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RVEY OF TRIAXIAL AND MODE- RED TECHNIQUES FOR MEASURING THE SHIELDING EFFECTIVENESS OF CONNECTORS AND CABLES

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This report is the result of an extensive literature search conducted in the field of connectors and cables, and of the problem dealing with radio frequency leakage characteristics and the ability to measure the shielding effectiveness of these connectors and cables. It reviews two measurement techniques for determining the shielding effectiveness: the triaxial test technique that has been used for over 20 years and the mode-stirred test technique that recently has started to gain in popularity. From this survey, certain inferences are drawn about these techniques in terms of device configuration, frequency range, and ease of measurement and are presented in chart form for comparative purposes.

Key Words: cables; connectors; mode-stirred; relative leakage power; shielding effectiveness; triaxial.

1. INTRODUCTION

In recent years, one major concern with the design and use of coaxial and multicontact connectors and accompanying cable assemblies has been the amount of electromagnetic (EM) energy or radio frequency (rf) leakage that can be tolerated in today's advanced electronic systems. Toward this end, these systems have been designed to withstand the effects of electromagnetic interference (EMI) at operating frequencies from a few megahertz to many gigahertz. To facilitate system design, shielding effectiveness data are required for connectors and cables that interconnect various components, subassemblies, equipment, and subsystems. The evaluation of shielding effectiveness measurements of connectors and cables has been the subject of a great deal of analysis and research for some time.

Methods of measuring the rf leakage of connectors and cables have received considerable attention over the years. Prominent among these are the use of the triaxial technique [1] which configures the test sample (connector/cable under test) as a segment of transmission line. Recently the mode-stirred technique [2] that utilizes a test chamber to expose the test sample to random incident fields has started to gain in popularity.

This paper briefly reviews the background and analytical principles involved with measuring the shielding effectiveness of test samples with the triaxial and mode-stirred techniques from which their advantages and limitations are given.

2. BACKGROUND

2.1 Shielding Effectiveness

In general, the shielding effectiveness (SE) of a coaxial transmission line is the ability of the outer conductor to protect the transmission line from being disturbed by EM fields leaking into or out of the transmission line. Many groups and organizations have spent considerable time and effort in studying measurement methods dealing with SE [3 - 5]. For connectors and cables, a measure for determining the SE is defined or specified in terms of transfer impedance or relative leakage power.

The transfer impedance is the ratio of the transferred voltage inside the coaxial line (into which the connectors are inserted) to the longitudinal current flowing on the outside of the coaxial line. The general theory of coaxial shields was first presented in 1934 by Schelkunoff [6], in his classic paper, that conceived the term "transfer impedance" to relate the open-circuit voltage induced in the conductors inside a cylindrical shield to the external current flowing on the shield. The evaluation of transfer impedance and thus SE is a relatively complex procedure that is especially difficult to implement for frequencies over 10 MHz [7] and will not be used here.

The relative leakage power, on the other hand, is a more convenient method to implement and use to determine the SE for both the triaxial and mode-stirred techniques. The relative leakage power for determining SE is the rf power which leaks into, or out of, a connector or other device, at a given frequency and is defined by the relationship,

$$SE = 10 \log_{10}(P_1/P_2) \text{ dB}, \qquad (1)$$

where

P_1 = total applied power, and
P_2 = total leaked power.

2.2 Sample Configuration

In the measurement of SE, the device (connector or cable) from which leakage is to be measured is incorporated in a coaxial transmission line which in turn is terminated in a matched load. The matched load simplifies both the measurement procedure and data reduction by minimizing the formation of standing waves which are a major source of error in SE measurements [8]. In measuring the SE of multicontact connectors in a triaxial test fixture, the interior of the connector must be configured as a segment of coaxial transmission line of known impedance. This is accomplished by removing the inserts and the multi-pin contacts from the connector and then substituting a coaxially located center conductor.

The assumption is made that the SE is identical whether the rf power is leaking into or out of the device. In the case of mode-stirring, the power leaking into the device is measured while with the triaxial technique, the power leaking out of the connector is determined.

3. MEASUREMENT TECHNIQUES

3.1 Triaxial Technique

The triaxial technique was developed by Zorgy and Muehlberger [1] for measuring the SE of connectors and cables and enhanced by others [9]. The triaxial technique is used by many organizations and prescribed in MIL-C-

39012B [10] for testing certain rf connectors and in MIL-C-38999H [11] for testing multicontact cylindrical connectors.

Figure 1 is a diagram of a test fixture that is used as the triaxial technique. The test fixture is a segment of coaxial transmission line surrounded by an outer tubular conductor which forms, externally, a second coaxial system that is normally configured for a characteristic impedance of 50 ohms. This implies for each connector and cable size measured that a new test fixture has to be designed and configured to maintain a constant 50-ohm characteristic impedance throughout the test fixture and reduce internal reflections which are a source of errors in the measured SE. The excitation of the outer coaxial line is believed to be principally TEM although it is possible for higher order modes to exist, depending on frequency. The wavelength at the operating frequency must be greater than the mean circumference of the coaxial system to prevent propagation of higher order modes.

