DOT/FAA/AR-06/41

Office of Aviation Research
and Development
Washington, DC 20591

In-Flight Radio Frequency Spectrum Measurements of Commercial Aircraft Cabins

September 2006

Final Report

U.S. Department of Transportation
Federal Aviation Administration

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT/FAA/AR-06/41		

4. Title and Subtitle	5. Report Date
IN-FLIGHT RADIO FREQUENCY SPECTRUM MEASUREMENTS OF COMMERCIAL AIRCRAFT CABINS	September 2006
	6. Performing Organization Code
7. Author(s) Bill Straus and M. Granger Morgan	8. Performing Organization Report No.
9. Performing Organization Name and Address Carnegie Mellon University Department of Engineering and Public Policy 5000 Forbes Avenue Pittsburgh, PA 15213	10. Work Unit No. (TRAIS) 11. Contract or Grant No. 01-C-AW-CMU
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Aviation Administration Office of Aviation Research and Development Washington, DC 20591	13. Type of Report and Period Covered Final Report 28 June 2002-29 October 2004 14. Sponsoring Agency Code AIR-100

15. Supplementary Notes

The Federal Aviation Administration Airport and Aircraft Safety R&D Division COTR was Anthony Wilson.

16. Abstract

The focus on the risk posed by portable electronic devices carried onboard commercial flights has continued to intensify. Recent measurements and analyses have been useful in developing a better understanding of the issues, but has not allowed one to draw firm conclusions about what is happening in today's revenue flight environments. This report summarizes results of a program that developed an instrumentation package and performed in-flight radio frequency (RF) spectrum measurements in commercial aircraft cabins on revenue flights in select aviation critical and personal electronics frequency bands. Specific objectives were to identify cellular in-flight calls and activity rates, assess maximum levels of received power, and identify areas that deserve further research.

Measurements were made on 38 flights over the period September 23 through November 19, 2003. These flights were on Boeing 737 (37 flights) and on Airbus 320 (1 flight) model aircraft. Two major U.S. airlines participated in the flight study.

This study provided the first reported characterization of the RF environment in the cabins of commercial airline flights. The key conclusions were that (1) onboard cellular telephone calls were observed in-flight and activity is appreciable; (2) signal activity was observed in the aviation critical frequency bands at field strengths capable on causing interference to onboard avionics; and (3) onboard spectral activity was observed at flight critical phases.

These findings carry implications for both future research and public policy. Before the industry moves forward with policy changes, significantly more field measurement and analysis of the potential for interference is urgently needed. These studies should include a consideration of the implications of having many onboard transmitters and the potential risks posed by intermodulation.

17. Key Words	18. Distribution Statement
EMI, Interference, RF environment, PED, Cellular phone	This document is available to the public through the National Technical Information Service (NTIS) Springfield, Virginia 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	76	

Form DOT F1700.7 (8-72) Reproduction of completed page authorize

ACKNOWLEDGEMENTS

The assistance of many Federal Aviation Administration and industry personnel and organizations was essential to the successful completion of this work. The investigators extend particular thanks to Mr. John Dimtroff, Mr. Tony Wilson, and Mr. Dave Walen for their early support. The work would not have been possible without the understanding and cooperation of three major airlines, whose identity by prior agreement remains anonymous. Thanks are extended to Professors Dan Stancil and Jay Apt of Carnegie Mellon University for their extensive advice and assistance. Finally, this program would not have been possible without the diligent and tireless efforts by Mr. Kent Horton, Mr. Tim Shaver, Mr. Brian Eppic, Mr. Mark Rudo, Mr. Jeff Campbell, and most especially Mr. Jamie Fowler.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

AMPS	Advanced Mobile Phone Service
ASRS	Aviation Safety Reporting System
BPSK	Binary phase shift keying
BW	Bandwidth
C/A	Coarse/acquisition code
CAR	Civil Aviation Regulation
CDM	Code division multiplexing
CDMA	Code division multiple access
CFR	Code of Federal Regulations
CW	Continuous wave
DCCH	Digital control channel
DME	Distance measuring equipment
EME	Electromagnetic Environment
ERP	Effective radiated power
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
FM	Frequency modulated
GPS	Global Positioning System
GS	Glide slope
GSM	Global System for Mobile Communication
ILS	Instrument Landing System
IPL	Interference path loss
ISM	Industrial, scientific, and medical
LAN	Local area network
LOC	Localizer
MIPL	Minimum interference path loss
NASA	National Aeronautics and Space Administration
PCS	Personal Communications System
PED	Portable electronic device
PRN	Pseudo-random noise
RF	Radio frequency
RTCA	Radio Technical Commission for Aeronautics
SE	Shielding effectiveness
TCAS	Traffic Alert and Collision Avoidance System
TDMA	Time Division Multiple Access
T-PED	Transmitting portable electronic device
VHF	Very high frequency
VOR	VHF omni-directional range
W	Watt

EXECUTIVE SUMMARY

This report summarizes results of a program to develop an instrumentation package and perform in-flight radio frequency (RF) spectrum measurements on revenue flights of commercial aircraft cabins in select aviation-critical and personal electronics frequency bands. The spectrum monitoring was performed from gate-to-gate. Specific objectives were to identify cellular in-flight calls and activity rates, assess maximum levels of received power, and identify spectrum areas that deserve further research.

Five critical navigation frequency bands were selected to be monitored: Very High-Frequency Omni-Directional Range (VOR) and Instrument Landing System (ILS) Localizer (LOC), 108-118 MHz; ILS Glide Slope (GS), 329-335 MHz; Distance Measuring Equipment (DME) and Traffic Alert and Collision Avoidance System (TCAS), 960-1215 MHz; and Global Positioning System (GPS), 1227.5 and 1575.42 MHz. There were four frequency ranges identified as likely to experience emissions from passenger electronics use: cellular uplink, 824-849 MHz; Personal Communications System (PCS) uplink, 1.85-1.91 GHz; and industrial, scientific, and medical (ISM), 902-928 MHz and 2.4-2.485 MHz. Limited monitoring was conducted in the ILS GS, GPS L2 (1227.5 MHz), and DME and TCAS bands.

Measurements were made on 38 flights over the period September 23 through November 19, 2003. All flights were revenue flights except for one maintenance flight with no passengers onboard. All flights were on Boeing 737 model aircraft except for one flight on an Airbus 320. Two airlines participated in the flight study with 29 flights on one airline and 9 flights on the other. A third airline assisted in validating instrumentation operation and measurement methodology. All flights occurred along the east coast, and flight durations were between 40 minutes and 2 hours. The passenger load factors were between 25% and 100%.

The research effort collected a total of 7534 spectrum traces representing over 51 hours of data. There were 1493 traces collected at the gate, 1596 traces collected during taxi, and 4445 traces collected in flight. The traces collected in flight represent over 32 hours of data.

This study provided the first reported characterization of the RF environment in the cabins of commercial airline flights. Key conclusions are as follows:

a. Cellular telephone calls were observed in all phases of flight at a rate conservatively estimated to be approximately one call per flight, and onboard cellular telephone activity is appreciable.

b. Considerable onboard RF activity was observed in the GPS L1 (1575.42 MHz) band, some of which appeared to have field strengths that, under appropriate circumstances, could result in interference with aircraft GPS equipment.

c. Elevated broadband noise was observed on many occasions in the VOR/ILS band, and at least some of these observations appear to be unique to specific aircraft.

d. While spectral measurements gave no indication of passengers using wireless devices other than cellular phones during takeoff, such use was observed during approach well after the portable electronic devices-prohibited cabin announcement.

These findings carry implications for both future research and public policy. Before the industry moves forward with the installation of onboard pico-cells for telephone and data use, significantly more field measurement and careful analysis of the potential for interference, especially in the GPS bands, is urgently needed. These studies should include a consideration of the implications of having many onboard transmitters, some of which will likely transmit at relatively high power levels, and the potential risks posed by intermodulation.

While the measurements reported here do not allow firm conclusions about the elevated emission levels in the VOR/ILS band, previous analysis of the Aviation Safety Reporting System database suggests that interference occurs and may be linked to these elevated emission levels. This issue deserves future studies with instrumentation more suitable to these frequencies, beginning with studies to establish the nature and variation of contributions made by aircraft themselves.

1. INTRODUCTION.

Airline passengers have carried portable electronic devices (PED) aboard commercial aircraft for use during flight since the 1950s. In May 1961, the U.S. Government formally recognized, with Civilian Aviation Regulation (CAR) 91.19,[1] the potential safety hazard posed to commercial flights from radio frequency (RF) interference. The regulation prohibited the operation of portable frequency-modulated (FM) radio receivers when the very high-frequency omni-directional range (VOR) receiver was being used for navigation purposes because of concerns about possible emissions from the FM radio's internal oscillators.

Since that time, the issue of an item of interest with PED interference has received a small amount of attention, periodically emerging as the focus of the media, Congress, and industry. The term PED interference refers to the disruption to avionics caused by PEDs.

The first major research on the impact of PEDs occurred after CAR 91.19 became effective. RTCA formed Special Committee 88 (SC-88) and issued its report, RTCA DO-119, on April 12, 1963 [1]. As a result of the report, the Federal Aviation Administration (FAA) issued Title 14 Code of Federal Regulations (CFR) 91.19 that extended the prohibition of using in-flight electronics to other PEDs. The responsibility for assuring compliance with these rules has always remained with the operator of the aircraft. No regulatory limits were placed on the radiation emissions of PEDs as a result of the RTCA findings, but SC-88 noted that installed electronic devices in aircraft have always been required to meet emission and susceptibility specifications.

Since the potential risk was identified over 40 years ago, there have been two major technology developments that have set the stage to significantly change the situation. The first was the creation of portable computers (laptops) with RF clocks, and the second was the development of mobile cellular phones. However, the impact of these technology advancements was not immediate. Early generation laptops which were bulky, had limited capability, and a low battery capacity that prevented large-scale, long-period use in flight produced significant unintentional RF emissions. Cellular phones were intentional transmitters and added a new dimension to the situation. Even so, the inability to use the early generation cellular phones at altitude reduced a substantial shift in risk.

The risks posed by the portable electronics technology developments have also been held in check by improvements in avionics immunity to RF interference and by federal government restrictions. There are stringent susceptibility requirements placed on avionics as part of the aircraft certification process and the Federal Communications Commission (FCC) has restricted cellular phone use onboard commercial aircraft since December 1991.

This report summarizes the results of a program sponsored by the FAA [2] to develop an instrumentation package and perform in-flight RF spectrum measurements on revenue flights of commercial aircraft cabins in select aviation-critical and personal electronics frequency bands.

---

[1] The current Title 14 Code of Federal Regulations were formerly CARs.

2. REVIEW OF PAST RESEARCH.

The initial investigations into the risk posed to commercial aircraft from PEDs centered on establishing RF emissions levels from PEDs, the susceptibility thresholds of avionics, and the interference path loss (IPL)[2] [3 and 4]. This remains the main approach in evaluating the risk. These research efforts have all arrived at similar conclusions, that PEDs cannot be ruled out as a potential risk to aircraft avionics, but the likelihood of interference is low.

2.1 RADIO TECHNICAL COMMISSION FOR AERONAUTICS.

The Radio Technical Commission for Aeronautics (RTCA) has produced three reports on the subject of PEDs. The first was DO-119 issued in 1963 [1]. The subsequent RTCA reports on PEDs, RTCA DO-199 [3] and DO-233 [4], examined the issues in greater depth and began to establish guidance for determining the risk posed to commercial aircraft. These investigations established RF emissions levels from PEDs and susceptibility thresholds of avionics and the IPL. While both of these latter reports concluded that the risk of interference to avionics from PEDs was low, they also recommended that further testing was desirable, public awareness was needed, and continued restrictions on PED in-flight use was prudent.

2.2 CIVIL AVIATION AUTHORITY.

Two studies by the Civil Aviation Authority have demonstrated the danger associated with onboard cellular use. A study in 2000 [5] established that cellular phone transmissions in the aircraft cabin can produce levels in excess of the levels that avionics are qualified to. A second study released in 2003 [6] demonstrated interference in cockpit instrumentation and navigation receivers from cellular phone transmissions.

Both of these studies concluded that the use of cellular telephones onboard aircraft should be prohibited to reduce risk and ensure safety.

2.3 NATIONAL AERONAUTICS AND SPACE ADMINISTRATION.

National Aeronautics and Space Administration (NASA) recently completed a study on the spurious emissions from cellular telephones [7]. While no emissions were observed that would challenge the integrity of commercial aircraft navigation radios, it was identified that maximum allowable FCC emissions provide insufficient safety margins. This was further amplified with the release of NASA report TM-2004-213001 [8] that described emissions from a particular make and model cellular phone that caused interference with onboard global positioning system (GPS) receivers while still being compliant with FCC rules.

The NASA study on wireless phones also found that intermodulation between some cellular phones caused emissions in the GPS and distance measuring equipment (DME) frequency bands.

Another NASA report [9] discussed portable wireless local area network (LAN) devices and two-way radios and their potential threat to avionics. Measurements established that wireless

[2] IPL is defined as the loss between a reference antenna (approximating the PED) located in the aircraft cabin and a particular aircraft radio receiver terminal.

LAN devices were in compliance with FCC Part 15 rules, but exceeded DO-160 category M[3] limits for radiated emissions [10]. The report also demonstrated that spurious emissions from the two-way radios were in excess of the DO-160 category M limits.

2.4 AVIATION SAFETY REPORTING SYSTEM.

The Aviation Safety Reporting System (ASRS) database has been used for a number of studies over the years concerning PEDs and the potential interference to avionics. It was first used to confirm the legitimacy of the investigations into the subject, such as the RTCA efforts. Later, it was used to further establish the nature and extent of the problem [11]. Finally, it was used to determine which avionics were most often affected and indicate which PEDs might be causing the interference [12].

3. MOTIVATION FOR A PROGRAM OF IN-FLIGHT MEASUREMENT.

While the measurements and analyses described in section 2 have been useful in developing an understanding of many of the issues that surround potential electromagnetic interference from PEDs, they have not allowed one to draw firm conclusions about what is happening in today's revenue flight environments. This limitation will become more serious as one moves from an era dominated by analogue devices that are under the direct control of users into an era dominated by ubiquitous digital devices, many of which have wireless features that operate without active or knowing user control.

As a consequence, decisions are being made and conclusions drawn on the basis of theory and theoretical extensions of static[4] measurements without correlation to the actual environment. The implication is that the behavior of passengers, the electronics they bring onboard, and external influences at altitude are not being addressed. The potential for over- or underdesign of avionics is real with consequences of excessive cost or potential safety-of-flight issues. In their writings on human factors and aviation accidents, McDonald and Johnston [13] note, "For too long theoretical models applied in practical situations have been derived from laboratory research though never validated in the context of their application."

Several factors support the need for real-time measurements in the cabins of commercial airliners.

a. Rare Events. When and if it occurs, significant interference with avionics from PEDs will be a rare event. While results from previous static measurements are certainly consistent with this conclusion, analysis methods used to date have not been designed to look for rare events. They look at the main paths and manifestations and establish the margin of safety. However, they do not assess the possible variance in their findings, leaving one to speculation whether these established margins are sufficient and, if not, how often they will be insufficient.

b. In-Service Effects on PEDs. The emissions from PEDs were explored in references 3, 4, and 9. These efforts mostly looked at relatively new electronic devices rather than

[3] This category is suitable for equipment located in the passenger cabin or cockpit.
[4] The term static refers to aircraft on the ground in controlled situations.

devices that had been in service, that is, devices which had been dropped, sent in for ad-hoc repairs, etc. There are no major studies that establish the in-service effects on PED emissions. These examinations and others have the common deficiency of a low sample size as well. The ability to identify outliers (i.e., high emission levels) or the variation in field strength is not possible with these data.

c. Transmitting PEDs. Transmitting PEDs (T-PED) have not been examined thoroughly. In the previous RTCA studies, T-PEDs were not yet an important issue. Only more recently, with the likelihood that some T-PEDs may be onboard aircraft, has the focus shifted. NASA has recently concluded two studies that focused on the unintentional emissions from T-PEDs [7 and 9], but much remains to be understood. As pointed out in the NASA report TM-2004-213001 [8], an unintentional emission from a T-PED may be allowable at a higher level than a non-T-PED, even in an aircraft-critical band.

d. Intermodulation Effects. The previous approaches have not looked at the effects caused by multiple PEDs or PEDs in combination with other aircraft-generated emissions or the external RF electromagnetic environment (EME). These effects are known as intermodulation. A recent NASA report [7] indicated that emissions in GPS and DME systems can occur from simultaneous use of multiple mobile phones.

Studies of in-flight RF spectrum on commercial flights with passengers should be beneficial for a number of reasons. They can address some of the deficiencies mentioned above and can also establish other relevant data, as described below.

a. Compliance With In-Flight Policies. The potential interference from T-PEDs, such as two-way radios and cellular phones, has always been recognized. However, the belief has been that most passengers comply with existing FCC-, FAA-, and airline-established policies prohibiting device use at certain phases of flight. In-flight measurements could analyze compliance aspects especially for cellular phones. The benefits extend beyond the issue and into passenger behavior concepts that are critical when establishing any aircraft-related policy.

b. Analyzes a Large Sample of PEDs. The low sample analysis of the past approaches is replaced by a higher sample approach. It also accounts for intermodulation products and T-PEDs. Although it is unknown how many or what types of PEDs are being assessed, the potential to see outliers caused by a number of potential influences is greatly increased. In any event, the RF EME onboard commercial aircraft had only been theorized and it places data where previously only theory existed.

c. PED Detectors and Data Mining. The development of PED detectors and locators has been examined and promoted for some time [14, 15, and 16]. These systems and approaches have, so far, been cost-prohibitive, and their usefulness has yet to be established. An understanding of the in-flight RF EME will be vital to the development of these and other in-flight monitoring systems.

With these considerations in mind, a system to make in-flight measurements of the RF EME in the cabins of commercial aircraft was developed and deployed. There were extensive consultations with the management and engineering staffs of two major U.S. air carriers, technical staff at the FAA, and the FCC prior to developing the system. On the basis of these discussions, a proposal titled "In-Flight RF Spectrum Measurements of Commercial Aircraft Cabins" was prepared and resulted in the FAA grant, Cooperative Agreement No. 01-C-AW-CMU, Amendment No. CMU-001 issued June 27, 2002. The results of the grant are the subject of this document. The value of this effort has recently been confirmed by the NASA report on wireless phone threat assessments. It recommended that data be collected on aircraft passenger cabin RF environments during flight [7]. The next section describes the instrumentation and its operation.

4. IN-FLIGHT RF SPECTRUM MEASUREMENT INSTRUMENTATION.

4.1 INSTRUMENTATION EQUIPMENT.

A compact RF spectrum measurement instrumentation package was developed for in-flight characterization of the EME in commercial aircraft revenue flights. The cooperating airlines stipulated that the instrumentation must be carry-on size[5], and its operation must be discreet so as not to raise concerns among passengers. To meet those requirements, the instrumentation needed to be compact, lightweight, automated, and cover a broad frequency range. This necessitated engineering trade-offs that created limitations that are discussed below.

The instrument package consisted of an Anritsu MS2711B spectrum analyzer, a broadband antenna manufactured by Antenna Research (CMA-118/A), a Gateway Solo Pro 9300 laptop computer, and associated cables and connectors all housed in a conventional piece of soft-side carry-on luggage, (figure 1). A summary of the equipment used is provided in table 1 along with the basis for judging its potential low risk to aircraft avionics.

FIGURE 1. THE COMPACT RF SPECTRUM MEASUREMENT INSTRUMENTATION

[5] The carry-on baggage size limitation is 21″ x 16″ x 8″ for overhead compartments.

TABLE 1. INSTRUMENTATION EQUIPMENT

Manufacturer/Model	Risk Assessment Basis
Antenna Research CMA-118/A Antenna	Identified antenna has no active electronics.
Anritsu MS2711B Spectrum Analyzer	Meets European community requirements for CE marketing.
Gateway Solo Model 9300 Laptop	Conforms to the limits for a Class B digital device, pursuant to Part 15 of the FCC rules.

CE = Conformité Européenne

4.1.1 Spectrum Analyzer.

The Anritsu MS2711B spectrum analyzer was selected for its compact size, frequency coverage at the desired resolution bandwidths (BW), and data export capability. Its operation is controlled through an RS-232 interface. The Anritsu MS2711B spectrum analyzer meets European community requirements for radiated emissions. Further information can be found at www.anritsu.com.

4.1.2 Antenna.

The Antenna Research CMA-118/A discone antenna was designed to cover 1-18 GHz with a gain of 2.0-6.1 dBi. The antenna is compact and measures 2.8″ high and has a diameter of 8″. The antenna contains no active elements. Further details can be found at www.ara-inc.com.

4.1.3 Laptop.

A Gateway Solo Model 9300 laptop computer was interfaced with the Anritsu spectrum analyzer via an RS-232 interface. The computer controlled and stored the data from the spectrum analyzer. The laptop conformed to FCC Part 15 radiated emissions rules.

