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Truong X. Nguyen and Jay J. Ely
Langley Research Center, Hampton, Virginia

Sandra V. Koppen
Lockheed Martin Corporation, Hampton, Virginia

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National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

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Abstract

This paper describes the implementation of mode-stirred method for susceptibility testing according to the current DO-160D standard. Test results on an Engine Data Processor using the implemented procedure and the comparisons with the standard anechoic test results are presented. The comparison experimentally shows that the susceptibility thresholds found in mode-stirred method are consistently higher than anechoic. This is consistent with the recent statistical analysis finding by NIST that the current calibration procedure overstates field strength by a fixed amount. Once the test results are adjusted for this value, the comparisons with the anechoic results are excellent. The results also show that test method has excellent chamber to chamber repeatability. Several areas for improvements to the current procedure are also identified and implemented.

I. Introduction

Digital avionics systems are increasingly being employed to perform flight critical functions in commercial aircraft. Their reliable operation is critical in ensuring flight safety. This fact raises concerns about the immunity of these systems to electromagnetic high intensity radiated field (HIRF). Test standards were developed in order to provide practical and repeatable test results for HIRF immunity. Efforts to develop commercial standards for bench testing avionics equipment resulted in the HIRF industry standards in RTCA/DO-160D [1], in the US and the EUROCAE/ED-14D [2] in Europe. Along with the common anechoic or semi-anechoic chamber test method, reverberation chamber method (also called mode-stirred method) was recently adopted as an alternate procedure for radiated susceptibility testing.

The mode-stirred method has several advantages, as well as disadvantages, over the anechoic testing method. The effort described in this paper, in coordination with Boeing Commercial Airplane Group (BCAG), attempts to provide a correlation on a typical “off-the-shelf” engine-data-processor (EDP) using the accepted procedures and field levels in the standard. In this work, the same EDP was tested using the anechoic method at Boeing and the alternate reverberation method at NASA Langley Research Center (NASA LaRC). The main purposes of this effort include providing comparative results between the two test methods, and identifying areas for improvement in the current mode-stirred test procedure. This paper describes the implementation of the mode-stirred procedure and the comparisons of the susceptibility thresholds measured from the two methods.

II. Test Article

Boeing Commercial Airplane Group provided the EDP system for this comparison testing. According to Boeing [3]:

"…the EDP (Engine Data Processor) system for this test is a subset of the Boeing 757 Fiber Optic In-Service evaluation program flying on eight revenue airplanes. The subsystem components for this test and their locations on the airplane are as follows:

- *The EDP (Engine Data Processor), mounted under the cowling on the left engine;*
- *OIC (Optical Interface Controller), installed in the EE Bay;*
- *TLA sensor with one two-channel fiber optic sensor (one redundant pair)…; and*
- *One fiber optic coupler box for connecting the ARINC 629 terminals together (one of two on the airplane, in the EE Bay and under the left wing-to-body fairing).*

The EDP and TLA sensors (optical and electrical) will be exposed to the RF environment inside the test chamber. The OIC will be outside the chamber connected through the chamber wall to the EDP the same way as on the airplane, via a fiber optic ARINC 629 bus and an electrical ARINC 429 data bus. An ARINC 429 monitor PC will be used in place of the optical flight data recorder to monitor the system under test."

"The EDP package was developed by a commercial engine control supplier for the U.S. Navy and NASA to be used for a variety of fiber optic test programs. The units flying in Boeing's 757 in-service evaluation program are under full production configuration control. However, the unit to be used for HIRF testing is the Boeing "SIL" (System Integration Laboratory) unit. This unit has been under engineering configuration control in the Boeing fiber optics lab. Although it is close to production configuration, it is not flight worthy and is marked "SIL Use Only" by the supplier."

"Any of the following general definitions constitute test failure:

- *Any terminal shutdown (OIC or EDP) during susceptibility testing of the EUT*
- *Any round-robin path faults (undetected error) logged during the test.*
- *Exceeded two detected errors during the ten second dwell time at each frequency, or exceeding one detected error in a 5 second time interval during the dwell time*
- *Logging of any faults or exceeding error rates, as described in Appendix A, during susceptibility testing of the EUT.*
- *Catastrophic failure of any component under test."*

The mounting locations of the EDP system on an airplane as part of the In-Service evaluation program are shown in Figure 1.

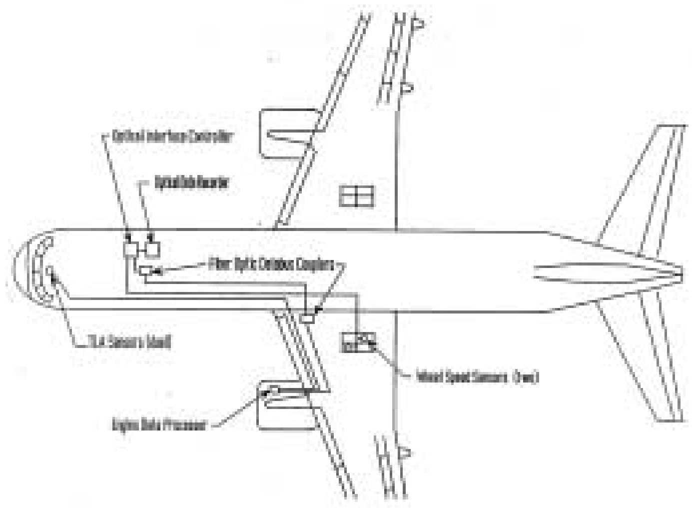

Figure 1: Fiber Optic In-Service Test Configuration (Courtesy of Boeing Commercial Airplane Group)