The second external coaxial system in figure 1 is terminated at one end in a sliding short circuit and at the other tapered transition in a matched

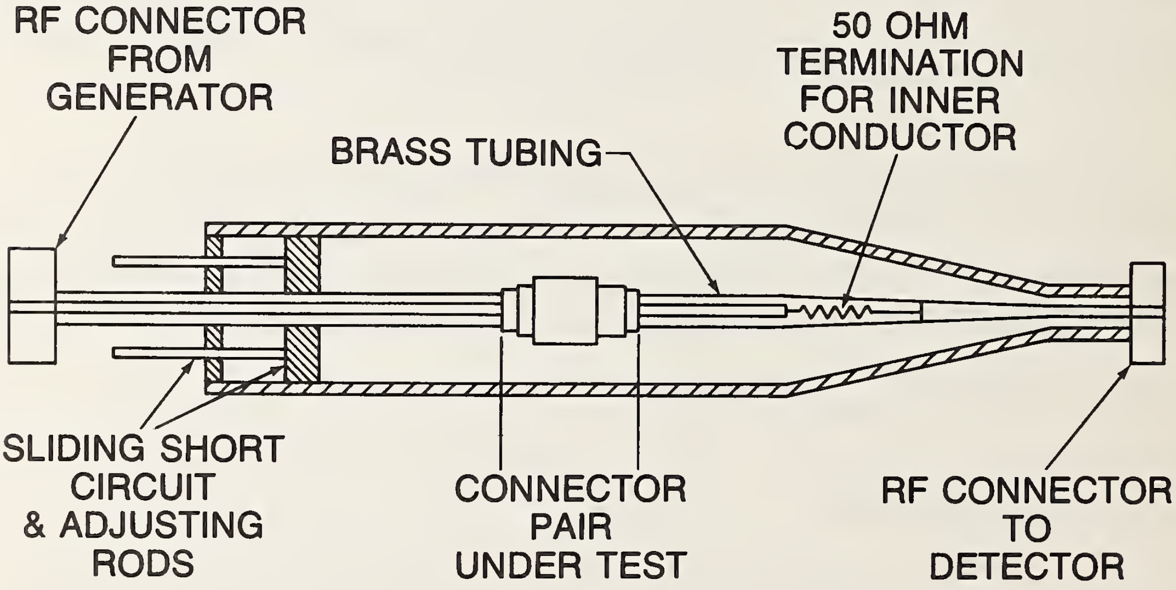

Figure 1. Triaxial test fixture.

detector. The sliding short circuit is positioned to produce a maximum indication at the detector for each test frequency measured. Positioning of the sliding short-circuit must exceed a half-wavelength between the short-circuit and the connector pair under test. On a connector assembly that is properly mounted on semi-rigid cables or air lines, there are three possible leakage areas: the region around the mating face and locking mechanism of the connector plus the two regions where the connector is attached to the cable or air line. For complete leakage measurements, the detector should couple to all three areas.

The SE of the connector pair under test is determined by establishing as a reference and measuring the total applied power P_1 that is fed through the inner coaxial line. Next the power P_2 leaking through the connector pair into the outer coaxial structure is maximized at the detector by the sliding short-circuit and measured. The SE of the connector pair in decibels is determined using equation (1).

Figure 2 is a block diagram of a substitution technique that is also used to determine the SE of the connector pair under test which requires producing a maximum indication at the detector. This is achieved by sliding the short-circuit until the power P_2 leaking through the connector pair into the outer coaxial structure is maximized at the detector. The detector is then connected directly to the power source and the amount of attenuation that is required to bring the detector back to the same detector level as before is measured. The measured amount in decibels is the SE. For low

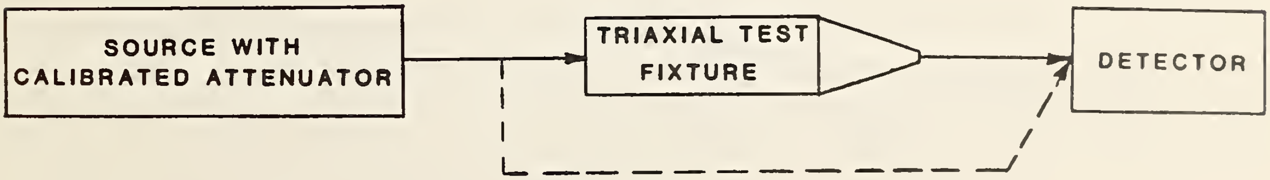

Figure 2. Block diagram of substitution technique.

level SE measurements below about 100 dB, the power source is enclosed in a well shielded enclosure to reduce spurious leakage pickup. If cables are used, additional shielding over the cables is required.

