.

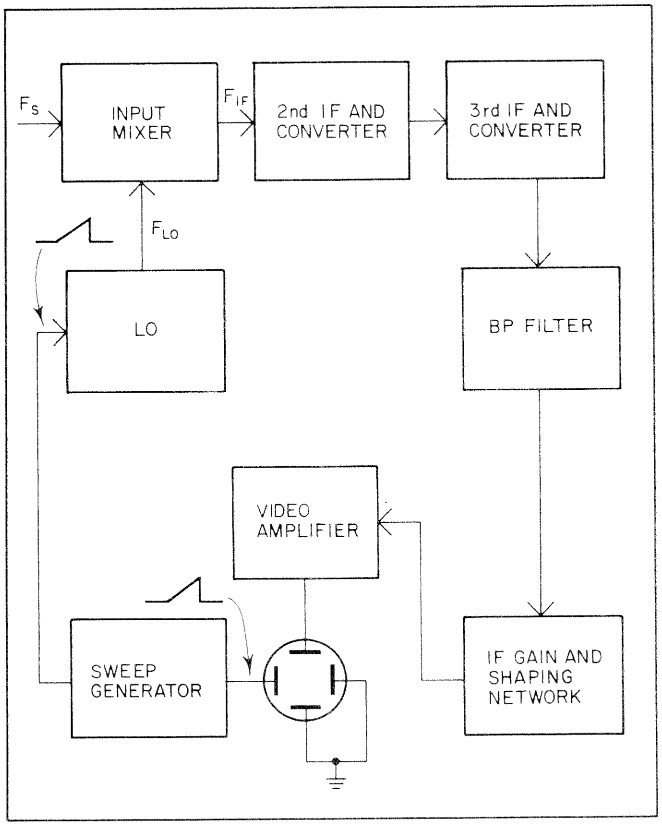


Figure 13. Functional Block Diagram

The spectrum analyzer is a superhetrodyne receiver with a swept CRT display. Signal amplitude is presented as a function of frequency.

Signal power is combined with local oscillator power in a mixer. The mixer is a nonlinear device and produces outputs at the sum and difference frequencies of the two input signals. If the mixer is driven hard enough by the local oscillator, harmonics of this signal are generated. These harmonics are also added with the signal, and sum and difference frequencies are present at the mixer output. The IF amplifier is tuned so that it responds to only one frequency, F_{IF}. The equation describing the output of the IF amplifier is:

$$F_S = nF_{LO} \pm F_{IF}$$

where

F_S = signal frequency

n = harmonic number

F_{LO} = local oscillator frequency (variable)

F_{IF} = intermediate frequency.

As F_{LO} is varied, the input band F_S is scanned. The analyzer bandwidth is determined by the bandpass filters, since these filters have the smallest bandwidth in the signal path. These filters are important for they determine the noise bandwidth and therefore the analyzer's ultimate sensitivity. The impulse bandwidth is also determined by the shape of these filters. (More information on the theory of operation of the spectrum analyzer is available in the instruction manuals for the instruments or in Application Note AN 63.)

Since extremely wide frequency bands are presented for analysis at once, time for EMI measurements can be considerably reduced. The HP 851/8551 Spectrum Analyzer is capable of displaying a 2 GHz spectrum in one sweep, but presently the frequency scan is limited by the antennas or preamplifiers available for use with the analyzer. The 8552A/8553L is a low frequency analyzer. With it you can view signals from 1 kHz to 110 MHz.

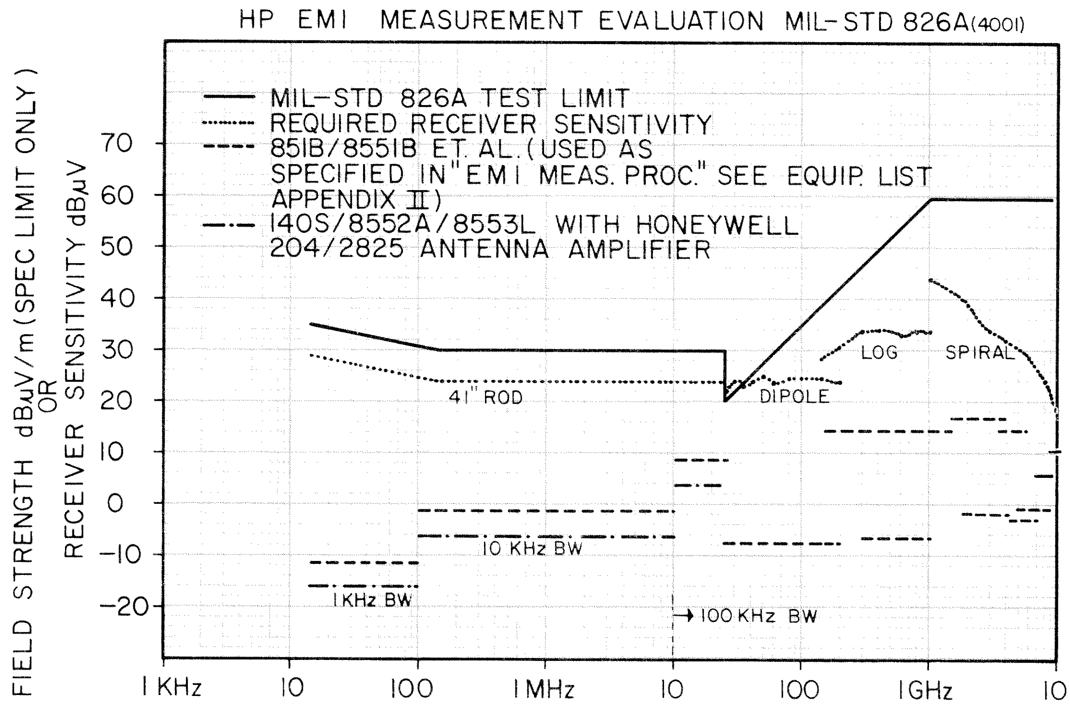
The flat response of these spectrum analyzers means that interference amplitude and frequency are the CRT display coordinates. At present, antennas and current probes have the only frequency-dependent transfer functions in the system, but it is a simple matter to incorporate these and the specification limit into a single line on the analyzer display. Recording data with a spectrum analyzer CRT photograph eliminates manual data plotting, since the photograph records signal amplitude versus frequency directly.

