Space Shuttle

Electromagnetic Effects (EME)

Investigation

Report

July 15, 1999

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Executive Summary

The National Aeronautics and Space Administration (NASA) has conducted an investigation into allegations of a danger to public health and safety arising from electromagnetic effects (EME) on the Space Shuttle. The investigation revealed no evidence that the Space Shuttle poses a "specific danger to public health and safety" as a result of EME induced either internally or externally. No violations of law, rule, or regulation were found. Areas for improvement in the Space Shuttle program EME process and documentation and the need for specific requirement changes were identified, with actions assigned for implementation.

Ms. Mary Harris, an employee of the Johnson Space Center (JSC), raised allegations of unsafe electromagnetic compatibility (EMC) practices within the Space Shuttle program. Ms. Harris is employed by JSC as an electrical engineer with responsibilities relating to EMC. She wrote a White Paper, dated December 1, 1997, documenting her allegations and concerns and concluding that the Space Shuttle may no longer be safe to fly. The employee sent her concerns to the Office of Special Counsel (OSC). The OSC referred her concerns to the NASA Administrator. The Associate Administrator for Safety and Mission Assurance established an EME Review Team to investigate Ms. Harris's concerns. Numerous meetings were held with Ms. Harris and others at JSC responsible for EMC and Space Shuttle safety. Ms. Harris is undoubtedly a serious and responsible individual. Although her concerns merited investigation, the investigation produced no evidence of unsafe conditions in the current Space Shuttle program due to EMC problems.

The EME Review Team found that the Space Shuttle EMC processes generally adhere to standard industry practices. While the existing processes provide and maintain a high level of safety for the Space Shuttle, the investigation did reveal some processes and recordkeeping in need of improvement. Improvement in the areas of requirement control, consistency of technical approach, and data and recordkeeping is warranted and will be undertaken by NASA. Additionally, NASA will complete the external radio frequency environment study, implement new susceptibility test specifications for future hardware procurements, and will determine the need to retest heritage hardware given the new susceptibility test specifications. Finally, NASA will perform another system-level EMC compliance assessment to verify that no significant degradation has occurred in meeting the required 6 dB margin of safety, updating the last system-level assessment performed in the late 1980's.

I. Introduction

On March 1, 1999, the U.S. Office of Special Counsel (OSC) referred to the National Aeronautics and Space Administration (NASA) information that, if true, demonstrated a substantial and specific danger to public safety. The referral consisted of allegations made by Ms. Mary Harris, a GS-850-14 Electrical Engineer, in the Test and Analysis Branch, Avionics Systems Division, at NASA's Johnson Space Center (JSC).

Ms. Harris, an electromagnetic compatibility (EMC) analyst, is responsible for analyzing avionics (electrical and electronic devices and systems) installations and changes to the Space Shuttle or its payloads, as assigned, to assure that they will not adversely affect Space Shuttle operations or safety. Ms. Harris alleges that officials at JSC have created and are perpetuating a serious risk to public safety by ignoring their own specifications and safety margins for electromagnetic effects (EME) between and among systems within the Space Shuttle. The allegations identify areas of concern that, according to Ms. Harris, could adversely affect public safety.

Electromagnetic Overview

The following paragraphs contain a brief introduction to the electrical engineering terms used throughout this document. This summary is intended to assist readers in understanding the technical aspects of the issues raised by Ms. Harris. It draws heavily from definitions contained in Volume 6, McGraw-Hill Encyclopedia of Science & Technology (8th ed. 1997).

Electrical interference, also called electromagnetic interference (EMI), is a disturbance to the normal or expected operation of electrical and electronic devices, equipment, or systems. Disturbances may range from nuisances (e.g., fluorescent lighting too close to a computer monitor resulting in a wavy screen) to catastrophes (e.g., aircraft accidents due to EMI-induced navigation errors during bad weather). EMI may originate from a variety of sources such as transmitters used for broadcast radio or television, communication, radar, or navigation; artificial incidental emission sources, such as automotive ignitions and fluorescent lamps; and natural phenomena like lightning. EMI may be radiated through the air and space without any physical contact of devices or equipment or conducted along the paths of electrical wires in power lines and cables.

The EMC discipline strives to eliminate the susceptibility of electrical/electronic devices, equipment, and systems to EMI. EMC exists when all electrical/electronic components and systems function as intended within the electromagnetic environment during all modes of operation. To achieve EMC, numerous design features are used, including metallic shields, electric filters, circuit and cable layouts, electrical bonding and grounding, and frequency spectrum controls. To ensure EMC, specific performance requirements are established and verified by test and analysis. For example, the Federal Communications Commission (FCC) has promulgated regulations in 47 CFR Parts 15, Radio Frequency Devices, and 18, Industrial, Scientific, and Medical Equipment, containing standards for EMI control in commercial products. The FCC regulations establish conducted and radiated emissions limits and measurement standards. Also, the Department of Defense has established its own EMI control standards for military devices, equipment, and systems.

System-level EMC is reasonably assured by a combination of reducing emissions from and enhancing immunities of individual components within the system. Immunity is the ability of a device, equipment, or a system to function as intended within the electromagnetic environment. Specifications define the limits of emissions and the required levels of immunities. System tests when practical and/or analyses verify compliance to applicable specifications.

A failure during testing reveals that the device, equipment, or system being tested exceeds emissions limits or is susceptible to EMI. Failures are resolved by redesign, by imposing operational limitations, or by granting waivers to the unmet requirements if analytical assessments or additional tests show that system-level operational performance will not be adversely impacted. Because both the interference and susceptibility requirements are somewhat conservative, waivers are frequently granted.

In the early 1970's, when the Space Shuttle program began, MIL-E-6051D, "Military Specification: Electromagnetic Compatibility Requirements, Systems," dated September 7, 1967, was used extensively by the EMC community for aircraft systems. MIL-E-6051D contained a requirement to design into the system a safety margin of 6 decibels (dB) for critical functions and 20 dB for ordnance. A failure of a critical function (e.g., the inertial navigation system or the general-purpose computers) would contribute to or cause a condition that would prevent the continued safe operation of the Space Shuttle. The Space Shuttle program EMC requirements were taken from MIL-E-6051D to form the basis for SL-E-0001, Specification: Electromagnetic Compatibility Requirements, and tailored to the Space Shuttle. SL-E-0001 includes the safety margins specified in MIL-E-6051D for Space Shuttle critical components and ordnance. To meet system design goals of 6 dB and 20 dB, the Space Shuttle program adopted most of the technical content of the related Military Standard (MIL-STD) 461A, "Electromagnetic Interference Characteristics Requirements for Equipment," dated August 1, 1968, as the test requirement for individual equipment.

