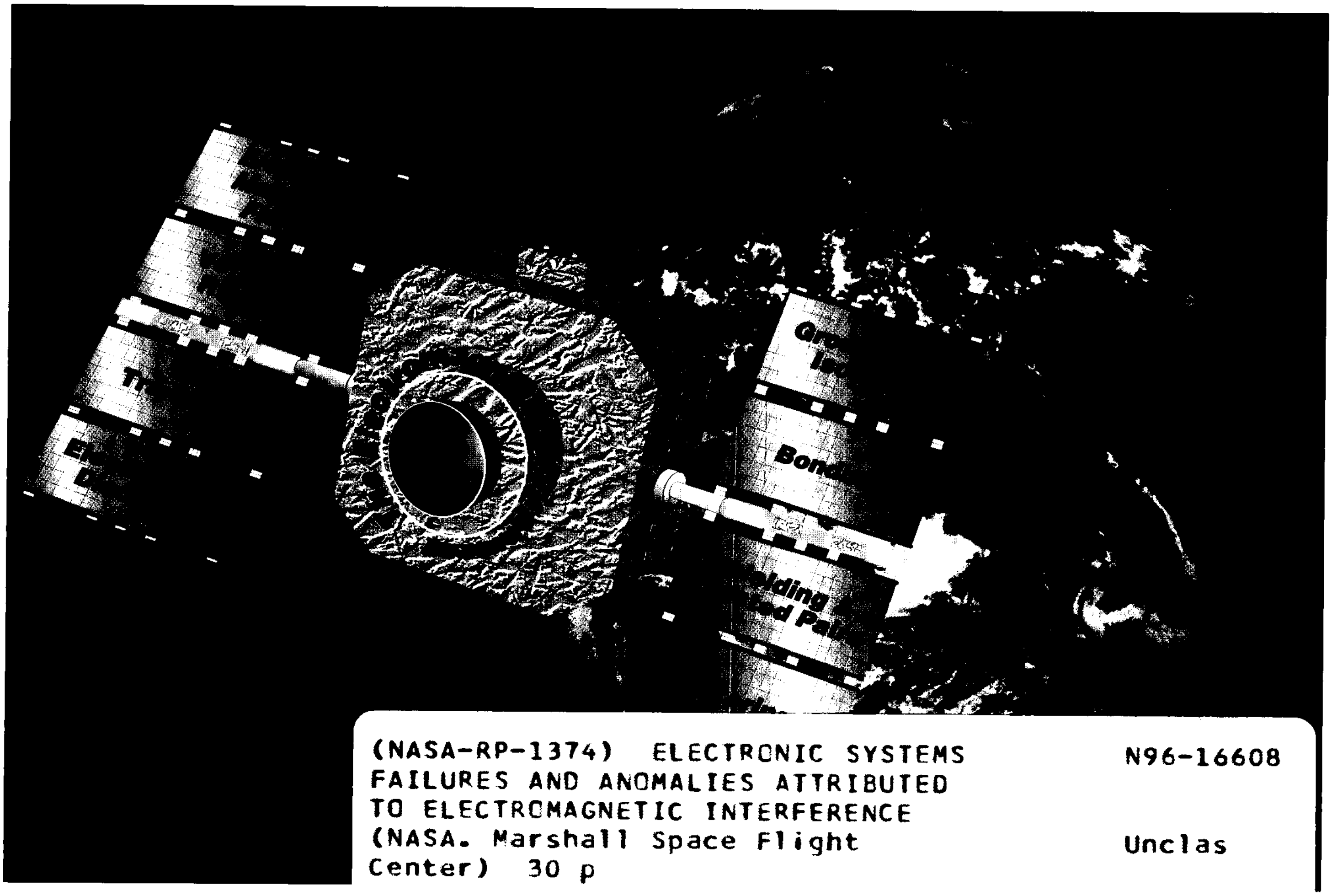
NASA Reference Publication 1374

Electronic Systems Failures and Anomalies Attributed to Electromagnetic Interference

R.D. Leach and M.B. Alexander, Editor



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Electronic Systems Failures and Anomalies Attributed to Electromagnetic Interference

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PREFACE

The effects of electromagnetic interference can be very detrimental to electronic systems utilized in space missions. Assuring that subsystems and systems are electrically compatible is an important engineering function necessary to assure mission success.

This reference publication will acquaint the reader with spacecraft electronic systems failures and anomalies caused by electromagnetic interference, and will show the importance of electromagnetic compatibility activities in conjunction with space flight programs. It is also hoped that the report will illustrate that evolving electronic systems are increasingly sensitive to electromagnetic interference, and that NASA personnel must continue to diligently pursue the electromagnetic compatibility on spaceflight systems.

This reference publication was developed by the Electromagnetics and Environments Branch, Systems Analysis and Integration Laboratory, Marshall Space Flight Center. The Branch is actively engaged in various electromagnetic compatibility activities.

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ABBREVIATIONS AND ACRONYMS

AAEU	aquatic animal experiment unit
AC	alternating current
ADF	automatic direction finder
AM	amplitude modulation
ASRS	aviation safety reporting system
CB	citizens band
CBS	Columbia Broadcasting System
CD	compact disk
COTS	commercial off-the-shelf software
EEG	electroencephalogram
EL54	mail code for MSFC Electromagnetics and Environments Branch
EMC	electromagnetic compatibility
EME	electromagnetic environment
EMI	electromagnetic interference
ESD	electrostatic discharge
EUVE	extreme ultraviolet explorer
FAA	Federal Aviation Administration
FDA	Food and Drug Administration
FEE	frog embryology experiment
FM	frequency modulation
GRO	Gamma Ray Observatory
GSM	global system for mobile communications
HF	high frequency
HIRF	high intensity radiated fields
I/O	input/output
ICT	integrated configuration test

IML	International Microgravity Laboratory
ISEAS	Integrated Space Station Electromagnetic Compatibility Analysis System
ISSA	International Space Station *Alpha*
KSC	Kennedy Space Center
LCEORF	linear compressor enhanced orbiter refrigerator freezer
MCM	multichip module
MEDIC	Marshall Space Flight Center Electromagnetic Compatibility Design and Interference Control (MEDIC) (Handbook)
MMIC	monolithic and millimeter-wave monolithic integrated circuits
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NDI	nondevelopmental item
NOAA	National Oceanographic and Atmospheric Administration
PGSC	*Spacelab* payload general support computer
RAU	remote acquisition unit
RF	radio frequency
RPV	remotely piloted vehicle
TCA	radio technical commission for aeronautics
SCM	spinal changes in microgravity
SL–J	*Spacelab*
STS	Space Transportation System
UV	ultraviolet
VOA	Voice of America
VOR	very high frequency omnirange