Use of a swept first local oscillator in the 851/8551 Spectrum Analyzer greatly reduces the cluttered display formerly common to spectrum analyzers. Furthermore, all signals appearing on the screen are easily and positively identified. However, it is desirable to clear up the display further with preselection filters. Fixed-tuned bandpass filters can be used for this purpose with good results, but the ideal solution (above 2 GHz) is the 8441 Preselector*, a voltage-tunable filter which tracks the spectrum analyzer input.

The 8552A/8553L Spectrum Analyzer has an internal preselection filter and uses only fundamental mixing. Therefore, input signals between 1 kHz and 110 MHz have only one response each. There is no ambiguity using this analyzer; it has been designed for fast, uncomplicated operation.

Sensitivity of the 851B/8551B is typically -100 dBm in a 10 kHz bandwidth from 10 MHz to 2 GHz. The 8553L Spectrum Analyzer has a sensitivity of typically -110 dBm in a 10 kHz IF bandwidth. Preamplifiers can be used to improve the basic analyzer sensitivity to that required for measurement to particular specification limits. The sensitivity of the spectrum analyzer systems is compared with the requirements of MIL-STD-826A and MIL-STD-461 in Figure 14a and 14b, respectively.

*The preselector also substantially increases the analyzer's dynamic range in broadband measurements since the spectrum analyzer has a nominal bandwidth of 50 MHz (see page 11 for further information).



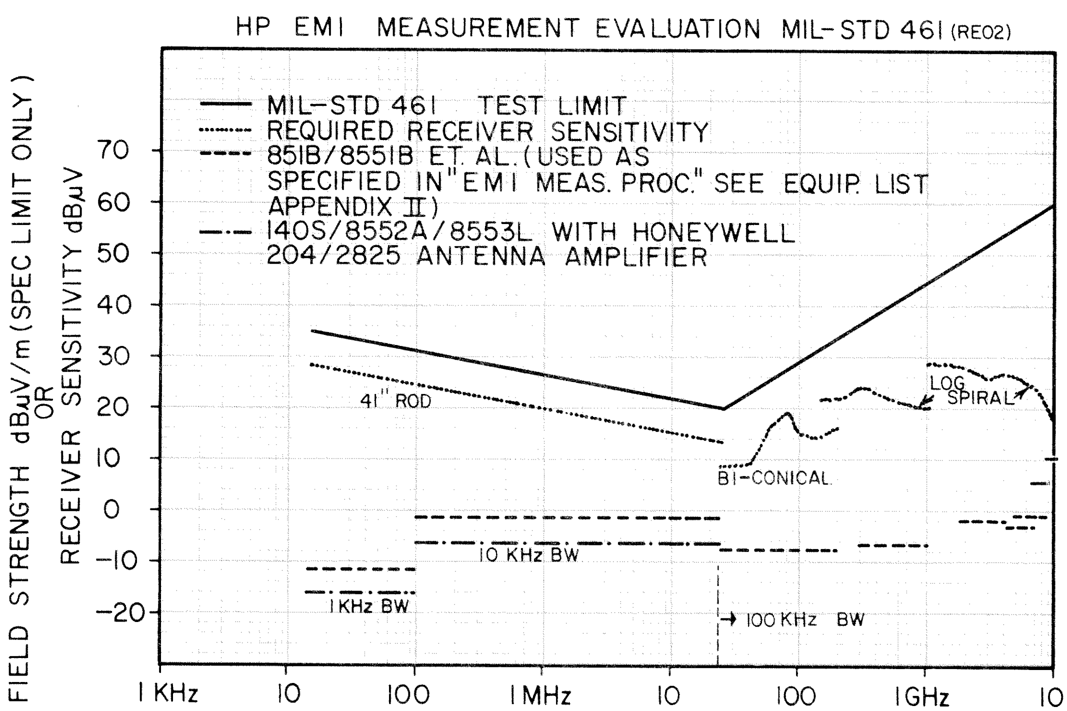


Figure 14a and 14b. Sensitivity of HP Spectrum Analyzers

These figures compare the spectrum analyzer capability with the requirements of MIL-STD-826A and MIL-STD-461. Since radiated emissions tests require the most sensitivity, only these limits are plotted. The graphs show that in all cases the analyzers and accessory equipment have adequate sensitivity for the measurement. For other measurements preamplifiers often are not needed. See Appendix II and the "EMI Measurement Procedure" for details.

Despite the advantages of fast measurement, broadband presentation, and easy troubleshooting that the spectrum analyzer brings to EMI measurement, the instrument has not been used extensively in the past. This is due in part to the fact that the previous spectrum analyzers were difficult to use and that they were not included in the lists of equipment approved for measurements to military specifications. But because of recent improvements in the spectrum analyzer and the need for faster measurements, it is expected that many future EMI tests will be performed by these instruments.

USING THE SPECTRUM ANALYZER FOR EMI MEASUREMENT

As a guide to the use of the spectrum analyzer, Hewlett-Packard has published a handbook <u>EMI MEASUREMENT PROCEDURE: Calibration and Operation of the HP 851B/8551B Spectrum Analyzer to Measure Electromagnetic Interference</u>. Test setups and test limits are drawn from MIL-STD-826A, and examples are worked with typical analyzer parameters to give the user a feeling for the results that can be expected and also a step-by-step procedure for use with MIL-STD-826A. However, the measurement procedure is not limited to testing to MIL-STD-826A; it can be used with other EMI specifications as well since the use of the analyzer will be essentially the same.

