

# Radio Frequency (RF) Attenuation Measurements of the Space Shuttle Vehicle

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**Abstract**—Following the loss of Columbia, the Columbia Accident Investigation Board (CAIB) provided recommendations to be addressed prior to Return To Flight (RTF). As a part of CAIB Recommendation 3.4.1 – Ground Based Imagery, new C-band and X-band radars were added to the array of ground-based radars and cameras already in-situ at Kennedy Space Center. Because of higher power density considerations and new operating frequencies, the team of Subject Matter Experts (SMEs) assembled to investigate the technical details of introducing the new radars recommended a series of radio frequency (RF) attenuation tests be performed on the Space Shuttle vehicle to establish the attenuation of the vehicle outer mold line structure with respect to its external RF environment. Because of time and complex logistical constraints, it was decided to split the test into two separate efforts. The first of these would be accomplished with the assistance of the Air Force Research Laboratory (AFRL), performing RF attenuation measurements on the aft section of OV-103 (Discovery) while in-situ in Orbiter Processing Facility (OPF) 3, located at Kennedy Space Center. The second would be accomplished with the assistance of the National Institute of Standards and Technology (NIST) and the electromagnetic interference (EMI) laboratory out of the Naval Air Warfare Center, Patuxent River, Maryland (PAX River), performing RF attenuation measurements on OV-105 (Endeavour) in-situ inside the Space Shuttle Landing Facility (SLF) hangar, also located at Kennedy Space Center. This paper provides a summary description of these efforts and their results.

**Keywords**;Columbia, CAIB, Space Shuttle vehicle, Kennedy Space Center, radio frequency attenuation, RF attenuation, Air Force Research Laboratory, NIST, NAVAL Air Warfare Center, PAX River

## I. INTRODUCTION

Following the loss of Columbia, the CAIB provided recommendations to be addressed prior to RTF. As a part of CAIB Recommendation 3.4.1 – Ground Based Imagery, new C-band and X-band radars were added to the array of ground-based radars and cameras already in-situ at Kennedy Space Center. These new monitoring radars radiated at frequencies and power levels the Space Shuttle vehicle had not previously been exposed to in launch/flight operations. In order to determine the needs of the Space Shuttle Program vis a vis potential new monitoring radars, a team of SMEs was formed by NASA, chaired by the AFRL out of Wright Patterson Air Force Base in Dayton, Ohio. After an exhaustive review of

existing assets and their capabilities, the SMEs determined a new set of assets would best perform the mission of using radar technology to closely monitor the Space Shuttle vehicle for debris events as it launched into space. Because of higher power density considerations and new operating frequencies associated with these new radar assets, the team of SMEs recommended a series of RF attenuation tests be performed on the Space Shuttle vehicle to establish the attenuation of the vehicle outer mold line structure with respect to its external RF environment, thus establishing the maximum allowable RF power density for the new radar assets. Because of time and complex logistical constraints, testing was split into two separate efforts. This was done based on the close similarity of the remaining three Orbiter vehicles, OV-103, OV-104, and OV-105, with respect to wiring and structural detail. The first measurement effort would be accomplished, with the assistance of the Air Force Research Laboratory, utilizing classical shielding effectiveness measurement techniques, on the aft section of OV-103, in preparation for flight STS-114, while in-situ in OPF number three. During this measurement effort, the RF attenuation of the aft section of the vehicle would be established. The aft section of the Orbiter vehicle contains the three main engines, associated control avionics, and three avionics bays containing various electrical and electronic boxes not directly related to engine control or operations. This decision was based on the fact that during launch operations, the most direct exposure of the Space Shuttle vehicle to the new monitoring radars would be orthogonal to the aft section, and it was determined the most critical exposure resulting from this exposure would be to the engine control avionics located therein. The second measurement effort would be accomplished with the assistance of NIST and the EMI laboratory out of PAX River, performing RF attenuation measurements on OV-105, in preparation for later flight activity, in-situ inside the SLF hangar. NIST would utilize proven, well established, direct time and frequency domain techniques measurements, while PAX River would utilize well established classical reverberation techniques. NIST and PAX River measurements would be performed on the flight deck, mid-deck, and payload bay volumes of OV-105. The flight deck is where the pilot and commander sit during launch and landing, and contains all of the necessary man-machine interface avionics to enable the astronaut crew to fly the Space Shuttle vehicle, and operate various peripheral systems, such as the Remote Manipulator System (RMS). The mid-deck is