To verify system-level EMC performance, the whole system may be tested to system-level requirements, including design margins. System-level testing is preferred when possible and was performed on a limited basis on Orbiter Vehicle 102 prior to the first Shuttle launch and in the Shuttle Avionics Integration Laboratory (SAIL) on flight-configured avionics equipment. As a practical matter, the size of the Space Shuttle and the complexity of testing equipment and facilities required to accurately simulate its operational environment preclude a complete system test of the Space Shuttle or direct margin demonstration on individual circuits. The method commonly used in the aerospace industry to verify system-level immunity of larger items, like the Space Shuttle, employs box-level test results and then analytic assessments to extrapolate the box-level test data to system-level conclusions. Additionally, testing may be performed on subsystems.

Because analytic assessments for EMC are extremely complicated and rely heavily on experience and judgment, analysts include additional margins when extrapolating from box-level test data to system-level conclusions. Using such margins to conservatively surround the problem is called a "worst-case analysis." The key in a worst-case analysis is to determine the proper level of conservatism. A margin of safety must be assured in the analysis; however, excessive safety margins can add unnecessary cost and complexity. When analyzing for avionics compatibility, experience, judgment, and consistency are valuable tools. An exact calculation is not possible, so thoughtful selection of testing and complementary analyses are the keys to validity.

The leading issue in Ms. Harris's allegations is the inability to quantitatively verify the system margin of safety and her concern about not knowing the exact safety margin.

Space Shuttle Safety and EME

A Space Shuttle consists of solid rocket boosters, an external tank, and the orbiter. Both the solid rocket boosters and external tank are used for launch; the boosters are retrieved and used again. The orbiter is a winged spacecraft capable of transporting humans into space and returning them safely to Earth. It contains engines, rocket boosters, living quarters, a command center, and large payload bay.

Engineering standards are used for design and certification of Space Shuttle avionics prior to flight. The Space Shuttle program used EMC design and test standards during the Design, Development, Test, and Evaluation (DDT&E) phase and continues to use them for equipment upgrades. Additionally, the JSC SAIL replicates the Space Shuttle avionics flight configuration and has been operated for over 100,000 hours with no failures due to EME. This test bed is used continuously to verify software and avionics upgrades. Given the size and complexity of the Space Shuttle, the most feasible way to test the entire system, with all contributing factors (such as the external environment) is actual flight. Functional tests, like those performed on orbit and in the SAIL demonstrate only compatibility. A margin of safety demonstration is not achievable; this type of test does not conclusively demonstrate any safety margin above zero.

The Space Shuttle program is in the enviable position of having the safest and most reliable record of any launch and space flight system in the world. The Space Shuttles have completed over 12,000 earth orbits during 93 missions with no safety-related incidents of EME. The inherent complexities and dangers involved in the operations of the Space Shuttle are such that a 1 in 233 chance of catastrophic failure exists anytime during a mission, with a 1 in 438 chance of catastrophic failure on ascent—odds that have steadily improved from a 1 in 78 chance of catastrophic failure on ascent at the time of the Challenger accident. These numbers are derived from a probabilistic risk assessment. Although risk is inherent in space flight, changes are continuously implemented to improve safety.

II. Summary of Allegations

OSC referred to the NASA Administrator allegations made by Ms. Harris that the Space Shuttle is no longer safe to fly due to adverse affects of the electromagnetic environment. The allegations are contained in a White Paper written by Ms. Harris in December 1997, entitled "The Space Shuttle EMI Control Process – Does Not Knowing Make It Safe?" In this White Paper, Ms. Harris outlines examples of alleged deficiencies in the Space Shuttle electromagnetic test, analysis, and certification processes. These alleged deficiencies form the basis for her assertion that not quantitatively knowing what safety margin is inherent in the Space Shuttle avionics systems makes the Space Shuttle unsafe for flight. Ms. Harris asserts that, because of limited resources, there is no way to adequately perform a system-level EMC assessment.

Ms. Harris alleges that:

A. System-level EMC confidence for the Space Shuttle is not assessed and, with limited resources, there is no way to adequately perform a system-level EMC assessment.

B. EMC safety margins used for converting box-level test data to the system level should be assessed in a systematic manner and should be very conservative. Ms. Harris proposes a Sigma Total (ΣT) analysis.

C. The required EMC control plans do not exist for all hardware, and the required periodic revisions have not been accomplished. The Orbiter EMC Control Plan has not been updated since 1973.

D. The tools (specifically, a family of graphical charts called "margin charts") that summarize EMC violations only contain the worst violators. The charts do not contain the totality of all hardware that have failed to meet the EMC specifications; the charts are not up-to-date; and the charts are not under configuration control.

E. The EMC waiver analysis process is inadequately handled. Officials at JSC have ignored their own specifications and safety margins. NASA officials approve waivers based on the fact that no EMI disaster has yet occurred, rather than on relevant, analytical results.

F. Inadequate attention has been given in system safety analyses to the combined effects of many waivers. One waiver may be acceptable, but the cumulative effects of waivers for many boxes may create an unacceptable situation.

G. The external radiated radio frequency (RF) environment is greater today than it was when the Space Shuttle was first built, and the resultant internal RF environment used as a specification in the 1970's needs to be changed. This RF environment is higher than the qualification levels for which existing boxes have been tested, and thus, a safety hazard may exist.

H. Both NASA and its contractors hide behind contractual requirements and other pressures, resulting in some EMC issues being handled improperly or not at all. Available resources are insufficient to perform the required quantitative assessments.

I. Historical test data are sometimes unavailable (records are inadequately maintained).

J. Cable shielding termination techniques, such as pigtails, do not meet today's best practices.

III. Conduct of the Investigation

Upon the receipt of the referral from OSC, the Associate Administrator for Safety and Mission Assurance (SMA) directed an investigation into the allegations. An EME Review Team was selected from organizations outside of NASA's Human Exploration and Development of Space Enterprise, which is responsible for the Space Shuttle program. Members of the Review Team are listed below; their biographies may be found in Appendix A.

Mr. Keith Hudkins, NASA Deputy Chief Engineer; Chairperson

Mr. Edward Dyer, P.E.; NCE, Electromagnetic Test Engineering Expert, Goddard Space Flight Center

Mr. William Hill, Office of SMA, Manager for Shuttle Operations SMA; Executive Secretary

Dr. J. L. Norman Violette, Ph.D., P.E.; EMI/EMC Expert/Consultant

Mr. Albert Whittlesey; EMC Expert, Jet Propulsion Laboratory

Ms. Doris Wojnarowski; Associate General Counsel for General Law

The EME Review Team was chartered to analyze and evaluate the merits of the allegations made by Ms. Harris. The members were asked to determine the potential adverse affects, if any, to Space Shuttle safety resulting from the conditions alleged and to make recommendations concerning the existing EMC processes to enhance Space Shuttle safety.

