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Reverberation Chamber Uniformity Validation and Radiated Susceptibility Test Procedures for the NASA High Intensity Radiated Fields Laboratory

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Acronyms

HIRF   High Intensity Radiated Fields

RTCA   Formerly the Radio Technical Committee on Aeronautics

RC   Reverberation Chamber

RS   Radiated Susceptibility

IVHM   Integrated Vehicle Health Management

EM   Electromagnetic

DUT   Device Under Test

EUT   Equipment Under Test

LUF   Lowest Usable Frequency

LAN   Local Area Network

RFID   Radio Frequency Identification

Q   Quality Factor

NIST   National Institute of Standards and Technology

E-field Electric Field

MLA   Maximum Loading Allowed

RS   Radiated Susceptibility

GPIB   General Purpose Interface Bus

SA   Spectrum Analyzer

NA   Network Analyzer

CCF   Chamber Calibration Factor

CLF   Chamber Loading Factor

VEE   Visual Engineering Environment

1. Introduction

Aircraft electronics are continuously upgraded with state-of-the-art systems that control flight critical functions. Today's aircraft are increasingly exposed to the world's changing electromagnetic environment due to a greater use of radars, satellite communications, and radio transmissions. In addition, the use of composites in the manufacture of airframes has the potential to increase the susceptibility of electronics to upset in high intensity electromagnetic environments. Compared to aluminum composite materials have less conductivity and reduced shielding effectiveness. Therefore, it has become even more important to evaluate the performance of these critical systems and to demonstrate their continued reliability when exposed to potentially hazardous environments.

Several standards exist today that serve as guidelines to help meet Federal Aviation Administration (FAA) regulatory requirements for testing the electromagnetic immunity of airborne equipment. The standards provide uniform methods and practices used by industry to demonstrate equipment immunity to high intensity radiated electromagnetic fields (HIRF).

1.1. Objective

The objective of this work was to update the NASA Langley Research Center High Intensity Radiated Fields (HIRF) Laboratory and to develop a new test capability based on the guidelines in the "RTCA/DO-160F Environmental Conditions and Test Procedures for Airborne Equipment, Radio Frequency Susceptibility, Section 20.6 Radiated Susceptibility Test; Alternate Procedure – Reverberation Chamber" [1]. The result is a customized procedure for use in HIRF Laboratory that implements the DO-160F requirements. This document serves as a reference and user guide to the new HIRF Lab test procedure entitled Reverberation Chamber Uniformity Validation and Radiated Susceptibility Test Procedure. The procedure provides for validating reverberation chamber (RC) uniformity and conducting electromagnetic radiated susceptibility (RS) tests in the HIRF Laboratory reverberation chambers. Development of the procedure was supported by the Aviation Safety Program's Integrated Vehicle Health Management (IVHM) project.

1.2. Scope & Approach

RTCA/DO-160F Section 20 provides guidelines that specify environmental test conditions and procedures for evaluating the functionality of airborne equipment when exposed to HIRF. Section 20.6 includes testing procedures using reverberation chambers (RCs) to simulate an electromagnetic environment. The HIRF Laboratory has implemented a three-process test procedure that captures the DO-160F guidelines and customizes testing for the HIRF facility. The procedure includes reverberation chamber calibration, which includes a uniformity validation process. The calibration provides a means to determine normalized field strength based on electric field probe measurements. Additionally, a process is included to determine the loading effects of equipment under test (EUT) and to calculate chamber characteristics. A radiated susceptibility test process utilizes the measured chamber characteristics to control test measurements. As specified in the DO-160F guidelines, RC mode-tuning techniques and isotropic electric field probe measurements were incorporated into the development of the new procedure.

The HIRF Laboratory's Chamber A, which is the largest of three available chambers, was used for development and verification of the test procedure. Chamber setup configurations and test data given in this document are for Chamber A only and are used to illustrate procedure operations and results. Calibrations, test processes, techniques, and results are discussed in detail.

1.3. Report Organization

The report is organized into sections that explain each of the three main processes of the new HIRF Laboratory test procedure, and includes RC Uniformity Validation, EUT Load Testing, and RS Testing. An effort is made to relate the test processes to DO-160F guidelines as they apply. Additional sections are included that describe RTCA/DO-160F guidelines, reverberation chambers, the HIRF Laboratory test facility, measurement results, and future plans. Test design, test operations, chamber configurations, file organization, and software are included in the test process discussions. Appendices are provided to further explain and illustrate software windows, DO-160F equations, and data files.

1.4. Reverberation Chamber Description

A reverberation chamber is a highly conductive shielded enclosure used for generating an electromagnetic (EM) environment for conducting RF radiated susceptibility testing and emissions measurements. The operational concept is similar to a very large microwave oven. The introduction of RF energy into a chamber produces complex field structures created by the resonant modes and multipath reflections. The resonating frequencies are determined by the dimensions of the chamber. Rotating mechanical stirrers in a chamber further "mixes" the energy, effectively changing the boundary conditions and creating new complex field structures. The changing multi-moded complex field results in a statistically uniform and isotropic test environment.

Mode-stirring and mode-tuning are two of the techniques that can be used in operation of reverberation chambers. During mode-stirring the stirrers continuously rotate at a set rate. Mode-tuning requires the stirrers to be incrementally stepped through a complete rotation with a set dwell time applied at each step. In either case, one complete stirrer rotation will result in a test environment that is statistically isotropic, uniform, and randomly polarized. The device under test (DUT) is, therefore, exposed to radiation from all aspect angles and polarizations, thus eliminating the need to move or rotate it.

A reverberation chamber is associated with a lowest usable frequency (LUF). This is the minimum frequency where a sufficient number of modes are generated to ensure adequate field mixing and uniformity within a chamber. This minimum frequency is influenced by a chamber's size and geometry. Generally, larger chambers have a lower minimum usable frequency.

RC's offer several advantages compared to anechoic chambers, such as, field uniformity and repeatability, the ability to generate higher field levels efficiently with less input power, reduced test time due to the isotropic nature of the electric fields, and a screened environment with no ambient signals. Disadvantages include loss of polarization and directivity data.

2. RTCA/DO-160F Overview

The RTCA/DO-160F is used by industry to comply with federal regulatory requirements for certification of commercial aircraft equipment. Section 20 addresses reverberation chamber calibration, equipment under test (EUT) loading effects, and radiated susceptibility testing. The following is a list of DO160F related requirements that were incorporated into the HIRF Laboratory chamber calibration and RS test procedures.

- Calibration to validate chamber uniformity are to be performed annually and after a modification to the structure of a chamber.

- A frequency range of 100 MHz to 1 GHz was chosen. This follows the requirement for normal operation beginning with a lowest usable frequency and continuing over the first decade of operation.
- Frequencies are computed to be logarithmically spaced.
- Chamber configurations are provided for:
  - Placement of test antennas, E-field probes, and test articles at a distance of at least 0.75 m or ¼ wavelength of the chamber's lowest test frequency from all chamber surfaces
  - Nine probe locations and measurement using a three-axis E-field probe
- Measurements are conducted in both an empty and loaded chamber.
- E-field standard deviations are determined from E-field probe data.
- Field uniformity is demonstrated by comparing E-field standard deviations to a DO-160F limit.
- A chamber's lowest usable frequency (LUF) is determined based on demonstrated field uniformity.
- EUT loading effects are determined and compared to the chamber's maximum loading allowed.
- Calculations are performed for the following:
  - Average input power
  - Maximum loading allowed
  - Chamber quality factor and time constant
  - Chamber loading factor
  - Chamber calibration factor
  - Antenna calibration factor
  - E-fields
- Mode-tuning is used for all testing.
- Test input power is determined using probe data, as well as receive antenna data during RS testing.
- An adequate number of stirrer steps are used to demonstrate and maintain chamber uniformity during all tests.
- Continuous, pulse, and square waveforms are used in tests.
- Additional guidelines considered:
  - If the EUT loading exceeds the maximum loading allowed (Fig. 5.2-2) then the chamber uniformity must be reevaluated.
  - RS tests are defined using the lowest usable frequency for Chamber A (f_s) which is 100 MHz over a range upto $10f_s$ which is 1 GHz.
  - RS tests are defined for continuous, square, and pulse modulated waveforms.
  - If the time constant is greater than 0.4 of the pulse width used during susceptibility testing for more than 10% of the test frequencies then absorber must be added to the chamber and the uniformity validation procedure repeated.

3. HIRF Lab Test Facility

3.1. Overview

The HIRF Lab test facility was designed, built, and developed in the early 1990's. Located at NASA's Langley Research Center the facility and its personnel are largely focused on research efforts that support the aerospace community to provide for safety of flight. The Lab's three co-located RC's can be used to create radiated electromagnetic environments similar to that encountered in aircraft equipment. Equipment placed in this environment is subjected to RF field levels to determine susceptibility thresholds and to characterize behavior. The Lab has the capability to perform distributed testing using multiple chambers simultaneously.

The facility consists of a large shielded room divided into five separate steel chambers: three reverberation chambers (Chamber A, Chamber B, Chamber C), an amplifier room (Chamber D), and a control room (Chamber E) as shown in Figure 3-1.   All chambers contain stirrers that can be independently controlled.   Chamber A's largest door measures twenty feet.   The chambers have been tested and shown to have 120 dB of shielding effectiveness. Table 3-1 gives the dimensions and lowest usable frequency for each chamber.
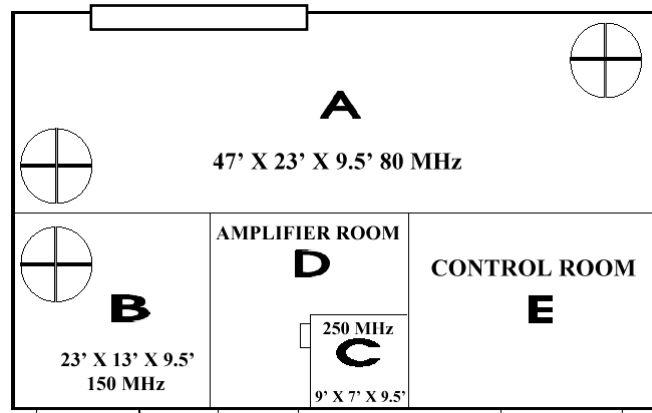
Figure 3-1: Layout of Reverberation Chambers in HIRF Laboratory.

Table 3-1: Chamber Size and Lowest Usable Frequency

Chamber	Length (ft.)	Width (ft.)	Height (ft.)	Lowest Usable Frequency (MHz)
A	47	23	9.5	80
B	23	13	9.5	150
C	9	7	9.5	250

The reverberation chambers have been used for RF radiated susceptibility testing of aircraft flight data computers, engine data processors, data communication systems, hydraulic actuators, and commercial sensors. In addition, the radiated EM environment is used as a fault injection method to characterize the behavior of fault-tolerant systems. The Lab's capabilities were expanded in 2002 to include RF emissions measurements on various portable electronic devices, such as mobile phones, wireless LANs, and RFID tags. The Laboratory personnel have supported field testing in aircraft, airports, and flight.

Recent additions to the Lab include indirect lightning effects test equipment and the capability to conduct cable, pin, and ground injection tests using DO-160 lightning waveforms. In 2005 a twenty foot door was added to Chamber A and a larger bulkhead installed between Chamber A and B. The door allows for accommodation of test objects as large as a general aviation aircraft. The bulkhead will allow for shielding effectiveness testing of composite materials using two RC's.

3.2. Performance and Capability

The performance of the HIRF Lab's RC's was evaluated by the National Institute of Standards and Technology (NIST) and reported in 1999 in NIST Technical Note 1508 [1]. The chambers were evaluated over a frequency range of 80 megahertz to 18 gigahertz, where the best performance occurs above 200 megahertz in Chamber A. The data show excellent test reproducibility and measurement agreement with theory.   The report indicates that the chambers have a field uniformity of +/- 2 dB and a repeatability of +/- 1 dB. The chambers were shown to have Quality (Q) Factors greater than 1000 at 200 megahertz and continuing upwards to greater than 10,000 at higher frequencies. High chamber Q means less input power is required to achieve required field strengths; however, it also means a longer time is needed to reach a steady state in the chamber. The Q is used to calculate the chamber's time constant or the required time to reach a steady state.   The time constant must be considered during pulse testing, and even though it does vary with frequency, 6 microseconds for an empty Chamber A is a conservative estimate. Section 6 includes data illustrating Chamber A's Q, time constant, as well as other characteristics.

The HIRF Lab is equipped with a full range of instruments and equipment needed to conduct RF radiated susceptibility tests. Field strengths as high as 3000 V/m are achievable depending on test frequency and chamber. In addition, the Lab has the capability to conduct emissions measurements, shielding effectiveness and interference path loss measurements, and indirect lightning effects tests.   Including all test methods, the Laboratory's test frequency range covers DC to 18 GHz. The Laboratory's instrument power and measurement capabilities are listed below:

- RF Power Amplifiers:
    - 100 to 1000 MHz - 1000 W CW
    - 10 kHz – 220 MHz - 2000 W CW, 4000 W Pulse
    - 1 – 2 GHz - 200 W CW
    - 2 – 4 GHz - 200 W CW
    - 4 – 18 GHz - 200 W CW
    - 8 – 18 GHz - 200 W CW
    - 1 – 18 GHz - 1000 W Pulse (80 – 1000 MHz, 2 – 8 GHz, 7 – 18 GHz)
- Gigahertz Transverse Electromagnetic (GTEM) Cell
- TEM Cells: 200 MHz, 500 MHz
- Lightning and Impulse Generators
- RF Sources: Analog Signal Generators, Vector Signal Generators, Arbitrary Waveform Generator
- Signal Measurement: Oscilloscopes, Spectrum Analyzers, Network Analyzers
- Power Meters and CW and Peak Power Sensors
- Electric field and current probes
- Horn and log periodic antennas
- Wireless base station simulator

4. HIRF Lab Test Procedure

The HIRF Lab Test Procedure includes processes for chamber uniformity validation, determining EUT loading effects, and RS testing.   The Lab's Chamber A was used for all test development. Following the DO-160F guidelines, electric field (E-field) probes are used for chamber calibration in both empty and loaded chamber configurations and mode-tuning is used during all testing.   Receive antenna measurements are calibrated to the E-field probe measurements and chamber loading effects are calculated from measured data. The procedure utilizes DO-160F equations for calculations of test and chamber parameters. These equations can be found in Appendix B.

4.1. Description

The HIRF Lab Test Procedure is composed of seventeen operations divided into three Test Processes as shown in Figure 4.1-1. The first test process, Chamber Uniformity Validation, is a set of tests to provide data for validation of chamber uniformity and to produce a maximum loading allowed (MLA) curve. The next test process, EUT Loading Effects, focuses on comparing the equipment under test's (EUT) loading effects to the maximum loading allowed curve. These two processes produce data that are used to characterize the chamber. The chamber data is used during the third test process, Radiated Susceptibility (RS) Testing.

Figure 4.1-1 illustrates data flow in and out of each test process, where all data is in the format of Excel workbooks and worksheets. A test process is defined by its operations shown in Table 4.1-1. Each test process is discussed in detail in separate sections. Operations, based on DO160F guidelines, are discussed, including software functions, specific chamber configurations, and analysis.

The procedure is composed of multiple, but dependent operations. Operations 1 through 16 are fully described and functional. Future plans include implementing Operations 17 and 18 during Phase 2 of HIRF Test Procedure development. Designs for these two operations are briefly discussed. Table 4.1-1 lists the procedure operations and the software associated with each. In general, there are two software programs: one for conducting automated tests, and another to compute and analyze chamber and test characteristics. A section is included describing software usage, data organization and file naming.
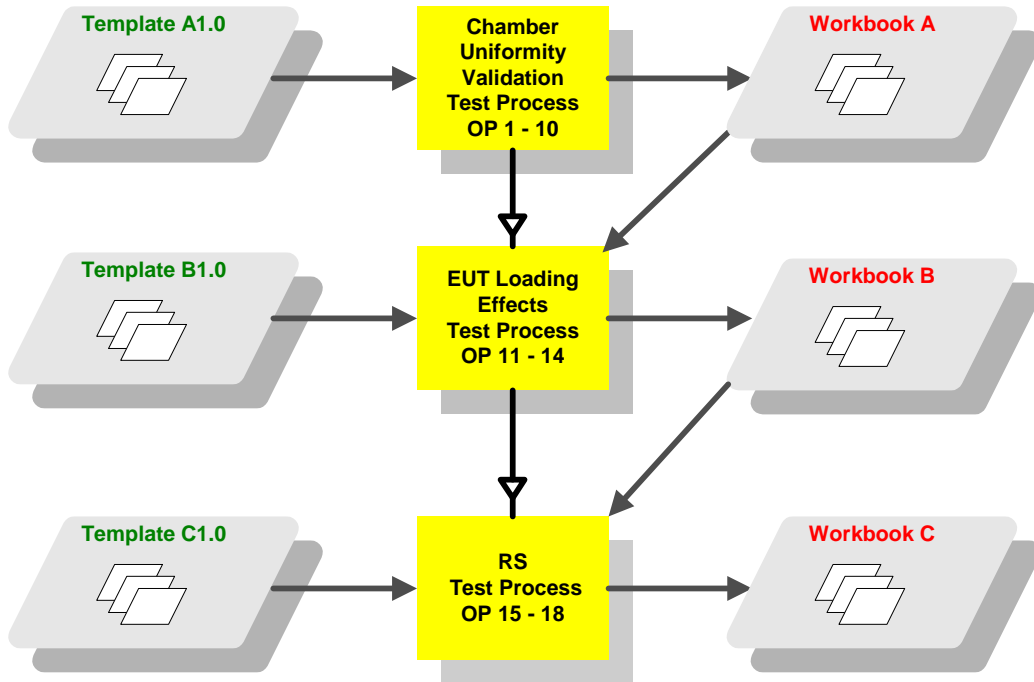
Figure 4.1-1: Procedure Test Processes and Data Flow.

Table 4.1-1: Process operations, descriptions and software

Operation	Description	Calibration RS Test	Process Data
Chamber Uniformity Validation Test Process			
1	Perform transmit & receive path calibrations	X	
2	Perform empty chamber calibration measurements	X	
3	Calculate empty chamber standard deviations & antenna calibration factor (ACF)		X
4	Plot empty chamber standard deviations against DO160F limit		X
5	Calculate & Plot Antenna – Probe = Delta		X
6	Perform loaded chamber calibration measurements	X	
7	Calculate loaded chamber standard deviations & antenna calibration factor (ACF)		X
8	Plot loaded chamber standard deviations against DO160F limit		X
9	Calculate & plot maximum loading allowed (MLA)		X
10	Is there sufficient loading?		X
EUT Loading Effects Test Process			
11	Perform chamber loading measurements with EUT in chamber	X	
12	Calculate chamber calibration factor (CCF) and chamber loading factor (CLF)		X
13	Compare maximum loading allowed against EUT loading		X
14	Calculate chamber Q & time constant using CCF from EUT data		X
RS Test Process			
15	Perform RS test pretest power leveling using CCF	X	
16	Perform RS test with CW	X	
17	Perform RS test with square waveform	X	
18	Perform RS test with pulsed waveform	X	

4.2. Software and Data Overview

The HIRF Lab Uniformity Validation and the RS Susceptibility Test Procedure relies on two software programs, *Calibration & RS Test* and *Process Data*. *Calibration & RS Test* automates tests for chamber uniformity validation, EUT loading effects, and RS testing. *Process Data* computes standard deviations, antenna calibration factors, chamber calibration factors, chamber Q, and chamber time constants. In addition, it will plot standard deviations together with DO160F limits, the delta between antenna and probe measurements, and a maximum loading curve.

Excel workbooks and worksheets are used for data input and output. Data file naming conventions use a numbering scheme that tracks the test process. In general, there are separate workbooks for empty and loaded chamber tests, maximum loading information, EUT loading tests, and RS tests. Each workbook contains several worksheets containing information on test hardware, test instrument setups, cable calibrations, power leveling results, and numerous test data sheets. Appendix C contains a detailed description of data files, worksheets, and associated test data.

The software was developed using Agilent Visual Engineering Environment (VEE) on a PC running Windows XP Professional Operating System.

4.3. Chamber Uniformity Validation Test Process

The Chamber Uniformity Validation Test Process includes empty and loaded (absorber added) chamber field uniformity measurements and test equipment setups. E-field standard deviations and antenna calibration factors (ACF) are computed, and a maximum loading effects curve is plotted. Software details and equations used for calculations are given in Appendices A and B, respectively. Figure 4.4-1 illustrates test equipment configurations in Chamber A, the amplifier room, and the control room for an empty or loaded chamber test. DO-160F test configurations requires nine probe positions in a chamber; however, for testing in Chamber A eleven positions were used in a non-rectangular configuration in an effort to extend the test volume.

