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Radiated Emissions From a Remote-Controlled Airplane—Measured in a Reverberation Chamber

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Abstract

A full-vehicle, subscale all-electric model airplane was tested for radiated emissions, using a reverberation chamber. The mission of the NASA model airplane is to test in-flight airframe damage diagnosis and battery prognosis algorithms, and provide experimental data for other aviation safety research. Subscale model airplanes are economical experimental tools, but assembling their systems from hobbyist and low-cost components may lead to unforseen electromagnetic compatibility problems. This report provides a guide for accommodating the on-board radio systems, so that all model airplane systems may be operated during radiated emission testing. Radiated emission data are provided for on-board systems being operated separately and together, so that poential interferors can be isolated and mitigated. The report concludes with recommendations for EMI/EMC best practices for subscale model airplanes and airships used for research.

1 Introduction

Little precedent exists for performing radiated emission measurements on a whole aircraft. Both RTCA/DO-160F[1] "Environmental Conditions and Test Procedures for Airborne Equipment" and MIL-STD-461F[2] "Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment" are tailored toward bench-top testing of line replaceable units, rather than entire aircraft. Military aircraft are subject to emission security (EMSEC) requirements, and whole airplanes may be tested for radio emission characteristics in anechoic chambers. Test procedures, standards and data for EMSEC are not readily available because of the need for security classification. Reverberation chambers are an unlikely option for EMSEC testing because enhanced multipath effect upon signal modulations would be undesirable. This report describes a radiated emission test performed on a subscale model of the successful aerobatic Zivko EDGE 540-T airplane. The NASA EDGE 540-R2 model airplane is an all electric, remote controlled (RC) model made by SIG Manufacturing Co. ,Inc.[3].

Small, hobbyist RC aircraft like the NASA EDGE 540-R2, and autonomous unmanned aerial vehicles (UAVs), and even lighter-than-air (LTA) vehicles, have become valuable research tools for testing innovative technologies such as all-electric power and adaptations of commercial-off-the-shelf (COTS) avionics, in high-maneauverability flight operations or hazardous operational environments.[4] [5] [6] These aircraft are very economical to purchase and fly, when compared to crewed vehicles. Flight electronics, radio and instrumentation systems installed on these aircraft generally meet FCC rules for electromagnetic compatibility (EMC), which assume that some interference is acceptable and can be managed by the researchers who configure and operate the aircraft. RC aircraft radio systems nearly always operate in unlicensed frequency bands, and operators therefore have no assurance of non-interference from other users in their vicinity. When assembling flight research systems from RC hobbyist and COTS components, EMC on-board the aircraft and EMC with the surrounding radio environment can become a serious problem.[7]

Radiated emission measurements were performed in a reverberation chamber, over a continuous, band from 100 MHz to 3 GHz. A photograph of the NASA EDGE 540-R2 is shown in Figure 1.

Figure 1: Photograph of the NASA EDGE 540-R2 in reverberation chamber. Also shown (right-inset) is a load cell attached to the chamber wall, for measuring aircraft thrust.

1.1 Reverberation Chamber Description

A Reverberation Chamber is an electrically-conductive shielded enclosure used for generating an electromagnetic (EM) environment for radiated susceptibility and emissions testing. The operational concept is similar to a very large microwave oven. Theoretically, a reverberation chamber is modeled as a large cavity resonator characterized by three-dimensional stationary wave patterns (i.e., resonance modes) at resonant frequencies determined by the dimensions of the chamber. A transmit antenna is used to emit RF power inside the chamber setting up a complex field structure within the chamber. Rotating mechanical stirrers then "mix" the energy, effectively changing the boundary conditions and creating new complex field structures. When sampled over time, this stirring results in a statistically uniform and isotropic test environment. A reverberation chamber is associated with a lowest usable frequency (LUF). The chamber size and geometry contribute to the generation of a sufficient number of modes to ensure adequate field mixing and uniformity. Generally, larger chambers have a lower LUF. EM environment testing is performed in open-area test sites, semi-anechoic chambers reverberation chambers, transverse-electromagnetic test cells, and other hybrid facilities. Reverberation Chambers offer several advantages over other test facilities, because of their characteristic field uniformity and repeatability, reduced test time, and a screened environment with no ambient signals.

1.2 Test Facility

Testing was conducted in the NASA Langley High Intensity Radiated Fields (HIRF) Laboratory. Figure 2 is a diagram of the layout of the facility which consists of five separate steel chambers. Chambers A, B, and C are reverberation chambers used for radiated emissions and susceptibility testing. Chambers D and E are used as an Amplifier Room and Control Room, respectively. Figure 2 also shows the LUF for each of the chambers. NASA LaRC's chamber's are described in NIST Technical Note 1508.[8]

Chamber A was used for measuring the EDGE aircraft emissions, as it provides a shielded environment with up to 120 dB of shielding effectiveness, a frequency range capability that easily accommodates that specified in the test requirements, and a high level of field uniformity[9]. In addition, the chamber provides an access-controlled test volume suitable for accommodating large test articles that emit high acoustic energy and pose other personnel hazards. Given the chamber door locations (Figure 2), it is possible to channel air-flow into one end of the chamber and out the other when not performing radiated emissions testing.

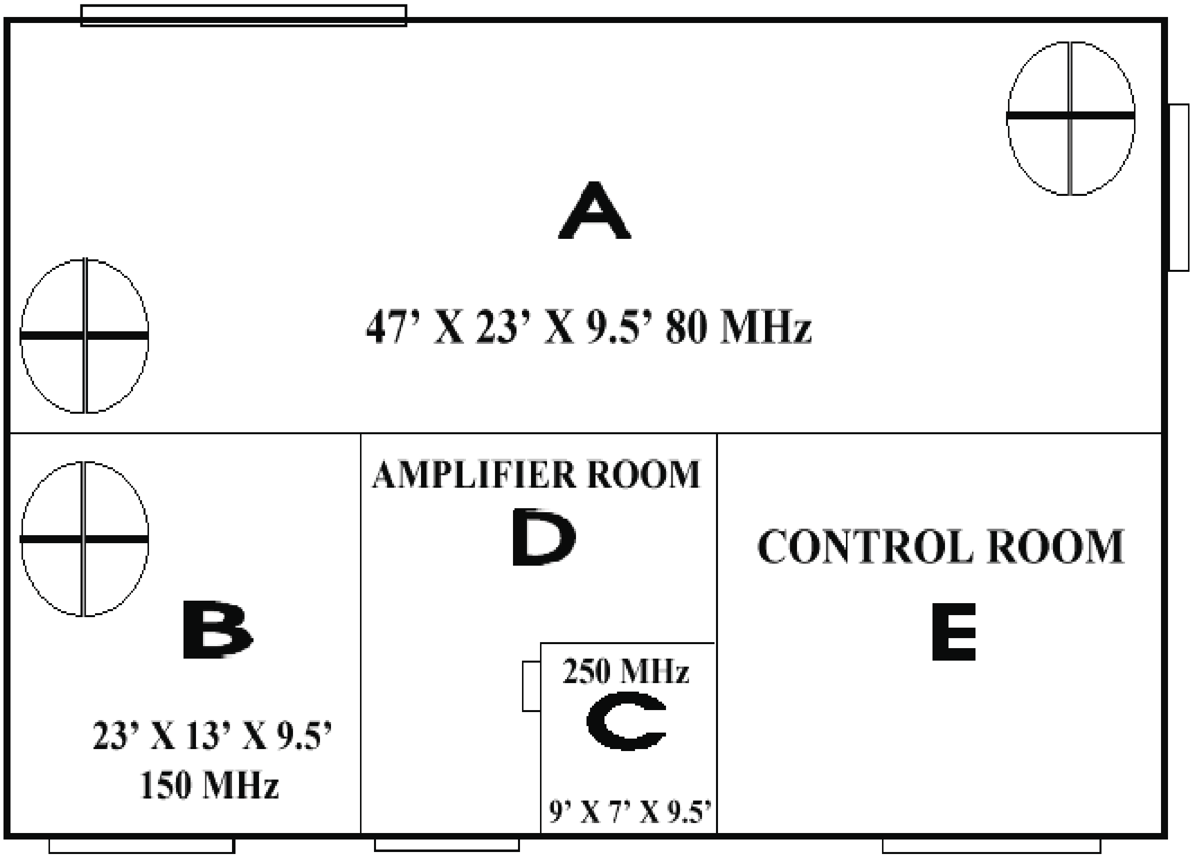

Figure 2: NASA HIRF Laboratory Diagram.

This report does not address radiated *susceptibility* testing of a whole aircraft in a reverberation chamber, however that is also a topic of significant HIRF Laboratory interest. The FAA provides guidance for performing high-level, outdoor RF field-illumination of whole aircraft in Advisory Circular 20-158[10]. Such testing is nearly always avoided because of the likelihood of interference in licensed and restricted frequency bands. Instead, aircraft low-level coupling tests are performed (outdoors), and the data are used to set full-threat level requirements to be performed upon equipment operating inside shielded test chambers. If a reverberation chamber is large enough to accommodate an entire airplane, and personnel hazards are properly addressed, whole aircraft radiated susceptibility testing becomes a viable option.

2 Objective: Radiated Emissions Test

The objective was to measure radiated emissions from the aircraft while its avionics were powered-up in a flight configuration. The measurements are compared to FCC 15.209 and RTCA/DO-160F Category M emission limits. Operational testing was conducted to determine functionality and performance of onboard aircraft experimental systems. The NASA EDGE 540-R2 test team was provided with radiated emission data for their research system (except the battery health monitor- BHM), operating in the flight configuration. Data are intended to set requirements for BHM enclosure shielding design, and to help identify sources of intra-system electromagnetic interference and optimize on-board radio performance. Secondary objectives were to explore and solve issues related to heat-dissipation from motor, air flow from propeller, restraint of test article, EMC of chamber video/audio equipment.

3 Background and Other Test Objectives

In addition to being a suitable facility for radiated emission testing, Reverberation Chamber A also provides an access-controlled test volume suitable for accommodating large test articles. Its welded steel walls, ceiling and floor provide excellent containment for high acoustic energy, high temperatures and other personnel hazards. It’s possible to channel air-flow into one end of the chamber and out the other when not performing radiated emission testing. The welded chamber containment characteristics first interested the EDGE test team in considering the HIRF laboratory for indoor testing. The following description of the system-under-test and the overall test objectives provides a necessary perspective for the radiated emission test.

The NASA EDGE 540-R2 model is instrumented for developing and testing algorithms for in-flight airframe damage diagnosis, provides a platform for extending and testing battery prognosis algorithms, and provides experimental data for further aviation safety research. Short-term goals for the aircraft are to demonstrate in-flight diagnosis of damage to metallic and composite aircraft structures, such as load bearing components, and the feasibility and accuracy of battery prognosis algorithms. This work supported the Aviation Safety Program, Integrated Vehicle Health Management (IVHM) Project[11] Airframe Diagnosis (managed from NASA Langley), and Battery Prognosis (managed from NASA Ames) elements. Specific IVHM milestones supported by this test include developing computationally efficient algorithms for in-flight diagnosis and characterization of damage to metallic and composite aircraft structures; validating methods and tools for diagnosis of failures associated with airframe materials and structural components impacted by adverse events; demonstration of structural fault injection, damage assessment, and degradation mitigation to show ability to recover from catastrophic failure; and subscale flight data acquisition for detection, diagnosis, prognosis, and mitigation project elements.

The NASA EDGE 540-R2 instrumentation system consists of a PC104[12] data acquisition unit, a Gumstix processor[13] with its own input/output (IO) board, and the RCATS[14] data acquisition and telemetry system. A JR-R1222 DSM2 2.4 GHz receiver[15] is used for remote control of aero-surfaces and motor, and the RCATS0900, 915 MHz transmitter downlinks flight parameters from the RCATS-GDL02 data-logger unit. The RCATS 915 MHz receiver is connected to a laptop computer serial port. The laptop computer is needed to provide feedback to the operator. BHM tests allowed for tuning the battery prognosis algorithm used to predict remaining operating time for motor batteries.