Calibration

The spectrum analyzer is easily calibrated for both narrow-band (dBμV) and broadband (dBμV/MHz) measurements. Since the analyzer response is flat throughout each frequency band, calibration need only be performed once for each band. Calibration of the spectrum analyzer consists of recording the response to a known signal level from a CW signal generator and assigning a calibration factor, C_2, to the instrument.

The voltage incident on the analyzer at any particular frequency is

$$V\ (\text{dB}\mu\text{V}) = A_o - G - |L| + C_2$$

where

- V = input signal level
- A_o = input attenuator setting in dB
- G = IF gain setting in dB
- $|L|$ = Magnitude of the signal peak read off the display in dB
- C_2 = the narrow band calibration factor for the spectrum analyzer. This is found by recording the response to a known signal level, V, and solving the above equation for C_2.

Since the 8552A/8553L Spectrum Analyzer is already calibrated in dBm, C_2 is a constant, 107 dB, and

$$V\ (\text{dB}\mu\text{V}) = V(\text{dBm}) + 107\ \text{dB}$$

An additional calibration factor must be used when measuring broadband signals. This calibration factor, B, can be derived from measurement of the impulse bandwidth BW_i as:

$$B = 20 \log (BW_i/1\ \text{MHz}).$$

B is subtracted from the measured signal level V at the input of the analyzer to give spectral intensity S required:

$$S\ (\text{dB}\mu\text{V/MHz}) = V\ (\text{dB}\mu\text{V}) - B\ (\text{dB MHz})$$

Measurement of the impulse bandwidth* to find the factor B is described in detail in the EMI MEASUREMENT PROCEDURE. The measurement involves the use of a precisely known pulse train or an impulse generator with a calibrated output. The bandwidth factor B is dependent only on the IF bandwidth and need be measured only once per bandwidth used; i.e., neither frequency bands nor broadband preamplifiers have an effect on B. In situations allowing reduced amplitude accuracy in the order of 1 or 2 dB, the 6-dB bandwidth can be used as an approximation of the impulse bandwidth. This can be measured from the display of a CW signal. See Figure 15.

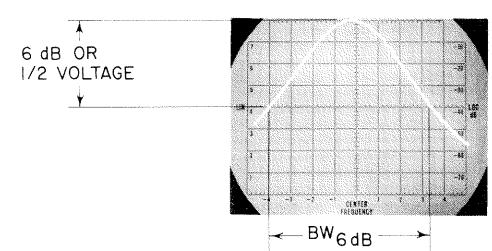


Figure 15. Measurement of 6-dB Bandwidth

Measurement of 6 dB bandwidth. The impulse bandwidth is closely approximated by the 6-dB bandwidth, which can be measured by examining the linear display. In linear, 6 dB is 1/2 voltage. In this case, the scan width is 20 kHz/div; therefore the 6-dB bandwidth is 148 kHz and B - 17 dB.

Addition of C_2, B, the spectrum analyzer gain, and the input attenuation to calibrate the spectrum analyzer is simplified by use of the EMI calibration slide rule available upon request from your HP field engineer.

*The impulse bandwidth is defined as the peak value of the response transient (V_p) divided by the spectral intensity (S) of the impulse signal causing the transient:

$$BW_i = V_p/S$$

Signal Identification

Three kinds of signals are encountered when making EMI measurements: broadband, narrow band, and spurious. With the HP spectrum analyzer it is easy to differentiate between these signals. Traditional EMI receivers have multiple detector functions that were used to classify broadband and narrow band in testing prior to MIL-STD-826A and 461, 2, and 3. Broadband and narrow-band signals were then defined in terms of the responses of average, peak, and quasi-peak detectors. These detectors differed in their time constants. However, with the present definition of broadband and narrow band signals (Page 11), only peak detection is needed.

Broadband random noise is easily recognizable from its spectrum signature (See Figure 9b). Impulse noise may also appear as a continuous function when observed on the analyzer; however, it may look like a series of regularly spaced CW signals. If the repetition frequency of the pulse is very low compared to the IF bandwidth, the response will vary with time. At certain settings of the scan (sweep) time, "lines" will appear. However, these "lines" are a function of time and are not spectrum lines. If changing the scan time changes the number of these responses, the signal is broadband.

Intermodulation responses will be generated if there is too much power incident on the input of any electronic receiver. These responses are generated inside the receiver and are not present at the input. For EMI measurement they do not give any useful information about the input signal and only make the display confusing. With the HP spectrum analyzer, these spurious signals will not be generated if the instantaneous voltage is less than 3 mV. (This is a -40 dBm CW signal into 50Ω). To determine if spurious responses are present due to overdriving the spectrum analyzer, increase the input attenuator in 10 dB steps. The signal level will go down in corresponding 10 dB steps if the signal is real. If, however, the signal is being generated by overdriving the analyzer, it will move in steps greater than 10 dB. When the mixer is not overdriven, all signals are true signals from the electromagnetic environment.

The 851B/8551B Spectrum Analyzer front end is wide open (i.e., no internal preselection) to allow greater versatility. However, since wideband signals are not limited, the analyzer may be overloaded by pulses or noise with broad spectral content. This condition of mixer saturation may be detected by using the input attenuator as above or noting the spectral intensity and the spectrum width of the signal. The maximum total power permissible at the 50Ω input of the mixer of the 8551B is -10 dBm (for 1 dB gain compression of a CW signal and 0 dB input attenuation). Thus, a broadband signal spread over 100 MHz could have a maximum power density of -33 dBm/MHz, or +74 dBμV/MHz.

The use of the HP 8441A Preselector above 2 GHz increases the maximum allowable input power density to +77 dBμV/MHz no matter what the actual noise spectrum width. This is possible since the preselector is a tracking filter with a nominal bandwidth of 50 MHz.

An added benefit of the preselector is that it virtually eliminates multiple responses. These responses are generated when one frequency, F_S, satisfies the mixing equation, $F_S = nF_{LO} \pm F_{IF}$, for several values of n as F_{LO} is varied. Then one signal may generate several responses. The preselector attenuates these responses since it is an input filter tracking F_S. The number of these responses may also be reduced with fixed-tuned filters passing only the frequency range of interest. If the preselector is not used, each signal can be identified using the signal identifier on the 8551B. The 100 MHz spectrum analyzer (141S/8552A/8553L) has a fixed preselection filter built in and there are no multiple responses.