In an Excel Template workbook the "Params" and "Hdwr" worksheets can be edited to contain appropriate test parameters and hardware. All test data will be written to worksheets in this workbook as the test process progresses. The test process includes Operations 1 through 10 as listed in Table 4.1-1. Each operation is discussed in detail.

4.4. Setup Chamber

The reverberation chamber, amplifier room, and control room should be configured as shown in Figure 4.4-1. The number/letter identifiers can be referenced to Table 4.4-1, which gives a list of the instrumentation and equipment that can be used. Note that an E-field probe (Figure 4.4-2) is placed inside Chamber A. The probe communicates with the control computer in the control room via a fiber optic RS232 interface. The receive antenna is located at other end of the chamber pointing at the other stirrer. The transmit antenna is positioned in a corner opposite the stirrer and pointing up into the corner or pointing at the stirrer. Care should be given so that the two antennas are pointed away from each other. Cable paths, instruments, and connections are also illustrated. An attenuator, in the receive path at the spectrum analyzer input port, serves to protect against exceeding the instrument's input power and causing damage. Connections between rooms are made through bulkhead connectors. All instrumentation, except the probe, uses a GPIB interface to communicate with the test control (1d) computer.
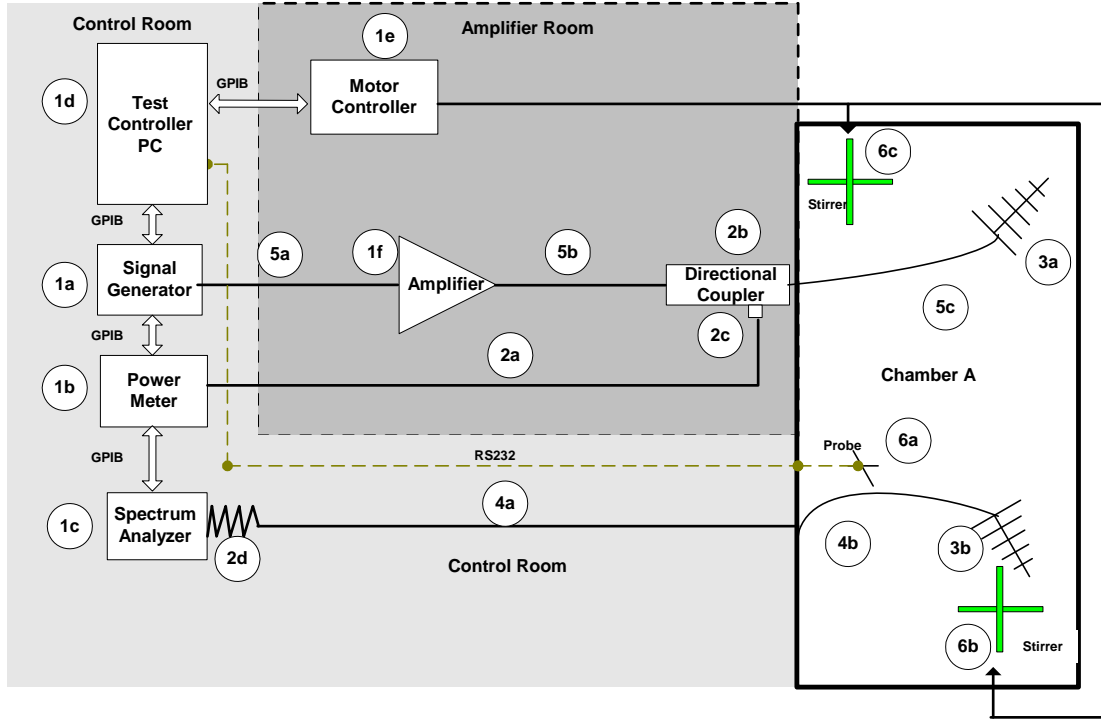
Figure 4.4-1: Test equipment setup for Chamber Uniformity Validation Test Process in Chamber A for empty or loaded configuration.

Table 4.4-1: Test Equipment in Figure 4.4-1 Setup

EQUIPMENT	MODEL	SERIAL / ECN NO.
1a Signal Generator	Agilent E8257D	SG48050 159
1b Power Meter	Gigatronics 8542C	1832083
1c Spectrum Analyzer	HP 70909A	1092135
1d Test Control PC	Dell Precision 670	ECN 1656758
1e Motion Controller 4000	Compumotor 4000	ECN 2100702
1f Power Amplifier	AR 40WD1000	
2a Power Sensor Cable	Gigatronics	
2b Directional Coupler	Werlatone C3908-10	S/N61170
2c Peak or Average Power Sensor	Gigatronics 80321A	1829995
2d Attenuator	Narda 776B-30	A014912
3a WB High Power Log Per. Ant (Tx)	AT 5080M1	S/N 303736
3b Log Per. Ant (Rx)	Emco LP-2 3144HP	
4a Receive cable (attenuator to bulkhead)	UFB293C-1-1800-506506	S/N98K0986
4b Receive cable (in chmbr)	UFB293C-1-18000-506506	S/N98K0986
	UFB293C-1-6000-506506	S/N98K0978
5a Transmit cable (SG to amplifier)	MicroCoax	EMRL 050-52
5b Transmit cable (amplifier to coupler)	UFB293C-0-0720-50U50U	64639-211010-001
5c Transmit Cable (In chmbr)	UFB293C-1-1800-506506	S/N98K0984
	UFB293C-1-1800-506506	S/N98K0985
	UFB293C-1-1800-506506	S/N98K0987
6a E-field Probe	Holaday HI 6005	S/N102090
6b Stirrer 1	Compumotor	9562300369
6c Stirrer 2	Compumotor	9562300368
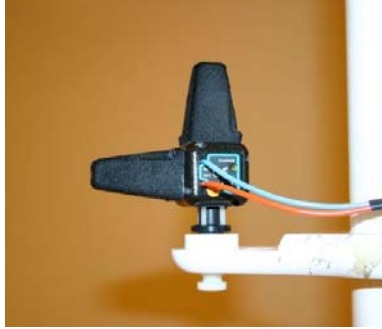
Figure 4.4-2: Holaday Electric Field Probe used during chamber uniformity validation. (Note the probe axes and electronics are packaged in one unit.)

4.4.1. Operation 1 - Transmit path, receive path, and coupler calibrations

The Chamber Uniformity Validation Test Process begins by performing path loss measurements on cables and couplers for both transmit and receive paths. The losses are used in determining forward power and receive power during test processes. For Chamber A, the calibration is performed over a frequency range of 50 MHz to 1.1 GHz collecting at least 200 frequency data points. Calibration procedures to measure losses are performed for each path using either a Network Analyzer (NA) or a Spectrum Analyzer (SA) in combination with an RF source. If using the SA method use *Calibration & RS Test* software "Cable Calibration (Peak)" operation and follow software instructions. The NA method is completely manual, but will produce greater accuracy.

The full transmit path as seen in Figure 4.4-1 is composed of cables 5a, 5b, 5c, and a directional coupler (2b). For calibration and test purposes only cable 5c and the directional coupler need to be measured. The receive path includes cables 4a, 4b, and attenuator 2d. The receive path cables inside the chamber must be the required length needed to reach all positions within the chamber's test volume. The components in each path may be calibrated as a whole unit or separately. If individual calibrations are done, then the measurements must be added (use Excel) to determine the complete path loss. This gives some flexibility if component replacements are required.

Once all calibrations are completed, frequencies and losses should be copied to the appropriate Excel worksheets "XmitCal", "RecCal", and "CplrCal", and a workbook created and given a name, such as ChmbrA Empty A1.0. The workbook should also have "Params" and "Hdwr" worksheets.

4.4.2. Operation 2 - Chamber measurements with probes in empty chamber

The next step is to conduct measurements in an empty chamber. The chamber should contain only the equipment needed, such as antennas, stirrers, and E-field probe and stand. No test bench or table should be in the chamber. See Figures 4.4-1 and Table 4.4-1 for configuration details.

Measurements are made with the E-field probe in eleven different positions and the receive antenna in nine different positions as illustrated in Figure 4.4.2-1. The probe positions are represented as numbers in parentheses and the antenna positions and pointing directions appear as numbered arrows. The positions of the E-field probe define the boundaries of the test volume in the chamber. Chamber A measurements include two additional positions, 7A and 8A, so as to take advantage of available space in the chamber. The probe and antenna positions are coordinated so that a test using probe position one also uses antenna position one, and so forth. Figure 4.4.2-2 gives a three dimensional view of the probe positions and placement distance of 0.75 m from walls, ceiling, and floor.   The distance corresponds to the minimum distance required by DO-160F of ¼ wavelength of the chamber's lowest test frequency (100 MHz). Using the minimum distance allows for a larger chamber test volume.

Figure 4.4.2-3 is a picture of Chamber A in an empty configuration. Note that the receive antenna is in the foreground in this picture, however, during testing it is actually moved to various locations in the chamber as shown in Figure 4.4.2-1.

The process uses mode-tuned techniques that require the stirrer to be stepped at specific intervals. Each measurement consists of a probe position, an antenna position, a frequency, and a stirrer step. At each stirrer step the operation steps through each frequency in the range at a specific power level.   Data is collected at each step and compiled at the end of a rotation. After the stirrers have completed a rotation the probe and receive antenna are moved, and the process repeats until all locations are used. The antenna and probe numbering in Figure 4.4.2-1 do not denote any particular order in which they should be moved.

The *Calibration & RS Test* software operation "Calibration with Probes (Empty and Loaded)" automates the measurements. Refer to Appendix C for data file and worksheet descriptions. During the test, power leveling to a 5 Watt input power for each test frequency is conducted at the first stirrer position only and recorded to worksheet "Freqs Pwr Lvl".   The power leveling results include the required source power level for each test frequency. The data are used for all stirrer steps needed to complete a rotation. The test is repeated at each probe position.

During the process, data and worksheets (Pos1 – Pos9 and Pos7a, Pos8a) are added for each new probe location.   The same file name with the A1.1 identifier should be used to record data during the process. At the completeion of the test the file will contain data and a worksheet for each probe position.
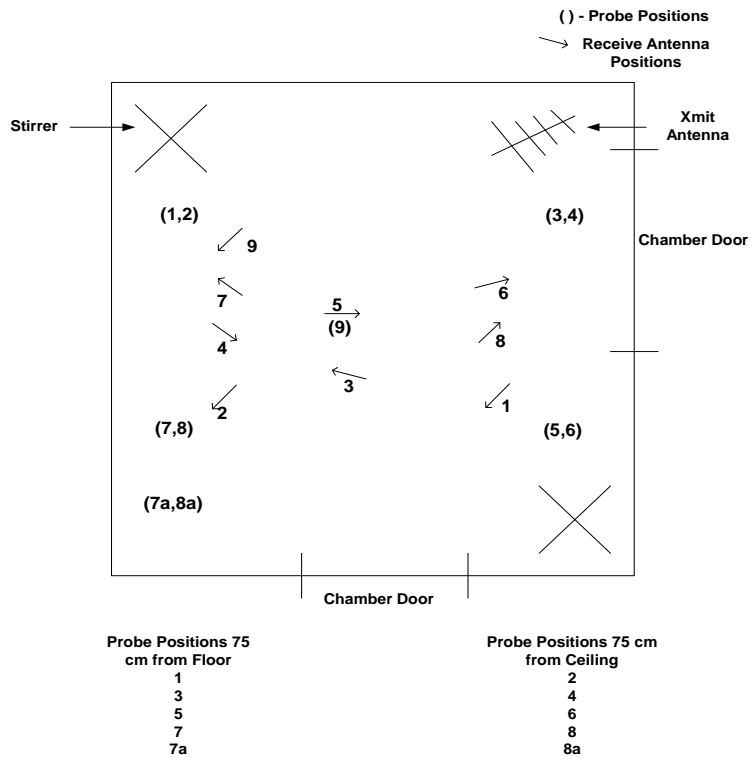
Figure 4.4.2-1: Probe and receive antenna positions in empty Chamber A.
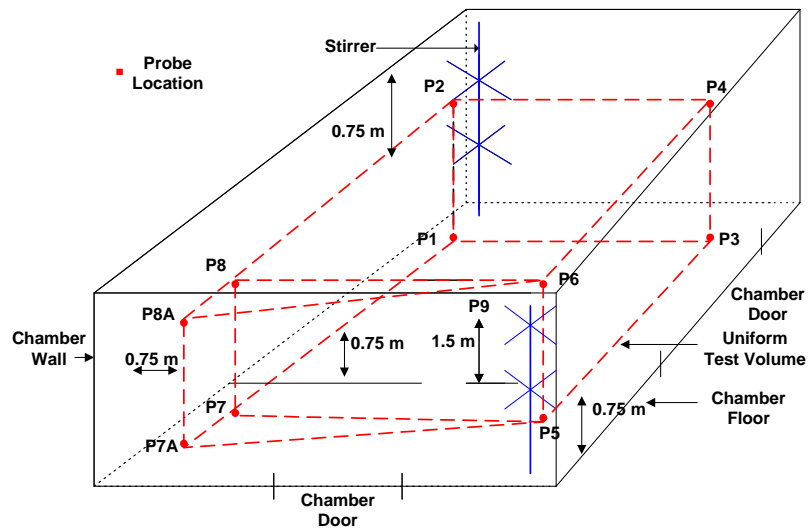
Figure 4.4.2-2: 3D probe placement in Chamber A.
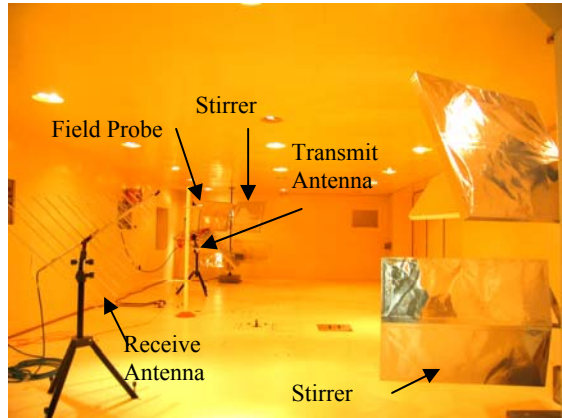
Figure 4.4.2-3: Typical empty chamber configuration in Chamber A.

4.4.3.   Operation 3 - Calculate standard deviations and Antenna Calibration Factor (ACF) for empty chamber

The standard deviations for the measured electric fields acquired in Operation 2 and the ACF are calculated. (See Appendix B for an explanation of DO-160F equations used for computations.) The *Process Data* software operation "Calculate Std. Deviations & ACF from Probe Data (OP-3)" applies the setup parameters, performs calculations, and creates and records data to worksheet "STD".   Figure A.3 in Appendix A shows the software window containing a list of data processing operations and chamber setup parameters. The file should be saved with an A1.2 identifier.

4.4.4.   Operation 4 - Plot standard deviations for empty chamber

The plotted standard deviation data is used to determine if the chamber uniformity passes the DO-160F requirement. The standard deviations are plotted in decibels (dB) for each E-field component, x, y, z, as well as a total of that data set. The red line on the chart represents the DO-160F limit. To pass, component data must not exceed the DO-160F limit for more than two frequencies, and the total standard deviation must not exceed the limit at any frequency. If the limit is exceeded, repeating the empty chamber test using more tuner steps or reducing the size of the test volume may produce acceptable results. If the limit is exceeded at lower frequencies, it may be that the chamber is not usable at the lower frequencies. The data can be used to indicate the chamber's lowest usable frequency (LUF).

The operation "Plot Normalized E-Standard Deviations (OP4) in the *Process Data* software will automatically generate an Excel or Matlab chart. Data is recorded to the worksheet "STD PLOT".   The chart is recorded and should be saved with a A1.2 identifier file name. A Matlab chart is saved as a separate file with .fts extension. An example of a standard deviation plot can be found in Figure 5.1-1.

4.4.5. Operation 5 - Calculate and plot antenna and probe Delta

Antenna and probe data are normalized to input power, and then the difference or Delta of the two is calculated. The Delta between the normalized antenna data and the normalized probe data gives an indication of the goodness of the measurements. Figure 5.1-3 shows a plot of Delta across the test frequency range, 100 MHz to 1000 MHz. Note that at all frequencies, delta is between +/- 4 dB and for most frequencies it is between +/- 3 dB. This calculation is not a requirement of DO-160F, but can reveal antenna chamber loading and can be used for the purpose of test validation.

The operation "Calculate & Plot Delta (OP5)" in the *Process Data* software, automatically retrieves data form the worksheet "STD" in the A1.2 file, calculates Delta, creates and records data to worksheet "Delta(Ant-Probe)", and then plots the data.

4.4.6. Operation 6 - Perform calibration measurements for loaded chamber

The test process is the same as the empty chamber test discussed for Operation 2 in section 4.4.2, except that absorber material is added throughout the chamber. The absorber material used in the test was of various sizes and shapes and composed of carbon-loaded foam, such as found in anechoic chambers. The size should be large enough to be effective at the test frequencies. All calibration measurements were made using low input power (5 watts). Figures 4.4.6-3 (a) and (b) show two chamber configurations with absorber. Data was acquired for both configurations. The configuration in (b) obviously includes more absorber material, and produced data that best simulated EUT loading effects in the chamber while still maintaining field uniformity. Testing with the increased loading was performed to comply with DO-160F recommendations that the chamber have sufficient loading to demonstrate a change in ACF of at least 12 dB. Figure 5.1-4 illustrates this change between empty and loaded chamber ACF's.

Figure 4.4.6-1 shows that ten probe positions are used not eleven as in the empty chamber test. This is due to the elimination of probe position nine, as the position is occupied by absorber material in the center of the chamber. Antenna position nine is replaced by position five. The number given to antenna and probe positions does not denote any particular order in which they should be used.   Figure 4.4.6-2 gives a three dimensional view of the probe positions for a chamber loaded with absorber material.

( ) - Probe Positions

Receive Antenna Positions

Stirrer

Xmit Antenna

(1,2)

(3,4)

5

Chamber Door

7

6

Absorber

4

8

3

2

1

(7,8)

(5,6)

(7a,8a)

Chamber Door

Probe Positions 75 cm from Floor
1
3
5
7
7a

* Note: Antenna position 5 was position 9 in empty chamber

Probe Positions 75 cm from Ceiling
2
4
6
8
8a
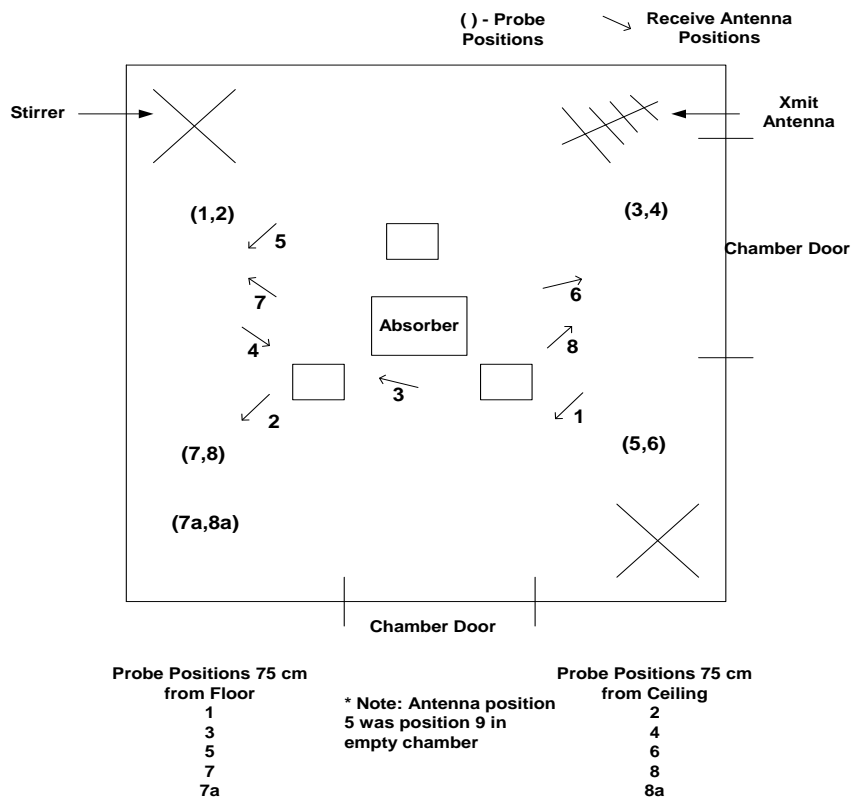
Figure 4.4.6-1: Diagram showing loaded configuration probe and antenna placement in Chamber A.