III. RF Test Levels and Modulations

The EDP system was tested to category Y and category P of DO-160D Section 20 in an anechoic chamber at Boeing and a reverberation chamber at NASA LaRC. Category Y specifies a field strength of 200 V/m from 100 MHz to 18 GHz for both continuous wave (CW) and square wave amplitude modulation (AM). The AM frequency is 1 kHz with 99% modulation depth. Category Y is intended for equipment and wiring installed in severe electromagnetic environments that might be found in non-metallic aircraft or exposed areas in metallic aircraft. In the test at NASA LaRC, the EDP system was exposed to field levels of 250 V/m, or approximately 2 dB above the category Y level. This was to provide an over test margin that was approximately the same as the chamber's field uniformity, to ensure all susceptibilities to category Y levels were detected.

Category P is a pulse modulated test environment and has a peak field level of 600 V/m from 400 MHz to 18 GHz. For this test, the pulse width used for category P was 1 microsecond, with 1 kHz pulse repetition frequency. For a few frequency bands where 600 V/m was not achievable, the EDP system was tested to the maximum obtainable field strength in the chamber with the available amplifiers.

IV. DO-160D Mode-Stirred Test Procedure

A simplified setup diagram for the mode-stirred method is shown in Figure 2. In this illustration, RF power radiated from the transmit antenna (Tx) sets up a certain field structure in a reverberation chamber. The two tuners (or stirrers) are used to change the boundary conditions in the chamber to set up new field structures as they rotate. The more effective the stirrers are, the more influence they have on field structure as they rotate. As a rule, a stirrer is effective if the power density in the chamber varies by more than 20 dB at a given location during a stirrer revolution for all chamber usable frequencies [4]. Once the stirrers complete a rotation, the EUT has been exposed to all possible incident field orientations and strengths, including the maximum field strength. The receive antenna (Rx) is used to monitor the power density in the chamber either for calibration or verification of field strength. The test sequence according to procedure in DO-160D is listed below:

- **DO-160D standard sequence:**

  - If pulse modulation is required, measure the quality factor Q and compute chamber time constant τ. If τ is less than 0.4 times the required pulse width, RF absorbent material must be added to chamber and the Q measurement repeated.

  - Perform chamber power density calibration.

  - Compute input power required.

  - Install EUT.

  - Conduct test using computed input power. Compensate with additional power if RF absorbent characteristics of EUT appreciably reduce calculated peak electric field intensity.

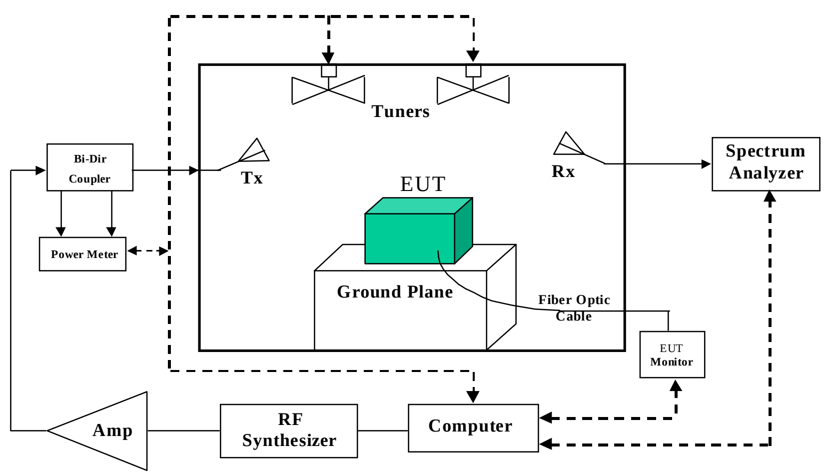

Figure 2: Simplified mode-stirred setup.

The details for each of the above steps are described in [1] and in sections below. As can be seen from the sequence, the procedure calls for performing chamber calibration before the EUT is positioned in the chamber. In addition, chamber's Q and τ are measured and adjusted without the presence of the device to be tested. These may lead to under testing, since many devices absorb RF power and cause more-than-desirable loading in the chamber. To compensate for the loading, DO-160D requires the chamber calibration factor to be monitored during the test and compensated with additional RF power if it drops by more than 3 dB from the original values. No correction is required if the difference is less than 3 dB.

The procedure used in the NASA implementation was similar to that described above, except that chamber calibration was performed *with* the presence of the EUT. The inclusion of the EUT during chamber calibration helped to account for loading effects directly in the calibration factor. Thus the calibration factors were more accurate, and there was no need to correct for equipment loading during the test. The actual test sequence is listed below:

- **DO-160D NASA Implementation:**
  - Install EUT
  - If pulse modulation is required, measure the quality factor Q and compute chamber time constant τ. Add absorber to the chamber if necessary according to DO-160D.
  - Perform chamber power density calibration.
  - Compute input power required.
  - Conduct test using computed input power. No power compensation needed.

The sections below describe the steps involved in performing the NASA implementation.