where the remainder of the crew sits during launch and landing, and houses a majority of the avionics and experimental equipment carried by the Space Shuttle vehicle on any given mission. The payload bay is where large payloads that cannot be easily accommodated in the mid-deck, that are intended to be released into their own orbits during the mission, or that are intended to be joined to the existing Space Station structure, such as truss segments, are located. Several avionics systems are located in the payload bay, among them the Ku-Band communications system antenna control hardware, some of the RMS electronics, various fuel cell electrical components and power system distribution and control electronics, and other miscellaneous avionics and electrical system and subsystem components related to collection and distribution of flight control information and sensor data.

## II. OV-103 RF ATTENUATION MEASUREMENTS

OV-103 RF attenuation measurements were planned for an in-situ process, with OV-103 in place inside OPF 3. The measurements were to be based on classical shielding effectiveness measurement techniques. In other words, data would be collected with the “shield” not in place between the transmitter and receiver elements, and with the “shield” in place between the transmitter and receiver elements. To accomplish this, NASA and the AFRL planned a measurement process using the AFRL Mobile Diagnostic Laboratory (MDL). The MDL is a one-of-a-kind RF diagnostic measurement system, typically used for radar cross section measurement of aircraft on the ground. It is a highly customized four wheel drive Ford van, has an environmentally controlled interior, and runs on commonly available diesel fuel. For this measurement, an Élan 2000 Radar transmitter was used as the RF source. Four receive antennas were mounted on the side of the van, height adjustable from 10 to 25 feet, in 5 foot increments. The instrumentation plan was to locate six different transmitting antennas inside the aft section of the Orbiter vehicle, one in close proximity to each of the three engine controllers, and one in close proximity to each of the three aft avionics bays. The receive antennas would be mounted on the MDL, which would be driven in three semicircular paths, with radii centered on an imaginary vertical line extending upward from avionics bay 6.



Figure 1. Space Shuttle Discovery in OPF 3

Three different radii would be used: 95 feet, 105 feet, and 115 feet. Each radius would be driven four times, once for each height setting. The radii and angle of measurement were selected based on the ability to collect and plot data across three cylindrical surfaces, thus establishing a vector direction that might aid in identifying any unexpected vulnerabilities, and the expected line of sight exposure of the monitoring radar as OV-103 launched into space. Fig. 1 shows OV-103 in-situ in OPF 3, just prior to measurement/data collection.

Fig. 2 shows the planned geometry between the MDL, OV-103, and the OPF, as described above. The test frequencies were chosen to coincide with the new monitoring radar frequencies in X-band and C-band, which included the existing range radar operating frequency range. Calibration was performed by using a single transmitter outside the aft section, centered below avionics bay 6, and located at the center of the MDL path radii. The results of the OV-103 measurements were found to be commensurate with expectations as compared to existing commercial and military aircraft of similar design to the Orbiter.