Stirrer

Probe Location

P2

P4

0.75 m

P1

P3

P8

P6

P8A

Absorber

Chamber Wall

0.75 m

Uniform Test Volume

P7

Chamber Floor

P7A

P5

0.75 m

Chamber Door
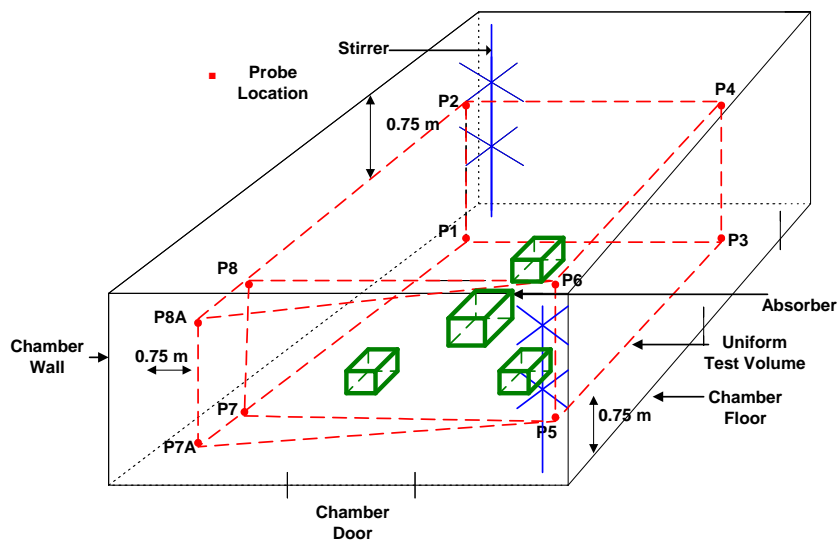
Figure 4.4.6-2: 3D diagram of probe placement in Chamber A, loaded configuration.

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Figure 4.4.6-3 (a) & (b): Two typical loaded configurations in Chamber A.

The same software program, *Calibration & RS Test,* that was used in Operation 2 is also used to automate measurements for the loaded chamber tests. The Template file should contain similar data, but be named with identifier A2.0. Power leveling is conducted at the first step position only, resulting in worksheet "Freqs Pwr Lvl". During the process, data and worksheets (Pos1 – Pos8 and Pos7a, Pos8a) are added one at a time for each new probe location. The data file name with an A2.1 identifier should be used during the process to record data for each probe location. The loaded chamber testing is completed after all probe positions are measured. The data file will then contain data and a worksheet for each probe position.

4.4.7. Operation 7 - Calculate standard deviations and Antenna Calibration Factor (ACF) for loaded chamber

The operation is the same as discussed in Operation 3. The standard deviations for the measured electric fields acquired in Operation 6 and the ACF are calculated. (See Appendix B for an explanation of DO-160F equations used for computations.)

The *Process Data* software operation "Calculate Std. Deviations & ACF from Probe Data (OP-3)" applies the setup parameters, performs calculations, and creates and records data to worksheet "STD". The data should be saved to a file with an A2.2 identifier.

4.4.8. Operation 8 - Plot standard deviations for loaded chamber

The operation is the same as discussed in Operation 4. The standard deviation data is plotted against the DO-160F limit. The same criteria applied in Operation 4 are used to determine if the chamber uniformity passes the DO-160F requirement.

The operation "Plot Normalized E-Standard Deviations (OP4)" in the *Process Data* software will automatically generate an Excel or Matlab chart. Data is recorded to the worksheet "STD PLOT" and should be saved to a file with a A2.2 identifier. A Matlab chart is saved as a separate file with .fts extension. An example of a standard deviation plot can be found in Figure 5.1-2.

4.4.9. Operation 9 - Calculate and plot Maximum Loading Allowed (MLA)

The MLA in the chamber is determined by comparing ACF's from the empty chamber data and the loaded chamber data. The DO-160F calculation is found in Appendix B, Equation B.3. The plotted MLA is shown in Figure 5.1-5.

The *Process Data* software operation, "Calculate & Plot Maximum Loading Allowed (OP-9)", automatically computes the MLA, creates and records data to worksheets "Chmber MaxLoading" and "Chmbr MaxLoadPlot". Empty chamber data is retrieved from an A1.2 identifier file and loaded chamber data from an A2.2 identifier file. Data should be save in a A3.0 identifier file.

4.4.10. Operation 10 – Sufficient loading

The MLA Plot (Figure 5.1-5) shows in decibels (dBm) the level of loading over the test frequency range. In order to sufficiently load the chamber to simulate EUT loading, DO-160F requires an increase in ACF of 12 dB over the empty chamber data. If this level is not reached after the chamber loading test, then repeat the chamber loading test process beginning at Operation 6, adding more absorber, and repeat the MLA calculation. It is important to maintain chamber uniformity during the operation.

Figure 4.4.6-3 (a) shows a Chamber A configuration with absorber where the desired loading was not achieved. The test was repeated using the configuration shown in (b). The increase in amount of absorber material produced the desired effect of increasing the MLA for the chamber. The effect of the absorber material is intended to produce loading that is higher than any EUT loading expected. Conformity to the field uniformity requirement must be demonstrated for the worst case.

Repeat Operations 6 to 9 until the desired maximum loading for a chamber is reached. In the EUT Loading Test Process, the MLA curve is compared with loading measurements acquired when the EUT is present. This is done to determine if a test object overloads a chamber.

4.5. EUT Loading Test Process

The loading effects of a test object in the chamber must be determined before it can undergo susceptibility testing. The EUT Test Process includes measurements with the EUT placed in the chamber and post data processing to calculate chamber factors. The test does not require field probe measurements as is necessary for chamber uniformity testing. Input power is measured at the transmit antenna and peak power levels are monitored at a receive antenna. A Chamber Calibration Factor (CCF) and Chamber Loading Factor (CLF) are determined and recorded. The CLF is then compared to the maximum loading allowed curve (Section 4.4.9 Operation 9). The chamber Q and time constant are then computed and recorded.

An Excel Template workbook, such as ChmbrA EUT Input Params B1.0, should contain worksheets "Params" and "Hdwr" with the appropriate test parameters. The same frequencies and number of stirrer steps as used during uniformity testing should be used.   All test data is written to worksheets as the test process progresses. The test process includes Operations 11 through 14. Each operation is discussed in detail in this section.

4.5.1. Setup chamber

Figure 4.5.1-1 and Table 4.5.1-1 show a Chamber A setup configuration and equipment list for EUT Loading. The EUT is added to the center of the chamber and transmit and receive antennas are positioned as they will be used during RS testing. There is no probe present.

Figure 4.5.1-1: Test equipment setup for EUT Loading Test in Chamber A, Amplifier Room, and Control Room

Table 4.5.1-1: Test Equipment in Figure 4.5.1-1 Setup for EUT Test Process

EQUIPMENT	MODEL	SERIAL / ECN NO.
1a Signal Generator	Agilent E8257D	SG48050 159
1b Power Meter	Gigatronics 8542C	1832083
1c Spectrum Analyzer	HP 70909A	1092135
1d Test Control PC	Dell Precision 670	ECN 1656758
1e Motion Controller 4000	Compumotor 4000	ECN 2100702
1f Power Amplifier	AR 40WD1000	
2a Power Sensor Cable	Gigatronics	
2b Directional Coupler	Werletone C3908-10	S/N61170
2c Peak or Average Power Sensor	Gigatronics 80321A	1829995
2d Attenuator	Narda 776B-30	A014912
3a WB High Power Log Per. Ant (Tx)	AR AT 5080M1	S/N 303736
3b Log Per. Ant (Rx)	Emco LP-2 3144HP	
4a Receive cable (attenuator to bulkhead)	UFB293C-1-1800-506506	S/N98K0986
4b Receive cable (in chmbr)	UFB293C-1-18000-506506	S/N98K0986
	UFB293C-1-6000-506506	S/N98K0978
5a Transmit cable (SG to amplifier)	MicroCoax	EMRL 050-52
5b Transmit cable (amplifier to coupler)	UFB293C-0-0720-50U50U	64639-211010-001
5c Transmit Cable (In chmbr)	UFB293C-1-1800-506506	S/N98K0984
	UFB293C-1-1800-506506	S/N98K0985
	UFB293C-1-1800-506506	S/N98K0987
6a Stirrer 1	Compumotor	9562300369
6b Stirrer 2	Compumotor	9562300368

4.5.2. Operation 11: Perform measurement with EUT in chamber

The test uses an input power level of 5 watts, power leveling at the transmit antenna, and power measurement at the receive antenna. The antenna locations should be the same as that used during the RS Test Process. The frequency range, number of frequencies per decade, and number of stirrer steps should be the same as used during Empty and Loaded Test Processes. Power leveling is conducted at the first stirrer position only, and then used for all remaining positions.

The *Calibration & RS Test* operation, "Calibration with EUT in Chamber", automates the test measurements and calculations. An input file, such as Chamber A EUT Input Params B1.0, should contain the appropriate data and worksheets. Worksheet "EUT" is automatically created and data recorded to it as the test progresses.

4.5.3. Operation 12: Determine Chamber Calibration Factor (CCF) and Chamber Loading Factor (CLF).

EUT test data, empty chamber test data, and MLA data are processed to determine two chamber characteristics, CCF and CLF.

The *Process Data* operation, "Calculate & Plot Chamber Loading Factor with EUT", retrieves data from an EUT file with a B1.2 identifier and an Empty Chamber data file with the A1.2 identifier, calculates the CCF and the CLF, and records results to a "CLF" worksheet.   Equations based on DO-160F requirements for performing calculations are located in Appendix B. Figure 5.2-1 illustrates the CCF.

4.5.4. Operation 13: Compare chamber Maximum Loading Allowed with EUT loading.

The CLF data is plotted against the MLA curve (Figure 5.2-2) to determine if the EUT has overloaded the chamber. As required by DO-160F, if more than 10% of the test frequencies have a greater value than the MLA curve, then the chamber is overloaded. If determined that the chamber is overloaded, the field uniformity test for a loaded chamber (Operations 6, 7, 8, and 9) should be repeated with the EUT in the chamber.

The *Process Data* operation, "Calculate & Plot Chamber Loading Factor with EUT", automatically plots the CLF data against the MLA curve.

4.5.5. Operation 14: Determine chamber Q & time constant using CCF from EUT data

The chamber Q and time constant are calculated and recorded in the "CLF" worksheet. The time constant should be less than 0.4 times a RS test waveform pulse width; otherwise, absorber must be added to the chamber in order to change the time constant, or the pulse width should be increased.

The *Process Data* operation, "Calculate Chamber Q and Time Constant" retrieves CCF and CLF data, calculates the chamber Q and time constant values, and records the data to the "CLF" worksheet. Data should be saved to a file with a B2.0 identifier, such as Chamber A EUT B2.0.

4.6. Radiated Susceptibility Test Process

The Radiated Susceptibility Test Process is largely automated and includes mode-tuning techniques, generation of a pretest power plan, and RS testing with continuous waveforms (CW), square waveforms (SW) and pulse modulation. The RS Test Process frequencies can vary from those used during Uniformity Validation and EUT Loading Test Processes, but must be inclusive of the frequencies used in those test processes. The number of stirrer steps should be at least as many as used during uniformity testing. The EUT should be monitored during testing using the Laboratory's video and camera system. The RS Test Process chamber setup and Operations 15 through 18 are discussed in this section.

Test parameters in an Excel Template file's "Params" worksheet can be modified to provide the required E-field levels, frequency bands, number of stirrer steps, as well as all other input needed for automating the test. See Appendix C for an example and description of the worksheet.

Beginning with Operation 15, the RS Test Process procedes by automating the power leveling operation to determine the required chamber input power level needed to achieve the required test E-fields. The data generated are then used during RS testing, Operation 16. The last two operations, 17 and 18, provide for square and pulsed waveforms in RS testing.

4.6.1. Setup chamber for pretest power leveling

The configuration illustrated in Figure 4.6.1-1 and equipment list in Table 4.6.1-1 should be used as a chamber setup and equipment guide for pretest power leveling. The lower wattage amplifier used during calibration and EUT loading test should be replaced with a higher power amplifier (2a) or as appropriate for a RS test. Note that cable 5c is changed from that used in previous test processes, and is now connected to a 1000 watt, 50 ohm load or high power termination located in the chamber to simulate the antenna. This allows for all input power to be transmitted into the load, so there is no power radiated into the chamber and no effect on the EUT during this part of the test.
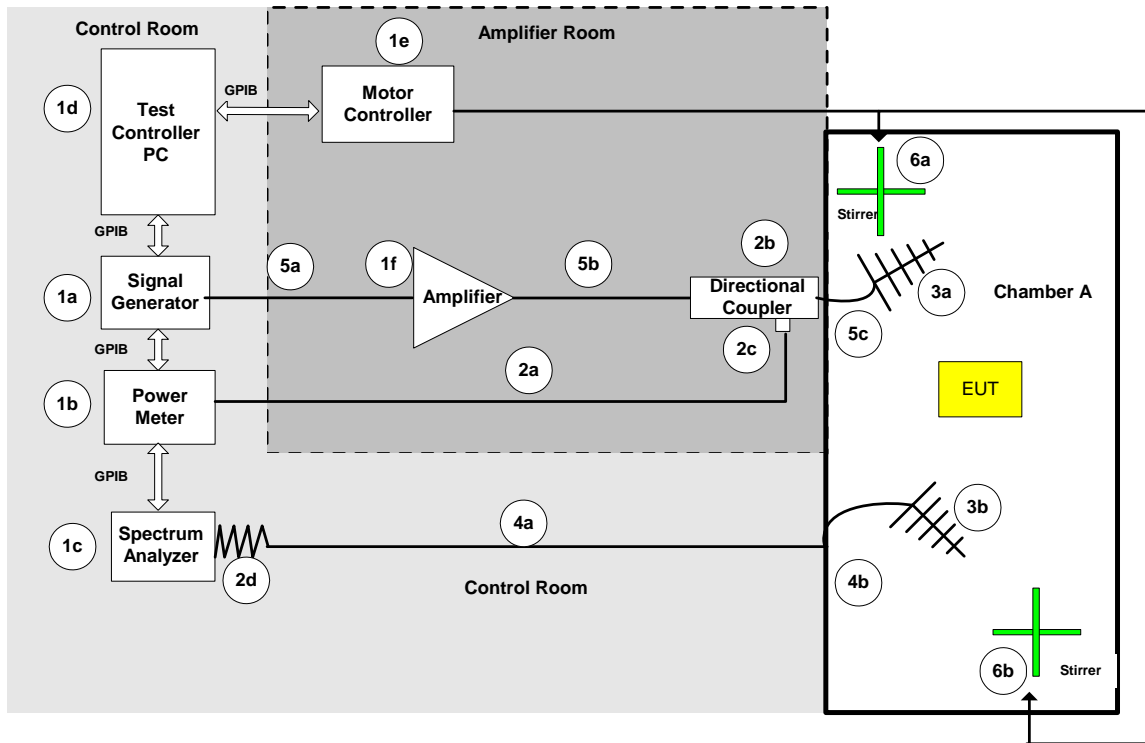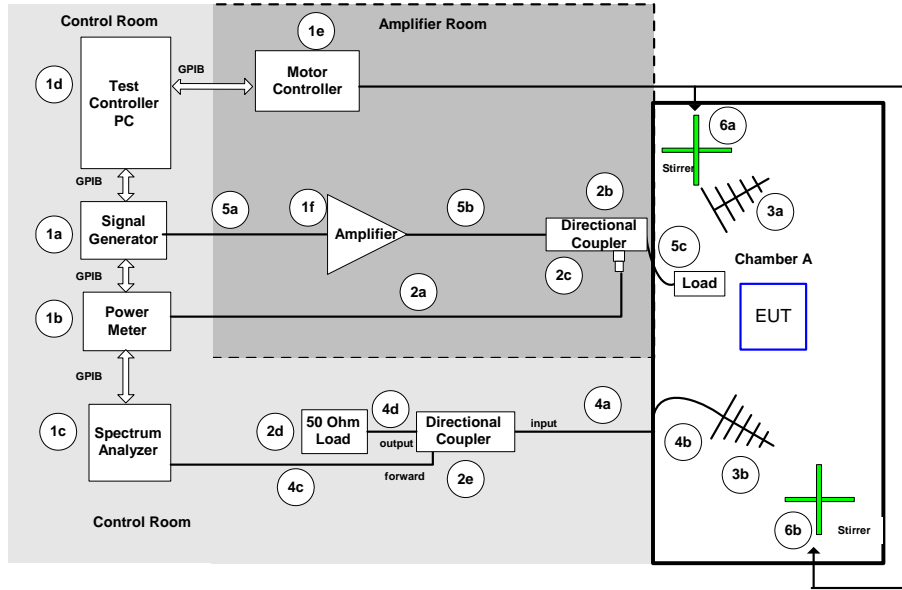
Figure 4.6.1-1: RS Pretest Power Leveling Test equipment setup in Chamber A, Amplifier Room, and Control Room.

Table 4.6.1-1: Test Equipment in Figure 4.6.1-1

EQUIPMENT	MODEL	SERIAL / ECN NO.
1a Signal Generator	Agilent E8257D	SG48050 159
1b Power Meter	Gigatronics 8542C	1832083
1c Spectrum Analyzer	HP 70909A Channel A	1092135
1d Test Controller PC	Dell Precision 670	ECN 1656758
1e Stirrer Motor Controller	Compumotor 4000	ECN 2100702
1f Power Amplifier	AR 1000WD1000	
2a Power Sensor Cable	Gigatronics	
2b Directional Coupler	Werlatone C3908-10	S/N61170
2c Peak or Average Power Sensor	Gigatronics 80421A	18300053
2d 50 ohm Load 1000 W	Termaline 83351	
2e Directional Coupler	Werlatone C3908-13	S/N 5661
3a WB High Power Log Per. Ant (Tx)	AT 5080M1	S/N 303736
3b Log Per. Ant (Rx)	Emco LP-2	9308-1004
4a Receive cable (bulkhead to cplr)	UFB293C-1-1800-506506	S/N 98K0986
4b Receive cable (in chmbr)	UFB293C-1-6000-506506	S/N98K0978
4c Receive cable (cplr to SA)	UFB293C-0-0480-506506	64639-311215-002
4d Receive cable (cplr to Load)	Microcoax	
5a Transmit cable (SG to amplifier)	EMRL 050-52	
5b Transmit cable (amplifier to coupler)	UFB293C-0-0720-50U50U	64639-211010-001
5c Transmit Cable (in chmbr)	UFB293C-1-1800-506506	S/N98K0984
6a Stirrer 2	Compumotor	95062300369
6b Stirrer 1	Compumotor	95062300368

4.6.2. Operation 15: Perform pretest power leveling for RS Test

Pretest power leveling is performed before the EUT is subjected to a radiated susceptibility test. Conducting power leveling using the configuration shown in Figure 4.6.1-1 before the actual RS test precludes exposing the EUT to potential overexposure to high RF levels due to fluctuating power levels induced during the power leveling operation. Since no power is radiated into the chamber during this operation, the EUT can be in the chamber or not, and the stirrers and receive antenna are not used. The test frequencies should be those needed for the RS testing. All power leveling is done to a required test E-field level using a CW signal.

The operation is automated and calculates the required input power, measures the forward power at a power sensor, computes the chamber input power, and controls that power by adjusting the signal generator output. The applied input power needed for a required E-field level is computed at the load input port. The calculation (Appendix B Equation 8) uses CLF data and the maximum normalized total E-field data. The transmit path calibration data is included in the computation to determine chamber input power. As the forward power is monitored at the power sensor, the signal generator power is increased or decreased as needed. The operation is automatically repeated for each test frequency. The operation results in a signal generator power level needed to achieve the required E-field for each test frequency. When pretest power leveling is completed, cable 5c is reconnected to the transmit antenna port for RS testing. The data can be used to control the input power level during RS testing.

The *Calibration and RS Test* software operation, "Pretest Power Leveling for RS Test", automates the test process. It retrieves test parameters and calibration data from an Excel Template file, such as RS Test C1.0, controls the power leveling process, and manages the data. Worksheets are created as each required test E-field level is processed. The worksheets are automatically named, Freqs Cals Pwr Efield xVM, where the "x" is replaced with test E-field level. Data in the worksheets include source power levels required to achieve each specific E-field test level for each test frequency. The resulting worksheets are compiled into a file to produce a pretest power leveling plan that is used during CW, square wave, and pulse modulated RS testing. The file should be saved with a C1.1 identifier. A pretest power leveling plan can be reused for several RS tests, assuming the RS test frequencies are included in the plan, and the chamber configuration remains the same.