Other Test Objectives included:

- Test and compare the power consumption and performance of current 26x10 propeller against 24x12 and 28x10 propellers. (i.e. 26 inch length x 10 degree pitch)
- Measure electric current levels in motor circuits at several points in the circuits to study noise characteristics. (For BHM data system filter tuning and sensor location selection.)
- Test new wiring system for noise from onboard RF environment. (Signal to noise ratios all data channels)
- Test new signal conditioning electronics for RPM and air data. RPM channel was observed for noise and calibrated against RPM from in-service RCATS system. Air data channels were observed for noise. Calibration of air data channel involved separate testing.
- Test functionality and interoperability of the Ames-built BHM. This is a research item and may have required some in-situ tuning during testing.
- Test EM compatibility of all systems operating in the flight configuration. (Spurious interruptions to communication between PC104/BHM/RCATS)

For reference, a diagram of the PC104 system is shown in Figure 3. No cabling to the aircraft was required, however the load cell was powered from a DC power supply located inside the chamber. The load cell data was taken by the onboard PC104 to correlate with RPM data. Given the possibility of propeller separation and the air flow forward and aft of the propeller, it was determined that there should be no personnel in the chamber and that the door should be closed during testing for safety reasons. The HIRF Lab camera system was used to view the airplane on the displays in the control room during testing.

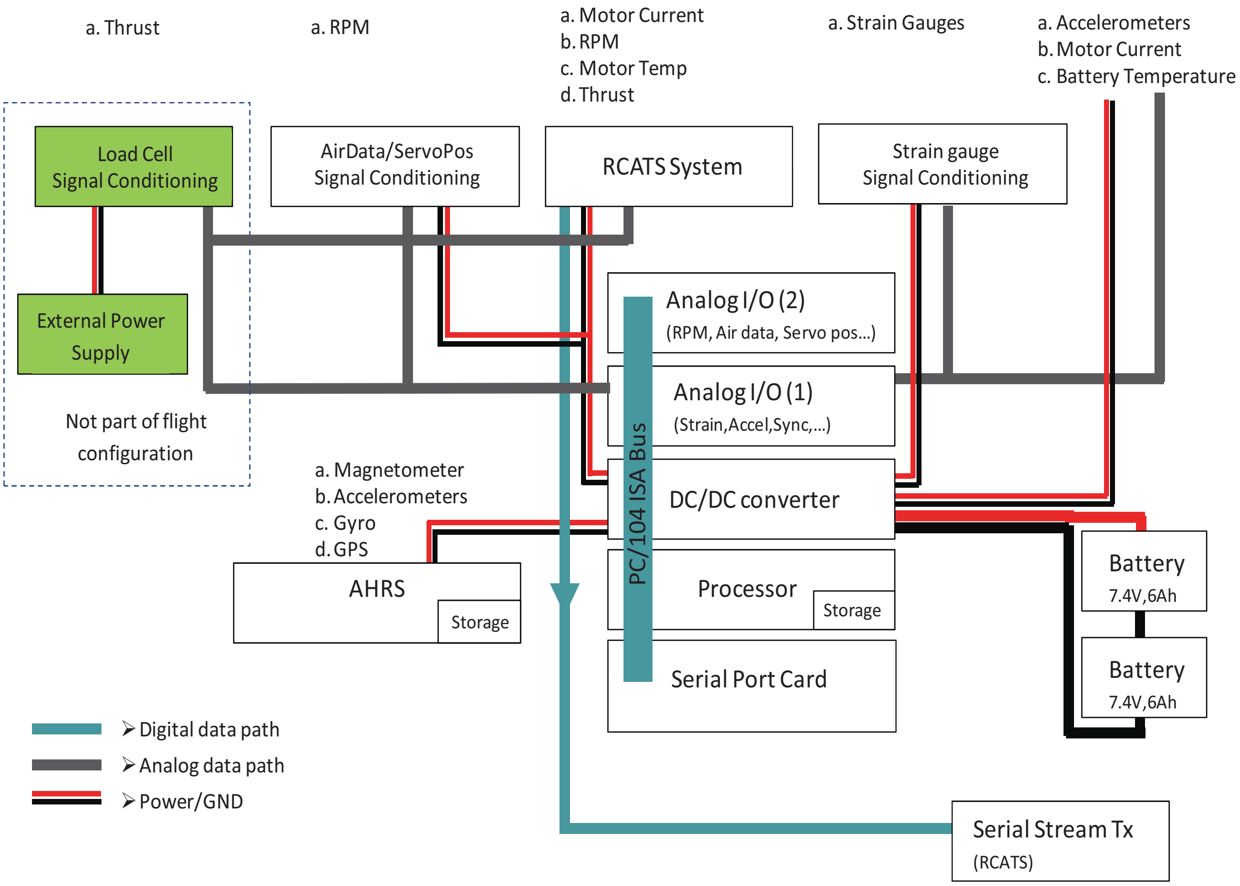

Figure 3: PC104 system and interfaces.

4 Emission Test Description

Testing was performed June 3, 2010, using RTCA/DO-160F Section 21 (“Radiated RF Emissions”), in NASA’s HIRF Laboratory. Reverberation Chamber A meets the field uniformity requirements of RTCA/DO-160F Section 20.6.3 (“Calibration: Chamber Field Uniformity and Loading Validation”) at and above 100MHz. A diagram of the reverberation chamber, instrumentation and experiment setup for calibration and radiated emission testing is shown in Figure 4.

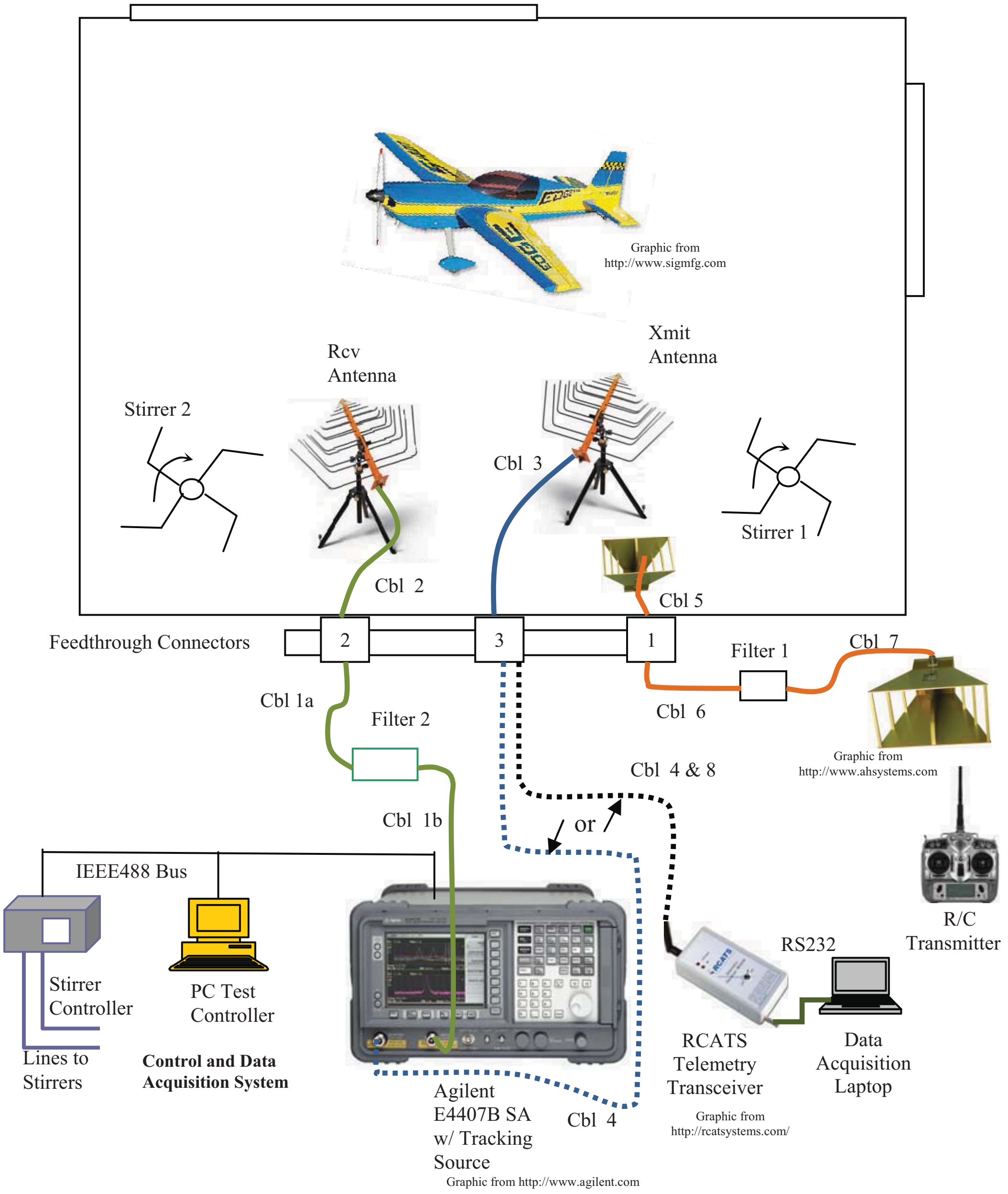

Figure 4: Chamber A and Control Room Configuration for Receive Path Calibration, Chamber Calibration, and Emission Test.

In Figure 4, it is important to note that Connector-3 serves dual purposes. During Chamber Calibration Connector-3 is connected to the Transmit Antenna (Cbl 3) and Spectrum Analyzer source (Cbl 4). During the Emission Test Cable 4 is disconnected from SA source and extended with Cable 8 to connect to the RCATS Telemetry Transceiver, as part of the retransmission system.

The numbered items in Figure 4 can be referenced in the Test Equipment List in Table 1. Photographs of the spectrum analyzer and control room video displays are shown in Figure 5.

Table 1: Test Equipment

Item	**Manufacturer/Model #**	**SN/ECN**
Spectrum Analyzer	Agilent E4407B	SG 44210434 / 3023864
Transmit Antenna	AR Radiant Arrow AT5080M1	303737
Receive Antenna	AR Radiant Arrow AT5080M1	303736
Reradiating Antenna #1	AH Systems SAS-571	1233/ A056941
Reradiating Antenna #2	AH Systems SAS-571	510
Filter 1: Rerad. System	K & L M/W 2.4 – 2.5GHz	S/N 2 7FV40-2450/T100-N/N
Filter 2: Receive Path	K & L M/N 2450MHz BW=137MHz	S/N 1 6N45-2450/3125-0/0
Cbl 1: Receive (before fltr.)	MicroCoax UFB293C-1-1800-506506	98K0986
Cbl 1b: Receive (after fltr.)	MicroCoax UFB293C-0-0480-506506	311215-001
Cbl 2: Receive (in cbr)	MicroCoax UFB293C-1-1800-506506	98K0984
Cbl 3: Transmit (in cbr)	MicroCoax UFB293C-1-1200-506506	98K0987
Cbl 4: Transmit	MicroCoax UFB293C-0-1200-50U50U	64639211012-001
Cbl5: Rerad. (in cbr.)	MicroCoax UFB293C-1-0960-506506	98K0989
Cbl6: Rerad (before fltr.)	RG214/U	2 D.K. RF Out
Cbl7: Rerad (after fltr.)	MicroCoax UFB293C-0-0480-50U50U	211009-002
Cbl8: RCATS	RG214/U	30' 4

The NASA Edge 540-R2 airplane was placed upon expanded-polystyrene blocks centered within the chamber, as seen in Figure 1. A live propeller was operated with the airframe attached to a load-cell, which was anchored using a steel cable attached to the Chamber A wall with a strong magnet. (See Figure 1 inset photo.) The airplane was in flight configuration, with 4 motor batteries, 2 receiver batteries, and 2 data system batteries. Its motor and actuators were operated from the control room using the DSM2 Radio. The RCATS0900 telemetry system was also operated in the control room, and provided parameters to a laptop computer display, including RPM, Motor Current, Motor Temperature and Thrust. The entire aircraft weighed about 42 lbs. The motor was driven at RPM levels of a typical flight (up to 5000). Additionally, airplane activity was monitored by two cameras installed in the chamber. The RF retransmission links for the airplane's remote control and RCATS data acquisition are described in the next section, and were tested prior to the thrust and emission testing.

Figure 5: Control Room Setup.

4.1 Retransmission System for Aircraft Telemetry & Control

Radio links between a test article located within a shielded chamber and equipment outside the chamber are a particular challenge when performing radiated emissions testing. Ideally, there should be no intentional transmission whatsoever of signals within the test chamber or control room. Signals transmitted from the test article may overload the input to the spectrum analyzer and cause intermodulation or damage. Signals transmitted into the chamber may contain harmonics or additional spurious emissions that could be mistakenly assumed to emanate from the test article. If RF cables can be attached between the antenna ports of radios on board the test article and in the control room, the opportunity is minimized for external signals to corrupt measurements. However, this ideal situation is not always possible. Compact circuit boards with embedded radios and certain low-cost devices often do not provide a means to connect between their transmitter and antenna. Radio units do not always provide a means (i.e. connector) to interrupt the transmission line to their antenna.