REFERENCE PUBLICATION

ELECTRONIC SYSTEMS FAILURES AND ANOMALIES ATTRIBUTED TO ELECTROMAGNETIC INTERFERENCE

1.0 INTRODUCTION

This report is to acquaint the reader with spacecraft electronic systems failures and anomalies caused by electromagnetic interference (EMI), show the importance of electromagnetic compatibility (EMC) activities in conjunction with space flight programs, and provide an investigation into the history of some well-known EMI system failures and anomalies in military and commercial electronic systems. Military and commercial systems are included due to the limited number of in-flight spacecraft failures and anomalies attributed to EMI that have occurred on National Aeronautics and Space Administration (NASA) programs. The inclusion of nonspace systems also helps to illustrate that evolving electronic systems are increasingly sensitive to EMI and NASA personnel must continue to be diligent in the pursuit of EMC on space flight systems.

NASA in-flight and preflight case histories, aircraft, ship and automobile case histories, and medical and commercial electronic equipment case histories are included. Several are unpublished anecdotes by NASA or contractor personnel involved in a particular project or program. Known in-flight anomaly cases are from published accounts of problems in NASA reports and data bases. Published data on aircraft and ship cases are not readily obtainable because it was often difficult to identify the cause of system upsets. In cases involving commercial incidents, manufacturers and service providers were often reluctant to discuss or publish issues that affect liability or the "bottom line."[1] Although for security reasons documented case histories concerning military aircraft are usually unavailable, several published anomalies are included despite filtered details.

Numerous case histories exist of spacecraft failures or anomalies attributed to EMI from spacecraft charging. This phenomenon, which occurs when an orbiting spacecraft accumulates electric charge from the natural space plasma, is not included in this report. A separate, similar report is in process to document failures and anomalies caused by spacecraft charging.

An electromagnetic incompatibility occurs when a system or equipment interferes with another system or equipment. When this interaction is traced to the transfer of electromagnetic energy from the culprit to the victim, it is termed EMI. EMC denotes the electromagnetically compatible, simultaneous operation of systems and equipment.

EMC, also defined as the absence of EMI, is an important element in the success of the NASA space flight programs. This report highlights the NASA EMC participation in past space program successes and its critical role in future activities.

Computer Science Corporation developed this report for MSFC Electromagnetics and Environments Branch, Mail Code EL54. Hopefully a better understanding of these failures and anomalies and associated causes will enable NASA engineers and program managers to more effectively minimize program risks and costs, optimize design quality, and successfully achieve mission objectives.

2.0 HISTORY

The NASA track record of EMI problems on operational spacecraft is a good one. Research of spacecraft anomalies attributed to EMI shows limited occurrences of in-flight anomalies.[2 3] The primary reason for this success is that NASA EMC personnel recognized potential problems during design and testing and used "lessons learned" to maximum advantage.

Application of EMI theory started during World War II when knowledge of the nature of EMI was used in the design and construction of wiring harnesses on military aircraft to prevent problems due to radiated emissions.[4] Another application was maintaining electromagnetic compatibility of onboard radar systems with other electrical flight systems. Since then, even though electrical/electronic systems continued to become more complex and more susceptible to EMI, the problem faced by EMC personnel remained one of essentially recognizing, detecting, and controlling the existence and location of culprit and victim systems, instead of EMI suppression techniques which have changed little over the last 50 years. Applications and technologies that comprise suppression techniques, however, have changed greatly.

2.1 NASA Preflight Case Histories

From the beginning space flight programs, NASA EMC personnel drew on previous military experience to evaluate and design for EMC. This contributed not only to successful designs but also to solid preflight testing and checkout procedures. Preflight activities uncovered many potential problems before they became in-flight anomalies or failures. These "lessons learned" established the building blocks for a solid EMC foundation. Numerous anomalies detected during preflight activities that contributed to the NASA experience base are described in the following.

2.1.1 Saturn Beat Frequency Case

During on-pad checkout at the Kennedy Space Center (KSC) prior to one of the early developmental test flights of the Saturn launch vehicle, the range safety receivers detected an extraneous signal. Because these receivers processed commands for engine cutoff, arm, and destruct, a thorough investigation was conducted to determine the cause of this unintended signal transmission. The problem appeared to be the production of spurious signals originating from the sum and difference combinations possible when signals frequencies are mixed. Although technically these spurious signals are not beat frequencies (associated with sound energy), this particular case is known within NASA as the beat frequency case and is maintained in this report by that title. The spurious signals were caused by the multitude of transmitters located on board to collect test data. Analysis determined that spurious signal frequencies very near the frequency of the range safety receivers were produced by a combination of frequencies from several telemetry transmitters in combination with one of the vehicle's tracking transponders. Further investigation determined that mixing sources for the signals were the hinged cable tray covers and chain handrails on the gantry. This insight and analysis proved to be useful later. With a Saturn vehicle on pad, the range safety receivers detected a spurious command signal for engine cutoff from a Titan launch vehicle checkout on the next pad. The Titan was using the same modulation frequencies on a different carrier frequency for its range safety receivers. A signal sent to the Titan vehicle was also received by the tracking transponder on the Saturn vehicle. The retransmitted signal of the transponder was mixed with certain telemetry signals resulting in the false engine cutoff command. After this incident, the decision was made to fly with the culprit transponder inactive (eventually it was removed from the vehicle). Later, both