1. Test Setup

The EDP system was set up according to DO-160D standard, Section 20.3 as shown in Figure 3. The equipment was positioned five centimeters above a wood table with a copper sheet on the top acting as a ground plane. The test table was positioned in the middle of the test chamber, and was at least 1 meter away from chamber structures. The EUT was set on top of its shock and vibration isolators, and grounded through secured contacts between the isolators and the ground plane. All EUT interconnecting wiring and cable bundles were supported approximately five centimeters above the ground plane according to DO-160 requirements. In addition, photographs of the Boeing semi-anechoic chamber experiment setup were used to make the mode-stirred chamber setup as similar as possible. Equipment power cable was shielded starting from the Line Impedance Stabilization Network (LISN) to the entry point on the chamber wall. Exposed cables were shielded from the point they left the table to the chamber wall.

The chamber setup is shown in Figure 4. Two sets of antennas were used to cover the entire test frequency range: a pair of log-periodic antennas to cover 100 MHz – 1 GHz, and a pair of dual-ridge horn antennas to cover 1 GHz – 18 GHz.

The transmit antenna and receive antenna were pointed to different corners of the test chamber or to the stirrers, away from the test table or each other. As required by the standard, they were positioned at least 1 meter away from the EUT, chamber walls or stirrer, except between 8 to 18 GHz. In this range, the transmit antenna was only about 0.5 m from the chamber's wall due to limited waveguide length. This distance was found to be acceptable since it was approximately 13 wavelengths at 8 GHz, which was many times more than the one third wavelength minimum suggested in [4] (on which the current DO-160D was based).

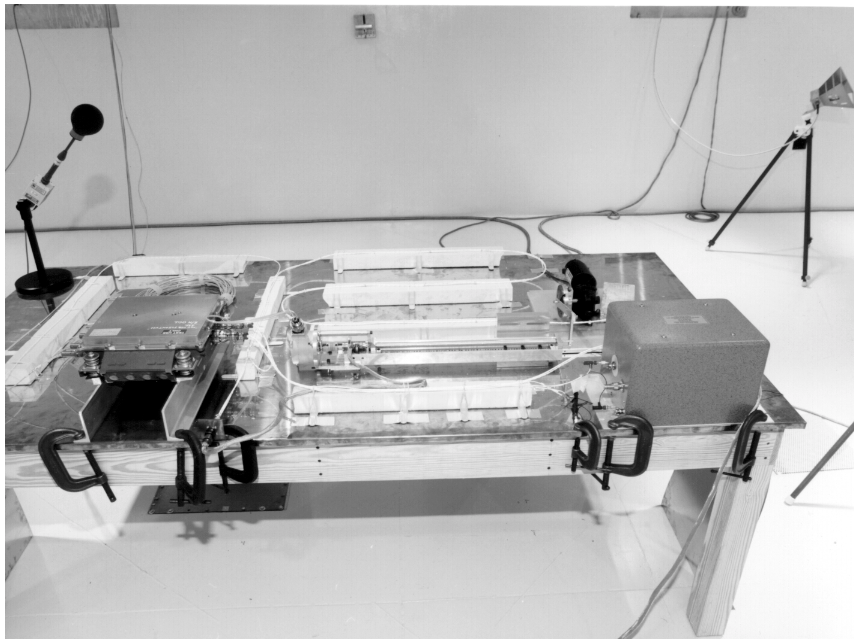

Figure 3: Setup of EUT on conducting table in a reverberation chamber

Figure 4: Setup in the large reverberation chamber

2. Q and τ Check Procedure for Pulse Tests

DO-160D Section 20 [1] pulse test category P requires that the chamber time constant be less than 0.4 of the pulse-width. This is to ensure that the field in the chamber rises to at least 92% of the pulse maximum values before the pulse is turned off. If the chamber time constant is too long, absorber should be added until the time constant requirement is met.

Recent modifications to the standard allow the test pulse width to vary to meet the requirement instead of adding absorber to the chamber, as long as the pulse width is at least 1 microsecond long. At the time of the test, however, this flexibility was not yet accepted by the standard committee. In addition, the EUT was tested in an anechoic chamber at Boeing using 1 microsecond pulse width. Efforts were made in this experiment to use as similar field excitations as possible, and the decision was made to add absorber rather than vary the test pulse width. A major disadvantage was that adding absorber reduces the chamber quality factor Q, causing more power to be required at the input to achieve a given required field strength. In the NASA LaRC's largest reverberation chamber, the necessary amount of absorber reduced chamber power density by as much as 5 dB.

The procedure for measuring Q and τ is described in the DO-160 standard. NASA LaRC's implementation is described briefly below:

From [1], chamber time constants (τ) and quality factor (Q) are expressed as:

$$\tau = \frac{Q}{2\pi f} , \tag{1}$$

and

$$Q = \left(\frac{16\pi V}{\lambda^3}\right)\left(\frac{P_{ave\_rec}}{P_{input}}\right) , \tag{2}$$

where V is the chamber volume (m^3), λ is the free space wavelength (m) at the specific frequency *f*, and $\left(P_{ave\_rec}/P_{input}\right)$ is the ratio of the average receive power over one complete stirrer rotation to the input power.