4.2 SAFETY PRECAUTIONS.

The instrumentation was intended to record on a continuous basis in the cabin of commercial flights from takeoff to landing. This required operation below 10,000 ft. Since this was a departure from standard operating procedures and the flying public was involved, safety was given the highest priority.

To avoid interference to aircraft avionics, the instrumentation was designed using equipment that adhered to industry standards for radiated emissions. In its final configuration, the instrumentation was subjected to careful radiated emission testing to ensure that it did not produce RF levels that might adversely affect aircraft avionics. The instrumentation satisfied DO-160D category M limits for radiated emissions [10]. The final design and emission results were submitted to the FAA Chief Scientific and Technical Advisor for Electromagnetic Interference and Lightning and the sponsoring airline engineering staffs for review and approval.

The instrumentation was ground-tested for compatibility with safety-of-flight avionics on all aircraft models prior to any in-flight use. Flight avionics were monitored for adverse effects, while the instrumentation was operated in its intended mode. This testing included ground taxi and a nonrevenue flight (i.e., no passengers).

As a final precaution, the instrumentation operator briefed each flight crew and accompanied the instrumentation during each flight. Additionally, a sponsoring airline engineering representative accompanied the instrumentation and researcher during the nonrevenue test flight and the first four revenue flights to ensure compatibility with aircraft avionics.

4.3 FREQUENCIES OF INTEREST.

While the monitoring of frequencies from 2 MHz to 18 GHz would allow for a complete comparison of the cabin RF environment and avionics immunity requirements, sponsoring airline requirements, technical challenges, complexity, and cost suggested that it would be best to start with a more limited effort.

Previously conducted statistical analysis with the ASRS database study indicated that certain avionics might be more affected than others, and also indicated which PEDs might be more likely to cause the interference [12]. The analysis suggested that interference is manifesting in the navigation rather than communication areas.

The ASRS database analysis suggested that laptops and cellular phones affecting VOR navigation are the most common form of PED-avionics interference; thus, the interest in cellular phone frequencies and VOR navigation frequency ranges. The increasing reliance on GPS navigation dictated the interest in those frequencies. There has been recent proliferation of devices in the 2.4-GHz band. Therefore, this range was also included in the frequencies of interest so that future assessments similar to this will have a comparison baseline.

Five critical navigation frequency bands were selected to be monitored: VOR and Instrument Landing System (ILS) Localizer (LOC), 108-118 MHz; ILS Glide Slope (GS), 329-335 MHz; DME and Traffic Alert and Collision Avoidance System (TCAS), 960-1215 MHz; and GPS, 1227.5 and 1575.42 MHz. There were four frequency ranges identified as likely to experience emissions from passenger electronics use: cellular uplink, 824-849 MHz; Personal Communications System (PCS) uplink, 1.85-1.91 GHz; and industrial, scientific, and medical (ISM), 902-928 MHz and 2.4-2.485 MHz.

There were limitations that necessitated changes to the intended frequencies of interest during the in-flight measurement program. The requirement that the instrumentation be compact necessitated that the spectrum analyzer and laptop be physically close to the antenna. This caused the instrumentation to receive some self-generated interference. In the ILS GS band (329-335 MHz), the interference was too large for useable data to be collected. The GPS L1 band (1575.42 MHz) is the band principally used by aviation, and it was carefully monitored. However, when nothing notable was observed in the GPS L2 band (1227.5 MHz), further monitoring was discontinued. The observed narrow-band signals in the 960-1215 MHz band, which contains DME and TCAS, were hard to differentiate from the many ground DME stations or actual TCAS signals. No wide-band signals were observed in this band, so monitoring was discontinued after flight 20 to focus on frequencies of greater interest. The frequencies considered in this monitoring effort are summarized in table 2.

TABLE 2. SYSTEMS AND FREQUENCY BANDS OF INTEREST

Avionics/Electronics Band of Interest	Technologies	Frequency Range
Critical Aviation		
VOR	VOR	108-118 MHz
ILS Localizer	ILS LOC	108-112 MHz
ILS Glide Slope*	ILS GS	329-335 MHz
Navigation*	TCAS and DME	960-1215 MHz
Global Positioning System (L2)*	GPS	1227.5 MHz
Global Positioning System (L1)	GPS	1575.42 MHz
Portable Electronic Device		
Cellular	AMPS, TDMA, and CDMA	824-849 MHz
Personal Communication System	TDMA, GSM, and CDMA	1850-1910 MHz
900-MHz ISM	Cordless Telephones	902-928 MHz
2.4-GHz ISM	802.11 and Bluetooth	2400-2485 MHz

* Limited data collection

4.4 SYSTEM PERFORMANCE.

Given a frequency range of interest covering 108 MHz to 2.5 GHz, a single antenna designed to cover that range would have dimensions much larger than a carry-on bag. A search of the commercially available antennas confirmed this. A two-antenna design would require multiplexing and increase system complexity and the potential for failure. Thus, the best performance possible with a single compact antenna was pursued.

The Antenna Research CMA-118/A discone antenna was identified as covering 1-18 GHz and meeting the size requirements. In calibration tests conducted in an open site test area[6] and onboard a parked aircraft, the antenna demonstrated that it was able to function adequately down to 108 MHz. Open-site tests were conducted at 113, 332, 836, 915, and 1227.5 MHz to determine the gain of the antenna. The measurements were performed on the antenna alone, not incorporated into the instrumentation package.

The distance at which the first Fresnel zone touches the ground is known as the breakpoint distance (d_0). The height of the antennas and the frequency were used in equation 1 to determine the breakpoint distance for all tested frequencies.

$$d_0 = \frac{4\pi\, h_t h_r}{\lambda} \quad (1)$$

The measured power-received was plotted versus distance for distances greater than the breakpoint distance out to 50 m. A best-fit trend line was calculated for the measured data beyond the breakpoint distance. A log curve using n = 2, as the general terrain model

[6] Gesling Stadium at Carnegie Mellon University, Pittsburgh, PA, was used. This is an artificial turf football field with two-story buildings no closer than 100 feet from the field.

predicts [17], was then fitted to intersect the trend line at the breakpoint distance by varying the receive antenna gain (CMA-118/A antenna). The results of the tests are provided in table 3.

TABLE 3. EMPIRICAL GAIN RESULTS FOR THE CMA-118/A ANTENNA

Frequency (MHz)	d_0 (m)[1]	Calculated Gain (dBi)	Manufacturer's Gain (dBi)
113	2.6	-19.5	N/A
332	7.7	-10.7	N/A
836	19.4	-1.0	N/A
915	21.2	+1.2	N/A
1227.5	28.4	-0.5	0.0[2]

Notes: 1. d_0 is the breakpoint distance.
2. Maximum using azimuth and elevation charts.
N/A = Not applicable

The results provided in table 3 were reasonable for an out-of-band antenna and the empirically determined value at 1227.5 MHz matched the manufacturer's specification. Furthermore, at 836 and 915 MHz, the measured data overlays well with the general terrain model inside the breakpoint distance.

In the 108-118 MHz frequency range, where the CMA-118/A antenna was determined to have a gain of -19.5 dBi, the system would be able to detect FCC Part 15 emission violations at a distance of 1 m or less. Since the system was located in an overhead compartment, this implies that any signals detected in that frequency range from onboard sources would probably involve such a violation.

In its final configuration, the instrumentation was tested in a parked Boeing 737-300 at Pittsburgh International Airport with an onboard emission source. The instrumentation was placed in overhead compartment and under seat locations throughout the aircraft. The results demonstrated that the overhead locations performed better than the under the seat locations and that adequate performance could be achieved with the CMA-118/A antenna. The results of the test are provided in appendix A and support previous work [18, 19, 20, and 21] that suggests the reverberant nature of the aircraft cabin with gradients.

Measurements were recorded on a single nonrevenue flight (no passengers) to provide ambient spectrum levels. It was desirable to obtain additional nonrevenue flights; however, logistics and scheduling difficulties prevented this.

4.5 DATA COLLECTION ROUTINES.

4.5.1 Spectrum Analyzer Settings.

The spectrum analyzer settings used in the in-flight measurements are summarized in table 4. The settings were chosen to meet the overall objective of identifying the RF EME in select aviation-critical and personal electronics frequency bands onboard commercial aircraft during revenue flights. The settings were also chosen to meet more specific objectives such as in the cellular phone bands: capturing in-flight calls, assessing maximum received power, and determining transmission activity rates.

TABLE 4. SPECTRUM ANALYZER SETTINGS FOR IN-FLIGHT MEASUREMENTS

Band	Start Frequency	Stop Frequency	Resolution BW	Video BW
1	108 MHz	118 MHz	10 kHz	10 kHz
2	329 MHz	335 MHz	10 kHz	10 kHz
3	824 MHz	849 MHz	30 kHz	30 kHz
4	902 MHz	928 MHz	30 kHz	30 kHz
5	960 MHz	1215 MHz	1 MHz	300 kHz
6	1215 MHz	1240 MHz	30 kHz	30 kHz
7	1565 MHz	1590 MHz	30 kHz	30 kHz
8	1850 MHz	1910 MHz	30 kHz	30 kHz
9	2.4 GHz	2.5 GHz	1 MHz	300 kHz

4.5.2 Spectrum Analyzer Sweep Protocols.

The data were obtained using two spectrum analyzer sweep protocols. The standard protocol collected approximately 1 minute of data in a maximum hold configuration. The Anritsu MS2711B spectrum analyzer does not provide for variable sweep time, rather, it is optimized for a given frequency range, resolution BW, and video BW. Thus, the sweep time was different for each frequency band measured. The maximum hold measurement approach is similar to that used by the National Telecommunications and Information Administration in their spectrum utilization assessments [22]. The high-temporal resolution or high-resolution protocol collected a single sweep of data. The standard collection protocol was used exclusively for all frequency bands, except the cellular bands.

In the cellular bands, the standard protocol was used at first. Once it was established that a high level of cellular activity was being observed, the high-resolution protocol was used to help quantify the activity rate and duration of cellular phone signals. During longer flights, the standard protocol was used to reduce the overall amount of data.

While the high-resolution protocol records more data, it results in a lower percentage of time monitored because of the approximate 6-second delay each time data are written to the computer and a new command is issued.

4.5.3 Flight Phases.

Each flight was divided into three phases: takeoff, cruise, and approach and landing. The flight phases were evaluated to determine the relevant frequency bands of interest. This was done to maximize the collection efficiency and produce the highest value data. For example, during approach, it was desirable to determine cellular phone usage since they are implicated in affecting ILSs [12].

The instrumentation did not support parallel recording of frequency bands. Thus, a sequential order was determined for each flight by prioritizing frequency bands according to flight phase. As described in section 4.3, the emphasis on frequency bands shifted during the in-flight measurement effort, including the cessation of monitoring in some frequency bands. The monitoring goals by flight phase for the standard protocol is provided in table 5. This table represents the goals for the final 20 or so flights. During some flights, the cellular and PCS bands were monitored exclusively using the high-resolution protocol. In the earlier flights, less attention was focused on the cellular and PCS bands, but the same general strategy was employed.

TABLE 5. FREQUENCY BAND MONITORING ALLOCATIONS BY FLIGHT PHASE
(Standard Resolution, After Flight 20)

Takeoff		Cruise		Landing	
Cellular	39%	Cellular	38-41%	Cellular	35-40%
PCS	39%	PCS	38-41%	PCS	35-40%
VOR/ILS LOC	9%	GPS	10%	VOR/ILS LOC	10%
900 MHz ISM	4%	VOR/ILS LOC	3-5%	ILS GS	3-6%
GPS	4%	900 MHz ISM	3-5%	900 MHz ISM	3-6%
2.4 GHz ISM	4%	2.4 GHz ISM	3-5%	2.4 GHz ISM	3-6%

Notes: 1. High-resolution protocol used exclusively to monitor cellular and PCS bands.
2. Monitoring prior to flight 20 included other bands with less emphasis on cellular and PCS bands.

5. SUMMARY OF THE DATA COLLECTED.

This section discusses the collected data from the in-flight RF spectrum measurements. The nomenclature and conventions associated with the data are explained. The postflight manipulation and filtering processes are also discussed. The data results and discussion are provided in section 6.

5.1 FLIGHT SUMMARY.

Measurements were made on 38 flights over the period September 23 through November 19, 2003. All flights were revenue flights except for one maintenance flight with no passengers onboard. All flights were on B-737 model aircraft except for one flight on an Airbus 320. Two airlines participated in the flight study with 29 flights on airline A and 9 flights on airline B. The identities of participating airlines are not disclosed by agreement. A third airline was used to validate instrumentation operation and measurement methodology. All flights occurred along the east coast, and flight durations ranged from 0:39 to 1:52 hours. The passenger loads were from 34 to 144 (load factor of 25% to 100%). The measurements were made from gate-to-gate. The measurement flights are summarized in table 6.

The instrumentation was centrally located in the aircraft coach section in the overhead storage compartment in all but one instance when it was placed under a seat. The orientation of the antenna (forward, backward, or out toward the cabin) was random from one flight to the next. There was no attempt to control what objects (luggage, handbags, boxes, etc.) were placed in proximity to the instrumentation in the overhead compartment.

TABLE 6. SUMMARY OF MEASUREMENT FLIGHTS

Flight No.	Date	Airline	Aircraft[1]	Tail Number[2]	Airport		Passengers
					Depart	Arrive	
1	9/23/03	B	B-732		ATL	ATL	0
2	10/8/03	A	B-733	1	PIT	EWR	34
3	10/8/03	A	B-733	1	EWR	PIT	44
4	10/8/03	A	B-734	2	PIT	EWR	40
5	10/8/03	A	B-734	2	EWR	PIT	92
6	10/14/03	A	B-733		PIT	EWR	63
7	10/14/03	A	B-734		EWR	CLT	106
8	10/14/03	A	B-734		CLT	MCO	122
9	10/15/03	A	B-733		MCO	DCA	120
10	10/15/03	A	B-733		DCA	BOS	106
11	10/15/03	A	B-733		BOS	PIT	105
12	10/21/03	A	B-733		PIT	EWR	45
13	10/21/03	A	B-734		EWR	CLT	63
14	10/21/03	A	B-734		CLT	MCO	144
15	10/22/03	A	B-733		MCO	DCA	71
16	10/22/03	A	B-733		DCA	BOS	75
17	10/22/03	A	B-733		BOS	PIT	99
18	11/4/03	A	B-733		PIT	EWR	42
19	11/4/03	A	B-734		EWR	CLT	75
20	11/4/03	A	B-734		CLT	MCO	144
21	11/5/03	A	B-733		MCO	DCA	100
22	11/5/03	A	B-733		DCA	BOS	89
23	11/5/03	A	A320		BOS	PIT	124
24	11/11/03	A	B-733	1	PIT	EWR	42
25	11/11/03	A	B-734		EWR	CLT	88
26	11/11/03	B	B-732		CLT	ATL	79
27	11/11/03	B	B-732	3	ATL	ORD	100
28	11/12/03	B	B-732	3	ORD	ATL	99
29	11/12/03	B	B-732		ATL	CLT	90
30	11/12/03	A	B-734	4	CLT	BWI	124
31	11/12/03	A	B-734	4	BWI	PIT	108
32	11/18/03	A	B-733		PIT	EWR	39
33	11/18/03	A	B-734	4	EWR	CLT	89
34	11/18/03	B	B-732		CLT	ATL	100
35	11/18/03	B	B-738	5	ATL	IAH	103
36	11/19/03	B	B-738	5	IAH	ATL	110
37	11/19/03	B	B-732		ATL	CLT	42
38	11/19/03	A	B-733		CLT	PIT	75

Notes:
1. Aircraft model: B-732 = 737-200, B-733 = 737-300, B-734 = 737-400, B-738 = 737-800, and A320 = Airbus 320.
2. Denotes aircraft with a common tail number. For example, flights 2, 3, and 24 were the same aircraft.

5.2 COLLECTED DATA.

5.2.1 Automated Data Collection.

The Anritsu MS2711B spectrum analyzer records data as a trace or plot. Each trace is comprised of 400 bins of data. There are multiple values observed in each bin based on the spectrum span being analyzed and the resolution BW setting. The spectrum analyzer used positive detection that directed the maximum received power value to be assigned to the bin. The use of positive detection was intended to obtain the maximum signal level present.

Immediately after each trace was recorded, it was output to an Excel spreadsheet file and saved. The structure of the Excel spreadsheet is shown in figure 2. The first column contains the header titles and the frequencies. Each additional column represents a trace and contains the header information and the measured power data. Multiple worksheets were used to represent the various frequency bands of interest. In the original raw data file, the altitude information was not present; it was added during the postflight data management process as described in section 5.3.2.

Altitude:	Gate	Gate	33,000
Start Frequency (Hz):	108000000	108000000	108000000
Stop Frequency (Hz):	118000000	118000000	118000000
RBW Setting (Hz):	10000	10000	10000
VBW Setting (Hz):	10000	10000	10000
Date:	11/12/03	11/12/03	11/12/03
Time:	8:22:30 AM	8:27:46 AM	9:02:19 AM
108.000	-86.590	-99.694	-108.001
108.025	-98.313	-105.918	-101.636
108.050	-104.257	-110.551	-108.726
⋮	⋮	⋮	⋮
117.950	-95.084	-96.652	-104.280
117.975	-97.143	-100.349	-101.098
118.000	-96.886	-98.056	-100.864

Header Information

Frequency Information

Data

FIGURE 2. SAMPLE DATA FILE

The research effort collected a total of 7534 spectrum traces representing 51:23 hours of monitoring. There were 1493 traces collected at the gate, 1596 traces collected during taxi, and 4445 traces collected in flight. The traces collected in flight represent 32:48 hours of monitoring. A summary of the collected data is provided in table 7. This includes a breakdown of data collected by frequency band and temporal resolution protocol for gate, taxi, and flight phases.

TABLE 7. SUMMARY OF COLLECTED DATA AND MONITOR TIMES

Frequency Band (MHz)	Gate		Taxi		In-Flight	
	Traces	Time[2]	Traces	Time[2]	Traces	Time[2]
108-118	52	0:47:40	39	0:35:45	242	3:41:50
329-335	41	0:37:35	28	0:25:40	163	2:29:25
824-849	259	3:57:25	172	2:37:40	489	7:28:15
824-849 high resolution[1]	450	0:14:20	564	0:17:57	1231	0:39:11
902-928	10	0:09:10	17	0:15:35	131	2:00:05
960-1215	0	0:00:00	5	0:04:35	94	1:26:10
1215-1240	0	0:00:00	6	0:05:30	93	1:25:15
1565-1590	7	0:06:25	18	0:16:30	196	2:59:40
1850-1910	244	3:43:40	183	2:47:45	471	7:11:45
1850-1910 high resolution[1]	419	0:29:41	550	0:38:57	1202	1:25:09
2400-2500	11	0:10:05	14	0:12:50	133	2:01:55
Totals	1493	10:16:00	1596	8:18:45	4445	32:48:40
Total Traces: 7534			Total Time: 51:23:25			

Notes: 1. See section 4.5.2 for a description of high-resolution protocol.
2. Time in hh:mm:ss format.

5.2.2 Manual Data Collection.

Prior to each flight, the investigator synchronized two digital clocks with the computer clock. The times of pushback, taxi, takeoff, the announcements allowing and discontinuing PED use, touchdown, and gate arrival were noted and manually recorded for use during postflight data management and analysis. Other noted events were maintenance delays, holding pattern announcements, and severe weather.

Because of the established agreements with the airlines, no real-time monitoring of the spectrum by the system operator was permitted. This reduced the possibility of correlating a passenger's electronics use with a signal event. However, to the extent possible, notes were taken on passengers' electronics use and the times of occurrence. For example, during flight 8, a passenger in seat 17C was observed attempting to make an in-flight cellular call between 6:31:38 and 6:37:26 p.m. Emissions associated with this attempt were subsequently observed in the data.

The use of game electronics, compact disc/digital versatile disc players, laptops, and other media players was observed. The task of manually observing and recording passengers' electronics use was considerable and could not be comprehensive. It did give some indication of passenger behavior and allowed for limited postflight correlation to signal events.

The flight crews for all flights were aware of the in-flight monitoring effort. During a short postflight debrief, the pilots were asked to comment on any anomalies observed during the flight. No remarkable events were reported.

Because the flight attendants were aware of the research, it is possible that they altered their normal announcements or enforcement policy concerning PED use. However, only in a few instances did the announcement seem stronger than usual, based on the operator's flying experience. While conflicts over PED usage are reported commonly in the ASRS, no in-flight conflicts were observed with respect to policy enforcement.

5.3 POSTFLIGHT DATA MANAGEMENT.

The manually recorded information was added to the computer file of spectrum measurements during the postflight data management phase. This included date, event times, passenger loads, instrumentation location, flight number and airline, aircraft tail number, and departure and arrival airport. Altitude data based on flight plans were added upon receipt from the airlines.