The investigation was performed through a continuous process of data collection, review, and analysis. The investigation included a review of requirements, specifications, and process descriptions concerning Space Shuttle EMI and EMC and interviews with Ms. Harris and members of the JSC EMC community.

Interviews with Ms. Harris were held on two occasions during the period of March 23-31, 1999. These interviews clarified the concerns expressed in the White Paper. In the same time period, interviews were held with representatives from the JSC and contractor EMC community supporting the Space Shuttle program, including:

- Civil service staff from the Space Shuttle Program Integration Office and the Engineering Directorate, including the Avionics Systems Division.
- Contractor staff from United Space Alliance (USA), Boeing North American/Reusable Space Systems (BNA/RSS), Science Applications International Corporation (SAIC), and Sverdrup Corporation, Huntsville Office.
- A retired civil servant who was responsible for Space Shuttle EMC in the 1980's.
- A Wright Patterson U.S. Air Force Base employee involved with the EMC/EMI MIL-STD writing team.

Throughout the investigation, information was gathered and assessed for technical merit, reasonableness of approach or methodology used, and the degree of consistency with applicable requirements and processes.

IV. Violation or Apparent Violation of Law, Rule, or Regulation

Ms. Harris cited no violation of law, rule, or regulation; nor has any violation, or apparent violation, of law, rule, or regulation been identified by NASA.

V. Evidence Obtained in the Investigation

Safety plays an integral role in NASA's quest to expand frontiers in space transportation. As it moves into the 21st century, NASA has designated safety as its highest priority. Today, the Space Shuttle is the safest and most reliable launch and space flight system in the world, completing 93 missions and making over 12,000 earth orbits safely. Nevertheless, the inherent complexities and dangers involved in the operations of the Space Shuttle mean that its flight will never be risk free.

Ms. Harris's allegations, outlined in Section II, are specifically addressed below. Although her suggested methodology for assessing system safety will not be adopted, NASA will make other improvements to the Space Shuttle's EMC processes as a result of investigating Ms. Harris's allegations. Actions taken and planned are listed in Section VI.

<u>Allegation A</u>: System-level EMC confidence for the Space Shuttle is not assessed and, with limited resources, there is no way to adequately perform a system-level EMC assessment.

Response: Disagree.

System-level requirements are contained in SL-E-0001 and the Space Shuttle EME Compatibility Control Plan. Specific paragraphs applicable to this discussion are quoted below:

> The system and all associated subsystem/equipment, both airborne and ground, shall be designed to achieve system compatibility. Every effort shall be made to meet these requirements during initial design rather than on an after the fact basis (SL-E-0001, Rev. D, May 13, 1998, paragraph 3.2).
>
> The Shuttle System Level Electromagnetic Compatibility Test Program...shall be prepared by the Shuttle integration contractor (Rockwell-Downey [now USA]) and shall also include Orbiter element level requirements.... The test program shall be documented in the system or element level general acceptance or checkout plan to the extent that demonstration of compliance with this specification can be verified during normal vehicle checkout activity (SL-E-0001, Rev. D, May 13, 1998, paragraph 4.2).
>
> EMI tests at the Element [subsystem] levels to verify margins will provide sufficient confidence of the compatibility of the integrated vehicle. However, normal GSE [ground support equipment] readouts during the prelaunch tests will be monitored and considered as evidence of system compatibility provided the readings remain within performance tolerances specified in the checkout procedures (Space Shuttle Electromagnetic Effects Compatibility Control Plan, Revision B, SD73-SH-0216B, March 1975, paragraph 8.4).

In addition to the above requirements, in program documentation outlined in the Orbiter Element Electromagnetic Effects Compatibility Control Plan, SD75-SH-214, NASA and Rockwell agreed that certification of component design would be verified at the box level and a complete Space Shuttle system EMC test would not be performed. This agreement is outlined in Rockwell International's letter 74MA4846, dated December 20, 1974; NASA letter EJ5-75-77, dated April 17, 1975; and Rockwell International's letter 75MA2647, dated May 29, 1975. At that time, a systems-level test would have required invasive instrumentation in safety-critical boxes to obtain accurate readings. Testing at the box level had been satisfactorily implemented on the Apollo program and an identical test plan was proposed by Rockwell for the Space Shuttle.

Selected tests were performed on the Space Shuttle prior to its first flight. At the launch pad, the Orbiter windows were exposed to 24 V/m (6.6 dB above the limits for RF systems) radiation at 400, 440, and 480 MHz with no anomalies. In a SAIL test prior to first flight, the forward avionics bays and associated wiring were exposed to S-band communications energy across the 1.77 to 2.30 GHz frequency spectrum from 4 V/m to 40 V/m (6 dB above the limits for payloads). Additionally, four critical avionics boxes in the payload bay of the Orbiter were exposed to Ku-band radiation at 15 GHz of 55 V/m at three different angles of incidence with no failures. These tests demonstrated that critical Space Shuttle systems would operate with known onboard transmitters and were not susceptible to their emissions.

Routinely, on each landing of the Orbiter, the tactical air navigation (TACAN) system (ground based transmitters) radiates at 80 V/m (12 dB above the requirement for design) at 1 GHz into the flight deck through the windows with no anomalies. This is additional evidence that the Orbiter's critical avionics are not susceptible to known transmitters.

The last complete system analysis of Space Shuttle EMC was performed in 1988 (NSTS STS-26 Electromagnetic Compatibility Compliance Report). The subsequent process of assessing system-level safety in response to proposed avionics changes is done in a "delta-analysis" method. That is, each changed or new electrical/electronic device added to the Space Shuttle is tested against the design requirements. If a waiver is required, the new or changed device is analyzed for its separate impact on the total system. Additionally, the avionics box is installed and operated in the SAIL and is subsequently operated during launch processing in the Orbiter Processing Facility and on the launch pad at the Kennedy Space Center (KSC) before it is flown. Overall, SAIL has operated for more than 100,000 hours with no failures attributed to EMI. There have been thousands of hours of ground-based testing at KSC and 93 missions flown with no safety-critical failures due to EMI.

System compatibility is continually maintained through good electromagnetic design practices, such as those implemented on the Space Shuttle elements at the box level, e.g., cable routing, shielding, bonding, and the deliberate control of intentional and unintentional radiation sources. However, considering the decade span since the last system-level EMC Compliance Report was issued, and because of many Space Shuttle avionics' upgrades, NASA will take the following actions to verify system EMC:

- The Space Shuttle program will perform another system-level EMC assessment to verify that no significant degradation has occurred in meeting the required 6 dB margin of safety. This assessment will utilize new or supplemental tests and analyses as appropriate.

- Because the Space Shuttle program is embarking on an avionics refurbishment program that will result in many new avionics, EMC requirements will be updated as needed and applied to new avionics.
- All existing safety-critical Space Shuttle hardware will be evaluated to determine if a retest is needed against the new requirements.