In short, τ and *Q* can be computed from the ratio $\left(P_{ave\_rec}/P_{input}\right)$, which can be obtained by performing a simple two-step measurement described below:

i) Measure system through-loss:

The two RF cables inside the chamber are connected together. A known power is injected into one end of the cable and the power output at the other end is measured with a spectrum analyzer. The measured power levels establish a baseline that accounts for cable length loss, equipment uncertainties, and other system losses. This procedure is typically performed with just a RF source and a spectrum analyzer. The measurement is repeated for all desired frequencies.

ii) Measure average chamber loss with antennas attached and system through-loss:

Maintaining everything the same as the previous step, the RF cables in the chamber are detached from each other and then attached to the appropriate transmit and receive antennas. The antennas are positioned to reduce direct coupling to each other and to maximize energy stirring by the paddles. Typically, they are directed into a corner or a stirrer. The stirrers are rotated continuously at about 5-10 seconds per revolution. The RF source is set to drive the same power into the cable as that during measuring system through loss. Also, the spectrum analyzer's sweep time is set to be the same as the stirrer rotation rate. The readings at the spectrum analyzer are then averaged over a complete stirrer revolution to yield average receive power. This value includes all of the systems effects measured in (*i*). In addition, it also includes the average chamber insertion loss, antenna inefficiency, and antenna mismatches. The ratio of this value and the value measured in step (*i*) results in the average chamber insertion loss, denoted as $\left(P_{ave\_rec}/P_{input}\right)$, assuming that antenna mismatches and inefficiencies are negligible. The steps are repeated for all desired frequencies.

Applying $\left(P_{ave\_rec}/P_{input}\right)$ into the equations for Q and τ yields the quality factors and chamber time constants at the measured frequencies. τ is then compared against 0.4 times the pulse width to ensure sufficient chamber loading. If the requirement is not met, absorber is added into the chamber, and the procedure is repeated until the rise time requirement is met with minimum amount of additional absorber.

In this test, the chamber time constant requirement, $\tau \leq 0.4\mu\sec$, was met using two absorber configurations, one for frequencies below 1 GHz and another for frequencies above 1 GHz. Absorber pieces were divided evenly at several locations in the chamber for uniform chamber power absorption. The absorber pieces were also positioned so as not to be directly in front of either the transmit antenna or the receive antenna in order to achieve better energy transmission and receive power readings.

3. Chamber Power Density Calibration

The procedure for performing chamber power density calibration is outlined in DO-160D. NASA LaRC's implementation of the procedure is almost identical to that described above for measuring the chamber's Q and time constant, except now the peak receive power (over a stirrer revolution) is measured instead of the average receive power. According to DO-160D, the chamber calibration factor (CF) is computed using [1]:

$$CF = \frac{8\pi}{\lambda^2}\left(\frac{P_{\max\_rec}}{P_{input}}\right). \tag{3}$$

$\mathrm{P_{max\_rec}}/\mathrm{P_{input}}$ is also called the maximum chamber gain. The chamber calibration factor *CF* relates power density in the chamber to 1 watt of input power. Using this calibration procedure, antenna mismatches as well as antenna efficiencies are ignored, even though the effects due to mismatched can be corrected for as shown in [6].

For many high loss situations, like at high frequency or long cable lengths, the spectrum analyzer may not have the necessary dynamic range (peak signal less than 20 dB higher than the spectrum analyzer's noise floor) if the source's output is maintained at the same level in both steps *i)* and *ii)*. In those cases, a pre-amplifier may be necessary, or the source output will have to be adjusted to ensure the receive signals fall within range of the spectrum analyzer. The P_{max_rec}/P_{input} ratio then has to be corrected accordingly to account for the differences in the two source power level settings or the presence of the pre-amplifier.

To reduce the effects of chamber non-uniformity, two different calibration measurements were performed instead of a single measurement calibration as required in DO-160D, with different combinations of positions/orientations of transmit and receive antennas. The results were then averaged to provide an improved estimate of chamber calibration factor.

In DO-160D Section 20, the effects due to antennas are typically assumed negligible. However, this is not always the case. High antenna mismatch (high VSWR) and low efficiency may increase uncertainties in the measurement data if they are not taken into account. The two types of antennas used in this test were a log periodic antenna for frequencies between 100 MHz to 1 GHz and a dual ridge horn antenna for frequencies above 1 GHz. A typical log periodic antenna may have a maximum VSWR of 1.8 and an efficiency of about 75%. A typical dual ridge horn antenna may have a maximum VSWR of about 2.5 and an efficiency of about 90%. A maximum VSWR=2.5 may lead to an uncertainty of 0.9 dB or less, and an 75% antenna efficiency may lead to an uncertainty of 1.2 dB. Uncertainty caused by VSWR can be corrected for using a procedure in [6], whereas antenna efficiency is much more difficult to measure and, therefore, to correct for. In this test, neither of the effects caused by VSWR or antenna efficiency were corrected for in the calibration factors in order to be consistent with the DO-160D procedure.

4. Calculate Required Input Power

From the calibration factors and the category field strength, the required power delivered to the transmit antenna's terminal can be computed [1] using

$$P_{input} = \frac{E^2}{377 * CF} \,, \tag{4}$$

where P_{input} is the required power (W) at the transmit antenna's terminal, *CF* is the chamber calibration factor $((W/m^2)/W)$ determined previously, and *E* is desired field strength (V/m).

5. Conduct Test

As in DO-160D Section 20, once the required power was known, that amount of RF power was delivered to the transmit antenna into the chamber. A power meter was used to provide power leveling with appropriate corrections for coupling factors and cable losses. The stirrer was stepped with a required dwell time or rotated continuously. The EUT was then monitored for any upsets.

Typically, new chamber calibration factors are computed from the measured input power and the receive power to ensure not more than a 3 dB drop from the original computed values. In this test, however, since the chamber was calibrated with the presence of the EUT, the new calibration factors were usually within tolerance. Therefore, it was not necessary to adjust input power to correct for EUT loading.