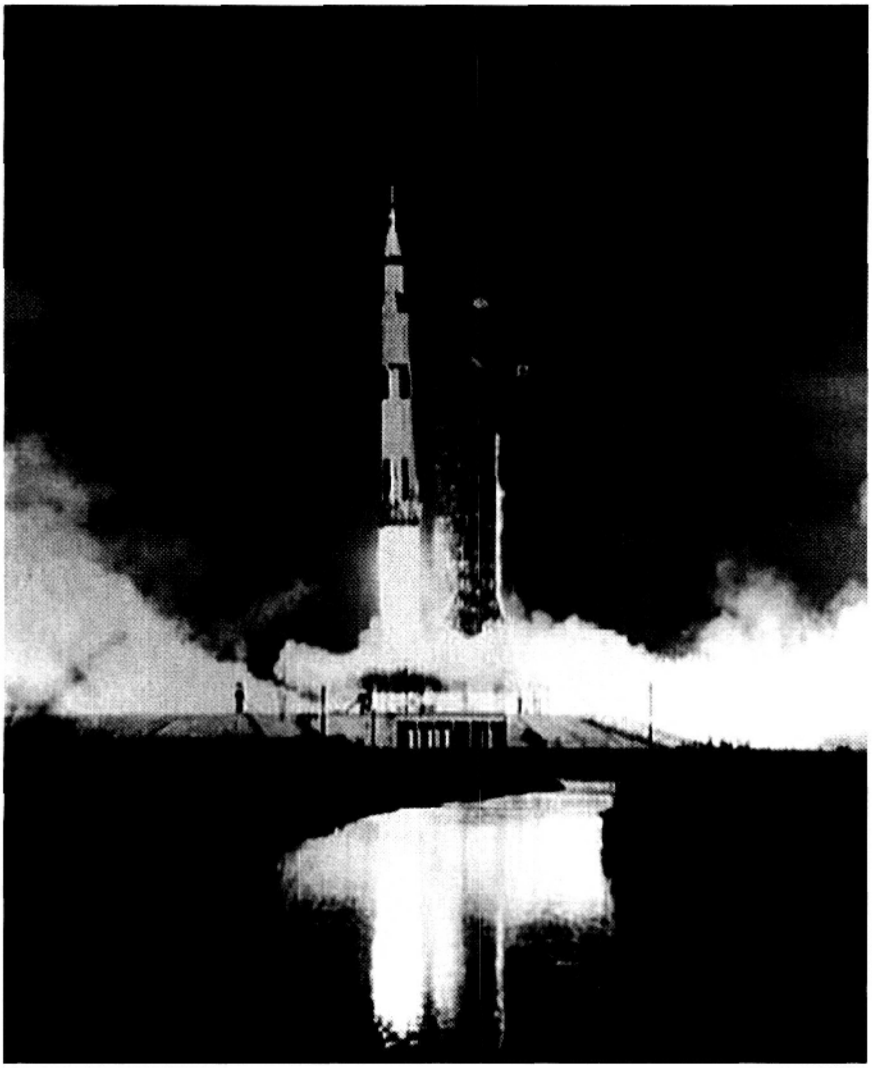

Figure 1. Saturn V launch.

telemetry and range safety transmissions were moved to a higher frequency range where the production of spurious signals did not interfere with the range safety system.[5]

2.1.2 Range Safety Interference

In another incident related to the range safety system on a Saturn vehicle, the range safety receivers detected a low-level signal from somewhere in the KSC vicinity. This signal was not always present. The possibility of signal mixing, detailed in the previous case, was considered and all radio stations and mobile transmitters in the area were investigated—no spurious signals detected. KSC and MSFC EMC personnel worked all one night trying to solve the problem. At one point soon after the signal suddenly stopped, one of the MSFC EMC personnel stepped outside the small trailer used to house test equipment, noticed daybreak had occurred and searchlights surrounding the vehicle had turned off. On his request, they were turned on again and the unwanted signal reappeared. Further investigation revealed the searchlights were carbon arc lamps that produced a broadband radio frequency (RF) signal and the lamp reflectors beamed the signal directly to the range safety antennas on the vehicle.[5]

2.1.3 *Skylab* Shielding

During checkout of the *Skylab* Apollo telescope mount, an EMC test was conducted that illuminated the entire *Skylab* with various *Skylab* transmitter frequencies. This test revealed the telemetry and measuring systems lacked proper shielding. The undetected deficiency would result in degraded or useless data transmission to scientists on the ground.[5]

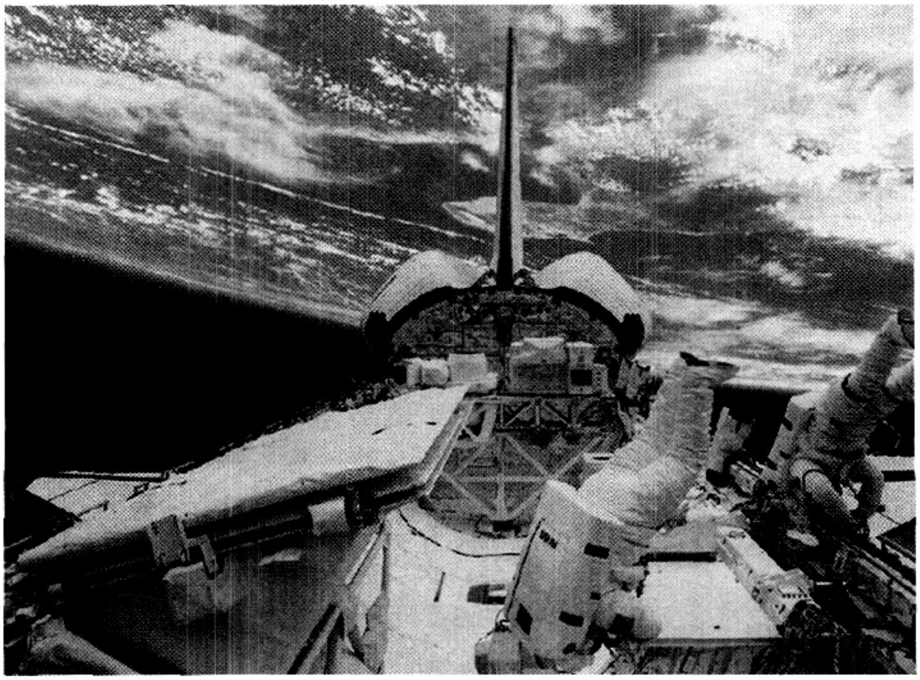

Figure 2. Shuttle payload bay.

