A DESCRIPTION OF THE HARDWARE ELEMENT OF THE NASA EME FLIGHT TESTS

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ABSTRACT

In support of NASA's Fly-By-Light/Power-By-Wire (FBL/PBW) program, a series of flight tests were conducted by NASA Langley Research Center in February, 1995. The NASA Boeing 757 was flown past known RF transmitters to measure both external and internal radiated fields. The aircraft was instrumented with strategically located sensors for acquiring data on shielding effectiveness and internal coupling. The data are intended to support computational and statistical modeling codes used to predict internal field levels of an electromagnetic environment (EME) on an aircraft.

The hardware, instrumentation, and sensors, forged the basis of the data acquisition system. The configuration of the hardware provided for accurate measurements of the electromagnetic environment during flight. The system operated at several specified frequencies and modulation schemes. Internal and external EME data were recorded by the acquisition equipment and additional flight parameters were acquired from the aircraft’s flight data bus.

This paper describes the flight instrumentation system on board the aircraft and concentrates on the hardware components employed during the EME flight test. Measurement instrumentation, sensors, and aircraft configurations, are illustrated and discussed. Particular attention is given to design, operation, and use of the hardware. The actualized flight test scenarios are discussed to give broader scope of the experiment, design requirements and philosophy are examined to highlight the quality and the limitations of the system, and flight data is presented as a representative sample of experiment results.

INTRODUCTION

The goal of the Fly-By-Light/Power-By-Wire (FBL/PBW) program is to provide advanced technology for future subsonic civil aircraft. This technology will include FBL/PBW systems and subsystems, modeling tools, and assessment techniques to aid in the prediction of the electromagnetic environment (EME) effects on flight critical electronics. Many questions need to be answered about the vulnerability of modern digital flight systems to the composite ambient electromagnetic environment. The trend in commercial aircraft design is to integrate increasing numbers of digital computers and electric actuators into flight critical systems. Additionally, composite materials will dominate the structures of twenty-first century aircraft. Composite structures may provide avionic systems with less shielding than conventional metals. High Intensity Radiated Fields (HIRF) are emitted by a multitude of electromagnetic sources that exist throughout the world. Many of these sources, such as air traffic control radars, are located in the vicinity of airports. The use of these and other high power radio sources are increasing daily as a result of the deployment of modern technology throughout all facets of our lives. An understanding of the electromagnetic transfer characteristics from the external environment through the aircraft skin and into the various internal aircraft cavities is needed.

A series of flight test have been conducted onboard a NASA 757 research aircraft to measure and characterize the interactions of electromagnetic environments incident upon commercially configured large transport aircraft. The research aircraft was instrumented with an array of internal and external sensors strategically positioned about the aircraft so as to study the electromagnetic coupling characteristics and shielding effectiveness of the various cavities and compartments such as the flight deck, avionics bay, and passenger cabin. The NASA 757 performed a series of flights against RF transmitters operating at specified output power levels, frequencies, and modulation schemes. The original plan called for conducting measurements in five different frequency bands, HF, VHF, UHF, S-Band, and C-Band. However, due to logistical constraints, no S-Band data were acquired. These fly-by’s took place over the Voice of America antenna farm in the vicinity of Greenville, North Carolina and at the NASA Wallops Flight Facility in Virginia.

The primary objective of this experiment was to collect electric field data while a large transport aircraft was flying through a defined electromagnetic environment.

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The EME experiment data will then be used in the validation of computational and statistical modeling codes. These codes will be used as tools to aid in the design and certification of future commercial aircraft. The EME flight test data will be made available to the EM community for application to the development of other computational electromagnetic methods and analyses. Additional information is available via the Internet on a World Wide Web page located at the address "http://erb-www.larc.nasa.gov".

**FLIGHT TESTS**

The EME flight experiments were conducted over several days in February 1995. The NASA 757 research aircraft flew a total of 56 data runs against four out of five selected RF sources. These runs consisted of several different flight profiles relative to the target emitter. The flight commander with the aide of the 757's preprogrammed flight management system conformably piloted the aircraft according to a number of parameters established for each profile. The critical parameters included the GPS course and timing; airspeed and ground speed; track, pitch, and roll angles; and altitude. The flight profiles were planned to insure that electromagnetic energy impinged on the aircraft fuselage at various angles of incident. Inbound and outbound flight paths were designed to illuminate the nose or tail of the aircraft and crossbound flight paths were designed for left or right broadside illumination of the fuselage.