Figures 3 and 4 show SE data obtained using the substitution technique by the National Bureau of Standards (NBS) and others for the IEEE I & M Technical Subcommittee on Precision Coaxial Connectors. The data are of 14-mm coaxial connector pairs measured for SE up to 3 GHz and of 7-mm coaxial connector pairs measured for SE up to 6 GHz using the triaxial technique, respectively. Moreover, these leakage data are representative of several 14-mm and 7-mm coaxial connectors pairs that were measured. About the only thing that can be stated about these measurement results is that the resulting leakage is at least that amount and may not be indicative of the total leakage. The specification limits in figures 3 and 4 are specified in the IEEE Standard on Precision Coaxial Connectors [12].

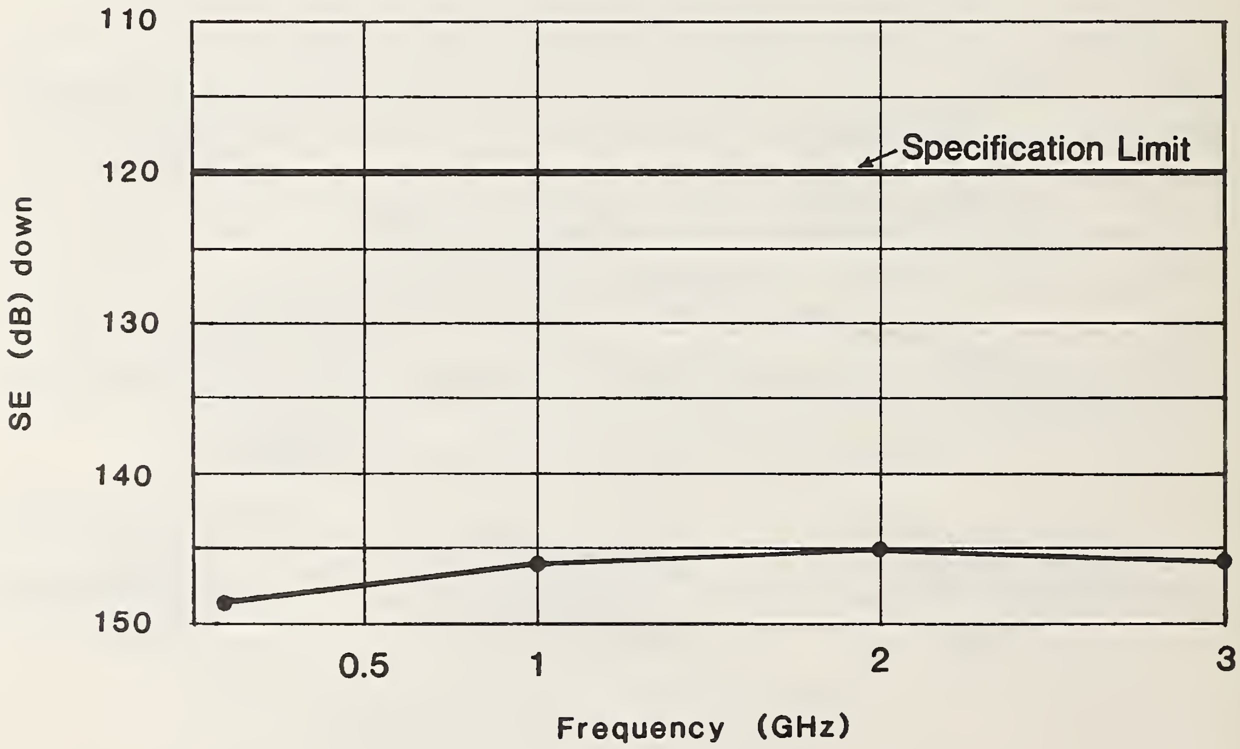

Figure 3. Representative SE of 14-mm coaxial connector pairs up to 3 GHz using the triaxial technique.