2.1.4 RAU Transient Susceptibility

The remote acquisition units (RAU's) are data transmission interfaces between Shuttle *Spacelab* payload experiments and experiment controllers on the ground. An RAU is designed to shutdown if its voltage drops below a certain level for a certain time period. During checkout of *Spacelab* payloads at KSC, RAU's experienced numerous shutdowns when various items of equipment were turned on or off. MSFC EMC personnel were called to conduct a problem investigation that determined the test setup used for preflight tests of *Spacelab* payloads did not accurately simulate fuel cell capacitance and line impedance. A representative capacitance was used in the proper location, power-up problems ceased, and testing proceeded unhindered. Solving this problem produced a valuable understanding of susceptibility of RAU's to transient signals. Another result of this investigation was the formulation of an EMI test requirement to insure that RAU's do not fail due to operation of experimental equipment.[5]

2.1.5 Frog Embryology Experiment (FEE)

The FEE was part of the *Spacelab* (SL–J) mission flown on STS–47 launched September 12, 1992. Prior to the flight, EMC data indicated that a potential problem existed with turnon transients that could cause an RAU problem. MSFC EMC personnel developed an incremental startup procedure to apply during preflight testing. Data from this procedure determined a potential problem still existed. A second startup procedure was implemented that indicated no in-orbit problems were likely to occur. No in-flight anomalies were reported.[6]

2.1.6 Aquatic Animal Experiment Unit (AAEU) Experiment

The AAEU was part of the International Microgravity Laboratory (IML–2) mission flown on STS–65 launched July 8, 1994. Prior to launch, MSFC EMC personnel discovered that the experiment might produce turnon transients detrimental not only to AAEU but also to other mission experiments. Recognition of this potential problem prompted the launch team to alter KSC integrated configuration test (ICT) and assembly procedures to allow detection of possible anomalies. It was determined that no problems were likely to occur in orbit, and none were reported.[7]

2.1.7 Spinal Changes in Microgravity (SCM) Experiment

The SCM, part of the IML–2 mission, flew aboard STS–65. SCM personnel experienced an alternating current (ac) interference problem in the lab, worried it might occur during flight, and requested a check at KSC ICT. MSFC EMC personnel developed a worst-case test procedure and found that a portable fluorescent light was causing the EMI. Payload operating procedures were modified to eliminate the potential EMI problem. No in-flight anomalies were reported.[7]

2.1.8 Linear Compressor Enhanced Orbiter Refrigerator Freezer (LCEORF)

The LCEORF was part of the IML–2 mission flown aboard STS–65. During preflight EMI testing of the LCEORF, it failed to meet the NSTS requirement for peak-to-peak voltage. There was also the possibility that its operation could interfere with other experiments utilizing the same power bus. Extensive current and voltage variation testing was conducted, with the conclusion that operation of the LCEORF would not be a problem on the mission. It was recommended, however, that a redesign be made prior to subsequent missions. No in-flight anomalies were reported.[7]

2.2 NASA In-Flight Case Histories

Most potential problems were identified and corrected during the developmental process as evidenced by the very limited number of documented in-flight anomalies.

2.2.1 *Spacelab* Payload General Support Computer (PGSC)

EMI occurred during the STS–47 flight when the *Spacelab* intercom operated in the vicinity of the PGSC. EMC personnel predicted that EMI problems would occur with the PGSC (it was commercial off-the-shelf (COTS)) affecting other equipment operating over a wide range of frequencies. The lesson learned suggested that EMI performance of COTS hardware should be reviewed for EMI prior to purchase.[8]

2.2.2 Wake Shield Experiment

The wake shield was an experiment, towed behind STS–60, launched February 3, 1994, to create a better quality vacuum than was available within the orbiter. Failure occurred because the small satellite used in the experiment could not be deployed due to EMI with its attitude control system. The EMI was caused by inductive coupling (crosstalk) between the unshielded attitude control sensor cable and the power bus of the spacecraft. The control systems cable was redesigned and shielding added. This was an unpleasant lesson learned at the cost of a failed experiment.[8]

2.2.3 Vacuum Cleaner Incident

During a *Spacelab* mission in 1985, the crew decided to use the middeck vacuum cleaner instead of the one in the lab. Switching the middeck vacuum on caused the voltage to drop and the RAU to shut off. In preflight EMI tests, the vacuum cleaner had not been tested and should not have been used in the lab. This case shows how careful and attentive one must be when dealing with EMC.[5]

2.2.4 Gamma Ray Observatory (GRO) Transponder Problems

This NASA satellite experiment, launched from STS–37 on April 7, 1991, experienced a transponder lockup that prevented the spacecraft from receiving command signals. EMI from a ground source, in combination with a design problem, was the lockup cause. A work-around method was devised to unlock the transponder when EMI occurred. The satellite experienced a 13-h loss of communications in June 1991 and a 13$^1/_2$-h loss in August of that same year; both losses were due to transponder lockup.[9]

2.2.5 NOAA–11 Phantom Commands

NOAA–11 is a weather satellite launched September 24, 1988, and operated by NASA for the National Oceanographic and Atmospheric Administration (NOAA). In September 1991, a series of phantom commands were observed and determined to be caused by EMI due to a noisy very high frequency (VHF) environment.[9]

2.2.6 NOAA–12 Problems With the VHF Environment

The NOAA–12 weather satellite was launched May 14, 1991. In September 1991, it experienced phantom commands when it flew over Europe. Controllers determined the commands were due to susceptibility of the satellite to the heavy commercial VHF environment over Europe. The phantom commands were countermanded from the ground without serious consequences.[9]

2.2.7 Extreme Ultraviolet Explorer (EUVE) Data Loss

The EUVE was launched June 7, 1992. In October and November of that year, EMI caused data loss in satellite transmissions to Earth.[10]

This short list of documented in-flight EMI cases reflects the diligent effort in design, procedures, standards, and preflight testing for EMC. Considering the complexity and scale of electrical and electronics systems in spacecraft and payloads, it makes that effort most impressive. To rest on past laurels, however, is not prudent or possible because electrical and electronics systems continue to evolve rapidly.

The seemingly continuous stream of technological advances in electronics has important future implications for EMC in regard to spacecraft and spacecraft payloads. The effects of electromagnetic interactions in electrical/electronics systems are of evergrowing concern because of the increasing susceptibility of system components to EMI, use of automated electronic systems, and pollution of the EME with electromagnetic emissions.[11] All these have significant impact on state-of the-art electronic systems, through increased sensitivity to EMI. EMI problems are prevalent enough that on December 1, 1994, CBS's investigative reporting TV program "Eye-to-Eye" presented a segment on EMI problems with aircraft, automobiles, and medical equipment.

2.3 Non-NASA Case Histories

Because of the limited number of in-flight spacecraft failures and anomalies on NASA programs attributed to nonspacecraft charging EMI, 17 documented cases for military and commercial aircraft, ships, automobiles, and medical equipment are included in this report. As advanced electronics systems migrate their way into spacecraft and spacecraft payload systems, these cases indicate the potential EMC problems that future space programs must deal with.

2.3.1 Aircraft/Ship/Automobile Cases

2.3.1.1 U.S.S. *Forrestal*

In 1967 off the coast of Vietnam, a Navy jet landing on the aircraft carrier U.S.S. *Forrestal* experienced the uncommanded release of munitions that struck a fully armed and fueled fighter on deck (fig. 3). The results were explosions, the deaths of 134 sailors, and severe damage to the carrier and aircraft. This accident was caused by the landing aircraft being illuminated by carrier-based radar, and the resulting EMI sent an unwanted signal to the weapons system. Investigations showed that degraded shield termination on the aircraft allowed the radar frequency to interfere with routine operations. As a result of this case, system level EMC requirements were revised to include special considerations for electroexplosive devices.[12]

Figure 3. Aftermath of U.S.S. *Forrestal* EMI incident.