All recorded traces were formatted and printed as a chart or graph to provide a visual representation of the received power as a function of frequency for each trace. The charts were arranged chronologically by frequency range for each flight. The description of RF electromagnetic environments is often given as field strength (V/m) or power density (W/m^2). This convention was not adopted because of uncertainties arising from antenna gain, instrument placement, and the reverberant nature of the aircraft cabin. Given that the primary objective of this project was to produce a first general characterization of the RF environment in commercial aircraft cabins, this was not viewed as a major limitation. The trace information recorded was not adjusted to field strength, but rather, left in terms of power received (dBm) by the instrumentation.

5.3.1 Data Anomalies.

As with all electronic systems, the spectrum analyzer and laptop computer used in the instrumentation emit electromagnetic energy. The overall emissions from the instrumentation and coupling between its electronics and antenna were minimized through device selection, shielding, and equipment orientation within the instrumentation package. However, due to the close proximity of the antenna to the laptop and spectrum analyzer, emissions were detected. These emissions were observed both during calibration tests (within an anechoic chamber) and during in-flight measurements. They were characterized and removed from the data during analysis as necessary. This also supported the termination of recording in the ILS GS band (329-335 MHz).

In the course of debugging the system, a condition was identified that resulted in the recording of invalid data. The problem arose during data transfer to the laptop when a delay caused the RS-232 buffer to overflow. The delay was caused when the hard drive lacked sufficient space to receive the incoming data and needed to find an adequate location. In debugging, it was confirmed that the problem did not affect the quality of subsequent recorded traces. A remedy for this situation was to defrag the hard drive, clear the Microsoft Windows® Temp folder, and reboot the computer.

Anomalies of this type occasionally appeared in the in-flight data and were not included in the analysis. An example of invalid data is shown in figure 3. The spectrum analyzer had the capability of recording between -30 and -130 dBm and obviously a portion of the data taken at 4:42:56 p.m. were invalid.

Altitude:	33,000	25,163
Start Frequency (Hz):	824000000	824000000
Stop Frequency (Hz):	849000000	849000000
RBW Setting (Hz):	30000	30000
VBW Setting (Hz):	30000	30000
Date:	10/22/03	10/22/03
Time:	4:38:44 PM	4:42:56 PM
⋮	⋮	⋮
835.591	-95.084	-89.959
835.654	-102.712	-87.853
835.717	-110.224	-138.713
835.779	-106.363	1006363.699
835.842	-109.358	1677452.392
835.905	-110.083	167502.996
835.967	-108.913	1207690.391
⋮	⋮	⋮

FIGURE 3. INVALID DATA EXAMPLE

When invalid data were observed, the data from the entire flight were carefully examined. It was observed that the invalid data occurred either for a single data trace or a few successive data traces and then recovered. As in the software debugging studies, there was no indication in the in-flight data that traces recorded before or after the invalid period were in error. Thus, all other data associated with that flight was presumed to be valid.

There was one other anomalous data event. At the conclusion of one flight, the laptop screen was blank, but the computer and spectrum analyzer were still running. After the computer was rebooted, the data file was examined. It contained data recorded up to the time when the computer was powered down, and thus, all data were considered valid.

5.3.2 Altitude Information and Limitation.

Altitude information for most flights was derived from flight plans provided by the airlines the day following a flight. The waypoint data contained in each flight plan were used to create straight-line approximations for altitude versus elapsed time into the flight. Each data point was assigned an altitude based on this straight-line approximation. This was a conservative approach, attempting to estimate the minimum altitude associated with each data point. This was done to help isolate signals most likely originating on the aircraft versus the ground. An example of a derived flight profile is given in figure 4.

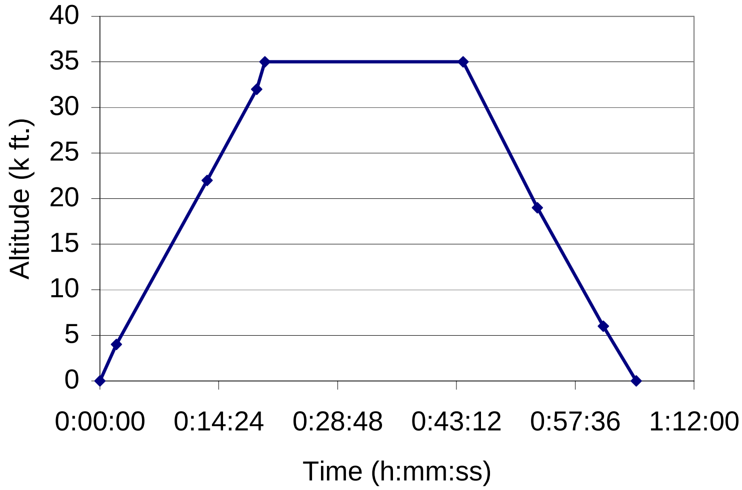

FIGURE 4. FLIGHT 8 ESTIMATED ALTITUDE PROFILE BASED ON FLIGHT PLAN

The assigned climb out and cruise altitudes are assumed to be moderately accurate. The takeoff times are known exactly and deviation during climb out is unlikely at low altitudes. No deviations from expected cruise altitudes were reported by the airlines.

The approach altitude estimates can be influenced by holding patterns and other in-flight delays. Two of the flights (4 and 10) involved in-flight holding patterns after the initiation of descent. The data observed after the initiation of descent are not used in any altitude specific analysis due to the uncertainty involved in assigning an altitude. The flight plans obtained from the airlines did not include the holding pattern information and were based only on anticipated flight paths. All other flight delays were experienced prior to takeoff and, thus, did not affect the flight plan with respect to elapsed time.

Actual altitude information was obtained for two flights involving B-737-800 aircraft that were equipped with telemetry systems and allowed postflight retrieval.

While altitude information is not strictly accurate, estimated values are likely good to within a few thousand feet. In all cases, the takeoff and landing times are exactly known so that in-flight versus ground data points are accurately known.

6. RESULTS AND DISCUSSION.

6.1 MOBILE CELLULAR.

There are several mobile phone technologies used in the U.S. They principally make use of two frequency bands: the 800-MHz band referred to as the cellular band and the 1900-MHz band referred to as the PCS band. The 800-MHz band uses 824-849 MHz for the reverse link (mobile to base station) and 869-894 MHz for the forward link (base station to mobile). Three technologies (Advanced Mobile Phone Service (AMPS), Time Division Multiple Access (TDMA), and Code Division Multiple Access (CDMA)) are used in this band. In the 1900 MHz-band, 1850-1910 MHz is used for the reverse link and 1930-1990 MHz for the forward link. Again, three technologies (TDMA, Global System for Mobile Communication (GSM) and CDMA technologies) are used in this band. The technologies are summarized in table 8.

TABLE 8. CELLULAR BAND MOBILE TECHNOLOGIES

Technology	Standard	Mobile TX Frequency	Channel BW	Transmission Method
AMPS	AMPS	824-849 MHz	30 kHz	Continuous
CDMA	IS-95	824-849 MHz 1850-1910 MHz	1.23 MHz	Continuous
GSM	GSM	1850-1910 MHz	200 kHz	Pulsed
TDMA	IS-54/IS-136	824-849 MHz 1850-1910 MHz	30 kHz	Pulsed

Other frequency ranges are increasingly being used for cellular service such as Integrated Dispatch Enhanced Network in the 806-821 MHz frequency range. Ultimately, this will make the potential for interference to avionics more likely and the ability to assess the situation more difficult. The technologies identified in table 8 residing in the cellular and PCS bands account for over 75% of the mobile phone service in the U.S. as of September 2003 and the time of this study. Thus, the in-flight monitoring effort of cellular phones concentrated on these two frequency bands to maximize efficiency.

For the cellular and PCS frequency bands and monitoring parameters selected, it was not possible to conclusively identify a detected signal's technology. However, the FCC permits only cellular telephones to operate in these frequency bands and restricts emissions from unintentional radiators. Even at 1 m, an unintentional radiator operating at the maximum allowable emission level would be detected more than 70 dB below that of an onboard cellular signal.

Given that CDMA technology signals are 1.23 MHz wide with a distinctive flat top look when observed in the frequency spectrum, it is very unlikely that received signals with this appearance would be generated from anything other than a cellular telephone, especially given the frequency band of observation and the high received signal strength. Received discrete signals could appear as AMPS, TDMA, or GSM signals; however, as stated above, the given power-received values would indicate that it is unlikely that they are not cellular signals. It can reasonably be concluded that most observed signals in these frequency bands are from a mobile cellular technology.

Consider figure 5 that displays data taken during flight 30. The wide-band signal on the right is likely a CDMA signal. It has a received power of around -54 dBm adjusted for the spectrum analyzer settings, as described in section 6.1.2, and a 1.25 MHz BW. It also occurs at a prescribed CDMA channel (466). The signal on the left is suspected to be either an AMPS or TDMA signal. The narrow BW (<60 kHz), high power-received value (-55 dBm), and frequency band again indicate a cellular signal.

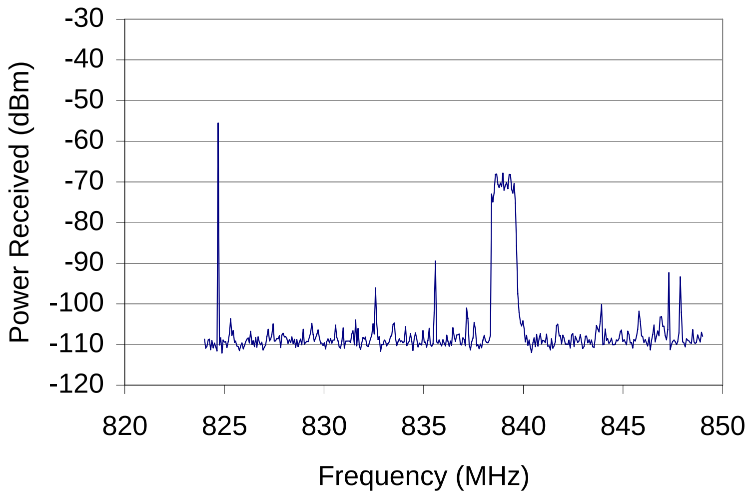

FIGURE 5. EXAMPLE OF SUSPECTED WIDE- AND NARROW-BAND CELLULAR SIGNALS

The underlying purpose of the in-flight monitoring effort for the cellular frequency bands was to (1) document in-flight cellular use, (2) determine an estimate of in-flight power density levels, and (3) determine transmission activity rates. These objectives are met even if a few cellular signals are not identified as cellular and others are misidentified as cellular.

6.1.1 Description of Collected Data.

As noted in section 4.5.2, the data in the cellular bands were obtained using two spectrum analyzer sweep protocols. The standard protocol collected approximately 1 minute of data in a maximum hold configuration and the high-resolution protocol collected single sweeps of data. The standard collection protocol was used exclusively in the first flights and longer duration flights. The high-resolution protocol was used to help quantify the activity rate and duration of cellular signals. The resolution BW and sweep protocols for the cellular and PCS bands were chosen to meet the objectives of capturing in-flight calls, assessing maximum received power, and determining onboard transmission activity rates.

The high-resolution protocol records more data, but results in a lower percentage of time monitored because of the 6-second delay for data to be written to the computer and a new command to be issued.

Overall, there were 6234 traces recorded in the cellular and PCS bands representing 31:30 hours of monitoring. Of the 3165 traces recorded in the cellular band, 1720 were in-flight and represented 7:57 hours of monitoring. Of the 3069 traces recorded in the PCS band, 1673 were in-flight and represented 8:36 hours of monitoring. The collected data was summarized in table 7.

6.1.2 General Observations.

A total of 6234 graphs were generated from the cellular and PCS bands. Clearly, digesting this much data was challenging. This section provides an overview of the general observations. The purpose is to provide the reader a degree of familiarity with the data without requiring a full graph-by-graph review.

The data recording sequence for each flight was initiated prior to passenger boarding. The main cabin door was open and remained in that position until boarding was complete. The data taken at the gate generally shows a large amount of signal activity that is substantially reduced when the aircraft doors were secured for pushback. This can be seen in figure 6 taken from flight 15. The aircraft environment at the gate with the cabin door open is represented by signal A and the environment with the cabin door closed during taxi is represented by signal B. The high activity at the gate can be attributed to both onboard and terminal phone activity. The signal activity generally continues to drop during taxi and reduces further once in flight. The in-flight environment was generally quiet except for onboard signals as discussed earlier in section 6.1. The environment picks up slightly during approach and is more active than on departure. This is probably due to the more moderate descent than assent (i.e., at low altitude for a longer period).

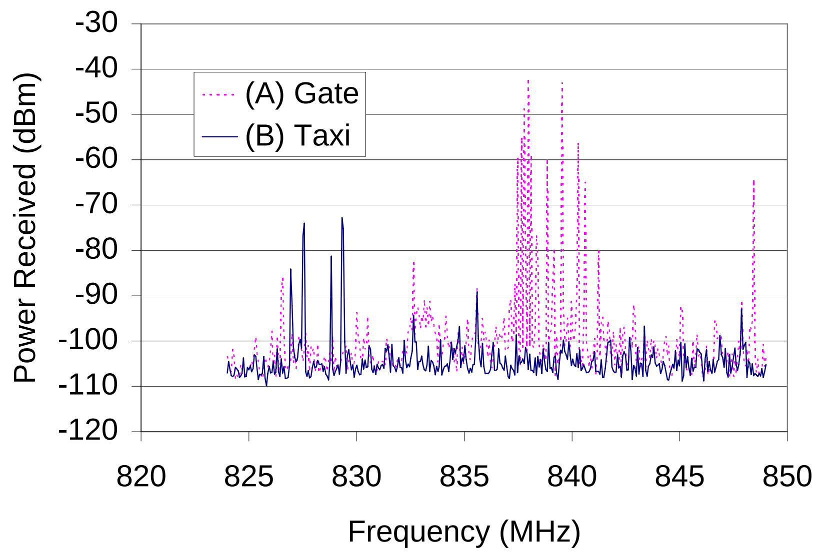

FIGURE 6. EXAMPLE OF THE ONBOARD CELLULAR BAND ENVIRONMENT AT THE GATE (A) AND DURING TAXI (B)

A cumulative summary of the cellular band in-flight environment for standard protocol measurements is provided in figure 7. This chart shows the maximum and minimum recorded values observed for each spectrum analyzer bin across all traces as well as the average for the 37 revenue flights. The BW of a CDMA signal is much larger than that of AMPS or TDMA signal. Thus, the cumulative representation is dominated by CDMA signals. Furthermore, the CDMA power-received measurements are undervalued because the resolution BW of the spectrum analyzer is smaller than the CDMA signal being measured. In the cellular and PCS range, the CDMA signals are undervalued by between 6.91 and 9.98 dB, as described in section 6.1.3.3.

All displayed graphics in this report associated with measurements of wide-band cellular signals are not adjusted to account for this undervaluing. However, the undervaluing is accounted for in all analyses of these signals. The high-resolution protocol data produces a similar cumulative graph, but is derived from less data resulting in a less occupied overall spectrum.

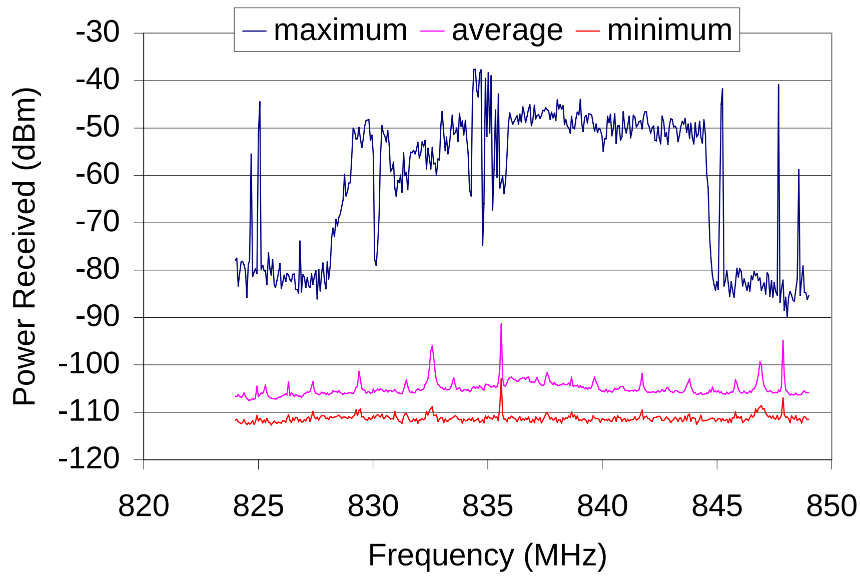

FIGURE 7. CELLULAR BAND IN-FLIGHT CUMULATIVE DATA
(Standard Measurement Protocol)

The average trace in figure 7 indicates that there is, overall, a low signal activity. It confirms that the instrumentation itself generates emissions, as described in sections 4.2 and 5.3.1. The self-generated emissions are mostly spaced at 2.05 MHz intervals and probably result from a circuit board clock frequency. In any case, the spurious emissions are of a low level (< -90 dBm), especially compared with cellular transmissions generated from within the aircraft cabin.

The low-level spurious emissions in the cellular band are removed from the data analysis. Emissions above -80 dBm are not removed and were considered actual signals in the aircraft environment. The purpose of removing the low level signals was to not incorrectly include them as ground-generated signals, and the purpose of retaining the higher-level signals was to not overlook onboard-generated cellular signals.

The PCS band had characteristics like the cellular band in that activity was highest at the gate, lower during taxi, and the least in flight. The cumulative summary of the PCS band in-flight environment for standard protocol measurements is provided in figure 8. It demonstrates that the signal activity is low and that there are self-generated emissions. The instrumentation emissions are lower in the PCS band than in the cellular band. The high-resolution protocol data produce a similar cumulative graph, but is derived from less data resulting in a less occupied overall spectrum.

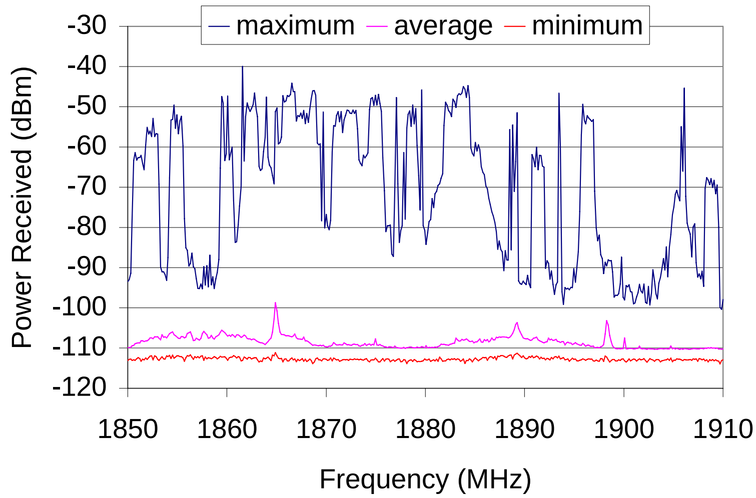

FIGURE 8. CUMULATIVE DATA FOR PCS BAND

6.1.3 Analysis Approach.

The steps to accomplishing the objectives of capturing in-flight calls, assessing maximum received power, and determining transmission activity rates were:

- Identify all cellular signals and categorize as narrow band or wide band
- Adjust measured power-received values of wide-band signals
- Determine which signals are generated from onboard sources
- Determine if narrow-band signals are registrations or calls
- Determine the activity rates of calls and registrations

6.1.3.1 Identifying Narrow-Band Cellular Signals.

The amount of data to analyze required an automated analysis routine. Rudimentary signal processing software was created that looked at the received power value in each spectrum analyzer bin. Narrow-band signals were defined as those for which spectrum analyzer bins showed 6 dB less power in neighboring bins. Some AMPS, TDMA, and GSM channels bridged the spectrum analyzer bins. Thus, any four-bin sequences whose center bins' values were within 3 dB of each other and were 6 dB greater than their remaining adjacent bin were also considered narrow-band signals. This essentially identified all signals with BWs less than 120 kHz in the cellular band and 300 kHz in the PCS band.

After all the narrow-band signals were identified, they were manually evaluated to ensure that they were not part of a CDMA or other wide-band signal, as explained in the next section. Appendix B provides information on cellular and PCS band channels. The cellular band signals were further categorized into data or voice transmissions based on table B-1 of appendix B.

6.1.3.2 Identifying Wide-Band Cellular Signals.

The CDMA signals were easy to identify, given their characteristic frequency spectrum, as seen in figure 5. The data charts were visually scanned and all potential CDMA signals were identified. The potential signals were cross referenced to the raw data files for comparison to the valid CDMA channel frequencies provided in tables B-2 and B-3 of appendix B. It is not possible to identify a CDMA signal as a call based on its frequency.

An example of an identified CDMA signal in the raw data is provided in figure 9. Note that the signal's power drops off at prescribed channel frequencies. There were other observations in the data that support this identification method. For example, no signals were identified that spanned valid CDMA channels. Also, many of the identified signals appeared intermittently at the same frequencies over seconds or even minutes. One particular signal was observed with a characteristic spectrum (distinctive side lobes) at a prescribed channel over several minutes during the beginning of a flight and then observed at a different channel later in the flight. The implication is that these are CDMA signals.

