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Acronyms

ADF	Automatic Direction Finder
ALA	Approach-and-Landing Accidents
AMPS	Advanced Mobile Phone Service
ARFCN	Absolute Radio Frequency Channel Number
ASRS	Aviation Safety Reporting System
BPSK	Binary Phase Shift Keying
BW	Bandwidth
C/A Code	Coarse/Acquisition Code
CAA	Civil Aviation Authority
CDI	Course Deviation Indicator
CDMA	Code Division Multiple Access
CFIT	Controlled Flight into Terrain
CW	Continuous Wave
DA	Decision Altitude
DCCH	Digital Control Channel
DME	Distance Measuring Equipment
EME	Electromagnetic Environment
ERP	Effective Radiated Power
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
FCC	Federal Communications Commission
FSF	Flight Safety Foundation
GPS	Global Positioning System
GS	Glide Slope
GSM	Global System for Mobile Communication
iDEN	Integrated Dispatch Enhanced Network
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 Agency
NTIA	National Telecommunications and Information Association
P Code	Precision Code
PCS	Personal Communications System
PED	Portable Electronic Device
PRN	Pseudo-Random Noise
RF	Radio Frequency
SE	Shielding Effectiveness
T-PED	Transmitting Portable Electronic Device
TCAS	Traffic Alert and Collision Avoidance System
TDMA	Time Division Multiple Access
UWB	Ultrawideband
VOR	VHF Omni-Directional Range

Abstract

The risk posed to commercial air travel by portable electronic devices (PEDs) carried onboard for use during flight was explored. The issue of PED interference has existed for over forty years, but has become more significant recently due to increasing numbers, complexity and variety of PEDs, wireless products and a societal acceptance of these devices.

Anecdotal evidence of PED interference was examined. Two aviation accident case studies indicated strong circumstantial evidence of PED interference involvement. Incident reports from the Aviation Safety Reporting System database further supported the risk that is posed by PED interference. A demonstration of how anecdotal stories were used to identify an actual PED interference problem was also provided. The anecdotal evidence provides a set of information that highlights the need for further investigation.

Existing data sets were quantitatively analyzed. A bounding analysis implied that PED interference is a causal factor in less than 6.5 % of all aviation accidents. An aviation safety database analysis identified laptops and cellular phones interfering with ILS and VOR systems as the most promising areas for further research. An occurrence rate for PED interference was estimated at 23 incidents per year. Previous work in industrial safety was applied to the occurrence rate to estimate an accident rate.

A survey of passenger in-flight electronics use was conducted. The results indicated that passengers are not aware of the reasons for the in-flight PED policies and they doubt that safety is an issue. It further indicated that they were using prohibited electronic devices and allowed devices at prohibited times.

A program to develop an instrumentation package and perform in-flight RF spectrum measurements on revenue flights of commercial aircraft cabins is described.

The Federal Aviation Administration sponsored the program [1]. The spectrum monitoring was performed from gate-to-gate in selected aviation critical and personal electronics frequency bands. Five critical navigation frequency bands were selected to monitor: VHF 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 MHz 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 GHz. 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 from September 23 through November 19, 2003. All flights were revenue flights except for 1 maintenance flight with no passengers onboard. All flights were on Boeing 737 model aircraft except for 1 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 in the Eastern U.S and were less than 2 hours in duration. The passenger load factors were between 25% and 100%.

A total of 7,534 spectrum traces representing over 51 hours of data were collected including 4,445 in-flight traces representing over 32 hours of data. The measurements provided the first reported characterization of the RF environment in the cabins of scheduled revenue commercial airline flights. Key findings were:

1. Onboard cellular activity is appreciable at cruise and during flight critical times. Signal activity was observed on average every 51 seconds and the analysis implied a rate of 1-4 calls per flight.
2. Signal activity was observed in the GPS (1575.42 MHz) band at field strengths that under appropriate circumstances could result in interference with aircraft GPS equipment.

3. Elevated broadband noise was observed on many occasions in the VOR/ILS band.
4. Passenger use of electronics including wireless devices is occurring at prohibited times including during approach.

A policy prescription is advanced that includes the management strategies of centralized research, a standing oversight committee, and monitoring tools. It is also concludes that strategies prohibiting certain electronic devices from powering on or transmitting at certain points in-flight will be required. Finally, this dissertation asserts that limiting passenger electronics use onboard should continue and is the only method available to ensure the near-term safety of the flying public.

Chapter 1

Introduction

1.1 BACKGROUND

Airline passengers have carried portable electronic devices (PEDs) aboard commercial aircraft for use during flight since the 1950's. The U.S. Government formally recognized the potential safety hazard posed to commercial flight from radio frequency (RF) interference in May 1961 with Civilian Aviation Regulation (CAR) 91.19.[1] 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 PED interference has received a small amount of attention, periodically emerging as the focus of media, Congressional, industry and research interest. The term ***PED Interference*** refers to the disruption to avionics caused by portable electronic devices.

The first major research effort occurred after CAR 91.19 became effective. RTCA[2] formed Special Committee 88 (SC-88) and on April 12, 1963 issued its report, DO-119 [2]. As a result of the report the Federal Aviation Administration (FAA) issued FAR 91.19 that extended the prohibition of using in-flight electronics to other PEDs. The

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[1] The current Federal Aviation Regulations (FARs) were formerly CARs.

[2] RTCA Inc. was formerly Radio Technical Commission for Aeronautics. RTCA is a not for profit corporation closely tied to the aviation safety community.

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.

While reported incidents of PED interference persisted throughout the next two decades, attention did not focus again until 1983. Around that time portable computers were emerging as a force and their prohibition by some air carriers was a concern to several computer trade publications. Some publications even suggested that their readers should avoid these airlines [3]. The second RTCA committee to investigate interference of aircraft by PEDs, Special Committee 156 (SC-156), noted the significant media attention by both aviation and portable computer trade press [3].

More recently, attention has stemmed from Congressional inquests. For example, a House Transportation Appropriations Bill [4] drove the 1992 request for RTCA to form a third investigative committee on the potential for interference of aircraft systems from carry-on PEDs, Special Committee 177 (SC-177). Again in 2000 [5], the House Committee on Transportation and Infrastructure, Subcommittee on Aviation, drove an hearing titled, "*Portable Electronic Devices: Do they really pose a safety hazard on aircraft?*" It is speculated that passengers and cellular phone manufacturers prompted this hearing. Passengers desired an alternative to the expensive in-flight seat-back phone service and the cellular manufacturers saw a path to expand services.

Major professional society journals like *IEEE Spectrum* have written on the potential for PED interference [6]. The industry media has not ignored the issue, either. Recent articles, like in *Avionics Magazine,* have asked how will regulators and operators address the inevitable move toward allowing wireless computers and cellular phones in the cabin [7]. Some articles, like ones in *Air & Space Magazine* [8] and *Air Safety Week* [9], still address the more basic issue that the potential for interference from PEDs exists and needs to be addressed.

Research efforts have been sporadic and mostly restricted to in-house efforts by aircraft manufacturers and airlines. The four RTCA studies published in 1963, 1988, 1996 [10], and 2004 [11] are the main influences on former and current FAA and industry policies. The findings of RTCA and other groups have been inconclusive and little industry consensus has been achieved on the risk that portable electronics pose to commercial and general aviation.

Since the potential risk was identified over forty years ago there have been two major technology developments that have set the stage to change the situation significantly. 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. While early generation laptops produced significant unintentional RF emissions, they were bulky, had limited capability and a low battery capacity that prevented large scale long-period use in-flight. Of course, 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 prohibited 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 [5].

1.2 STATEMENT OF THE PROBLEM

The last decade has seen a number of changes that reemphasizes the importance of this topic. For one thing, technology advances are coming at an increased pace. The increasing numbers, complexity and variety of PEDs many of them outfitted with wireless capability make it difficult for the aviation community to fully digest the implications to safety. The development of a wide range of additional wireless products and a societal expectation of ubiquitous use will surely act to further exacerbate the situation.

The competitive pressure on air carriers has intensified especially post September 11th. This has severely limited the ability of aircraft manufacturers and airlines to devote resources to this issue.

Further complicating the issue is: solidified passenger expectations for electronics use, changes to policies and rules such as allowing cellular phone use after landing and the FCC's consideration of allowing cellular phone use in-flight [12], an aging commercial aircraft fleet [13] that can have degraded grounds, shielding and other electromagnetic interference control features, a continued lack of communication between the FAA and FCC, and the failure of the aviation industry and FAA to inform the flying public fully of the safety implications. Also, the data for a full analysis are not complete and the resources available to pursue them are decreasing creating larger risk uncertainties.

Finally, given that the aviation industry has eliminated or is effectively managing most large and obvious sources of risk, small persistent risks increasingly warrant attention. As airline travel increases, these small persistent risks become more and more critical to address as can be seen in Figure 1.1.

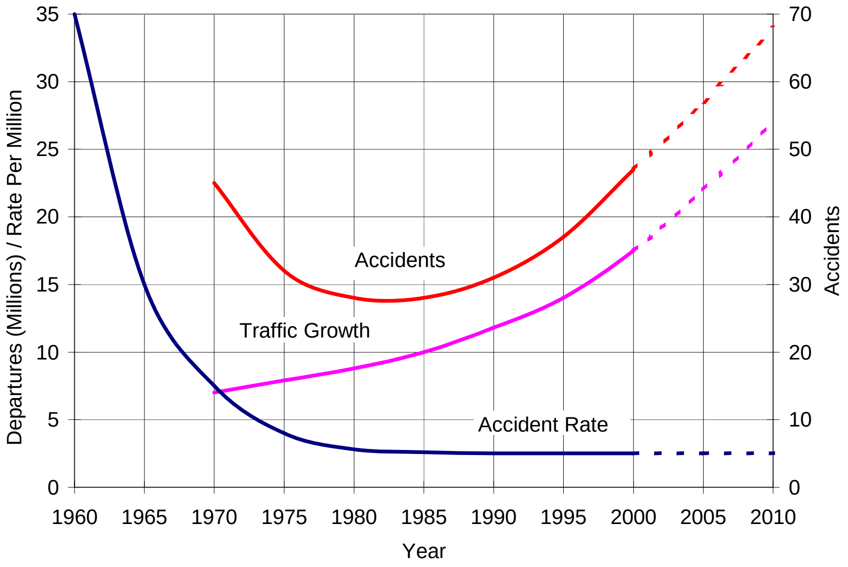

Figure 1.1: Effect of Static Accident Rate and Accompanying Traffic Growth on Number of Accidents (Source: Flight Safety Foundation)

The breakthroughs in technology have created new electronics that can both provide aircraft systems capable of safer more efficient air travel and consumer systems that provide sophisticated passenger comforts and communication capable of interfering with safe flight. Whether these technology advances coupled with the other influences on the aviation industry (economic, societal, regulatory, etc.) are creating a riskier air travel environment is the question this thesis explores.

1.3 PURPOSE OF THE RESEARCH

The purpose of this research has been to clarify the existing information and data sets and to provide new data that help direct research activities and assist policy makers in their short and long-term decisions such that the flying public's safety is reasonably assured. The focus is mostly on larger commercial aircraft, but the arguments and much of the evidence are valid for smaller regional and general aviation aircraft.

At the inception of this research the state of knowledge in brief was:

1. Anecdotal stories existed that suggested a potential problem.
2. Research had demonstrated some risk, but it was not well quantified and no consensus had been reached.
3. Policies existed that in theory minimized the risk to flight safety.

To accomplish the research objectives the anecdotal stories were explored to determine how much weight they should be given. Many in this debate have dismissed these stories because the interference that the incident reports describe has been difficult to duplicate in laboratory tests. This is not surprising since the likelihood of duplicating the in-flight conditions in a laboratory setting is low. Next, existing data sets were qualitatively and quantitatively analyzed to help substantiate the phenomena of PED interference, bound the issue and assess the value of the possible research areas. Finally, new data were obtained to analyze the adherence of passengers to current policies and provide quantitative analysis of the implications for safety.