4.6.3. Setup chamber for RS test with CW

Equipment and instrument configurations are shown in Figure 4.6.3-1 and Table 4.6.3-1. The amplifier (2a) is the same as used during the power leveling operation. Included in the configuration is a load (2d) and directional coupler (2e) in the receive path. The change in receive path configuration is needed to protect instrumentation, as high power levels are frequently required during this test. The forward power from the directional coupler is connected to the spectrum analyzer input port, and the direct output is connected to the load. The EUT is normally placed in the center of the chamber; however, if it is composed of several parts, it can be distributed in the chamber test volume, being careful to maintain the proper minimum distance from chamber surfaces and hardware (1/4 wavelength of lowest test frequency). The receive antenna is used to monitor and verify that the input power control is functioning properly and should be in the same location as during the EUT Loading Test Process.
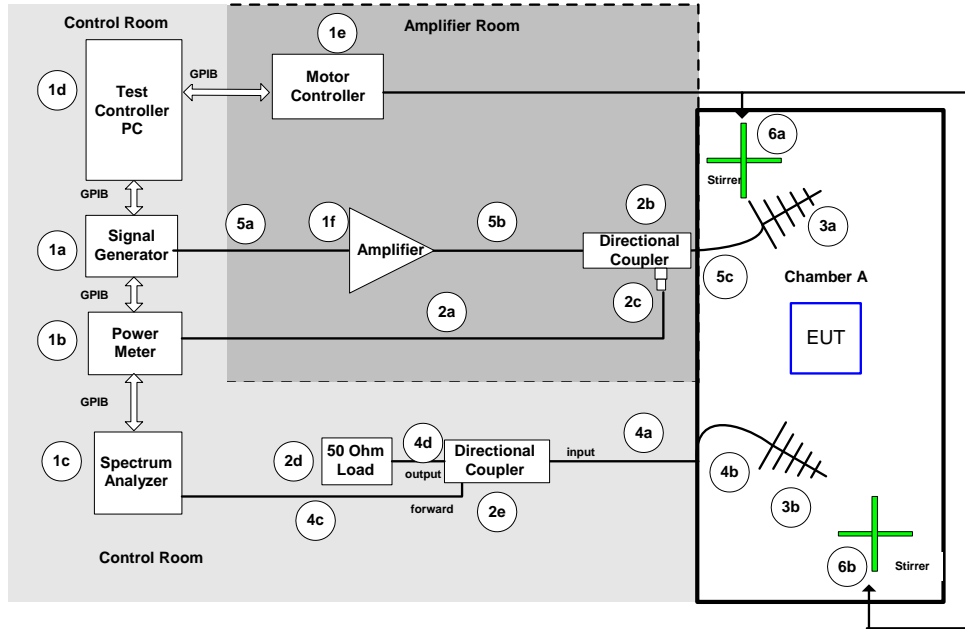
Figure 4.6.3-1: Equipment setup for Radiated Susceptibility Test Process in Chamber A.

Table 4.6.3-1: Test Equipment for Figure 4.6.3-1

EQUIPMENT	MODEL	SERIAL / ECN NO.
1a Signal Generator	Agilent E8257D	SG48050 159
1b Power Meter	Gigatronics 8542C	1832083
1c Spectrum Analyzer	HP 70909A Channel A	1092135
1d Test Controller PC	Dell Precision 670	ECN 1656758
1e Stirrer Motor Controller	Compumotor 4000	ECN 2100702
1f Power Amplifier	AR 1000WD1000	
2a Power Sensor Cable	Gigatronics	
2b Directional Coupler	Werlatone C3908-10	S/N61170
2c Peak or Average Power Sensor	Gigatronics 80321A	1829995
2d 50 ohm Load 1000 W	Termaline 83351	
2e Directional Coupler	Werlatone C3908-13	S/N 5661
3a WB High Power Log Per. Ant (Tx)	AT 5080M1	S/N 303736
3b Log Per. Ant (Rx)	Emco LP-2	9308-1004
4a Receive cable (bulkhead to cplr)	UFB293C-1-1800-506506	S/N 98K0986
4b Receive cable (in chmbr)	UFB293C-1-6000-506506	S/N98K0978
4c Receive cable (cplr to SA)	UFB293C-0-0480-506506	64639-311215-002
4d Receive cable (cplr to Load)	Microcoax	
5a Transmit cable (SG to amplifier)	EMRL 050-52	
5b Transmit cable (amplifier to coupler)	UFB293C-0-0720-50U50U	64639-211010-001
5c Transmit Cable (in chmbr)	UFB293C-1-1800-506506	S/N98K0984
6a Stirrer 2	Compumotor	95062300369
6b Stirrer 1	Compumotor	95062300368

4.6.4. Operation 16: Perform RS test with CW

The RS Test Process uses a CW signal input into the chamber. Test input power levels are acquired from a pretest power plan, such as RS Test C1.1. The pretest power plan frequencies and the RS Test frequencies must be identical. The number of stirrer steps must be at least as many as used to verify chamber uniformity. For instance, if it was determined that 60 stirrer steps were needed to demonstrate uniformity, then at least 60 steps must be used during RS testing. Future plans to enhance this procedure will allow reducing the number of stirrer steps during RS testing while maintaining chamber uniformity requirements.

The "Params" worksheet in the pretest power plan should be modified to contain the correct test E-field before beginning testing. As the RS Test progresses and each E-field is tested, additional worksheets are added to the data file. The worksheets are automatically created and named "Testn", where n can be any text or numbers needed to identify a test. There is a restriction on using a worksheet name that already exists, so the name should be unique. At the conclusion of a group of tests, this file will contain all output test data and worksheets, and should be renamed with the identifier, C1.2. For every tested E-field there will be a test worksheet that corresponds to a power plan worksheet. It is suggested that the output data worksheets be grouped into files based on a common test requirement, such as type of input signal (CW or pulse) or EUT configuration. File name identifiers should follow the nomenclature from Table C.1-1; otherwise, the file name is unrestricted.

During execution of a test the "Radiated Susceptibility Test Window" will display values for several "Test Status" parameters (Appendix A Figure A-5). Displayed parameter values present test progress, such as current test frequency and stirrer step; however, the values can indicate a problem has occurred during a test. For instance, under "Xmit Antenna" the required forward power display and forward power display should be very close. Note that the forward power is calculated at the transmit antenna port. Another indicator of a problem is a low value in the "Power Meter" display. If the display indicates that there is no measurable forward power, it may be pointing to a problem with the amplifier. The "Receive Antenna" values that are displayed can be used to monitor the power in a chamber.

DO-160F does not offer any guidance for monitoring the chamber environment during testing, however, this procedure does provide calculated data based on the *current* input power and *maximum* receive power. It should be noted that at the end of a test, data is compiled and E-fields are determined based on *average* input and *average* receive powers over a completed stirrer rotation. The computed data as displayed is based on maximum values and can differ from that based on average values. The data displayed during testing is intended for monitoring purposes only.

 Two display areas are used to monitor the chamber E-field and provide some means of feedback on the E-field levels present inside a chamber. The "Calibrated Efield" display contains the E-field level computed from the chamber input power at the transmit antenna during the test. Equation B.9 in Appendix B is used to determine this value. The "Meas'd E-field" displays a running maximum E-field that is computed for each frequency using maximum receive power. This value is determined from Equation B.10. Both values are updated as the test steps through the test frequencies at each stirrer position. The "E-field Ratio" display contains a ratio of the "Meas'd E-field" to the required test E-field.

4.6.5. Operation 17 and 18: Perform RS test with square and pulsed waveforms

Equipment and instrument configurations for square wave and pulsed modulated tests are shown in Figure 4.6.5-1 and Table 4.6.5-1. The RS Test Process is designed to use square wave and pulse modulated input signals for RS testing, applying the same power leveling plan data files as used for CW testing. The pretest power leveling plan frequencies and the RS Test frequencies must be identical. Test instrumentation includes an oscilloscope for monitoring the input signal using the power sensor's detector-out port. The sensor, also, has a trigger-in port that is used during pulse testing and controlled by the signal generator. Note the "trigger in" cable is red and connects to the Signal Generator pulse video out port.

DO-160F includes requirements for both square wave and pulsed testing. The square wave modulated test signal has a 50% duty factor. During RS pulse testing, consideration must be given to the test pulse width. The chamber time constant, as determined during the EUT Loading Test Process, should be less than 40% of the pulse width used. If the pulse width is too short, then a maximum steady state will not be reached in the chamber, resulting in under testing. Analysis of Chamber A data (Figure 5.2-3) indicates a high Q factor and fast time constant (Figure 5.2-4). It is determined that Chamber A requires a pulse width of at least 5 to 6 microseconds depending on frequency. The operation will be completed and square and pulse waveform measurement results subsequently provided as part of a Phase 2 HIRF Test Procedure document.

Figure 4.6.5-1: Equipment setup for Radiated Susceptibility Test with Square and Pulse Modulated Waveforms in Chamber A.

Table 4.6.5-1: Test Equipment for Figure 4.6.5-1

EQUIPMENT	MODEL	SERIAL / ECN NO.
1a Signal Generator	Agilent E8257D	SG48050 159
1b Power Meter	Gigatronics 8542C	1832083
1c Spectrum Analyzer	HP 70909A Channel A	1092135
1d Test Controller PC	Dell Precision 670	ECN 1656758
1e Stirrer Motor Controller	Compumotor 4000	ECN 2100702
1f Oscilloscope	Tektronix DPO 4054	ECN 1641291
2a Power Amplifier	AR 1000WD1000	
2b Werlatone Directional Coupler	C3908-10	S/N61170
2c Peak Power Sensor	80350A	1828269
2d 50 ohm Load 1000 W	Termaline 83351	
2e Directional Coupler	Werlatone C3908-13	S/N 5661
2f Power Sensor Trigger In Cable	Gigatronics	
2g Power Sensor Detector Out Cable	Gigatronics	
2h Power Sensor RF Cable	Gigatronics	
3a WB High Power Log Per. Ant (Tx)	AR AT 5080M1	ECN 2100676
3b Log Per. Ant (Rx)	Emco LP-2 3144HP	9308-1004
4a Receive cable (bulkhead to cplr)	UFB293C-1-18000-506506	S/N98K0986
4b Receive cable (in chmbr)	UFB293C-1-18000-506506	S/N98K0986
4c Receive cable (cplr to SA)	UFB293C-0-0480-506506	64639-311215-002
4d Receive cable (cplr to Load)	Microcoax	
5a Transmit cable (SG to amplifier)	EMRL 050-52	
5b Transmit cable (amplifier to cplr)	UFB293C-0-0720-%0U50U	64639-211010-001
5c Transmit Cable (in chmbr)	UFB293C-1-1800-506506	S/N98K0984
6a Stirrer 1	Compumotor	95062300269
6c Stirrer 2	Compumotor	95062300268

5. Measurement Results for Chamber A

Chamber A data are plotted for the three test processes, Uniformity Validation, EUT Loading, and RS. Several of the plots in Section 6.1 and 6.2 are automatically generated during their respective test processes and are required to demonstrate compliance with DO-160F. Section 6.3, RS Test Process, includes manually generated plots of test input power and E-field levels. All data were measured in HIRF Laboratory Chamber A using the portable camera system (Figure 5-1) as the EUT. The Laboratory's camera system is composed of a TDK Color Video Camera System Model VC-04 installed in a copper enclosure for additional shielding during radiated electromagnetic susceptibility testing. It was chosen as a suitable EUT to demonstrate the test processes and to test the copper enclosure's ability to shield the camera from interference or damage at E-field levels higher than the camera's 200 V/m limit.

A test frequency range of 100 MHz to 1 GHz in log spaced steps was used during all test processes. DO-160F states that 100 MHz is the LUF for normal operation, and that field uniformity should be demonstrated over the first decade of operation, or in this case to 1 GHz. For future test, using a frequency range of 80 MHz to 1 GHz may further define Chamber A's uniformity. Chamber uniformity validation is required above 1 GHz, but only three probe and receive antenna positions are needed.

Figure 5-1: HIRF Laboratory portable camera in shielded enclosure.

5.1. Uniformity Validation Test Process

During the Uniformity Validation Test Process using the *Calibration and RS Test* software, several plots are automatically generated and used to analyze the characteristics of the chamber. E-field standard deviation plots for both empty (Fig. 5.1-1) and loaded (Fig. 5.1-2) chambers are used to demonstrate compliance with the DO-160F limit. The plots indicate that the standard deviations are well below the DO-160F limit in both empty and loaded chamber configurations. The ratio of the difference between the receive antenna data and the E-field probe data for empty and loaded chambers is determined (Equation B.12) and plotted as Delta in Figure 5.1-3. These data offer a means of comparison of the two types of in-chamber measurements. However, during RS testing only the E-field probe data measurements are used to determine input power.

The empty and loaded chamber Antenna Calibration Factors (ACF) are plotted in Figure 5.1-4. The Maximum Loading Allowed (MLA) is plotted in Figure 5.1-5 and determined from Equation B.3 and ACF data. MLA data is compared with the EUT's Calibration Loading Factor (CLF) data in the EUT Test Process.

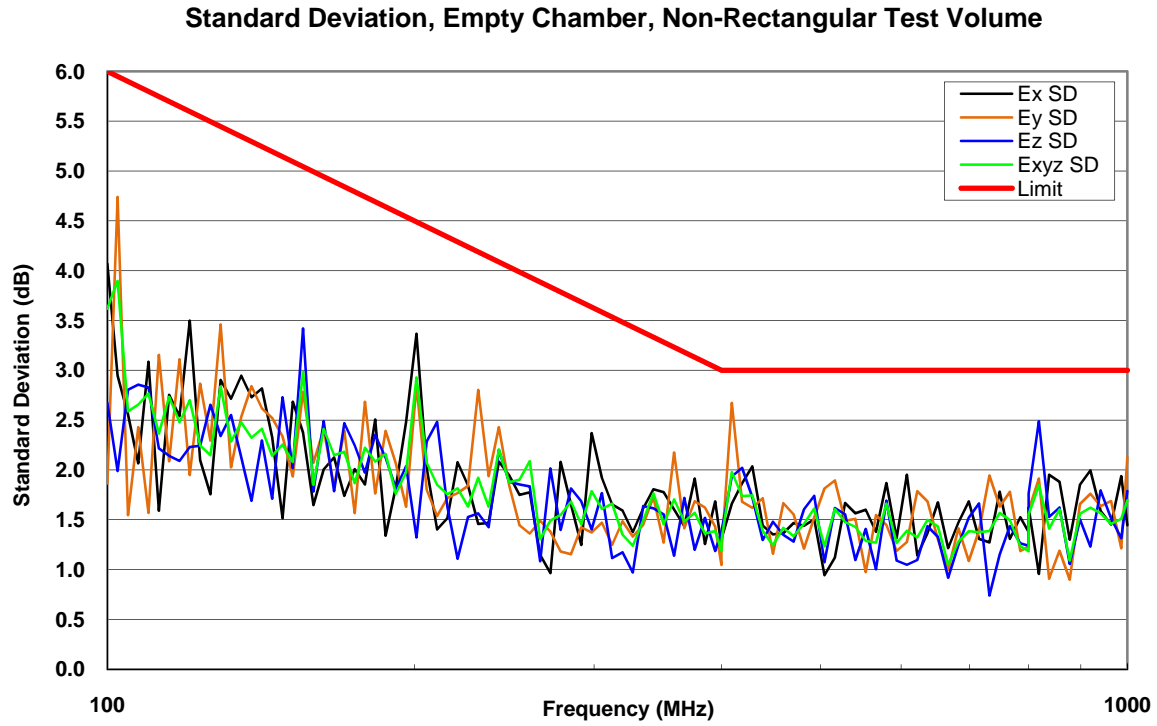**Standard Deviation, Empty Chamber, Non-Rectangular Test Volume**

Figure 5.1-1: Empty chamber E-field standard deviations (dB) relative to the mean compared to DO-160F limit.
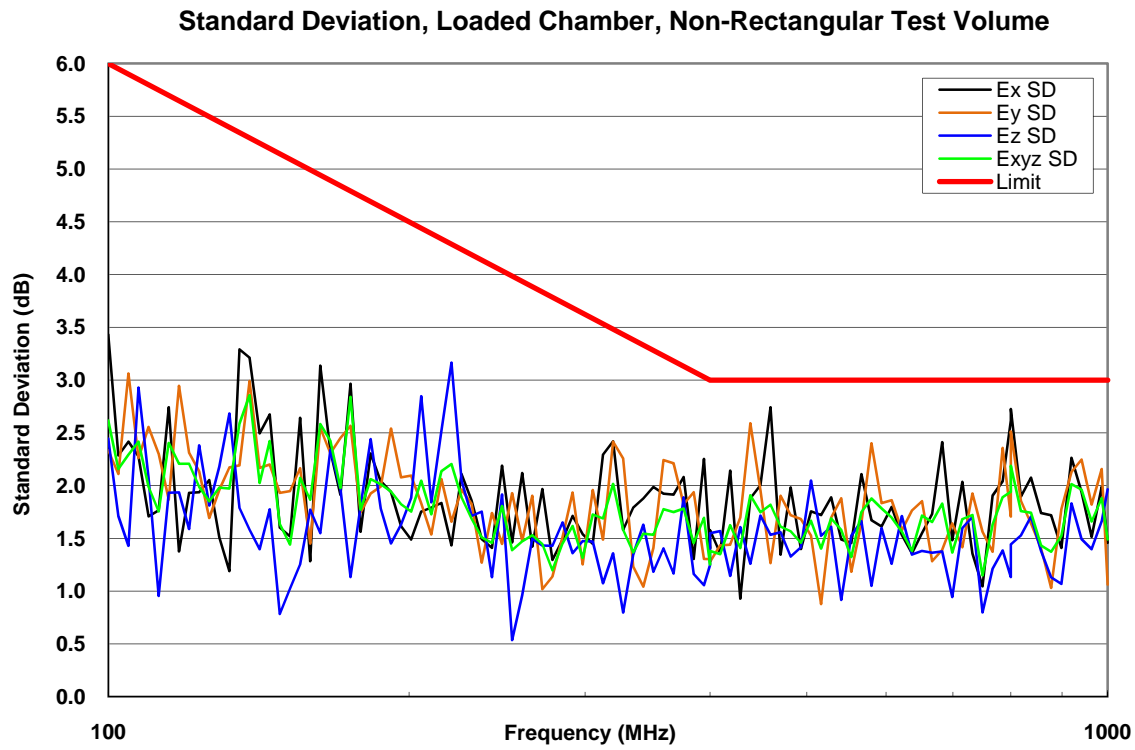
Standard Deviation, Loaded Chamber, Non-Rectangular Test Volume

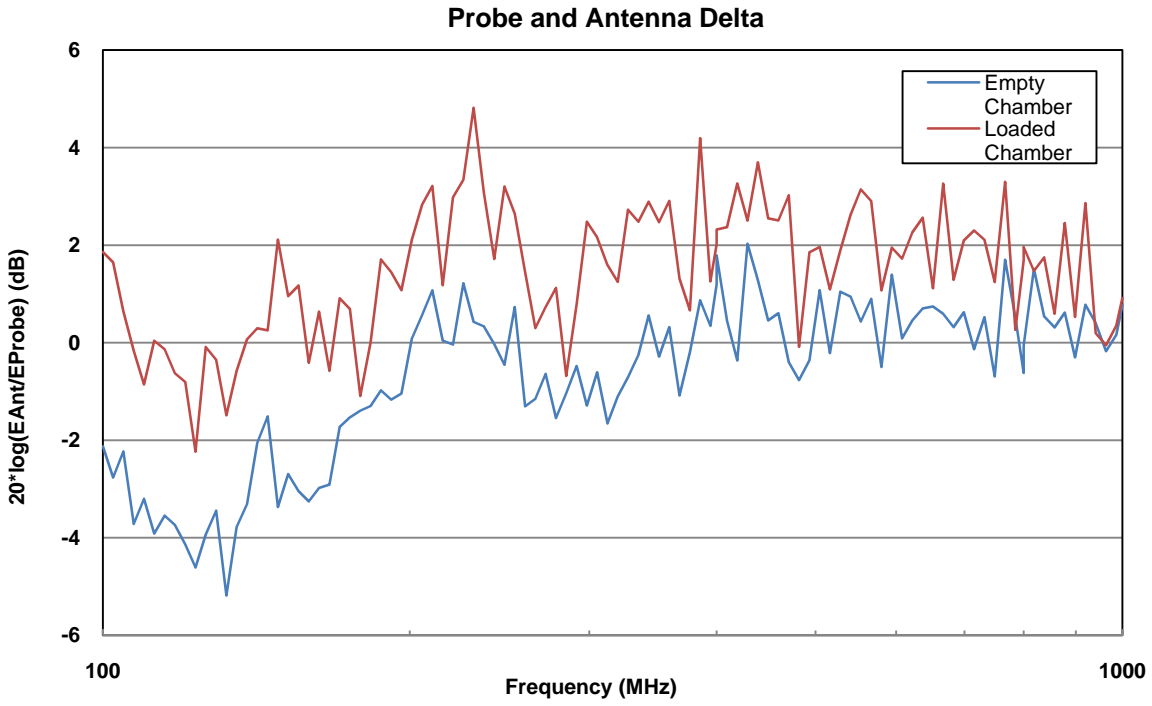Figure 5.1-2: Loaded chamber E-field standard deviations (dB) relative to the mean compared to DO-160F limit.