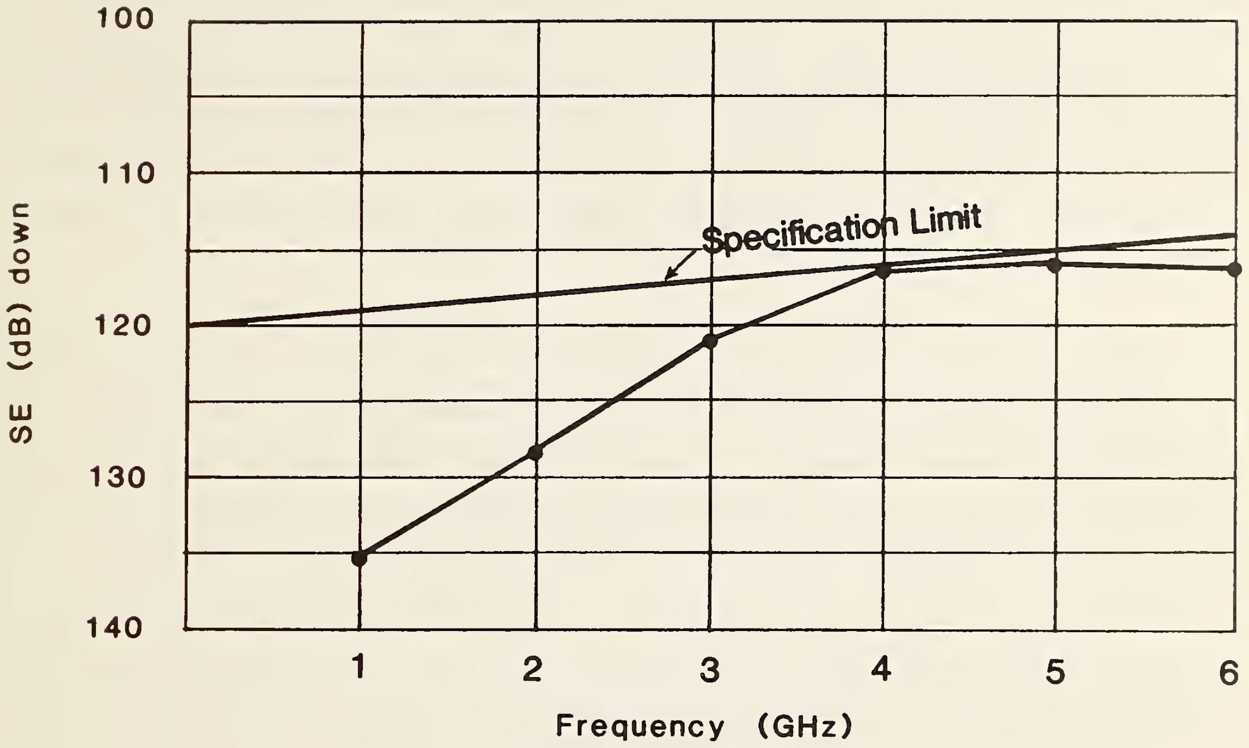

Figure 4. Representative SE of 7-mm coaxial connector pairs up to 6 GHz using the triaxial technique.

TE_{11} mode propagation in the external line of the triaxial test fixture is a possible source of error at frequencies about the cutoff frequency for propagation of this mode. Therefore, for reliable measurement results of SE in typical test fixtures, a high-frequency limit for a 14-mm coaxial connector is 3 GHz while that for a 7-mm coaxial connector is 6 GHz. The regular operating frequencies of these same connectors outside the test fixtures are 8.5 and 18 GHz respectively which precludes the use of the triaxial technique for determining SE on these same connectors over their high-frequency limits because of higher order modes.

A low-frequency limit of 500 MHz is suggested because of the excessive length (30 cm) required for the position of the sliding short-circuit of a half-wavelength below this frequency. Under certain conditions e.g., test fixture size and detector sensitivity, 100 MHz can be achieved by moving the the sliding short-circuit as close as possible to the connectors under test.

To ensure that maximum leakage is obtained, the measurement is repeated for several different orientations of the connector pair. Much effort is required to assure that extraneous signals are not present at the detector. The connector coupling and attachment system are set to the torque limits specified by the manufacturer.

While the triaxial technique has been used for over 20 years for determining the SE of connectors and cables, there are a number of limitations associated with the use of this technique that make this technique experimentally difficult to implement. Typical limitations include one or more of the following:

1. Elaborate test fixture;
2. Problem with higher order modes;
3. Lack of sensitivity at the detector;
4. Requirement of matched terminations to reduce test fixture and generator reflections;
5. Unsuitable for multicontact connectors and test objects not having a cylindrical geometry;
6. Limited in frequency to about 35% of the upper frequency limit of the connector/cable under test;
7. Long setup times.

The main advantage of the triaxial technique is the wide dynamic range (leakage measurements to -150 dB) that can be achieved in the triaxial test fixture.

Finally, special care must be taken to assure that the test cable or connector system that makes up the inner coaxial system must be mounted concentrically with respect to the outer tubular conductor, to minimize TE_{11} mode generation.

Some SE measurements of connectors and cables using quadraxial and quintaxial test methods have been tried [3]. The quadraxial method is somewhat complex to implement but it does allow both the signal generator and detector path to be matched at all frequencies from DC up to that frequency for which TEM modes predominate thus eliminating the need for a sliding short-circuit. The quintaxial test fixture is designed for greater ease of access to the device under test which requires less modification to measure different diameter size connectors and cables.

3.2 Mode-Stirred Technique

The mode-stirred technique is a relatively new method for radiated susceptibility/vulnerability testing using a reverberation chamber. The idea of stirring or tuning the modes inside a large shielded enclosure (reverberation chamber) for electromagnetic compatibility (EMC) measurements was first proposed in 1968 [13]. The objective is to obtain a statistical, time averaged distribution of field strength or power density within a test volume inside the enclosure such that the location of the equipment or device under test (EUT) or (DUT) inside the chamber is not important.