While being exposed to RF, EUT performance was monitored for any abnormal behaviors according to failure criteria listed previously. Once errors are found, the susceptibility threshold was determined by first reducing the field strength until no upsets found. Input power was then increased gradually (in 0.2 dB steps) until upsets were again detected. The lowest input power at which upsets were detected was then used to compute the susceptibility threshold using:

$$E = \sqrt{377 * CF * P_{input}} \,, \tag{5}$$

where E is field strength (V/m), CF is the calibration factor, and P_{input} is input power at the antenna terminal (W).

The DO-160D Section 20 procedure specifies that either a mode-tuning or a mode-stiring to be used. In the mode-tuned method, the stirrer is stepped through a minimum of 200 steps per revolution while dwelling at each position. Ten seconds of dwell time required for this particular EUT (the time required for error-rate monitoring) translated into 33 minutes per test frequency per power level, which was considered impractical. Thus, either the number of steps had to be reduced, or mode-stirring used.

It was confirmed through testing that this EUT had the same susceptibility threshold with the stirrer either continuously rotated (mode-stirred) or stepped, as long as the EUT was exposed for about 30 seconds or longer. Subsequently, the mode-stirred method was chosen as a more practical approach. For this test, the stirrers continuously rotated at ten seconds per revolution, and the EUT was exposed to RF for a minimum of 30 seconds at each frequency and field intensity level.

The test was conducted in frequency bands that match the bandwidth of the available CW amplifiers: 100 MHz – 1 GHz, 1-2 GHz, 2-4 GHz, 4-8 GHz and 8-18 GHz. The same CW amplifiers were also used for the pulse tests. As stated previously, the EUT was tested to 250 V/m for both CW and AM rather than the required 200 V/m as in category Y.

For pulse category P, the EUT was tested to the maximum available amplifier power up to 600V/m. For test frequencies over 1 GHz, it was not possible to achieve the required peakfield strength with a single 200W CW amplifier, especially with the additional absorber in the chamber. A special procedure was therefore developed to achieve higher field strengths that used two separate 200W amplifiers to drive two different transmit antennas. This procedure involved performing chamber calibration in the presence of two transmit antennas, with one antenna terminated in a load to simulate the second amplifier's output impedance. An additional power meter, power sensor, and directional coupler were also needed for the second transmit path. Furthermore, the test software was modified to account for powers from both transmit antennas. This special procedure can be applied for more than two transmit antennas, as long as appropriate considerations are made for additional equipment and antenna loading. Phase matching of the two transmit paths is not required for reverberation testing.

The presence of the additional transmit antenna in the chamber may or may not have a significant effect on the chamber calibration factor depending on frequency. At frequencies above 1 GHz, antenna loss was not a significant factor compared to other factors (such as wall losses). As a result, chamber calibration factors with two transmit antennas were very similar to those with a single transmit antenna. The same calibration factor with a single transmit antenna could just as well have been used without major effect on the results. Near the lowest chamber operating frequencies, antenna loading becomes a dominant source of loss. Thus, it is important to perform chamber calibration with all antennas in the test chamber.

This test procedure, utilizing two amplifiers, was performed between 1-4 GHz due to the availability of additional amplifiers. The results were very comparable to that with a single amplifier, except higher field strengths were achieved. This validates the use of multiple transmit antennas procedure described. The comparison is shown in Figure 7 along with anechoic chamber test results.

V. Summary of Deviations from DO-160D

The test procedure closely followed that outlined in DO-160D, except with the following differences or improvements:

- CW and AM tested to 250 V/m instead of 200 V/m as in category Y.
- Tested to maximum available power up to 600 V/m for pulse modulation.
- Utilized two amplifiers for pulse testing between 1-4 GHz. This required calibrations to be performed with two transmit antennas and a test procedure that sums the powers at the transmit antennas' terminals.
- Chamber calibration was performed with EUT in the chamber to include EUT loading.
- Two independent calibrations were performed and the results were averaged.
- Used 200 test frequencies per decade as opposed to the minimum 100 per decade as in DO-160D Section 20.

VI. Test Results and Comparison with Anechoic Method

The RF susceptibility test using the described reverberation procedure was performed on the EUT from 100 MHz to 18 GHz for CW and AM excitation, and from 400 MHz to 18 GHz for pulse modulated excitation. The only susceptible band found was between 1-2 GHz, with the lowest susceptible level at approximately 1.7 GHz. Figures 5-7 compare results from the test in Boeing's anechoic chamber to that in the NASA LaRC reverberation chamber using the current procedures in DO-160D Section 20. In addition, results from tests in a smaller reverberation chamber at NASA LaRC on the same EUT are presented in Figure 8. This is to provide additional data on repeatability using the mode-stirred method.

A significant finding of this test was that this particular EUT's susceptibility levels were sensitive to the modulation rise time. A faster modulation rise time lowered the susceptibility level of this EUT by as much as 6 dB in a reverberation chamber compared to a slower modulation rise time. This finding was also confirmed in a NASA LaRC's anechoic chamber. Fast modulation rise time in the anechoic chamber test reduced the EUT's susceptibility threshold by as much as 11 dB compared to a slower modulation rise time. This phenomenon is significant since it may pose a problem in test repeatability if not addressed properly. In this paper, however, only results with similar modulation rise times as that used in the anechoic test at Boeing are compared. The effects on the EUT caused by fast modulation rise time are presented in another paper [5].