1.4 ORGANIZATION

A brief review of the literature concentrating on major organized efforts is presented in Chapter 2. A breakdown of the most compelling anecdotal evidence is provided in Chapter 3. A set of analyses derived from existing data that help to clarify the problem and identify the issues that still need research attention are provided in Chapter 4. A survey of passenger understanding and adherence to PED aviation rules is provided in Chapter 5. The main research of this dissertation involved in-flight RF spectrum measurements on commercial revenue flights. The motivation and description for this effort is presented in Chapter 6 and the collected data are described in Chapter 7. The results and discussion are provided in Chapter 8. The recommendations for this dissertation including a set of policy prescriptions are provided in Chapter 9.

1.5 THESIS STATEMENT

The use of passenger electronics onboard commercial aircraft should continue to be limited because there is a small persistent risk that could grow as a result of the proliferation of electronics, mounting airline economic pressures, and incomplete available data on the potential for interference with critical aviation systems. Management strategies should be employed that include centralized research efforts, a standing oversight committee, and monitoring tools that will enable a better understanding of the issue and reduce the risk to the flying public.

1.6 RELEVANT REGULATIONS, STANDARDS AND DOCUMENTS

The following is a brief list of regulations, standards and documents associated with the material in this dissertation.

1.6.1 RTCA

a. DO-160D, Environmental Conditions and Test Procedures for Airborne Equipment [14].

b. DO-119, Interference to Aircraft Electronic Equipment from Devices Carried Aboard [2].

c. DO-199, Potential Interference to Aircraft Electronic Equipment from Devices Carried Onboard [3].

d. DO-233, Portable Electronic Devices Carried on Board Aircraft [10].

e. DO-294, Guidance on Allowing Transmitting Portable Electronic Devices (T-PEDs) on Aircraft [11].

1.6.2 FCC

a. Title 47 of the Code of Federal Regulations, Part 15 – Radio Frequency Devices, 1 October 2004.

b. Title 47 of the Code of Federal Regulations, Part 22, Section 22.925 - Prohibition on airborne operation of cellular telephones, 1 October 2004.

1.6.3 FAA

a. Title 14 of the Code of Federal Regulations, 91.21 - Portable Electronic Devices, 1 January 2004.

b. Advisory Circular 91.21-1, Use of Portable Electronic Devices Aboard Aircraft, FAA, Washington, D.C., 2 October 2000.

1.6.4 Joint Aviation Authorities

a. JAR-OPS 1.110 Portable Electronic Devices, 1 March 1998.

b. Technical Guidance Leaflet No. 29, Guidance Concerning The Use Of Portable Electronic Devices On Board Aircraft, Civil Aviation Authority, 1 October 2001.

Chapter 2

Review of Past Research and Literature

The potential for interference from in-flight use of PEDs has been addressed in both major research efforts and smaller specialized works. The major efforts reflect most of the findings of the research in this area. Thus, this research and literature review focuses on the major research efforts. The chapter is arranged by the organizations that performed the research with the exception of a section that is related to all research that utilized the Aviation Safety Reporting System (ASRS) database. Other smaller scale work and papers are discussed throughout the body of this dissertation where they are most relevant.

Most of the major research efforts have arrived at similar conclusions, that PEDs cannot be ruled out as a potential risk to aircraft avionics, but the likelihood of interference is low. The categorization of the risk as low has remained largely a qualitative rather than a quantitative assessment.

2.1 RTCA, INC.

RTCA, Inc. is a private, not-for-profit corporation that develops consensus-based recommendations regarding aviation systems and issues. RTCA functions as a Federal Advisory Committee. Its recommendations are used by the FAA as the basis for policy, program, and regulatory decisions and by the private sector as the basis for development, investment and other business decisions. Today RTCA includes roughly 250 government, industry and academic organizations from the United States and around the world.[3]

The RTCA has produced four reports on the subject of PEDs in 1963, 1988, 1996, and 2004. These efforts can be viewed as the most important since the previous and current FAA and airline policies are in fact based on the RTCA report findings [5].

2.1.1 DO-119

The first RTCA report on PEDs was DO-119 issued in 1963 [2]. This report recognized PEDs as a potential risk to flight safety and explored regulation, avionic equipment shielding and education as methods to address the problem. The report recognized the potential difficulty in establishing a regulatory solution noting, “This approach, however, entails a very difficult administrative problem.” The report was cautious not to “penalize” manufacturers of equipment that did not interfere with avionics and to “burden” flight crews with the responsibility of checking the cabin for PED use. The ability to effectively shield avionics was addressed, but it was concluded that the task was overwhelming. Finally, “education” avenues were examined. The report indicated that efforts were already underway to inform the industry of the problem. However, education of the public was considered “unrealistic” because, “An education program pre-supposes that the users…possess the technical knowledge.”

As a resolution to the problem DO-119 established permissible limits of RF radiation from PEDs for use onboard aircraft. These limits were based on FAA tests that determined the susceptibility of common avionics. The report recognized the complexity of the situation pointing out that the RF energy from a PED would be attenuated by distance, could couple directly onto wires, and would vary considerably based on the age of components and condition of batteries. The report also pointed out that energy from multiple PEDs could either add or cancel. Short of the data to understand the situation they adopted a limit 6 dB down from the measured susceptibility values for avionics. The report also implied that compliance would fall on the equipment manufacturers, but that the appropriate government agencies should impose the requirement to comply.

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[3] Taken from RTCA website, www.rtca.org.

It is interesting to note that in the course of the research for the DO-119 report, three portable AM/FM radios were documented to cause interference to a VOR system both on the ground and in-flight. Nevertheless, the claim continues to be made even by RTCA that in-flight PED interference has not been duplicated during ground tests. The Executive Summary of DO-233 [10] states, “While a small list of suspected incidents of such interference from PEDs had been generated over time, interference from a PED could not be duplicated under controlled conditions.”

The two subsequent RTCA reports on PEDs, DO-199 [3] and DO-233 [10], examined the issues in greater depth and began to establish guidance for determining the risk posed to commercial aircraft. These investigations centered on establishing RF emissions levels from PEDs, the susceptibility thresholds of avionics and the interference path loss (IPL) [3], [10]. IPL is defined as the loss from the reference antenna (approximating the PED source) located in the aircraft cabin to a particular aircraft radio receiver terminal. This remains the main approach in evaluating the risk. While both of these 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.

2.1.2 DO-199

The second RTCA report on PEDs was DO-199 issued in 1988 [3]. This report used incident reports to confirm the legitimacy of the investigations into PED interference. However, they placed limited weight on incident reports:

> *The committee concluded that although airline reports suggested the existence of interference from portable devices, the information in the reports was not adequate to confirm the interference or define emission levels from devices. Consequently, this information cannot be used for data analysis.*

The report recognized the influence of cumulative effects. This included intermodulation from both onboard and ground sources. An emphasis was placed on the potential for onboard sources to combine with ground sources (i.e. in the vicinity of airports).

This report identifies that while there are many specifications limiting RF emissions of both PEDs and avionics none address emissions for PEDs operated on aircraft. They also recognize the obstacles to achieving such a requirement. For one thing industry manufacturers would be slow to warm to such an idea due to cost and because airline verification in-flight would be difficult without employing a clearly visible compliance label.

A main effort of the report centered on investigating the susceptibility limits of commercial avionics. DO-199 developed procedures for testing the vulnerability of navigation and communication equipment. The selected interfering test signal was unmodulated and continuous wave (CW) in nature. At the time the main concern was emissions generated from the internal clocks of electronic games, receivers and computers and no modulated signals were anticipated. Manufacturers were invited to test their equipment using the developed procedures.

The results of the manufacturers' tests were reported. Interference with VOR systems was indicated in many of the incident reports at that time and these systems were recognized to be vulnerable to relatively small signal levels. Thus, they were more thoroughly evaluated. They were found to be especially vulnerable, but interference was deemed to be "more likely to be 'nuisance' rather than 'hazardous' in nature and can be, at some future date, dealt with accordingly."

Another main effort of DO-199 was to determine IPL, referred to as path loss function (PLF) in the report. As part of the effort the IPL for various aircraft models was determined. The influences of aircraft body type, emission source location, ground reflection and in-flight effects were investigated. Furthermore, a procedure for estimating the maximum allowable PED emission using IPL was developed.

The final main effort undertaken in DO-199 was establishing the emission characteristics of PEDs. There were 34 devices selected and tested per DO-160 testing standards for radiated emissions of installed avionics. The findings were that several devices did exceed the DO-160 limits. This conveys that if these PEDs were avionics, then they would not be acceptable for installation into the aircraft. They also found that some PEDs were incorrectly classified as FCC Part 15 Class A devices when in fact they should have been classified as Class B devices thus allowing 10 dB greater emissions.

Finally, using the determined IPL values it was concluded that stricter limits on PED emissions would be required to reduce the possibility of avionics disruption.

The recommendations in the report included establishing acceptable emission limits and associated test methods for portable electronic devices, creating a new classification by the FCC for portable devices that may be operated on aircraft, forging an initiative to provide guidance for acceptable methods of compliance and develop methods to enhance public awareness, and developing a standardized method for operators to report suspected PED interference. With the exception of establishing the acceptable emission limits for PEDs the recommendations have not been followed.

2.1.3 DO-233

The third RTCA report on PEDs was DO-233 issued in 1996 [10]. The DO-233 report extended the efforts presented in DO-199. This included gathering incident reports from various sources, additional IPL measurements to cover many new aircraft models and build the statistical number of measurements, emission measurements of newer PEDs, and analysis of communication and navigation equipment immunity using more varied potential interference sources. The main difference in DO-233 compared with DO-199 was an attempt to analyze the risk in more detail.

The report gathered data from a number of sources pertaining to incident reports of PED interference. They used incident reports to the previous committee (SC-156), their committee (SC-177), the ASRS database, and the International Air Transport Association (IATA). In all they identified 137 reports, 10 of which correlated the interference to the offending source being turned off and back on again. The DO-233 report was more willing to loan credibility to the incident reports as proof of a problem compared to the DO-199 report.

IPL measurements on aircraft models conducted for the DO-199 report were repeated for comparability. The results were similar in most instances, but large variations were also observed. The difference could be related to the specific aircraft models used, but also could represent the influence of other factors such as test equipment, measurement procedure, antenna locations, aircraft age, human factors, and interior arrangement.

The emissions of a cross section of PEDs were also measured. Composite spectra were created for the PED emissions. The PEDs represented newer model electronics.

The susceptibility of avionics was explored with more potential sources of interference in mind (i.e. broadband noise, modulated carriers and impulse signals). This also included evaluating the manifestations of interference for the various sources.

The updated PED emissions and IPL data were used to create a set of worst-case interference margins, assuming least path loss and highest-level PED emissions. The least robust systems were VOR and ILS. In each case the probability of occurrence was estimated and compared to allowable operational conditions. The analyses were rudimentary.

As in previous studies the generalized finding indicated that the probability of interference to installed aircraft systems from PEDs, singly or in multiples, was low. However, it noted that the possibility of interference to aircraft navigation and information systems during critical phases of flight, e.g., takeoff and landing, should be viewed as potentially hazardous and an unacceptable risk for aircraft involved in passenger-carrying operations.

Within that conclusion was a recommendation to still pursue appropriate regulatory structure to ensure safety. The adopted approach was to limit PED operation during critical flight phases. Additionally, it argued that transmitting PEDs (T-PEDs) should be prohibited unless testing could “ascertain its safe use.” The operational approach recognized the enforcement difficulty in a total ban and thus recommended a restriction on certain types of electronics and at certain flight phases. The report also recommended a continued testing of PEDs to identify their emission profiles. The report indicated the vital need for the FAA and FCC to work closely. Educational awareness and onboard detection were also mentioned.