Frequency	No Signal	Signal	
⋮	⋮	⋮	
1872.707	-110.294	-111.581	
1872.857	-112.470	-105.380	
1873.008	-112.119	-80.459	
1873.158	-111.417	-62.043	channel #475
1873.308	-110.177	-63.213	channel #475
1873.459	-112.096	-64.079	channel #475
1873.609	-110.247	-64.640	channel #475
1873.759	-110.528	-62.020	channel #475
1873.910	-111.417	-62.722	channel #475
1874.060	-109.943	-62.183	channel #475
1874.211	-109.311	-64.313	channel #475
1874.361	-112.025	-63.611	channel #475
1874.511	-112.072	-88.134	
1874.662	-111.464	-96.277	
1874.812	-110.434	-104.584	

FIGURE 9. EXAMPLE OF A CDMA SIGNAL IN THE RAW DATA FILE (PCS BAND)

6.1.3.3 Identifying Onboard Signals.

The initial approach to identifying which signals originated from onboard the aircraft involved a strictly theoretical calculation. The theoretical power received at the aircraft by the instrumentation was calculated using the Friis free-space equation.

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L} \tag{2}$$

Using the Friis free-space equation is a conservative approach erring on the side of not identifying some onboard signals. It is unlikely that line of sight conditions prevailed and signals originating from the ground would be lower due to reflection, diffraction, and scattering. The following parameter values were used in equation 2 to estimate a threshold to identify narrow-band cellular signals originating onboard.

- Mobile Power Output = 3 watt (W)
- Mobile Antenna Gain = 3 dB
- Instrumentation Antenna Gain = 0 dB
- Distance = Aircraft Altitude

The maximum permitted mobile power output of portable cellular telephones is 7 W effective radiated power (ERP) peak in the cellular band and 2 W ERP peak in the PCS band. The average power is usually less for TDMA and GSM technologies because of their pulsed nature and CDMA technologies because of its implemented power control. The power output and antenna gain values are optimistic. The antenna in the instrumentation package is out-of-band in the cellular range, and table 3 suggests a value of 0 dB is conservative. The manufacturer's specifications imply that 0 dB is also conservative in the PCS band. The aircraft altitude as described in section 5.3.2 involved some modest uncertainty. Further, since altitudes are relative to sea level and all flights were over land, this value may not be conservative. However, the approach of being conservative where possible should negate the impact of altitude uncertainty, plus or minus a few thousand feet. At higher altitudes, this is less of a factor with respect to identifying onboard signals.

Signals originating from outside the aircraft cabin will be reduced by the shielding effectiveness (SE) of the aircraft. For the frequencies of interest in the passenger cabin, the minimum SE is expected to be 18 ±5 dB [18]. Thus, as a conservative approach to identifying onboard signals, the result from equation 2 is reduced by 10 dB to produce the threshold for the maximum received power from a signal originating on the ground. This threshold will be referred to as the onboard threshold throughout this report. The identified narrow-band signals above the threshold were considered to be onboard signals. As described in section 6.1.4, this was supported by a number of observations.

The method to evaluate CDMA signals originating from the aircraft was as follows. A threshold value for each data chart was calculated using equation 2 and the minimum shielding effectiveness. The identified CDMA signals were assigned a received power value by adjusting the maximum received value to account for the inherent undervaluing caused by the resolution BW setting of the spectrum analyzer being less than the BW of the CDMA signals. The adjustment was made after statistically determining the mean and standard deviation for the difference between the peak recorded value and the overall power contained in the recorded signal. The maximum received power value was increased by a value that was two standard deviations below the mean plus 3 dB to account for the resolution BW being half the width of the spectrum analyzer bin width. Only fully captured CDMA signals were used in the analysis to determine the adjustment values. The adjustment values are provided in table 9.

TABLE 9. ADJUSTMENT VALUES FOR WIDE-BAND CELLULAR SIGNALS

Frequency Band (MHz)	Sweep Protocol	Samples	Average (dB)	Standard Deviation (dB)	Adjustment Value (dB)
824-849	Standard	11	11.89	1.24	9.41
824-849	High resolution	14	11.84	0.93	9.98
1850-1910	Standard	24	9.15	1.12	6.91
1850-1910	High resolution	17	9.77	0.69	8.39

There were observations where only a partial CDMA signal was recorded. The described methodology allowed partial CDMA signals to be evaluated. It had the added benefit of providing faster analysis. The partial signal captures can occur if the signal begins at a point where the spectrum analyzer has already passed its lowest frequency or if the signal terminates at a point before the spectrum analyzer has passed its highest frequency. Either of these occurrences are a result of the relatively slow scan rate of the spectrum analyzer (~2-4 sec) compared with the duration of a CDMA registration (on the order of milliseconds). These partial signals were considered valid signals.

As an example, figure 10 overlays fully and partially captured CDMA signals. These signals were observed on successive charts taken during flight 11. Notice that the left sides of the signals commence at the same frequency, but that the right side of the partially captured signal falls off prior to the fully captured signal. Also note that the partially captured signal falls off at a higher rate and has little side-band energy.

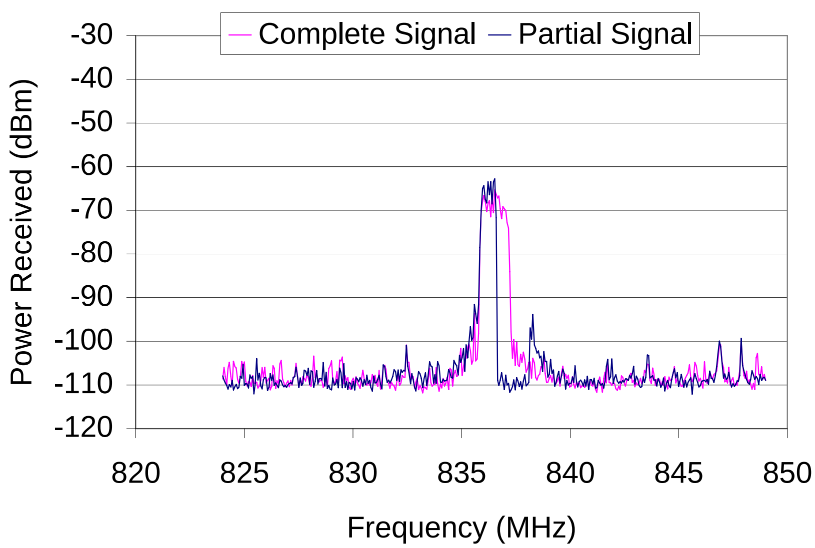

FIGURE 10. FULL AND PARTIAL CAPTURE OF A CELLULAR SIGNAL

6.1.4 Analysis.

There were 393 signals identified as originating from onboard the aircraft. They are categorized by narrow band and wide band for the cellular and PCS bands and provided in tables C-1 through C-4 in appendix C.

A graphical presentation of the narrow-band signals observed in the cellular band is presented in terms of measured power versus altitude and is provided in figure 11. Notice that the calculated threshold for the maximum received power from a signal originating on the ground, onboard threshold, is displayed. All signals belonging to a wide-band signal were removed using the method outlined in section 6.1.3.2. There were 19 signals that exceeded the onboard threshold. All signals identified as calls above the threshold in the cellular band are identified. The categorization of signals as calls was accomplished on the basis of frequency according to table B-1 in appendix B.

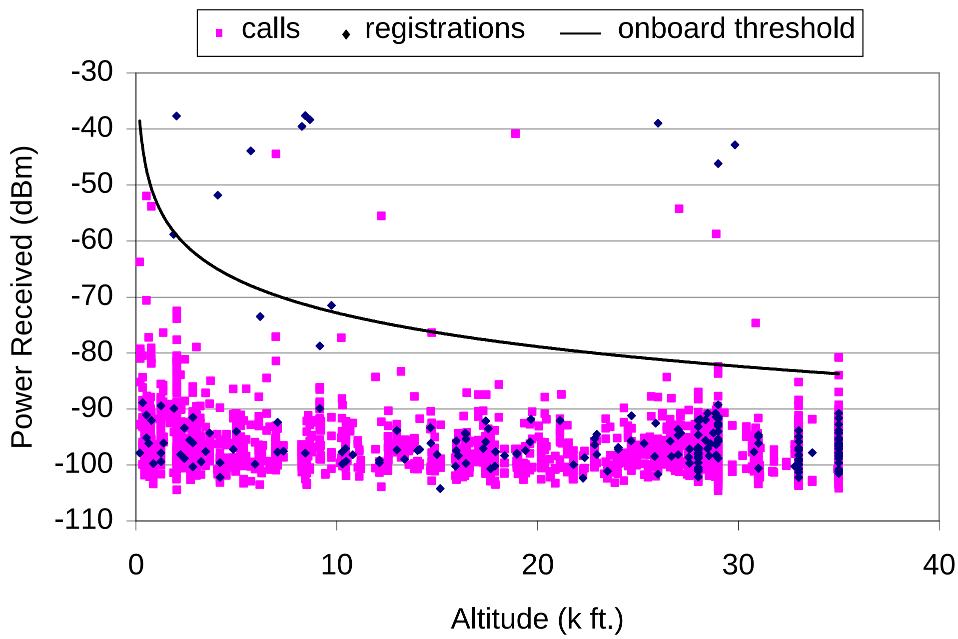

FIGURE 11. NARROW-BAND SIGNALS IN THE CELLULAR BAND POWER RECEIVED VERSUS ALTITUDE

The reverberant nature of the aircraft cabin and the inefficiency of the instrumentation make it likely that some signals originating onboard were misidentified as originating on the ground because the power received was below the established onboard threshold. Thus, reported counts likely represent a lower bound.

There are a few noteworthy aspects of figure 11. First, most of the signals fall well below the threshold line. This is likely due to (1) the onboard threshold being a conservative estimate, (2) the aircraft shielding was estimated at 10 dB, but is likely closer to 18 dB [23], (3) the instrumentation may have been shielded further with surrounding luggage, and (4) line of sight conditions do not hold with reflection, diffraction, and scattering influences.

Second, in most cases, the signals identified as originating from onboard the aircraft are above the threshold by 15 dB or more. This enhances the conclusion that these signals are from the aircraft. The signals that are close to the threshold, including some below the threshold, are likely in nulls created from the reverberant characteristics of the aircraft cabin.

A graphical presentation of the narrow-band signals observed in the PCS band is presented in figure 12. This figure also provides the onboard threshold for reference. The use of digital control channels (DCCH) for the TDMA, GSM, and CDMA technologies in the PCS band prevents identification of signals as calls versus registrations based on frequency.

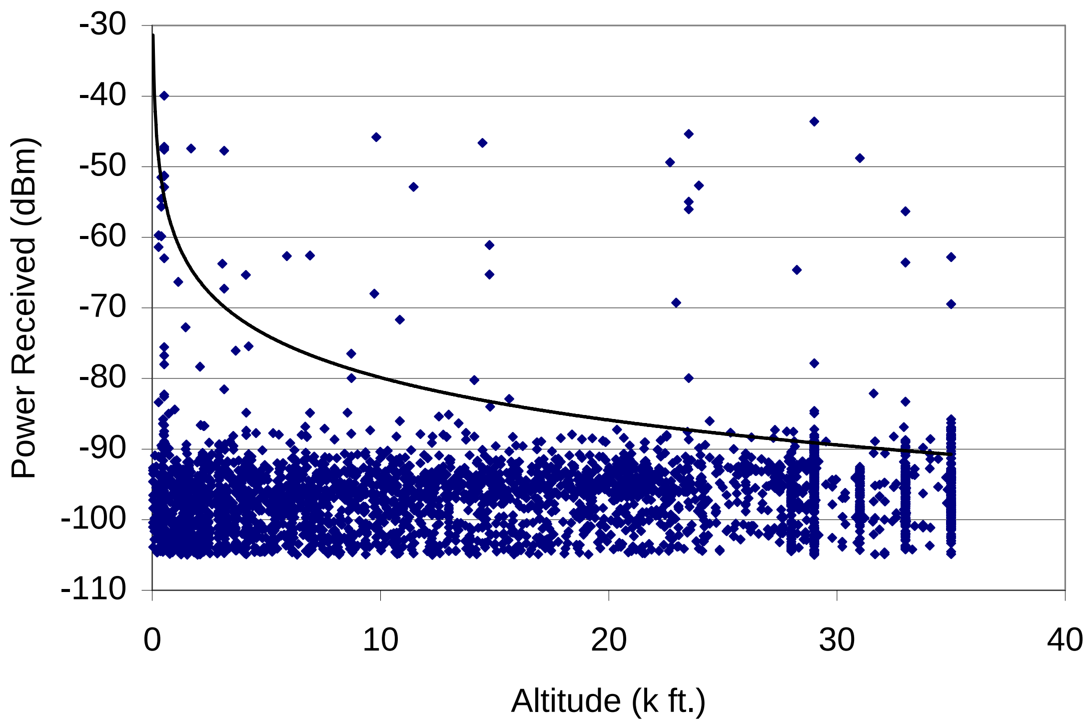

FIGURE 12. NARROW-BAND SIGNALS IN THE PCS BAND POWER RECEIVED VS ALTITUDE

6.1.4.1 Calls Originating From Onboard the Aircraft.

The eight signals identified as calls originating from the aircraft in the cellular band are described in table 10. This considers only narrow-band technologies in the cellular band. It is not possible to identify CDMA technology signals as calls with the instrumentation used, and the use of DCCH prevents identification of calls in the PCS band based on frequency. It is likely that calls were observed but could not be identified as such.

TABLE 10. IN-FLIGHT, NARROW-BAND SIGNALS IDENTIFIED AS CALLS

Flight No.	Frequency (MHz)	Altitude (ft)	Measured Power (dBm)	Threshold (dBm)	Margin (dB)
36	847.68	18,903	-40.843	-78.368	37.525
6	825.07	6,978	-44.447	-69.712	25.265
35	838.66	27,050	-54.275	-81.481	27.206
30	824.69	12,227	-55.514	-74.584	19.070
36	848.56	28,897	-58.767	-82.054	23.287
25	836.91	30,867	-74.679	-82.627	7.948
25	833.02	35,000	-80.763	-83.719	2.956
25	833.02	35,000	-80.833	-83.719	2.886

It is likely that calls were initiated using CDMA technologies and a few signals suspected of being calls are described below. For example, on approach during flight 11, there were four consecutive charts that detected a signal on the same channel and at approximately the same received power. The detected signals were first recorded at about 10,000 ft and continued until after landing. The time period covered approximately 8 minutes.

On another occasion, the system operator actually observed a passenger who appeared to be initiating and completing a call while in flight soon after takeoff. A signal was detected at the time of the apparent call and on a prescribed CDMA channel leading to the conclusion that a call was completed.

In the PCS band during flight 29, a signal was detected on 5 of 13 charts at the same channel over a 4-minute span. A similar series was seen on flight 26.

The above results are clear evidence that calls are being made from commercial aircraft. This is in disagreement with the commonly held belief that calls are not completed from aircraft at altitude and in violation of FCC rules. In fact, this research shows that calls are made with some regularity. The in-flight calls are likely dropped within minutes, and this implies that during some measurement scenarios, calls could have been missed. The bottom line is that in-flight calls have now been documented.

6.1.4.2 Activity Rates.

The cellular phone activity rate is a further gauge on how passengers adhere to policy and a description of their habits. The purpose of determining this rate is not to conclusively present a passenger use rate, but rather, to gauge the general magnitude of the issue. The previous sections determined that cellular phones are left in standby and intentionally used to make or receive calls during commercial flights. This section attempts to further define how commonly cell calls are made, how often phones are left in standby, and the resulting signal activity rate.

All the identified onboard signals in the cellular and PCS bands are summarized in appendix D, tables D-1 through D-12. The summary is broken down by the standard and high-resolution measurement protocols and narrow-band versus wide-band signals. Low altitude (<10,000 ft) data is also presented.

The activity rate is demonstrated to be higher when employing the high-resolution measurement protocol. This is likely due to the miscounting of signals during the standard resolution measurement protocol. During the standard measurement protocol, a trace is composed of 28 frequency band sweeps in the cellular band. If a signal appears during that time, it would only be counted once. During a high-resolution measurement protocol that same signal may be counted many times and thus indicate a higher and more accurate rate.

The overall total rate in the cellular band is given in table D-3 of appendix D that can be taken as a lower limit. The high-resolution measurement protocol total rate given in table D-2 is likely a more realistic rate. Using the high-resolution measurement protocol total rate given in table D-2 implies that a signal is generated onboard every 51 seconds. As can be expected, the rates are generally higher at low altitude. This is demonstrated in tables D-4 through D-6 for the cellular band. It should also be noted that signals were likely missed due to the slow sweep rate of the spectrum analyzer compared with the duration of a cellular technology control signal. This implies that the actual rates are higher than presented in these tables.

The activity rates for the PCS band are similar to the cellular band. The rates for the PCS band are provided in tables D-7 through D-12.

Given that cellular phone use onboard aircraft is strictly prohibited, these rates demonstrate either passenger disregard for policies or a lack of communication of the policies. If cellular phones have the potential to interfere with ILS approaches [12], then this level of activity should raise concern.

The previous section described 12 likely onboard cellular calls. Since the cellular and PCS bands were only monitored for a portion of the flights, it can be inferred that there were other calls that were not identified. Since these bands were only monitored 38% of the total in-flight time, the actual number of calls can be estimated.

$$Actual\ Calls = (Observed\ Calls)\frac{T_{Total}}{T_{Observed}} \tag{3}$$

$$Actual\ Calls = (12)\frac{2644\,\text{min}}{993\,\text{min}} = 32.0\ calls \tag{4}$$

Alternatively, about 33% of the total mobile cellular activity in the cellular and PCS bands can be attributed to AMPS or TDMA technology in the cellular band. The eight calls identified using these technologies in the cellular band implies that 24 calls were made in the cellular and PCS bands during the cellular band monitored period. Again, using equation 3 with $T_{Observed}$ = 487 minutes indicates as many as 130 calls made on the 37 revenue flights. However, the lack of truly independent samples indicates that this number should be applied cautiously.

While it is likely that some calls were missed or misidentified and that the analysis may have a large uncertainty, the analysis does imply that calls from onboard aircraft occur at a rate of at least one per flight.

6.1.4.3 Aircraft Cabin EME Field Levels.

The maximum field strengths can be calculated from the measured maximum power-received levels with some assumptions. However, the measurement system was designed mostly to identify signals for the purpose of establishing in-flight calls and the rate of cellular activity. The uncertainty associated with this measurement system suggests that it is best for future work to clearly establish how cell phone transmissions manifest within the aircraft cabin.

That said, the maximum received power measurement was -36.689 dBm. This occurred in the PCS band, and the signal was wide band. The maximum received measurements for the narrow- and wide-band signals in the cellular and PCS bands are provided in table 11. The values are all similar, but are somewhat below what might be expected. The received power levels are less than might be expected; this is likely explained by the inefficiency of the instrumentation, inability to control luggage near the instrumentation, and cavity insertion losses (passenger acting as absorbers, energy exiting through windows, etc.).

TABLE 11. MAXIMUM POWER-RECEIVED MEASUREMENTS IN THE CELLULAR AND PCS BANDS

Signal Type	Cellular Band	PCS Band
Narrow band	-37.638 dBm	-39.931 dBm
Wide band	-34.688 dBm	-36.689 dBm

6.1.5 Summary of Mobile Cellular Bands.

This section has shown that calls are accomplished from onboard commercial aircraft at a rate of at least one per flight. The activity rate due to registrations from passengers leaving their cellular telephones in standby is appreciable. The received power levels are less than might be expected, but this may be due to the inefficiency of the instrumentation, inability to control luggage near the instrumentation, and aircraft cabin insertion losses.

6.2 GLOBAL POSITIONING SYSTEM.

This section presents a brief overview of how the GPS works, explains why GPS receivers have an inherent vulnerability to some forms of signal interference, and describes the signal characteristics that are most likely to cause interference to GPS receivers. The data collected in GPS bands is summarized and used to calculate safety margins for current commercial aircraft.

6.2.1 Global Positioning System Operation and Vulnerability.

The GPS is made up of 24 satellites in approximately 11.5-hour orbits. The satellites transmit signals on two L-band frequencies, 1227.5 and 1575.42 MHz, designated L2 and L1, respectively. The primary role of signals in the L2 frequency is to allow corrections for errors introduced by variations in ionospheric propagation. Simply put, the L1 transmits information to provide navigation and the L2 transmits information that improves accuracy.

Each satellite transmits a pair of binary phase shift keying (BPSK) pseudo-random noise (PRN) sequences orthogonally modulated on the carrier with the information-bearing data. The coarse acquisition (C/A) code is a unique Gold-spreading code with a period of 1023 chips used to control the spreading and is transmitted at 1.023×10^6 chips per second, resulting in a code period of 1 millisecond. The precision (P) code is transmitted at 10.23×10^6 chips per second and has a code period of 1 week.