The NASA EDGE 540-R2 research system includes two radio links, as described previously, including a DSM2 2.4 GHz radio for remote control of aero-surfaces and motor, and a 915 MHz RCATS0900 telemetry system. Neither the DSM2 handheld transmitter nor the aircraft-mounted receiver unit allow connection of an external antenna, so a re-radiation system is required. Figure 4 shows the connection of two dual-ridge horn antennas (one in the control room, one in the test chamber), with a 2.4 GHz bandpass filter installed between them. The 2.4 GHz bandpass filter is intended to prevent spurious signals from the control room from leaking into the chamber, thus appearing to be emissions from the EDGE 540-R2 electronic systems. (The control room is also a shielded room, and its door could be closed to further eliminate external signals. Closing this door was not necessary for this test.) In the case of the RCATS0900, its ground tranceiver used in the control room has a reverse-SMA connector, allowing direct connection. Figure 4 shows the direct connection of the coaxial cable to the RCATS0900 ground transciever. In the reverberation chamber, the transmit antenna was re-purposed as a RCATS re-radiating antenna. Figure 6 shows the retransmission system components.

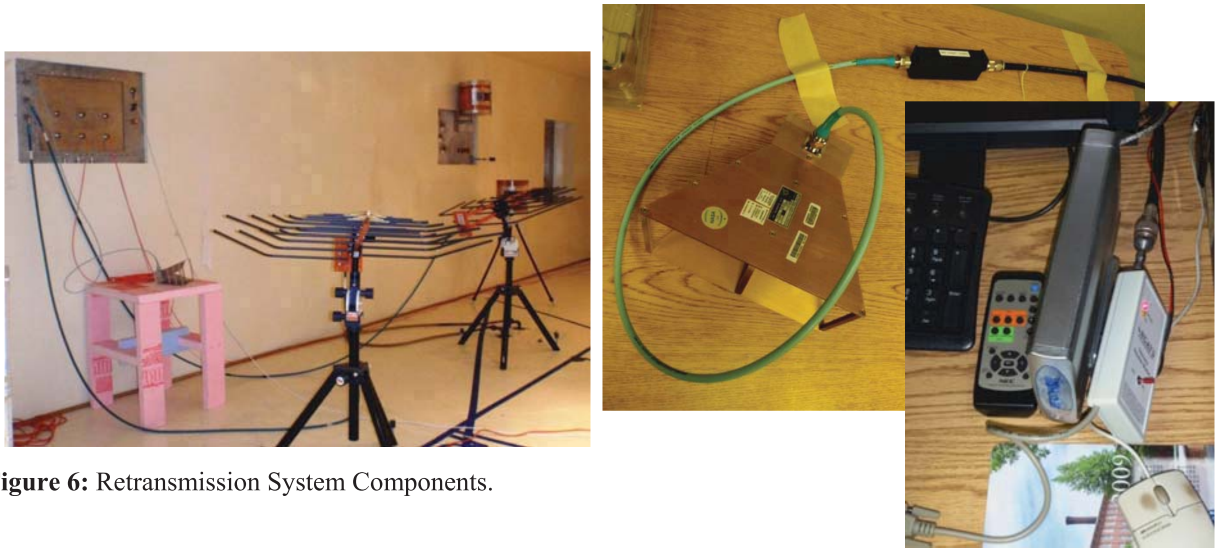

Figure 6: Retransmission System Components.

4.2 Video & Audio Monitoring

The NASA HIRF Laboratory Chamber A video system consists of two TDK RF Solutions VC-04-NTSC color video cameras and a TDK SI-300CC Control Unit[16]. The VC-04 cameras are located in the test chamber, and must not contribute to the radiated emission environment, nor be susceptible to HIRF. The SI-300CC control unit is located in the control room, so that the NASA EDGE 540-R2 experiment team can monitor the video. The VC-04 is designed specifically for remote monitoring of equipment during EMC testing in a shielded room or anechoic chamber. The VC-04 is EMI shielded to operate in electric field environments of 200 V/m from DC to 18 GHz, and operates on 12V DC supplied from battery or an AC adapter. NASA's VC-04's are additionally shielded by placing them in a copper cylinder, with a copper screen window aperture. Both cameras include capability for iris control, zoom, pan and tilt, even when mounted inside their copper cylinders. NASA testing has confirmed that the cameras, when mounted inside their copper cylinders, are immune to electric field intensities up to 800 V/m between 100 MHz and 1000 MHz.[17] One of the cameras also includes the audio monitoring option. The cameras and control unit are connected together using fiber-optic cable. A desktop computer with a Pinnacle Studio MovieBox recording software suite is used to capture video and audio, and record to DVD. Photographs of the system and components are shown in Figure 7.

Graphics from http://www.tdkrfsolutions.com

Figure 7: TDK RF Solutions video monitoring system component photographs.

4.3 Transmit Path Calibration

The Transmit Path was composed of cables 1a, 1b, and 2 as shown in Figure 4. The Agilent E4407B Spectrum Analyzer with internal tracking source was configured as shown in Figure 8.

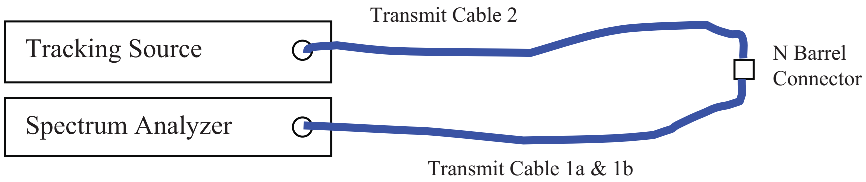

Figure 8: Setup for Transmit Path Calibration.

The spectrum analyzer was set to sweep from 100 MHz to 3 GHz with 5801 data points (500 kHz frequency spacing). A complete list of instrument setup parameters is given in Table 2. The transmit path calibration data acquisition was automated and computer-controlled.[18]

Table 2: Transmit Path Calibration Instrument Settings

Parameter	**Setting**	**Notes**
Frequency Start/Stop	100 MHz to 3000 MHz	-
Spectrum Analyzer Trace Length	5801 Data Points	2900MHz/2 +1→ 500kHz spacing
Tracking Source Amplitude	-10 dBm	-
Spectrum Analyzer Dwell Time	2 Sec	-
Spectrum Analyzer SA Sweep Time	Default (65.64ms)	-
Spectrum Analyzer SA Reference Level	-10dBm	-
Spectrum Analyzer SA Resolution BW	300 kHz	-
Spectrum Analyzer SA Attenuation	0dB	-
Spectrum Analyzer Internal Preamp.	OFF	-

4.4 Receive Path & Chamber Calibration

Chamber A and equipment were configured as shown in Figure 4. Cable 4 was connected to the spectrum analyzer tracking source output. A complete list of instrument setup parameters is given in Table 3. All experimental systems were powered OFF and the chamber doors closed. Stirrers were rotated at 12 sec/rev in continuous mode. The transmit path calibration data acquisition was automated and computer-controlled.[19]

Table 3: Receive Path and Chamber Calibration Instrument Settings

Parameter	**Setting**	**Notes**
Frequency Start/Stop	100 MHz to 3000 MHz	-
Spectrum Analyzer Trace Length	5801 Data Points	2900MHz/2 +1→ 500kHz spacing
Tracking Source Amplitude	-10 dBm	-
Spectrum Analyzer Dwell Time	120 Sec	-
Spectrum Analyzer Sweep Time	Default (65.64ms)	58ms used to prevent cal warning
Spectrum Analyzer Reference Level	-10dBm	-
Spectrum Analyzer Resolution BW	300 kHz	-
Spectrum Analyzer Attenuation	0dB	-
Spectrum Analyzer Internal Preamp.	ON	-

4.5 Emission Measurement

Chamber A and equipment were configured as shown in Figure 4. Cable 4 was connected to the RCATS0900 telemetry receiver. Chamber doors were closed. Stirrers were rotated at 12 sec/rev in continuous mode. A complete list of instrument setup parameters is given in Table 4. Aircraft systems were configured as indicated in Table 5.

Table 4: Emissions Test Instrument Settings

Parameter	**Setting**	**Notes**
Frequency Start/Stop	100 MHz to 3000 MHz	-
Spectrum Analyzer Trace Length	5801 Data Points	2900MHz/2 +1→ 500kHz spacing
Tracking Source Amplitude	OFF	-
Spectrum Analyzer Dwell Time	120 Sec	-
Spectrum Analyzer Sweep Time	Default (65.64ms)	58ms used to prevent cal warning
Spectrum Analyzer Reference Level	-10dBm	-
Spectrum Analyzer Resolution BW	300 kHz	-
Spectrum Analyzer Attenuation	0dB	-
Spectrum Analyzer Internal Preamp.	ON	-

Table 5: Emission Test Airplane Operating Modes

Name (Data file nomenclature)	**Description**
NFLOOR	Noise Floor Scan: All Electronic Systems OFF in Chamber.
BKGND	Background Scan: All Support Systems ON (Load Cell using 120VAC facility power, RCATS Ground Transceiver, RC PWM - Transmit each axis/command.) All aircraft systems OFF.
PC104_Only	Aircraft PC104 ON; RCATS & Servo XCVR OFF. Support Systems OFF also.
RCATS_Only	Aircraft RCATS ON; PC104 & Servo XCVR OFF. Support Systems OFF also.
RCATS_Laptop Cmd	Aircraft RCATS ON; PC104 & Servo XCVR OFF. Support Systems OFF also, <u>except for Laptop RCATS exchanging data from control room.</u>
Servo XCVR_Only	Aircraft Servo XCVR ON; RCATS, & PC104 OFF. Support Systems OFF also.
Servo XCVR_RC PWM Cmd	Aircraft Servo XCVR ON; RCATS, & PC104 OFF. Support Systems OFF also, <u>except for RC PWM Transmitting each axis/command.</u>
Servo XCVR & Motor	Aircraft Servo XCVR <u>& Motor Controller ON</u>; RCATS, & PC104 OFF. Support Systems OFF also, except for RC PWM Transmitting each axis/command.
PC104_RCATS_Servo_PropX_RPM=yyy	X=Propeller Size, yyy= Motor RPM (0, 2000, 4000)

Note: -Aircraft Attitude Heading Reference System (AHRS) assumed not to be installed.

The following equations were used to determine the emission levels in dB-microvolts-per-meter (dBuV/m). The reverberation chamber emissions measurement process is discussed in detail in NASA TP-2003-212446[20]. Emission levels were calculated across the test frequency band using the Equation 1, and converted to dBuV/m units using Equation 3.

$$P_{TRP\,(dBm)} = P_{Meas\,(dBm)} - CblCal_{(dB)} + CbrCal_{(dB)} \qquad \text{Equation 1}$$

Where:

$P_{TRP\,(dBm)}$ = Total radiated power in dBm

$P_{Meas\,(dBm)}$ = Power measured at spectrum analyzer during Emission Test in dBm

$CblCal_{(dB)}$ = Transmit path loss calculated during Transmit Path Calibration in dB

$CbrCal_{(dB)}$ = Receive path and chamber loss calculated during Chamber Calibration in dB.

Electric Field Intensity, caused by the device emissions, is calculated from RTCA/DO-160F, Sec. 21[21].

$$E = \sqrt{\frac{D \cdot P_{TRP}(W) \cdot 377}{4\pi}} \qquad \text{Equation 2}$$

Where:

E=Electric Field Intensity, in V/m

$P_{TRP\,(W)}$ = Maximum Total Radiated Power, in Watts

D= 1.64, the estimated directivity of the equipment under test

Converting $P_{TRP}(W)$ to $P_{TRP}(dBm)$ and solving Equation 2 for dBuV/m.

$$\text{dBuV/m} = [20\log(E)] + 120 = P_{TRP}(\text{dBm}) + 106.92 \qquad \text{Equation 3}$$

5 Emission Test Data

5.1 Noise Floor and Background Scan

The purpose of the Noise Floor Scan is to establish the dynamic range of the measurement system, and to verify that no emitter or noise source is present that exceeds the radiated emission limits. All aircraft and ground-support systems are powered OFF during the Noise Floor scan. The purpose of the Background Scan is to obtain a baseline measurement of the radio environment with all sources present ***except*** the equipment under test (EUT). For the Background Scan, all ground support systems are powered ON and all aircraft systems OFF. Table 6 shows the system configuration for the Noise Floor and Background scans. Radiation emission limits are selected to be RTCA/DO-160F Category M, but also shown are FCC 15.209 limits (converted to 1 meter). RTCA/DO-160F Category M is intended for “equipment and interconnected wiring located in areas where apertures are electro-magnetically significant and not directly in view of radio receiver’s antenna”.