2.1.4 DO-294

The most recent special committee, SC-202, was tasked to evaluate PED use onboard commercial aircraft with emphasis on intentional transmitters. Departing from the previous approaches this committee centered on establishing a process for assessing the risk of a specific T-PED technology with any aircraft type and model. The result of the SC-202 studies was the report DO-294 [11], published in 2004. This report does not recommend specific ground or in-flight policies for specific T-PED technologies.

Included in the conclusions section of this report was a determination that current operation procedures are not fully effective and that onboard use of T-PEDs introduces a new source of potential interference and requires a reassessment of aircraft protection methods and procedures. The report also found that path loss data is insufficient and there are no standard measurement practices creating large uncertainty. The report stressed the need for clear markings on T-PEDs to indicate their operating state. Finally, the report stated that T-PED spurious emissions at the FCC limits are sufficient to cause interference to aircraft critical systems.

2.2 THE CIVIL AVIATION AUTHORITY

Two studies by the Civil Aviation Authority (CAA) in the United Kingdom have demonstrated the danger associated with onboard cellular phone use. A study in 2000 established that cellular phones transmitted in the aircraft cabin could produce levels in excess of the levels that some avionics are qualified to [15]. A second study released in 2003 demonstrated interference in cockpit instrumentation and navigation receivers from cellular phone transmissions [16].

The 2000 report established that installed avionics are qualified to a number of different susceptibility levels based on the year of qualification. Thus, any aircraft may have avionics qualified to various susceptibility levels. This report demonstrated field strengths of up to 4.51 V/m in the flight deck. These levels could disrupt avionics qualified to older standards.

This report also noted large variations in the received signal levels depending on the location of the transmitter (aisle, window, etc.). These tests were performed using single cellular phone transmissions.

The 2003 report concentrated more on the susceptibility of avionics to cellular phone transmissions. The study investigated general aviation equipment assembled to create an integrated system. The set-up included a VHF communication transceiver, a

VOR/ILS navigation receiver and associated indicators, and a gyro-stabilized remote reading compass system. The tests covered three cellular phone transmission frequencies used in Europe (412, 940 and 1719 MHz). The applied interference field strengths were up to 50 V/m for a single frequency, and 35 V/m for dual frequencies.

The report identified several anomalies for interference levels above 30 V/m, a level that can be produced by a cellular phone operating at maximum power and located 30 cm from the victim equipment or its wiring harness. The identified anomalies included instability of indicators, VOR bearing display errors, VOR and ILS course deviation indicator errors with and without a failure flag, and reduced sensitivity of the ILS Localizer receiver.

Both of these studies recommended that the use of cellular telephones onboard aircraft should be prohibited to reduce risk and ensure safety. They also recommended awareness campaigns and continued testing.

2.3 NASA

National Aeronautics and Space Agency (NASA) has recently completed two major studies related to PED interference. One studied cellular telephones [17] and the other looked at portable wireless LAN devices and two-way radios [18]. In both cases the spurious emissions from the devices were examined for the potential to interfere with aircraft navigation and communication systems.

The study of cellular telephones [17] found that none of the eight (four CDMA and four GSM) wireless handsets tested would individually be likely to interfere with aircraft VOR, LOC, GS, or GPS navigation radios, although there was some potential based on the worst-case scenarios. Furthermore, cellular phone spurious emissions equal to the maximum allowable FCC limits would result in large negative safety margins, even when considering “reasonable minimum” radio receiver interference thresholds.

The NASA study on wireless phones also found that intermodulation between some cellular phones caused emissions in the frequency bands used by GPS and distance measuring equipment (DME). The report identified other combinations of common passenger transmitters that could potentially produce intermodulation products in aircraft communication and navigation radio frequency bands.

The report also found that spurious emissions from most intentional transmitters are not required to meet more rigorous FCC standards applicable to non-intentional transmitters. Furthermore, the FCC does not restrict airborne use of Personal Communication Services (PCS) wireless handsets. FCC limits for spurious radiated emissions for PCS handsets are the same as for cellular handsets, however only cellular handsets are restricted from airborne operation.

Another NASA report [18] discussed portable wireless local area network (LAN) devices and two-way radios and their potential threat to avionics. Measurements established that wireless LAN devices were in compliance with FCC Part 15 rules, but exceeded RTCA DO-160 category M[4] limits for radiated emissions in the TCAS, Air Traffic Control Radar Beacon System (ATCRBS), and DME frequency bands. The report also demonstrated that spurious emissions from the two-way radios were in excess of the DO-160 category M limits.

The report also identified that interference safety margin calculations varied broadly and could be positive or negative depending on the IPL and interference threshold values used.

NASA also issued technical memorandum TM-2004-213001 [19] that described emissions from a Samsung SPH-N300 cellular phone. The phone had been implicated as a source of interference with onboard global positioning system (GPS) receivers. The study found that there were emissions in the GPS band capable of causing the interference. However, the emissions were compliant with FCC rules. This report is discussed further in section 3.4.

2.4 AVIATION SAFETY REPORTING SYSTEM

The Aviation Safety Reporting System (ASRS) is a voluntary, confidential, and non-punitive system operated by NASA that allows flight crews, air traffic controllers,

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[4] This category is suitable for equipment located in the passenger cabin or cockpit.

maintenance personnel and others to submit reports involving safety incidents. The reports are sanitized and summarized by a staff of experienced pilots and air traffic controllers in a form that assures confidentiality. Conditional immunity is granted to those who file reports. Analysts can search the database either by making a search request to NASA or by performing a search through the FAA's Office of System Safety's web page.[5]

The ASRS database has been utilized 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 in the RTCA efforts. Later, it was used to further establish the nature and extent of the problem by breaking down the incidents by criticality of occurrence, flight phase, altitude, single or multiple-PEDs involvement, and other relevant categories [20].

Finally, the author used the ASRS database to identify the most promising avenues for research by determining which avionics were most often affected and indicated which PEDs might be causing the interference [21]. The usefulness of an incident database as a qualitative tool has been generally accepted. However, reporter and end user bias has prevented its use as a quantitative tool. The largest objections in PED interference incident reports stem from their potential accuracy. The ability to address this with large numbers of similar accounts and correlation techniques has been stated [22]. And, the database utilized random entries between 1995 and 2001 allowing for legitimate time-series assessments.

2.5 NTIA

National Telecommunications and Information Administration (NTIA) has recently performed studies on ultrawideband (UWB) technology and the potential impact to U.S. spectrum-dependent systems currently in operation. There was specific emphasis on the potential impact to GPS receivers. While the studies were not specifically performed for aircraft GPS receivers the results are applicable and noteworthy.

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[5] www.nasdac.faa.gov

One study [23] sought to define maximum allowable UWB emission levels that can be tolerated by GPS receivers, when used within various operational applications. These levels were then compared to the current FCC Part 15 limits. For the aviation applications considered the UWB emissions levels would require that the current FCC Part 15 limits be lowered to ensure compatibility.

The other NTIA study [24] measured the degree of interference of various GPS receivers from different UWB signal types and up to six UWB sources. The report established thresholds for loss of lock and reacquisition time.

Chapter 3

Anecdotal Evidence

> ***an·ec·dote*** *a usually short narrative of an interesting, amusing, or biographical incident {source: Merriam-Webster Online}*
>
> ***an·ec·dot·al*** *based on or consisting of reports or observations of usually unscientific observers {source: Merriam-Webster Online}*

The above definitions in no way imply that the information being transmitted is necessarily false or untrue. The attachment of the anecdotal term to PED interference events has obstructed a clear vision of the information. Anecdotal stories of PED interference have possessed embellished qualities that may have led some to deem them unreliable. And others have concluded that the incident reporters may have a specific agenda and thus the information contained therein was false. This is unfortunate because along with the failure of the FAA and aviation industry to take significant action towards informing the public of the potential danger of in-flight PED use, the flying public, regulators, and aviation community can easily discount these stories.

The following sections relay a sample of the strongest anecdotal evidence. The final section provides a demonstration of how anecdotal stories were used to identify an actual PED interference problem. These cases individually do not provide decisive evidence of a problem, but collectively they do provide a set of information that should not be dismissed casually and they highlight the need for appropriate investigation to adequately address the risks.

3.1 ASRS INCIDENT REPORT NARRATIVES

The ASRS database incident report narratives have been utilized to confirm the legitimacy of the investigations into PED interference as in RTCA DO-199:

> *The committee concluded that although airline reports suggested the existence of interference from portable devices, the information in the reports was not adequate to confirm the interference or define emission levels from devices. Consequently, this information cannot be used for data analysis.*

However, the DO-199 report did not believe the incident reports established a clear indication of a problem and doubted the ability of these incident reports to be valid for data analysis. The ensuing RTCA report on the potential of PEDs to interfere with aircraft, DO-233, was more willing to lend credibility to the incident reports as proof of a problem:

> *Most of the reports contain very few details of a correlation confirmation, but there were several cases where the PED was turned off and then on again and a definite correlation was indicated.*

The reports with high levels of correlation are indeed compelling. Unfortunately, most incidents cannot be fully explored when they occur. Pilot Richard Innes explains, “When you’re in the cockpit, your main focus is flying. You don’t have time to play flight test engineer.” [8].

The following incident reports are some of the most convincing. The actual descriptions from these reports are provided in Appendix A. The ASRS database uses a format that includes all caps and abbreviations that do not provide ease of readability. The incident reports described below capture the essence of the full descriptions.

3.1.1 ASRS Incident Report Number 440557

A pilot who is also an instructor at his airline’s flight academy filed this incident report. He stated that he had heard of reports from other pilots describing interference from DVD movie players.

On this flight the pilot observed a 30-degree difference between his #1 and #2 VOR (redundant systems) needles at a specific VOR frequency. He stated that his DME and course deviation indicator (CDI) displays were consistent with his #1 VOR indicator.

At this point the pilot because he had heard of the DVD movie player interference checked the cabin and located a passenger using a DVD movie player.

The passenger was asked to turn off his DVD player. After the DVD player was turned off the #2 VOR needle moved to coincide with the #1 VOR indication. The passenger was asked to turn the unit back on and once again a 30-degree split between the #1 and #2 VOR needles was observed.

The interference was checked with two other VOR frequencies. For one the #2 needle "wavered" when the DVD player was on and for the other no effect was seen. This demonstrates the frequency dependence that can be associated with PED interference.

3.1.2 ASRS Incident Report Number 274861

The pilot reported that the CDI deflected erratically. The deviations were in both directions and in varying degrees. They were within 30 nm of the VOR station meaning that the signal would be strong. There was no lightning in the immediate area. The pilot requested that the flight attendant check for PED use. The flight attendant reported that a "family was playing with two Gameboys which were connected by a cord." The family was located in the first two rows of the cabin.

The pilot requested that the devices be turned off. The CDI deflections ceased. At some point later in the flight the deflections were observed, but to a lesser degree. It was found that one of the Gameboys was being operated, this time without the connecting cord. At this point a request was made for the Gameboys to be turned off and put away. No further disturbances were reported.

3.1.3 ASRS Incident Report Number 239173

In this incident report the #1 compass precessed 10-degrees to the right. The pilot requested the flight attendant to check the cabin for PED use. It was reported that a passenger had just turned on his laptop. The passenger was asked to turn off his laptop for a period of 10 minutes. He complied and the compass returned to normal operation for the 10-minute period.

The passenger was asked to turn on his laptop. The compass immediately precessed 8-degrees to the right. The computer was turned off for 30 minutes during which the compass was verified as operating normally.

The pilot stated, “It was very evident to all on the flight deck that the laptop computer operation was adversely affecting the operation of the #1 compass.”

3.2 ACCIDENT NUMBER DCA98MA023: 9 FEBRUARY 1998, O’HARE AIRPORT, CHICAGO

On the morning of February 9, 1998, an American Airlines 727 on final instrument approach to Chicago’s O’Hare International Airport suddenly pitched downward. Despite the pilot’s corrective actions, the aircraft hit the ground just short of the runway. Twenty-three people were injured, and the aircraft was substantially damaged [25].

The FAA investigated the ILS system for the runway where the accident occurred. They found no evidence of interference from the local environment and blamed the accident on pilot error and an out-of-date setting of the autopilot [27].