Probe and Antenna Delta

Figure 5.1-3: Delta for empty and loaded chamber data (See Equation B.12).

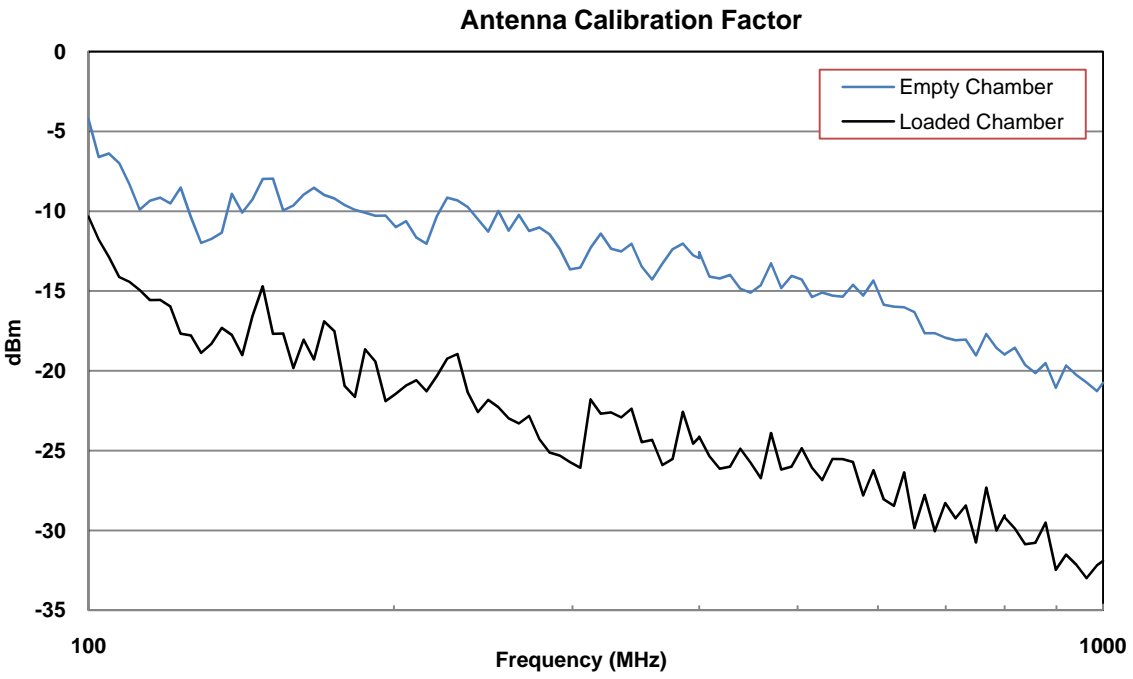**Antenna Calibration Factor**

Figure 5.1-4: Empty and loaded chamber ACF.
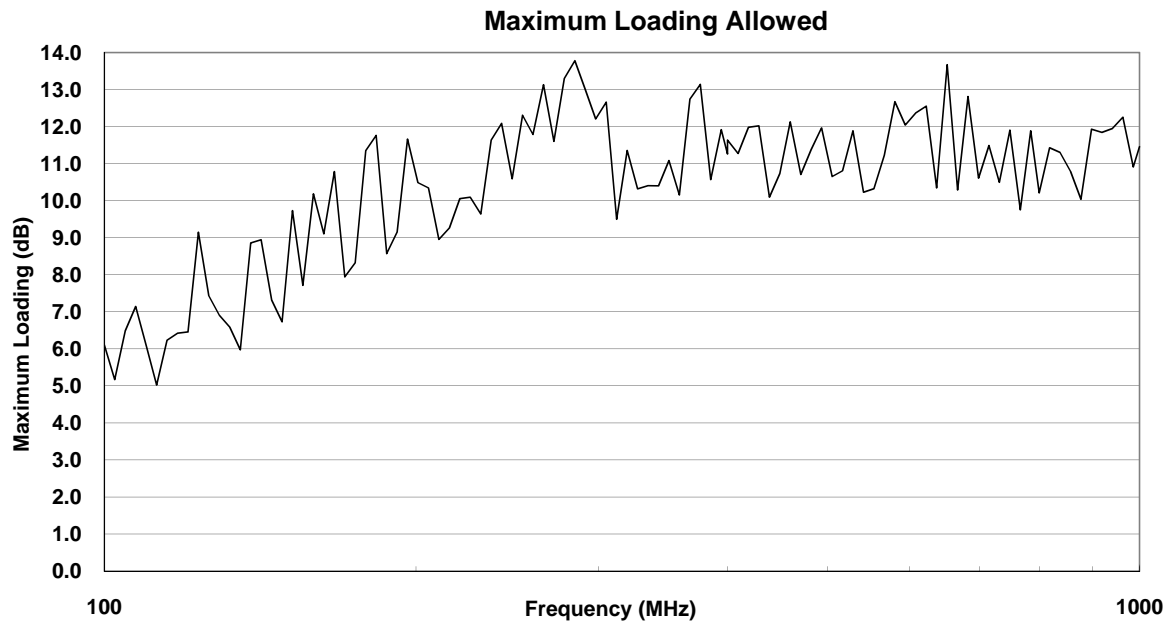
Maximum Loading Allowed

Figure 5.1-5: Chamber A Maximum Loading Allowed.

5.2. EUT Loading Test Process

The EUT Test Process's measurement data are used by the *Process Data* software to calculate a Chamber Calibration Factor (CCF) using Equation B.4 and a Chamber Loading Factor (CLF) using Equation B.5. The CCF plotted in Figure 5.2-1 is the normalized averaged receive power over a stirrer rotation. To reduce measurement uncertainty the Smoothed CCF is determined by averaging over five frequencies. It is plotted with the CCF for comparison. The CLF is plotted and compared to the Maximum Loading Allowed (MLA) in Figure 5.2-2 as specified in DO-160F. If the CLF is greater than the MLA for more than 10% of the test frequencies, then the chamber is over-loaded and the E-field uniformity may be affected. In this case, the Uniformity Validation Test Process should be repeated with the EUT in the chamber.

The *Process Data* software is also used to automatically calculate and record the chamber Quality Factor (Eq. B.6) and Time Constant (Eq. B.7). Figures 5.2-3 and 5.2-4 illustrate Chamber A's Q and Time Constant, respectively.   The chamber has a high Q Factor, which means that less input power is required to achieve required field strengths; however, it also means a longer time is needed to reach a steady state in the chamber. As seen in Figure 5.2-4 the maximum time constant in this case is about 5 microseconds; however, it is suggested that using 6 microseconds would allow for any variations.
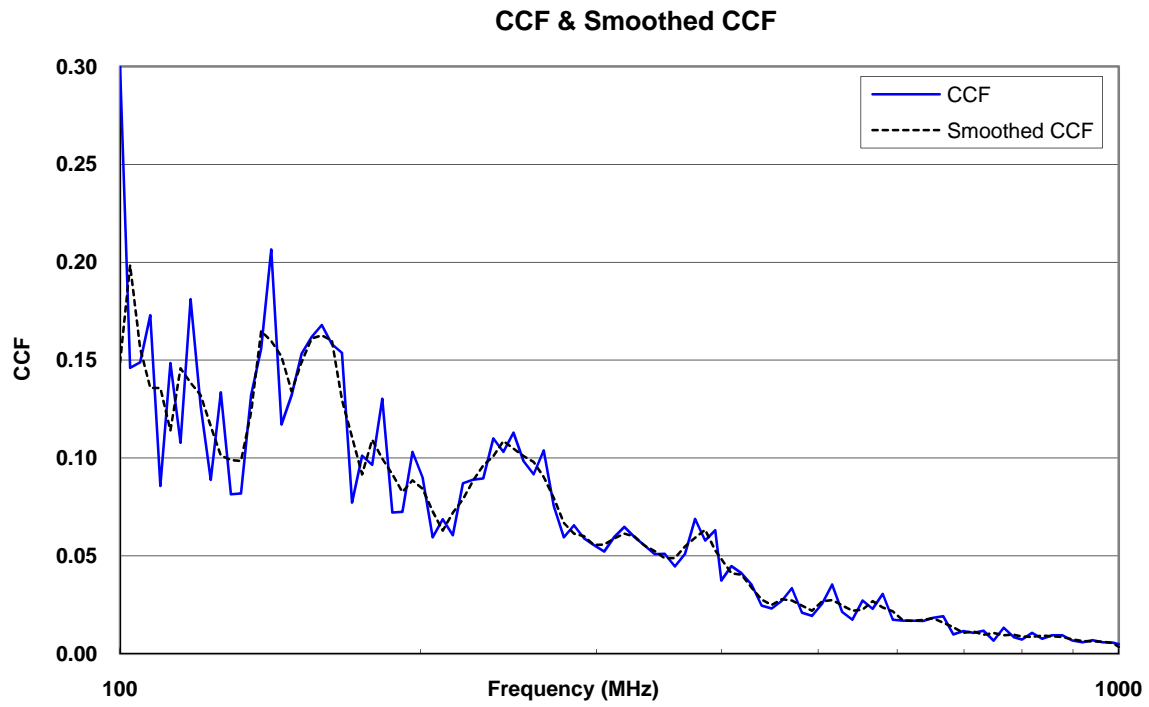
CCF & Smoothed CCF

Figure 5.2-1: CCF & smoothed CCF data.

EUT Chamber Loading & Maximum Loading Allowed
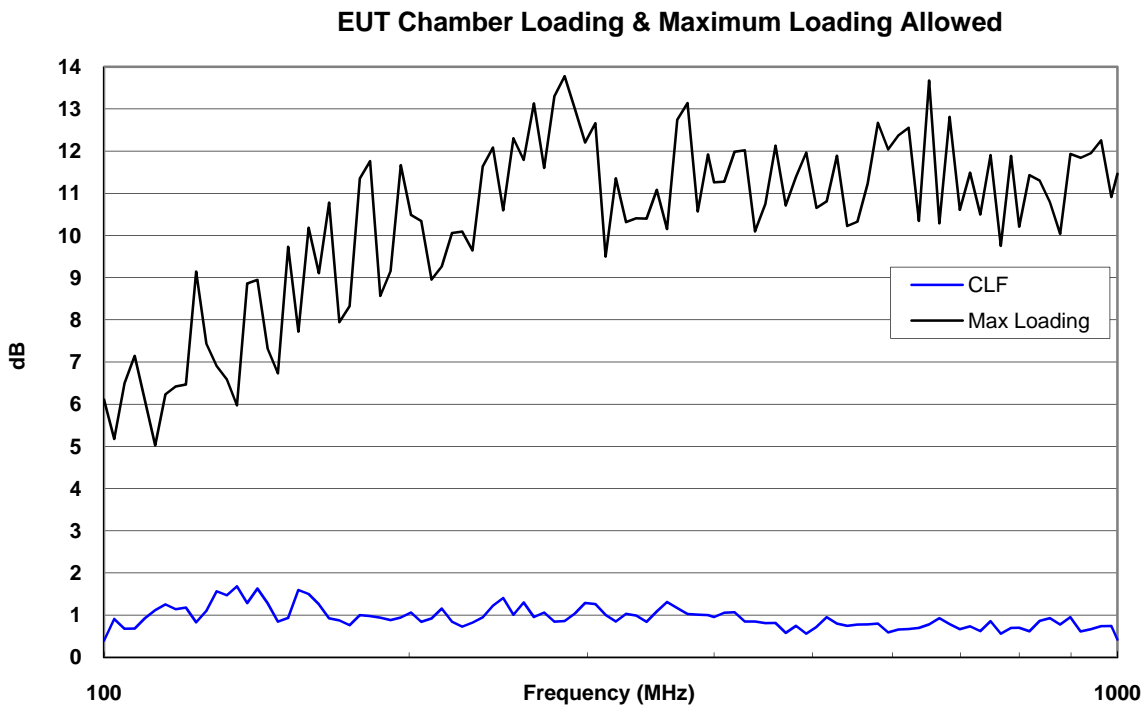
Figure 5.2-2: Chamber Maximum Loading Allowed compared with EUT Chamber Loading Factor (CLF).

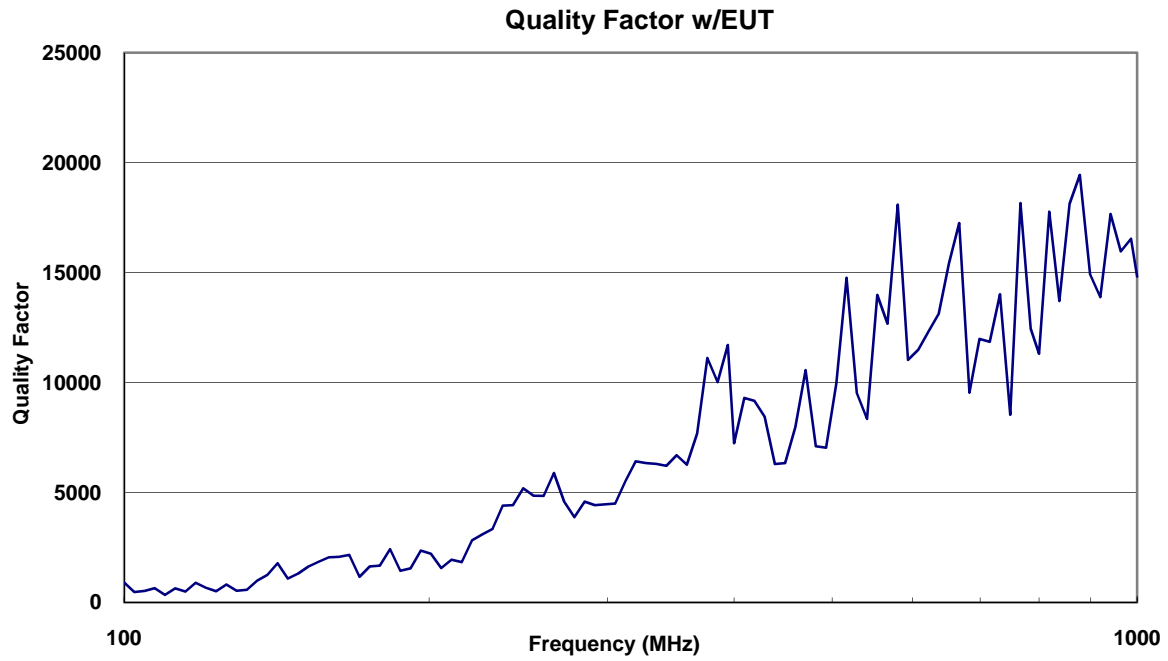**Quality Factor w/EUT**

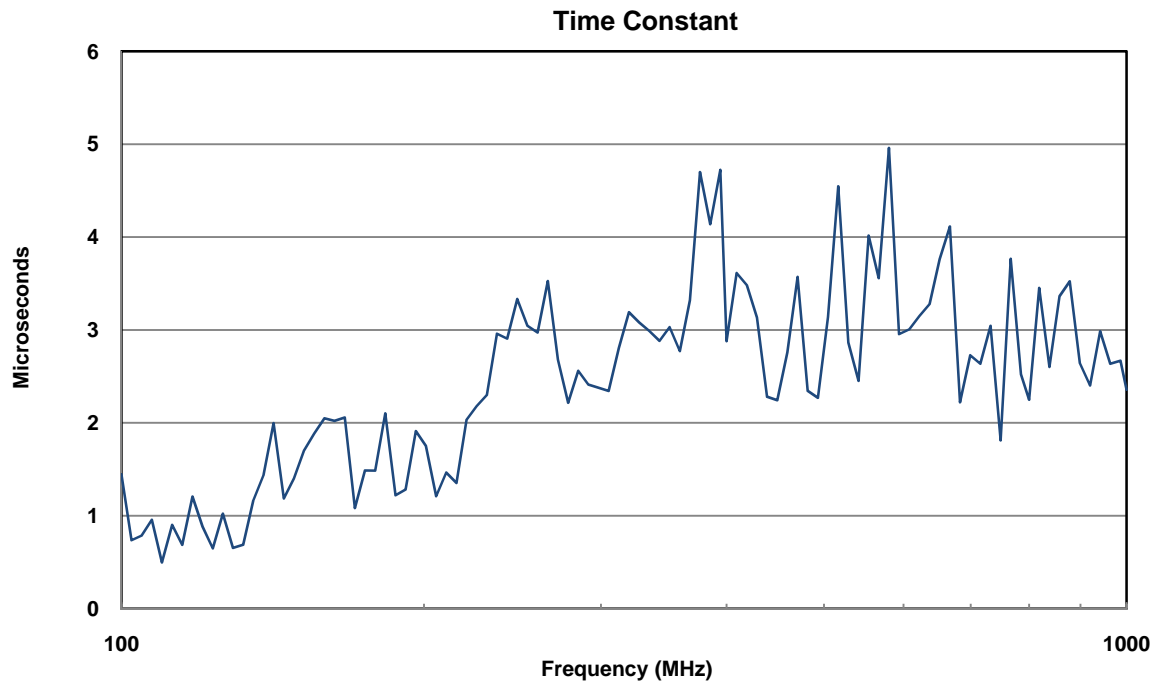Figure 5.2-3: Chamber Q Factor with EUT in chamber.

Time Constant

Figure 5.2-4: Chamber Time Constant with EUT in chamber.

5.3. RS Test Process

RS Test Process data are plotted showing the input power levels and the E-field levels based on two different types of in-chamber measurements; probe and receive antenna. The required input power, determined to produce the test E-field inside the chamber, is plotted in Figures 5.3-1 & 5.3-2 for 200 V/m and 800 V/m, respectively. Each plot contains two data sets, one of power levels that are generated using probe based measurements and the other from receive antenna based measurements. The input power for a RS test is calculated at the transmit antenna using Equation B.8 and the normalized total E-field data from the probe measurements. Additionally, the input power is also calculated using Equation B.9 and average receive antenna measurements. All data are recorded to the Pretest Power Leveling Plan. Data from both calculations is presented as a verification of the test process; however, only the probe based measurements are used for power control during RS testing.

If the antenna based measurements are to be used to determine required input power, DO-160F requires that the two of in-chamber measurements be compared. For frequencies above 400 MHz the differences must be less than +/- 3 dB. Differences between the two measurements can be seen at the lowest frequencies (Fig. 5.3-1); however, at frequencies above 400 MHz the data tracks very closely. The differences at the lower frequencies could be caused by power picked up on the antenna cables or the antenna being too close to objects in the chamber.

During RS testing E-fields are determined and recorded. These results are manually plotted in Figures 5.3-3 and 5.3-4. The measured E-field is determined using Equation B.10 and the calculated E-field using Equation B.11. Both are derived from DO-160F equations for determining input power at a specific test E-field. The measured E-field is based on receive antenna measurements and the calculated E-field is based on probe measurements during calibration.