The three steps to signal identification are summarized in Table 2.

Measurements with the Spectrum Analyzer

Once the analyzer system is calibrated in terms of the input voltage and the interference signals identified, the interference level must be compared with the specification limit. To do this, you must account for the antenna factor or the current probe factor or the transfer function of the particular pick-up used. Adding

Table 2. Signal Identification

Broadband or Narrow-band?	Change Scan (sweep) time.	If the spacing between signals changes, response is broadband. If not, it is narrow-band.
Spurious? A. Intermodulation Product	Add Input Attenuation in 10 dB steps.	If the response amplitude decreases by more than 10 dB, intermodulation responses are generated. Increase the input attenuation until all signals drop in 10 dB steps.
B. Multiple Response (due to harmonic mixing.)	Identify frequency and harmonic number or use preselection.	This step is necessary when the 852A/8551B is used without preselection. It is not necessary with the 141S/8552A/8553L.

these factors you convert to the units used to define the specification limit.

When you are making a series of measurements to a particular EMI specification, you may find it convenient to mark the specification limit directly on the analyzer CRT. A marking pencil or a fiber-tip pen is satisfactory for this purpose. If the same measurements are repeated often, you may find it convenient to make up transparent overlays for the CRT with the specification limits and frequency range marked on them. A photograph of the CRT will show both the interference level and the specification limit for documentation and future comparison.

EXAMPLE VI

The calibration of the spectrum analyzer for EMI measurements is actually quite easy. To illustrate, consider the following example:

In this power line conducted measurement we have a broadband signal between 0 and about 16 MHz and a narrow band signal at 12.3 MHz. Since the analyzer used is the 8553L/8552A, we can read the narrow band signal level directly. The top graticule line (LOG REF) is -37 dBm or 70 dB μV (-37 dBm + 107 dB) and the scale is 10 dB/division; the signal level is, therefore, 43 dBμV.

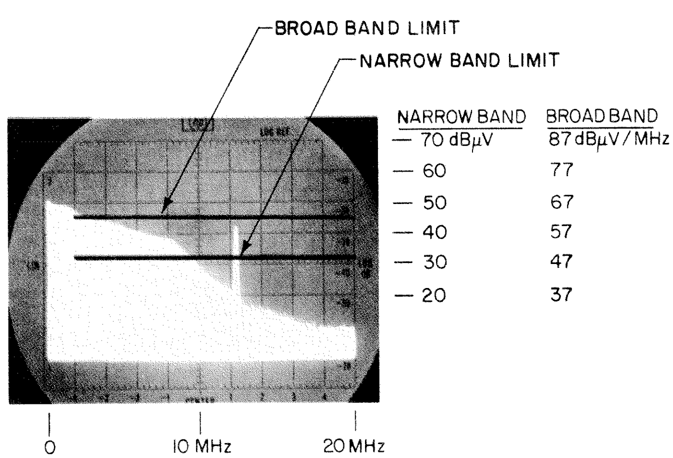
To find the broadband signal level we will calibrate each graticule line using the bandwidth factor, -17 dB, previously measured. The top line is 70 dBμV; therefore,

$$S \frac{\text{dB}\mu\text{V}}{\text{MHz}} = 70\ \text{dB}\mu\text{V} - (-17\ \text{dB}) = 87\ \frac{\text{dB}\mu\text{V}}{\text{MHz}}$$

At 10 MHz the broadband signal level is 45 $\frac{\text{dB}\mu\text{V}}{\text{MHz}}$.

The specification limit between 2 and 50 MHz from MIL-STD-461 method CE03 is 20 dBμA for narrow band signals and 50 dBμA/MHz for broadband signals. The current probe factor, 12 dBΩ at these frequencies, will be added to the specification limit.* For narrow band signals the derived limit becomes 32 dB μV (20 dB μA + 12 dB mV/MHz) and the broadband limit is 62 dB μV/MHz. Comparing these limits with the measured signal levels, we see that the narrow band signal is 11 dB out of spec while the broadband signal is below the limit above 3 MHz.

* If we add the probe factor to the specification limit, (the same technique is used in Figure 14 for radiated measurements), measurements are greatly simplified. Then the probe factor need only be taken into account once and the signal levels can be referred to the resulting "derrived specification limit".



CONCLUSIONS

The spectrum analyzer will be most valuable to the EMC engineer as a time-saving device. Measurements which, in the past, took him days can now be completed in hours. This time saved can be used for more thorough investigation narrowing the gap between the ideal of compatibility and the reality of interference. Furthermore, due to the reduced cost of faster EMI measurement, the recommendations of the EMC engineer will be better received by management.

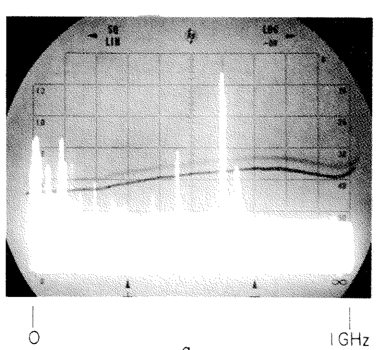
Design engineers will also greatly benefit from the use of the spectrum analyzer in EMI testing. The time saved means that the project will be returned sooner. If time for EMI testing can be reduced sufficiently, projects can be tested during the early design stages and compatibility can be designed in. In fact, since many design engineers are already familiar with and use the spectrum analyzer, they can make many preliminary EMI tests at their bench. This will be a great help in evaluation of design changes and will speed completion of the project.

On the previous pages we have surveyed the compatibility problem, have looked closely at EMI measurements, and have seen several examples of EMI measurements made with HP spectrum analyzers. In particular we have learned how to use the Hewlett-Packard spectrum analyzers for these applications. What remains is to see typical EMI measurements made with the 851A/8551B and the 141S/8553L/8552A Spectrum Analyzers.