In statements filed with the National Transportation Safety Board (NTSB), American Airlines, the Allied Pilot’s Association, and the Association of Professional Flight Attendants all argued that electromagnetic interference was a possible cause of the crash [26]. American Airlines wrote, “Possible causes for the distortion in the glide slope signal were electromagnetic interference (EMI) from onboard portable electronic devices (PEDs), EMI from ground based equipment…” And in a joint statement the Allied Pilot’s Association and the Association of Professional Flight Attendant wrote that “circumstantial evidence points towards…an improper glide slope signal received by the aircraft’s ILS receiver due to [EMI] from onboard electronic devices or ground-based equipment.” American Airlines requested that the FAA study and issue guidance concerning the potential EMI effects on aviation safety and operations from PEDs.

While it is likely that the NTSB conclusion on the cause of this accident was correct there is no evidence that PED interference was ever seriously looked at as a contributing factor. The aviation accident explored in the following section demonstrates how investigators are inclined to avoid giving serious consideration to PED interference even when the evidence for such interference is strong.

3.3 AVIATION OCCURRENCE 03-004: 6 JUNE 2003, CHRISTCHURCH, NEW ZEALAND

There are no documented cases of a fatal aircraft accident caused by RF interference from portable electronics. The following aviation accident description and discussion are presented to demonstrate that in this case there was strong circumstantial evidence that a cellular phone may have played a part in the accident and in general this is the "how it will happen" scenario that this research effort hopes to avoid. This accident involved a regional size aircraft, but demonstrates the issue and translates to larger commercial aircraft.

On Friday 6 June 2003, a Piper PA 31-350 Navajo Chieftain was performing a charter flight from Palmerston North to Christchurch, New Zealand. The aircraft was flying an instrument approach at night in instrument meteorological conditions. The aircraft descended below minimum altitude in a position that prevented runway lights from being seen and collided with trees and terrain 1.2 nm short of the runway. Eight of the ten people onboard including the pilot were killed [28].

The factual findings from the accident investigation indicate that the pilot initiated a cellular phone call just prior to intercepting the glide path on an instrument landing approach [28]. The call remained connected until the accident occurred. The aircraft was below the glide path at all times. Post-accident analysis indicated that the final positions of the pilot's glide slope (GS) indicators were primary pointer full down and secondary pointer 1 dot down. These both were indicators for the pilot to descend further. The other factual findings of interest were:

1. The pilot had previously worked as a marketing manager for a cellular phone company. The pilot provided a brief that included permission to use laptops and cellular phones during the flight.

2. One survivor recalled the pilot using his cellular phone "late" on the flight.

3. Telephone records confirmed that passengers and the pilot used cellular phones during the flight. The pilot initiated a call that remained connected for final 3 minutes and 9 seconds of the flight.

4. The pilot’s call was connected to a voicemail system. His partner listened to the first minute of the message, heard only engine noise, and deleted the message.

The accident report concluded that it was unlikely that the ground instrument landing system (ILS) was malfunctioning. It also concluded that the deviation from the glide path could have resulted from “a faulty glide slope indication.” The report goes on to indicate that the “possibility must remain that … interference from the pilot’s own cellphone might have caused erroneous indications.”

There is no doubt that the pilot’s actions were a major contributor in this accident. The barometric altimeters were not set the same, prohibiting a cross check on altimeter indications. Additionally, the radar altimeter was not functioning, so no “low altitude” warning was available. The automatic direction finding (ADF) equipment was not tuned for a missed approach, a good standard practice. The use of his cellular phone during an instrument landing approach would not be good pilot practice either.

Ultimately, this aviation accident should have been avoided. Even with an erroneous GS indication the pilot should have terminated the approach at the decision altitude (DA)[6] given the meteorological conditions. The accident investigation report officially listed the cause as:

> *The accident probably resulted from the pilot becoming distracted from monitoring his altitude at a critical stage of the approach. The possibility of pilot incapacitation is considered unlikely, but cannot be ruled out.*

Other safety issues identified in the report included “the need for VFR/IFR operators to have practical procedures for observing cellular phone rules during flight.”

The general point illustrated by this case is that PED interference is not likely to cause an aircraft to fall out of the air, but it can be a subtle contributor to a chain of events causing an accident. In this case, if interference was present, then it likely distracted or deceived the pilot causing him to miss other important information that could have averted the accident.

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[6] The DA is the altitude where the runway must be visible to continue an approach.

The aviation accident described above had indicators pointing to PED interference as a potential if not significant influence. Yet, the PED interference was not found to be a causal factor. This stems in part from how aviation accidents are evaluated, using concrete and factual information to the greatest extent and theorizing as little as possible. It is unlikely that PED interference will be indicated as a causal factor in an aviation accident because it is unlikely that there will be a smoking gun.

For one thing, PED interference is time and space dependent. It occurs for a given set of parameters and conditions. This is why the aviation community has been frustrated in their attempts to reproduce PED interference observed in-flight on the ground. This comes as no surprise to EMC engineers who know how elusive some interference issues can be. There are a number of incidents where laptops have been purchased by the airlines from passengers suspected of causing interference only to find nothing upon ground testing or subsequent in-flight testing.

There is no single piece of hardware to evaluate after an accident that would indicate PED interference as a cause. For example, if a rear stabilizer fails, then a post-accident investigation might find a manufacturing defect. However, as in the accident described in this section, the glide slope indicator can only be assumed to have shown erroneous data. And, there are a number of potential causes (pilot misinterpretation, faulty indicator, etc.) only one of which is PED interference. PED interference is the least supportable in terms of concrete data and precedence. There are “forensic” tests that can indicate a gauge’s final reading, but it is just a last snapshot of what was occurring and these tests are always open to interpretation.

Thirdly, flight data recorder information, if it exists, will not likely indicate interference. For example, a stall has the characteristics of a high pitch and low speed that could be easily seen on a flight data recorder. However, flight data recorders indicate parameters from the avionics and not necessarily what the gauges indicated. Thus, for PED interference to be indicated a witness would need to survive and then the reliability of their memory would be an issue. In this case study there was a witness, but the investigators did not weight their recollection heavily.

Fourth, no aviation accident has yet had PED interference listed as the causal factor. This precedence is very powerful against PED interference being indicated. In this case study, the conclusions and recommendations are sound and follow the mold of transportation safety board investigations worldwide, but PED interference is not identified as a causal factor. It does find PED interference to be a credible potential factor, "the pilot 's own cellphone…could have interfered with his glide slope indication," but it fails to emphasize PED interference relative to other potential causes based on the evidence. For example, it refuses to rule out carbon monoxide or coronary artery disease as influences in the accident when there is no appreciable supporting data. These items are noteworthy and should be included in the discussion. However, given that there was concrete evidence that a cellular call was active inches from the cockpit instruments it seems hard to not place its likelihood ahead of carbon monoxide or coronary artery disease influences.

This case study is yet another example of how aviation accidents are a chain of events. It has often been concluded that removing any one item in the chain would be sufficient to avert disaster [29]. This case study shows that the presence of PED interference along with other factors such as long workday, IFR conditions, and pilot inexperience is a "scenario" that could lead to disaster. The conclusion that PED interference did not cause this accident does not mean it should be ruled out as involved. This case study demonstrates strong circumstantial evidence that PED interference may have been involved in an aviation accident. It further demonstrates the resistance of accident investigators to indicate PED interference as a causal factor and provides explanations why.

3.4 ANECDOTAL STORY PROVES TRUE

This chapter has presented anecdotal evidence that portrays PED interference as a credible risk to aviation. Traditionally, doubters have pointed to the inability to reproduce PED interference as proof of its non-existence. The RTCA DO-199 report recognized this:

> *The anecdotal reports of PED interference by aircrews are of a qualitative nature and have not been repeatable on a later occasion. This non-repeatability*

> *has caused considerable uncertainty within the industry, the FAA and the traveling public as to the seriousness of the problem."*

A recent set of incident reports have been essentially reproduced in a laboratory setting. This should be cause for the aviation community to reassess the weight placed on anecdotal evidence.

The FAA received correspondence in July 2003 from a company who owned a small aircraft that stated it had observed multiple instances of interference to their onboard GPS receivers from a Samsung SPH-N300 cellular telephone. The correspondence indicated that the interference occurred when the phone was on, but not actively involved with a call. There was particular interest because the interference occurred at different geographic locations, occurred with three different GPS receivers using separate antennas, and was repeatable on multiple flights on different days. The company reported that the interference could be correlated to the cellular phone being turned on and off.

The company investigated further, indicating that other phones did not produce similar interference and the interference only occurred in-flight. They also provided spectral plots of the RF emissions from the phone in the GPS band using a spectrum analyzer.

The FAA forwarded the information to the RTCA Special Committee 202 and requested NASA Langley Research Center to conduct measurements using proven and reliable methods and facilities.

NASA issued a technical memorandum [19] that indicated the presence of emissions in the GPS band that "show that the threat of interference from a particular mobile phone to aircraft GPS receivers is real." The phone did not produce emission levels capable of interfering with GPS receivers when in standby and not actively engaged in transmissions. However, it is assumed that the phone when used in-flight was transmitting registrations during the time of the interference.

The NASA report also points out that the emissions were permitted under the governing FCC rules {47 CFR 24.238} that allow out-of-band spurious emissions below prescribed levels relative to the permitted power output at the transmission frequency. This accentuates the need for FAA and FCC cooperation.

The NASA report also indicated that previous emission measurements on laptops [18] demonstrated a capability to cause interference.

3.5 CONCLUSION

This chapter has provided samples of anecdotal evidence indicating PED interference as a risk to aviation. In each case the evidence is highly suggestive, but does not clearly demonstrate a risk. However, when the cases are considered in total they provide a set of information that cannot be dismissed and call for appropriate investigation to adequately address the risks.

Chapter 4

Analyses with Existing Data

The previous two chapters have presented evidence and studies that demonstrate PED interference as a potential risk to commercial aviation. However, the risk to aviation safety has not clearly been identified quantitatively. This chapter analyzes existing data sets with the objective of providing quantitative information that can assess the risk of PED interference to commercial aviation. In part this chapter performs qualitative analyses that clarify the validity of existing data so that it can be utilized in quantitative assessments. A bounding analysis is performed that uses aviation accident data to enhance the case that PED interference should not be dismissed as a serious risk to commercial aviation solely because it has not yet been indicated as a primary causal factor in an aviation accident. The bounding analysis helps define the potential magnitude of the issue by determining an upper bound for aviation accidents caused by PED interference. A strategy for using the ASRS database to identify the most promising areas for further research sectors is developed by assigning evidence levels to incident reports and then statistically analyzing the data. The ASRS analysis also identifies a potential occurrence rate for PED interference. The chapter concludes by applying previous work in industrial safety to the occurrence rate to estimate an accident rate.

4.1 BOUNDING ANALYSIS

The purpose of this analysis was to determine an upper bound for commercial aviation accidents caused by PED interference. The analysis builds on the case study findings in Chapter 3 that demonstrated interference could be a possible cause of an aviation accident without being clearly identified as a cause.

4.1.1 Definitions

A ***Causal Factor*** is an event or item judged to be directly instrumental in the chain of events leading to an accident.

A ***Primary Causal Factor*** is the causal factor selected as the most significant in the chain of events.

A ***Circumstantial Factor*** is an event or item that was judged not to be directly in the causal chain of events but could have contributed to the accident.

4.1.2 Sources of Data

The two sources of data were the Boeing Commercial Airplanes Group summary of worldwide accidents, “Statistical Summary of Commercial Jet Airplane Accidents: Worldwide Operations 1959-1999” [30] and the Flight Safety Foundation (FSF) special report, “Killers in Aviation: FSF Task Force Presents Facts About Approach-and-landing and Controlled-flight-into-terrain Accidents” [31]. These two sources used the findings of the accident investigation body in charge as their primary source of information.