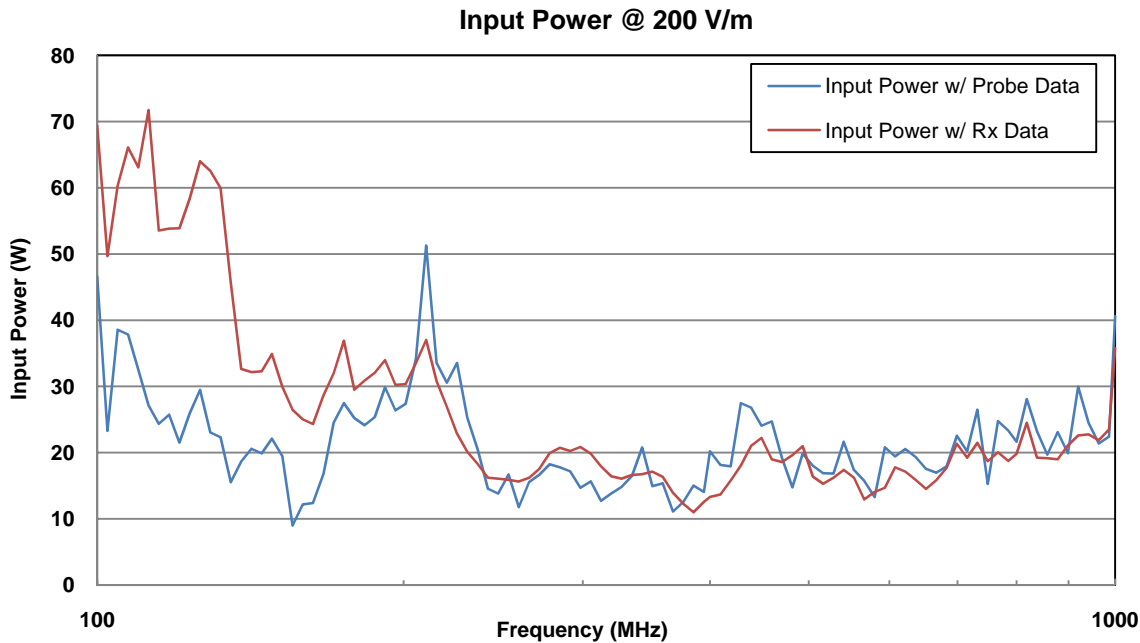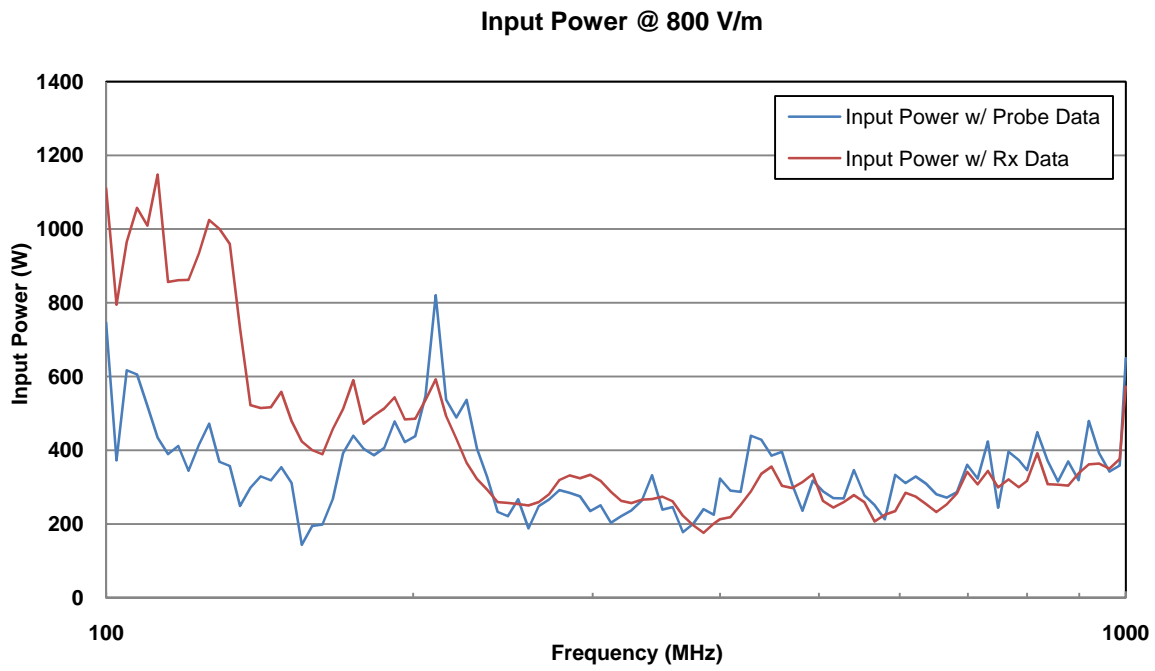Figure 5.3-1: Input power required for a 200 V/m E-field.
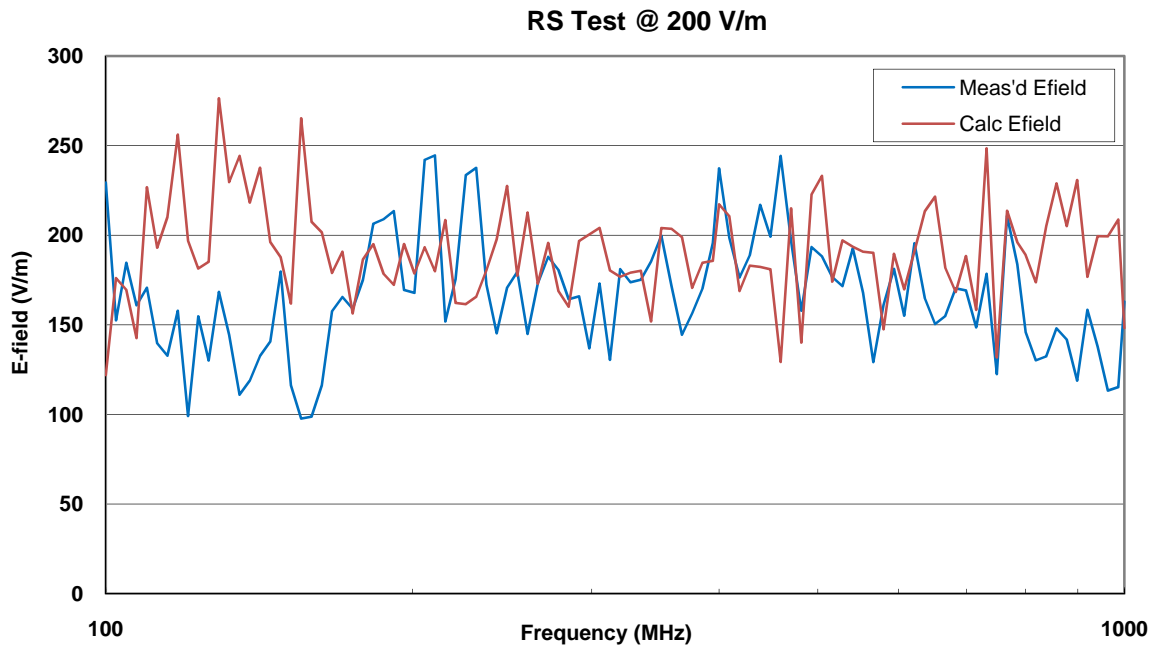
Input Power @ 800 V/m

Figure 5.3-2: Input power required for a 800 V/m E-field.

RS Test @ 200 V/m

Figure 5.3-3: RS Test measured and calculated E-field during a 200 V/m test.
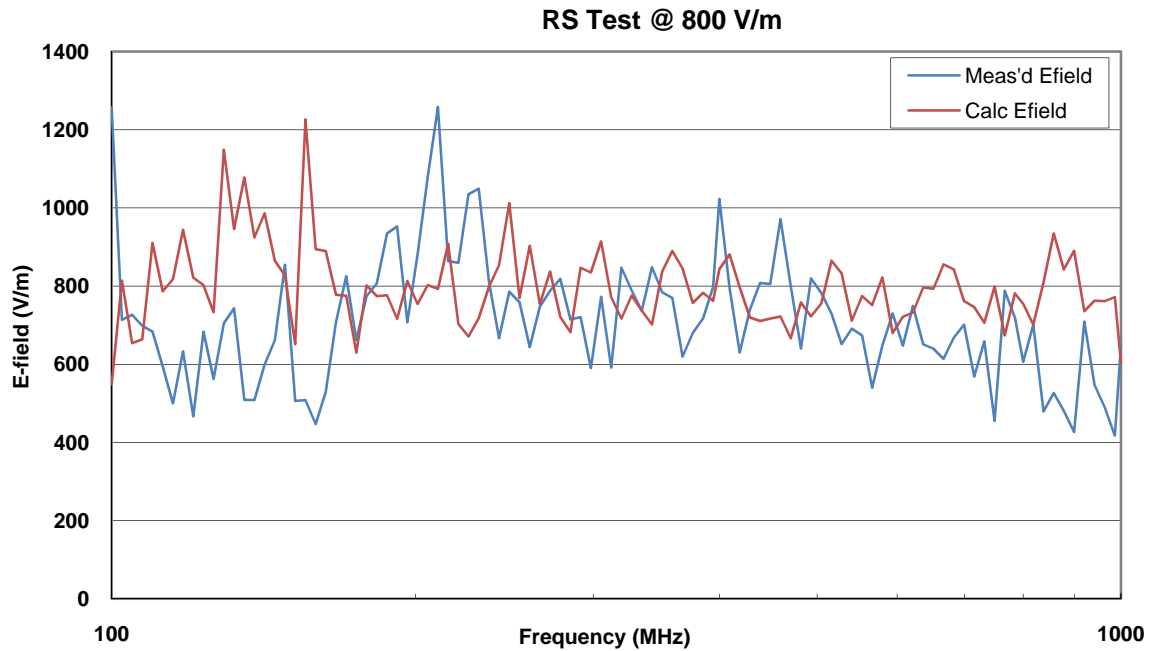
RS Test @ 800 V/m

Figure 5.3-4: RS Test measured and calculated E-field during a 800 V/m test.

5.4. Observations

The Antenna and Probe Delta plot (Figure 5.1-3) can be used as validation during testing. The plot compares the maximum receive antenna measurement normalized to the average input power and the total maximum E-field measurement normalized to the average input power. The plot as shown in Figure 5.1-3 indicates a degree of power fluctuation over the lower frequencies (less than 200 MHz) that approaches 5 dB in one case. It is speculated that this is due to the receive antenna loading the chamber; and therefore, the antenna measurement may not accurately represent the true E-field in the chamber. Field calculations determined from the antenna values may not be appropriate when the antenna is a dominant source of chamber loading. It can, also, be observed that above 200 MHz the plot of Delta becomes more stable and centers about zero for the empty chamber data. Delta is computed using Equation B.12 and antenna E-field values derived from DO-160D mode-stirring techniques.

In Figures 5.3-1 and 5.3-2 the required input power for 200 V/m and 800 V/m, respectively, are plotted for the receive antenna and the probe. Required input power is calculated by Equation B.8 using probe data and Equation B.9 using antenna data. In order to use input power calculated using antenna data, the antenna input power data must compare within +/- 3 dB with probe input power data for frequencies above 4 times the lowest usable frequency ($4f_s$). It is observed that at the lower test frequencies the two data plots diverge, but track closely above 200 MHz. Therefore, the antenna data could be used instead of the probe data at frequencies above $4f_s$. Below $4f_s$, probe data must be used.

6. Future work

The test processes documented define Phase 1 of the HIRF Test Procedure development and primarily focus on compliance to DO-160F guidelines.   However, the HIRF Laboratory has traditionally focused on research and not on compliance testing. Therefore, additional test flexibility and functionality are often needed. To this end, future versions of the procedure will have the capability to deviate from compliance requirements and the required use of mode-tuning techniques. Phase 2 of the HIRF Lab procedure will include mode-stirring, extended frequency ranges and power levels, and a method for applying a reduced number of mode-tuning stirrer steps.

In Phase 1 the calibration process acquires data at each stirrer position over a complete rotation, and then performs calculations to summarize that data. In order to investigate the effect on chamber uniformity of using fewer stirrer steps, requires repeating the complete calibration process. This is neither time nor resource efficient. Consequently, a method was investigated to capitalize on the calibration process test time and data. Since the method was realized later in the development of Phase 1, it was decided to incorporate it into Phase 2.

In the current calibration process the summary data are recorded, but the individual step data are not.   A capability to use fewer stirrer positions, while maintaining field uniformity, could be added. This change would provide the capability to determine field uniformity using fewer stirrer positions by selecting a partial set of data from a complete set of test measurements. The Uniformity Validation Process could, for instance use 72 stirrer positions during calibration and record data from each position. In post processing, field uniformity would be examined for partial sets of 12, 18, 24, and 36 uniformily spaced steps, and the minimum number of steps chosen that still meets the field uniformity requirement.

In addition, future work could extend the procedure to include RS testing in Chambers B and C, and at higher test frequency ranges. The changes will require modifications in hardware and chamber configurations, as well as software.

7. Conclusions

NASA Langley Research Center's HIRF Laboratory has the capability to perform reverberation chamber calibrations and RS tests based on RTCA\DO-160F Section 20.6 guidelines for susceptibility testing in reverberation chambers. This includes utilizing E-field probes to demonstrate chamber uniformity, applied mode-tuning techniques, automated calculation of chamber parameters, measurement of EUT loading effects, creation of power leveling plans for RS testing, and RS testing with CW, square wave, and pulsed signals. Procedure operations are organized into three test processes and data sets. The numbered operations identify tests, calculations, and data in Excel worksheets. Custom developed software automates test control, calculations, and data acquisition and management.

In addition to a new capability for the Laboratory, this procedure confirmed that Chamber A's performance was not affected by recent structural modifications. The modifications included the installation of a 20 foot door and a large bulkhead opening and panel between Chambers A and B. The data indicate that the chamber's performance is well within the limits of the DO-160F uniformity requirements, and similar to that measured by NIST.

Future testing will utilize the procedure to determine chamber loading due to the effect of EUT's before conducting RS testing. Additional chamber uniformity validation measurements should be repeated annually or if the chamber's physical structure changes.

In conclusion, the procedure creates an efficient and well defined method for conducting RC calibrations and susceptibility tests based on DO-160F in the HIRF Laboratory. The procedure enhances the Laboratory's capability to conduct RS testing to evaluate the electromagnetic radiated susceptibility of electronic equipment and upsets in flight critical fault-tolerant architectures.

8. References

(1) RTCA/DO-160F, Section 20.6, "Radiated Susceptibility (RS) Test; Alternate Procedure – Reverberation Chamber", *Environmental Conditions and Test Procedures for Airborne Equipment*, Dec. 2007.

(2) RTCA/DO-160D, Section 20.6, "Radiated Susceptibility (RS) Test; Alternate Procedure – Reverberation Chamber", *Environmental Conditions and Test Procedures for Airborne Equipment,* Oct. 2000.

(3) Ladbury, J.; Koepke, G.; Camell, D.: *Evaluation of the NASA Langley Research Center Mode-Stirred Chamber Facility*, U.S. Department of Commerce, National Institute of Standards and Technology, Boulder, CO, NIST Tech Note 1508, 1999.

(4) SoftPlot, Athena Ltd., Cambridge, U.K.

Appendix A.   Software Windows and Menus

The appendix gives examples of software windows including menus, test operations, test data and test status. All windows presented are generated by the *Calibration and RS Test* software and the *Process Data* software. Main Windows for each software program are presented with lists of available test operations and calculations. Information displays located in the software windows provide guidance on using the software and test procedures. An example window for data file name entry in *Process Data* is presented as representative of all data processing operations.

A.1.   Calibration and RS Test Windows
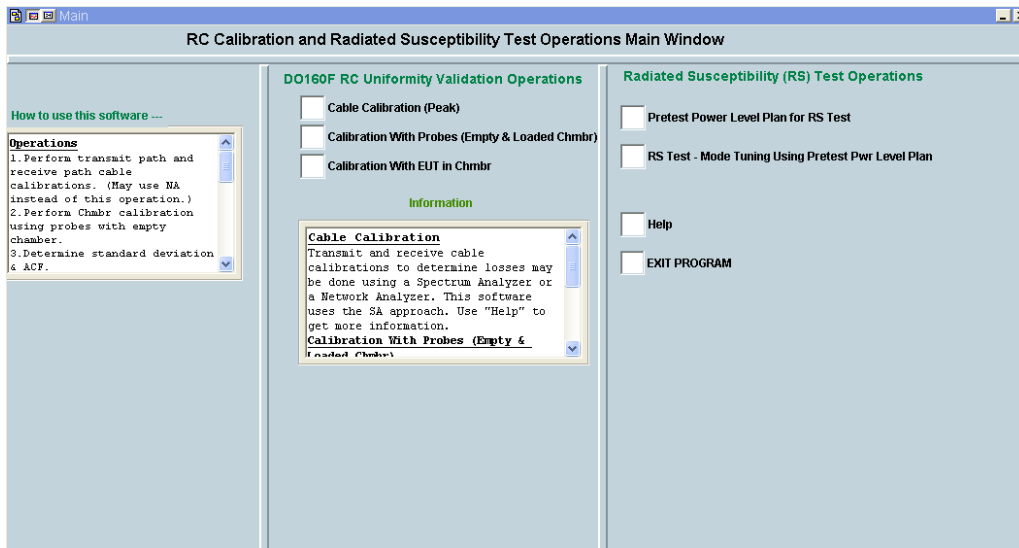
Figure A-1: Main Window.
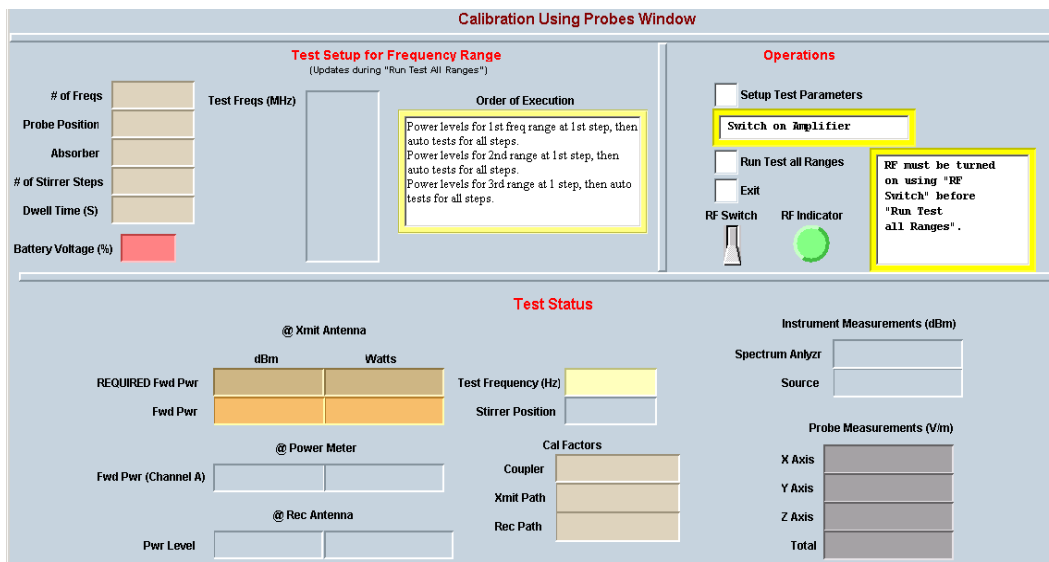
Figure A-2: Calibration Using Probes Window.

Calibration using EUT

Calibration Using EUT Window

Test Setup for Frequency Range

(Updates during "Run Test All Ranges")

Order of Execution

# of Freqs

Freqs Range (MHz)

Absorber

# of Stirrer Steps

Dwell Time (S)

Power levels for 1st freq range at 1st step, then auto tests for all steps.
Power levels for 2nd range at 1st step, then auto tests for all steps.
Power levels for 3rd range at 1 step, then auto tests for all steps.

Operations

Setup Test

Switch on Amplifier

Run Test all Ranges

Exit

RF Switch   RF Indicator

RF must be turned on using "RF Switch" BEFORE "Run Test all Ranges".

Test Status

@ Xmit Antenna

dBm   Watts

REQUIRED Fwd Pwr

Fwd Pwr

Test Frequency (Hz)

Stirrer Position

Instrument Measurements (dBm)

Spectrum Anlyzr

Source

@ Power Meter

Fwd Pwr (Channel A)

Cal Factors

Coupler

Xmit Path

Rec Path

@ Rec Antenna

Pwr Level

Figure A-3: Calibration Using EUT Window.

Pretest Pwr Lvling

Pretest Power Leveling Window

Operations

Setup Test from files

Start DO160F Pwr Leveling

EXIT PROGRAM

Power Meter

dBm

Fwd Pwr

Source

Freq (Hz)

Pwr (dBm)

Modulation

Efield (V/m)

Required

RF Switch

Start Frequency (MHz)

Stop Frequency (MHz)

Instrument Controls

Figure A-4: Pretest Power Leveling Window.
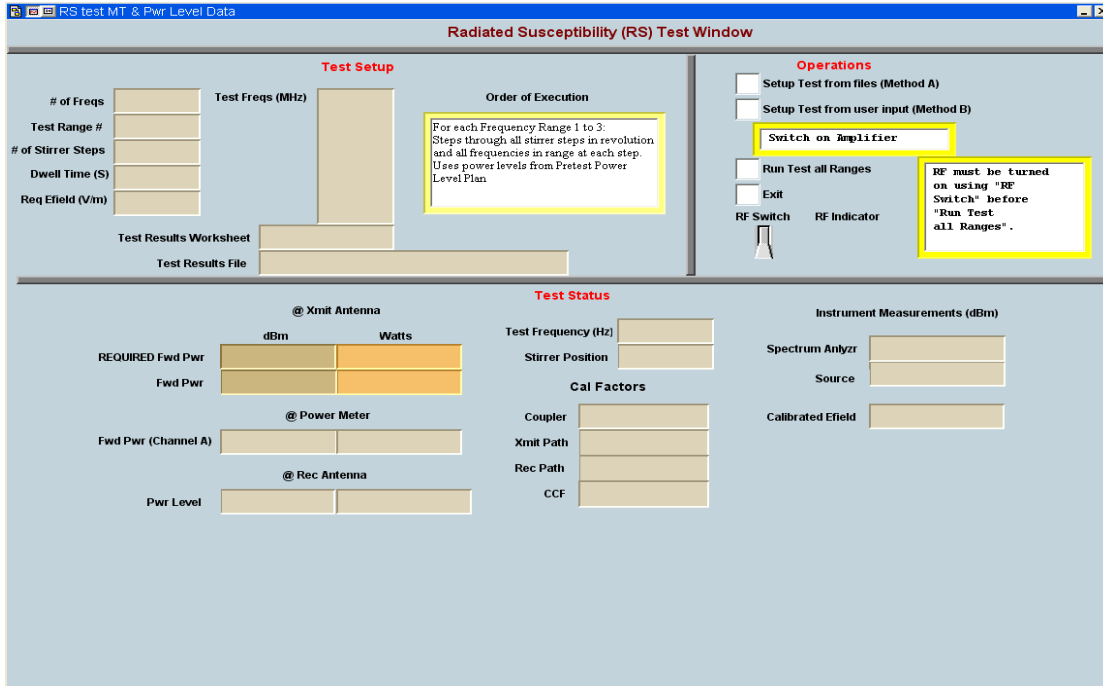
Figure A-5: Radiated Susceptibility Test Window.