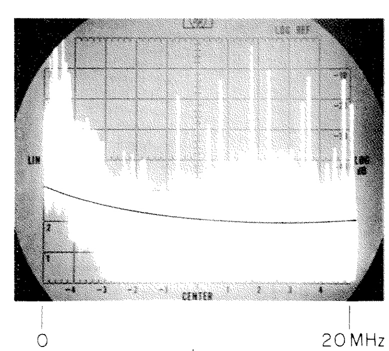
EXAMPLE VII

EMI ENVIRONMENT

In this example we illustrate the magnitude of the EMC problem. In photograph a we are looking at the frequency range of 10 MHz to 1 GHz. High level commercial signals (TV and FM) are easily spotted and, through strict controls and high power levels, there is little interference. However, at lower frequency levels, the public communications channels, 0.2-20 MHz, are exceedingly crowded (Photograph b). A low-power signal is easily lost in the background noise. It is obviously important that electronics systems generate energy only within their assigned frequencies. In both photographs the line drawn on the CRT is the MIL-STD-461 radiated interference limit.



a.



b.

APPENDIX I

Quasi-Peak Measurements Using a Spectrum Analyzer

AN 63E-1

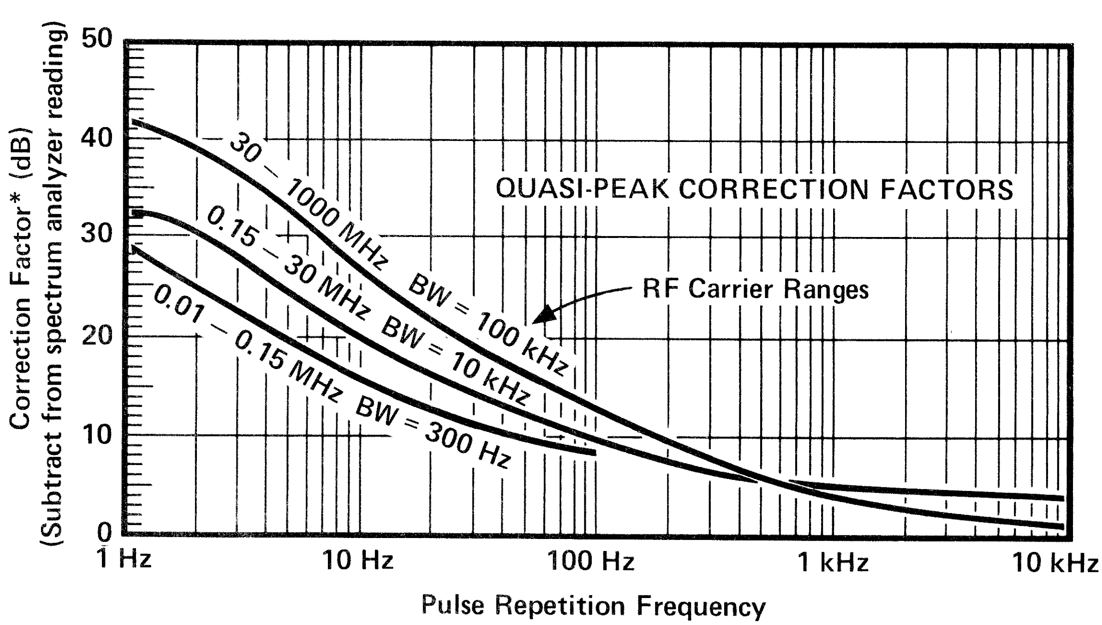
INTRODUCTION

With the rapid increase in electrical and electronic equipment and communications systems come more and more problems of Electromagnetic Compatibility (EMC) and Electromagnetic Interference (EMI, RFI). This interference is due primarily to broadband noise resulting from repeated impulses. Early work of C.I.S.P.R. (Comite International Special des Perturbations Radioelectriques = International Special Committee on Radio Interference) led to the conclusion that the best measure of the effect of this type of interference would be by using a quasi-peak type of voltmeter. This type of voltmeter gives a weighted value depending on PRF (pulse repetition frequency) such that a lower PRF (pulses occurring less frequently) results in a lower reading. Subsequent experience has shown that a true peak or r.m.s. voltmeter might be more accurate, but the quasi-peak measurement has been retained because 1.) peak and quasi-peak indications are nearly the same for relatively high PRF's; 2.) there is extensive experience with quasi-peak readings which reflect the "nuisance value" of broadband noise; 3.) a large number of test sets using quasi-peak type voltmeters are already in existence.

HOW TO GET QUASI-PEAK VALUE

HP Spectrum Analyzers can be used to make quasi-peak measurements if the PRF is known or measured from the Spectrum Analyzer display. The quasi-peak value is found by subtracting the factors in the graph below from the indicated peak value on the Spectrum Analyzer in the bandwidths indicated on the curves. If another bandwidth is chosen, subtract 10 dB *more* for *each step wider* in bandwidth (with 1, 3, 10 sequence). For example, if the level on the analyzer is +44 dBμV (-63 dBm) at 20 MHz in the 30 kHz bandwidth and the PRF is 10 Hz; then the quasi-peak value is +44 dBμV -20 dB (correction factor) -10 dB (bandwidth correction) or +14 dBμV.

These curves are valid for C.I.S.P.R., V.D.E., British Standards, Australian Standards, and others based on C.I.S.P.R. For CW signals, quasi-peak and true peak voltmeters give similar readings.



In the 30 - 1000 MHz range, quasi-peak = r.m.s. if PRF > 10 kHz.

In the 0.01 - 30 MHz range, quasi-peak is undefined for PRF's > 10 kHz because the spectral lines are resolved.

*Includes conversion of spectrum analyzer IF bandwidth to equivalent impulse bandwidth.