2.3.1.2 Power Down Case

An anecdote was related to the author concerning a U.S. Navy vessel on shakedown maneuvers. While underway at full power, suddenly and unexpectedly a power shutdown occurred. It was determined that high frequency (HF) transmissions caused an oil pressure sensor to falsely sense a low reading. Before engineers could intervene, the false signal caused a shutdown signal in the automated power control system.[13]

2.3.1.3 PIONEER Remotely Piloted Vehicle (RPV)

PIONEER was an RPV with nondevelopmental item (NDI) status. It was essentially a nonmilitary specification item that relied on COTS hardware. Because of this, the Navy anticipated EMI problems during a test flight in January 1987 aboard the U.S.S. *Iowa.* The RPV pilot, using a portable remote control box, experienced a series of uncommanded control transfers between his remote control box and another used by a student pilot. These uncommanded signals caused loss of control and a crash landing. There were also instances during other RPV flights of anomalous signals and switching. Subsequent investigation found that the remote control boxes received EMI from HF communication transmitting antennas located aboard the *Iowa* that coupled into the box due to inadequate shielding and cable termination. Utilizing improved cables and cable connectors, proper shielding, filters, and internal logic changes corrected the problem. The HF signal caused other problems with the RPV internal systems, but eventual modifications also corrected these. Generally, use of COTS hardware makes the hardening of electronics necessary to protect them from the very harsh EME found aboard Navy vessels.[14]

2.3.1.4 H.M.S. *Sheffield* Catastrophe

During the Falklands War, the British Ship H.M.S. *Sheffield* sank with heavy casualties after being hit by an Exocet missile. Despite the *Sheffield* having the most sophisticated antimissile defense system available, the system created electromagnetic interference to radio communications to and among the contingent of *Harrier* jets assigned to the ship. While the *Harrier*s took off and landed, the missile defense was disengaged to allow communications with the jets and provided a window of opportunity for the Exocet missile.[12]

2.3.1.5 B–52 Stability Case

When op-amp-based flight control systems were first added to the B–52 bomber autopilot stability augmentation system, use of the HF radio resulted in the uncommanded activation of all rear empennage flight control surfaces. The wiring system, which had not been changed, was found to be susceptible to HF. This was a case of using new (at that time) technology and introducing a potentially dangerous problem that had not existed before using the new technology.[8]

2.3.1.6 B–52 Missile Interface Unit

During a B–52 missile interface unit test, an uncommanded missile launch signal was given. One of the contributing factors was crosstalk in the systems wiring. Another factor was not adhering to the EMC control plan requirements. The outcome was a year-long redesign and test effort.[8]

2.3.1.7 UH–60 *Blackhawk* Case

An Army Sikorsky UH–60 *Blackhawk* helicopter, while flying past a radio broadcast tower in West Germany in 1987, experienced an uncommanded stabilator movement. Spurious warning light indications and false cockpit warnings were also reported. Subsequent investigation and testing showed that the stabilator system was affected by EMI from high intensity radiated fields (HIRF). The *Blackhawk* has a conventional mechanically linked flight control system with hydraulic assist. The stabilator system, however, uses transmitted digital signals (fly-by-wire) to automatically adjust its position relative to control and flight parameters. These digital signals are highly susceptible to HIRF. When the *Blackhawk* was initially designed, the Army did not routinely fly near large RF emitters. The Navy version of the *Blackhawk*, the SB–60 *Seahawk*, however, has not experienced similar EMI problems because it is hardened against the severe EME aboard modern ships. Despite the Army identifing several hundred worldwide emitters that could cause problems and instructing its pilots to observe proper clearance distances, between 1981 and 1987 five *Blackhawk* helicopters crashed and killed or injured all on board. In each crash, the helicopter flew too near radio transmitters. The long-term solution was to increase shielding of sensitive electronics and provide as a backup some automatic control resets.[15] [16]

2.3.1.8 AH–64 *Apache* Helicopter

The *Apache* helicopter (fig. 4) was designed primarily as an airborne antitank weapon to provide quick-strike capability against tanks and armored vehicles. The *Apache* is essentially an electronic device with multiple electric and electronic systems that control navigating and fighting abilities. During early missions, pilots complained that HIRF signals interfered with electronics. In one case, EMI triggered an overspeed condition that could have resulted in double engine failure. Subsequent reports showed that the aircraft was susceptible to low-level emitters such as commercial microwave, television, and airport and missile radar. At one point, the Army concluded that the *Apache* should not be used on aircraft carriers. After determining that the source of unwanted signals was coupling in the I/O cables, the shielding was redesigned; but not before many costly aircraft were built with EMI deficiencies.[12]

Figure 4. AH–64 *Apache* attack helicopter.

2.3.1.9 F–117A Targeting Lockon

During development of the F–117A fighter, EMI problems occurred in the targeting lockon system. Use of poor shielding techniques and old hardware designs caused these problems, which after considerable testing and redesign were ultimately solved.[17]

2.3.1.10 F–16 Flight Controls

An F–16 fighter jet crashed in the vicinity of a Voice of America (VOA) radio transmitter because its fly-by-wire flight control system was susceptible to the HIRF transmitted. Since the F–16 is inherently unstable, the pilot must rely on the flight computer to fly the aircraft. Subsequently, many of the F–16's were modified to prevent this type EMI, caused by inadequate military specifications on that particular electronics system. This F–16 case history was one of the drivers for institution by the Federal Aviation Administration (FAA) of the HIRF certification program.[8]

2.3.1.11 Blimp Problems

Another VOF transmitter case involved a blimp over Greenville, NC. Flying near the VOA transmitter, the blimp suddenly had double engine failure. The flight crew followed emergency procedures and made a successful unpowered landing. An investigation determined that the failure of the ignition system was extreme EMI. Subsequent to this event, blimps were outfitted with ignition systems protected from HF transmissions.[1]

2.3.1.12 Boeing *747* Automatic Direction Finder (ADF)

A Boeing employee related this incident. During testing, audio reception on the Boeing *747* communications receivers was unacceptable while the ADF system was in use. Investigation showed that wire-to-wire coupling was the problem because the ADF antenna lead was not separated far enough from other wiring.[8]

2.3.1.13 Severmorsk Disaster

In mid-May 1984, a Soviet ammunition depot exploded. The cause of the accident, according to the Soviets, was an over-the-horizon radar that had illuminated the depot.[16]

2.3.2.14 *Tornado* Fighter Case

Another VOA HIRF case occurred in 1984 near Munich, Germany. A West German *Tornado* fighter crashed after flying too close to a powerful VOA transmitter.[16]

2.3.1.15 Libyan Strike

In 1986 during the US air strike on Libya, several missiles failed to strike designated targets and an F–111 fighter crashed. Air Force officials blamed these incidents on EMI caused by U.S. aircraft transmissions interfering with each other.[16]

2.3.1.16 Antilock Braking System (ABS) Failure

Early ABS systems on both aircraft and automobiles were susceptible to EMI. Accidents occurred when the brakes functioned improperly because EMI disrupted the ABS control system.