A.2. Process Data Windows
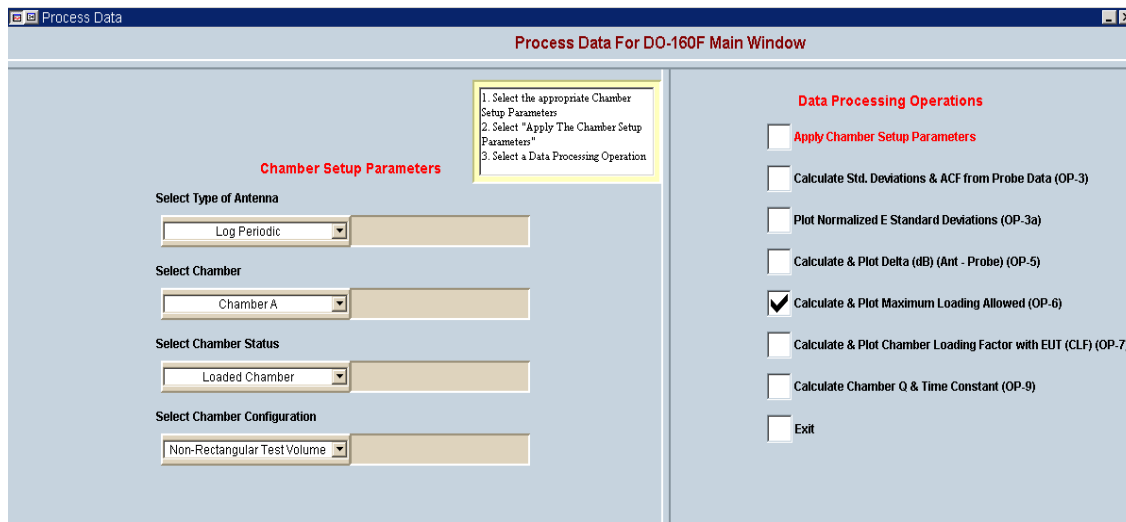
Figure A-7: Main Window.
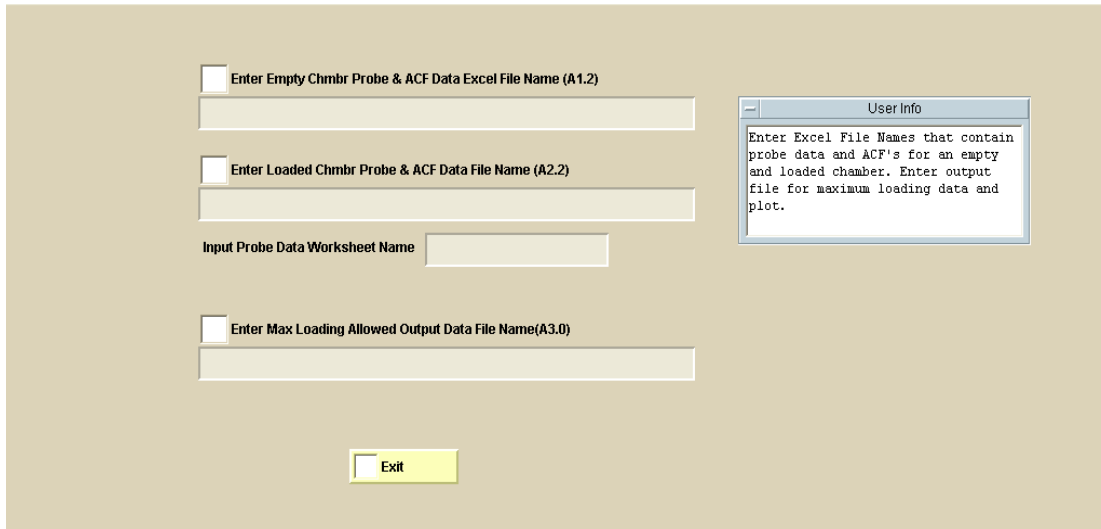
Figure A-8: Calculate Maximum Loading Allowed Operation Window.

Appendix B. DO-160F Calculations

The appendix contains definitions and equations for computing input power, receive power, chamber characteristics, and test E-field levels. Equations are derived from DO-160F [1].

Note: $\langle \ \rangle$ indicates arithmetic mean

B.1. Average Input Power

The average input power is calculated using input power over a complete revolution for each frequency as shown in Equation B.1.

$$P_{InputAvg} = \frac{1}{N} \sum_{1}^{N} P_{Input} \ , \qquad\qquad\qquad\qquad (\text{Eq. B.1})$$
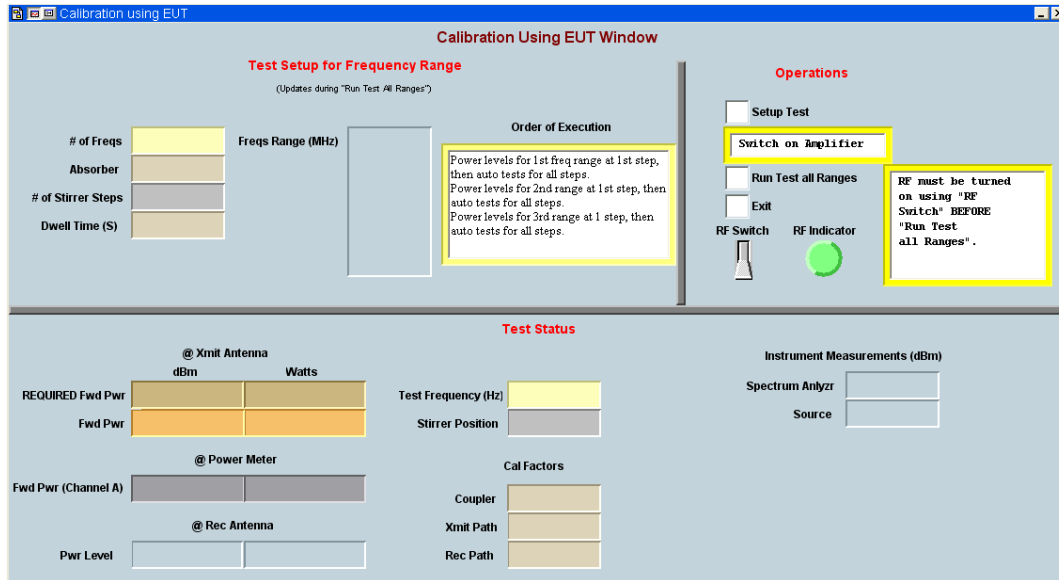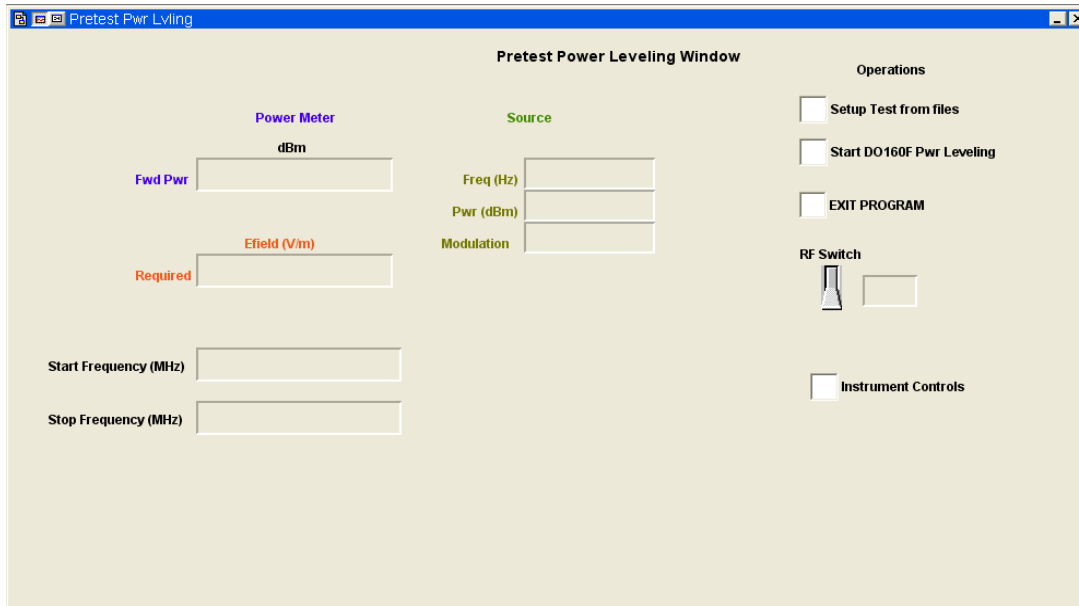
where

$P_{InputAvg}$ = average input power computed over a complete revolution,

P_{Input} = input power or forward power in Watts at the transmit antenna = Soure power + coupler loss + transmit path (cable) loss,

N = number of stirrer position or number of samples.

B.2. Antenna Calibration Factor

An Antenna Calibration Factor (ACF) is calculated in Equation B.2 for both Empty chamber and a Loaded chamber using data from the each chamber configuration.

$$ACF = \langle \frac{P_{RecAvg}}{P_{InputAvg}} \rangle_n \,, \qquad \text{(Eq. B.2)}$$

where

ACF = average receive power normalized to the average input power over 1 rotation for all probe position,

$P_{InputAvg}$ = input power or forward power averaged over a complete rotation,

P_{RecAvg} = receive power averaged over a complete rotation,

n = 9 if frequencies < 10f, or 3 if frequencies => 10f.

B.3. Maximum Loading Allowed

The Maximum Loading Allowed (MLA) in a chamber is calculated using the ACF's from Empty and Loaded chamber data as shown in Equation B.3.

$$MLA = \frac{ACF_{Empty}}{ACF_{Loaded}} \,, \qquad \text{(Eq. B. 3)}$$

where

ACF_{Empty} = ACF for empty chamber,

ACF_{Loaded} = ACF for loaded chamber.

B.4. Chamber Calibration Factor

The chamber calibration factor (CCF) is calculated in Equation B.4 using data from the EUT Test Process.

$$CCF = \langle \frac{P_{RecAvg}}{P_{InputAvg}} \rangle_{n,f} \,, \qquad \text{(Eq. B.4)}$$

where

CCF = the ratio of the average received power to the average input power over a complete stirrer rotation at n antenna positions at every test frequency,

P_{RecAvg} = receive power averaged over a complete stirrer rotation,

$P_{InputAvg}$ = input power or forward power averaged over a complete stirrer rotation,

n = the number of antenna locations where the CCF is evaluated for use. Only one location is required,

f = frequency.

B.5. Chamber Loading Factor

The Chamber Loading Factor (CLF) is defined in Equation B.5 as the ratio of CCF from the EUT Test Process data and ACF from the Empty Test Process data.

$$CLF = \frac{CCF}{ACF} ,$$
(Eq. B.5)

where

CLF = ratio of the CCF and the ACF from the Empty Test Process,

CCF = ratio of the average received power and the average input power over a complete stirrer rotation at n antenna positions at every test frequency,

ACF = average receive power normalized to the average input power over 1 rotation for all probe position for an empty chamber.

B.6. Chamber Q

$$Q = \left(\frac{16\pi^2 V}{\eta_{Tx}\eta_{Rx}\lambda^3}\right) * CCF ,$$
(Eq. B.6)

where

Q = chamber Q factor,

η_{Tx} = transmit antenna efficiency factor, 0.75 for log periodic, 0.9 for horn,

η_{Rx} = receive antenna efficiency factor, 0.75 for log periodic, 0.9 for horn,

λ = frequency wavelength,

V = volume (Table A-1) of the chamber (m^3) in calibration.

Table A-1: Chamber Volumes [3]

Chamber	Volume (m^3)
A	290.8
B	80.43
C	16.8

B.7. Time constant

$$\tau = \frac{Q}{2\pi f} ,$$
(Eq. B.7)

where

τ = chamber time constant (sec),

Q = chamber Q,

f = test frequency (Hz).

B.8. Input Power for Mode-Tuned RS Test Using Probe Data

The input power required for each test frequency during a RS test must be determined as shown in Equation B.8, and recorded prior to actually conducting the test. Pretest power leveling in the *Calibration and RS Test* software will automate the process and record the data. The equation includes the required E-field, the mean of the normalized total E-field data from the probe positions, and the Chamber Loading Factor.

$$P_{InputRS} = \left[\frac{E_{Test}}{\langle E_{normTot} \rangle_{n} * \sqrt{CLF}} \right]^{2} ,$$
(Eq. B.8)

where

$P_{InputRS}$ = input power at the transmit antenna port required to achieve the test E-field level,

E_{Test} = required test E-field level in V/m,

$\langle E_{normTot} \rangle_{n}$ = mean of the normalized maximum total E-field in V/m over all probe positions recorded during empty chamber uniformity validation testing, total E-field / 1 Watt,

CLF = ratio of the CCF from the EUT Test Process and the ACF from the Empty Test Process.

B.9. Input Power for Mode-Tuned RS Test Using Receive Antenna Data

The RS Test Process uses the input power determined from Equation B.8; however, the power is also determined in Equation B.9 using the average receive power over a complete stirrer rotation. See DO-160F Section 20.6.3.3 and 20.6.4.4.2 for more information. The result is then compared with the input power determined using the probe measurements (Fig. C.3.1 and C.3.2). The equation includes the required E-field, the Chamber Loading Factor, and the maximum squared magnitude of the total E-field and the average receive power over a complete stirrer rotation.

$$P_{Input} = \frac{E^2_{Test}}{|E_{normTot}|^2\,_{max} * \sqrt{CLF}} ,$$
(Eq. B.9)

$$|E_{normTot}|^2\,max = \langle \frac{P_{recavg}}{P_{Input*\eta_{rx}}} \rangle * \frac{8\pi\eta}{\lambda^2} * R ,$$

where

E_{Test} = required test E-field level in V/m,

CLF = ratio of the CCF from the EUT Test Process and the ACF from the Empty Test Process,

$|E_{normTot}|^2$ max = maximum squared magnitude of the total E-field per Watt,

P_{recavg} = average receive power over complete stirrer rotation,

45

P_{Input} = average input power over complete stirrer rotation,

η_{rx} = receive antenna efficiency factor for log periodic = 0.75.

η = wave impedance of free space ($120\pi = 377$).

R = maximum to average ratio of squared magnitude of E-field as found in DO-160F Table 20-7 for 60 stirrer steps = 2.76,

λ = wave length (m).

B.10. Calculated Test E-field from Input Power

The *Calibration and RS Test* software displays and records a Calculated E-field. The E-field is displayed during execution of a RS test and calculated for each test frequency using the current input power at the transmit antenna. The E-field is also determined over a complete stirrer rotation and calculated using the average input power. Equation B.10 is derived from Equation B.8.

$$E_{Test} = \langle E_{normTot} \rangle_n * CLF * \sqrt{P_{InputRS}} \; , \qquad\qquad\qquad \text{(Eq. B.10)}$$

where

E_{Test} = test E-field level in V/m,

$\sqrt{P_{InputRS}}$ = input power at the transmit antenna port required to achieve the test E-field level,

$\langle E_{normTot} \rangle_n$ = mean of the normalized maximum total E-field in V/m over all probe positions recorded during empty chamber uniformity validation testing, total E-field / 1 Watt,

CLF = ratio of the CCF from the EUT Test Process and the ACF from the Empty Test Process.

B.11. Measured Test E-field from Maximum Receive Power

Equation B.11 is derived from Equation B.9 and DO-160F equations in Section 20.6.3.3 and 20.6.4.4.2, which calculate the input power based on the normalized average squared total E-field. In the DO-160F equations, the total E-field is computed using the average receive power and represents the total E-field per 1 Watt of input power. This procedure uses the maximum receive power, P_{recmax}, to compute the test E-field that is displayed during testing.   The average receive power, P_{recavg}, to compute the test E-field is recorded at the end of testing.

$$E_{Test} = \sqrt{\frac{P_{rec}}{\eta_{rx}} * \frac{8\pi\eta}{\lambda^2} * R} \; , \qquad\qquad\qquad \text{(Eq. B.11)}$$

where

E_{Test} = test E-field level in V/m,

P_{rec} = maximum receive power in watts at a frequency at a stirrer step when displayed during testing,

η_{rx} = antenna efficiency factor for the receive antenna = 0.75 for a log periodic,

η = wave impedance of free space = 120π,

R = maximum to average ratio of squared magnitude of E-field as found in DO-160F Table 20-7 for 60 stirrer steps = 2.76,

λ = frequency wavelength in meters.

B.12. Antenna and Probe Delta

Delta compares the maximum receive antenna measurement normalized to the average input power and the total maximum E-field measurement normalized to the average input power. Delta is computed and plotted during chamber uniformity validation for both empty and loaded chambers. The computation of $E_{normAnt}$ is derived from DO-160D equations [2] and uses the maximum receive power to calculate $E_{normAnt}$.

$$Delta = 20\, Log\, \left(\frac{\langle E_{normAnt}\rangle n}{\langle E_{normProbe}\rangle n}\right), \qquad\qquad \text{(Eq. B.12)}$$

$$E_{normAnt} = \frac{\left(8.0\pi/\lambda\right)* \sqrt{(5*P_{RecMax})/\eta_{Rx}}}{\sqrt{P_{input}}},$$

where

$\langle E_{normProbe}\rangle n$ = mean of the normalized maximum total E-field in V/m over all probe positions, total E-field / 1 Watt,

$\langle E_{normAnt}\rangle n$ = mean of the $E_{normAnt}$ over all probe positions,

P_{RecMax} = receive power maximum over a complete stirrer rotation,

P_{Input} = average input power over complete stirrer rotation,

η_{Rx} = receive antenna efficiency factor, 0.75 for log periodic, 0.9 for horn,

λ = frequency wavelength,

n = number of antenna and probe positions.

Appendix C. Data **Files and Worksheets**

Files and worksheets are used to support the test processes, serving as containers for input information and repositories of test results. Data are recorded to worksheets both during a test and during post processing. Worksheets contain headers that provide data sources, such as file names, test parameters, and column titles. The first column always contains a list of test frequencies applied during a test or post process. Note that all column data are a summary of measurements evaluated over a complete stirrer rotation. The recorded data are defined here by worksheet and column title.

C.1. Data File Description

The Excel workbooks or data files will grow in size to contain more worksheets as a process progresses. Each of the basic processes has its own workbook containing a defined set of worksheets. In addition, the workbooks have a unique number incorporated into their name that can be related to operations within the process.   The format of this workbook should not be changed; however, the data is changeable. Any method used for file naming will work; however, it is recommended that the file naming and number scheme defined here be used. The file name nomenclature is described as, File Name + File ID + .xls, where File Name can be any text, File ID is a specific letter and number identifier, and .xls is the Excel extension.

Table C.1-1 illustrates file organization and content. The File ID letters, A, B, C are associated with the Test Processes, Chamber Uniformity Validation, EUT Loading Effects, and RS Testing, respectively. Table C.1-1 lists File ID's and their associated workbooks and worksheets. A suggested File Name is also given in the second column. As an example, a file with the name, "ChmbrA Empty A1.2.xls", suggests that the test was done in Chamber A with an empty configuration and in its competed state will contain the worksheets Hrdw, Params, XmitCal, RecCal, CplrCal, Freqs_Cals_Pwr, Pos1…9, STD, SD_plot, and Delta(Ant-Probe)_Plot as listed in the "Worksheet Names" column in the table. Note that the File Name may be reused with a different File ID as worksheets are added during the process.

An input template workbook is referenced in Table C.1-1's Description column for File ID's A1.0, A2.0, B1.0, and C1.0. This workbook must contain the required input information that is required by all test processes and must be manually created before beginning a test process.