HOW TO DETERMINE PRF

The way we determine PRF depends on whether the pulses are periodic or random burst. For example, if the pulses repeat at a regular interval i.e., periodic, then with a wide bandwidth we will see a "pulse" spectrum rather than a "line" spectrum*, as shown in figure 1a. Then we can video trigger on the pulses and vary the scan time of the analyzer to determine the PRF from the scan time per division setting (see figure 1b). Now that the PRF is known, the quasi-peak level can be determined for any frequency in the "pulse" spectrum using the appropriate correction factor from the graph.

Pulses may sometimes occur at random intervals rather than periodic. The maximum level for a quasi-peak meter in the "pulse" spectrum is a result of the pulses spaced closest together. This pulse spacing can be determined by single scanning the Spectrum Analyzer several times and using the greatest PRF displayed to determine the quasi-peak level.

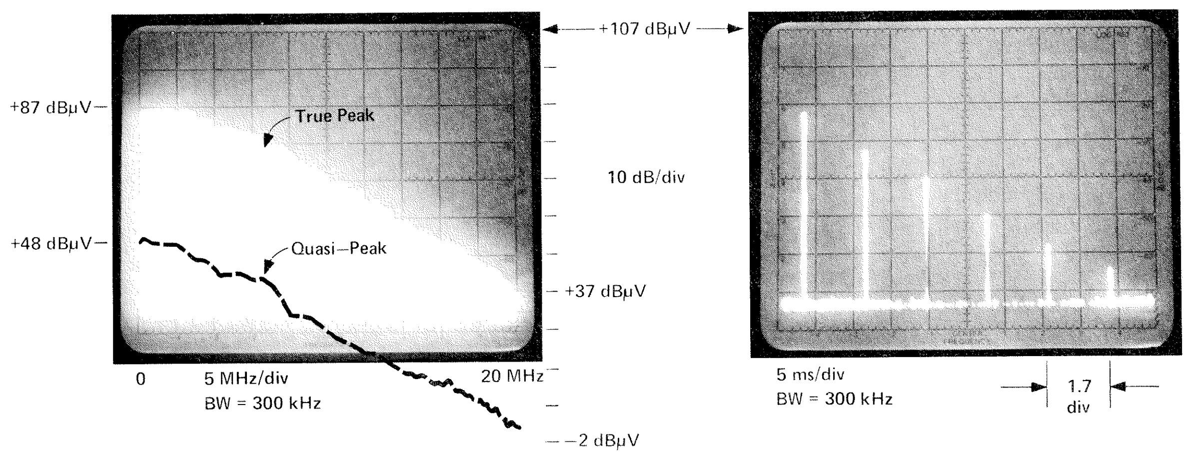


FIGURE 1. (a) This is the true peak of conducted EMI from an SCR light dimmer, and the quasi-peak level found from the graph. (b) The PRF is determined by video triggering and using the calibrated scan time to determine the time between pulses.

In the example above, the $\text{PRF} = \frac{1}{1.7\ \text{DIV} \times 5\ \text{ms/DIV}} \cong 120\ \text{Hz}$. From the graph, the quasi-peak correction factor is 9 dB in the 0.15-30 MHz range. The 300 kHz bandwidth used in this measurement is 3 steps (300 kHz, 100 kHz, 30 kHz, 10 kHz) *wider* than the 10 kHz bandwidth designated in the graph. Hence, the bandwidth correction factor is 30 db. Therefore, the quasi-peak level is 39 dB down from the level indicated on the Spectrum Analyzer.

NOTE: In situations where broadband measurements must comply with exacting CISPR standards, the spectrum analyzer may be limited in terms of potential overload or lack of sensitivity. These limitations, however, can be overcome through the use of external preselection and/or preamplification.

*Refer to HP Application Note 150-2 (Lit. No. 5952-1039) for detailed discussion of pulsed RF spectra.

APPENDIX II

HEWLETT-PACKARD RECOMMENDED EQUIPMENT FOR MIL-STD-826A

The following list is the equipment recommended by the Hewlett-Packard Company for EMI testing to MIL-STD-826A. The list is designed around use of the HP 852A/8551B Spectrum Analyzer. (The 851B Spectrum Analyzer Display Section can be substituted in all cases for the 852A Variable Persistence Display.) To record spectrum displays, the 197A Oscilloscope Camera is recommended for all tests. Additional equipment peculiar to the instrument under test may also be required.

Method	Description	Freq. Range	Manufacturer	Model No.
3001 Conducted Interference (30 Hz to 14 kHz)	Hewlett-Packard Wave Analyzers (302A, 310A, 312A) being tested for compatibility with 826A. Cannot recommend at this time.			
3002 Conducted Interference (14 kHz to 100 MHz)	Spectrum Analyzer	1.0 kHz to 100 MHz	HP	141S/8553L/8552A
	Current Probe	15 kHz to 50 MHz	Genistron or	GCP 5130
		30 Hz to 100 MHz	Stoddart or equivalent	91550-1
	10 μF feedthrough capacitors (two required)	---	Solar or	6512-106
			Genistron or equivalent	GF-4150-1
	Oscilloscope Camera	---	HP	197A
3003 Antenna, Terminal Conducted, Lower Power, 14 kHz to 10 GHz	Spectrum Analyzer	10 MHz - 40 GHz	HP	852A/8551B
	Spectrum Analyzer	1.0kHz - 100 MHz	HP	141S/8553L/8552A
	Preselector	1.8 GHz - 12.4 GHz	HP	8441A
	Low Pass Filter	0 - 1.8 GHz	I-Tel	FLT/02-1800-23/50-28A/28A
	Low-Noise Traveling-Wave Tube Amplifier	4 GHz - 8 GHz	Watkins-Johnson	WJ-286 or WJ-423
	Traveling-Wave Tube Amplifier	7 GHz - 11 GHz	Watkins-Johnson	WJ-287 or WJ-424
	Oscilloscope Camera	---	HP	197A
3004 Antenna, Terminal Conducted, High RF Power, 14 kHz to 10 GHz	Spectrum Analyzer	10 MHz - 40 GHz	HP	852A/8551B
	Spectrum Analyzer	1.0kHz - 100 MHz	HP	141S/8553L/8552A
	Preselector	1.8 GHz - 12.4 GHz	HP	8441A
	Low Pass Filter	0 - 1.8 GHz	I-Tel	FLT/02-1800/23/50-28A/28A
	Low-Noise Traveling-Wave Tube Amplifier	2 - 4.5 GHz	Watkins-Johnson or equivalent	WJ-281-2