For aircraft, the initial solution was to provide a manual switch to lock out the ABS function when it was inoperable due to EMI and to use the normal braking system. Later, the solution was to qualify prior to flight the ABS system based on the expected EME. For automobile systems, the solution was to ensure, if EMI occurs, that the ABS system degrade gracefully to normal braking—essentially an automatic version of the aircraft manual switch. Eventually, automobile ABS was qualified by EMI testing prior to procurement.[8]

2.3.1.17 Mercedes-Benz Case

During the early years of ABS's, Mercedes-Benz automobiles equipped with ABS had severe braking problems along a certain stretch of the German autobahn. The brakes where affected by a near-by radio transmitter as drivers applied them on the curved section of highway. The near-term solution was to erect a mesh screen along the roadway to attenuate the EMI. This enabled the brakes to function properly when drivers applied them.

2.3.2 Aircraft Passenger Carry-On Devices Cases

Passenger carry-on devices provide another group of case histories. They show the increased susceptibility to external EMI sources that modern automated electronic systems aboard aircraft experience. This external EMI is generated by seemingly innocuous electronic devices, which include portable computers, AM-FM "walkman" cassette players, dictaphones, radios, heart monitors, and cellular phones.

NASA maintains a data base, known as the FAA Aviation Safety Reporting System (ASRS) and administered by Battelle, which is a compilation of voluntary reports detailing safety problems submitted by pilots or crew members flying a wide variety of commercial and private aircraft. These reports are, for the most part, anonymous with nonspecific aircraft models and unidentified operating companies. At present, the data base contains 46,798 full-form reports submitted since January 1, 1986. This author requested an ASRS data base to find all cases that referenced passenger carryon electronic devices.[18] The results were 56 citations, of which 29 appear definitely to be EMI caused anomalies. Twelve other cases could be EMI related, but additional information is required to make this determination. Table 1 contains a tabulation of the 29 EMI events by affected equipment and suspected cause.

Table 1. Pilot/crew reports of EMI caused by passenger carryon devices.

	Victim Equipment			
Suspected Cause	Navigation Aids	Communications	VOR	Totals
Cellular Phone	4	1	3	8
Laptop Computer	3	0	2	5
Radio	3	1	0	4
Electronic Game	1	0	2	3
CD Player	0	1	1	2
Tape Player	2	0	0	2
AM-FM Recorder	0	0	1	1
AM-FM Walkman	0	0	1	1
Dictaphone	0	0	1	1
Heart Monitor	0	1	0	2
Television	1	0	0	1
Totals	14	4	11	29

Apparently, operational frequencies of cellular phones, computers, radios, and electronic games are often EMI culprit sources. Many airlines have established rules forbidding or limiting the use of these devices. A special report by the Radio Technical Commission for Aeronautics (RTCA) concluded that a culprit carryon device has to operate at a frequency that falls within the operating frequency of a particular aircraft system, and that the device probably has to be oriented with its maximum radiation directed out a nearby window for navigation and communication antennas to pick up the emitted radiation.[19] A particularly interesting case from the ASRS search was one whereby the pilot of a large aircraft actually performed an experiment with a passenger and his laptop computer. The pilot asked the passenger to switch the computer on and off for varying time intervals while he monitored the effect on the aircraft VOR. The pilot reported it was very evident that the computer affected his flight instruments.

One well-known EMI case is not included in the ASRS data base. In February, 1993, a DC–10 autopilot was disrupted during final landing approach by a battery-powered CD player operated by a passenger in first-class. To prevent the aircraft from crashing after suddenly veering off course, the pilot had to manually take control of the aircraft.

2.3.3 Medical Equipment Cases

Modern medical equipment have experienced EMI problems. From 1979 to 1993, the FDA received over 90 reports concerning EMI problems in the field.[20] These reports are shown in table 2 by EMI categories defined by the Food and Drug Administration (FDA) and by equipment type. Silverberg pointed out in his article that users experiencing medical equipment performance degradation may not suspect EMI as a possible cause. Thus, EMI problems are more likely to be under reported to the FDA than other equipment problems.

Table 2. Cross tabulation of FDA medical device EMI problem reports.

Conducted Interference	No.	Radiated Interference	No.	Magnetic Interference	No.	ESD	No.	
Bloodcell Counter	1	Fetal Heartbeat Monitor	2	Respirator (1D)	2	Respirator	2	
Blood Warner	1	Blood Pressure Monitor	2	Iefibrillator	1	Ventilator	2	
Cardiac Monitor	5	Infusion Pump	2	Pacemaker	1	Infusion Pumps	2	
Defibrillator	2	Pacemaker (1D)*	9	MRI Machine	1	Apnea Monitors	1	
Ventilator (1D)	2	Vascular Recorder	1	Pulse Oximeter	1	Radiation Therapy Unit	1	
UV Phototherapy Unit	2	Cardiac Monitor (3D)	8			Feeding Pump	1	
Infant Incubators	1	Defibrillator	2			Radiant Warmer	1	
Infusion Device	2	Ventilator	8					
Intra-aortic Balloon Pump	1	Neo-natal Monitor	1					
Laparoscopy System	1	Chiropractic Table	1					
Radiation Therapy Device	1	Nerve Simulator	1					
Physiological Monitor	1	Pulse Oximeter	1					
Oxygen Monitor	1	Microsurgical Drill	1					
		Radiant Warmer	1					
		Laparoscopy System	1					
		Heater/Humidifier	1					
		Blood Warmer	1					
		Telemetry Monitors	1					
		Gas Monitor	1					
		Apnea Monitor	2					
		Blood Pressure Monitor	1					
		Ultrasound Scanner	1					
		Hearing Aid	1					
		Audiometer	1					
		Incubator	1					
		Wheelchairs	3					
Totals	20		55		6		10	91

*(#D) = number of deaths.