GPS receivers use correlation with locally generated BPSK PRN sequences to recover the information-bearing data sequence from the satellites. The GPS uses code division multiplexing (CDM) spread spectrum, meaning that all satellites transmit on the same frequency. Thus, each satellite must have its own code for differentiation. A common PRN sequence is known as a maximal-length sequence. The autocorrelation function of a maximal-length sequence has a symmetric triangle-shaped, unity height main lobe and a constant small negative value for all offsets greater than one chip duration. This characteristic is desirable; however, the cross-correlation characteristics are not. Thus, a special class of PRN sequences known as Gold sequences or Gold codes [24] are used. The GPS Gold codes have excellent cross-correlation properties at the expense of causing the autocorrelation function to produce small correlations that make GPS receivers vulnerable to certain types of interference.

The power spectrum of a GPS C/A code is made up of 1-kHz-spaced impulses that approximately follow a sinc-squared envelope function, which nulls every 1023 kHz. There are certain strong lines caused by the autocorrelation of the Gold codes adversely affecting the cochannel rejection in the GPS receiver. In most cases, a continuous wave (CW) interference signal, when correlated, will be spread and not adversely affect the receiver operation. If however, the interference falls close to a strong line, the resulting correlation fails to suppress the interference.

The vulnerability of GPS to interference has been known for some time. A 1996 FAA-sponsored research effort clearly identified the issue. The study found that a transmitter operating with less than 1 mW of power could deny satellite acquisition on a small aircraft [25]. It has been demonstrated in theory [26] and practice [27] that a 1-W emitter can jam civil GPS receivers at distances of 30 km or greater.

Further efforts have produced a clear characterization of the vulnerabilities. The susceptibility from CW interference sources is much more significant than from pulsed interference sources [28]. The impact of both CW and pulsed interference sources are discussed below.

<u>6.2.2 Continuous Wave Interference Sources</u>.

A CW interference signal can prevent or disrupt a GPS receiver’s ability to generate a valid navigation solution. Early assessments found that narrow- and wide-band CW interference affected GPS performance [29]. As expected, signals closer to the GPS center frequency caused greater interruption. There was a 16 dB variation in susceptibility between the receivers tested. The initial assessments were performed on C/A code receivers.

Additionally, a CW interference signal can be erroneously locked on to and used in the navigation solution causing position errors in excess of 22 km prior to detection [30]. The ability of an interference signal to not only jam, but spoof the GPS receiver is of great concern. This becomes critical as the aviation community heads towards GPS as a sole-means navigation system [28] and utilization of GPS in landing systems.

The immunity of GPS receivers to the effects of pulsed interference has been shown to be considerably more robust than to CW interference [28]. The pulsed interference duty cycle must approach 80% before loss-of-lock occurs, this being at the same interference-to-signal level as for CW interference. The amount of interference power received is basically irrelevant, except where the interference has the signal strength to saturate the receiver or cause component damage.

There have been reports by private pilots that a particular make or model cellular phone has caused their GPS navigation systems to lose satellite lock. Subsequent analysis by NASA has shown that these phones have significant emissions in the L1 band [8].

6.2.3 Global Positioning System Band Data.

In the current project, there were a total of 196 traces collected on 31 flights for the L1 band. This represents approximately 3 hours of in-flight monitoring. As explained in section 4.3, relatively few measurements were made in the L2 band (this band is currently not heavily used in aircraft operations) and few notable events were observed in this band. Consequently, in this discussion, the focus is on measurements made in the L1 band. None of the aircraft on which measurements were made were GPS-equipped.

The cumulative result of the L1 band EME for the 31 flights is shown in figure 13. The appearance of signals in the GPS band creates the potential for interference. As future dependence on GPS grows for activities, such as precision approach, the threat posed by such interference will become more serious. Thus, any observed signals should raise concern. There were signals observed on 58 of 196 traces, about 30% of the time. Because the spectrum analyzer recorded traces using a maximum hold protocol, the duration of each identified signal is not known.

Assessment of the instrumentation package in an anechoic chamber[7] indicated that there was an increased system noise floor above 1585 MHz as well as some narrow-band discrete signals between 1565 and 1585 MHz. The instrumentation emissions can be clearly seen in figure 13. The discrete signal activity is observed in the average of the cumulative result, and the wide-band interference above 1585 MHz can be observed on minimum, average, and maximum traces. The average received signal floor was around -110 dBm.

While the avionics community specifically attempts to avoid emissions in this band, DO-160, category M and H, this study revealed onboard signal content within the L1 band. The data in figure 13 are a cumulative representation of signal activity in the GPS band.

[7] An anechoic chamber is a shielded room lined with RF-absorbing material. The chamber used for this test was the Aircraft Anechoic Test Facility at the Naval Air Warfare Center in Patuxent River, MD. Typical shielding from the external environment is 80 dB or greater at the frequencies of interest.

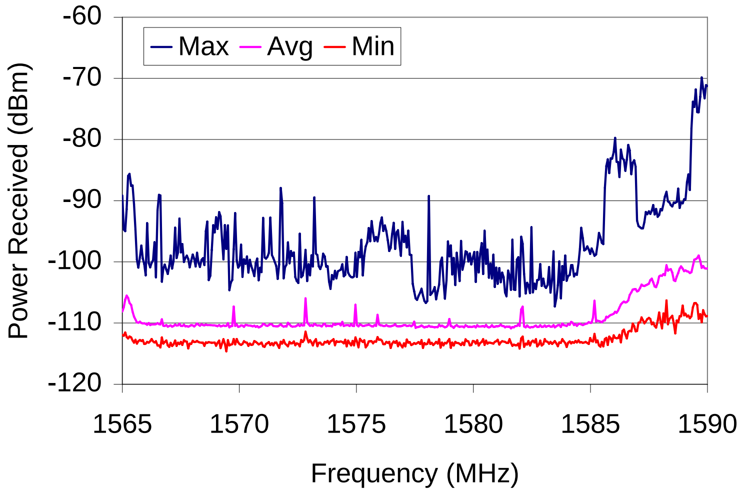

FIGURE 13. SUMMARY OF IN-FLIGHT GPS L1 BAND MEASURMENTS

Of course, the presence of signals within the GPS band does not automatically mean there will be interference. As discussed in section 6.2.1, pulsed interference is not likely to cause interference unless it contains significant power. None of the observed signals contained sufficient power to raise concerns, if they are pulsed in nature. However, if the signals were CW in nature, then there is some potential to cause interference to commercial GPS receivers.

The susceptibility of GPS receivers has been thoroughly explored [26, 27, 29, 30, 31, and 32]. The results of these analyses have produced industry specifications based on theory and validated in practice. The DO-235A [33] defines the current accepted interference environment for GPS receivers. For CW interference, the power received by the GPS receiver and the BW of the interference influence the likelihood of interference. Assuming that all signals observed in this monitoring effort are CW in nature allows a worst-case estimate of the safety margin associated with each observed signal to be determined.

The observed signals in the GPS band were characterized using their BW and center frequency. A threshold was developed for each signal using the information in DO-235A, see appendix F. That information specifies the RF interference environment at and around GPS L1 receivers. The threshold was developed by first using the BW of the potential interference signals and Figure F-2 of DO-235A and then adjusting the threshold using the center frequency of the potential interference signals and Figure F-1 of DO-235A. The observed signals and derived thresholds are provided in table 12. The wide-band signals in table 12 have been adjusted to account for undervaluing due to spectrum analyzer settings. The threshold provided is for acquisition mode. Acquisition mode is the time period when a GPS receiver is acquiring signals and has not established a navigation solution. If a solution has been established, then the receiver is in track mode and the threshold would increase by 6 dB. It can be quickly deduced that the signals in table 12 all have more power than the derived thresholds; however, this does not account for path loss.

TABLE 12. SAFETY MARGIN FOR SIGNALS OBSERVED IN THE GPS (L1) BAND USING MINIMUM IPL FOR MEDIUM TRANSPORT AIRCRAFT

Flight No.	Altitude	Center Frequency (MHz)	BW (MHz)	Measured Power (dBm)	Threshold (dBm)	Margin (dB)
25	35,000	1,589.56	0.75	-59.067	-100.500	-0.433
25	23,031	1,589.56	0.75	-60.868	-100.500	1.368
3	26,000	1,576.28	2.25	-77.157	-112.984	5.173
25	35,000	1,586.24	1.38	-67.456	-101.420	7.036
25	35,000	1,576.65	0.94	-83.229	-114.500	9.729
3	26,000	1,579.85	2.00	-79.869	-107.995	12.873
19	12,818	1,565.25	0.63	-75.607	-103.500	13.107
19	12,818	1,569.14	0.75	-81.086	-108.500	13.586
6	29,000	1,571.77	0.13	-84.913	-112.250	13.663
22	33,000	1,578.10	0.06	-89.234	-114.512	15.722
19	35,000	1,573.21	0.06	-93.516	-115.512	19.004
6	12,195	1,571.33	0.13	-89.757	-111.700	19.057
19	35,000	1,566.57	0.19	-84.276	-105.000	20.276
19	5,182	1,577.09	0.06	-95.739	-116.112	20.627
25	28,767	1,585.43	1.81	-80.647	-100.922	20.725
25	35,000	1,571.02	0.06	-92.814	-112.012	21.802
19	35,000	1,572.58	0.06	-95.411	-114.312	22.099
30	29,000	1,566.63	0.13	-86.154	-105.000	22.154
9	33,000	1,568.63	0.13	-90.389	-107.750	23.639
22	33,000	1,572.08	0.06	-96.815	-113.512	24.303
11	28,000	1,573.21	0.06	-98.641	-115.012	24.629
19	5,182	1,585.68	0.06	-88.766	-104.512	25.254
19	5,182	1,582.48	0.06	-94.335	-108.512	26.823
19	12,818	1,581.67	0.06	-96.371	-110.012	27.359
23	10,479	1,582.04	0.06	-95.879	-109.312	27.567
6	29,000	1,581.92	0.13	-96.239	-108.000	29.239
22	33,000	1,566.07	0.06	-93.680	-105.312	29.368
30	29,000	1,584.61	0.06	-94.429	-105.812	29.617
19	28,281	1,566.38	0.13	-93.782	-104.700	30.082
21	33,000	1,567.44	0.06	-97.775	-107.512	31.263
19	5,182	1,568.01	0.06	-98.804	-108.012	31.792
11	23,902	1,584.86	0.06	-97.471	-106.012	32.459
6	29,000	1,565.75	0.06	-99.202	-105.512	34.690

Notes:
1. Measured power is adjusted for signal BWs larger than the spectrum analyzer resolution BW.
2. Threshold derived from frequency and BW and DO-235A.
3. Margin uses MIPL for medium size aircraft of 41 dB.

The expected path loss for signals transmitted from within an aircraft cabin to the GPS antenna port is assessed in DO-233 and defined as the IPL. According to NASA report TP-2003-212438 [9] in the GPS band, the minimum interference path loss (MIPL) is 41 dB for medium size aircraft (i.e., B-737, B-727, etc.) and the average IPL is 64.4 dB. This NASA report includes data recently measured and from DO-233. The MIPL value is used to adjust the observed signal received power to a value that would be present at the GPS receiver. A safety margin was calculated using equation 5, and the results are provided in table 12 for observed signals in the GPS band.

$$Margin = P_{Threshold} - (P_{Signal} - MIPL) \quad (5)$$

The worst-case signal listed in table 12 has a negative value and could prevent a GPS receiver from acquiring a navigation solution. The margins will be worse on smaller commuter and general aviation aircraft. The signal is shown in figure 14 at the far right of the trace. This signal was observed 9 minutes earlier on the same flight, (second entry in table 12), indicating that the signal was present for an extended period of time. The signal was not observed on the other four traces taken during the flight.

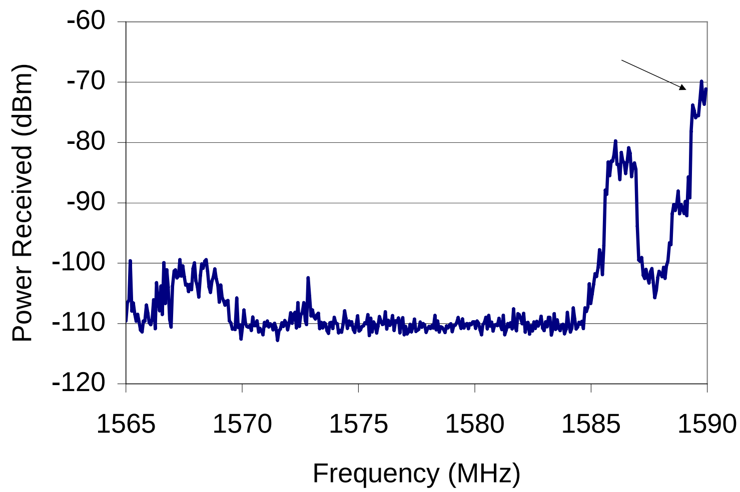

FIGURE 14. POTENTIAL INTERFERENCE SIGNAL

The third entry in table 12 was observed during flight 3 and is presented in figure 15. It is notable for being within 6 dB of the potential to cause interference and its characteristic shape.

In considering the safety margins presented in table 12, it must be noted that the locations of the signals are not known. The data in appendix A and in reference 18 suggest that gradients exist for signals in an aircraft cavity. Furthermore, given the reverberant nature of the aircraft cabin, one cannot eliminate the possibility that recorded signals were observed in a null. Thus, some of the values provided in table 12 may be undervalued.

Twelve signals were identified as having a safety margin less than 20 dB. Given that the GPS band was only monitored about 7% of the time, this leads to an estimate of 176 signals on 37 revenue flights or a rate of five signals per flight with safety margins less than 20 dB.

Considering the emphasis that the FCC and avionics community places on limiting emissions in this band, it is unsettling to see such a high rate.

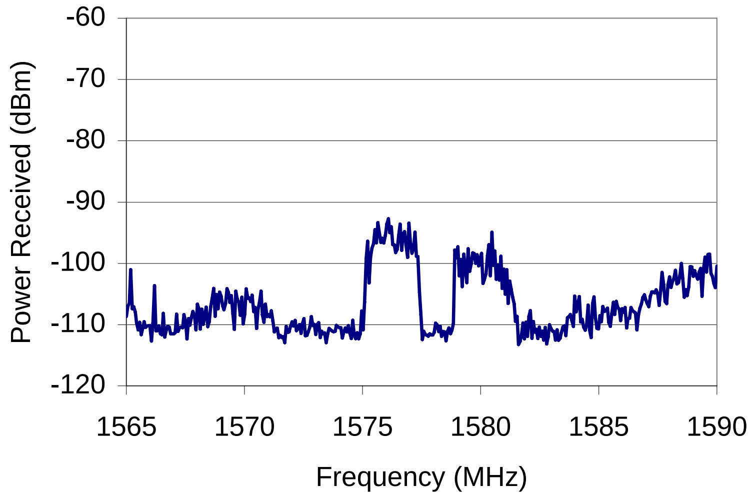

FIGURE 15. SIGNALS OF INTEREST IN THE GPS L1 BAND

It is unknown where the potentially interfering signals originated from. However, current data indicates cellular phones as one potential source of interference [8]. Given the demonstrated high activity level of cellular phone use onboard, it is possible that the detected signals are coming from these devices.

6.2.4 Summary.

It is likely that GPS will play a much greater role in future systems for navigation and precision approach. The FAA is aggressively implementing GPS into critical aviation functions [28]. This includes navigation in the en route, terminal area, approach and landing, and surface operating regimes. Obviously, the importance of protecting the purity of GPS navigation from on-aircraft or off-aircraft interference sources has been amplified.

The potential for GPS interference takes on new criticality in the context of precision approach. The needed exposure times on approach are relatively short (~150 seconds), but system continuity and integrity requirements are stringent [31].

The observed signal with a negative margin, the potential of undervalued signals, and the high rate of observed signals all suggest that this is an issue that warrants careful future attention.

6.3 INDUSTRIAL, SCIENTIFIC, AND MEDICAL.

As the name implies, the industrial, scientific, and medical bands are used for those applications. Currently there are two bands frequently used for commercial electronics, the 900-MHz ISM (902-928 MHz) and 2.4-GHz ISM (2.4-2.4835 MHz). The guidance for products in these bands is provided in FCC Part 18. There are no licenses required or power limitations in these bands, but there are strict limitations on out-of-band emissions.

Under FCC Part 15 rules, transmitting devices can also use the ISM bands, but must transmit below prescribed emission limits. The 900-MHz ISM band is used mostly for portable phones, microwave ovens, and other household products. However, the 900-MHz band has also been used for aircraft baggage smoke detector systems.[8]

The 2.4-GHz ISM band is heavily used in today's electronics and computer markets. The products found using this frequency band use the 802.11b and Bluetooth wireless standards. As with the 900-MHz ISM band, the 2.4-GHz ISM band is being considered for use with wireless avionics. These are attractive solutions for retrofitting, since installing wiring throughout an aircraft is a formidable task and costly.

Both of these bands were of interest for monitoring because they permit T-PEDs and have avionics uses. The ability to determine how to use these bands and at what flight phases was desirable.

6.3.1 The 900-MHz Band.

There were 127 data charts taken during 30 revenue flights. This represents approximately 2 hours of monitoring. There were four data charts taken during the 1 nonrevenue maintenance flight (no passengers). The cumulative summary of the 900-MHz ISM band is provided in figure 16. Notice that the average value is somewhat elevated above the minimum values, indicating more activity.

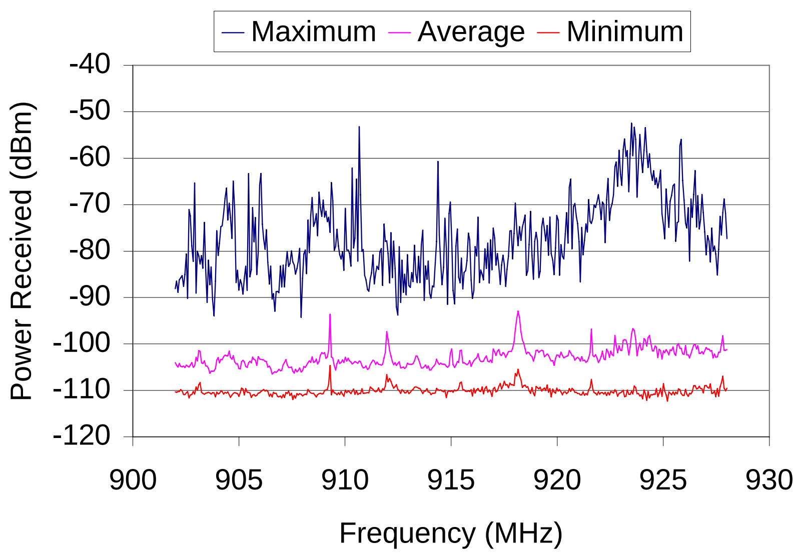

FIGURE 16. THE 900-MHz ISM BAND SUMMARY

There was activity observed during all flights. The right-hand side of figure 16 around 924 MHz has the most activity. The signals are probably emanating from the ground and are not due to passenger use of PEDs. There are permitted transmissions by ham radio operators and television

[8] Securaplane ST3000 Smoke Detection System.

remote uplinks in this frequency band that could be contributing to the overall signal content. The highest received power level was -52.25 dBm and was a narrow band.

It was not possible with the existing data to determine if any of the observed emissions originated onboard. It is interesting and relevant to the onboard RF environment regardless of where the signals originate from. They are consistently seen on flights at appreciable levels.

6.3.2 The 2.4-GHz Band.

There were 129 data charts taken during 30 revenue flights in the 2.4-GHz band. This represents approximately 2 hours of in-flight monitoring. There were four data charts taken during the 1 nonrevenue maintenance flight (no passengers). The maintenance flight was unremarkable.

The cumulative summary of the 2.4-GHz ISM band is provided in figure 17. The maximums are likely composed mostly of narrow-band signals deriving from 802.11 or Bluetooth type signals. The maximum received signal was -44.26 dBm.

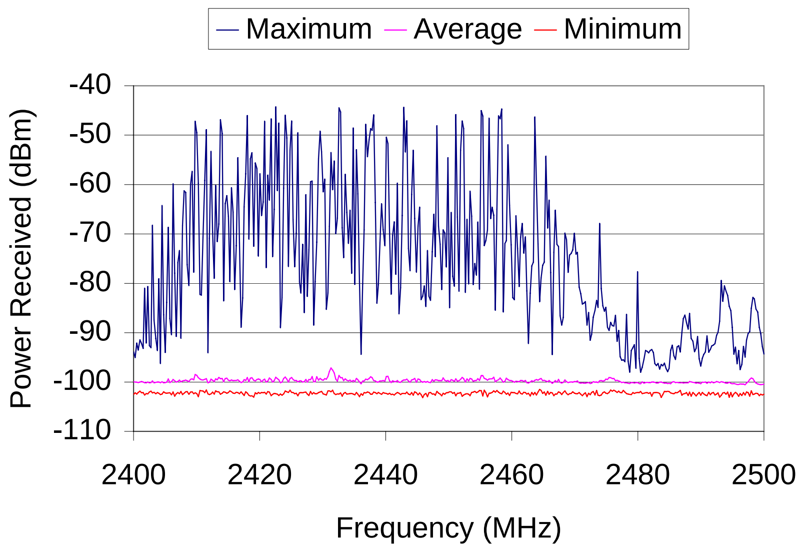

FIGURE 17. THE 2.4-GHz ISM BAND SUMMARY

Activity was observed on 11 of 30 flights (33%). Of the 11 flights observed with activity, only two showed activity during a PED use-prohibited time period. A summary of the observations is provided in table 13. Activity during approved PED use time was seen 25% of the time. This largely derived from observations of the 11 flights where activity was observed throughout the PED-approved period. This finding suggests that passengers were using wireless devices in this range throughout the flights.