4.1.3 Method

The primary causal factors of commercial aviation accidents were evaluated to determine the likelihood that PED interference could have actually been a causal or circumstantial factor in the aviation accident, but not identified as such. The primary causal factors were selected because only one is assigned to each accident. There are on average 10 causal factors listed for each accident [31]. Of all the primary causal factors, close to 70% are attributed to flight crew actions [32].

A category was assigned to each primary causal factor based on the likelihood that PED interference could have actually been a causal or circumstantial factor in the accident. The “likelihood categories” were highly unlikely, unlikely, or possible. The categorization was subjective and based solely on the assigned primary causal factor and the author’s 16 years of experience in the field of aircraft electromagnetic interference analysis and testing. For example, the likelihood that interference played a part in an “in-flight fire” is remote, thus those accidents were categorized as highly unlikely. On the other hand, “landing short” of the runway could indicate an erroneous readout on the ILS caused by PED interference that in turn caused the pilot to have too steep of an approach. Thus, these accidents were categorized as possible. It is important to note that individual accidents were not reviewed in this assessment.

4.1.4 Results

The primary causal factors for 385 commercial aircraft accidents for the period 1990-1999 were evaluated [30]. The accidents included passenger, cargo and ferry flights for worldwide commercial jet airplanes that are heavier than 60,000 pounds maximum gross weight. Airplanes manufactured in the Commonwealth of Independent States (former Soviet Union) are not included. The results are displayed in Table 4.1. There were 77 accidents categorized as “possible.” These were considered to have some appreciable potential that the actual cause could have been PED interference rather than the indicated cause. The 77 identified accidents included controlled flight into terrain (CFIT), landing short, ground collision, miscellaneous, and unknown causes.

Only 1 of the 8 miscellaneous factors potentially involved PED interference. It was an “instrument error.” The remaining 7 factors were: coffee maker explosion, jet blast, taxied across ditch, fuel spill, pilot incapacitated, window failed and tail strike.

The accidents with primary causes listed as CFIT, landing short, and ground collision belong to a class of accidents known as approach-and-landing (ALA) accidents. A FSF study identified primary causal factors in 279 fatal ALA accidents from 1980-1996 [31]. This study included only Western-built jets. It was determined that PED interference was possible for three of the causal factors associated with ALA accidents. They were lack of positional awareness in the air, flight handling, and system failure flight deck information. Others factors could have been involved, but the likelihood seemed significantly less. It should be emphasized that a scenario could be developed for almost any causal factor that interference actually was an influence. The factors characterized as possible accounted for 27.5% of the ALA accidents.

The FSF study implies that only 17 of the 62 ALA classified accidents should be categorized as possible. Thus, including the miscellaneous (instrument error) and unknown causal factors, an upper bound for commercial aviation accidents potentially caused by PED interference is 6.5 % (25/385) and a lower bound is 0.0 %.

Table 4.1: Likelihood of PED Interference Causing an Aviation Accident Based on Primary Causal Factor: Commercial Aviation Accidents from 1990-1999

Primary Causal Factor	Total	Highly Unlikely	Unlikely	Possible
Hard landing	55		55	
Off end on landing	49		49	
Off side on landing	37		37	
Controlled flight into terrain	36			36
Gear collapse/fail/up	31	31		
Loss of control	30		30	
Landing short	16			16
Runway incursion with vehicle/people	16	16		
Refused takeoff – off end	14	14		
Engine failure/separation	10	10		
Ground collision	10			10
Off side on takeoff	8	8		
Miscellaneous	8			8
Fire on ground	8	8		
Fuel management/exhaustion	7		7	
Ground crew injury	7	7		
Unknown	7			7
Ice/snow	6	6		
Aircraft structure	6	6		
In-flight fire	5	5		
Boarding/deplaning	4	4		
Wind shear	3	3		
Takeoff configuration	3	3		
Turbulence fatality	3	3		
Midair collision	2		2	
Fuel tank explosion	2	2		
Wing strike	2	2		
Totals	385	128	180	77

4.2 Aviation Safety Reporting System Database Analysis

The accident case study of the previous chapter showed that EMI could play a role in aviation accidents and that it would be hard to detect. The analysis presented above, based on the fact that PED interference would be hard to detect in an aviation accident, explored categorizing primary causal factors as a method to bound the problem.

How commonly does radio frequency interference cause safety problems for commercial aircraft? The bounding analysis of the previous section indicates that if PED does cause accidents, then it is a small contributor to the total number of accidents. This section explores the more central issue and attempts to determine how often PED interference occurs and what the affects are. This analysis used incident reports from the ASRS database that describe interference to avionics from PEDs. The purpose of this analysis was to clarify the validity of the incident reports, further quantify the problem, provide research direction, and reemphasize the critical nature of the problem.

This section contains six parts. The first provides a description of the ASRS, its usefulness, and limitations. The second explains how the data were obtained and categorized. The third provides a summary of the incident reports and an estimate for the reporting rate and its implication on the actual rate of PED interference incidents. The fourth reports which avionics and PED combinations demonstrated statistical significant relationships. The fifth section emphasizes the critical nature of PED interference by presenting narratives taken from the incident reports that highlight the potential consequences. The final section provides the key findings.

4.2.1 Aviation Safety Reporting System Database and Description

The ASRS is a voluntary, confidential, and non-punitive system operated by NASA that allows flight crews, air traffic controllers, maintenance personnel and others to submit reports involving safety incidents. The reports are sanitized and summarized by a staff of experienced pilots, air traffic controllers and aviation industry personnel in a form that assures confidentiality. Conditional immunity is granted to those who file reports. Analysts can either make a search request to NASA or perform a search through the FAA's Office of System Safety's web page (www.nasdac.faa.gov).

ASRS has received more than 500,000 incident reports, issued more than 4,000 safety alerts and identified approximately 60 reports and papers that have drawn upon the database. In testimony last year before the House, Linda Connell, ASRS Director, enumerated the many ways it has been used to address real aviation safety issues [33]. The ASRS is an important aviation safety tool. It has become a cornerstone of aviation safety, and a model for other fields, such as medicine [34].

The usefulness of an incident database as a qualitative tool has been generally accepted. Sheryl Chappell, former ASRS scientist, states that, "Incident data are ideally suited for proving the existence of a safety issue, understanding its possible causes, defining potential interventions…" [22]. Its acceptance as a quantitative tool has been less enthusiastic. Chappell points out that caution is required in quantitative analysis of incident data. The largest objections in PED interference incident reports stem from their potential accuracy.

In 1996, RTCA issued a report on the potential for interference to aircraft systems from carry-on PEDs, DO-233 [10], in response to a 1992 House Transportation Appropriations Bill [4]. The data in DO-233 covered the period from 1982 to 1993. It identified 34 incidents in the ASRS database and another 103 incidents from International Air Transport Association (IATA) and earlier RTCA Special Committees 88 and 156. The report was hesitant to accept these database entries as strong evidence of a problem:

> *Most of the reports contain very few details of correlation confirmation, but there were several cases where the PED was turned off and on again and a definite correlation was indicated.*

The DO-233 report remains the basis for existing airline policies and regulations.

There are several sources of bias in the ASRS data. The influence of both reporters and users of incident data has been documented [22]. Reporter bias can arise from media coverage, employment status, or the seriousness of the incident.[7] Researcher (end user) bias can be introduced through improper coding or recording of data.

The processing of data by ASRS staff also creates bias. The ASRS staff chooses entries to the database on the basis of a "watch list." Certain incidents are considered critical and are automatically entered. These incidents typically predominate. The staff then exercises their judgment in choosing other entries. Their focus shifts over time as different kinds of events command attention. About 20-25% of the reports that are submitted to the ASRS are entered into the database. Between 1995 and 2001, 10% of the submitted reports were randomly selected and this was about half of all the entries being made. Thus, this period is valid for statistical time-series analysis. This practice has since been discontinued due to budget cuts. Since, only a small number of the

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[7] For example, a large amount of recent attention has been given to runway incursions. The FAA spent $57 million on this problem in FY2001 compared with an average of $25 million over the past 15 years [35]. Since 1999, the FAA has made runway incursions a top agency priority and in 2000 they appointed a Runway Safety Director. This type of attention surely places awareness of such events in the forefront of the minds of pilots and aircrew.

incident reports received by ASRS are entered into the database and reviewers have considerable leeway on selection criteria, bias is a concern.

The ability to address the voluntary and confidential nature of incident reports with large numbers of similar accounts and to deal with reporting bias through correlation techniques has been stated [22]. And, the random entries made between 1995 and 2001 can overcome the staff processing bias. However, care is required.

4.2.2 Methodology

The ASRS database was searched to identify incident reports involving interference to avionics from PEDs. The data used in this analysis are the result of ASRS database searches performed over the period April – June 2002 using the FAA's Office of System Safety's web page. The available data were current through March 2001.

Initial queries to the database revealed that searching on broad terms such as "portable electronic device" or "PED" was insufficient to identify all PED-related reports of interference. To overcome this, an exhaustive list of terms that covered most commercial electronic devices was developed. The search strategy was impractical for certain terms like "computer," that produced over 2,500 hits. Initial review of these reports showed that very few of these involved interference to avionics. Thus, refinements were made to identify the target reports using Boolean operators. A search of "computer" AND "interference" yields only 24 responses. Other refinements included accounting for misspellings and searching for the affected avionics (autopilot, VOR, radio, etc.). A sample of the search strategies is shown Table 4.2.

Table 4.2: Sample ASRS Database Search Strategies

cell phone	DVD
cellular	laptop AND interference
cellular AND phone	medical AND device
Gameboy	VOR AND interference
game AND boy	VOR AND laptop

The pertinent information from each report was recorded: report number, date of occurrence, affected avionics, suspected PED(s), aircraft model, and flight phase. A determination of the avionics affected and the suspected PED(s) causing the interference were made after reading the incident report narrative. This determination was based on the researcher's experience in consultation with Jay Apt, an experienced pilot and former NASA Astronaut. The report narratives sometimes were vague and only relayed suspicions of an interference event or what caused it. However, many reports provided sufficient evidence and detail that it was likely that an identified device(s) did cause or contribute to an anomaly. It is possible that some of the identified PEDs did not contribute to the interference even though they were identified as the "sources."

A coding instrument was developed to capture the degree to which the narrative supported a finding of interference. The coding scheme is similar to the "level of correlation" used in the RTCA DO-233 report. The "evidence" level, as defined in Table 4.3, was assigned after considering the report author's event description. The researcher did not attempt to second-guess the report author, but rather tried to interpret the narrative presentation. The evidence level does not imply independent verification of the event or that any subsequent evaluation produced support for the reporter's conclusion. Loosely speaking a high evidence level identifies those reports that had correlation between PED usage and an interference event.

Concern over the accuracy of these reports has been raised. However, the reporting of a large number of similar incidents over an extended period of time reduces the likelihood of erroneous associations [22].

Table 4.3: Evidence Level Definitions

Level	Description
5	The affected aircraft system returned to normal operation after termination of PED operation and subsequently demonstrated anomalous activity when the suspected PED was operated again.
4	The interference corrected soon after a pilot or flight attendant announcement was made requesting that electronic devices be turned off. There was confirmation that the passengers complied with the request.
3	The interference corrected soon after a pilot or flight attendant announcement was made requesting that electronic devices be turned off. There was no confirmation that passengers complied with the request.
2	A PED was known to be on the aircraft and there were indications that it was in use at some point during the flight, but no check was performed to correlate to the interference.
1	It is unknown if a PED was in use or on the aircraft at the time of the anomaly

4.2.3 Summary of Incident Reports and Rates

The database searches revealed 125 incident report entries regardless of their assigned evidence level. There were 57 incident reports where the evidence level was 4 or 5 and 77 incident reports where the evidence level was at least 3. The incident report entries by year are presented in Figure 4.1. The aircraft involved in the 125 incidents were all commercial aircraft operating under Federal Aviation Regulation (FAR) Part 121 or 135 except for one helicopter operating under FAR Part 91. The sample of incident reports reproduced in Appendix A are all evidence level 4 and 5.