Figures 5-7 show the comparisons of test results for CW, AM and pulse modulation in a reverberation chamber against results from tests in the anechoic chamber at BCAG. For anechoic chamber test results, both vertical and horizontal polarization results are shown in the figures. However, only the horizontal polarization data should be used for comparison purposes since Boeing found the vertical polarization results unrepeatable.

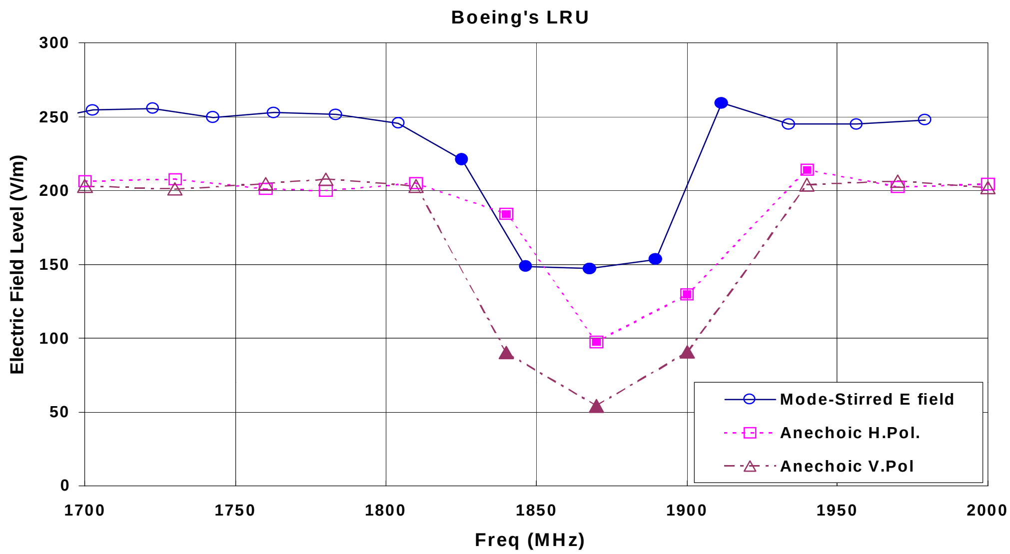

Figure 5: Comparison of EUT's susceptibility thresholds to CW excitation tested in a reverberation chamber and an anechoic chamber. Solid Markers– EUT faillevel; Holow Markers – EUT pass level.

In general, the susceptibility threshold on this EUT was found to be very repeatable, even with the continuous paddle rotation. This EUT was susceptible to the chamber's peak field, and therefore continuous paddle rotation was valid for testing. Peak field susceptibility was confirmed with a comparison test between continuous and stepped paddle rotation, and the results agreed within 0.5 dB at the check frequencies. In addition, both the AM and CW test results were the same. It was expected that the AM and CW results would be different if this EUT was susceptible to the average field, since the CW signal average power is two times larger than the AM signal average power.

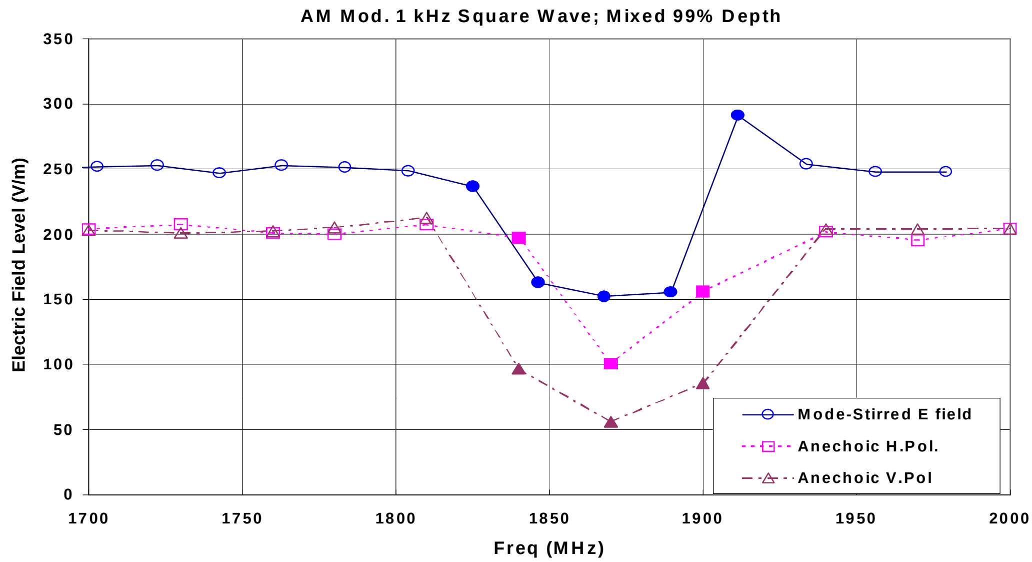

Figure 6: Comparison of EUT's susceptibility thresholds to AM excitation tested in a reverberation chamber and an anechoic chamber. Solid Markers– EUT fail level; Hollow Markers – EUT pass level.