TABLE 13. THE 2.4-GHz ISM BAND SUMMARY OF ACTIVITY

PED Use	Data Charts Recorded	Charts With Activity
Allowed	113	28
Prohibited	16	2
Total	129	30

Use of wireless devices during prohibited periods was observed only twice, and both occurrences were during approach and landing. This indicates that passengers may not immediately terminate use of their wireless devices when requested. No use was observed during takeoff and climb out. Generally, the data support the conclusion that passengers are complying with airline policies to not turn on devices until they have reached cruising altitude. This conclusion does not extend to cellular phone use, as described in section 6.1.

6.4 VERY HIGH-FREQUENCY OMNI-DIRECTIONAL RANGE AND ILS FREQUENCY BANDS.

The 108-118 and 329-335 MHz bands are used by commercial aviation for VOR and ILS. VOR is the primary navigation aid used in commercial aviation today and operates on frequencies between 108.00-117.95 MHz. The ILS has two components, the LOC and GS. The LOC provides horizontal guidance during landing and operates at frequencies between 108.10-111.95 MHz. The GS provides vertical guidance during landing and operates between 329.15-335.00 MHz.

As previously noted, the observations made in the GS band were dominated by large amounts of interference generated from the instrumentation itself. Monitoring of this band was terminated after flight 20. The data taken in this band has been determined to be unusable for this evaluation.

There were 242 data charts taken during 30 revenue flights. This represents approximately 3:41 hours of in-flight monitoring. There were four data charts taken during the one nonrevenue maintenance flight (no passengers). The 108-118 MHz band produced three observations.

a. Most in-flight traces contained only a few narrow-band signals. The ground VOR stations were identifiable on the traces; however, exact aircraft locations were not known so correlation of the ground VOR stations to specific narrow-band signals was not possible. No further analysis was performed on the narrow-band signals.

b. Many flights showed an elevated measurement floor. Generally, this was observed for an entire flight and did not correlate to say low versus high altitude. Two in-flight charts are compared in figure 18 to demonstrate an elevated measurement floor. The indication is that particular aircraft may have characteristic emissions or instrumentation location that may be causing the broadband noise. It is noteworthy that the instrumentation was placed in the overhead compartments located near aircraft wiring and electronics (in-flight entertainment systems, lighting, etc.). The close proximity to these systems could be creating the appearance of high-emission levels.

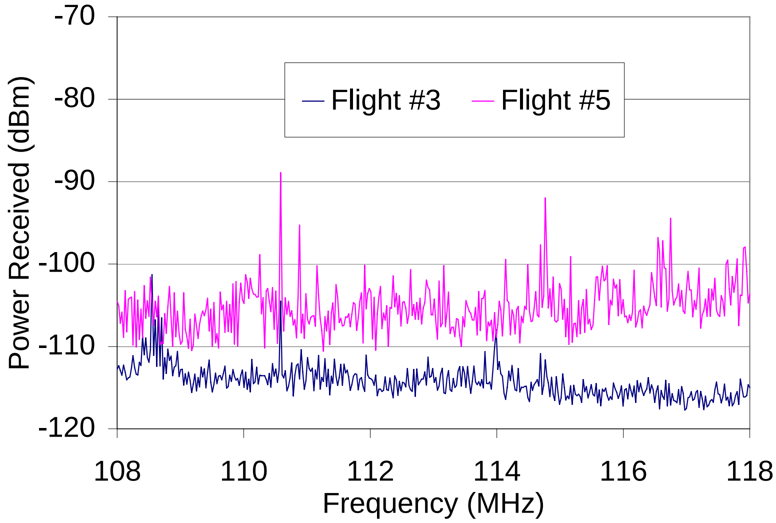

FIGURE 18. EXAMPLE OF A FLIGHT WITH AN ELEVATED MEASUREMENT FLOOR

c. There were three flights that produced a distinct noise pattern. These flights (17, 28, and 35) involved different aircraft models, different airports, and different locations of the instrumentation package. This leads to the conclusion that the instrumentation either generated this noise under certain conditions that could not be established or that a high-level emission was received causing the amplifier to saturate raising the measurement floor and exposing a characteristic emission from the instrumentation not normally observed. The observed pattern is demonstrated in figure 19.

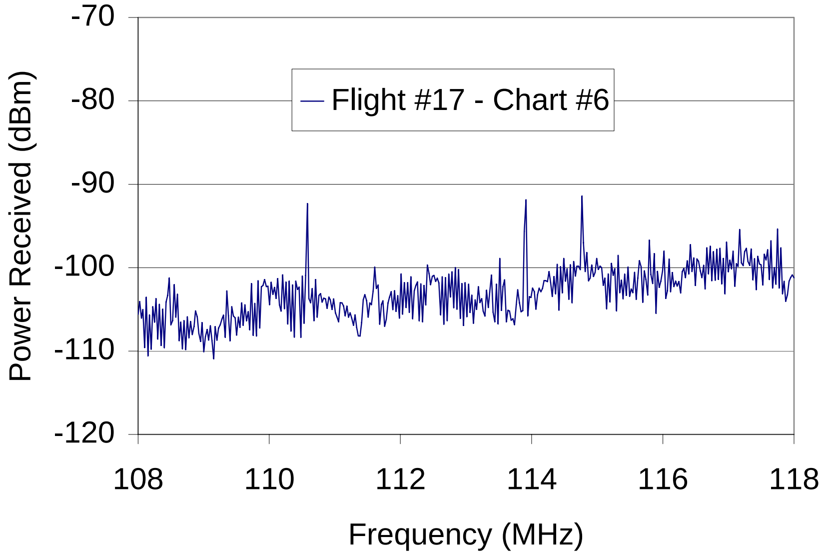

FIGURE 19. EXAMPLE OF AN UNIDENTIFIED NOISE PATTERN OBSERVED ON THREE FLIGHTS

7. SUMMARY.

This study provides the first reported characterization of the radio frequency (RF) environment in the cabins of commercial airline flights. Key findings are as follows:

a. Cellular telephone calls were observed in all phases of flight at a rate conservatively estimated to be approximately one call per flight.

b. Onboard cellular telephone activity was observed on all flights and at a rate estimated to be one signal per minute.

c. Considerable onboard RF activity was observed in the Global Positioning System (GPS) L1 band, some of which appeared to have field strengths that, under appropriate circumstances, could result in interference with aircraft GPS equipment.

d. Because of the likely growing future dependence on GPS for commercial aircraft navigation and precision approach, the emissions observed in the GPS L1 band are the most troubling. It is very likely that many of these emissions are associated with the use of cellular telephones.

e. Elevated broadband noise was observed on many occasions in the very high-frequency omni-directional range (VOR) and Instrument Landing System (ILS) band, but it has not been possible to determine the source of these signals, or to definitely rule out an instrumentation artifact. At least some of these observations appear to be unique to specific aircraft.

f. While spectral measurements gave no indication of passengers using wireless devices other than cellular phones during takeoff, such use was observed during approach well after the portable electronic devices-prohibited cabin announcement.

The above findings carry implications for both future research and public use of cell phones onboard aircraft. Before the industry moves forward with the installation of onboard pico-cells for telephone and data use, significantly more field measurement and careful analysis of the potential for interference, especially in the GPS bands, is urgently needed. These studies should include a consideration of the implications of having many onboard transmitters, some of which will likely transmit at relatively high power levels, and the potential risks posed by intermodulation.

While the measurements reported here do not allow firm conclusions about the elevated emission levels in the VOR/ILS band, previous analysis of the Aviation Safety Reporting System database suggests that interference occurs and may be linked to these elevated emission levels. This issue deserves future studies with instrumentation more suitable to these frequencies, beginning with studies to establish the nature and variation of contributions made by aircraft themselves.

8. REFERENCES.

1. RTCA DO-119, "Interference to Aircraft Electronic Equipment from Devices Carried Aboard," RTCA, Inc., Washington, DC, 1963.

2. FAA Grant 01-C-AW-CMU, "In-Flight RF Spectrum Measurements of Commercial Aircraft Cabins," issued June 27, 2002.

3. RTCA DO-199, "Potential Interference to Aircraft Electronic Equipment from Devices Carried Onboard," RTCA, Inc., Washington, DC, September 1988.

4. RTCA DO-233, "Portable Electronic Devices Carried on Board Aircraft," RTCA, Inc., Washington, DC, August 1996.

5. CAA Report 9/40:23-90-02, "Interference Levels in Aircraft at Radio Frequencies Used by Portable Telephones," West Sussex, UK, May 2000.

6. CAA Paper 2003/3, "Effects of Interference from Cellular Telephones on Aircraft Avionic Equipment," West Sussex, UK, 2003.

7. NASA/TP-2003-212446, "Wireless Phone Threat Assessment and New Wireless Technology Concerns for Aircraft Navigation Radios," NASA Langley Research Center, Hampton, VA, July 2003.

8. NASA/TM-2004-213001, "Evaluation of a Mobile Phone for Aircraft GPS Interference," NASA Langley Research Center, Hampton, VA, March 2004.

9. NASA/TP-2003-212438, "Portable Wireless LAN Device and Two-Way Radio Threat Assessment for Aircraft Navigation Radios," NASA Langley Research Center, Hampton, VA, July 2003.

10. RTCA DO-160D, "Environmental Conditions and Test Procedures for Airborne Equipment," RTCA, Inc., Washington DC, July 1997.

11. NASA/CR-2001-210866, "Portable Electronic Devices and Their Interference with Aircraft Systems," NASA Langley Research Center, Hampton, VA, June 2001.

12. Strauss, B., "Avionics Interference from Portable Electronic Devices: Review of the Aviation Safety Reporting System Database," *21st Digital Avionics Systems Conference Proceedings*, October 2002.

13. McDonald, N. and Johnston, N., "Applied Psychology and Aviation: Issues of Theory and Practice," *Aviation Psychology in Practice*, Neil Johnston, Nick McDonald, and Ray Fuller, eds., Ashgate Publishing Company, Brookfield, Vermont, Chapter 1, 1995, pp. 8.

14. Helfrick, A. and Wilson, A., "Investigation Into a System for the Detection and Location of Potentially Harmful Radiation From Portable Electronics Carried Onboard Aircraft," *17th Digital Avionics Systems Conference Proceedings*, Vol. 1, October 1998, pp. D47/1-8.

15. MegaWave Corporation, "Determination of the Technical and Operational Feasibility of Implementing a Portable Electronic Device Detection System on Air Transport Category Aircraft: Final Technical Report," Boylston, MA, 1998.

16. Woods, R., Ely, J., and Vahala, L., "Detecting the Use of Intentionally Transmitting Personal Electronic Devices Onboard Commercial Aircraft," *2003 IEEE EMC Symposium Proceedings,* Vol. 1, August 2003, pp. 263-8.

17. Rappaport, T., *Wireless Communications: Principles and Practice*, Prentice Hall, Upper Saddle River, NJ, 1999.

18. Johnson, M.D., et al., "Phase II Demonstration Test of the Electromagnetic Reverberation Characteristics of a Large Transport Aircraft," Naval Surface Weapons Center, Dahlgren Division, Dahlgren, VA, September 1997.

19. Freyer, G.J. and Hatfield, M.O., "Aircraft Test Applications of Reverberation Chambers," *1994 IEEE International EMC Symposium Proceedings*, 1994, pp. 491-6.

20. Johnson, M.D., et al., "Comparison of RF Coupling to Passenger Aircraft Avionics Measured on a Transport Aircraft and in a Reverberation Chamber," *1998 IEEE International EMC Symposium Proceedings*, Vol. 2, 1998, pp. 1047-52.

21. Freyer, G.J., Hatfield, M.O., and Slocum, M.B., "Characterization of the Electromagnetic Environment in Aircraft Cavities Excited by Internal and External Sources," *15th Digital Avionics Systems Conference*, October 1996, pp. 327-332.

22. NTIA Report 95-321, "Broadband Spectrum Survey at Denver, Colorado," U.S. Department of Commerce, September 1995.

23. Freyer, Gustav J., et al., "Shielding Effectiveness Measurements for a Large Commercial Aircraft," *1995 IEEE EMC Symposium Conference Record*, August 1995, pp. 383-86.

24. Haykin, S., *Communication Systems*, 4th Edition, John Wiley and Sons, Inc., New York, 2001.

25. Fuller, G. and Horton, K., "Protecting GPS Availability From EMI," *2000 Digital Avionics Systems Conference Proceedings*, Vol. 1, October 2000, pp. 3C2/1-7.

26. Landry, R. and Renard, A., "Analysis of Potential Interference Sources and Assessment of Present Solutions for GPS/GNSS Receivers," *Proceedings of the 4th Saint Petersburg International Conference on Integrated Navigation Systems*, St. Petersburgh, Russia, May 1996.

27. Owen, J.I.R., "A Review of the Interference Resistance of SPS GPS Receivers for Aviation," Defense Research Agency, 1992.

28. Geyer, M. and Frazier, R., "FAA GPS RFI Mitigation Program," ION GPS 99, Nashville TN, September 1999.

29. Winer, B.M., et al., "GPS Receiver RFI Laboratory Tests," *Proceedings of the Institute of Navigation National Technical Meeting*, Santa Monica, CA, January 1996.

30. Johnston, K.D., "Analysis of Radio Frequency Interference Effects on a Modern Coarse Acquisition Code Global Positioning System (GPS) Receiver," Thesis, Air Force Institute of Technology, Wright Patterson AFB, OH, ADA36 Volume 1, March 1999.

31. Erlandson, R.J., "Susceptibility of GNSS Sensors to RFI," *15th Digital Avionics Systems Conference*, October 1996, pp. 273-278.

32. Hegarty, et al., "Suppression of Pulsed Interference through Blanking," *Proceedings of the IAIN World Congress*, San Diego, CA, June 2000.

33. RTCA DO-235A, "Assessment of Radio Frequency Interference Relevant to the GNSS," RTCA, Inc., Washington, DC, December 2002.

APPENDIX A—INSTRUMENTATION PERFORMANCE RESULTS ONBOARD A BOEING 737-300 AIRCRAFT

The instrumentation in its final configuration was tested onboard a Boeing 737-300 aircraft at Pittsburgh International Airport on April 28-29, 2003. A log-periodic Antenna Research LPD-3500 antenna was placed at the beginning of the coach class of the aircraft (row 3) and pointed towards the rear of the aircraft. A 0 dBm signal was provided by a signal generator. Line losses were minimal, but accounted for.

Measurements were recorded by the instrumentation at six locations (rows 5, 7, 9, 13, 16, and 19) for overhead compartment and underseat placement. The underseat placement was varied between aisle, middle, and window seat locations. A test personnel was seated above the instrumentation to simulate potential in-flight conditions.

Previous research [A-1 through A-4] suggests that directionality and polarization effects are minimized by the reverberant characteristics of the aircraft cabin. However, figures A-1 through A-8 demonstrate that there are gradients and approximately follow free-space losses (n = 2). The deviations from the free-space model are likely data recorded in the reverberant cavity nulls.

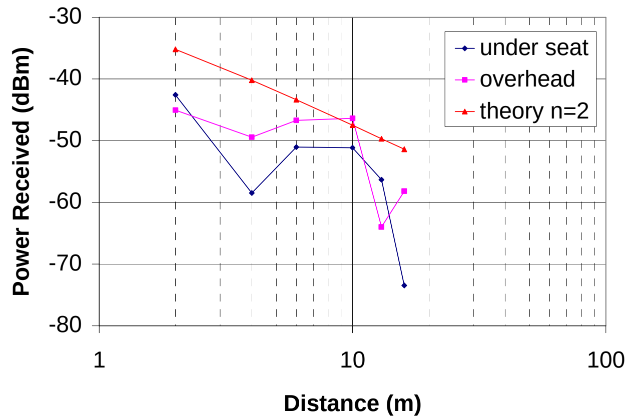

FIGURE A-1. DATA TAKEN ON A B-737 AT 113 MHz

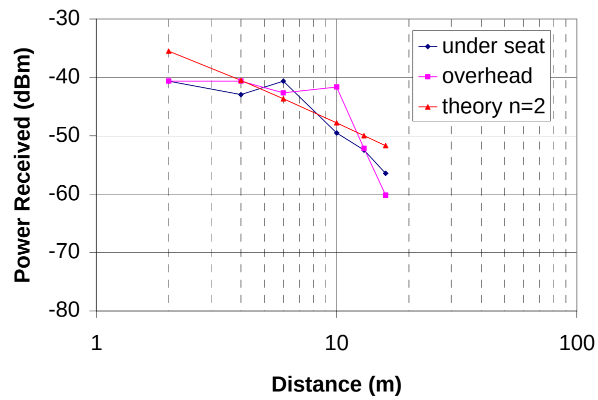

FIGURE A-2. DATA TAKEN ON A B-737 AT 332 MHz

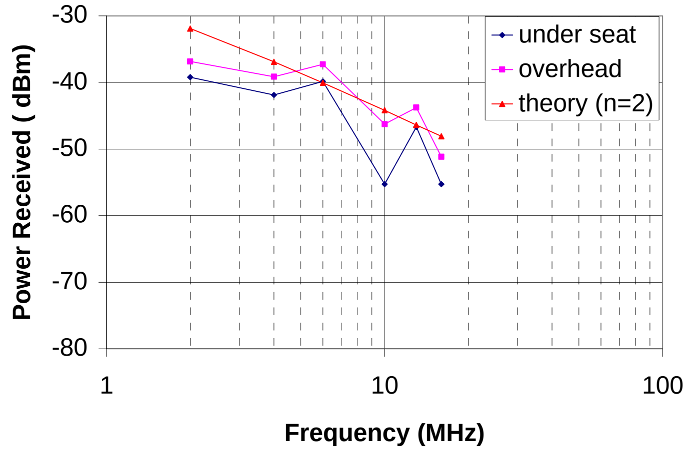

FIGURE A-3. DATA TAKEN ON A B-737 AT 836 MHz

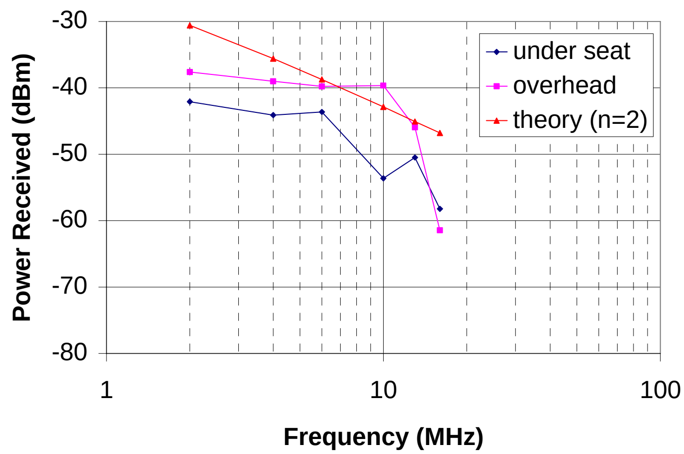

FIGURE A-4. DATA TAKEN ON A B-737 AT 915 MHz

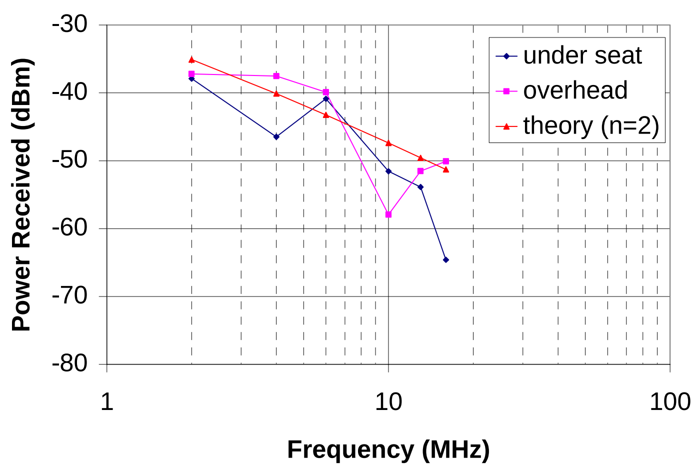

FIGURE A-5. DATA TAKEN ON A B-737 AT 1227 MHz

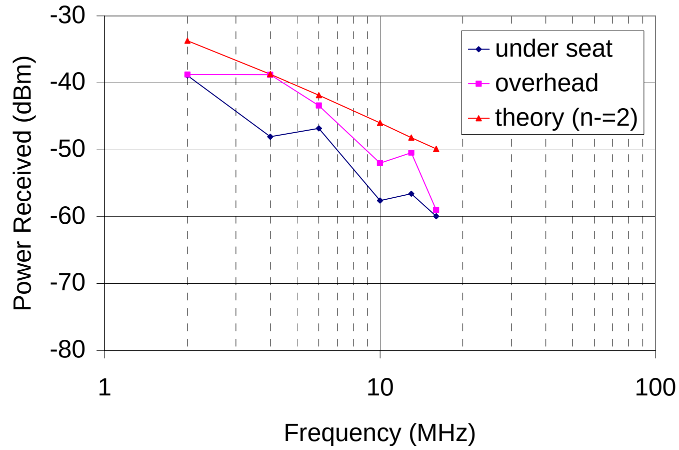

FIGURE A-6. DATA TAKEN ON A B-737 AT 1577 MHz

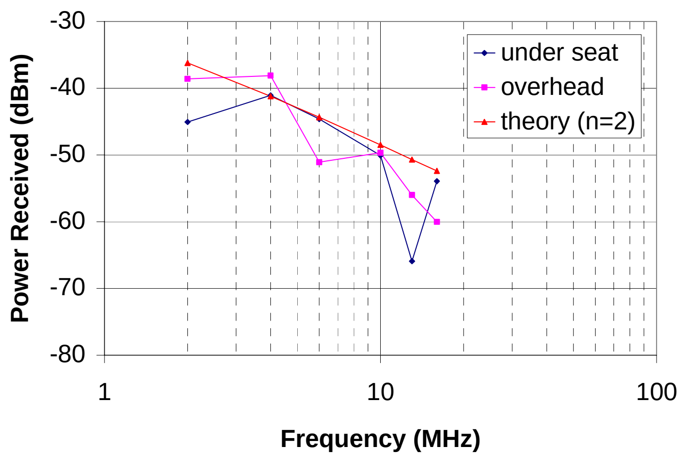

FIGURE A-7. DATA TAKEN ON A B-737 AT 1880 MHz

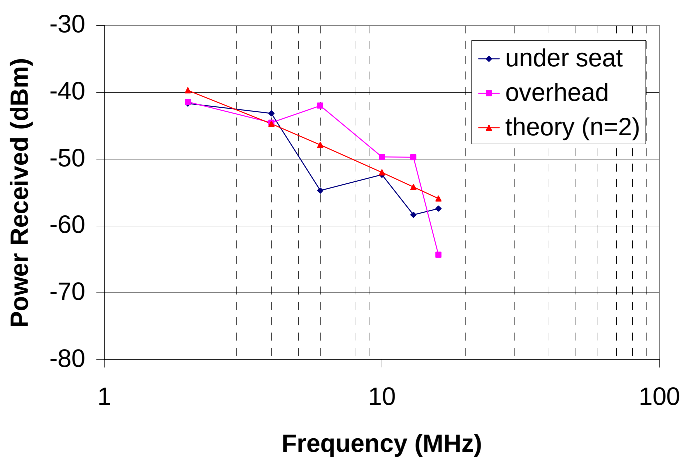

FIGURE A-8. DATA TAKEN ON A B-737 AT 2450 MHz

REFERENCES.