The peak entries come in 1993 and 1994. This coincides with the Congressional interest that prompted RTCA Special Committee 177. The entries decline over the next few years. This occurs soon after airlines begin adopting policies that require passenger electronics to be turned off below10,000 ft. After 1996, the trend is increasing. This is possibly due to the increasing number of flights, consumer electronics proliferation including cellular phones, aging aircraft systems, and/or passenger non-compliance with airline policies. The increasing trend after 1996 coincides with the random entries that accounted for half of all database entries between 1995 and 2001.

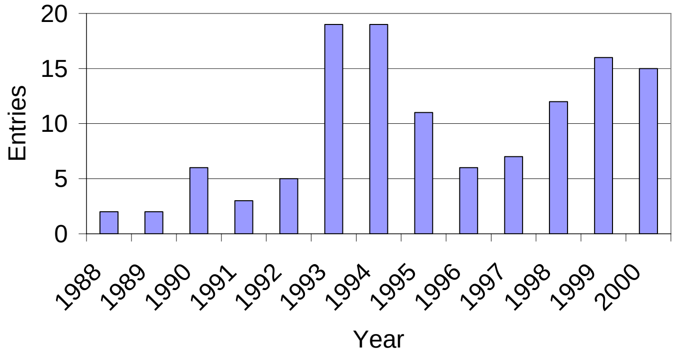

Figure 4.1: Incident Reports of Interference to Avionics from PEDs: ASRS Entries by Year (1988-2000)

4.2.3.1 Reporting Rates

As indicated above, not all submitted incident reports are entered into the database and those not selected for entry are destroyed within 6 months. Thus, establishing the number of PED interference reports filed is left to estimation. Due to the infrequent nature of these types of reports NASA claims to enter “most” [36]. However, no formal records are available to confirm this assertion.

The random sample incident reports filed between 1995 and 2001 were used to establish a yearly average ($\mu = 1.5$, $\sigma = 1.05$). This implies that the actual mean is between 0.66 and 2.34 using a 95% confidence interval. Based on the 1 in 10 random sampling used, that the actual yearly reporting rate could be as high as 23.

The number of incident reports should not be considered the number of occurrences. First, it is not known if all reported incidents are entered into the database. Second, some of the reported incidents may not be interference events (i.e. false positives). Third and most important, the amount of underreporting is not known. Underreporting can be influenced by reports being filed elsewhere, the event not being recognized as interference (false negative), or the flight crew not attaching significance to the event. This means that PED interference events could be occurring a few times each month. Given that hazardous incidents have been shown to lead to accidents [29], [37] these numbers are too large to ignore.

4.2.3.2 What avionics were affected?

The most frequently cited aircraft systems involve navigation. The VOR navigation was the most cited system. The VOR incidents tended to be easily noticed by the flight crew and non-critical in nature. However, a few created hazardous situations. ASRS Report 226306 described a missed approach and ASRS Report 440557 a potential in-flight collision with another aircraft.

Also, many of the incidents involved critical systems. Instrument landing systems were affected 17 times, autopilot systems were affected 8 times and an engine fuel controller was affected once. The potential for serious consequence is markedly increased when critical systems are affected. A summary of the avionics involved in the incidents is provided in Table 4.4.

Table 4.4: Avionics Associated with Incidents

Aircraft System	Occurrences
VOR	47
Navigation*	33
Instrument Landing System	17
Communication Radio	12
Radar Altimeter	10
Autopilot	8
GPWS	7
TCASII	4
Compass	4
Flight Display	3
Caution/Advisory Light	2
Gyro	1
Engine Fuel controller	1

* Navigation other than VOR

4.2.3.3 What PEDs are causing the interference?

The PEDs most often cited as being potential offending sources of interference were cellular phones and laptop computers. They accounted for almost 60% of the incidents. Electronic games, AM/FM radios, CD/DVD players, and pagers were also frequently cited. Medical electronic devices were mentioned only twice; however new medical electronics (such as insulin pumps) may become an issue. A list of cited PEDs is provided in Table 4.5.

Table 4.5: PEDs Associated with Incidents

PED	Occurrences
Cellular phone	41
Laptop computer	34
Electronic game	15
AM/FM radios and cassette players	12
CD/DVD player	7
Pager	6
Camera/video	3
Portable TV	3
Transmitter	3
Heart monitor	1
Electronic device	1
Calculator	1
Hearing aid	1
PDA	1
Unknown	23

While any effort to characterize PED emission profiles or their potential to interfere with avionics is encouraged, analytic resources are limited. The starting point should concentrate efforts on cellular phones and laptop computers. Further support for this assertion is that they are among the most utilized consumer portable electronics. The influence of age on laptops may be particularly interesting. Finally, given the rapidly changing electronics market attention should also be paid to emerging technologies and devices, such as ultrawideband.

4.2.3.4 Which PED-avionics combinations occurred the most?

The most cited combination of PED-avionics interference was cellular phones affecting VOR navigation systems, 20 incidents. Laptop computers affecting VOR systems were also prevalent, cited 15 times. The most common combinations are shown in Table 4.6. Cellular phones and laptop computers were involved in the 4 most frequent combinations. They were also involved in 6 of the 8 most frequent combinations. This reaffirms that research should be concentrated on the evaluation of cellular phones and laptop computers.

Table 4.6: PED-Avionics Combinations Associated with Incidents

PED-Avionics Combination	Occurrences
Cellular phone-VOR	20
Laptop-VOR	15
Cellular phone-navigation*	9
Laptop-navigation*	9
Electronic game-VOR	8
Cellular phone-ILS	6
Cell phone – aircraft radio	6
AM/FM radio**-VOR	6
AM/FM radio**-navigation*	5

* Navigation is other than VOR
** AM/FM radio includes cassette players

4.2.3.5 When does the interference occur?

The majority of incidents occurred during the cruise portion of flight. However, close to half occurred within the “sterile” cockpit window.[8] Incidents that occur during this phase of flight are more critical and their importance cannot be overstated. These results indicate that passengers may not be complying with the airline requirements that

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[8] The “sterile” cockpit prohibits crew members from performing non-essential duties when the aircraft is involved in taxi, takeoff, landing and all other operations conducted below 10,000 ft MSL due to the criticality of flight [FAR 121.542] and [FAR 135.100].

all electronics be turned off and stowed during critical phases of flight. This is supported by incident reports to the ASRS, informal reports from colleagues, and a small mail-survey of passengers conducted in 2001, see Chapter 5. The breakdown of flight phase for PED interference events is shown in Table 4.7.

Table 4.7: Flight Phase Associated with Incidents

Flight Phase	Occurrences
Pre-flight	4
Departure	25
Cruise	62
Approach	34

* Departure includes takeoff and climb
** Approach includes descent and landing

4.2.3.6 What aircraft models are affected?

Given the nature of the data used for this evaluation it would be unfair to make any authoritative statement about the aircraft models or manufacturers involved in the anomalies. However, two findings seem to be fair and noteworthy.

First, many aircraft models and manufacturers were found to be involved. Overall, there were 13 different aircraft models and 7 manufacturers found to be involved. The actual number of models and manufacturers may be higher, but prior to 1994 only a general aircraft description was given in the incident reports.[9] The characteristics of the aircraft models involved were varied: large, medium and small transport; jet and turbo propeller; "fly-by-wire;" etc.

Second, analysis did not show any particular aircraft model or manufacturer to be involved in a disproportionately large number of incidents. However, the influence of reporting bias may be significant in this analysis. For example, a particular airline may use mostly one model of aircraft and they also may encourage their pilots to report incidents. This could act to erroneously mask the percentage of incidents associated with an aircraft model or manufacturer.

The involvement of many aircraft models and manufacturers implies that the problem needs to be addressed at an industry level. Government support in the form of

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[9] For example, large transport, low wing, 3 turbojet engines.

both financial and engineering support seems appropriate given the public safety implications and the current industry economic situation.

4.2.4 Correlations

To obtain a clearer picture of what relationships might exist, the data were grouped and evaluated at various evidence levels. They are referred to as high evidence data (levels 4 and 5), intermediate evidence data (levels 3, 4 and 5), and low evidence data (all levels). Correlation was performed between the aircraft systems described in Table 4.4 and the passenger electronics described in Table 4.5. The Pearson correlation values described below are not very high, however the level of significance may be more important for this application as the evaluation involved a large number of parameter correlations.

4.2.4.1 Cell phones vs. ILS

The correlation between cellular phones and ILS anomalies showed a weak significance for high evidence data, $r = 0.2025$ with $p = 0.1873$ using Fisher's Exact Test. The correlation was less significant when using lower evidence data sets. However, the correlation between unknown sources and ILS anomalies was significant for intermediate evidence data, $r = 0.5286$, $p < 0.0001$ and low evidence data, $r = 0.3537$, $p < 0.0001$. It is theorized that many of these unknown sources are cellular phones. This is derived from the following:

1. Passengers are more likely to initiate calls during approach due to aircraft proximity to the ground (i.e. cellular base stations) and the desire to inform friends, relatives, or colleagues of their impending arrival. Flight crews are busy during landing and might not have had time to determine which PEDs were in use.
2. A higher percentage of approach phase incidents are observed for the low evidence levels (1, 2 and 3).

Thus, cellular phones interfering with ILS intuitively makes sense and is supported by the data.

4.2.4.2 Electronic games vs. VOR

The correlation between electronic games and VOR anomalies was significant for high evidence data, r = 0.3485 with p = 0.0204 using Fisher's Exact Test. The correlation was less significant for intermediate and low evidence data.

Electronic games operate at relatively low clock speeds that are close to the VOR operating frequency range. Game electronics are very likely to be dropped, thrown, or mishandled by their child owners and this can render electromagnetic emission control measures ineffective. Thus, this finding seems to be worth further exploration.

4.2.4.3 CD/DVD players vs. radio communications

The correlation between CD and DVD players and aircraft radio communication system anomalies was significant for high evidence data, r = 0.3157 with p = 0.0696 using Fisher's Exact Test. The correlation was less significant for intermediate and low evidence data.

There is no immediate insight as to why this relationship may exist. The large number of correlations performed creates an expectation that by chance a few relationships will appear significant when there is no causal relationship, and this could be the case here.

4.2.5 Beyond Numbers: The Narratives

The following narrative excerpts demonstrate how interference creates hazardous situations that can become incidents or accidents.

A crew who had lost their electronic flight instrument system (EFIS) stated:

> *While in this event no serious harm was done, the effect could have been different if the aircraft was in heavy weather flying a complicated departure or arrival.*[10]

In one incident the flight crew experienced fuel flow changes, "as the Captain applied power for taxi, the left engine rolled back to less than idle and was shut down."[11]

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[10] ASRS Report 236534.

[11] ASRS Report 265426.

Luckily, this incident occurred on the ground. If it had taken place in-flight, then the situation would have immediately been critical.

After being unaware he was off course a pilot stated, "[I] would have really been sweating if it had been instrument flight rules in that mountain area."[12] Another crew reported, "abruptly, the airplane entered a 30 degree bank."[13] If that occurred during takeoff, landing, a high workload period or in bad weather the consequences could be catastrophic. Finally, one pilot reported:

> *We were advised by air traffic control that our course was 7 mi off the center course…A possible contributing factor was caused by poor human performance reaction, due to extended scheduled long duty days prior to this flight.*[14]

The subtle nature of PED interference can be such that flight crews may not react immediately or at all. This can create extreme hazards as in the case of course deviations.

4.2.6 ASRS Database Analysis Summary

The following provides a summary of the key findings from analysis of the ASRS database:

1. There were 125 entries in the ASRS database that involved suspected PED interference. This translates to an incident rate of as high as a couple of events each month. Given that only 20-25% of filed reports are entered into the database and that underreporting is likely, the topic should not be ignored.
2. Critical aircraft systems have been reported as affected in these incidents.
3. Incidents were reported as occurring at critical flight phases (i.e. approach and landing).
4. Many aircraft models and manufacturers were involved in the incidents. This suggests that the problem needs to be addressed at an industry level.
5. Certain passenger electronics were shown to be correlated to aircraft systems and may be good starting points for more aggressive evaluation.
6. The report narratives provide evidence of the hazards created by these incidents and highlight the potential for catastrophe.