For each inbound path, outbound path, and crossbound path, the aircraft was configured in one of three configurations. These were designated clean, flaps, and gear/flaps. The clean configuration was flown with the aircraft control surfaces trimmed to neutral and the landing gear up with the bay doors closed. The flaps configuration was flown with the aircraft flaps extended to 15 degrees. The gear/flaps configuration was flown with the aircraft gear down, the gear bay doors open, and the flaps extended to 15 degrees. These three configurations were planned into the test matrix to help define EME coupling apertures and to determine if changes in the aircraft configuration significantly affected shielding effectiveness.

The flight test were conducted at four of the five frequencies recommended by the EME committee formed at the FBL/PBW workshop held at Langley Research Center in March 1992. RF surveys at the VOA and Wallops sites were conducted on the ground and in the air to ensure suitability. These test sites were selected based on their ability to meet the desired test requirements for HF, VHF, UHF, S-Band, and C-Band frequencies.

**SOURCE EMITTERS**

The HF source was located at the VOA Site-B complex. The selected operating frequency was 25.85 MHz using the Rhombic Antenna BR-17 as the source emitter. The antenna had a gain of 23 dBi and was fixed in the horizontal polarization. The antenna beamwidth was 14 degrees in the electric field plane (E-Plane) and 14 degrees in the magnetic field plane (H-Plane). The amplifiers were capable of delivering 500 kW of power to the source. The transmitter was configured in a continuous wave (CW) mode of operation. The NASA 757 research aircraft flew 16 flight profiles against this HF source.

The VHF source was provided by the US Naval Surface Warfare Center Dahlgren Division and located at the Wallops Flight Facility. This system was a trailer mounted equipment container that held a 1 kW transmitter and a log periodic antenna. The EME test operating frequency was 173.15 MHz. The log periodic had a gain of 7.5 dBi and could be positioned in either vertical or horizontal polarization. The antenna beamwidth was 60 degrees in the electric field plane (E-Plane) and 105 degrees in the magnetic field plane (H-Plane). The transmitter was used in the CW mode of operation. Thirty-two flight profiles were flown against the VHF source. Seven runs were used for equipment setup and check-out, and 25 were data runs.

The UHF source was located at the Wallops Flight Facility. This source was a ranging and tracking radar system with a range of 1481.6 kilometers for a 1 square meter skin target. The antenna was an 18 meter parabolic reflector with a 36 dBi gain. It had a 2.9 degree beamwidth in both planes, and was capable of either vertical or horizontal polarization though only the vertical polarization was employed. The operating frequency was 430 MHz. The transmitter had a peak power output of 6 MW and an average power output of 18 kW. To keep within the experiment test and safety guidelines, only 58 kW of power was transmitted using a 2 microsecond pulse width modulation scheme and a pulse repetition rate of 1280 pulses per second. Six flight runs were flown against the UHF source using a lazy-L ground track. This particular flight path allowed for data collection at 12 unique flight profiles.

The S-Band source was located at the Wallops Flight Facility, however due to time and logistic constraints no
S-Band data were acquired. The intended test frequencies were 2740 to 2880 MHz at 135 kW of pulsed power.

The C-Band source was also located at NASA Wallops. This source was one of several FPS-16 radars at WFF. The EME test operating frequency was 5400 MHz. The antenna was a parabolic reflector with a gain of 43 dBi. The beamwidth was 1.23 degrees and capable of both vertical and horizontal polarization. Only the vertical polarization was used for this test. The transmitter peak output power was 1 MW of pulsed power using a modulation scheme of a 1 microsecond pulse and a pulse repetition rate of 640 pulses per second. This power level exceeded the test guidelines, however a special waiver was granted due to the well established history of NASA research aircraft operations with this radar in the past without incident. Two flight runs were flown against the C-Band source using a similar lazy-L ground track described previously. This allowed for data collection at four unique flight profiles.

Station logs and pertinent ground facility variables such as antenna position, antenna polarization, transmitter power, modulation waveforms, etc. were recorded at each of the described emitter source sites. These parameters were later used in the flight data reduction procedures and also to aid in the reconstruction of the electromagnetic field that would have existed in the absence of the aircraft. Also, a van portable global positioning system (GPS) reference receiver was located at surveyed locations for each site. This system allowed for accurate measurements of the airborne research platform with respect to the source emitters.

**FLIGHT SENSORS**

The NASA-757 was instrumented with an array of electric field sensors, current sensors, and measurement hardware. The sensors were located at points of interest defined by the principle investigators. These sensing devices were integrated into a real-time data acquisition system. This system consisted of two flight hardened equipment racks called the EME instrument pallet. The pallet contained all of the instrument controllers and receiving equipment and was located in the first class section of the 757's passenger cabin. A GPS receiver was also located in the EME pallet. The GPS receiver and the aircraft's own flight instruments were used by the measurement system to acquire aircraft position and attitude information. These and other flight parameters were recorded from the aircraft’s internal data bus.