Allegation B: EMC safety margins used for converting box-level test data to the system level should be assessed in a systematic manner and should be very conservative. Ms. Harris proposes a Sigma Total (ΣT) analysis.

Response: Generally agree but not with the sizable error factors suggested.

Ms. Harris has suggested that the EMC safety margins used for converting box-level test data to the system level should be assessed in a systematic manner and should be very conservative. This is referred to in her White Paper as the Sigma Total (ΣT) analysis. In doing this analysis, Ms. Harris has calculated a very large error margin to apply to single box analysis. This results in her conclusion that a safety problem may exist when she extrapolates the data to the system level. The following discussion explains why her suggested approach is overly conservative and therefore not appropriate.

Ms. Harris has adapted the material from chapter 8, "Errors in EMI Testing," Volume 6, Edwin L. Bronaugh and William S. Lambdin, Electromagnetic Interference Test Methodology and Procedures (1988), which applies to the calculation of test measurement errors. This text suggests that a statistical approach should be used when doing a systems analysis to account for various sources of errors. The reason that error factors must be included in a systems analysis is that measurements are not exact and analysis tools and data are not exact. The error factors vary substantially with frequency, and the analyst must use them properly.

The error factors offered for consideration by Ms. Harris for 25 MHz are:

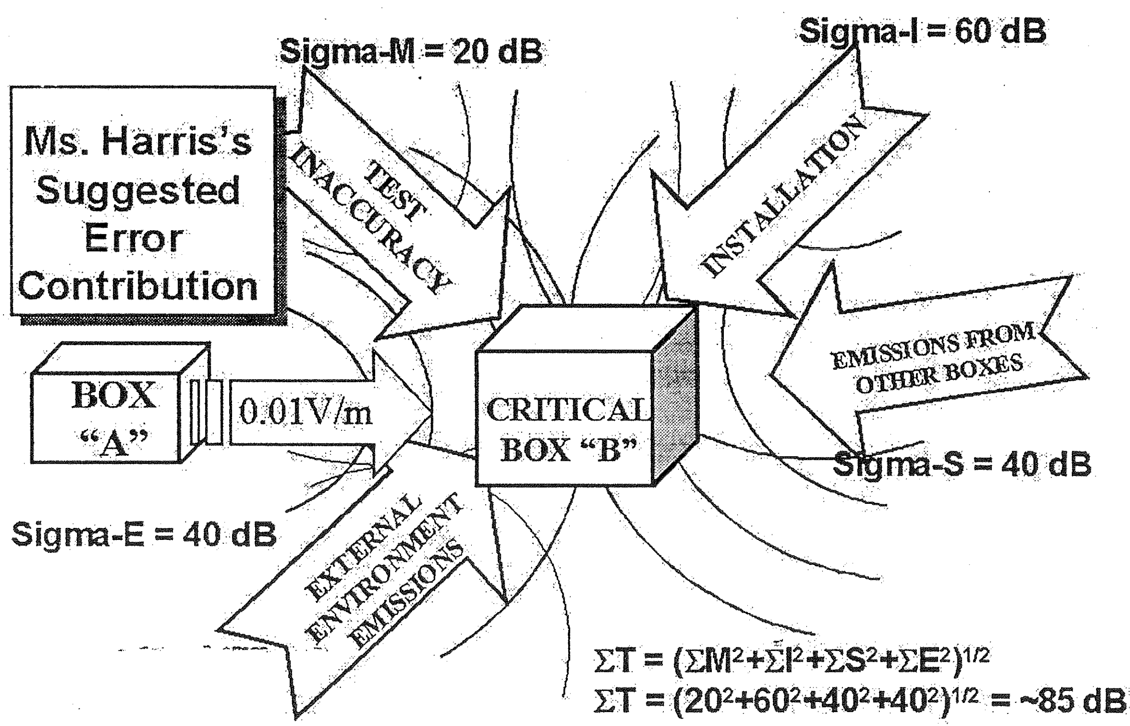
> Sigma-M (ΣM) is the standard deviation of the error in the measurement process and is estimated to be 20 dB;
>
> Sigma-I (ΣI) is the standard deviation of the error for installation differences from the tested configuration and is estimated to be 60 dB;
>
> Sigma-S (ΣS) is the standard deviation of the error for multiple boxes involved and is estimated to be 40 dB;
>
> Sigma-E (ΣE) is the standard deviation of the error in the environmental description and is estimated to be a 40 dB error; and

Sigma-T (ΣT) is the total standard deviation of the error to be used during system analysis, based on the four items above.

Ms. Harris offered other error factors at two additional frequencies in the spectrum. Ms. Harris uses the following equation to determine the total error (Sigma T):

ΣT = square root of $(\Sigma E^2 + \Sigma M^2 + \Sigma S^2 + \Sigma I^2)$

Using Ms. Harris's estimated error factors, this computes to approximately 85 dB, or an error factor of about 17,500 to 1 to be used in her systems analysis of effects from one box, as graphically depicted below. The 85-dB total safety margin far exceeds any known margin used in the aerospace industry and is not one typically used for conservative analysis. A much smaller 33-dB margin is characterized in the reference adapted by Ms. Harris as an "enormous and costly design margin."



Ms. Harris's approach of estimating various error factors is not necessary because values for her four sigmas can be obtained from known data; however, a standard approach has not been formalized by the Space Shuttle program.

The sigma-M error is addressed in the Space Shuttle EMC requirements document, SL-E-0002, Specification: Electromagnetic Interference Characteristics, Requirements for Equipment. Paragraph 5.8.2 states that the required test measurement accuracy is +/- 4 dB unless otherwise stated by the test entity in its report. This factor is consistent with established measurement (sigma-M) error factors in a well-controlled test lab (Reference: NIS 81, The Treatment of Uncertainty in EMC Measurements, May 1994, published by the National Physics Laboratory, Teddington, Middlesex, TW11 0LW, England). Consequently, there is no need for the EMC analyst to estimate a test measurement error factor.

The installation of boxes (sigma-I) error factor is based on the fact that radiated signal measurements, using a prescribed antenna configuration, will increase or decrease as boxes are moved closer or further away than at the one meter distance at which the measurements are made. Because box-to-box interference rarely happens irrespective of distance unless the boxes are intended receivers, EMC analysts generally accept minor specification exceedances for radiated emissions. In fact, the most recent versions of system-level military EMC specifications (e.g., MIL-STD-464, DoD Interface Standard, Electromagnetic Environmental Effects Requirements for Systems, Appendix, Requirement Lessons Learned, A5.6, dated March 18, 1997; MIL-STD-464 superseded MIL-E-6051D) support this statement.