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[12] ASRS Report 337254.

[13] ASRS Report 277118.

[14] ASRS Report 255695.

4.3 IMPLICATIONS OF THE HEINRICH PYRAMID

In 1941 H. W. Heinrich [37] described a hazards/incidents/accidents pyramid and showed that it held for a wide variety of industries. In 1972, Diehl and Ayoub [38] verified the relationship between hazards, incidents and accidents. The relevance to the aviation industry has also been shown. In 1973, Col. Nichols demonstrated that U.S. Air Force accidents and incidents followed the pyramid ratios almost exactly [39]. And Diehl implied that this pyramidal relationship holds for aviation accidents involving bird strikes [29].

It seems plausible that this relationship would also exist for PED interference events. The anecdotal evidence provided in Chapter 3 supports this hypothesis. In this chapter, the ASRS analysis demonstrates that PED interference events are causing hazardous situations to occur and the bounding analysis supports the conclusion that occasional accidents caused by PED interference cannot be ruled out.

The hazards/incidents/accidents pyramid described by Heinrich approximates that regardless of the industry there will be 30 minor accidents and 300 hazardous incidents for every one major accident, Figure 4.2. Applying this relationship to the incident reporting rate developed in section 4.2.3.1 suggests 1 accident every 12 years due to PED interference. Given that in-flight PED usage is increasing there is reason for concern.

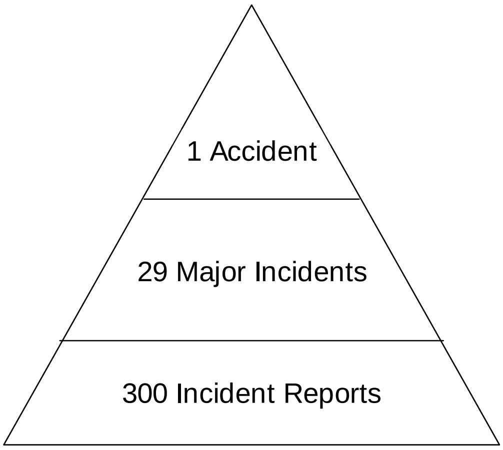

Figure 4.2: Heinrich Industrial Safety Pyramid

Chapter 5

Passenger Use of Electronics In-Flight: A Survey

The previous chapters have presented evidence that PED interference is occurring on commercial flights. The data suggest that passengers are using prohibited devices and permitted devices at prohibited times. The ultimate success in controlling risk in this area may rely on passenger adherence to policies. Thus, a survey of passenger in-flight electronics use was advantageous to understand how passengers may be contributing to the problem and how successful certain policies may or may not be in the future.

This chapter discusses the results of a survey performed in late 2001. The survey questions and results are provided in Appendix B. The survey was intended to be a first cut review of passenger understanding and adherence to PED aviation regulations. Specifically, the survey was designed with the intent of:

1. Establishing passengers understanding of the rules governing PEDs carried on board aircraft.
2. Identifying the flying public's belief on how safe it is to use PEDs and cellular phones during flight.
3. Developing an understanding of how often cellular phones are used in-flight.
4. Identifying the level of desire the flying public has for using cellular phones and Third Generation (3G) wireless products during flights.

5.1 SURVEY DESIGN

The survey was designed to be anonymous and non-invasive so as to elicit truthful responses. The survey was distributed to a Pittsburgh travel agency that supplied a copy of the survey with a return postage envelope to flying customers who expressed a desire to participate. The surveys did not contain any tracking or identification numbers so that respondents could respond anonymously. The return postage envelope minimized the effort required by the respondent. The particular travel agency used had a strong association with Carnegie Mellon University and thus the expectation was that the responses might be composed largely of business flyers.

There were twelve multiple-choice questions with four requiring further response based on the initial response and there were two written response questions. The questions were grouped into five basic categories as described in Table 5.1.

Table 5.1: Intention of Survey Questions

Question Number	Intent
1, 6, 7, and 11	Establish passengers understanding of the rules governing PEDs carried onboard aircraft.
3, 4, and 5	Determine how frequently cellular phones are used in-flight
2, 7, and 8	Identify what significance the flying public believes safety is an issue with PEDs carried onboard.
9, 10, and 12	Identify the level of desire that the flying public has for using cellular phones and Third Generation (3G) wireless products during flights.
13 and 14	Determine the extent and purpose of travelers.

5.2 SURVEY RESULTS

One hundred surveys were distributed to customers by a Pittsburgh travel agency during October and November of 2001. There were 39 responses received (4 blank) as of January 5, 2002. The survey questions and results are contained in Appendix B.

The respondents were probably made up of business flyers as anticipated. There were 22 respondents (63%) indicating that their last trip was business compared with 13 (37%) for pleasure. Also, most respondents travel often. Only 16 flyers (46%) flew less than 25,000 miles per year, 15 (43%) flew between 25,000 and 50,000 miles, and 4 (11%) flew more than 50,000.

The results of this survey document that passengers are using their cellular phones in violation of FCC rules. Ten respondents (31%) reported having seen cellular phone use in-flight and one respondent (3%) admitted using their cellular phone.[15] Twelve respondents (34%) reported having left their cell phone on during a flight. Most cellular phone systems use a registration protocol that activates on power up, after an elapsed time (determined by the cellular system), and when entering a new cell. At commercial flight altitudes and airspeeds the cellular boundaries are traversed almost constantly and have the potential to cause cellular phones to frequently transmit registration signals. Additionally, at the higher altitudes it is likely that the cellular phones will transmit at the highest power in an attempt to reach the distant tower.

Thirty-two respondents (91%) stated they thought the rule prohibiting cellular phone use was due to the potential for avionics interference, but only 14 respondents (40%) believed that there is a *serious safety risk*. Some who stated that they believe that there is a serious safety risk seemed to have contradictory fill-in responses. In responding to “When do you believe that it is safe to use a cell phone on an airplane?” one replied “almost always, especially during flight,” another “at certain times, yes” and still another “it wouldn't be too bad after the plane has reached its coasting elevation and the weather is clear.” Some respondents erroneously pointed to the air phone (seat back phones) as justification, “it seems to me that if it is safe to use an air phone - it is safe to use a cell phone” and “when considering most planes have phone service already, it is probably safe anytime.” The air phones are permanently installed and use externally mounted antennas. They use licensed air-ground radiotelephone service frequencies that have been assessed for compatibility to aircraft communication and navigation systems. In addition, they are installed and tested in accordance with the appropriate certification and airworthiness standards. As discussed in previous chapters cellular phones have only recently been selectively tested on aircraft for compatibility and this has mostly been limited to ground testing.

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[15] This call was made with pilot permission during a flight on September 11, 2001.

Only 20 respondents (57%) thought laptops were secured during takeoff and landing to prevent interference with avionics compared with 32 respondents (91%) that believed the cellular phones were turned off to prevent interference with avionics.

Respondents reflected a desire to use their own cellular phones in-flight if allowed (66%), but most (20 of 31) would only do so *rarely*. Respondents were not enthusiastic about using wireless laptop products with 94% stating they would *rarely* use them. It is likely that this number could be significantly different if the survey were performed today. The recent availability and advancement of wireless laptop products and services has been well received with the public in general and this would likely transfer to the flying public.

There were only 3 respondents who correctly identified the FCC as the agency prohibiting in-flight cellular phone use and 8 respondents believed that the rule existed to protect the "profitability of the air phone service." As stated earlier, the House hearings on PEDs in 2000 [5] were driven in part by this misconception. This confusion by the public is also a prime example of the failure of the FAA and industry to "develop methods to enhance public awareness" as recommended by RTCA in 1988 [3] and to initiate a "public awareness campaign…to educate the flying public regarding the potential interference hazards from PED, especially those designed as intentional radiators." as recommended by RTCA in 1996 [10]. The impact of the uninformed public may be in part the reason that passengers are willing to violate in-flight rules regarding PEDs.

5.3 SUMMARY

It is clear that misinformation is a problem. Many passengers are not aware of the reasons for the in-flight PED policies and rules or do not believe they are needed. This has at least in part been responsible for passenger non-compliance with those policies. Passengers did not comply with rules at the time of the survey especially those relating to cellular phones. The indication is that any future policy including passenger prohibition of electronic devices in total or during certain phases of flight will be difficult to construct and cannot be pursued without other support. One option for assistance is a "silencer" that would disable a cellular phone from transmitting. These systems would require that the device manufacturer install such a technology within the product. The ability to implement such a strategy is unlikely given the financial impacts to the manufacturers and complicated by the tenuous relationship between the FAA and FCC.

Chapter 6

In-Flight RF Spectrum Measurements: Motivation and Program Description

While the measurements and analyses described in the preceding chapters have been useful in developing an understanding of many of the issues that surround PED interference, 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 we move 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[16] measurements without correlation to the actual environment. The implication is that the behavior of passengers, the electronics they bring onboard and the aircraft influences are not being fully addressed. The potential for over or under-design 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 [40] 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."*

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[16] The term static refers to aircraft on the ground in controlled situations.

The subsequent three chapters summarize a program sponsored by the FAA [1] to develop an instrumentation package and perform in-flight RF spectrum measurements on revenue flights of commercial aircraft cabins in selected aviation critical and personal electronics frequency bands.[17] The title of this project was, "In-Flight RF Spectrum Measurements of Commercial Aircraft Cabins." The FAA grant, Cooperative Agreement No. 01-C-AW-CMU, Amendment No. CMU-001 was issued on June 27, 2002. 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. The value of this effort has recently been confirmed by the NASA report on wireless phone threat assessments [17]. It recommended that data be collected on aircraft passenger-cabin RF environments during flight.

6.1 MOTIVATION

Several factors support the need for real time measurements in the cabins of commercial airliners. The most important are discussed below. In any event, the RF electromagnetic environment (EME) onboard commercial aircraft had only been theorized and this effort places data where previously only theory existed.

6.1.1 Rare Events

Significant PED interference with avionics is likely to 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 speculate whether these established margins are sufficient and if not, then how often they will be insufficient.

6.1.2 In-Service PED Emissions

The emissions from PEDs have been explored during a number of studies [2], [3], [10], [18]. These efforts concentrated on relatively new electronic devices rather than

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[17] Granger Morgan and Bill Strauss served as the principal investigators on the grant.

devices that had been in-service, that is a device, 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. The existing studies have the common deficiency of a low sample size. The ability to identify outliers (i.e. high emission levels) or the variation in field strength is not possible with the current data. Although it is unknown how many or what types of PEDs are being assessed with the in-flight measurements the potential to see outliers caused by a number of potential influences is greatly increased.

6.1.3 Transmitting PEDs

Transmitting PEDs (T-PEDs) 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. The most current RTCA effort only determined a process for establishing the safety of T-PEDs on aircraft [11]. NASA has recently concluded two studies that focused on the unintentional emissions from T-PEDs [17], [18], but much remains to be understood. As pointed out in the NASA report TM-2004-213001 [19] an unintentional emission from a T-PED may be allowable at a higher level than a non-T-PED even in an aircraft critical frequency band.

6.1.4 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 EME. These effects are known as intermodulation. One NASA report [17] indicated that simultaneous use of multiple mobile phones causes emissions in GPS and DME frequency bands.

6.1.5 Compliance with In-Flight Policies

The potential interference from T-PEDs, such as 2-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. The ASRS database analysis presented in Chapter 4 and the survey presented in Chapter 5 contest that belief. In-flight measurements create the ability to analyze compliance aspects especially for cellular phones. The benefits of understanding passenger behavior will be critical when establishing any aircraft related policy.