Various RF sensors were used as probes to directly measure the electromagnetic environment. The sensors were divided into two categories, external and internal. The external sensors were used as probes to measure the electric field outside the aircraft fuselage. These measurements, made with the presence of the research aircraft perturbing the external field, are to be compared with computed field calculations without the aircraft present. The internal sensors were used as probes to measure the electric fields and currents inside the aircraft fuselage. There were two external sensors and six internal sensors. An appropriate external sensor was always paired with an internal sensor during each data acquisition cycle. This technique allows for improved accuracy in determining aircraft shielding effectiveness.

A VHF blade antenna and a UHF blade antenna made up the external sensor array. These were standard blade communications antennas and were mounted atop the 757's fuselage. The antennas were good probes when used in their intended frequency bands. Their individual frequency response characteristics were factored into the calibration procedures and the post processing data reduction. It should be noted that previously these sensors, and all of the other sensors, were used on the aircraft while beneath a large rhombic antenna during broadband ground testing and checkout tests conducted with Phillips Lab at Kirtland Air Force Base, New Mexico. The antennas had broad and excellent radiation patterns for the ground tests described at Phillips, but only adequate far field radiation patterns for the EME flight test. This did not seriously effect the measurements due to sufficiently high transmitter powers and very good receiver sensitivities. However, in future airborne testing where the source emitters are located on the ground, below the flying aircraft, it is prudent to use antennas located on the bottom of the aircraft.

The internal sensors consisted of three Prodyn AD-60(A) D-dot electric field sensors, two Prodyn I-320 current sensors, and a long wire antenna used as a sensor. These probes all had characteristic frequency responses which were taken into account during system calibration and data reduction. Each probe located about the interior of the was airplane linked to the EME instrument pallet via low loss 50 ohm transmission line.

The Prodyn Technologies AD-60 D-dot sensors are very sensitive broadband devices. They are hemi-spherical electric field sensors designed to measure time rate-of-change of the electric displacement over a wide frequency spectrum. They are specified to operate at frequencies greater than 400 MHz, however, signals were measured across all of the EME flight test frequency bands. Above 400 MHz these sensors have a linear response similar to a broadband dual ridge horn antenna. Below 150 MHz
they began to roll off sharply. We were able to successfully employ the use of the sensor below 400 MHz because of detailed and extensive calibrations performed by the National Institute of Standards and Technology (NIST) using a unique insertion loss time domain measurement technique. Discussion on the theory of operation of the D-dot sensor or the NIST calibrations of the probes is beyond the scope of this paper.

The Flight Deck D-dot (F-D60) was located on the flight deck aft of the first officer’s seat. The Electronics Bay D-dot (E-D60) was located in the main electronics equipment bay aft of the nose wheel well. The Cabin D-dot (C-D60) was located on top of the EME instrument pallet in the first class section of the passenger cabin. All of the D-dots were aligned in the vertical polarization with respect to the aircraft.

The Prodyn I-320 current probes were used to sense currents induced onto the shielding of wire bundles in the aircraft. They are wide band clamp-on devices designed to facilitate current measurements on conductors. There is a linear ohmic relationship between the current sensed and the voltage output across the spectrum. The I-320’s specified bandwidth is 200 kHz to 500 MHz. The calibrations for these sensors were provided by Phillips Labs in Albuquerque, New Mexico.

The Electronics Bay I-320 (E-I320) was located in the main electronics bay. The I-320 was coupled to a cable that ran from an E-Bay Line Replaceable Unit (LRU) along the interior left side of the aircraft fuselage to the left flight deck windscreen heat mesh embedded in the captain’s window. The sensor was used to sense currents that are presently theorized to be induced onto cable bundles from external electromagnetic energy impinging on the 757’s nose and entering the window apertures of the aircraft’s flight deck. The Cabin I-320 (C-I320) current probe was located in the passenger cabin and was connected to a cable that ran from the EME instrument pallet to the feed cable of the cabin long wire antenna. It was used to sense currents on the shielded outer conductor of the semi-rigid transmission line that linked the cabin long wire sensor to the pallet.

The Cabin Long Wire (CLW) sensor was a 20 foot long wire-antenna that ran in the direction of the longitudinal axis of the aircraft and was suspended with dielectric standoffs one foot below the ceiling of the passenger cabin. This antenna was extremely broadband. The insertion loss frequency response of the long wire antenna is linear, but monotonically decreases with increasing frequency. It was designed to work for the lower EME test frequencies, particularly in the HF-Band, however it was responsive to signals across the test spectrum.

**FLIGHT INSTRUMENTATION**

The EME instrument pallet was the center for acquisition and control during the flight experiment. It was an equipment rack located in the first class section of the passenger cabin. The pallet contained the measurement instruments, the switch matrix, the signal amplifier, the interface cards, and the acquisition and control computer. All of the passive sensors were connected to the instrument pallet with transmission line and routed through a patch panel into the switch matrix.