Method	Description	Freq. Range	Manufacturer	Model No.
3004 (cont'd)	Low-Noise Traveling-Wave Tube Amplifier	4 - 8 GHz	Watkins-Johnson or equivalent	WJ-286
	Low-Noise Traveling-Wave Tube Amplifier	7 - 11 GHz	Watkins-Johnson or equivalent	WJ-287-2
	Resistive Divider Probe 10:1 (20 dB)	---	HP	10201B
	Resistive Divider Probe 50:1 (34 dB)	---	HP	10201C
	Resistive Divider Probe 100:1 (40 dB)	---	HP	10201D
	Dual Directional Coupler	100 MHz - 2 GHz	HP	778D
	Dual Directional Coupler	1.9 GHz - 4.0 GHz	HP	777D
	Directional Coupler	3.7 GHz - 8.3 GHz	HP	798C
	Directional Coupler	8.0 GHz - 12.4 GHz	HP	H01-789C

Fundamental Frequency Rejection Filters: low pass, high pass or band rejection filters that offer minimum attenuation for frequencies other than the fundamental frequency and offer high attenuation for the fundamental frequency.

Measurement Range	Minimum Rejection for Fundamental Frequency
14 kHz - 100 MHz	90 dB
100 MHz - 1.8 GHz	77 dB
1.8 GHz - 10 GHz	50 dB

Method	Description	Freq. Range	Manufacturer	Model No.
	Turret Attenuator	0 - 12.4 GHz	HP	354A
	Attenuator Pad	0 - 12.4 GHz	HP	8491A, Op 20
	Oscilloscope Camera	---	HP	197A
3005 Conducted Interference, 30 Hz to 150 kHz. Inverse Filter Procedure.	Cannot recommend at this time.			
4001 Radiated Interference, 14 kHz to 10 GHz	Spectrum Analyzer	10 MHz - 40 GHz	HP	852A/8551B
	Spectrum Analyzer	1.0 kHz - 100 MHz	HP	141S/8553L/8552A
	Preselector	1.8 GHz - 40 GHz	HP	8441A
	Low Pass Filter	0 - 1.8 GHz	I-Tel	FLT/02-1800-23/50-28A/28A
	Wideband Antenna Amplifier	14 kHz - 30 MHz	Honeywell	AW-204/2825
	Broadband Dipole Antenna	20 MHz - 65 MHz, 65 MHz - 200 MHz	Singer	MD-105-T1
		25 MHz - 90 MHz	Stoddart	91865-2
		90 MHz - 200 MHz	Stoddart	91870-2
	Log Conical Antenna	100 MHz - 2000 MHz	Emco	CLP-1A

Method	Description	Freq. Range	Manufacturer	Model No.
4001 (cont'd)	Log Conical Antenna	950 MHz - 12 GHz	Emco	CLP-1B
	Preamplifier	10 kHz - 400 MHz	HP	35002B
		300 MHz - 1 GHz*	Avantek	AL-50B
	Low-Noise Traveling-Wave Tube Amplifier	4 GHz - 8 GHz	Watkins-Johnson or equivalent	WJ-286
	Low-Noise Traveling-Wave Tube Amplifier	7 GHz - 11 GHz	Watkins-Johnson or equivalent	WJ-287-2
	Oscilloscope Camera	---	HP	197A
4002 Radiated Interference, 20 Hz to 50 kHz (Magnetic Field	Cannot recommend at this time.			
5001 Conducted Susceptibility, 30 Hz to 150 kHz	Oscillator	5 Hz - 600 kHz	HP	200CD
	Power Amplifier		To be determined.	
	Isolation Transformer (per Fig. 5001-1 of Mil-Std 826A)	---	Possible: Solar Co.	
	Low Frequency Scope		HP	
	Phase Shifter (if device under test is AC powered) per Fig. 5001-3 of Mil-Std 826A.			
5002 Conducted Susceptibility, 150 kHz to 400 MHz	Signal Generator	50 kHz - 65 MHz	HP	606B†
	Signal Generator	10 MHz - 480 MHz	HP	608E†
5003 Intermodulation, Two-Signal, 14 kHz to 20 GHz	Signal Generators up to 21 GHz	10 Hz - 10 MHz	HP	651B
	2 each:	10 MHz - 480 MHz	HP	608E
		450 - 1230 MHz	HP	612A
		800 - 2400 MHz	HP	8614A
		1800 - 4500 MHz	HP	8616A
		3.8 GHz - 7.6 GHz	HP	618C
		7.0 GHz - 11 GHz	HP	620B
		10 GHz - 15.5 GHz	HP	626A
		15 GHz - 21 GHz	HP	628A
	Coaxial Accessories:			
	2 each 10 dB Attenuators	0 - 12.4 GHz	HP	8491B, Op 10
	1 each 6 dB Attenuator	0 - 12.4 GHz	HP	8491B, Op 06
	1 each Type N Tee			

†(External monitoring specified in 826A manual is meter readout on 606B & 608E.)