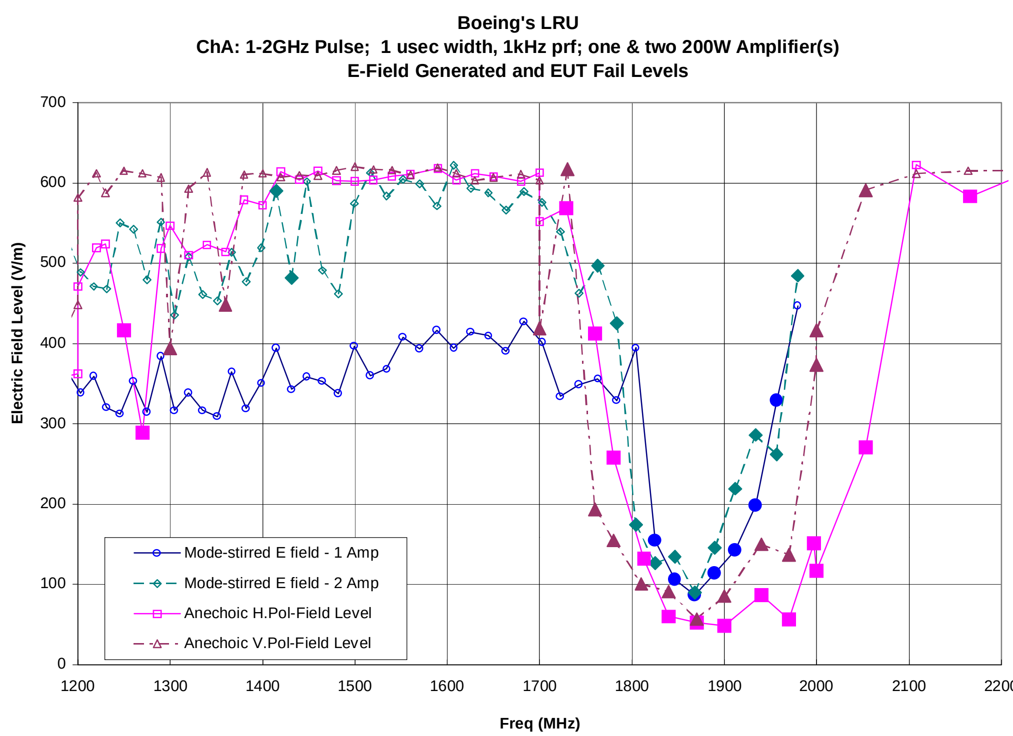

Figure 7: Comparison of EUT's susceptibility thresholds to pulse modulated excitation tested in a reverberation chamber with one and two transmit antennas, and in an anechoic chamber. Solid Markers– EUT fail level; Hollow Markers – EUT pass level.

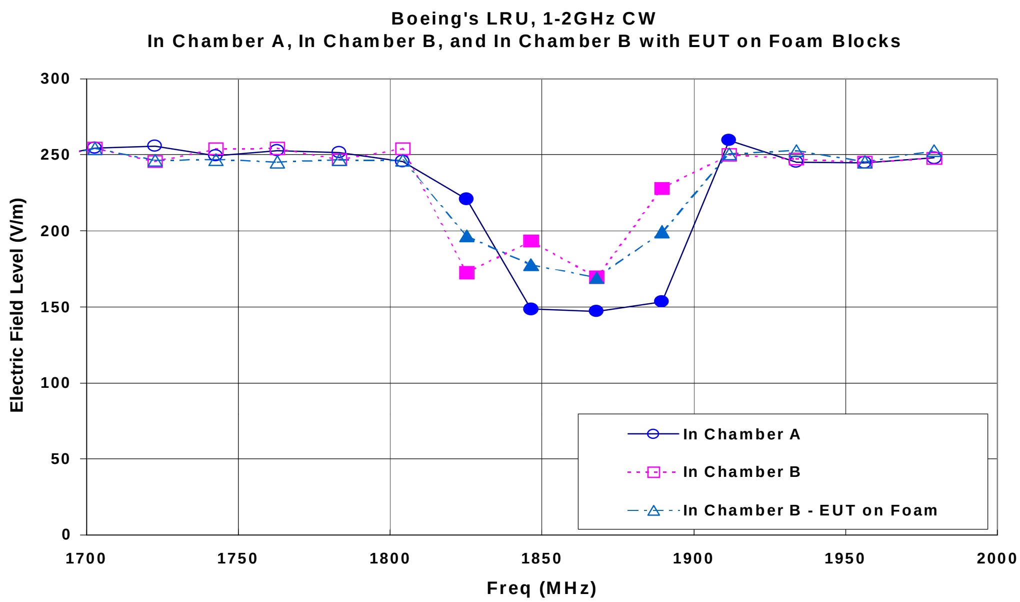

Figure 8: Comparison of EUT's susceptibility thresholds to CW excitation tested in (a) Reverberation chamber A; (b) Reverberation chamber B; and (c) Reverberation chamber B with EUT on foam. Solid Markers– EUT fail level; Hollow Markers – EUT pass level.

Similar results were seen when the CW test was repeated in a smaller reverberation chamber (chamber B) at NASA LaRC. In this chamber, the CW test was performed once with the EUT on the ground plane as required in DO-160D. The test was then repeated with the EUT positioned on a foam block. The results compared with the same setup in the larger chamber (chamber A) are shown in Figure 8. The result differences are within 1.22 dB. This demonstrates very good repeatability when considering a whole different test chamber was used. In addition, the presence of the ground plane did not appear to make a difference to the susceptibility threshold in this range of frequencies, for this particular EUT

Table 1 summarizes the comparison of the susceptibility thresholds using the mode-stirred method relative to Boeing's anechoic results. The data shown, derived from Figures 5-8, were the ratio of the lowest susceptibility thresholds between mode-stirred results and anechoic results with the corresponding modulation types. Also, only horizontal polarization data of the anechoic results was used since the vertical polarization data was found to be unrepeatable by Boeing.