Table 6: System Configuration for Noise Floor and Background Scan

Systems		**Noise Floor**	**Background Scan**
Aircraft	Airplane RCATS0900	OFF	OFF
	Airplane Servo XCVR	OFF	OFF
	PC104	OFF	OFF
	AHRS	Not Installed	Not Installed
Ground	Load Cell	OFF	ON
	RCATS Gnd Xcvr	OFF	ON
	RC PWM	OFF	ON

Note: The test chamber video system was ON for the background scan and all other testing.

Radiated emission data for Noise Floor and Background Scan, compared to DO-160F and FCC15.209 limits are plotted in Figure 9. These data show that the measurement system is sensitive enough to test to the FCC and DO-160F limits, and that the non-aircraft emitters (Laptop RCATS, Remote Control Transmitter) are not contributing significant emissions to the test environment. The 2.4 GHz signal from the RC PWM (JR-R1222 DSM2 handheld transmitter) is clearly present, and expected.

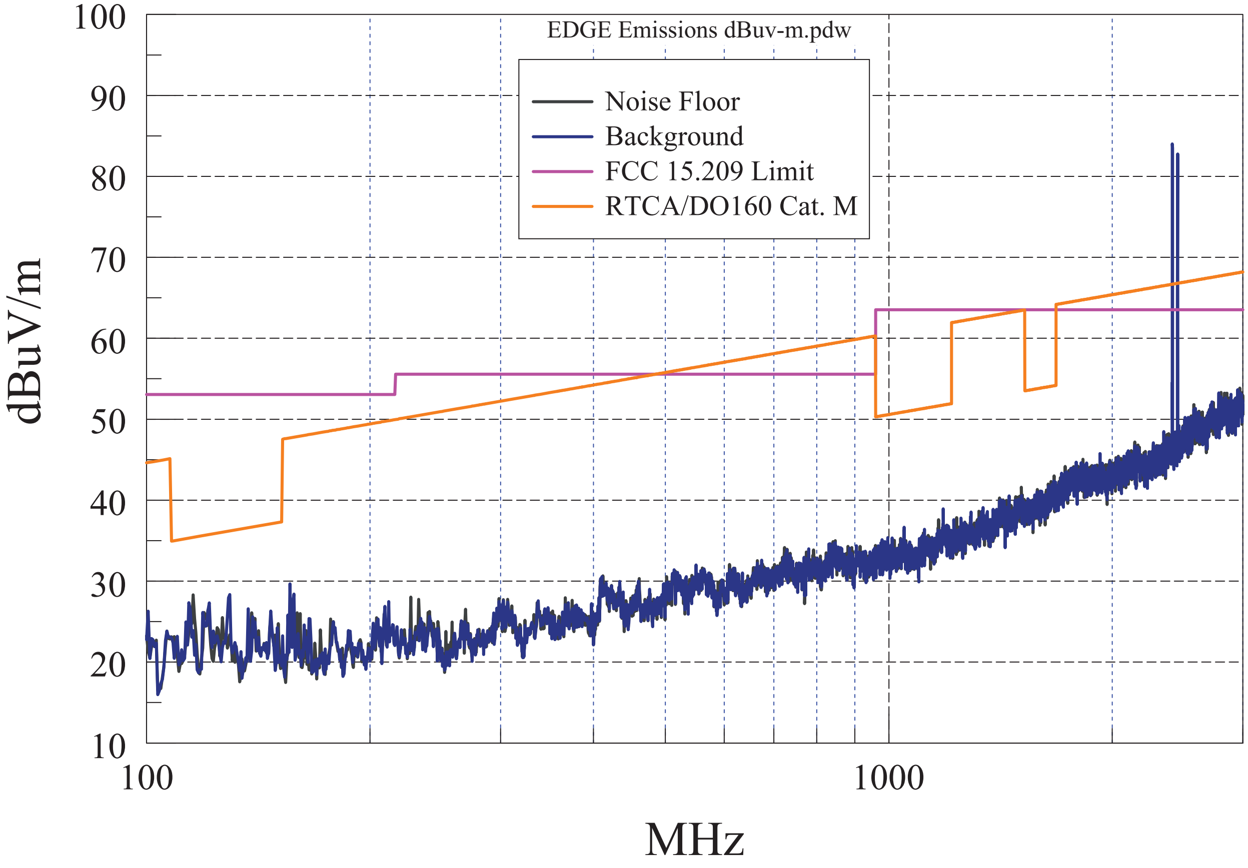

Figure 9: Noise Floor and Background Scan Emission compared to DO-160F and FCC15.209 Limits. (Electric Field Intensity normalized to 1 meter distance, versus Frequency). The 2.4 GHz control signal from the RC PWM is clearly present, and expected for this test setup and configuration.

5.2 PC104 Evaluation

The first system-of-interest was the PC104 stack. PC104 is an embedded-computer standard that utilizes personal computer (PC) bus and software architecture with compact (3.6" x 3.8") stackable modules.[22] The NASA EDGE 540 design team selected the PC104 architecture to obtain reliable data acquisition, light weight and ruggedness in a simple, easy-to-adapt platform. The PC104 system used in the airplane is manufactured by Adlink Technologies Inc. A photograph of the PC104 is shown in Figure 10. Table 7 shows the system configuration for the PC104 evaluation.

Table 7: System Configuration for the PC104 Evaluation

Systems		**State**
Aircraft	Airplane RCATS0900	OFF
	Airplane Servo XCVR	OFF
	PC104	ON
	AHRS	Not Installed
Ground	Load Cell	OFF
	RCATS Gnd Xcvr	OFF
	RC PWM	OFF

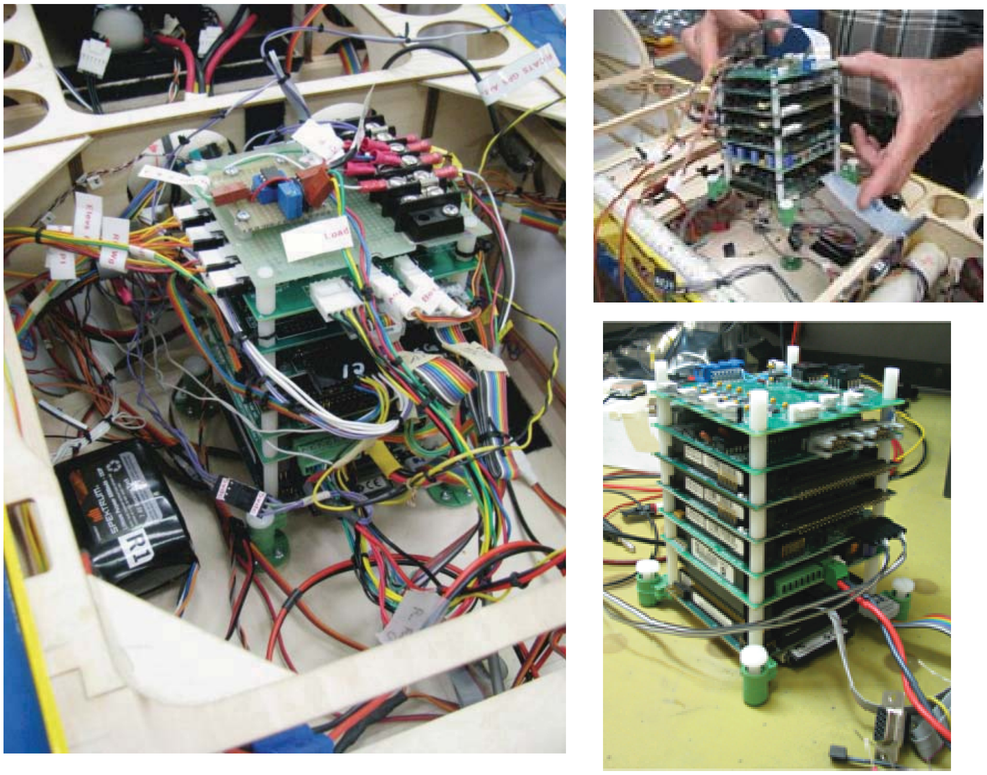

Figure 10: Photographs of PC104 stack installed in the NASA EDGE 540-R2. No shielding is present, and wire-routing optimized for minimizing cable length, rather than to reduce possibility of coupling.

Radiated emission data for the PC104, compared to DO-160F and FCC15.209 limits, are plotted in Figure 11. These data show that significant RF emissions, exceeding FCC 15.209 and DO-160F limits below 300 MHz. PC104 would likely cause noise to on-board radios operating below 300 MHz.

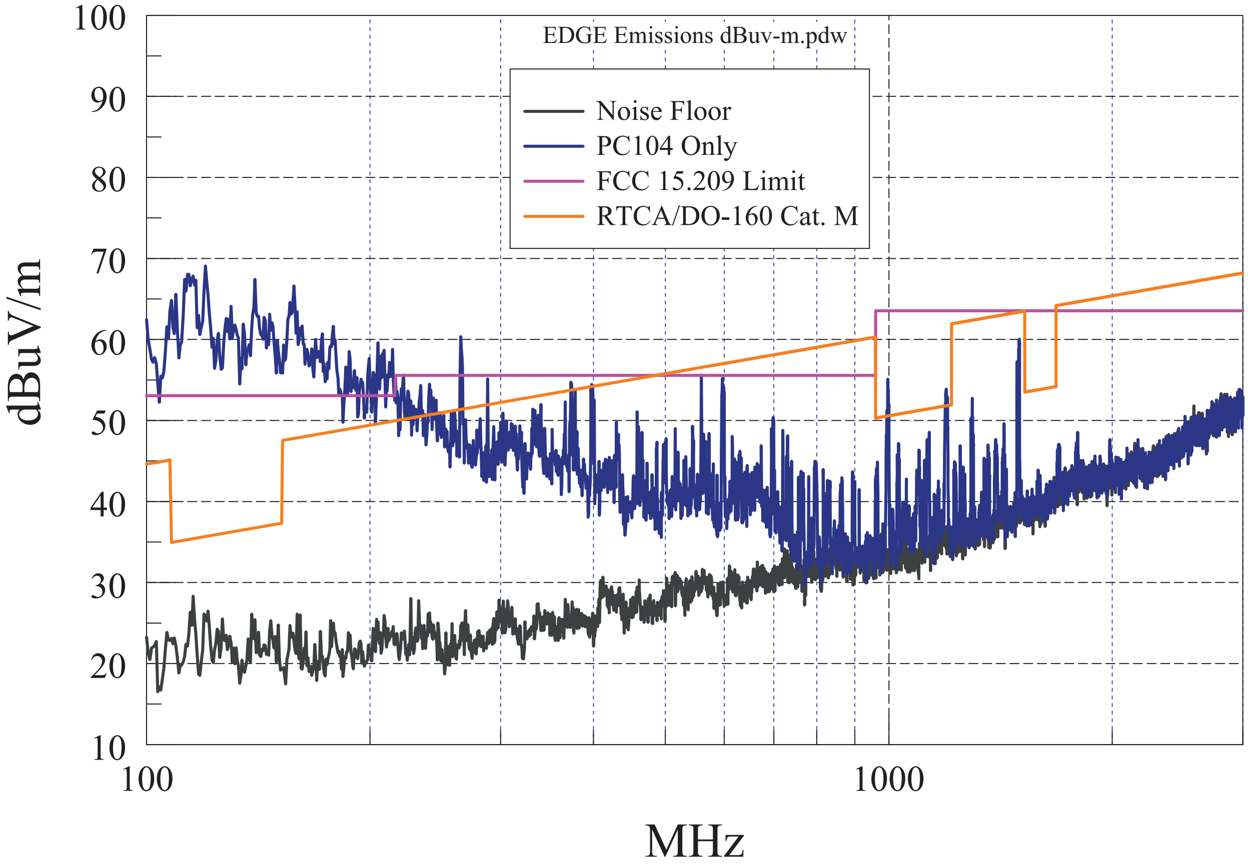

Figure 11: PC104 Scan Emission compared to DO-160F and FCC15.209 Limits. (Electric Field Intensity normalized to 1 meter distance, versus Frequency)

5.3 RCATS Evaluation

The airplane RCATS0900 system consists of a compact transmitter module (3” x 1.75”), geohelix GPS antnenna and input peripherals (i.e. Pitot tube lines, thermocouples, RPM, motor current sensor, G-sensor, etc.) Table 8 shows the system configuration(s) for the airplane RCATS0900 evaluation. Radiated emission data for the PC104, compared to DO-160F and FCC15.209 limits, are plotted in Figure 12.