Table C.1-1: Organization of File ID's to Workbooks and Worksheets

File ID	Workbook File Name	Description	Worksheet Names
A1.0/A2.0	Uniformity_Val_Input_Params	Input Template for reuse for Empty and Loaded Calibration	Hrdw, Params, XmitCal, RecCal, CplrCal
A1.1	ChmbrA_Empty	Input and Output data for 9 probe position msmts in empty chamber	Hrdw, Params, XmitCal, RecCal, CplrCal, Freqs_Cals_Pwr, Pos1…9
A1.2	ChmbrA_Empty	Input and Output data for 9 probe position msmts in empty chamber + Output for calculated STD, Delta calculation & ACF	Hrdw, Params, XmitCal, RecCal, CplrCal, Freqs_Cals_Pwr, Pos1…9, STD, SD_plot, Delta(Ant-Probe)_Plot
A2.1	ChmbrA_Loaded	Input and Output data for 8 probe positions in loaded chamber	Hrdw, Params, XmitCal, RecCal, CplrCal, Freqs_Cals_Pwr, Pos1…8
A2.2	ChmbrA_Loaded	Input and Output data for 8 probe positions in loaded chamber + Output for calculated STD & ACF	Hrdw, Params, XmitCal, RecCal, CplrCal, Freqs_Cals_Pwr, Pos1…9, STD, SD_plot, Delta(Ant-Probe)_Plot
A3.0	ChmbrA_MaxLoading_Allowed	Output for calculation	Chmbr_MaxLoading, Chmbr_MaxLoad_Plot
B1.0	ChmbrA_EUT_Input_Params	Input Template for EUT calibration in chamber	Hrdw, Params, XmitCal, RecCal, CplrCal
B1.1	ChmbrA_EUT (File B1.0 + EUT data)	Output data for test with EUT in chamber, CCF	Hrdw, Params, XmitCal, RecCal, CplrCal, Freqs_Cals_Pwr, EUT
B1.2	ChmbrA_EUT (File B1.1 + CLF data)	Output data for test with EUT in chamber + Output for calculation of CLF	Hrdw, Params, XmitCal, RecCal, CplrCal, Freqs_Cals_Pwr, EUT, CLF, MaxLoad_vs_CLF_Plot
B2.0	ChmbrA_EUT (File B1.2 + Q data)	Output data for calculation of Max Loading with EUT, CLF(adds Q, time constant, maxload allowed	Hrdw, Params, XmitCal, RecCal, CplrCal, Freqs_Cals_Pwr, EUT, CLF, MaxLoad_vs_CLF_Plot
C1.0	RS_Test_Input_Params	Input parameters for test	Hrdw, Params, XmitCal, RecCal, CplrCal
C1.1	RS_Test	Input parameters + Power leveling data	Hrdw, Params, XmitCal, RecCal, CplrCal, Freqs_Cals_Pwr_xVM (for each required efield)
C1.2	RS_TestX-CW or RS_TestX-Pulse	Input parameters + Power leveling data + RS test data	Hrdw, Params, XmitCal, RecCal, CplrCal, Freqs_Cals_Pwr_xVM, Test1, Test2,……

C.2. Worksheet Descriptions

Worksheets may contain both input and output data depending on operations. Table C.2-1 identifies the data contained within each worksheet and the test processes that require it. The first four worksheets listed, Params, XmitCal, RecCal, CplrCal, and Hdwr, are manually created. All others are automatically generated by the software.

Table C.2-1: Organization of worksheets and data

Worksheet Name	Test Process	Data
Hrdw	All	Instruments, Sensors, Cables, Attenuators, Couplers
Params	All	Start Freq, Stop Freq, # Stir Pos, Freqs/Decade, Dwell Time, Required Efield, Stir Mode, Pwr Tolerance, MaxPwr@Source, MaxPwr@PM, MaxPwr@XmitAnt, Absorber, Chmbr
XmitCal	All	Frequencies, Cal Values (dBm)
RecCal	All	Frequencies, Cal Values (dBm)
CplrCal	All	Frequencies, Cal Values (dBm)
Freqs_Cals_Pwr	All	Freq, XmitCal, RecCal, CplrCal, FwdPwr (@ source)
Pos1....Pos9	Chamber Uniformity Validation	Freq, ExNormMax, EyNormMax, EzNormMax, EtotalNormMax, ExMaxNorm, EyMaxNorm, EzMaxNorm, EtotalMaxNorm, FwdPwrAvg, PwrRecMax, PwrRecAvg, ExMax, EyMax, EzMax, EtotalMax, # of Steps, Probe Pos, Absorber
STD	Chamber Uniformity Validation	Freq, ExSDtoMean, EySDtoMean, EzSDtoMean, ExyzSDtoMean, EnormProbe, EnormAnt, Delta(Ant-Probe), ACF
STD_Plot	Chamber Uniformity Validation	Plot Standard Deviation
Delta (Ant-Probe) Plot	Chamber Uniformity Validation	Plot Delta
Chmbr_MaxLoading (File ID A)	Chamber Uniformity Validation	Freq, MaxLoadAllowed (dB), ACF (Empty Chmbr)
EUT	EUT Loading Effects	Freq, FwdPwrAvg, PwrRecMax, PwrRecAvg, CCF
CLF	EUT Loading Effects	Freq, ACF (W) Empty, CCF, CLF
MaxLoad_vs_CLF_Plot	EUT Loading Effects	Plot Max Loading Allowed & EUT Loading Effect
CLF	EUT Loading Effects	Freq, MaxLoadAllowed (dB), ACF (W) Empty, CCF, CLF, Q, TimeConstant
Freqs_Cals_Pwr_Efieldx	RS Test	Freq, XmitCal, RecCal, CplrCal, FwdPwr (@ source)
Test1.....Testn	RS Test	Timestamp, Freq, PM, FwdPwr, CalEfield, SA, Efield, Efield Ratio

C.2.1. Parameters (Params) Worksheet

Figure C.2.1-2 is an example of the Params worksheet used during a Uniformity Validation Test Process in an empty Chamber A. The data are used to setup and control instrumentation, calculate test values, conduct tests, and process data. The yellow sections, columns 1, 2, and 3, can be changed as needed; however, the format must remain the same. The parameters contained in the Params worksheet are required for all the test processes discussed and must be included in the input template workbooks.

In the example, the "Parameters/Range" section contains parameters organized into three test ranges by Start Freq and Stop Freq. The number of ranges can be as few as one or more than three, but each range must be defined in the worksheet. Three of the parameters that define test frequency ranges, number of frequencies per decade, and number of stirrer positions are listed in Table C.2.1-1 as an example for Chamber A. The number of stirrer positions was taken from DO-160D requirements [2]. Frequency ranges are chamber dependent and should consider the chamber's lowest usable frequency. The "Instrument Setup Parameters" section shows setup values for initialization of test instruments.

The worksheet parameter fields are defined below.

- Start Freq – first frequency in a test range
- Stop Freq – last frequency in a test range
- # Stir Pos – number of stirrer steps required during a complete rotation
- Freqs/Decade – a required number of frequencies per decade
- Dwell Time – amount of wait time at each test frequency in seconds
- Req. Fwd Pwr / E-field – required forward power in watts during uniformity validation tests or required E-field in V/m during RS testing
- Stir Mode – set to "Step" for Mode-Tuning or "Continuous" for Mode-Stirring.
- PwrTolerance – defines the tolerance level between actual power meter reading and required value in dB during power leveling
- Max Pwr @ Source – maximum power level or power limit in dBm at the signal generator during a test.
- Max Pwr @ PM – maximum power level in dBm allowed at the power meter
- Max Pwr @ Xmit Ant – maximum power level in watts allowed at the transmit antenna
- Absorber – this field is set to "No" during empty chamber testing, "Yes" during loaded chamber testing, and "EUT" during EUT and RS testing
- Chamber – denotes chamber where test is conducted, A, B, or C
- SA-RBW – spectrum analyzer resolution bandwidth setting in Hz at the beginning of a test
- SA-ST – spectrum analyzer sweep time setting in seconds at the beginning of a test
- SA-RL – spectrum analyzer reference level setting in dB at the beginning of a test
- PM-Mode – power meter mode setting is "CW during calibration testing and "CW" or "Pulse" during RS testing.
- Source-Initial Freq – signal generator frequency in MHz at the beginning of a test
- Source-Initial Pwr – signal generator power level in dBm at the beginning of a test
- Stir-Velocity – stirrer velocity in sec/rev
- Stir-Accel – stirrer acceleration rate in sec/rev

Parameters/Ranges	1	2	3
Start Freq	100.00	400.00	800.00
Stop Freq	400.00	800.00	1000.00
#Stir Pos	60.00	36.00	18.00
Freqs /Decade	100.00	100.00	100.00
Dwell Time (sec)	0.50	0.50	0.50
Req. Fwd Pwr (W)/Efield	5.00	5.00	5.00
Stir Mode	Step	Step	Step
PwrTolerance	0.20	0.20	0.20
Max Pwr @ Source (dBm)	5.00	5.00	5.00
Max Pwr @ PM (dBm)	10.00	10.00	10.00
Max Pwr @ Xmit Ant (W)	10.00	10.00	10.00
Absorber	No	No	No
Chamber	A	A	A
Instrument Setup Parameters			
SA-RBW (Hz)	1000000.00		
SA-ST (sec)	0.50		
SA-RL (dB)	-1.00		
PM-Mode	CW		
Source-Initial Freq (MHz)	100.00		
Source-Initial Pwr (dBm)	-30.00		
Stir-Velocity (sec/rev)	10.00		
Stir-Accel (sec/rev)	10.00		

Figure C.2.1-1: Example of a Params Worksheet.

Table C.2.1-1: Parameters Used in Uniformity Validation Test Process Template for Chamber A

Frequency Range (MHz)	Number of Frequencies/ Decade	Number of Stirrer Steps [2]
100 – 400	100	60
400 - 800	100	36
800 – 1000	100	18

C.2.2. Hardware (Hdwr) Worksheet

An example Hrdw worksheet shown in Figure C.2.2-1 contains the instrumentation, cable, and equipment information specific to a test. This worksheet can be edited to reflect current test hardware or any other information needed to document a test. It should be included in all test files used in the Uniformity Validation and RS Test Process. The example worksheet is organized into five general sections; instruments, cables, sensors, attenuators, and couplers. Any information needed to identify equipment should be included, such as manufacturer, type, and serial number.

	A	B	C	D
1	**Test Hardware**			
2	Instruments:	Bus Address		
3	Holaday Probe HI 6005	Serial 1		
4	Signal Generator - Agilent E8257D	GPIB 19		
5	Power Meter Gigatronics 8541C	GPIB 26		
6	Spectrum Analyzer HP70900	GPIB 18		
7				
8	Cables:			
9	Xmit Cable1-UFB293C-1-1800-506506 S/N:98K0984			
10	Xmit Cable2-UFB293C-1-1800-506506 S/N:98K0985			
11	Xmit Cable3-UFB293C-1-1800-506506 S/N:98K0987			
12	Rec cable 1: UFB293C-1-1800-506506 S/N98K0986			
13	Rec cable 2: UFB293C-1-6000-506506 S/N98K978			
14				
15	Sensors:			
16	(2) Power Sensors-Gigatronics High Power 80421A (CW/Pulse) .01-18 GHz			
17				
18	Attenuators:			
19	Attenuator: Narda 776B-30 A014912			
20				
21	Couplers:			
22	Coupler: Werlatone C3908-10 S/N61170			

Figure C.2.2-1: Example of a Hdwr Worksheet.

C.2.3. XmitCal, RecCal, and CplrCal Worksheets

These three worksheets are included in the input template file for all test processes. They each contain calibration data that was collected for a transmit path, receive path, and directional coupler. They are manually created by populating the worksheet with the measured path loss data. A three row header and a two column format are required when creating these worksheets. The first column contains frequencies and the second column contains path loss data. It is suggested that the first 3 rows be used to document details of the calibration and file locations.

C.2.4. Pos 1 to Pos 9 Worksheets

During Uniformity Validation Testing, worksheets Pos1 through Pos9 are added one at a time during chamber uniformity measurements for both empty and loaded chambers using the *Calibration & RS Test* software. Each worksheet contains data for a field probe position used during the process. At the end of the process there is a data worksheet for every probe position. The data is a composite of measurements taken over a complete stirrer rotation. Included in the header, are the number of stirrer steps, the probe position number, and whether any absorber material is used. The following is a list of data contained in the worksheets.

- Freq (MHz) – a list of test frequencies in megahertz units
- ExNormMax – maximum of the normalized (to input power) E-field x component
- EyNormMax – maximum of the normalized (to input power) E-field y component
- EzNormMax – maximum of the normalized (to input power) E-field z component
- EtotalNormMax – maximum of the normalized (to input power) E-field total
- FwdPwrAvg – average input power in watts
- PwrRecMax – maximum receive power in watts
- PwrRecAvg – average receive power in watts
- ExMax – maximum of E-field at x axis in V/m
- EyMax – maximum of E-field at at y axis in V/m
- EzMax – maximum of E-field at z axis in V/m

- EtotalMax – maximum of total E-field in V/m
- ExMaxNorm – ExMax (V/m) normalized to the average input power (FwdPwrAvg)
- EyMaxNorm – EyMax (V/m) normalized to the average input power (FwdPwrAvg)
- EzMaxNorm – EzMax (V/m) normalized to the average input power (FwdPwrAvg)
- EtotalMaxNorm – EtotalMax (V/m) normalized to the average input power (FwdPwrAvg)

C.2.5. STD Worksheet

The STD worksheet is added by the *Process Data* software as part of the Uniformity Validation Test Process. It contains the standard deviation data computed from the field probe measurements. The worksheet also includes the difference or delta computed from the receive antenna and the probe measurements and the calculated antenna calibration factor (ACF). This worksheet is located in both empty and loaded data files. The following is a list of data contained in the worksheet.

- Freq (MHz) – list of test frequencies in megahertz
- ExSDtoMean(dB) – calculated E-field x component standard deviation to mean in dB
- EySDtoMean(dB) – calculated E-field y component standard deviation to mean in dB
- EzSDtoMean(dB) – calculated E-field z component standard deviation to mean in dB
- ExyzSDtoMean(dB) – calculated total E-field standard deviation to mean in dB
- EnormProbe – normalized total E-field from probe data in V/m
- EnormAnt – normalized E-field from antenna data in V/m
- Delta Ant-Probe(dB) – difference between EnormProbe and EnormAnt in dB
- ACF(W) – Antenna Calibration Factor – ratio of average receive power to average input power over complete stirrer rotation for an empty chamber in watts
- ACF(dBm) – Antenna Calibration Factor – ratio of average receive power to average input power over complete stirrer rotation for an empty chamber in dBm
- Limit – DO-160F limit for evaluation of chamber E-field standard deviations
- Limit Freq (MHz) – list of frequencies used for plotting DO-160F limit

C.2.6. STD Plot Worksheet

The STD_PLOT worksheet uses data from STD worksheet and plots the standard deviations against the DO-160F limit. The standard deviation data for each E-field component, x, y, z, and total appears in a different color. The DO-160F limit line is presented in red. The worksheet is located in both empty and loaded data files.

C.2.7. Delta (Ant-Probe) Plot Worksheet

The Delta(Ant-Probe) Plot worksheet uses data from the STD worksheet and plots the Delta of the receive antenna and the probe measurements over frequency.

C.2.8. Chmbr Max Loading Worksheet

The Chmbr Max Loading worksheet is created by the *Process Data* software using data generated in Uniformity and Validation Test Process. It contains four columns; frequencies, the computed Maximum Loading Allowed (MLA) in the chamber, and the empty and loaded chamber ACF's that are used in the computation. The ACF data are copied from the STD worksheets in the empty and loaded chamber workbook, respectively. The following is a list of data contained in the worksheet.

- Freq – list of test frequencies in megahertz units
- Max Loading Allowed – the maximum loading allowed (dBm) in a chamber while maintaining chamber uniformity
- ACF Empty – Antenna Calibration Factor – ratio of average receive power to average input power over complete stirrer rotation for an empty chamber copied from "STD" worksheet in empty chamber data file
- The ACF Loaded – Antenna Calibration Factor – ratio of average receive power to average input power over complete stirrer rotation for an empty chamber copied from "STD" spreadsheet in loaded chamber data file

C.2.9. The Max Load Plot Worksheet

The Max Load Plot worksheet is created by the *Process Data* software using data from the Chmbr Max Loading worksheet to plot the frequency and MLA. The plot is used during the EUT Loading Test Process to compare a EUT's loading effects against the MLA in the chamber.

C.2.10. EUT Worksheet

The worksheet contains measured forward and receive power data acquired during the EUT Test Process. The Calibration & RS Test software is used to automate the process and collect the data. TThe data are a compilation over a complete stirrer rotation. The following is a list of data contained in the worksheet.

- Freq – list of test frequencies in megahertz units
- Fwd Pwr Avg – average input power computed at the transmit antenna port
- Pwr Rec Max – maximum receive power computed at the receive antenna port
- Pwr Rec Avg – average receive power computed at the receive antenna port

C.2.11. CLF Worksheet

The CLF worksheet is added by the *Process Data* software. The CCF acquired from the EUT workbook EUT worksheet, and the ACF data acquired from a STD worksheet in an Empty chamber workbook are used as inputs and are copied to the CLF worksheet to serve as reference. Computation of the Q uses the CCF data located on this worksheet. The following is a list of data contained in the worksheet.

- Freq – list of test frequencies in megahertz units
- ACF Empty – Antenna Calibration Factor – ratio of average receive power to average input power over complete stirrer rotation for an empty chamber
- CCF – Chamber Calibration Factor – ratio of average receive power to average input power over a complete stirrer rotation with EUT in the chamber
- CLF – Chamber Loading Factor – ratio of CCF to ACF
- EUT Max Loading – maximum loading allowed curve for the chamber copied from Chmbr Max Loading worksheet
- Smoothed CCF – CCF data averaged over four frequencies on either side of test frequency
- Q – chamber Q factor calculated from CCF
- Time Constant – chamber time constant calculated from Q

C.2.12. Max Load vs CLF Plot worksheet

This worksheet contains a plot of CLF and MLA data.

C.2.13. Freqs Cals Pwr Worksheet and Freqs Cals Pwr Efield Worksheet

The Freqs Cals Pwr and Freqs Cals Pwr Efield worksheets are added to the test workbook during an automated power leveling operation by the Calibration & RS Test software.   They include the input power needed for a required test E-field or required power level. The Freqs Cals Pwr worksheet is created during a calibration test, where there is only a single worksheet needed. The Freqs Cals Pwr Efield worksheet is created during a RS test, and there is a different Freqs Cals Pwr Efield worksheet for each required test E-field. The following is a list of data contained in the worksheets.

- Freq – list of test frequencies in megahertz units
- Xmit – transmit path calibration in dBm
- Rec – receive path calibration in dBm
- Cplr – directional coupler in the transmit path calibration in dBm
- Fwd Pwr @ Source – required power level (dBm) at the signal generator needed to achieve the required test power level in a chamber
- Required Efield – RS test E-field in V/m
- FwdPwr @ Ant (dBm) – input power at the transmit antenna port in dBm calculated using the mean of the normalized maximum total E-field measured during calibration
- FwdPwr @ Ant (W) – input power at the transmit antenna port in watts calculated using the mean of the normalized maximum total E-field measured during calibration
- FwdPwr Use Rant @ Ant dBm) - input power at the transmit antenna port in dBm calculated using maximum squared total E-field and average receive power
- FwdPwr Use Rant @ Ant (W) – input power at the transmit antenna port in watts calculated using maximum squared total E-field and average receive power
- ENormMean – average value computed from ENormMax data from the empty chamber calibration data file
- CLF - Chamber Loading Factor – ratio of CCF to ACF copied from CLF worksheet.

C.2.14. Test1 - Testn Worksheets

The worksheets are created by *Calibration & RS Test* software during the RS Test Process. As the process progresses, worksheets Test 1 through Test n are added and used to record RS test data. As a result, there will a different worksheet for each test. These worksheets include a timestamp, averaged forward power, spectrum analyzer measurements and E-field levels over a complete stirrer rotation. The following is a list of data contained in the worksheet.

- Pinput@Ant Avg – average input power in watts at the transmit antenna over a complete stirrer rotation
- Pmaxrec Max – maximum receive power in watts over a complete stirrer rotation
- Pmaxrec Avg – average receive power in watts over a complete stirrer rotation
- Rev CCF – ratio of the average receive power to the average input power over a complete stirrer rotation
- Rev Measured Efield (V/m) – E-field determined over a complete stirrer rotation using Eq. 11 and the average receive power
- Rev Efield Ratio – ratio of the Measured Efield to the test E-field

- Rev Cal Efield (V/m) – the calculated E-field determined over a complete stirrer rotation using Eq. 10, the average input power and the average normalized total E-field, ENormMean

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14. ABSTRACT

The NASA Langley Research Center's High Intensity Radiated Fields Laboratory has developed a capability based on the RTCA/DO-160F Section 20 guidelines for radiated electromagnetic susceptibility testing in reverberation chambers. Phase 1 of the test procedure utilizes mode-tuned stirrer techniques and E-field probe measurements to validate chamber uniformity, determines chamber loading effects, and defines a radiated susceptibility test process. The test procedure is segmented into numbered operations that are largely software controlled. This document is intended as a laboratory test reference and includes diagrams of test setups, equipment lists, as well as test results and analysis. Phase 2 of development is discussed.

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