The mode-stirred technique uses two operational approaches depending upon frequency for performing EMC measurements inside the chamber. The first approach, mode tuned (used when the input VSWR is relatively large in the order of 1.5 or more), steps the tuner at selected uniform increments (typically 200 steps or more), permitting measurements of the net input power, reference antenna received power, and the monitored EUT response at each tuner position. This allows corrections to be made for the variations in the chamber's test field resulting from changes in the VSWR of the transmitting antenna as a function of the tuner position. The second approach, mode stirred (used when the input VSWR is below 1.5), rotates the tuner continuously while sampling the reference antenna received power and EUT response at rates much faster than the tuner revolution rate. Large data samples up to 9,999 can be obtained for a single tuner revolution.

The mode-stirred technique for measuring the SE of connectors and cables was adapted by Bean and Hall [2] and is based upon a technique developed by Jarva [14] and work performed by others [15]. The military reported the use of the mode-stirred technique for measuring the SE of connectors and cables in 1978 in proposed MIL-STD-1377A [16]. MIL-STD-1344A [17] was later issued as a design guide of a mode-stirred test chamber and Method 3008 of the same standard for measuring the SE of multicontact connectors. One major manufacturer of electrical connectors developed their own mode-stirred test facility [18] in 1981 in accordance with Method 3008 of MIL-STD-1344A [17] for measuring the SE of multicontact connectors in the 1 to 10 GHz frequency range.

Figure 5 is a diagram of a mode-stirred test system as specified in accordance with Method 3008 of MIL-STD-1344A [17]. The test chamber is essentially a low loss shielded enclosure that includes an input antenna, a reference antenna and a mode stirrer. Testing is conducted inside the test chamber whose smallest dimension is at least three wavelengths at the lowest test frequency to assure an ample mode density which is a necessary

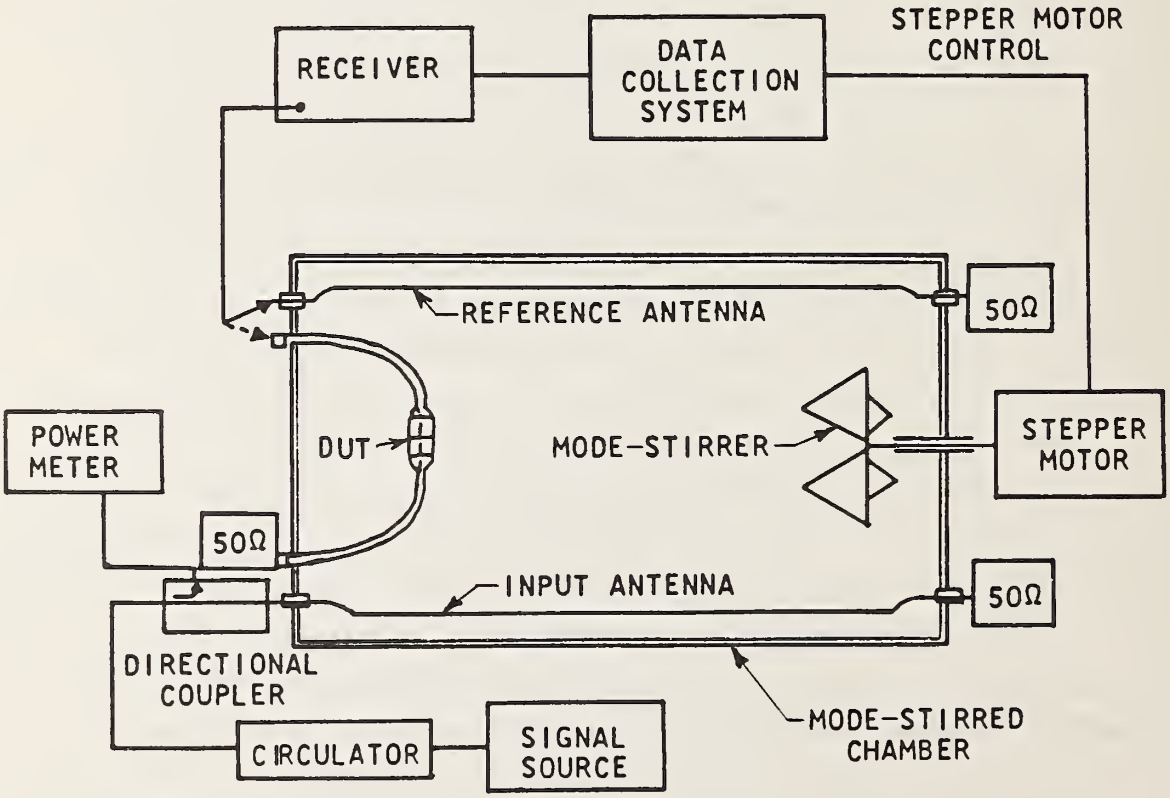

Figure 5. Diagram of mode-stirred test system from MIL-STD-1344A.

condition for the validity of the mode-stirred technique [19]. In addition, the minimum distance between the DUT and the chamber walls is at least one wavelength at the lowest test frequency to maintain a uniform electric field throughout the chamber. The chamber is excited by an input antenna provided by a long wire mounted parallel to the chamber walls. To reduce reflections, impedance matching tapers are used at both ends of the antenna. One end of the antenna is terminated in 50 ohms while the other end is connected to the signal source. A reference antenna of the same length as the input antenna is mounted on the opposite wall with one end connected to a receiver and the other terminated into 50 ohms through impedance matching tapers. The mode stirrer or paddle wheel tuner serves to randomize the multi-mode EM fields existing inside the test chamber when rotated by significantly altering the complex standing wave patterns. Rotation of the mode stirrer changes the relative amplitude of the modes and is intended to ensure that the net field at any point is uniform on a time averaged basis.