Table 2 shows that six deaths occurred due to EMI with medical equipment.

It is interesting to note that FDA data, like FAA aircraft data, indicate that cellular phones are frequent EMI culprit devices. They have interfered with the operation of incubators, infusion pumps and controllers, dialysis equipment, and defibrillators as well as with aircraft systems. A large hospital in Chicago and a large healthcare center in Indiana have banned the use of cellular phones.[21] These phones are also banned in some European hospitals.[20] Cellular phones that use the new European GSM standard have been reported to produce audible interference in hearing aids up to a distance of 30 m.

Details of several interesting cases concerning medical equipment are given in the following.

2.3.3.1 Talking EEG Machine

This case involved EMI that prevented proper testing of surgically implanted probes used in monitoring specific portions of a patient's brain activity. With probes in direct brain contact, the potential between any two points is measured on an EEG machine. The EEG provides critical feedback to the surgeon during surgery. This particular EMI manifested itself on the analog plotting needles of the EEG machine as a modulated signal easily recognized as speech—hence a talking EEG machine! The EMI-caused noise was so severe that it completely masked the EEG signals and made the machine alarmingly ineffectual during surgery. The signal was from a local AM radio station, and the noise during surgery was from common impedance coupling between the EEG machine and the operating table. Bonding the EEG with the operating table eliminated the EMI and restored the critical brain monitoring function.[22]

2.3.3.2 Ambulance Heart Monitor/Defibrillator

Susceptibility of medical equipment to conducted or radiated emission is a concern. In this case, a 93-year-old heart attack victim was being taken to the hospital and the medical technician had attached a monitor/defibrillator to the patient. Because the machine shut down every time the technicians turned on the radio transmitter to request medical advice, the patient died. An investigation showed that the monitor/defibrillator was exposed to exceptionally high radiated emissions because the ambulance roof had been changed from metal to fiberglass and fitted with a long-range radio antenna. Reduced shielding combined with the strong radiated radio signal resulted in EMI to the vital machine.[21]

2.3.3.3 Runaway Wheelchairs

Wheelchairs came under the scrutiny of the FDA (fig. 5) because of reported erratic, unintentional powered-wheelchair movements. These movements included sudden starts that caused wheelchairs to drive off curbs or piers when police, fire, or CB transmitters were activated near the chairs. Although no fatal injuries have been reported, FDA has ordered manufacturers of motorized wheelchairs to shield them from EMI and to educate users on the potential EMI hazards.[21]

Figure 5. Testing a wheelchair for EMI.

2.3.3.4 Apnea Monitor Case

A physician at a major university hospital reported that apnea monitors would not work in some surrounding neighborhoods. Prolonged sleep apnea (cessation of breathing) is detrimental to adults and can be fatal to infants. Other reports of monitor failures prompted the FDA to conduct tests. The conclusion that low levels of EMI detected by commercial apnea monitors could erroneously indicate respiration prompted a recall of those particular monitors.[20]

2.4 Summary Comments

A careful review of the cases outlined in this section reinforces the important role EMC activities have played in NASA space programs and will play in the future. The important points are the following:

(1) NASA EMC personnel have done a creditable job applying EMC techniques and principles and utilizing past experience to prevent serious in-flight anomalies caused by EMI.

(2) The extreme importance of having up-to-date EMC guidelines, standards, and test procedures is established.

(3) Constant and diligent attention must be paid to the EMC of spacecraft systems by assuming that every new system is different, and past assumptions on susceptibility to EMI should be carefully reconsidered and thoroughly retested.

(4) Any spacecraft anomaly caused by EMI is serious. Although an anomaly by itself might appear trivial, it in combination with a certain series of events may cause irreparable damage to a space mission or experiment.

(5) HIRF can have serious effects on advanced electronic systems. The consequences of EMI on automated electronic systems used for critical functions are increasingly serious.

(6) Use of COTS hardware potentially increases EMI risks.

(7) Everyone working with advanced electrical or electronic systems must be aware of the potential consequences of EMI.

If the old adage "you learn from history to apply to the future" holds true, then NASA EMC personnel have built a solid EMC foundation to face a future fraught with new trends to impact EMC activities. Before discussing in section 4 the exact nature of these trends, section 3 details the present activities of the MSFC Electromagnetics and Environments Branch in EMC.

3.0 PRESENT

Understanding the failures and anomalies reported in these and other case histories will enable NASA engineers and program managers to minimize program risks and costs and to optimize design quality. The MSFC Electromagnetics and Environments Branch actively pursues development of new techniques and processes to deal with current and future programs and technologies.

Recently Electromagnetics and Environments Branch personnel developed the MSFC Electromagnetic Compatibility Design and Interference Control (MEDIC) handbook. This handbook provides practical and helpful EMC information for the designers and manufacturers of electrical systems and subsystems. An introduction to EMC, an overview of typical NASA EMI test requirements, and examples of associated test setups are provided in the handbook. Design techniques to minimize the risks of EMI, compliance techniques, and retrofit fixes for noncompliant equipment are also included.

Electromagnetics and Environments Branch personnel are currently engaged in the development, validation, and utilization of the Integrated Space Station Electromagnetic Compatibility Analysis System (ISEAS) computer model. This model calculates system-level EMC margins using equipment-level EMI test data and pertinent engineering parameters. ISEAS analyzes EMI trends and predicts EMC levels for all systems and subsystems aboard the International Space Station *Alpha* (ISSA) and numerous other NASA projects. Using ISEAS will enable EMC personnel to quickly and accurately make technical decisions.

4.0 FUTURE

Current state-of-the-art electronic systems in military and commercial aircraft and in medical equipment provide a preview of future spacecraft and payload electronics. The case histories in this report reveal the challenges EMC personnel faced as more complex electronic systems are incorporated into various programs. An examination of three major trends that state-of-the-art electronics are now experiencing provides an indication of the nature of these future challenges. Three major trends are:

(1) Increasing susceptibility of electronic systems to EMI

(2) Increasing use of automated electronic systems in aircraft

(3) Increasing pollution of the EME.

4.1 Increasing Susceptibility of Electronic Systems to EMI

Electronic systems susceptibility to EMI is increasing because of the increasing use of low voltage or current electronic components, the increasing densities of electronics used in systems, and the increasing use of COTS hardware and composite materials.