> There is often confusion regarding perceived margins between emission and susceptibility requirements. The relationship between most emission control requirements and susceptibility levels is not a direct correspondence. For example, MIL-STD-461 requirement RS103 (RS-03) specifies electric fields which subsystems must tolerate (susceptibility limits). Requirement RE102 (RE-02) specifies allowable electric field emissions from subsystems. RE102 levels are orders of magnitude less than RS103 levels. Margins on the order of 110 dB could be inferred. The inference would be somewhat justified if the limits were strictly concerned with a one-to-one interaction.

The emissions limits of RE102 are established to protect sensitive RF receivers, typically much more sensitive than wire-connected boxes. The RS103 susceptibility test limits correspond to radiated emissions from antenna-connected transmitters, much greater than cable emissions. Consequently, there is no direct correlation between RE102 and RS103 limits. Therefore, unless intended receivers are involved, sigma-I becomes zero. When intended receivers exist, a more refined analysis and or test is required in order to assure system compatibility. In her calculations, Ms. Harris arbitrarily chooses a large value for this error factor.

The error factor (sigma-S) for multiple avionics boxes considers electromagnetic influences from other boxes. The likelihood of multiple boxes all having common attributes within the Space Shuttle is so small that 20 dB is much too high to estimate this error. From a theoretical viewpoint, if 10 boxes radiating signals with equal amplitude were at exactly the same frequency, in phase, and the same distance from the potentially susceptible box, then the electric field at the susceptible box would be 10 times (20 dB more than) the field from a single box. It is very unlikely that boxes located around a potentially susceptible box at the same distance will radiate similar high-level signals in the same direction, at the same frequency, and in-phase (with polarities aligned), or will result in any significant multiplied signals, as is suggested by the high error margin. The physical dimension of the boxes, coupled with the directional nature of radiated signals, generally preclude significant signal accumulations, even in a close environment similar to the Space Shuttle.

The external environment (sigma-E) error factor also should be treated differently than the manner suggested by Ms. Harris. The major contributors to the environment are known and can be obtained from the Department of Defense Joint Spectrum Center and the intelligence community, e.g., the Central Intelligence Agency and the National Security Agency. Therefore the error factor should approach zero. Additionally, the Space Shuttle has been flying through the environment with no critical anomalies and no indication of degradation due to EMI.

The White Paper's emphasis on the error factors, combined with its large estimated errors, presents a false view of the EMC analysis process currently used in the Space Shuttle program. More refined analyses within the program, based on actual data coupled with orbiter processing and launch pad checkout, leads to technically sound results. These results point to Space Shuttle safety. Each of the identified error sources should be handled explicitly by the analyst in such a manner that the analysis uncertainty is reduced, as opposed to simply using the worst case values as proposed by Ms. Harris. This is the approach that is currently used by the BNA/RSS analysts. However, the EMC analysis approaches employed by the various Space Shuttle EMC analysts are not consistent. A more common analysis approach would provide additional confidence in the results.

As a result of its findings, NASA will take the following action:

- The Space Shuttle program will institute a standard system analysis approach for all future EMC/EMI waivers.

<u>Allegation C</u>: The required EMC control plans do not exist for all hardware and the required periodic revisions have not been accomplished. The Orbiter EMC Control Plan has not been updated since 1973.

Response: Partially agree. Although control plans have not been updated recently, all required plans exist.

The preparation of an EMC Control Plan is an important step in the methodical control of EMI. Electromagnetic phenomena are complex and involve many variables. A good control plan is a blueprint for the design, engineering, construction, and testing aspects of the EMC program.

SL-E-0001, paragraph 3.3, requires the integration contractor, now USA, to prepare an EMC control plan outlining the contractor's approach to EMC. The plan shall include system EMC analysis and demonstration and subcontractor EMC management. Paragraph 3.3.1 of SL-E-0001 provides that the plan shall be updated through supplements or revisions as specified by contract.

With the exception of the Space Shuttle Main Engine (SSME), all the major Space Shuttle subsystems, known as elements, have documented EMC control plans. SSME development was years ahead of the other Space Shuttle elements and its developer had an internal EMC control plan that followed good EMC practices. Once the Orbiter Control Plan was in place, the SSME was treated as part of the Orbiter and subject to the Orbiter EMC Control Plan. The Orbiter EMC Control Plan was approved in December 1976 and still contains valid approaches for essential EMI control in the Space Shuttle to ensure its safe operation. Three supplements have been issued: STS81-0335, STS-1 EME/Lightning Compatibility Report, Rockwell International, March 1981; STS82-0418, Partial Verification for EMI-DDT&E, June 1982; and STS82-0790, EME/Lightning Compatibility Report, Rockwell International, November 1982.

In addition to the element control plans, a Space Shuttle System EMC Control Plan exists (SD73-SH-0216B, current rev. March 1975) and the Space Shuttle Space Flight Operations Contractor, USA, is responsible for the overall EMC of the Space Shuttle elements.

- Because the last EMC control plans were prepared in the early 1980's, NASA will update the system and element EMC control plans.

<u>Allegation D</u>: The tools (specifically, a family of graphical charts called "margin charts") that summarize EMC violations only contain the worst violators. The charts do not contain the totality of all hardware that failed to meet the EMC specifications; the charts are not up-to-date; and the charts are not under configuration control.

Response: Partially agree.

BNA/RSS, the Orbiter contractor, developed a set of margin charts to document all radiated and conducted susceptibilities and emissions for safety-critical Orbiter hardware. The charts have evolved as a tool for EMC analysis. The margin charts are a simplified tool for assessing electromagnetic emissions against known susceptibility by frequency. They have substantial utility in the EMC analysis process and their value has increased as they have become more complete over the years. Evaluating system-level compatibility involves, in part, comparing the impact of the emissions from all boxes against the susceptibility levels of potentially impacted boxes. The boxes of most concern are those identified as safety critical. Of the safety critical boxes, the most important parameter is their level of susceptibility to the external environment. The margin charts quickly show the most susceptible boxes at a given frequency.

The margin charts have been updated as of April 30, 1999, and now include the totality of the hardware that has failed to meet the EMC specifications. Because the margin charts are just an analytical tool, there is no requirement in the Space Shuttle documentation to provide or maintain margin charts. Thus, the charts are not and should not be under configuration control.

<u>Allegation E</u>: The EMC waiver analysis process is inadequately handled. Officials at JSC have ignored their own specifications and safety margins. NASA officials approve waivers based on the fact that no EMI disaster has yet occurred, rather than on relevant, analytical results.

Response: Disagree, although improvements will be made to the waiver process.

SL-E-0001, Paragraph 3.1.1, requires establishment of an EMC board to govern the system EMC and to ensure that element contractors comply with EMC requirements. SL-E-0001, Paragraph 3.2.4.1, requires subsystems/equipment to be designed to meet SL-E-0002 and MIL-STD-462, Measurement of Electromagnetic Interference Characteristics. Recognizing that the design requirements may be severe, impact of the requirements on system effectiveness, cost, and weight shall be considered. Proposed modifications to the limits shall be included in EMC plans. SL-E-0001, Paragraph 3.5.c, provides that if government furnished equipment (GFE) does not meet emissions and susceptibility specifications, the specifications may be modified if approved by the procuring activity.