Table 8: System Configuration for the Airplane RCATS 0900 Evaluation

Systems		**State**
Aircraft	Airplane RCATS0900	ON
	Airplane Servo XCVR	OFF
	PC104	OFF
	AHRS	Not Installed
Ground	Load Cell	OFF
	RCATS Gnd Xcvr	OFF, then **ON**
	RC PWM	OFF

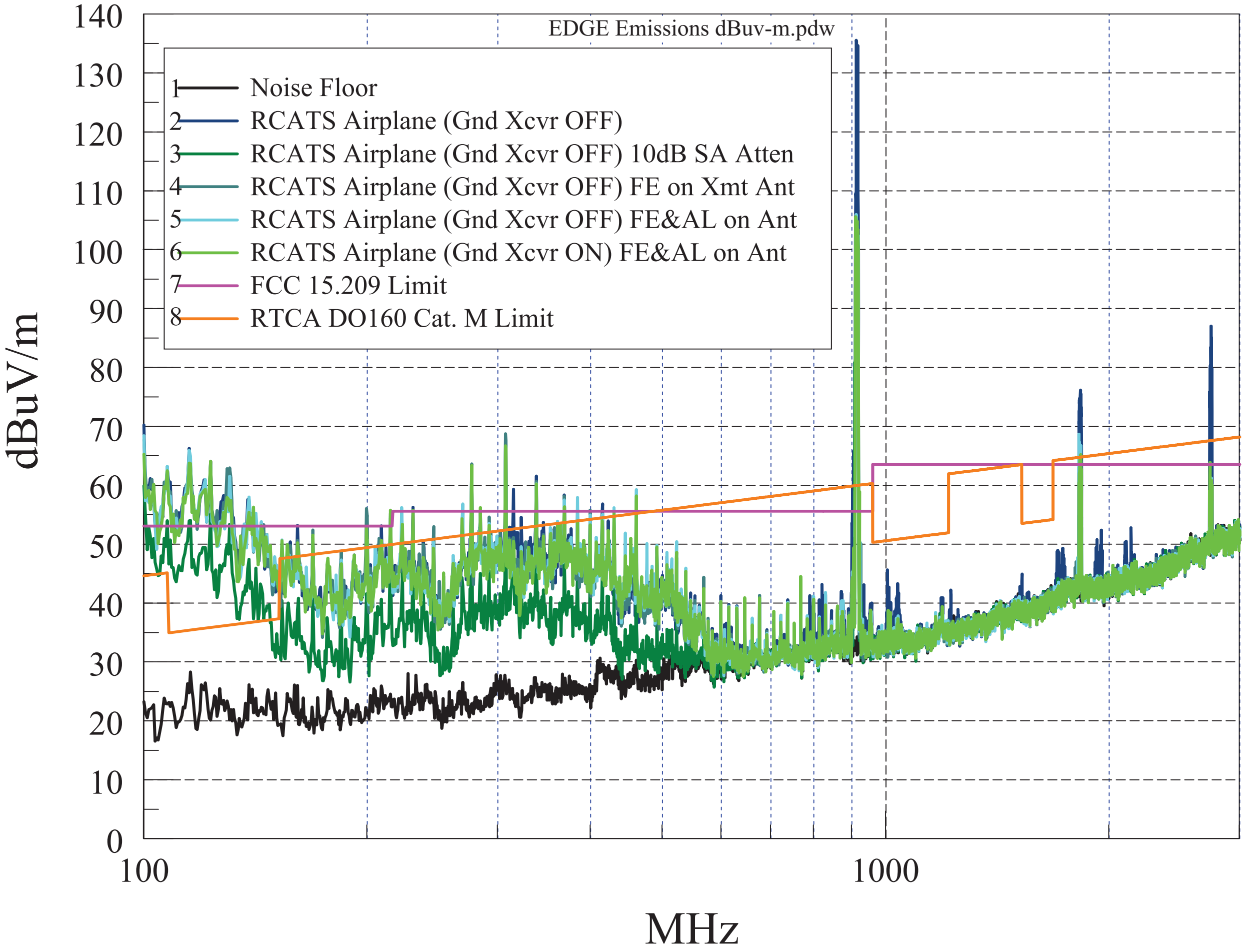

Figure 12: RCATS0900 Scan Emission compared to DO-160F and FCC15.209 Limits. (Electric Field Intensity normalized to 1 meter distance, versus Frequency).

Figure 12 shows that significant spurious emissions occur below 500 MHz, intentional emission in 910 to 920 MHz band, and significant harmonics in 1820 to 1840 MHz and 2730 to 2760 MHz bands. To determine whether the 1830 MHz and 2745 MHz harmonics were being generated by the aircraft RCATS transmitter or in the receiver section of the spectrum analyzer, a 10 dB attenuator was added to the spectrum analyzer input. The gray/green trace (Legend #3) shows the resulting 10 dB attenuation for emissions below 600 MHz, as expected. However the resulting ~30dB attenuation at 915 MHz and 2745 MHz do reveal that the spectrum analyzer input was being overloaded by the unattenuated 915 MHz signal. The 10 dB attenuator was then removed from the spectrum analyzer input (restoring to Figure 4 setup), and instead, small ferrite cores were placed over the aircraft RCATS antenna wire, thereby reducing transmitted power (whereas the 10 dB attenuator had reduced the power measured at the spectrum analyzer). Figure 14 shows a close-up of the 900-930 MHz RCATS transmit band. The graph nomenclature is described as follows:

- "FE on Xmt Ant": Ferrite beads placed over airplane RCATS transmit antenna wire
- "FE&AL on Ant": Ferrite beads and aluminum wrap placed over airplane RCATS transmit antenna wire. Figure 13shows a photograph of this configuration.

Figure 13: Photograph of ferrite beads and aluminum tape before wrapping over airplane RCATS transmit antenna wire (circled in **red**) inside NASA EDGE 540. De-tuning the RCATS transmit antenna in this manner allowed better sensitivity for radiated emission measurements.

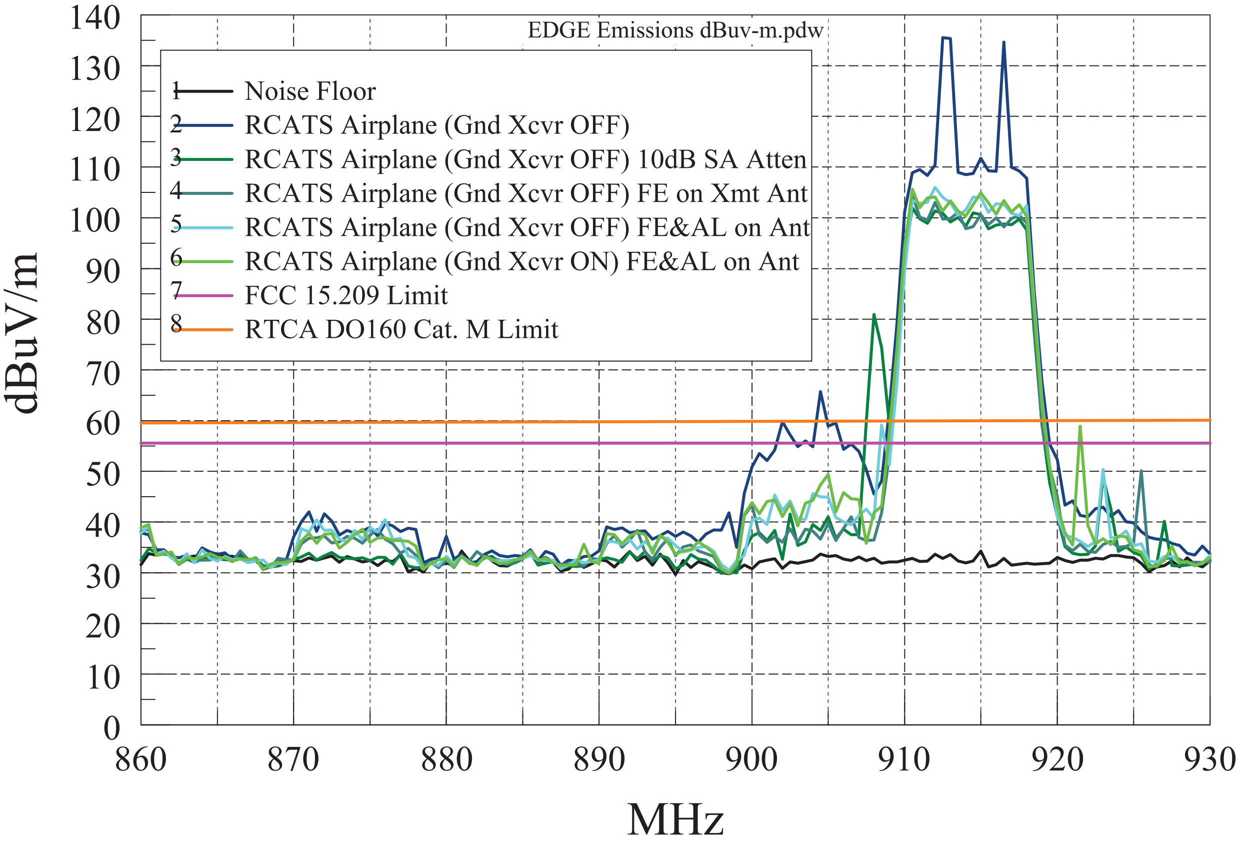

Figure 14: RCATS0900 Scan Emission in the RCATS transmit band (900-930 MHz). (Electric Field Intensity normalized to 1 meter distance, versus Frequency)

The dark-blue trace (Legend #2) in Figure 14 shows the peak amplitude of nearly +30dBm between 910 and 920 MHz. All the other traces (except Noise Floor) are fairly close together. So adding about 10 dB attenuation on the spectrum analyzer input, or attenuating the transmitted power, both had a comparable effect of reducing the 915 MHz band emission by about 30 dB. Figures 15 and 16 show the 1830 MHz and 2745 MHz bands, respectively. These are 2nd and 3rd multiples of 915 MHz. These figures show that either 10 dB attenuation at the spectrum analyzer or attenuating the transmitted power, both reduced primary and harmonic amplitudes by greater than 10 dB. These data indicate that the spectrum analyzer was indeed being overloaded by the 915 MHz transmit signal.

Because adding 10 dB attenuation to the spectrum analyzer input also has the undesirable effect of reducing measurement sensitivity by 10 dB at all frequencies, it was preferred to rather detune the RCATS transmit antenna instead. Comparing Traces 4, 5 & 6 in Figures 14, 15 and 16 show that detuning the RCATS transmit antenna with ferrite beads alone was more effective than also adding aluminum wrap over the antenna wire.