To reduce power requirements, integrated circuits chips are designed with transistors that require less voltage or current to initiate a change of state. Thus, less magnetic energy is required to initiate an upset in the chips circuitry. This results in an electronic component that is more sensitive (susceptible) to EMI.

Increasing densities of state-of-the-art electronics in systems have increased susceptibility to EMI. In the past, integrated circuit chips were designed with more circuits and with logic gates in smaller areas. Now state-of-the-art electronics place on a chip not only basic circuit elements but also complete subsystems and systems. Examples of system-on-a-chip are monolithic and millimeter-wave monolithic integrated circuits (MMIC). MMIC chips contain many communications related components in a very small area; a chip one-tenth of an inch square contains all the functions previously located on a 5- by 8-inch circuit board.[23] MMIC's, developed and supported by the Department of Defense, are becoming more attractive to the space industry because of substantial weight and space savings. Although EMI considerations for chips are the designer's responsibility, the user must be cognizant of the fact that many systems-on-a-chip are packed closer together. EMC between chips may pose problems now beyond the chip designer's responsibility.

Another example of system-on-a-chip is the new generation of multichip modules (MCM). They, like MMIC's, are being advocated by the military because MCM's allow the high density packaging of mixed analog, digital, and microwave devices. They are soon expected to be used in commercial applications and space vehicles. Rhorbaugh[24] indicates that a wide range of potential EMI problems exits in MCM's in susceptibility to high levels of EMI, crosstalk, and radiated emissions. He states that MCM's must be treated as entire systems and EMI treated on the system level using system-wide design rules. Although MCM designers must deal with these considerations, MCM's will probably be packed together. Thus, EMC personnel must be prepared to determine what EMC specifications must be met for checkout and preflight testing. In fact, the MEDIC handbook discussed in section 3 is evidence that EMC personnel are already involved with in-box design.

Because systems and subsystems are now able to be packed so closely together, any EMI, especially pulses, increases the risk that an entire subsystem or system (not just a component, gate or circuit segment) will be affected. Thus, the impact of any EMI event becomes potentially more serious to a mission or payload.

As the PGSC and Pioneer cases in section 2 illustrated, COTS hardware can also contribute to EMC problems. If the trend to require using more COTS hardware is adopted by the space industry, EMC personnel will have to be especially diligent to see that this hardware, especially in the field, meets EMC standards.

Increased use of composite materials has spread from military aircraft to commercial aircraft.[24] Because of the weight savings they afford, composite structures are desirable in aircraft and spacecraft, however, increased use of composite materials decreases the EMI shielding provided by metal structures and possibly increases susceptibility to ambient radiation. Research at MSFC into implications of composite materials to EMC in spacecraft systems is in the planning stages. Current susceptibility protection methods tend to offset the advantages of composite materials by adding weight and cost. Researchers anticipate investigating the electrical and electromagnetic properties, conductive coatings, and bonding techniques of various conductive materials to find more cost-and-weight efficient methods of providing susceptibility protection. EMC personnel will be required to draft and evaluate new EMC specifications and procedures as composite materials enter spacecraft and payload systems.

4.2 Increasing Use of Automated Electronic Systems in Aircraft

Military and commercial aircraft operations are increasing the use of digital electronics to provide automated systems such as engine controls, flight surface controls, cockpit displays, sensor data (i.e., military targeting, early warning, countermeasures, flight environment), communications, and navigation. This trend increases EMI susceptibility in several ways. First, additional onboard electronic systems, whether analog or digital, increase the possibility of EMI. Secondly, digital systems by their nature present the increased possibility of radiating electromagnetic energy at high frequencies that can affect neighboring systems, especially analog systems such as radios. Third, automated digital systems have not only replaced critical mechanical, hydraulic, or analog systems, but also the human interface. As illustrated in section 2 in the *Forrestal*, power down, B–52, *Blackhawk*, *Apache*, and F–16 cases, EMI susceptibility has become a mission-critical concern, as well as a human safety one.

Even advanced systems using optical fibers, primarily to eliminate potential EMI problems, must be carefully checked and tested for EMI. Fiber-optic systems proved to be susceptible to HIRF EMI because of the existence of poor interconnections within the fiber system.[25]

4.3 Increasing Pollution of the Electromagnetic Environment

The third major trend is the increasing pollution of the electromagnetic environment (EME). Radio, TV, microwave, aircraft power systems, aircraft and automobile electronics, lightning, electronic warfare systems, cellular phones, personnel communication systems, direct broadcasting systems, and remote sensing systems (radar surveillance of space by world-wide military and scientific satellite systems) all contribute to this pollution. The EME also includes the near-Earth environment of operating spacecraft. As the GRO and NOAA–12 cases in section 2 showed, the effects are already being felt and will become more severe as the world continues to advance into the information age. Thus, EMC personnel must continue to diligently assess the potential impacts the ever-increasing global pollution of the electromagnetic environment has on electronic systems.

5.0 SUMMARY

Hopefully, through the use of illustrative EMI anomaly case histories, this report has given not only insight into the contribution that the NASA EMC activities have made in space programs but also a glimpse into the nature of future problems. These case histories suggest that in-flight electronic systems used in spacecraft and their experiments will become more susceptible to EMI. This is due not only to the sensitivity of the electronics, but also to the increasing reliance on electronics to operate and control critical spacecraft systems in an increasingly hostile EME. They also suggest the importance of up-to-date EMC guidelines, standards, and test procedures, and of constant attention given to EMC considerations during spacecraft systems design.

Past success is due to both the diligence of EMC personnel and the strong commitment of NASA. Despite tighter program budgets and closer public scrutiny, this commitment must continue to mitigate the increasing risk of mission failure due to inadequate EMC.

As part of the MSFC commitment, the Electromagnetics and Environments Branch is active in the development of new techniques and processes that address current technologies and extend an already solid base into the future.

If you have any questions or comments about this report, contact the MSFC Systems Analysis and Integration Laboratory, Electromagnetics and Environments Branch, Steven D. Pearson at 205–544–2350.

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13. ABSTRACT *(Maximum 200 words)*

The effects of electromagnetic interference can be very detrimental to electronic systems utilized in space missions. Assuring that subsystems and systems are electrically compatible is an important engineering function necessary to assure mission success.

This reference publication will acquaint the reader with spacecraft electronic systems failures and anomalies caused by electromagnetic interference and will show the importance of electromagnetic compatibility activities in conjunction with space flight programs. It is also hoped that the report will illustrate that evolving electronic systems are increasingly sensitive to electromagnetic interference and that NASA personnel must continue to diligently pursue electromagnetic compatibility on space flight systems.

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