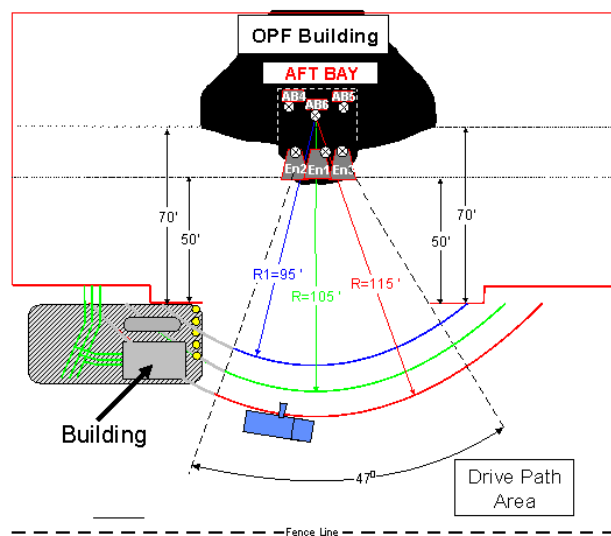


Figure 2. Geometry of MDL, OV-103, and OPF

## III. OV-105 RF ATTENUATION MEASUREMENTS

RF attenuation measurements for OV-105 were planned based on direct time and frequency domain techniques measurements and/or classical reverberation measurements, both of which would be performed on OV-105 inside the SLF hangar, located at Kennedy Space Center. This effort was more extensive in nature, with the intended volumes to be measured including the flight deck, the mid deck and the payload bay. Moreover, the hangar itself would need to be characterized for its Q, field uniformity, and the ambient background. The hangar measurements were accomplished first without a vehicle in the hangar, so as to establish a baseline performance. The vehicle was then located inside the hangar, and measurements were taken over the entire frequency range for which the Orbiter is specified.

The hangar measurements were performed over about a week's time. NIST performed measurements over 3200 individual frequencies, over an 8 octave span. PAX River performed over 54 separate swept measurements over a 14 GHz span. Hangar Q and field uniformity reported by both NIST and PAX were acceptable for the Orbiter test. Ambient reported by both NIST and PAX did not contain radio frequency energy that would interfere with successful Orbiter attenuation measurements. A picture of the SLF hangar is shown in Fig. 3 below.



Figure 3. Space Shuttle Landing Facility (SLF) Hangar

Following the successful characterization effort in the SLF hangar, OV-105 was relocated from its OPF facility to the SLF hangar, and prepared for the actual vehicle attenuation measurement process.

NIST performed their measurements first, from 30 MHz to about 6 GHz. In excess of 5,000,000 individual data points were collected by NIST, with a typical statistical variation on the order of +1.5/-5 dB in the worst case. The NIST measurement system is based on commercially available

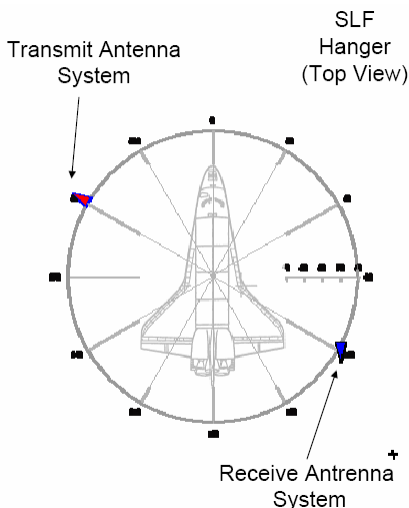


Figure 4. NIST Reference and Measurement Clock Layout

off-the-shelf software, a readily available vector network analyzer, two analog optical links which provide low loss, high dynamic range, and eliminate common mode interference, NIST-developed transverse electromagnetic (TEM) horns, operating from 30 MHz to 1.5 GHz, common 3117 dual ridged horns, operating from 1 GHz to 18 GHz, and a dual-band architecture. Both magnitude and phase data were collected, allowing for sophisticated time and frequency domain signal processing, using very low power levels and obtaining a high acquisition speed.

A clock pattern was laid out surrounding OV-105, and used to control the positioning of transmit antenna platforms on which were mounted two each TEM horns and 3115 horns, as well as acting as the carrier for the vector network analyzer to collect and store the data until download onto a laptop for further processing. Fig. 4 shows this clock pattern approach as employed by NIST to establish a baseline prior to actual data collection. The measurement process used the same layout and clock position approach, with the exception that the receive antennas were located inside the vehicle.

PAX River performed their measurements once NIST completed their effort, from about 4 GHz to 18 GHz. PAX River measurements were performed using a series of classic reverberation techniques. Traditionally, a reverberant shielding effectiveness test is performed using "nested reverberation chambers." The field in each chamber is "stirred" using an electrically large metallic tuner that is capable of suitable displacement at the lower frequency range of the test. Statistically, this "stirring" produces a very uniform field over a revolution of the tuner. Since it was physically impractical to construct and locate a tuner that would be large enough to be effective in a chamber of the size of the SLF hangar, this test used several antennas placed around the aircraft to provide spatial sampling instead of displacement sampling. An array of