It can be seen from the Figures 5-8 and from Table 1 that the susceptibility threshold measured in the reverberation chamber was consistently higher than that measured in an anechoic chamber. The ratios of susceptibility thresholds for test conducted in the large chamber to the thresholds for test conducted in an anechoic chamber were 3.6 dB for CW and AM and 5.3 dB for pulse modulation. In the smaller test chamber, the ratio is 4.8 dB, with the EUT either on a ground plane or on a foam block

There are several reasons for susceptibility thresholds consistently being higher in a reverberation chamber. They include uncertainty associated with the EUT's antenna gain characteristics, and antenna efficiency and mismatch. However, the most significant reason is the error in chamber calibration calculations in the current procedure. According to recent NIST [6,7] publications, the current calibration procedure overstates the actual field strength by about 4.77 dB. This is caused in part by the fact that the current procedure computes for the total field, while the EUT is susceptible to the rectangular component of that total field. The agreement with the anechoic test results is much closer if the correction for the 4.77 dB is made. The results would agree within 1.2 dB for CW and AM excitation, and 0.5 dB for pulse modulated excitation. The lowest susceptibility thresholds for test conducted in the smaller reverberation chamber would match the anechoic results exactly if the adjustment is made.

Table 1: Ratio of susceptibility thresholds found using reverberation chamber method to thresholds found in an anechoic chamber- horizontal polarization. Results shown in dB.

Reverberation Chamber Test Configurations	**Modulation Types**		
	CW	AM	Pulse
In large chamber (EUT on ground plane)	3.6 dB	3.6 dB	5.3 dB
In small chamber, (EUT on ground plane)	4.8 dB	Not Performed	Not Performed
In small chamber EUT on foam block	4.8 dB	Not Performed	Not Performed

Several other observations can also be made from Figure 7. The mode-stirred method detected a susceptibility at 1430 MHz that the anechoic method failed to detect. This is typically expected with the mode-stirred method. Since the EUT is illuminated with incident fields from all possible angles, not from just one angle as with the anechoic method, therefore, it should detect all susceptibilities the anechoic method would detect or more.

However, the data also show the anechoic method detected additional susceptibilities near 1270 MHz and 1300 MHz that the mode-stirred method failed to detect! At first, this was mystifying, since the mode-stirred method was expected to be a more thorough method for detecting susceptibilities. Again, the explanation is in the 4.77 dB error in the calibration factor stated previously. At these frequencies, the mode-stirred result curves in Figure 7 show the maximum fields achievable with the available amplifiers. If the curves were adjusted (lowered) for the 4.77 dB, the maximum field level that could be generated would fall below the susceptible levels shown in the anechoic method's results. In short, there was not enough RF power for detecting these susceptibilities at these frequencies.

VII. Future Plans

The reverberation chamber test procedures in DO-160D and ED-14D are both under major revisions. New procedures being proposed include new calibration methods that are more accurate. In a new proposal, field probes are used to calibrate the chamber and the receive antenna, thus providing the accuracy of field probes while still maintain the speed advantage of an antenna during tests.

Once the new procedures are standardized, the susceptibility levels found in this test can be adjusted to reflect the new test procedure. This correction can be achieved by comparing the chamber calibration factors from the two procedures and adjust the susceptibility thresholds accordingly, thus allowing adjustments to the results without repeating the test.

VIII. Conclusions

The comparison test presented in this paper validates the reverberation method as a viable alternative to the standard anechoic method. It provides a very repeatable method for HIRF testing. The presented RF susceptibility thresholds result was an attempt to provide a correlation using the two accepted test procedures in DO-160D. The results show only 3.6 dB - 5.3 dB differences in the measured susceptibility thresholds between the standard anechoic method and the reverberation chamber method. That is very good considering the two entirely different approaches to testing, and that the tests were performed at two different facilities. Better comparisons are expected with improvements to the calibration and test procedures to both methods. Current efforts by the industry to develop a new and more rigorous reverberation chamber calibration and test method using field probes are steps in the right direction to improving the reverberation chamber procedures. However, it is believed that strengthening the anechoic method is also needed. That may be achieved by incorporating field uniformity requirements into the calibration procedure and by implementing multiple test incident angles. Only then can the results correlations between the two methods be reliably demonstrated.

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Truong X. Nguyen
Jay J. Ely
Sandra V. Koppen

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NASA Langley Research Center
Hampton, VA 23681-2199

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13. ABSTRACT *(Maximum 200 words)*
This paper describes the implementation of mode-stirred method for susceptibility testing according to the current DO-160D standard. Test results on an Engine Data Processor using the implemented procedure and the comparisons with the standard anechoic test results are presented. The comparison experimentally shows that the susceptibility thresholds found in mode-stirred method are consistently higher than anechoic. This is consistent with the recent statistical analysis finding by NIST that the current calibration procedure overstates field strength by a fixed amount. Once the test results are adjusted for this value, the comparisons with the anechoic results are excellent. The results also show that test method has excellent chamber to chamber repeatability. Several areas for improvements to the current procedure are also identified and implemented.

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