Space Shuttle Electromagnetic Effects Compatibility Control Plan, Revision B (SD73-SH-0216B), Paragraph 9.1, states that "each waiver and/or deviation shall be documented together with the technical and program rationale for granting it and a copy provided to the appropriate NASA Program Office, IC [integration contractor], and the NASA-JSC within 30 days following the grant."

Hardware, including commercial off-the-shelf equipment and military off-the-shelf equipment, that has failed its EMC requirements and for which a waiver is requested is handled in one of two different paths depending on whether it is Orbiter equipment or not. Although the two paths are similar, they are not exactly equal. If there is a failure to meet EMC requirements that is not fixed through redesign, then a waiver of the specification or a similar approval is requested. First, an analysis is performed to assure that there are no safety-of-flight issues. If the analysis demonstrates that waiving the specification would be safe, approval may be documented by interface change notice for payloads or a waiver for equipment other than Orbiter equipment. The Program Requirements Control Board grants these approvals after a review by the Integration Control Board. Waivers for Orbiter equipment are granted through a change to the procurement specification approved by the Vehicle Engineering Change Board.

NASA agrees that the waiver process was inadequately handled until April 1998. For example, 91 appropriate waivers granted through procurement specification changes were not properly documented and communicated per the SL-E-0002 requirement. On April 21, 1998, the Space Shuttle Vehicle Engineering Manager directed, through letter MV-98-029, "Contractor Furnished Equipment (CFE) Electromagnetic Interference (EMI) Exceedance Resolution," that:

> Effective immediately, CFE EMI exceedances will be presented to the Vehicle Engineering Control Board (VECB) via orbiter change request (OCR) before any procurement specification update will be authorized.

The requirement for the EMC Board (EMCB) in SL-E-0001 is not being met. Early in the Space Shuttle program, a board composed of NASA and contractor personnel, meeting monthly, coordinated the EMC process. All waivers and changes were reviewed by the board, thus ensuring system-level coordination. That board no longer exists, and the required function is no longer performed.

As far as approving waivers based on previous flight experience, because a complete system test of the Space Shuttle cannot practicably be performed, NASA considers previous flight experience to be extremely important, along with analytical results, when approving waivers for new or changed equipment.

Based on its findings, NASA will take the following actions:

- EMC waiver recordkeeping will be improved.
- The Space Shuttle program will institute a standard system analysis approach for all future EMC/EMI waivers, because a common analysis methodology is not used throughout the program.
- EMC test and qualification data records, including historical records, will be made complete to enable an audit of installed hardware qualifications.
- The Space Shuttle program will assure that the functions vested in the EMCB, as specified in SL-E-0001, are performed, including provision of oversight and coordination for the waiver process and maintenance of EMC records.

Allegation F: Inadequate attention has been given in system safety analyses to the combined effects of many waivers. One waiver may be acceptable, but the cumulative effects of waivers for many boxes may create an unacceptable situation.

Response: Disagree.

In practice, emissions from different sources do not combine, or add to one another, in phase at a given location beyond the emission sources. For a problem to exist, the emissions would have to be at the same frequency and in phase, in addition to being at the same location to result in a cumulative effect. Only emissions on antenna-connected RF receivers are of concern because receivers are susceptible to interference at designated frequencies. Requests for waivers are evaluated on a case-by-case basis by comparing the emission level(s) from the tested equipment with the susceptibility of neighboring equipment. The discussion in item V.b on sigma-S provides additional analysis on this point.

__Allegation G__: **The external radiated radio frequency (RF) environment is greater today than it was when the Space Shuttle was first built, and the resultant internal RF environment used as a specification in the 1970's needs to be changed. This RF environment is higher than the qualification levels for which existing boxes have been tested, and thus, a safety hazard may exist.**

Response: Although NASA is confident that increased RF levels do not pose an immediate danger to the Space Shuttle, it otherwise agrees with the allegation. There is a need to understand the RF environment to better assess the likelihood and consequence of the potential hazard that the RF environment presents.

The Space Shuttle was designed in the early 1970's, built in the late 1970's, and used RF environmental requirements from that era. The requirement for RF susceptibility was established and based on MIL-STD-461A. This standard required susceptibility testing to be performed at 1 V/m over a specified frequency range, thus qualifying the box for system-level integration.

The question of how to deal with the issue of the external RF environment is not unique to the Space Shuttle program. Increased power levels from ground-based radio transmitters and the advent of space and satellite communications have resulted in an increased external RF environment. MIL-STD-461D, Electromagnetic Interference Characteristics Requirements for Equipment, dated January 1, 1993 (Table 1B, External EME for space and launch vehicle systems), the current military EMI standard, specifies testing at 20 V/m for military space applications and extends the test frequency range at the high end from 10 GHz to 40 GHz. RTCA/DO-160D, "Environmental Conditions and Test Procedures for Airborne Equipment," July 29, 1997 (published by the Radio Technical Commission for Aeronautics, Washington, DC), for commercial avionics applications (which NASA is considering adopting as an Agency standard) specifies several test limits ranging to 20 V/m and higher, but emphasizes defining test levels to match the operating environment. Although the Space Shuttle does not use the current version of MIL-STD 461, the current version requires that any known RF environment is considered in addition to the specified test frequency range.

> The limits specified for different platforms are simply based on levels expected to be encountered during the service life of the equipment. They do not necessarily represent the worst-case environment to which the equipment may be exposed. RF environments can be highly variable, particularly for emitters not located on the platform....Possible tailoring by the procuring activity for contractual documents is to modify the required levels and required frequency ranges based on the emitters on and near a particular

installation. Actual field levels can be calculated from characteristics of the emitters, distance between the emitters and the equipment, and intervening shielding. MIL-STD 461D, Paragraph 50.3.16 (5.3.16), RS103 (Radiated susceptibility, electric field, 10 kHz to 40 GHz)

The most significant contributors to the Space Shuttle external RF environment are the emitters located at the launch and landing sites. Emissions by the sources at these locations have been controlled at levels defined in agreements between NASA and the range operators. For example, at KSC, Air Force range radar tracks the Space Shuttle on ascent. NASA and the Air Force have an agreement documenting the radar attenuation schedule to limit the Space Shuttle's RF exposure. These agreed-to limits exceed the susceptibility test value, i.e., 1 V/m, at certain frequencies. The combination of shielding provided by the vehicle and the immunity of critical Space Shuttle boxes at the frequencies of exceedance protects the overall system from the Air Force range radar's radiated energy.