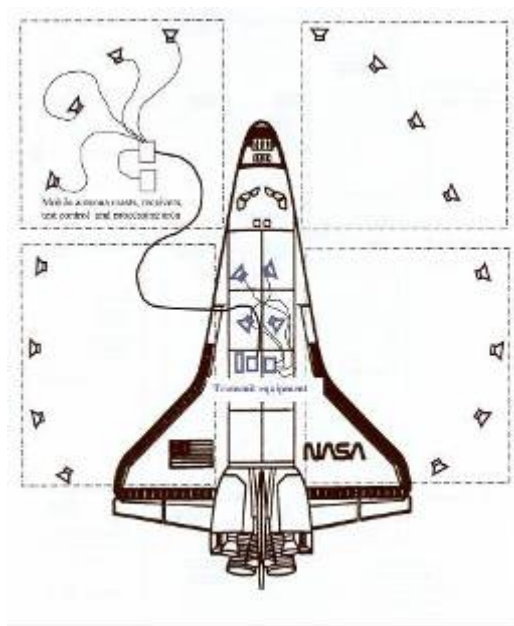


Figure 5. PAX River Antenna Array Layout

antennas was placed inside the aircraft. The array was then moved to various locations for internal spatial sampling. Fig. 5 shows the antenna array layout approach as utilized by PAX River for this test. Frequency averaging, or electronic stirring, was used to simulate the physical boundary movement of the RF standing wave patterns and augment the statistical sampling in the cavity.

As in traditional methods, the received levels were then compared to those received when the aircraft was not present, otherwise referred to as the reference measurements. The difference between these values represents the shielding effectiveness of the aircraft. A big advantage of this method is that it avoids the inaccuracies associated with conventional direct radiation methods caused by standing wave patterns, radiation aspect angle, and antenna factor errors, all of which tend to render very inaccurate and unrepeatable measurements.

PAX River collected sufficient data to provide a minimum of 1280 data points for each predicted value of attenuation, with a repeatability of  $\pm 3$  dB. The overlap in frequency was intentional, to provide a range over which the results of the two separate and distinct techniques could be compared for a sanity check. Agreement of the data from the flight deck and mid-deck volumes was excellent. A discernible difference was seen in the payload bay data, but statistical processing brought the two data sets into acceptably close agreement.

Several factors are believed to have affected the data from the payload bay. The NIST measurement technique transmits from outside the vehicle, with the antennas aimed at the vehicle, whereas the PAX River measurement technique transmits from inside the vehicle, with the receive antennas aimed away from the vehicle. The NIST measurement equipment exhibited its worst signal to noise ratio performance in the frequency overlap region. The payload bay doors have a longitudinal seam that runs the length of the payload bay, and two semi-circular seams at either end of the payload bay. Fig. 6 shows a view of the payload bay door seam looking up from inside the payload bay.



Figure 6. Payload Bay Door Seam, Looking Up

These seams are interrupted at regular distances by latch mechanisms. This configuration appears to form a set of distributed dipole antenna elements. These dipoles may have been electrically excited to differing degrees by the presence of RF signals transmitted by the NIST and PAX River antennas. It is currently unknown how any re-radiation from these dipoles may have interacted with the hangar volume.

In similar fashion to the OV-103 measurement, the results of the OV-105 measurements were found to be commensurate with expectations as compared to existing commercial and military aircraft of like design to the Orbiter.

#### IV. SUMMARY

Following the loss of Columbia, the CAIB provided recommendations to be addressed prior to RTF. As a part of CAIB Recommendation 3.4.1 – Ground Based Imagery, new C-band and X-band radars were added to the array of ground-based radars and cameras already in-situ at Kennedy Space Center. Because of higher power density considerations and new operating frequencies, the team of SMEs assembled to investigate the technical details of introducing the new radars recommended a series of RF attenuation tests be performed on the Space Shuttle vehicle to establish the attenuation of the vehicle outer mold line structure with respect to its external RF environment. Because of time and complex logistical constraints, the testing was split into two separate efforts. The first of these was accomplished with the assistance of the AFRL, performing RF attenuation measurements on the aft section of OV-103 while in-situ in OPF 3, located at Kennedy Space Center. The second effort was accomplished with the assistance of NIST and the EMI laboratory out of PAX River, each performing RF attenuation measurements on OV-105 while in-situ inside the SLF hangar, also located at Kennedy Space Center. Attenuation values for all areas were found to be commensurate with expectations as compared to existing commercial and military aircraft of like design to the Orbiter.

#### ACKNOWLEDGMENT

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