A-1. Johnson, M.D., et al., "Phase II Demonstration Test of the Electromagnetic Reverberation Characteristics of a Large Transport Aircraft," Naval Surface Weapons Center, Dahlgren Division, Dahlgren, VA, September 1997.

A-2. Freyer, G.J. and Hatfield, M.O., "Aircraft Test Applications of Reverberation Chambers," *1994 IEEE International EMC Symposium Proceedings*, 1994, pp. 491-6.

A-3. Johnson, M.D., et al., "Comparison of RF Coupling to Passenger Aircraft Avionics Measured on a Transport Aircraft and in a Reverberation Chamber," *1998 IEEE International EMC Symposium Proceedings*, Vol. 2,1998, pp. 1047-52.

A-4. Freyer, G.J., Hatfield, M.O., and Slocum, M.B., "Characterization of the Electromagnetic Environment in Aircraft Cavities Excited by Internal and External Sources," *15th Digital Avionics Systems Conference*, October 1996, pp. 327-332.

APPENDIX B—CELLULAR PHONE CHANNELS

The tables presented in this appendix provide information on the cellular channels in the cellular and Personal Communications Systems (PCS) bands. The information in table B-1 was used to identify calls verses registrations in the cellular band. The information in tables B-2 and B-3 was used to identify Code Division Multiple Access (CDMA) signals. Finally, the Global System for Mobile Communications (GSM) channels used in the PCS band are provided in table B-4, but this information was not specifically used in the analysis.

TABLE B-1. CELLULAR BAND AMPS AND TDMA CHANNEL ASSIGNMENTS

Channel	Frequency (MHz)	Band	Control/Voice
991-1023	824.04 - 825.00	A	Voice
1-312	825.03 - 834.36	A	Voice
313-334	834.39 - 834.99	A	Control
335-356	835.02 - 835.62	B	Control
357-666	835.65 - 844.98	B	Voice
667-716	845.01 - 846-48	A	Voice
717-799	846.51 - 848.97	B	Voice

TABLE B-2. CELLULAR BAND CDMA CHANNEL ASSIGNMENTS

CDMA Channel	AMPS/TDMA Channel		Frequency (MHz)	
	Lower	Upper	Start	Stop
1019	999	16	824.28	825.48
037	17	57	825.51	826.71
078	58	98	826.74	827.94
119	99	139	827.97	829.17
160	140	180	829.20	830.40
201	181	221	830.43	831.63
242	222	262	831.66	832.86
283	263	303	832.89	834.09
384	364	404	835.92	837.12
425	405	445	837.15	838.35
466	446	486	838.38	839.58
507	487	527	839.61	840.81
548	528	568	840.84	842.04
589	569	609	842.07	843.27
630	610	650	843.30	844.50
691	671	711	845.13	846.33
777	757	797	847.71	848.91

Amps = Advanced Mobile Phone Service.
TDMA = Time Division Multiple Access.

TABLE B-3. PCS BAND CDMA CHANNEL ASSIGNMENTS

Block	CDMA Channels[1]	Frequency (MHz)	
		Start	Stop
A	25, 50, 75, 100, 125, 150, 175, 200, 225, 250, 275	1850	1865
D	325, 350, 375	1865	1870
B	425, 450, 475, 500, 525, 550, 575, 600, 625, 650, 675	1870	1885
E	725, 750, 775	1885	1890
F	825, 850, 875	1890	1895
C	925, 950, 975, 1000, 1025, 1050, 1075, 1100, 1125, 1150, 1175	1895	1910

Note: 1. Center Frequency = Channel Number * 50 kHz + 1850.00 MHz.

TABLE B-4. PCS BAND GSM CHANNEL ASSIGNMENTS

GSM Channel	Frequency (MHz)	
	Start	Stop
512	1850.20	1850.40
513	1850.40	1850.60
514	1850.60	1850.80
•	•	•
•	•	•
•	•	•
808	1909.20	1909.40
809	1909.40	1909.60
810	1909.60	1909.80

Note: 1. GSM Start Frequency = 1850.20+0.2*(absolute radio frequency channel number 512)

2. Channel Width = 200 kHz

APPENDIX C—IDENTIFIED ONBOARD CELLULAR SIGNALS

Tables C-1 to C-4 identify all the observed onboard signals as determined by the analysis described in section 6.1. The column titled Margin refers to the measured level above the onboard threshold described in section 6.1.4. Received power is the measured value at the instrumentation and adjusted accounts for measurement undervaluing of wideband signals.

TABLE C-1. NARROW-BAND SIGNALS IN THE CELLULAR BAND

Flight No.	Frequency (MHz)	Altitude (ft)	Received Power (dBm)	Onboard Threshold (dBm)	Margin (dB)	Signal Type
36	847.68	18,903	-40.843	-78.368	37.525	call
35	838.66	27,050	-54.275	-81.481	27.206	call
6	825.07	6,978	-44.447	-69.712	25.265	call
36	848.56	28,897	-58.767	-82.054	23.287	call
30	824.69	12,227	-55.514	-74.584	19.070	call
25	836.91	30,867	-74.679	-82.627	7.948	call
25	833.02	35,000	-80.763	-83.719	2.956	call
25	833.02	35,000	-80.833	-83.719	2.886	call
3	835.15	26,000	-38.995	-81.137	42.142	registration
38	835.47	29,827	-42.832	-82.330	39.498	registration
6	835.34	29,000	-46.202	-82.085	35.883	registration
14	834.46	8,437	-37.638	-71.362	33.724	registration
23	835.03	8,665	-38.340	-71.593	33.253	registration
15	834.90	8,267	-39.556	-71.184	31.628	registration
8	834.53	5,718	-43.909	-67.983	24.074	registration
14	834.40	2,025	-37.684	-58.966	21.282	registration
14	834.96	4,082	-51.841	-65.055	13.214	registration
24	834.53	29,000	-75.755	-82.085	6.330	registration
8	834.46	9,738	-71.497	-72.606	1.109	registration

TABLE C-2. WIDE-BAND SIGNALS IN THE CELLULAR BAND

Flight No.	CDMA Channel	Altitude (ft)	Max P_r[1] (dBm)	Adjusted[2] (dBm)	Onboard Threshold (dBm)	Margin (dB)
12	425	29,000	-44.096	-34.686	-82.085	47.399
25	425	35,000	-46.389	-36.979	-83.719	46.740
19	548	35,000	-46.600	-37.190	-83.719	46.529
25	507	35,000	-47.115	-37.705	-83.719	46.014
24	384	29,000	-46.179	-36.199	-82.085	45.886
25	589	35,000	-47.466	-38.056	-83.719	45.663
25	384	35,000	-47.770	-38.360	-83.719	45.359
23	384	28,000	-46.623	-36.643	-81.781	45.138
2	384	29,000	-46.904	-37.494	-82.085	44.591
6	507	29,000	-46.951	-37.541	-82.085	44.544
25	589	35,000	-48.776	-39.366	-83.719	44.353
13	466	29,300	-47.395	-37.985	-82.175	44.190
3	466	26,000	-46.647	-37.237	-81.137	43.900
34	242	21,826	-46.225	-36.245	-79.617	43.372
24	384	29,000	-48.893	-38.913	-82.085	43.172
7	242	31,000	-49.689	-39.709	-82.665	42.956
17	384	20,067	-45.547	-36.137	-78.887	42.750
18	425	29,000	-49.431	-40.021	-82.085	42.064
25	466	24,508	-48.214	-38.804	-80.624	41.820
19	384	35,000	-51.490	-42.080	-83.719	41.639
32	425	19,512	-47.442	-37.462	-78.643	41.181
2	384	19,357	-46.810	-37.400	-78.574	41.174
6	384	28,957	-50.367	-40.957	-82.073	41.116
6	548	28,957	-50.437	-41.027	-82.073	41.046
5	425	17,524	-46.389	-36.979	-77.710	40.731
23	384	28,000	-51.163	-41.183	-81.781	40.598
9	384	23,801	-49.221	-39.811	-80.369	40.558
25	466	35,000	-52.941	-43.531	-83.719	40.188
10	425	17,444	-47.208	-37.798	-77.670	39.872
6	425	18,080	-47.793	-38.383	-77.981	39.598
7	507	31,000	-53.175	-43.195	-82.665	39.470
38	201	23,678	-50.531	-41.121	-80.324	39.203
23	384	28,000	-53.152	-43.172	-81.781	38.609
5	384	17,524	-48.916	-39.506	-77.710	38.204
23	425	28,000	-53.596	-43.616	-81.781	38.165
23	384	28,000	-53.737	-43.757	-81.781	38.024
1	283	13,000	-46.530	-37.120	-75.116	37.996
13	548	31,000	-54.135	-44.725	-82.665	37.940
14	201	35,000	-55.280	-45.870	-83.719	37.849

Note: 1. The maximum power-received measurement.
2. Adjusted to account for measurement setup undervalue.

TABLE C-2. WIDE-BAND SIGNALS IN THE CELLULAR BAND (Continued)

Flight No.	CDMA Channel	Altitude (ft)	Max P_r[1] (dBm)	Adjusted[2] (dBm)	Onboard Threshold (dBm)	Margin (dB)
38	384	31,000	-54.439	-45.029	-82.665	37.636
19	160	14,667	-48.191	-38.781	-76.164	37.383
34	283	21,514	-52.192	-42.212	-79.492	37.280
7	242	25,408	-53.713	-43.733	-80.937	37.204
38	384	26,440	-53.526	-44.116	-81.283	37.167
23	425	28,000	-54.252	-44.842	-81.781	36.939
24	425	29,000	-55.397	-45.417	-82.085	36.668
8	384	27,883	-54.930	-45.520	-81.744	36.224
7	425	17,611	-51.841	-41.861	-77.753	35.892
24	384	29,000	-56.216	-46.236	-82.085	35.849
34	384	20,821	-53.596	-43.616	-79.207	35.591
34	384	20,884	-53.690	-43.710	-79.234	35.524
24	384	29,000	-57.012	-47.032	-82.085	35.053
24	425	29,000	-57.152	-47.172	-82.085	34.913
10	384	33,000	-57.925	-48.515	-83.208	34.693
23	425	28,000	-57.199	-47.219	-81.781	34.562
29	283	9,557	-48.425	-38.445	-72.444	33.999
34	283	21,557	-55.631	-45.651	-79.509	33.858
19	589	35,000	-59.446	-50.036	-83.719	33.683
25	507	14,866	-52.146	-42.736	-76.281	33.545
9	384	6,510	-45.126	-35.716	-69.109	33.393
13	425	19,667	-54.930	-45.520	-78.712	33.192
2	466	9,162	-48.448	-39.038	-72.077	33.039
34	119	7,139	-46.951	-36.971	-69.910	32.939
19	242	14,667	-52.941	-43.531	-76.164	32.633
5	589	26,000	-57.971	-48.561	-81.137	32.576
9	425	6,510	-46.038	-36.628	-69.109	32.481
13	384	19,667	-55.865	-46.455	-78.712	32.257
19	283	14,667	-53.386	-43.976	-76.164	32.188
34	201	10,767	-52.099	-42.119	-73.479	31.360
13	630	29,300	-60.265	-50.855	-82.175	31.320
6	384	18,080	-56.872	-47.462	-77.981	30.519
18	425	20,440	-58.510	-49.100	-79.047	29.947
22	283	33,000	-62.839	-53.429	-83.208	29.779
25	630	5,492	-48.285	-38.875	-67.632	28.757
14	283	35,000	-64.383	-54.973	-83.719	28.746
25	283	10,667	-54.111	-44.701	-73.398	28.697
3	384	21,194	-60.405	-50.995	-79.362	28.367
27	384	11,128	-54.813	-45.403	-73.766	28.363

Note: 1. The maximum power-received measurement.
2. Adjusted to account for measurement setup undervalue.

TABLE C-2. WIDE-BAND SIGNALS IN THE CELLULAR BAND (Continued)

Flight No.	CDMA Channel	Altitude (ft)	Max P_r[1] (dBm)	Adjusted[2] (dBm)	Onboard Threshold (dBm)	Margin (dB)
24	384	29,000	-64.055	-54.075	-82.085	28.010
30	384	9,200	-54.111	-44.701	-72.113	27.412
24	425	29,000	-64.828	-54.848	-82.085	27.237
37	384	3,414	-46.296	-36.316	-63.503	27.187
5	466	26,000	-64.336	-54.926	-81.137	26.211
5	589	26,000	-64.711	-55.301	-81.137	25.836
19	119	14,667	-59.820	-50.410	-76.164	25.754
19	201	14,667	-59.960	-50.550	-76.164	25.614
5	548	10,270	-57.527	-48.117	-73.069	24.952
34	384	7,139	-55.140	-45.160	-69.910	24.750
12	384	13,867	-60.452	-51.042	-75.677	24.635
11	384	17,906	-62.768	-53.358	-77.897	24.539
12	425	6,129	-54.369	-44.959	-68.585	23.626
22	384	33,000	-69.578	-59.598	-83.208	23.610
30	283	25,888	-67.425	-58.015	-81.099	23.084
14	242	35,000	-70.444	-61.034	-83.719	22.685
19	242	7,061	-57.106	-47.696	-69.815	22.119
19	630	35,000	-71.473	-62.063	-83.719	21.656
32	425	29,000	-70.561	-60.581	-82.085	21.504
24	425	24,921	-69.274	-59.294	-80.769	21.475
34	384	7,729	-59.375	-49.395	-70.600	21.205
35	283	16,906	-65.764	-56.354	-77.398	21.044
27	384	6,168	-57.386	-47.976	-68.640	20.664
22	283	33,000	-72.971	-62.991	-83.208	20.217
24	384	29,000	-72.503	-62.523	-82.085	19.562
34	425	2,920	-54.415	-44.435	-62.145	17.710
5	384	10,270	-65.062	-55.652	-73.069	17.417
33	160	27,125	-73.766	-64.356	-81.505	17.149
24	425	29,000	-74.983	-65.003	-82.085	17.082
28	384	8,250	-63.658	-54.248	-71.167	16.919
11	384	9,972	-65.319	-55.909	-72.813	16.904
24	425	20,246	-72.433	-62.453	-78.964	16.511
20	242	5,727	-61.060	-51.650	-67.996	16.346
22	425	6,644	-63.096	-53.116	-69.286	16.170
30	466	12,227	-67.846	-58.436	-74.584	16.148
24	425	3,050	-56.497	-46.517	-62.523	16.006
30	425	9,200	-65.553	-56.143	-72.113	15.970
23	425	3,253	-57.363	-47.953	-63.083	15.130
10	425	3,703	-58.814	-49.404	-64.209	14.805

Note: 1. The maximum power-received measurement.
2. Adjusted to account for measurement setup undervalue.

TABLE C-2. WIDE-BAND SIGNALS IN THE CELLULAR BAND (Continued)

Flight No.	CDMA Channel	Altitude (ft)	Max P_r[1] (dBm)	Adjusted[2] (dBm)	Onboard Threshold (dBm)	Margin (dB)
33	425	21,219	-74.071	-64.661	-79.372	14.711
13	283	19,667	-73.977	-64.567	-78.712	14.145
30	466	9,200	-68.618	-59.208	-72.113	12.905
38	242	10,294	-69.788	-60.378	-73.089	12.711
6	548	29,000	-79.523	-70.113	-82.085	11.972
9	384	15,156	-74.211	-64.801	-76.449	11.648
9	384	31,700	-80.646	-71.236	-82.859	11.623
34	283	5,331	-68.291	-58.311	-67.374	9.063
24	384	29,000	-84.203	-74.223	-82.085	7.862
3	466	770	-52.192	-42.782	-50.567	7.785
11	384	2,039	-60.686	-51.276	-59.026	7.750
34	283	1,518	-59.212	-49.232	-56.463	7.231
24	425	9,050	-76.762	-66.782	-71.970	5.188
25	425	10,227	-77.300	-67.890	-73.032	5.142
13	425	8,750	-77.768	-68.358	-71.678	3.320
6	283	28,957	-88.789	-79.379	-82.073	2.694

Note: 1. The maximum power-received measurement.
2. Adjusted to account for measurement setup undervalue.