On orbit, the Space Shuttle is only briefly illuminated by fixed or scanning ground based beams as the Space Shuttle orbits the Earth at nearly 18,000 miles per hour. Such illumination is momentary (0.5 to 1.0 second depending on altitude), and hardware and software are designed for graceful degradation in the event of brief periods of data interruption. Given a high gain transmitting antenna powerful enough to emit levels exceeding 1 V/m at which equipment has been tested for susceptibility, the beam from such an antenna would be so narrowly focused that the Space Shuttle would pass through it in less than a second. Space Shuttle flight experience shows that critical electronic functions have not been affected by ground RF sources. Energy levels from orbiting satellites are low and, therefore, do not pose significant EMI concerns.

A study by BNA/RSS concerning the RF environment has been performed. The Space Shuttle program is reviewing the study but has yet to accept its recommendations. These recommendations include the potential for increasing the requirements for RF radiated susceptibility testing above the current 1 V/m for specific frequency ranges.

As a result of its findings, NASA will take the following actions:

- The Space Shuttle program will complete its review of the RF environment study and implement new susceptibility test specifications for future hardware.
- The Space Shuttle program will determine if existing safety-critical hardware needs to be retested against new RF requirements.

Allegation H: Both NASA and its contractors hide behind contractual requirements and other pressures, resulting in some EMC issues being handled improperly or not at all. Available resources are insufficient to perform the required quantitative assessments.

Response: Disagree.

Ms. Harris asserts that both NASA and its contractors have hidden behind contract language, rather than taking responsibility to assure that the contract requirements are valid. At NASA, mission success starts with safety. In fact, safety is the first core value delineated in the NASA Strategic Plan. Both NASA management and its contractors are held accountable for safety; safety permeates everything we do.

Requirements assuring Space Shuttle electromagnetic safety are contained in SL-E-0001 and SL-E-0002. NASA has found no evidence that our contractors have relied on contractual requirements where the requirements were insufficient to assure safe operations. Moreover, NASA has a well publicized, confidential communications channel that may be used by both civil servants and contractor employees to raise safety concerns to the highest levels of NASA management. Reports made through this channel, the NASA Safety Reporting System (NSRS), are received by an independent contractor and the reporter's anonymity is guaranteed; no record of the reporter's identification is kept. All reports are investigated and approved for closure by the NASA Safety Director at NASA Headquarters.

NASA and its contractors share responsibility to assure the safety of flight. In 1996, responsibility for operations support for EME was transferred to USA, the Space Flight Operations Contractor. NASA engineering responsibilities were reduced accordingly to analysis of only out-of-family (new or unique) EME issues and EME requirement changes. Although no evidence has been found to support Ms. Harris's allegation, NASA will verify that appropriate resources are applied to the Space Shuttle EMC program.

<u>Allegation I</u>: Historical test data are sometimes unavailable (records are inadequately maintained).

Response: Agree.

There are some historical documents, prepared over the life of the Space Shuttle program (for example, results of the SAIL S-band test prior to the first Shuttle flight and similar results of testing performed at KSC), that cannot be found. Ms. Harris is correct that a complete data set for EMC evaluations is important. NASA agrees that better recordkeeping is appropriate and NASA will take the following action to correct this situation:

- The Space Shuttle program will assure that the functions vested in the EMCB, as specified in SL-E-0001, are performed, including provision of oversight and coordination for the waiver process and maintenance of EMC records.

Allegation J: **Cable shielding termination techniques, such as pigtails, do not meet today's best practices.**

Response: Disagree.

Cable shield termination is an area that is very important to EMC designers. The best technique for cable shield termination is to use a metallic backshell connector that provides 360-degrees of contact with the cable shield. It is not always practical or economical to do so. Normal industry design practice considers performance, weight, space, and cost. The use of "pigtails" (terminating the shield near the connector and grounding the shield via a wire to the connector) to terminate cable shields is acceptable, but the pigtails should be kept as short as possible and their application evaluated.

The existing Space Shuttle cable shielding termination process, using functional requirements rather than specific design requirements, properly serves the Space Shuttle's safety and performance needs.

VI. Actions Taken or Planned as a Result of the Investigation

NASA found that while the existing processes provide and maintain a high level of safety for the Space Shuttle, there are some areas in need of improvement. The margin charts used in analyzing waivers have been updated as of April 30, 1999, and waivers for orbiter equipment, previously granted through procurement specification changes, must now be approved by the Vehicle Engineering Control Board. The following list summarizes the actions NASA plans to take as a result of this investigation.

The Space Shuttle program will:

a. Perform another system-level EMC assessment and verify that no significant degradation has occurred in meeting the 6 dB safety margin requirement.

b. Update EMC requirements and apply to new avionics. All existing safety-critical hardware will be evaluated to determine if a retest is needed against new requirements.

c. Institute a standard system analysis approach for all future EMC/EMI waivers.

d. Update the system and element EMC control plans.

e. Complete the RF environment study and implement new RF susceptibility specification.

f. Determine if existing safety-critical hardware needs to be retested against new RF requirements.

g. Improve EMC waiver recordkeeping.

h. Ensure EMC test and qualification data are complete to enable an audit of installed hardware qualifications.

i. The Space Shuttle program will assure that the functions vested in the EMCB, as specified in SL-E-0001, are performed, including provision of oversight and coordination for the waiver process and maintenance of EMC records.

j. Verify that appropriate resources are applied to the EMC program.

The Space Shuttle program is developing an approach to address each of these actions and will provide a schedule for completion to NASA Headquarters by August 15, 1999.

In summary, while not all of Ms. Harris's allegations were substantiated, many of her concerns were valid and will result in enhancements to the Space Shuttle EMC program.

Appendix I
Review Team Biographies

Mr. Keith Hudkins

Mr. Hudkins is currently the NASA Deputy Chief Engineer and the Executive Secretary for the Agency Program Management Council. Prior to this assignment, he was the Chief Engineer for the Office of Space Flight and subsequent to that assignment he was the Orbiter Programs Director. He started his NASA career in 1973 at the Johnson Space Center and subsequent to that he worked for the Boeing Company as a support contractor for the JSC. Before transferring to Headquarters he was the Program Manager for the Shuttle Extravehicular Mobility Unit (Spacesuits) development. His hobbies are sailing and auto-mechanics.

Mr. Hudkins holds a Bachelor and Masters of Science in Aerospace Engineering from the University of Texas. He is married to Teresa Hudkins and has three grown children.