To measure the SE of the connector pair under test (DUT), the power P_1 is fed through the input antenna and received by the reference antenna to establish a reference level. Next the power P_2 leaking into the DUT is measured. The SE of the DUT is determined using equation (1) by taking the ratio of the averages (P_1 and P_2) over one rotation of the mode stirrer.

Figure 6 is a block diagram of the mode-stirred reverberation chamber and measurement system at NBS-Boulder. This chamber was developed and evaluated [20] by NBS over a three year period starting in 1982 for performing radiated susceptibility/vulnerability measurements. The dimensions of the chamber are 2.74 m x 3.05 m x 4.57 m, which allows a typical frequency range of application from about 200 MHz to 18 GHz or higher. The test field is established by means of rf source(s) connected to the transmitting antenna(s) placed inside the chamber. Four antennas are required to cover the 200 MHz to 18 GHz frequency range which include:

1) Long wire (200 MHz - 1000 MHz), receiving mode,
2) Log periodic (200 MHz - 1000 MHz), transmitting mode,

3) Ridged horn (1 GHz - 10 GHz), transmitting and receiving modes,
4) Double ridged circular horn (2 GHz - 18 GHz), transmitting and receiving modes.

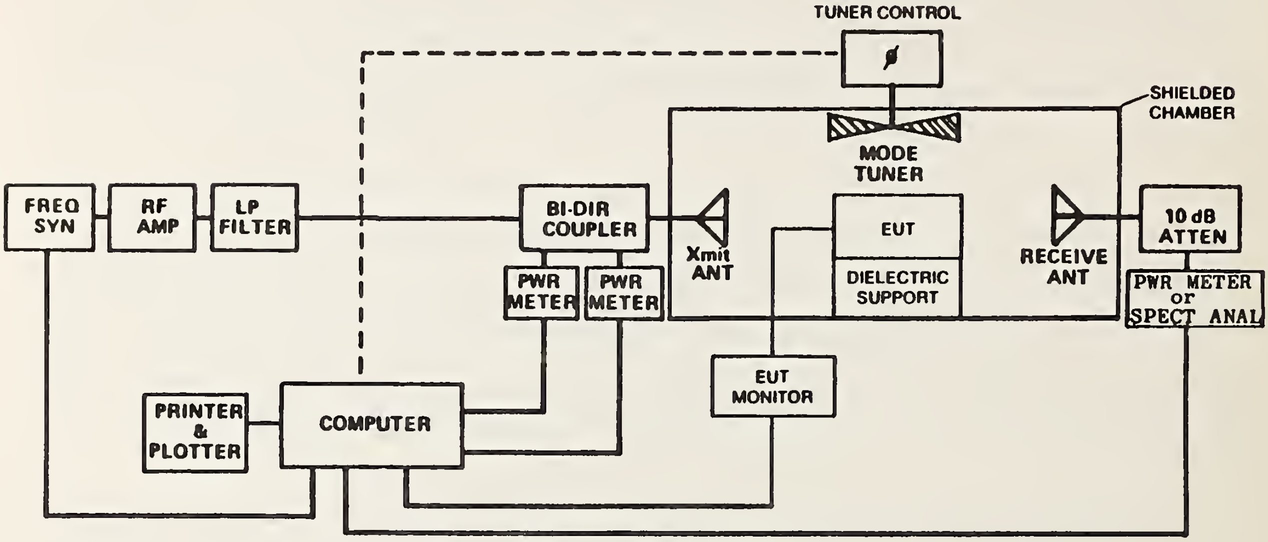

Figure 6. Block diagram of mode-stirred reverberation chamber and measurement system at NBS-Boulder.

Within the recommended frequency bands of operation, the long wire and log periodic antennas can accommodate (below about 500 MHz) up to 1000 W input power while the ridged horns and double ridged circular horns can accomodate up to 200-W input power. Some of these power requirements are necessary for various reference conditions.

Figure 7 shows the placement of a DUT inside the NBS mode-stirred reverberation chamber. The DUT consists of a pair of SMA coaxial connectors mounted on 1.5 m (5 ft) lengths of 0.351 cm (0.141 in) semi-rigid coaxial cable terminated at one end into a 50-ohm load. To measure the SE of the DUT, the power is fed through the transmit antenna and detected by the receive antenna to establish a reference level. Next the power P_2 leaking into the DUT is sampled continuously (mode-stir) and averaged over one tuner revolution. The SE of the DUT in decibels is determined using equation (1).