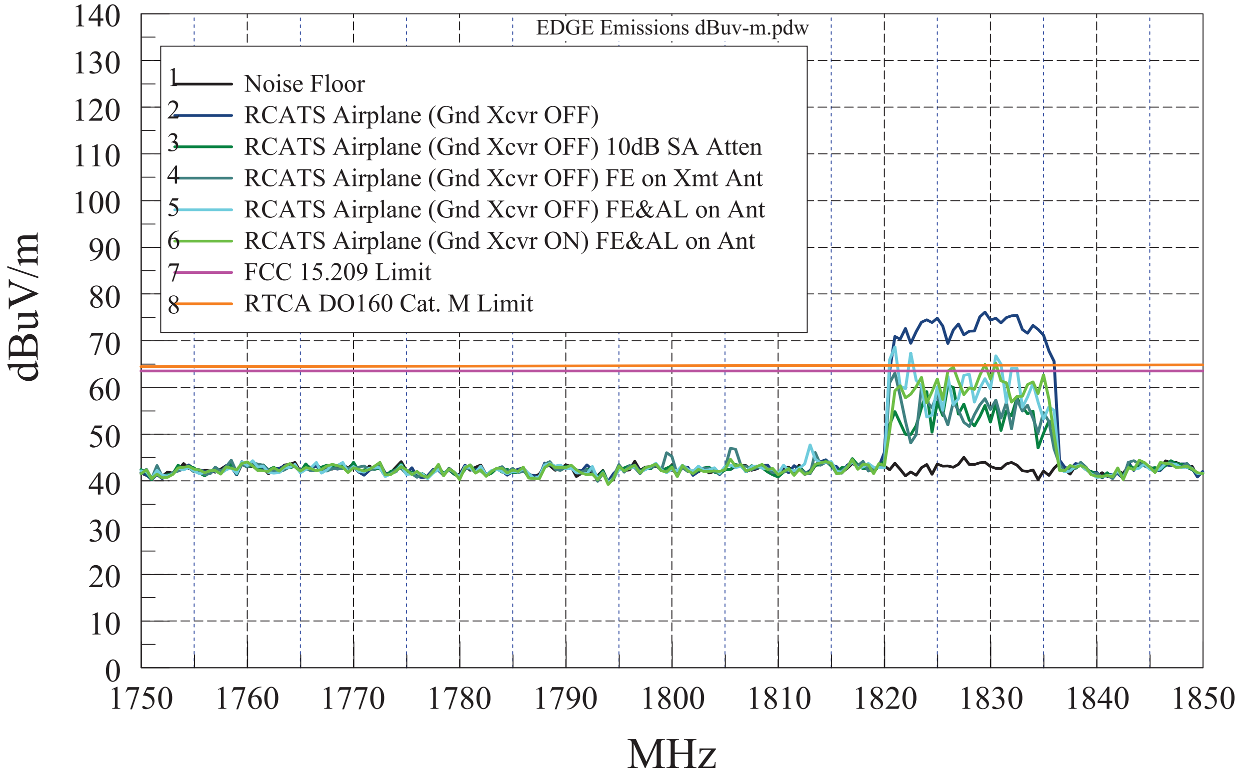

Figure 15: RCATS0900 Scan Emission in the RCATS 2nd harmonic band (1815- 1845 MHz). (Electric Field Intensity normalized to 1 meter distance, versus Frequency)

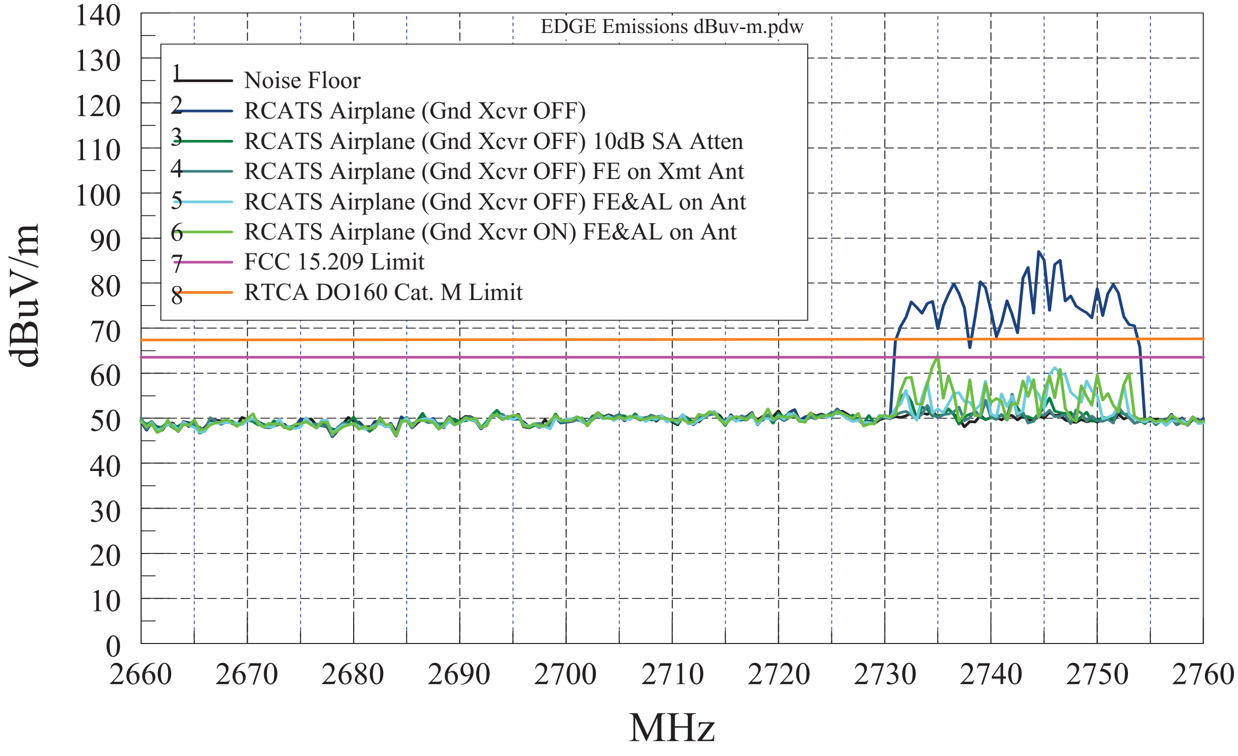

Figure 16: RCATS0900 Scan Emission in the RCATS 3rd harmonic band (2730- 2760 MHz). (Electric Field Intensity normalized to 1 meter distance, versus Frequency)

5.4 Whole-Aircraft Radiated Emission Test at Multiple RPM Settings

The whole aircraft test was the culmination of the radiated emission measurement effort. All systems were operated simultaneously, under typical operational conditions. All ground systems, aircraft PC104, RCATS0900 and Servo XCVR were required to operate the aircraft motor, so this test added the emissions from the motor-controller and motor. This test was intended to help identify any possible EMI threats to the BHM electronics and shielding, which were still being designed. Sections 5.1, 5.2, and 5.3 document a baseline for comparison with the fully-operational radiated emission results described in this section. RCATS aircraft antenna remained detuned with Ferrite and Aluminum shielding (based upon results of Section 5.3).

Table 9: System Configuration for the Full Aircraft Radiated Emissions Test at Multiple RPM Settings

Systems		**State**
Aircraft	Airplane RCATS0900	ON
	Airplane Servo XCVR	ON
	PC104	ON
	AHRS	Not Installed
Ground	Load Cell	ON
	RCATS Gnd Xcvr	ON
	RC PWM	ON

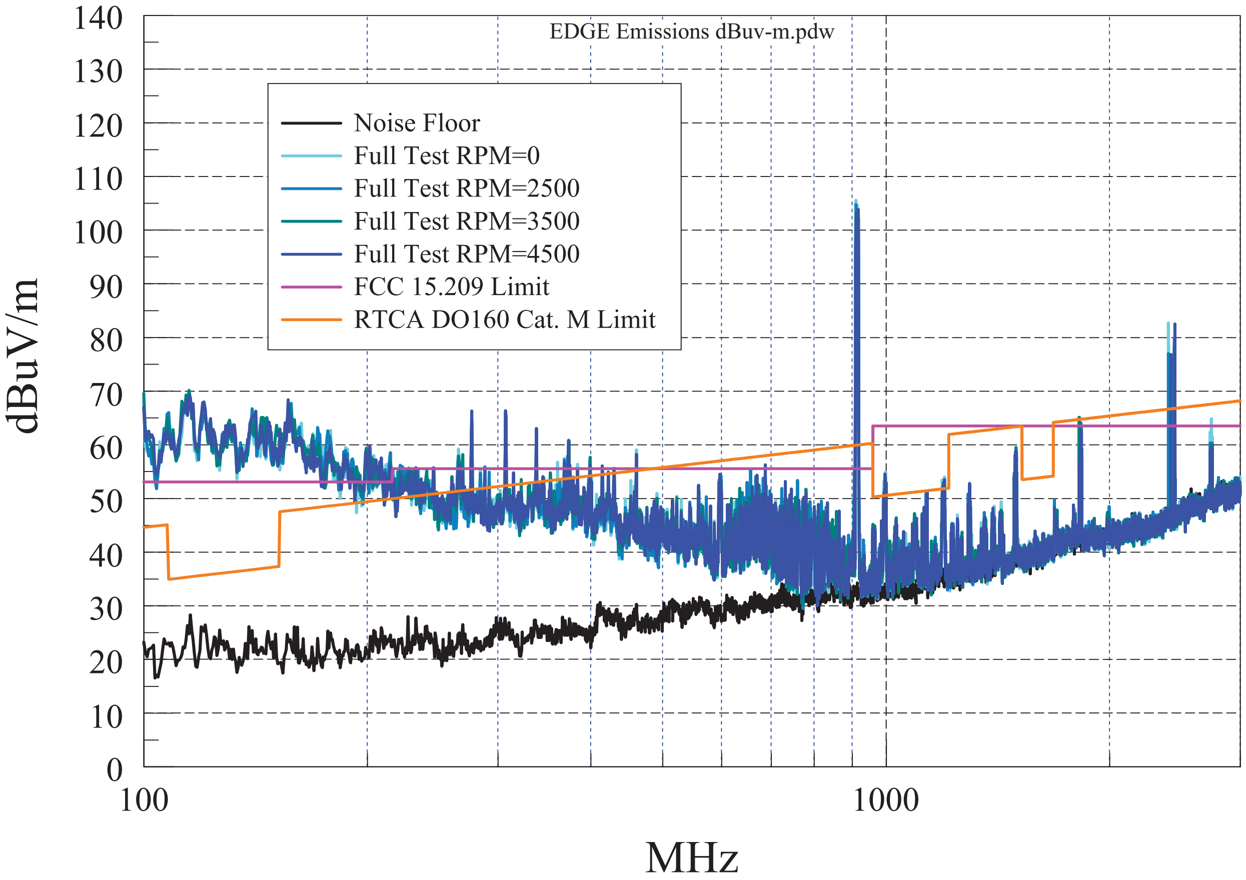

Figure 17: Full Aircraft Scan Emission at different motor RPM settings, compared to DO-160F and FCC15.209 Limits. (Electric Field Intensity normalized to 1 meter distance, versus Frequency).

Table 9 shows the system configuration for the airplane with all systems operating normally. Radiated emission data with the aircraft motor operating at different RPM settings, compared to DO-160F and FCC15.209 limits, are plotted in Figure 17.

Figure 18 shows a 250MHz to 350 MHz window of Figure 17, so that differences between different RPM traces can be visually identified. Figures 17 and 18 show clearly that radiated emissions do not change appreciably with motor RPM setting.

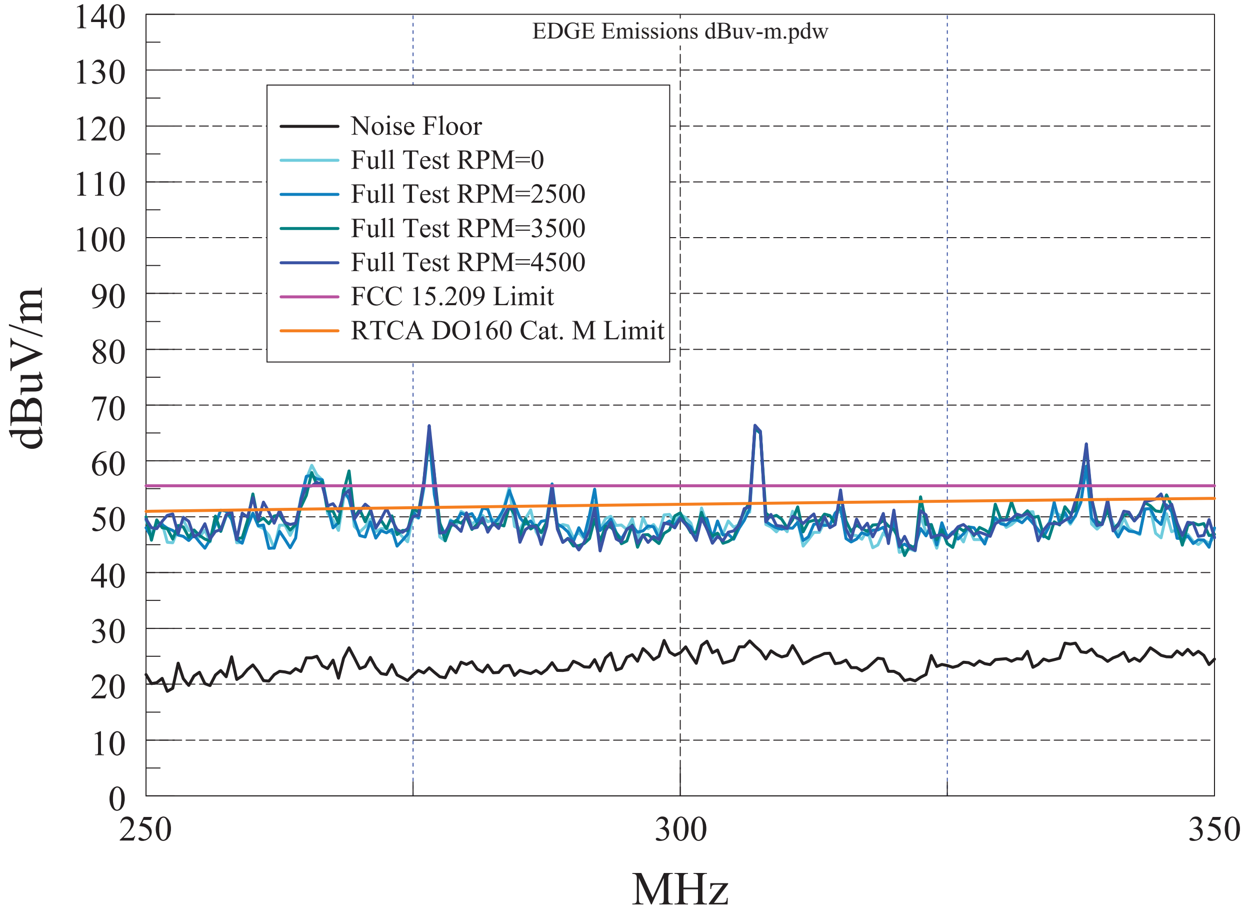

Figure 18: 250 MHz to 350 MHz zoom of Full Aircraft Scan Emission at different motor RPM settings, compared to DO-160F and FCC15.209 Limits. (Electric Field Intensity normalized to 1 meter distance, versus Frequency)