TABLE C-3. NARROW-BAND SIGNALS IN THE PCS BAND

Flight No.	Frequency (MHz)	Altitude (ft)	Power Received (dBm)	Onboard Threshold (dBm)	Margin (dBm)
32	1883.83	29,000	-43.605	-89.114	45.509*
2	1906.09	23,500	-45.360	-87.287	41.927
7	1883.23	31,000	-48.776	-89.693	40.917*
16	1895.86	22,688	-49.384	-86.982	37.598
16	1893.46	14,472	-46.623	-83.077	36.454
26	1866.69	23,945	-52.660	-87.451	34.791*
28	1873.16	33,000	-56.310	-90.236	33.926
6	1879.62	9,822	-45.804	-79.710	33.906
2	1905.79	23,500	-54.954	-87.287	32.333
2	1874.36	23,500	-56.029	-87.287	31.258
26	1865.64	11,455	-52.848	-81.046	28.198*
35	1866.84	35,000	-62.815	-90.747	27.932
28	1871.95	33,000	-63.564	-90.236	26.672
36	1866.69	28,242	-64.617	-88.884	24.267
36	1868.05	14,778	-61.107	-83.259	22.152
3	1877.07	3,150	-47.723	-69.832	22.109
20	1865.64	35,000	-69.461	-90.747	21.286
36	1859.32	14,778	-65.272	-83.259	17.987
26	1895.56	22,959	-69.250	-87.085	17.835*
13	1859.47	1,705	-47.419	-64.498	17.079
6	1861.58	526	-39.931	-54.289	14.358
23	1881.88	6,909	-62.581	-76.655	14.074
32	1876.02	5,900	-62.675	-75.283	12.608*
37	1869.40	9,728	-67.987	-79.626	11.639*
4	1881.43	29,000	-77.861	-89.114	11.253
19	1885.49	10,848	-71.660	-80.573	8.913
16	1886.24	31,600	-82.120	-89.860	7.740
2	1906.99	23,500	-79.944	-87.287	7.343
6	1868.95	526	-47.161	-54.289	7.128
28	1873.31	33,000	-83.290	-90.236	6.946
6	1860.08	526	-47.372	-54.289	6.917
38	1869.40	4,100	-65.319	-72.122	6.803
6	1863.98	526	-47.606	-54.289	6.683
31	1866.69	3,076	-63.751	-69.625	5.874*
14	1864.89	35,000	-85.771	-90.747	4.976
2	1850.75	29,000	-84.577	-89.114	4.537
14	1864.89	35,000	-86.285	-90.747	4.462
24	1865.19	29,000	-84.928	-89.114	4.186*
19	1864.89	35,000	-86.870	-90.747	3.877
19	1864.89	35,000	-87.011	-90.747	3.736

* High-resolution protocol data

TABLE C-3. NARROW-BAND SIGNALS IN THE PCS BAND (Continued)

Flight No.	Frequency (MHz)	Altitude (ft)	Power Received (dBm)	Onboard Threshold (dBm)	Margin (dBm)
19	1864.89	35,000	-87.175	-90.747	3.572
35	1864.89	35,000	-87.292	-90.747	3.455
10	1858.27	32,933	-86.894	-90.219	3.325
14	1864.89	35,000	-87.479	-90.747	3.268
6	1864.89	526	-51.233	-54.289	3.056
6	1869.70	526	-51.327	-54.289	2.962
19	1864.89	35,000	-87.853	-90.747	2.894
35	1864.89	35,000	-88.017	-90.747	2.730
28	1868.20	14,117	-80.225	-82.861	2.636
35	1864.89	35,000	-88.157	-90.747	2.590
3	1872.86	3,150	-67.285	-69.832	2.547
35	1864.89	35,000	-88.345	-90.747	2.402
35	1864.89	35,000	-88.438	-90.747	2.309
33	1884.74	8,722	-76.481	-78.679	2.198
25	1865.49	35,000	-88.579	-90.747	2.168
35	1864.89	35,000	-88.649	-90.747	2.098
19	1864.89	34,094	-88.579	-90.520	1.941
24	1865.19	29,000	-87.198	-89.114	1.916*
19	1865.04	32,483	-88.204	-90.099	1.895*
35	1864.89	35,000	-89.140	-90.747	1.607
24	1865.19	24,417	-86.028	-87.620	1.592*
28	1865.04	33,000	-88.719	-90.236	1.517
35	1864.89	35,000	-89.257	-90.747	1.490
6	1852.56	526	-52.894	-54.289	1.395
15	1864.89	33,000	-88.859	-90.236	1.377
28	1865.19	33,000	-88.930	-90.236	1.306
24	1865.04	27,280	-87.292	-88.583	1.291*
19	1865.04	28,089	-87.549	-88.837	1.288*
14	1864.89	27,800	-87.502	-88.747	1.245
28	1865.04	33,000	-89.070	-90.236	1.166
24	1865.19	29,000	-87.994	-89.114	1.120*
19	1864.89	35,000	-89.632	-90.747	1.115
24	1865.19	29,000	-88.017	-89.114	1.097*
35	1864.89	35,000	-89.749	-90.747	0.998
19	1865.04	31,667	-88.906	-89.878	0.972*
33	1855.71	35,000	-89.795	-90.747	0.952
10	1884.74	15,639	-82.892	-83.750	0.858
18	1898.57	29,000	-88.274	-89.114	0.840
24	1865.19	29,000	-88.345	-89.114	0.769*
9	1886.54	33,000	-89.538	-90.236	0.698

* High-resolution protocol data

TABLE C-3. NARROW-BAND SIGNALS IN THE PCS BAND (Continued)

Flight No.	Frequency (MHz)	Altitude (ft)	Power Received (dBm)	Onboard Threshold (dBm)	Margin (dBm)
35	1864.89	33,764	-89.795	-90.435	0.640
15	1864.89	33,000	-89.725	-90.236	0.511
19	1898.27	35,000	-90.287	-90.747	0.460
15	1865.04	33,000	-89.819	-90.236	0.417
14	1889.25	400	-51.490	-51.907	0.417
24	1865.19	29,000	-88.766	-89.114	0.348*
28	1865.19	29,517	-88.930	-89.267	0.337
24	1898.57	29,000	-88.813	-89.114	0.301*
24	1865.19	29,000	-88.813	-89.114	0.301*
24	1865.19	25,333	-87.666	-87.940	0.274*
24	1865.19	29,000	-88.883	-89.114	0.231*
24	1865.19	27,212	-88.415	-88.561	0.146*
24	1865.19	29,000	-88.976	-89.114	0.138*
19	1864.89	35,000	-90.661	-90.747	0.086
19	1898.27	35,000	-90.661	-90.747	0.086
24	1865.19	29,000	-89.070	-89.114	0.044*
33	1861.73	35,000	-90.708	-90.747	0.039
6	1865.19	29,000	-89.093	-89.114	0.021
15	1864.89	33,000	-90.217	-90.236	0.019

* High-resolution protocol data

TABLE C-4. WIDE-BAND SIGNALS IN THE PCS BAND

Flight No.	CDMA Channel	Altitude (ft)	Max P_r[1] (dBm)	Adjusted[2] (dBm)	Onboard Threshold (dBm)	Margin (dB)
9	350	33,000	-45.62	-38.71	-90.24	51.53
25	325	35,000	-47.44	-40.53	-90.75	50.22
25	675	26,733	-45.64	-38.73	-88.41	49.68
25	675	33,000	-47.54	-40.63	-90.24	49.61
7	675	31,000	-48.78	-40.39	-89.69	49.31
28	175	33,000	-47.96	-41.05	-90.24	49.19
25	675	22,197	-44.75	-37.84	-86.79	48.95
2	1125	23,500	-45.36	-38.45	-87.29	48.84
18	675	24,698	-46.60	-39.69	-87.72	48.03
4	500	29,000	-48.38	-41.47	-89.11	47.65
23	650	28,000	-48.10	-41.19	-88.81	47.62
29	325	16,585	-45.08	-36.69	-84.26	47.57
23	250	28,000	-49.83	-41.44	-88.81	47.37
2	500	23,500	-47.14	-40.23	-87.29	47.06
28	175	33,000	-50.13	-43.22	-90.24	47.01
17	675	28,000	-48.78	-41.87	-88.81	46.94
8	350	35,000	-51.19	-44.28	-90.75	46.47
25	325	19,306	-46.18	-39.27	-85.58	46.31
28	42	28,154	-49.57	-42.66	-88.86	46.19
28	160	33,000	-50.95	-44.04	-90.24	46.19
26	325	20,415	-48.36	-39.97	-86.07	46.10
17	575	27,500	-49.55	-42.64	-88.65	46.01
35	325	35,000	-51.70	-44.79	-90.75	45.96
4	500	29,000	-50.13	-43.22	-89.11	45.89
29	325	18,263	-47.84	-39.45	-85.10	45.65
26	325	23,945	-50.30	-41.91	-87.45	45.54
30	325	29,000	-50.58	-43.67	-89.11	45.45
29	325	16,285	-47.21	-38.82	-84.10	45.28
29	325	18,831	-48.96	-40.57	-85.36	44.79
4	675	29,000	-51.42	-44.51	-89.11	44.60
4	650	29,000	-51.44	-44.53	-89.11	44.58
30	350	28,488	-51.56	-44.65	-88.96	44.31
28	160	25,606	-50.81	-43.90	-88.03	44.13
35	325	18,000	-47.77	-40.86	-84.97	44.11
4	675	29,000	-52.03	-45.12	-89.11	44.00
25	675	12,538	-44.99	-38.08	-81.83	43.76
26	325	18,098	-49.74	-41.35	-85.02	43.67
35	500	31,567	-53.25	-46.34	-89.85	43.52
29	325	11,997	-46.44	-38.05	-81.45	43.40
28	175	25,606	-51.77	-44.86	-88.03	43.17

Note: 1. The maximum power-received measurement.
2. Adjustment to account for measurement set-up under-value.

TABLE C-4. WIDE-BAND SIGNALS IN THE PCS BAND (Continued)

Flight No.	CDMA Channel	Altitude (ft)	Max P_r[1] (dBm)	Adjusted[2] (dBm)	Onboard Threshold (dBm)	Margin (dB)
29	325	17,703	-50.09	-41.70	-84.83	43.13
35	325	35,000	-54.86	-47.95	-90.75	42.80
26	325	13,248	-48.21	-39.82	-82.31	42.49
23	575	28,000	-53.29	-46.38	-88.81	42.43
26	925	22,852	-53.04	-44.65	-87.04	42.40
8	350	20,991	-50.88	-43.97	-86.31	42.33
30	325	18,482	-49.81	-42.90	-85.20	42.31
32	675	19,960	-52.03	-43.64	-85.87	42.23
17	925	24,000	-52.19	-45.28	-87.47	42.19
36	425	20,918	-51.19	-44.28	-86.28	42.00
29	350	10,205	-46.69	-38.30	-80.04	41.74
7	350	16,472	-51.30	-42.91	-84.20	41.29
28	116	20,320	-51.77	-44.86	-86.02	41.16
28	160	19,861	-51.72	-44.81	-85.83	41.01
29	1175	10,459	-47.93	-39.54	-80.26	40.71
36	50	28,253	-55.09	-48.18	-88.89	40.70
35	425	22,734	-53.64	-46.73	-87.00	40.27
35	325	17,274	-51.61	-44.70	-84.61	39.92
35	325	35,000	-57.81	-50.90	-90.75	39.85
20	350	20,294	-53.15	-46.24	-86.01	39.77
28	116	12,084	-48.71	-41.80	-81.51	39.71
25	475	35,000	-58.14	-51.23	-90.75	39.52
29	325	18,079	-54.11	-45.72	-85.01	39.29
26	325	11,221	-50.11	-41.72	-80.87	39.15
28	160	14,117	-50.84	-43.93	-82.86	38.94
26	325	12,604	-51.72	-43.33	-81.88	38.54
25	325	8,861	-47.19	-40.28	-78.82	38.54
36	500	28,242	-57.41	-50.50	-88.88	38.38
26	325	23,839	-57.43	-49.04	-87.41	38.37
5	650	28,667	-57.95	-51.04	-89.01	37.98
26	325	16,764	-54.79	-46.40	-84.35	37.95
10	675	15,639	-52.71	-45.80	-83.75	37.95
26	325	12,147	-52.31	-43.92	-81.56	37.64
36	200	27,627	-58.04	-51.13	-88.69	37.56
25	325	5,417	-44.14	-37.23	-74.54	37.31
35	425	24,194	-57.43	-50.52	-87.54	37.02
26	325	11,455	-52.85	-44.46	-81.05	36.59
29	350	8,362	-50.23	-41.84	-78.31	36.48
2	675	29,000	-59.70	-52.79	-89.11	36.32
29	325	5,731	-47.26	-38.87	-75.03	36.17

Note: 1. The maximum power-received measurement.
2. Adjustment to account for measurement set-up under-value.

TABLE C-4. WIDE-BAND SIGNALS IN THE PCS BAND (Continued)

Flight No.	CDMA Channel	Altitude (ft)	Max Pr[1] (dBm)	Adjusted[2] (dBm)	Onboard Threshold (dBm)	Margin (dB)
36	200	27,203	-59.38	-52.47	-88.56	36.09
29	350	4,931	-46.55	-38.16	-73.72	35.56
17	825	27,500	-60.03	-53.12	-88.65	35.53
36	325	24,855	-59.17	-52.26	-87.77	35.52
36	325	27,000	-60.15	-53.24	-88.49	35.26
36	325	14,778	-55.02	-48.11	-83.26	35.15
29	350	7,295	-50.39	-42.00	-77.13	35.13
35	325	35,000	-62.82	-55.91	-90.75	34.84
29	350	4,677	-47.26	-38.87	-73.27	34.40
36	350	16,981	-57.27	-50.36	-84.47	34.11
36	25	27,203	-61.41	-54.50	-88.56	34.06
29	325	11,234	-55.30	-46.91	-80.88	33.96
26	325	15,147	-58.07	-49.68	-83.47	33.80
26	325	15,381	-58.44	-50.05	-83.61	33.56
36	350	14,778	-57.06	-50.15	-83.26	33.11
35	325	35,000	-65.44	-58.53	-90.75	32.22
36	425	13,075	-57.01	-50.10	-82.19	32.09
28	126	6,356	-50.91	-44.00	-75.93	31.93
20	925	35,000	-65.95	-59.04	-90.75	31.71
2	675	23,500	-62.79	-55.88	-87.29	31.41
36	200	20,553	-61.69	-54.78	-86.12	31.34
36	325	28,242	-64.62	-57.71	-88.88	31.18
36	325	28,253	-64.73	-57.82	-88.89	31.06
28	160	29,517	-65.25	-58.34	-89.27	30.93
26	325	13,753	-60.17	-51.78	-82.63	30.85
36	25	27,627	-64.87	-57.96	-88.69	30.73
29	350	7,828	-55.42	-47.03	-77.74	30.71
26	325	9,135	-56.87	-48.48	-79.08	30.60
36	350	13,075	-58.53	-51.62	-82.19	30.57
9	275	4,306	-49.03	-42.12	-72.55	30.42
29	325	2,567	-46.39	-38.00	-68.05	30.06
29	325	3,876	-50.06	-41.67	-71.63	29.96
25	675	3,106	-46.74	-39.83	-69.71	29.88
17	650	9,238	-56.36	-49.45	-79.18	29.73
21	1175	33,000	-67.59	-60.68	-90.24	29.56
26	325	10,273	-58.95	-50.56	-80.10	29.54
35	25	33,764	-68.01	-61.10	-90.44	29.34
25	1175	31,867	-67.85	-60.94	-89.93	29.00
29	350	2,046	-46.51	-38.12	-66.08	27.97
3	250	11,168	-59.82	-52.91	-80.83	27.92

Note: 1. The maximum power-received measurement.
2. Adjustment to account for measurement set-up under-value.

TABLE C-4. WIDE-BAND SIGNALS IN THE PCS BAND (Continued)

Flight No.	CDMA Channel	Altitude (ft)	Max P_r[1] (dBm)	Adjusted[2] (dBm)	Onboard Threshold (dBm)	Margin (dB)
9	250	12,986	-61.15	-54.24	-82.14	27.89
36	200	29,000	-68.34	-61.43	-89.11	27.69
26	325	13,050	-63.10	-54.71	-82.18	27.47
36	375	7,564	-57.53	-50.62	-77.44	26.82
26	925	22,959	-69.25	-60.86	-87.09	26.23
36	325	20,553	-66.86	-59.95	-86.12	26.17
2	675	15,067	-64.90	-57.99	-83.43	25.44
36	350	12,278	-63.66	-56.75	-81.65	24.90
12	675	27,440	-70.72	-63.81	-88.63	24.82
26	325	10,987	-64.76	-56.37	-80.68	24.32
27	650	28,000	-71.82	-64.91	-88.81	23.90
11	25	24,100	-71.47	-64.56	-87.51	22.94
21	1175	33,000	-75.26	-68.35	-90.24	21.88
36	50	28,673	-74.59	-67.68	-89.02	21.34
23	675	1,468	-49.08	-42.17	-63.20	21.03
23	650	6,909	-62.58	-55.67	-76.65	20.98
36	350	7,564	-64.78	-57.87	-77.44	19.57
7	350	30,358	-79.71	-71.32	-89.51	18.19
29	350	2,834	-60.43	-52.04	-68.91	16.88
9	25	4,306	-62.61	-55.70	-72.55	16.85
37	375	3,724	-63.26	-54.87	-71.29	16.42
8	425	8,004	-68.83	-61.92	-77.93	16.01
29	350	6,507	-69.23	-60.84	-76.13	15.30
29	350	9,404	-73.39	-65.00	-79.33	14.33
31	325	3,076	-63.75	-55.36	-69.63	14.26
20	425	3,125	-64.31	-55.92	-69.76	13.84
37	375	3,949	-66.42	-58.03	-71.80	13.77
36	375	4,344	-66.44	-59.53	-72.62	13.09
27	325	6,992	-71.12	-64.21	-76.76	12.55
37	375	4,163	-68.46	-60.07	-72.25	12.19
29	350	9,671	-76.95	-68.56	-79.58	11.02
4	250	2,957	-66.21	-59.30	-69.28	9.99
19	325	10,848	-81.09	-74.18	-80.57	6.39
37	375	4,602	-77.04	-68.65	-73.13	4.47
27	625	3,654	-74.00	-67.09	-71.12	4.03
32	675	12,598	-86.59	-78.20	-81.87	3.67
14	425	6,704	-80.48	-73.57	-76.39	2.82
26	350	2,142	-72.32	-63.93	-66.48	2.56
37	375	1,027	-66.49	-58.10	-60.10	2.00
29	350	724	-65.06	-56.67	-57.06	0.39

Note: 1. The maximum power-received measurement.
2. Adjustment to account for measurement set-up under-value.

APPENDIX D—MOBILE CELLULAR ACTIVITY RATES

TABLE D-1. IN-FLIGHT CELLULAR BAND ACTIVITY RATE
(Standard Resolution Measurement Protocol)

	Signals Detected	Analyzer Sweeps (approximate)	Monitored Time (sec)	Rate (signals/min)
Narrow band	18	14081	26895	0.04
Wide band	87	14081	26895	0.19
Total	105	14081	26895	0.23

TABLE D-2. IN-FLIGHT CELLULAR BAND ACTIVITY RATE
(High-Resolution Measurement Protocol)

	Signals Detected	Analyzer Sweeps (approximate)	Monitored Time (sec)	Rate (signals/min)
Narrow band	1	1230	2349	0.03
Wide band	45	1230	2349	1.15
Total	46	1230	2349	1.17

TABLE D-3. IN-FLIGHT CELLULAR BAND ACTIVITY RATE
(Overall)

	Signals Detected	Analyzer Sweeps (approximate)	Monitored Time (sec)	Rate (signals/min)
Narrow band	19	15311	29244	0.04
Wide band	132	15311	29244	0.27
Total	151	15311	29244	0.31

TABLE D-4. LOW-ALTITUDE CELLULAR BAND ACTIVITY RATE
(Standard Resolution Measurement Protocol)

	Signals Detected	Analyzer Sweeps (approximate)	Monitored Time (sec)	Rate (signals/min)
Narrow band	8	2591	4949	0.10
Wide band	17	2591	4949	0.21
Total	25	2591	4949	0.30

TABLE D-5. LOW-ALTITUDE CELLULAR BAND ACTIVITY RATE
(High-Resolution Measurement Protocol)

	Signals Detected	Analyzer Sweeps (approximate)	Monitored Time (sec)	Rate (signals/min)
Narrow band	0	370	707	0.00
Wide band	11	370	707	0.93
Total	11	370	707	0.93

TABLE D-6. LOW-ALTITUDE CELLULAR BAND ACTIVITY RATE
(Overall)

	Signals Detected	Analyzer Sweeps (approximate)	Monitored Time (sec)	Rate (signals/min)
Narrow band	8	2961	5656	0.08
Wide band	28	2961	5656	0.30
Total	36	2961	5656	0.39

TABLE D-7. IN-FLIGHT PCS BAND ACTIVITY RATE
(Standard Resolution Measurement Protocol)

	Signals Detected	Analyzer Sweeps (approximate)	Monitored Time (sec)	Rate (signals/min)
Narrow band	73	6095	25904	0.17
Wide band	103	6095	25904	0.24
Total	176	6095	25904	0.41

TABLE D-8. IN-FLIGHT PCS BAND ACTIVITY RATE
(High-Resolution Measurement Protocol)

	Signals Detected	Analyzer Sweeps (approximate)	Monitored Time (sec)	Rate (signals/min)
Narrow band	9	1202	5109	0.11
Wide band	57	1202	5109	0.67
Total	66	1202	5109	0.78

TABLE D-9. IN-FLIGHT PCS BAND ACTIVITY RATE
(Overall)

	Signals Detected	Analyzer Sweeps (approximate)	Monitored Time (sec)	Rate (signals/min)
Narrow band	82	7297	31012	0.16
Wide band	160	7297	31012	0.31
Total	242	7297	31012	0.47

TABLE D-10. LOW-ALTITUDE PCS BAND ACTIVITY RATE
(Standard Resolution Measurement Protocol)

	Signals Detected	Analyzer Sweeps (approximate)	Monitored Time (sec)	Rate (signals/min)
Narrow band	12	1035	4399	0.16
Wide band	18	6095	25904	0.25
Total	30	6095	25904	0.41

TABLE D-11. LOW-ALTITUDE PCS BAND ACTIVITY RATE
(High-Resolution Measurement Protocol)

	Signals Detected	Analyzer Sweeps (approximate)	Monitored Time (sec)	Rate (signals/min)
Narrow band	3	378	1607	0.11
Wide band	23	1202	5109	0.86
Total	26	1202	5109	0.97

TABLE D-12. LOW-ALTITUDE PCS BAND ACTIVITY RATE
(Overall)

	Signals Detected	Analyzer Sweeps (approximate)	Monitored Time (sec)	Rate (signals/min)
Narrow band	15	1,413	6005	0.15
Wide band	41	7297	31012	0.41
Total	56	7297	31012	0.56