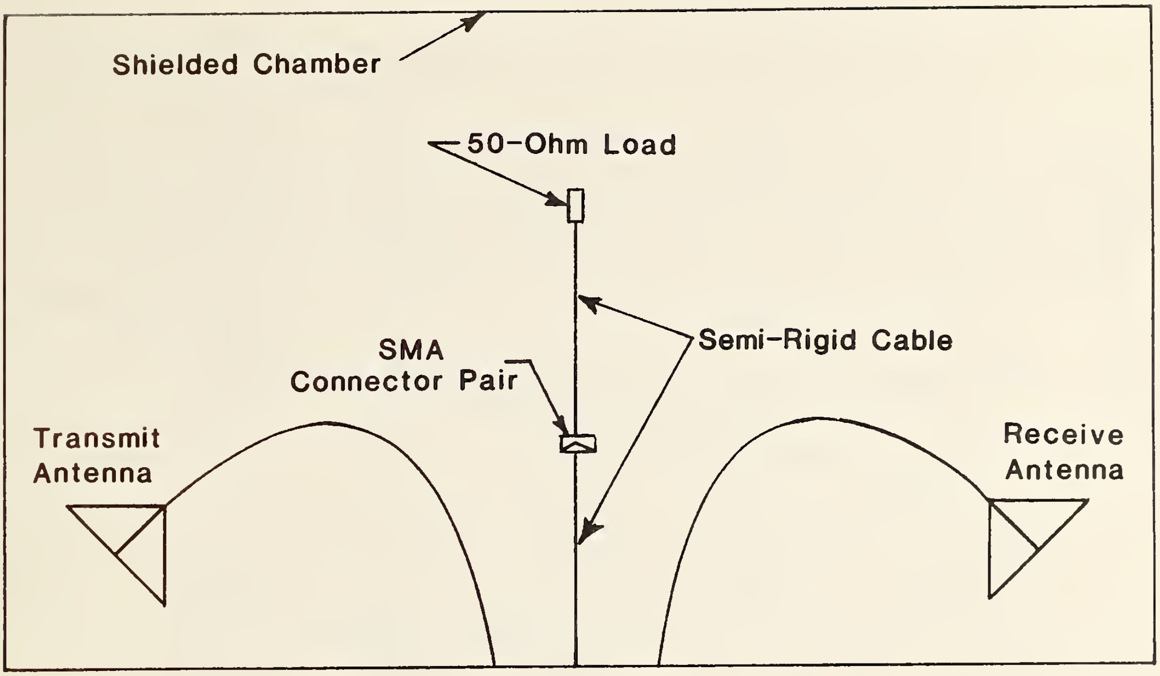

Figure 7. Placement of the DUT (SMA connector pair inside) the NBS mode-stirred reverberation chamber.

Figure 8 shows the SE data that were obtained on the pair of SMA coaxial connectors from figure 7 which were measured for SE at discrete frequencies of 8, 10, 14 and 18 GHz using the mode-stirred technique. MIL-C-39012B [10] lists a specification limit of -90 dB between 2 and 3 GHz for the SE requirements of SMA connectors mounted on semi-rigid cable.

While the mode-stirred technique is a relatively new method for radiated susceptibility/vulnerability testing using a reverberation chamber, there are a number of advantages associated with this technique that make it worth considering for SE measurements on connectors and cables. Typical advantages include one or more of the following:

1. An easily automated test system;
2. Rapid processing of large quantities of test data;
3. Short setup times and test time requirements;
4. The ability to generate high level fields efficiently around the DUT;
5. Easy access to the DUT;