Method	Description	Freq. Range	Manufacturer	Model No.
5004 Intermodulation, Broadband	Cannot recommend at this time.			
5005 Rejection of Undesired Signal at Input Terminals, 30 Hz to 20 GHz	Same as listed under 5003.			
	Frequency measurement equipment (± 0.5% accuracy)			
	Electronic Counter	0 - 50 MHz	HP	5245L
	Frequency Converters	50 - 512 MHz	HP	5253B
		0.2 - 3 GHz	HP	5254B
		3 - 12.4 GHz	HP	5255A
	Frequency Meters	0.96 - 4.20 GHz	HP	536A
		3.7 - 12.4 GHz	HP	537A
		3.95 - 5.85 GHz	HP	G532A
		5.30 - 8.20 GHz	HP	J532A
		7.05 - 10.0 GHz	HP	H532A
		8.20 - 12.4 GHz	HP	X532B
		10.0 - 15.0 GHz	HP	M532A
		12.4 - 18.0 GHz	HP	P532A
		18.0 - 26.5 GHz	HP	K532A
5006 Spike Susceptibility	Cannot recommend at this time.			
5007 Cross-Modulation 14 kHz to 20 GHz	Same as listed under 5003. (Need a signal generator that can be amplitude modulated below 50 kHz.)			
5008 Squelch Susceptibility	Cannot recommend at this time.			
6001 Radiated Susceptibility, 14 kHz to 20 GHz	Spectrum Analyzer	10 MHz - 40 GHz	HP	852A/8551B
	Spectrum Analyzer	1.0 kHz - 100 MHz	HP	141S/8553L/8552A
	Resistive Divider Probe 100:1 (40 dB)		HP	10201D
	Dual Directional Coupler	100 MHz - 2 GHz	HP	778D
	Dual Directional Coupler	1.9 GHz - 4.0 GHz	HP	777D
	Directional Coupler	3.7 GHz - 8.3 GHz	HP	798C
	Directional Coupler	8.0 GHz - 12.4 GHz	HP	H01-789C
	Vertical Remote Antenna	14 kHz - 150 kHz	Singer or Stoddart	VR-1-105, 41" 92199-3, 92221-2, 92943-1
			or equivalent	

Method	Description	Freq. Range	Manufacturer	Model No.
6001 (cont'd)	Vertical Remote Antenna	150 kHz - 30 MHz	Singer or Stoddart or equivalent	VA-105, 41" 92197-3, 92198-3, 92199-3
	Broadband Dipole Antenna	20 MHz - 200 MHz	Singer (74.5")	MD-105-T1
		25 MHz - 90 MHz	Stoddart	91865-2
		90 MHz - 200 MHz	Stoddart	91870-2
	Log Conical Antenna	100 MHz - 2000 MHz	Emco	CLP-1A
	Log Conical Antenna	950 MHz - 12 GHz	Emco	CLP-1B
	Horn Antennas	10 GHz - 20 GHz	Empire	
	50Ω Coaxial Termination	0 - 4 GHz	HP	908A
	Signal Generators: (amplifier required)	10 kHz - 10 MHz	HP	651B
		50 kHz - 65 MHz	HP	606B
		10 MHz - 480 MHz	HP	608E
		450 - 1250 MHz	HP	612A
		800 - 2400 MHz	HP	8614A
		1.8 - 4.5 GHz	HP	8616A
		3.8 - 7.6 GHz	HP	618C
		7.0 - 11.0 GHz	HP	620B
		10.0 - 15.5 GHz	HP	626A
		15.0 - 21.0 GHz	HP	628A
	Sweep Generators: Can be used in place of signal generators (amplifier required).	1 - 2 GHz	HP	8691A
		2 - 4 GHz	HP	8692A
		4 - 8 GHz	HP	8693A
		8 - 12.4 GHz	HP	8694A
	Amplifiers:	10 - 500 MHz	HP	230A
		500 - 1000 MHz	To be determined	
		1 - 2 GHz	HP	489A
		2 - 4 GHz	HP	491C
		4 - 8 GHz	HP	493A
		8 - 12.4 GHz	HP	495A
6002 Radiated Suscepti-bility, Induction Field	Cannot recommend at this time.			
7001 Internal Combustion Engines, Equipment and Vehicle Using, 14 kHz to 400 MHz	Cannot recommend at this time.			

APPENDIX III

A LIST OF SOME OF THE IMPORTANT EMI SPECIFICATIONS

MIL-I-16910A. Interference Measurement, Radio, Methods and Limits;14 kc - 1000 mc. This standard was originated by the Navy in 1954. The objective of this specification was to provide uniform and repeatable measurements.

MIL-I-26600. Interference Control Requirements, Aeronautical Equipment. This specification, first issued in 1958, covered the frequency range 150 kHz - 10 GHz. It is divided in three classes differing by the distance from antenna to instrument under test.

MIL-I-6181D. Interference Control Requirements, Aircraft Equipment. This specification is nearly identical to MIL-I-26600, except that only one antenna distance is required. It was originated in 1959.

MIL-I-6051C. Electrical/Electronic System Compatibility and Interference Control Requirements for Aeronautical Weapon Systems, Associated Sub-systems and Aircraft, 1960. This specification was generated to be used on system-level tests. Frequency range and test setup are specified as those in normal system operation. Test limits allow 6 dB safety margins for malfunction.

MIL-STD-449C. Radio Frequency Spectrum Characteristics, Measurement of. This standard, written for the Armed Forces Supply Support Center in 1965, provides standard techniques for the measurement of the radio-frequency-spectrum characteristics of electronic equipment or spectrum signatures. It is used extensively at the Electromagnetic Compatibility Analysis Center, ECAC.

MIL-STD-826A. Electromagnetic Interference Test Requirements and Test Methods, originated in 1966. This specification supersedes MIL-I-26600. It represents a significant departure from previous Mil Standards. To this point Mil Standards had been nearly identical, differing only in test setup and specification limit details. Contributions of this spec were the addition of swept measurement techniques and the measurement of transient emission and susceptibility. Hewlett-Packard has published a detailed procedure for using the spectrum analyzer to make EMI measurements to this specification.

MIL-STD-461, -462, and -463. Requirements, Measurement, and Definition of Electromagnetic Interference Characteristics. These are the recently approved (1967) tri-service specs. They represent an effort to standardize and combine EMI measurement with the object of increased probability of compatibility. It is intended that they supersede many previous standards.

In-House Specifications. These procedures, written by manufacturers, are generally modifications of one of the military standards mentioned above. State of the art techniques are used in many of these specifications. Manufacturers use these specifications to test their own equipment. Vendors supplying components to these manufacturers are often required to meet these specs also.

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