Operation of the aircraft propellers at high RPM generated considerable acoustic energy, air flow and even heat (on the aircraft motors and batteries). The NASA LaRC HIRF Laboratory Chamber A proved to be an excellent facility to perform this type of test. Controlling access to the hazardous area was easily accommodated. Acoustic noise attenuation was excellent. When not performing radiated emission testing, significant acoustic attenuation could still be achieved by partially closing the doors to Chamber A, as well as the Control Room, where the test team was located. Both doors to Chamber A could be partially opened, allowing air to flow around the airplane, facilitating cooling and limiting turbulence (when not performing radiated emission testing). The TDK audio/video system allowed remote monitoring of the chamber during all testing, and was particularly valuable for verifying that the aircraft was operating normally (i.e. no smoke, fire or unstable movement).

6 Summary and Conclusions

6.1 Measurement System

Full-vehicle radiated emission testing was performed in a reverberation chamber, from 100MHz to 3GHz. A retransmission system was successfully designed and demonstrated to allow an aircraft to receive 2.4 GHz control signals and transmit 915 MHz telemetry signals inside the chamber during radiated emission testing. Data show that the measurement system is sensitive enough to test to the FCC and DO-160F Category M limits from 100 MHz to 3 GHz, and that the non-aircraft emitters (Laptop RCATS, Remote Control Transmitter) did not contribute significant radiated emissions to the test environment. Mechanical and supporting challenges were successfully accommodated, including heat-dissipation from motor, air flow from propeller, restraint of test article, and EMC of chamber video/audio equipment.

Full-vehicle radiated emission data could also be useful for minimizing the potential for a small, unmanned aircraft to interfere with radio systems present in its operational environement. Such data could also be used to ensure that such aircaft are not easily detected by their radio emissions.

6.2 Experimental system

This report provides the NASA EDGE 540-R2 test team with radiated emission data for their research system (except the battery health monitor- BHM), operating in the flight configuration. Data may be used to set requirements for BHM enclosure shielding design, and to help identify sources of intra-system electromagnetic interference and optimize on-board radio performance.

Testing found that PC104 radiated emissions exceed DO-160 and FCC limits, and the system would likely cause noise to on-board radios operating below 300 MHz. RCATS radiated emissions exceed DO-160 and FCC limits below ~400 MHz to a small degree (several peaks up to 20 dB above limits), and would possibly cause possible noise to on-board VHF radios, if installed. It was also shown that radiated emissions do not change appreciably with motor RPM setting.

Other test objectives, outside the scope of this report were also accomplished:

- Power consumption and thrust performance of several propellers were compared: 26x10 versus 24x12 and 28x10 propellers. (i.e. 26 inch length x 10 degree pitch)
- Electric current levels in motor circuits were measured at several points in the circuits to study noise characteristics. (For BHM data system filter tuning and sensor location selection.)
- A new wiring system was tested for noise from onboard RF environment. (Signal to noise ratios all data channels)
- New signal conditioning electronics for RPM and air data were tested. RPM channel was observed for noise and calibrated against RPM from in-service RCATS system. Air data channels were observed for noise.
- Functionality and interoperability of the Ames-built BHM were demonstrated.
- EM compatibility of all systems operating in the flight configuration was demonstrated.

For future testing, it may be desirable to include conducted emission measurements. RTCA/DO-160 Section 21 includes procedures and limits for conducted emissions from 150 KHz to 152 MHz. Such data could be very helpful in determining the compatibility of additional systems that may be added to the NASA EDGE 540-R2 research airplane.

7 Recommendations for EMI/EMC in Small Research Airplanes

Small RC airplanes are becoming valuable tools for experimental testing of new aerospace technologies. Small UAVs and even LTA (lighter-than-air) airships may also be purchased off-the-shelf, at relatively low cost. Amateur hobbyists, technology enthusiasts and engineering schools are fueling a growing market for highly-capable, light-weight electronics for telemetry and flight control of small air vehicles. Because of their increasing popularity, RC radio products incorporate coding and channel sharing techniques that make them increasingly secure and reliable. As these new technologies are combined into integrated aircraft systems, increasing attention to EMI/EMC becomes necessary. Early consideration of EMI/EMC will minimize and prevent degradation in the performance of the various electronic systems from interactions with undesired signals of origins both internal and external to the aircraft.

This report section was requested by the EDGE team,and provides recommendations for EMI/EMC in small research airplanes. The guidance is limited and exploratory in nature. If the information proves useful and generates further interest, this section may be expanded into its own NASA report at a later date. Subsection 7.1 outlines design “best-practice” guidance that can help developers of small research airplanes to formulate system designs and EMI-mitigation strategies for their flight electromagnetic environment. Subsection 7.2 describes measurements and testing that can reveal possible EMI/EMC issues, and resolve the source of EMI/EMC-caused malfunctions. Subsection 7.3 provides operational guidance to help avoid and mitigate EMI/EMC problems during flight.

7.1 Design

Perhaps one of the most exciting aspects of working with small RC research airplanes is integrating the subsystems into a working research platform. As the value and electronic complexity of the aircraft increase, so does the concern for EMI/EMC. There’s a huge difference in the EMI/EMC design and build practice for passenger airplanes versus hobbyist airplanes. Passenger airplanes are subject to extensive EMC/Lightning/HIRF certification processes, requiring manufacturers to employ highly-trained staff, laboratories and sophisticated test equipment. Lightning, precipitation-static and most HIRF sources are assumed to be avoided by small research airplanes. Hobbyist RC aircraft incorporate no more EMI/EMC expertise than their amateur builders can supply. EMI/EMC design practices may add complexity and weight, and may even be regarded as trade secrets and patented, or at least unadvertised. However, there are some good sources of best-practice guidance in NASA References.

NASA Marshall Space Flight Center published an excellent handbook for EMC Design and Interference Control (NASA Reference Publication 1368).[23] NASA’s Safety and Mission Assurance organization maintains a standard on crimping, interconnecting cables, harnesses and wiring, that includes a section on general RFI/EMI practices.[24] NASA Langley’s Electronics Systems Branch maintains a “Lessons Learned” webpage that includes a small EMI/EMC Design section.[25] The webpage includes references to past projects and personnel who may provide insight regarding specific topics. In addition, the NASA Spaceflight community has produced several EMI/EMC practice documents that may be useful to the small research airplane community. [26] [27]

Assuming that a small research airplane builder has limited EMI/EMC training, and limited resources on-hand for specialized EMI/EMC tools, basic guidance for EMI/EMC best-practices are summarized below. Limited theory and no equations are provided.

7.1.1 Grounding

All electronic system and subsystem ground references should originate from a single point (i.e. Single Point Grounding), allowing all circuits to share the same voltage reference. (Many people prefer the term "voltage reference" to "ground" for aircraft, because one hopes that their operation is usually away from the ground.) RC aircraft are typically non-metallic, necessitating the use of a ground bus. While it may require less wire and less effort to daisy-chain ground wires, time-varying current drawn by one system will affect the reference voltage of the daisy-chaned system differently than all other systems. Also, unintended loops are unintended circuits. Ground loops occur when ground line (structure, ground plane, etc.) acts as a signal return (intended or not), and become sources of Common Mode noise. Any ground loop will act as an antenna, and will transmit and receive signals resulting from any time-varying magnetic field or impressed current, respectively. Single point grounding eliminates ground loops. Practically, it's very difficult to interconnect data devices without introducing ground loops. In these cases, wire routing should be evaluated to minimize ground loop-area.

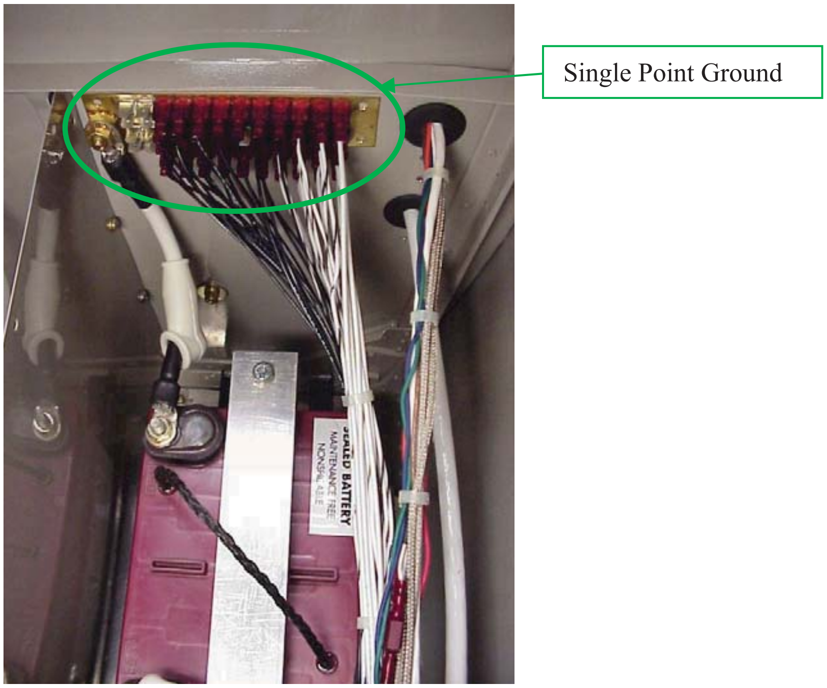

Figure 19: A good example of a Single-Point Ground aircraft installation. The main ground stud from the terminal battery also connects to aircraft structure. Photo from http://www.romeolima.com/RV8/Electrical.htm (Used with permission.)

7.1.2 Wire-Type and Wire-Separation

Ampere's Law describes how electrical current flowing along a wire interacts with the magnetic field around that wire. It's important to keep a mental-image of how wires may share energy via their magnetic field. Fast-changing and/or high-level current flow increases the magnetic field intensity around wires.

Wiring of small research airplanes may be categorized into four applications, described in Table 10.

Table 10: Wiring Types found on Small Research Airplanes

Application	**I, V, f Characteristics**	**Typical Wiring Type**
1. Sensor	milliamps, Volts, DC to ~1 kHz	TP, SB, Coax
2. Data & Digital Signals	milliamps, Volts, 1 kHz to 1 GHz	TP, SB, Coax
3. Power and Flight Control Servos	Amps, Volts, DC to ~100 Hz	TP
4. Radio/Antenna	nanowatts to Watts, 30 MHz to 6 GHz	Coax

Note: TP=Twisted-Pair, SB=Sheilded Bundle, Coax=Coaxial Cable
Note: I= Electrical Current, V=Electrical Voltage, f=frequency content

Note that ribbon-cable is not specified as a "typical" wiring type. Ribbon cable should be replaced with TP or SB at every opportunity, to minimize loop-area and cross-coupling. If ribbon-cable must be used, it may also be twisted, and will benefit from the resulting reduction in loop area and cancellation of magnetic field.