Mr. William C. Hill

Mr. Hill joined NASA in July 1994 and has been the lead engineer addressing safety and technical issues for Space Shuttle missions for the Office of Safety and Mission Assurance. In this capacity, Mr. Hill is responsible for assuring that each issue is independently addressed by the Safety and Mission Assurance staff at each of the Human Exploration and Development of Space (HEDS) Enterprise Centers prior to each Shuttle Flight Readiness Review and Launch. Mr. Hill independently assesses each safety and technical issue and recommends rationale for flight to the Associate Administrator for Safety and Mission Assurance. As a member of the Shuttle System Safety Review Panel, Mr. Hill has a comprehensive understanding of the overall risk posture of the Shuttle Program and Project Elements. Mr. Hill serves as the liaison to the Office of Space Flight and the Kennedy Space Center SMA Office, and is a member of the Shuttle Range Safety Panel. Prior to joining NASA, Mr. Hill worked at the Vitro Corporation since 1979 on Shuttle Safety and various Department of Defense contracts. Mr. Hill has been involved with each Shuttle mission, either as a contractor or Civil Servant, since STS-27, January 1989.

Mr. Hill holds a Bachelor of Science in Mechanical Engineering from West Virginia [University] Institute of Technology and Master of Business Administration from Frostburg State University.

Ms. Doris A. Wojnarowski

Ms. Doris A. Wojnarowski currently serves as the Associate General Counsel for General Law at NASA Headquarters. In this position, she is responsible for providing legal advice to management officials in the areas of personnel, EEO, civil rights, environmental law, fiscal law, ethics, safety, security, real and personal property, claims, information disclosure, and other general law matters. She is also responsible for drafting the annual NASA authorization bill. From May 1996 through February 1998, she served as the Chief, Management Effectiveness Staff, U.S. Coast Guard Headquarters, with responsibility for an array of general management issues. From October 1994 to May 1996, she was the Chief of the Coast Guard's Office of General Law. Ms. Wojnarowski was a senior attorney in the Office of the Assistant General Counsel for Environmental, Civil Rights, and General Law, Office of the General Counsel, U.S. Department of Transportation, from October 1991 through October 1994. From April 1986 through October 1991, Ms. Wojnarowski was a staff attorney in the Coast Guard's Office of General Law. She has previous legal experience with the U.S. Department of Education and the Social Security Administration.

Ms. Wojnarowski is admitted to the Pennsylvania bar. She is a 1981 graduate of the Dickinson School of Law, Carlisle, Pennsylvania. Ms. Wojnarowski earned a cum laude Bachelor of Arts in Political Science from the University of Pennsylvania and a Master of Science from its Graduate School of Education, both in 1978.

Dr. J. L. Norman Violette, PhD, P.E.

Dr. J. L. Norman Violette, Ph.D., P.E., is founder (1979) and President of the Violette Engineering Corporation (VECorp) He is also the CEO and co-founder (1988) of Washington Laboratories, Limited (WLL), an EMI/EMC, product safety, and compliance testing facility for products destined for military and general global markets. He is a member of the Board of Directors of the IEEE EMC Society, and Past Chairman of the Washington, D.C./Northern Virginia EMC Chapter. He served as an EMC Distinguished Lecturer, and has presented over 200 seminars and workshops on various EMI/EMC topics in the US, Canada, and several other countries in Europe, Asia, Africa, and South America. He is a member of the ANSI C63 Committee (EMC Standards) and has written a number of technical reports and papers on EMC. He is an independent EMC and Lightning Protection consulting engineer. Clients include Government DoD (Military Departments) and civilian Agencies (NASA TRMM, XTE & Shuttle), and industrial manufacturers of military and commercial products. USAF retired (21 years).

Education: BSEE (Rensselaer Polytechnic Institute); MBA (Auburn Univ.); Ph.D. (NC State Univ.)

Mr. Edward Dyer, P.E.

Mr. Dyer has, since joining NASA in 1989, been Section Head of the NASA/GSFC Electromagnetics Test Engineering Section. He was previously the Senior Staff Engineer responsible for Electromagnetic Compatibility design and test at the former Westinghouse Aerospace Test Center, Baltimore, MD, where he had collateral duties as a member of the EIA G-46 committee on Automatic Spectrum Plotting. While working at Mantech, he supported the development of the SSF EMC specification. Mr. Dyer has presented technical papers on the Optimized Anechoic Conversion of the GSFC Large EMC facility at the 2nd Annual Euromagnetics Conference in France in 1995; on Automatic Spectrum Plotting at a joint IES/IEEE-EMC meeting at the Rome Air Development Center, NY; and on High-Speed Image Processing at the Indian National Computer Conference in Bengalore, India. He has visited and evaluated the EMC test facilities at ESA's ESTEC facility in Noordwijk; MBB's Magnetics and EMC facilities in Munich and Kiel; and NASDA's EMC facilities in Tsukuba Space City, Japan. He is a NARTE-certified Senior EMC Engineer; a Registered (Maryland) Professional Engineer (Electrical Engineering); and a Member of the Maryland State Bar.

Mr. Dyer has a BSEE degree from Tufts University; an MSEE-equivalent from graduate-level engineering courses taken at UCLA, JHU, and the former WEC School for Applied Engineering. He has a Masters in Engineering Management from GWU, and a Juris Doctorate from the University of Baltimore. Mr. Dyer is a member of the Maryland State Bar and has served as Chief Engineer, Executive Officer, and Commanding Officer of various selected-reserve Destroyer-Escorts. He is married to Heidi von der Burg; has five grown children, including a recent Duke/Vanderbilt PhD , and USAF Academy, VPI, and UMBC/Emerson attendees.

Mr. Albert Whittlesey

Albert Whittlesey graduated from the California Institute of Technology with a BS Physics degree, in 1962. Since that time he has worked at JPL in the field of electromagnetic compatibility. Additional formal education and training has come from night school courses in Fortran programming, linear algebra, electrical engineering, and probability theory and statistics at UCLA. He has also attended company training courses relating to his work at JPL. He has continued his education by subscribing to and reading various technical journals. He has worked in all facets of EMC, including shield room EMC testing, field testing, EMC design requirements and test specification preparation, RF interactions analysis for transmitters and receivers, pyrotechnic RF hazard analysis and testing, lightning hazard analysis, and others. He has interfaced with other space agencies for EMC working groups and monitored contractor performance of EMC programs. He has acted as a consultant for at least five major aerospace companies in and out of his performance at JPL work. He is a member of the IEEE (EMC Society subgroup), Sigma Xi, and is a NARTE Certified EMC Engineer since 1990 (EMC-00836-NE). A partial list of awards includes: a Hubble Space Telescope Servicing Medallion

(1994); the NASA Exceptional Service Medal for ESD support to Voyager, Magellan, and Galileo programs (1990); he was awarded a NASA Tech Brief (Control of ESD on Paint Surfaces (shared with Philip Leung also of JPL) (1992), and has received a NASA commendation for Galileo Launch Safety Approval Support (1990). He invented, fabricated, and uses at work a slide rule analysis aid for dc magnetic field equations. He has written and presented numerous technical papers and is the co-author of several NASA technical handbooks.