HP-E1368A RF switches and one HP-11636A power divider comprised the switch matrix. From here an EME internal sensor’s signal would be selected, paired with the appropriate external sensor’s signal, and routed through one of two HP-8495G attenuators. These were variable attenuators controlled by HP-E1370A attenuator drivers. The attenuators were used to attenuate the high level signals, expected to be measured by an external sensor, so as not to overdrive the in-line HP-8447D amplifier that was used to amplify the low level signals typically measured by the internal sensors. After the EME signal was amplified, it would pass through a final HP-E1368A switch where the paired signals were directed to one of two spectrum analyzers and one of two channels on a digitizing oscilloscope. These instruments were the systems signal receivers. The EME measurement system signal receivers consisted of two HP-8561E spectrum analyzers and a HP-54720A digitizing oscilloscope.

The pair of spectrum analyzers and the digital scope were setup for specific parameters. These criterion included frequency, span, resolution bandwidth, and sweep time for the spectrum analyzers; and timebase, vertical scale, sample rate, and trigger level for the scope. For the collection of data within the HF and VHF bands where the transmitted signals were continuous wave, the spectrum analyzer was the primary measurement instrument. Setting the spectrum analyzers to a zero span established an amplitude versus time mode. The result was that only the absolute power levels at the frequency of interest were measured. For the UHF and C-Band data, where the source was pulsed, the digital scope was the primary instrument. Characteristics of the digital scope allowed for the measurement of the time signature which was needed to determine the rise time of the pulsed transmitter signals. Additionally, the oscilloscope does not suffer from pulse desensitization or spreading in the manner of the analyzers.
The VXI controller served as the measurement system’s command and control manager. The controller was an HP-320 computer running C-code and Hewlett Packard’s Visual Engineering Environment (HP-VEE). The computer was the heart of the system. Every instrument, switch driver, and interface card was linked to the controller. The instruments were tied to the system via the general purpose interface bus (GPIB), the switches, drivers, GPS timing and ARINC-429 interface cards were connected to the VXI bus, and the GPS receiver via RS-232. The ARINC data is composed of 11 values; ground speed, track angle, true heading, drift angle, pitch angle, roll angle, inertial vertical speed, air speed, air temperature, altitude, and radio height. The GPS data is composed of 5 values, latitude, longitude, bearing, distance, and universal time clock (UTC) in hours, minutes, and seconds. During the flight tests the control program cycled through eight sensors approximately every 2 to 3 seconds saving the sensor data to disk files. GPS and ARINC data was taken and recorded at the same time each sensor was read. A typical single flight run would last from several seconds to approximately 3 minutes.

FLIGHT EXPERIMENT DATA

The sensor and aircraft system data was processed and reduced to files. The files were organized by frequency bands, test runs, and sensors. The sensor data files were organized into columnar text formats and chronologically order with the measured sensor levels, time step increments, and aircraft position data for one test run. The aircraft system data consisting of the 11 values of ARINC data were associated with each sensor data file. A complete discussion of the data reduction process is beyond the scope of this paper. These details may be found in S. V. Koppen’s paper “A Description of the Software Element of the NASA EME Flight Test”. From the reduced data it was possible to construct calibrated data sets from any particular flight profile for visualization and analysis.

DATA ANALYSIS

The analysis of the data acquired during the NASA 757 Electromagnetic Environment (EME) flight test can be approached from two major points of view, an empirical perspective or the theoretical perspective. The one mode or the other of analyzing the data are equally valid. Our team of researchers will make use of both techniques. However, the initial review and analysis of the data has concentrated on the former technique rather than the latter. Emphasis has been placed on performing a number of comparisons. These concentrated on calculated field strengths, shielding effectiveness, symmetry comparisons, similar sensors, dissimilar sensors, identical sensors, polarization comparisons, baseline comparisons, ambients, dissimilar instrument comparisons, and uncertainty analysis. We define these category comparisons to be the minimum that should be made in order to construct a coherent explanation of the observed phenomenon measured during the EME flight test.

SUMMARY AND CONCLUSION

The collection of EME data during the NASA B757 flight test was completed in 1995. A unique flight experiment for measuring a large commercial transport aircraft’s interaction with an electromagnetic environment has been described. The flight sensors, instruments, data acquisition and control hardware used during the test proved reliable and suitable for the task. Supporting ground facilities and related hardware were illustrated to present the various types of RF emitters used in the experiment. A data reduction process was developed for the purpose of reducing the flight data to a form that could be used to validate EME modeling predictions. A limited amount of this data was introduced as a representative sample of the system’s capability.

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