It's generally acceptable to route sensor wiring with other sensor wiring and power with other power wiring. It's also generally acceptable to route digital data with other digital data, as long as the wire-type is selected to minimize the coupling and radiation of magnetic field, either by twisted pair, shielded bundle, coaxial cable or triaxial cable (in order of increasing EMI control). Table 11 shows the level-of-concern for EMC among wiring types. Low indicates that wiring may be co-routed with minimal concern for EMC, Med indicates that careful selection of wiring type may be required to ensure EMC in co-routed bundles, Hi indicates that wiring types should always be separated.

Table 11: Level-of-Concern for EMC Among Wiring Types

	Sensor	Digital	Power & Control	Antenna
Sensor	Low	Hi	Hi	Med
Digital		Med	Med	Med
Power & Control			Low	Low
Antenna				Low

Loop-area should be minimized for all circuit wiring. Signal and return paths should be routed together. Pigtails are loops, so their loop-area should be minimized by making them as short as possible and twisting & taping to bundle. Circumferentially-sheilded cables and connectors are always better than pigtails.

7.1.3 Sheilding

Small research airplanes, and especially hobbyist RC airplanes, are generally constructed with non-metallic fuselages. This lack of electromagnetic shielding makes the onboard electronics more susceptible to external electromagnetic threats (such as HIRF, precipitation static and lightning), as well as internal electromagnetic threats (by increasing inductance thereby reducing coupling between systems via their wiring). Non-metallic aircraft should be operated in clear weather, away from broadcast towers and radar installations, to operationally-mitigate the external EMI threat.

Particularly vulnerable, or noisy on-board systems may benefit from the use of conductive enclosures within the airplane. Any wiring extending from the shielded enclosure will act as a re-transmitting antenna, and must also be shielded all the way to it's end-item for maximum protection. Wiring connections through the shield must be included in the shielding design. Aluminum or copper screen may be used to facilitate air-flow. Such enclosures add weight and significant complexity, and are not recommended as an EMC first-control option.

Some shielding may be obtained by routing wiring as close as possible to metal foil tape (usually aluminum or copper), applied along the fuselage interior. Such tapes are easily purchased, and very lightweight. One end of all metal foil tapes should overlap at the single-point ground location and be electrically bonded together there. The foil tape width should be at least twice the width of all wiring routed along the tape. It is not necessary to bond wiring shields or ground wires to the conductive tape. Wiring should be secured as close to the tape as possible. The adhesive side of the tape should adhere to the fuselage interior. Many foil tapes utilize electrically conductive adhesive, which can facilitate interconnection of foil tape.

An alternative to conductive tape may be conductive wiring conduit or U channels. As with foil tape, one end of any conductive conduit or U-channel should be electrically-bonded (at one end) at the single-point ground location. Figure 20 shows photographs of aluminum foil tape and conductive wiring conduit.

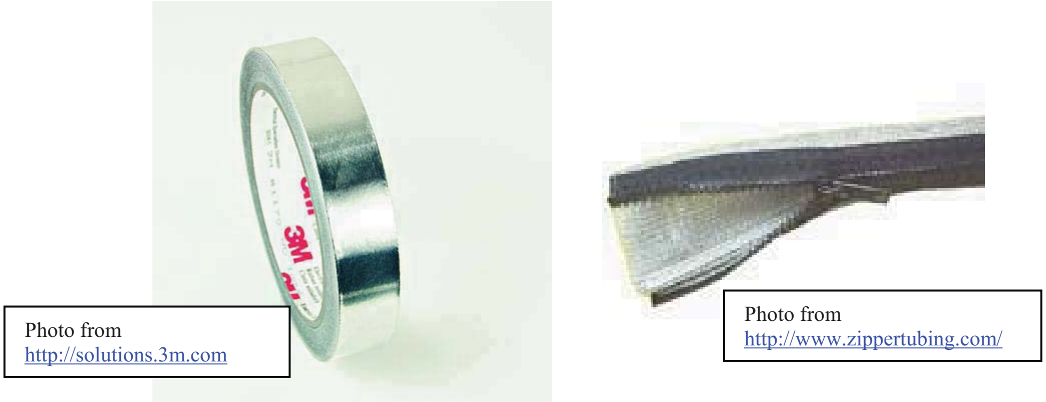
Photo from http://solutions.3m.com

Photo from http://www.zippertubing.com/

Figure 20: Options for shielding of wiring and cable.

7.1.4 Filtering, Electronic Components and System Settings

If entry or exit of undesired electromagnetic energy from equipment can be blocked with filtering, controlling it with grounding, wire separation and shielding becomes less important. In most cases, undesired electromagnetic energy takes the form of switching transients and harmonics of periodic signals, so the undesired signal frequencies are higher than the desired signal frequencies, and low-pass filtering should be effective. Adding capacitance in parallel and/or inductance in series to suspected EMI sources or victims can be used to bypass, absorb or reflect unwanted high-frequency noise. Filtering components should be selected carefully, so that they do not affect desired signals. It's important to remember that capacitor and inductor components behave less ideally as frequencies exceed 100kHz, and may even self-resonate.

Ferrite beads are useful for identifying pathways of unwanted coupling. Suspected wiring can be wrapped around a ferrite bead, while operating, and system performance can be observed real-time to determine improvement. Because ferrite beads are heavy, the aircraft designer may want to replace them with inductors or capacitors in the circuit, after the interfering path has been identified with the ferrite bead.

Clock settings of on-board processors should be evaluated to avoid harmonics that may overlap other system clock settings or on-board radio channels. Some computer BIOS settings allow clock-dithering and longer digital signal rise & fall times, to help reduce spectral content around the clock frequency. Utilization of such BIOS settings should be considered.

7.1.5 Antennas

The simplest, most economical and most common antenna is the quarter-wave monopole. Most RC control units and telemetry systems use quarter-wave monopole antennas. In its simplest form, a quarter-wave monopole consists of a wire extending from a circuit board (where the circuit board ground plane functions as the antenna ground plane). The wire length is cut to a length of ¼ of the wavelength of the operating radio frequency (i.e. 8.2 cm for 915 MHz, or 3.13 cm for 2.4 GHz).

A monopole-type antenna depends upon the reflection of a ground-plane at the feed-point so that it may operate as a virtual dipole antenna. A typical monopole antenna extends through a hole in the middle of a ground plane, and the coaxial-cable shield is connected to the hole in the ground plane. A metallic fuselage provides a ground-plane for on-board monopole antennas. Without a ground plane, any cabling or circutry near the antenna feed-point becomes part of the antenna system, affecting the antenna pattern and efficiency, and possibly providing a pathway for EMI.

A ground-plane may be added to the fuselage of a small non-metallic airplane, using conductive foil tape. It's important that the coaxial cable shield be connected to the ground plane. To optimize antenna efficiency and pattern, the diameter of the ground plane should be at least one wavelength of the operating radio frequency (32.8 cm for 915 MHz, 12.52 cm for 2.4 GHz). Smaller diameter ground planes are better than no ground plane. Ground planes are not required to be circular, however circular ground planes tend to have more predictable antenna directivity. A ground-plane that conforms to the fuselage (i. e. non-planar) is assumed for small airplanes, but will also result in an antenna directivity pattern that is non-symetric.

For best performance, antennas should be separated as much as possible from other electronic systems and metallic aircraft structures. Antennas should have unobstructed line-of-sight view of other antennas to which they are intended to communicate (i. e. antennas should typically be placed on top or bottom of aircraft fuselage).

7.2 Test

EMI/EMC device or system testing may be separated into 4 categories:

- Radiated Emissions
- Conducted Emissions
- Radiated Susceptibility
- Conducted Susceptibility

This report describes a full-vehicle Radiated Emissions test performed over the frequency range of 100 MHz to 3 GHz. For small research airplanes, it may also be useful to use near-field probes to identify on-board sources of radiated emissions. Such probes do not require electrical contact with airplane circuitry, and are designed to be used with a signal-analyzing device such as an oscilloscope or spectrum analyzer. Near Field probes can be very helpful in identifying whether additional shielding is necessary, or whether wire-type or wire-separation issues need to be resolved.

Photo from
http://www.ets-lindgren.com/

Figure 21: Photograph of ETS-Lindgren Model 7405 E & H Near Field Probe Set.

Conducted emissions are defined as electrical signals generated by the system-under-test, onto its wiring. Conducted emissions may be intentional (per-design) or unintentional (spurious). In general, unintended conducted emissions have the potential to affect other interconnected systems in unintended ways, and may even electromagnetically-couple or radiate to other wiring that is not connected by wiring. RTCA/DO-160F contains measurement procedures and conducted emission limits for airborne equipment, but is focused on conducted emissions of RF energy. Grounding and Filtering minimize the potential for unintended conducted emissions. Test-point measurements, using an oscilloscope, may be useful in identifying unintended signals (and better understanding the intended ones too). It's important to use high-impedance contact probes so that the measurement system does not adversely affect the measurement.

Radiated susceptibility may be a concern for small research aircraft if any on-board electronics are sensitive to signals from an on-board transmitter, or if the aircraft is operated in the vicinity of HIRF. A reverberation chamber may be used to perform a whole-vehicle radiated susceptibility test.

Conducted susceptibility testing for general-purpose airborne equipment may be extensive. RTCA/DO-160F includes test methods for Power Input, Voltage Spike, Audio Frequency Conducted

Susceptibility, Induced Signal Susceptibility, conducted RF Susceptibility, Lightning Induced Transient Susceptibility and Electrostatic Discharge.[28] It may be excessively-costly and impractical to subject subscale model research airplane electronics to general-purpose RTCA/DO-160 tests, however review of RTCA/DO-160F procedures and limits may provide insight as to which type of conducted threats may affect system peformance. Again, test-point measurements, using an oscilloscope, may be useful in identifying threat signals that may affect on-board systems.

7.3 Flight Operations

Subscale model research airplanes should be operated only in clear-weather, thus minimizing the threat of atmospheric electricity. Special attention should also be given to identifying towers for broadcast and cellular radio, microwave relays, radars, etc., located in the vicinity of flight operations. Any flight test site should be visited in advance, to identify such HIRF threats. It's a good idea to draw diagrams of local antenas, their size and orientation relative to airpace that will be used by the model airplane. If possible, a radio survey should be performed with a spectrum analyzer and broadband antenna, before and during flight operations. Because RC model airplanes typically use unlicensed radio bands (i.e. 13.6, 27.1, 40.7, 433.9, 915, 2450, 5800 MHz) special attention should be given to monitoring these bands for conflicting operations.

8 References

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[1] RTCA/DO-160F Section 21 provides test procedures, limits and guidance for radiated and conducted radio emissions for U. S. civilian equipment, and is identical to EUROCAE ED-14E, thus setting the international civilian test standard.

[2] MIL-STD-461F provides test procedures, limits and guidance for radiated and conducted radio emissions for U. S. military equipment.

[3] SIG Manufacturing Co., Zivko Edge 540T Description http://www.sigmfg.com/IndexText/SIGRC100ARF.html . http://www.zivko.com/edge/index_edge.html , http://en.wikipedia.org/wiki/Zivko_Edge_540

[4] M. Logan, J. Chu, M. Motter, D. Carter, M. Ol, C. Zeune, "Small UAV Research and Evolution in Long Endurance Electric Powered Vehicles", AIAA 2007-2730, 5/7/2007, http://hdl.handle.net/2060/20070021697

[5] C. Reid, M. Manzo, M. Logan, "Performance Characterization of a Lithium-Ion Gel Polymer Battery Power Supply System for an Unmanned Aerial Vehicle", NASA/TM-2004-213401, 11/2004, http://hdl.handle.net/2060/20050019219

[6] M. Motter, "Autonomous Flying Controls Testbed", AUVSI's Unmanned Systems North America 2005 Symposium and Exhibition, 6/30/2005, Baltimore, MD; http://hdl.handle.net/2060/20050220693

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14. ABSTRACT

A full-vehicle, subscale all-electric model airplane was tested for radiated emissions, using a reverberation chamber. The mission of the NASA model airplane is to test in-flight airframe damage diagnosis and battery prognosis algorithms, and provide experimental data for other aviation safety research. Subscale model airplanes are economical experimental tools, but assembling their systems from hobbyist and low-cost components may lead to unforseen electromagnetic compatibility problems. This report provides a guide for accommodating the on-board radio systems, so that all model airplane systems may be operated during radiated emission testing. Radiated emission data are provided for on-board systems being operated separately and together, so that poential interferors can be isolated and mitigated. The report concludes with recommendations for EMI/EMC best practices for subscale model airplanes and airships used for research.

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