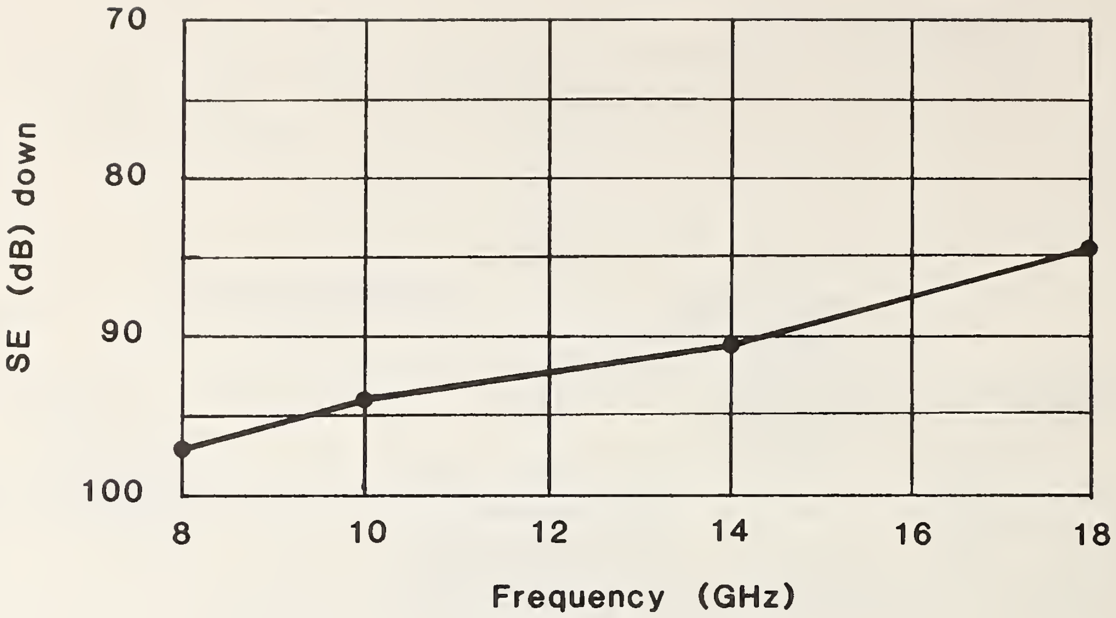

Figure 8. SE of SMA coaxial connector pair at discrete frequencies of 8, 10, 14 and 18 GHz using the mode-stirred technique.

6. Broad frequency coverage up to a least 18 GHz;
7. No requirement to physically rotate the DUT;
8. Easy to configure for multicontact connectors;
9. Convenient for measuring cables;
10. Suitable for measuring connectors and cables having different diameter sizes in the same chamber.

One limitation of the mode-stirred technique is that stray leakage from other leakage paths cannot be directly identified with mode-stirred measurements without retesting. Also, sealing to prevent stray leakage from other sources except the DUT can be a problem, especially with the low SE levels that can be achieved with the mode-stirred system. Another possible limitation with the mode-stirred system is the ability to achieve a dynamic range of -120 dB. This value is dependent to a certain degree upon input power and detector sensitivity limitations, in addition to isolation aspects.

3.3 Comparison of Techniques

Table 1 contains a comparison chart for the triaxial and mode-stirred techniques used for measuring the SE of connectors and cables. The information is taken from the summary of techniques contained in sections 3.1 and 3.2.

TABLE 1

COMPARISON OF THE TRIAXIAL AND MODE-STIRRED TECHNIQUES

TECHNIQUE	Frequency Range	Dynamic Range	Setup Time	Test Time	Elaborate Test Fixture
Triaxial	100 MHz to 6 GHz*	-150 dB	Long	Long	Yes
Mode-Stirred	~500 MHz** to 18 GHz	-120 dB***	Short	Short	No

* - the frequency range can be extended somewhat by adding a mode filter to the triaxial test fixture.

** - lower frequency limited by size of chamber.

*** - dynamic range of the chamber could be extended by placing the measurement system (power sources, detector, computer and etc.) inside a separate shielded enclosure and then use low-noise preamplifiers to extend the usable dynamic range of the detector (spectrum analyzer).

TABLE 1 (continued)

COMPARISON OF THE TRIAXIAL AND MODE-STIRRED TECHNIQUES

TECHNIQUE	Detector Sensitivity	Problem With Stray Leakage	Accessability to DUT	Need to Rotate DUT
Triaxial	Poor*	Average	Hard	Yes
Mode-Stirred	Good	Yes	Easy**	No

* - sliding short-circuit required in triaxial test fixture.

** - Also, much easier to configure and measure multicontact connectors and cables inside the chamber.

Some good agreement (~2 dB) between the triaxial and mode-stirred techniques has been reported [18] on SE measurements taken on a simulated connector using both techniques at overlapping frequencies between 1 and 2 GHz.

4. CONCLUSIONS

The triaxial and mode-stirred measurement techniques for determining the SE of connectors and cables were reviewed and the information compared in chart form. From the information presented, there are a number of advantages associated with the mode-stirred technique that makes this technique worth considering for conveniently measuring the SE on connectors and cables over a wide frequency range above a few hundred megahertz. Toward this end, the NBS plans to build another mode-stirred chamber to specifically accommodate SE measurements of connectors and cables plus additional requirements for SE measurement of composite materials and cable shield terminations for the U.S. Army Aviation Systems Command (AVSCOM).

To date, there have been comparisons of test results [20, 21] of approximately 5 dB between different-sized reverberation chambers at different test facilities of EM susceptibility response measured on the same EUTs. Other interlaboratory comparisons on an artifact need to be performed and the results compared.

5. ACKNOWLEDGMENTS

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11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

This report is the result of an extensive literature search conducted in the field of connectors and cables, and of the problem dealing with radio frequency leakage characteristics and the ability to measure the shielding effectiveness of these connectors and cables. It reviews two measurement techniques for determining the shielding effectiveness: the triaxial test technique that has been used for over 20 years and the mode-stirred test technique that recently has started to gain in popularity. From this survey, certain inferences are drawn about these techniques in terms of device configuration, frequency range, and ease of measurement and are presented in chart form for comparative purposes.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

cables; connectors, mode-stirred; relative leakage power; shielding effectiveness; triaxial

13. AVAILABILITY

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