6.1.6 PED Detectors and Data Mining

The development of in-flight PED detection and location systems has been examined and promoted for some time [41], [42], [43]. These systems and approaches have so far been cost prohibitive and the usefulness of locators has yet to be established. Once cost effective detectors are developed they could be used in conjunction with flight data recorders. Modern flight data recorders—the familiar “black boxes” that serve as tools for investigating aircraft crashes—have hundreds of channels for recording data. Major airlines already routinely apply data-mining methods to the records from each flight in order to improve operational efficiency and quality assurance and to search for anomalies that may be indicative of problems [44], [45]. It would be relatively straightforward to incorporate the PED detectors into the flight data recorders so that analysts could then include an examination of the cabin RF EME in their search for anomalous conditions. An understanding of the in-flight RF EME will be vital to the development of these and other in-flight monitoring systems.

6.2 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 (21” x 16” x 8” for overhead compartments) and its operation discreet so as not to raise concerns among passengers. In order to meet those requirements, the instrumentation needed to be compact, lightweight, and automated, but still needed to 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 broad-band 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 6.1. A summary of the instrumentation equipment is provided in Table 6.1 along with the basis for judging its potential low risk to aircraft avionics.

Figure 6.1: The Compact RF Spectrum Measurement Instrumentation

6.2.1 Spectrum Analyzer

The Anritsu MS2711B spectrum analyzer was selected for its compact size, frequency coverage at the desired resolution bandwidths, and data export capability. Its operation was controlled through an RS-232 interface. The Anritsu MS2711B spectrum analyzer met European community requirements for radiated emissions.

6.2.2 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.

Table 6.1: 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.

6.2.3 Laptop

A Gateway Solo Model 9300 laptop computer 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.

6.3 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 RTCA DO-160D category M limits for radiated emissions [14]. The final design and emission results were submitted to Mr. Dave Walen, 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 non-revenue flight (i.e. no passengers).

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

6.4 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.

The statistical analysis with the ASRS database presented in Chapter 4 indicated that certain avionics might be more affected than others and also indicated that certain PEDs might be more likely to cause interference [21]. 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 PEDs in the 2.4 GHz band. Thus, 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 monitor: VOR and 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 MHz and 1575.42 MHz. There were four frequency ranges identified as likely to experience emissions from passenger electronics use: cellular uplink, 824 – 849 MHz; PCS uplink, 1.85 – 1.91 GHz; and Industrial, Scientific, and Medical (ISM), 902 – 928 MHz and 2.4 – 2.485 GHz.

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 narrowband signals in the 960-1215 MHz band, that contains

DME and TCAS, were hard to differentiate from the many ground DME stations or actual TCAS signals. No wideband signals were observed in this band so monitoring was discontinued after flight 20 in order to focus on frequencies of greater interest. The frequencies considered in this monitoring effort are summarized in Table 6.2.

6.5 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 roll-on bag. A search of the commercially available antennas confirmed this. A two-antenna design would require multiplexing and increase system complexity and a greater potential for failure. Thus, the best performance possible with a single compact antenna was pursued.

Table 6.2: 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 Telephone	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

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[18] 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 MHz, 332 MHz, 836 MHz, 915 MHz and 1227.5 MHz to determine the gain of the antenna.

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[18] Gesling Stadium at Carnegie Mellon University. This is an artificial turf football field with two story buildings no closer than 100 feet from the field and open on one end.

The measurements were performed on the antenna alone, not incorporated into the instrumentation package.

The distance at which the 1st Fresnel zone touches the ground is known as the breakpoint distance (d_0). The height of the antennas and the frequency were used in (6-1) to determine the breakpoint distance for all tested frequencies.

$$d_0 = \frac{4\pi\ h_t h_r}{\lambda} \tag{6-1}$$

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 predicts [46], was then fitted to intersect the trend line at the breakpoint distance by varying the receive antenna gain (CMA-118/A antenna). The results for the tests are provided in Table 6.3.

The results provided in Table 6.3 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 MHz and 915 MHz the measured data overlays well with the general terrain model inside the breakpoint distance.

Table 6.3: 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
1228	28.4	-0.5	0.0[2]

Notes: 1. d_0 is the breakpoint distance used in calculating the gain
2. Maximum using azimuth and elevation charts

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.

The instrumentation in its final configuration was tested onboard a Boeing 737 aircraft parked at Pittsburgh International Airport with an onboard emission source. A signal generator transmitting a CW signal through a log-periodic antenna was the onboard emission source. The source antenna was placed at the beginning of the coach class of the aircraft and pointed towards the rear of the aircraft. The instrumentation was placed in overhead compartment and under seat locations throughout the aircraft. The results demonstrated the adequacy of the CMA-118/A antenna and that the overhead locations provided better performance than the under the seat locations. The influence of instrumentation orientation was minimal. The results of the measurements are provided in Appendix C and support previous work that suggests the reverberant nature of the aircraft cabin with gradients [47], [48], [49], [50].

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

6.6 DATA COLLECTION ROUTINES

Under the author’s supervision, automation software used to control the spectrum analyzer and download the data to the laptop was developed by Matt Pardini, an undergraduate student at CMU, and then subsequently refined by the author as needed. The software saved the data after the completion of each spectrum analyzer trace so that any power interruption would cause minimal data loss.

6.6.1 Spectrum Analyzer Settings

The spectrum analyzer settings used in the in-flight measurements are summarized in Table 6.4. 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 6.4: 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

6.6.2 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 bandwidth (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 NTIA in their spectrum utilization assessments [51]. The “high temporal resolution” or “high resolution” protocol collected a single sweep of data. The standard collection protocol was utilized 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 six second delay each time data are written to the computer and a new command is issued.

6.6.3 Flight Phases

Each flight was divided into three phases: takeoff, cruise, 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 and landing it was desirable to determine cellular phone usage since they are implicated in affecting instrument landing systems [21].

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 above, 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 are provided in Table 6.5. This table represents the goals for the final twenty or so flights. During some flights the cellular and PCS bands were monitored exclusively using the high resolution protocol. In the first flights, less attention was focused on the cellular and PCS bands, but the same general strategy was employed.

Table 6.5: Monitored Frequency Band Allocations by Flight Phase (Standard Resolution, Post 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 was used exclusively to monitor cellular and PCS bands.
2. Prior to flight 20, monitoring included other bands and less emphasis on cellular and PCS.

Chapter 7

In-Flight RF Spectrum Measurements: Collected Data and Handling

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

7.1 SUMMARY OF FLIGHTS

Measurements were made on 38 flights over the period from 23 September through 19 November 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 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 in the Eastern U.S. and flight durations ranged from 39 minutes to 112 minutes. 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 7.1.

Table 7.1: Summary of Measurement Flights

Flight #	Date	Airline	Aircraft[1]	Tail Number[2]	Airport		Passengers
					Depart	Arrive	
1	9/23/03	B	B732		ATL	ATL	0
2	10/8/03	A	B733	1	PIT	EWR	34
3	10/8/03	A	B733	1	EWR	PIT	44
4	10/8/03	A	B734	2	PIT	EWR	40
5	10/8/03	A	B734	2	EWR	PIT	92
6	10/14/03	A	B733		PIT	EWR	63
7	10/14/03	A	B734		EWR	CLT	106
8	10/14/03	A	B734		CLT	MCO	122
9	10/15/03	A	B733		MCO	DCA	120
10	10/15/03	A	B733		DCA	BOS	106
11	10/15/03	A	B733		BOS	PIT	105
12	10/21/03	A	B733		PIT	EWR	45
13	10/21/03	A	B734		EWR	CLT	63
14	10/21/03	A	B734		CLT	MCO	144
15	10/22/03	A	B733		MCO	DCA	71
16	10/22/03	A	B733		DCA	BOS	75
17	10/22/03	A	B733		BOS	PIT	99
18	11/4/03	A	B733		PIT	EWR	42
19	11/4/03	A	B734		EWR	CLT	75
20	11/4/03	A	B734		CLT	MCO	144
21	11/5/03	A	B733		MCO	DCA	100
22	11/5/03	A	B733		DCA	BOS	89
23	11/5/03	A	A320		BOS	PIT	124
24	11/11/03	A	B733	1	PIT	EWR	42
25	11/11/03	A	B734		EWR	CLT	88
26	11/11/03	B	B732		CLT	ATL	79
27	11/11/03	B	B732	3	ATL	ORD	100
28	11/12/03	B	B732	3	ORD	ATL	99
29	11/12/03	B	B732		ATL	CLT	90
30	11/12/03	A	B734	4	CLT	BWI	124
31	11/12/03	A	B734	4	BWI	PIT	108
32	11/18/03	A	B733		PIT	EWR	39
33	11/18/03	A	B734	4	EWR	CLT	89
34	11/18/03	B	B732		CLT	ATL	100
35	11/18/03	B	B738	5	ATL	IAH	103
36	11/19/03	B	B738	5	IAH	ATL	110
37	11/19/03	B	B732		ATL	CLT	42
38	11/19/03	A	B733		CLT	PIT	75

Notes:
1. Aircraft model: B732 = 737-200, B733 = 737-300, B734 = 737-400, B738 = 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.

7.1.1 Instrumentation Location

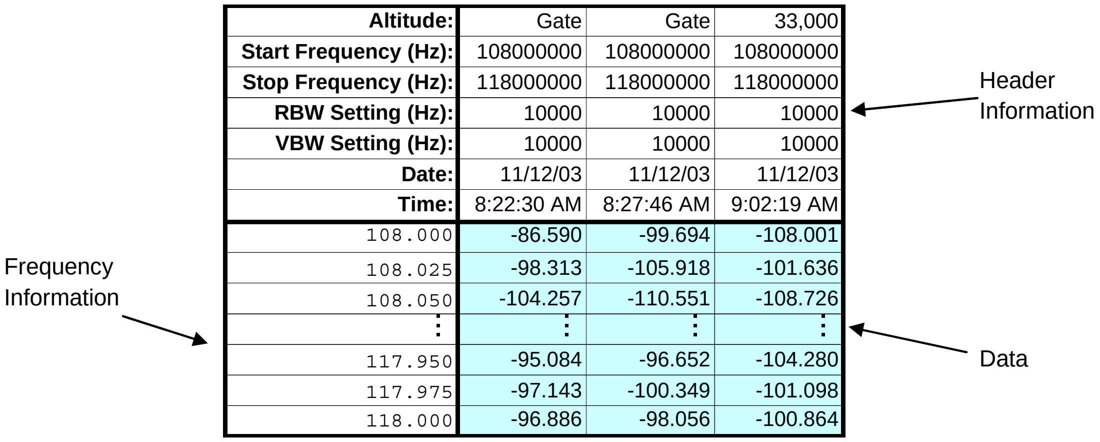
The instrumentation was centrally located in the aircraft coach section in the overhead storage compartment in all but one instance when it was placed under a seat. The orientation of the antenna (forward, backward or out toward the cabin) was random from one flight to the next. There was no attempt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

7.2 COLLECTED DATA

7.2.1 Automated Data Collection

The Anritsu MS2711B spectrum analyzer records data as a “trace” or “plot.” Each trace is comprised of 400 “bins” or “buckets” of data. Each bin represents a frequency span and time frame based on the overall frequency span being analyzed and the set sweep time. Usually there are multiple values observed in each bin and a method must be chosen to assign a “value” to that bin. The spectrum analyzer was set for positive detection assigning the maximum received power value for the bin. The use of positive detection was intended to utilize the maximum signal level present. Other detection choices were sample, negative detection and average.

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 7.1. 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 post-flight data management process as described in section 7.3.2



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

Figure 7.1: Sample Data File

The research effort collected a total of 7,534 spectrum traces representing over 51 hours of monitoring. There were 1,493 traces collected at the gate, 1,596 traces collected during taxi, and 4,445 traces collected in-flight. The traces collected in-flight represent over 32 hours of monitoring. A summary of the collected data is provided in Table 7.2. This includes a breakdown of data collected by frequency band and resolution protocol for gate, taxi, and flight phases.

Table 7.2: Summary of Collected Data and Monitor Times

	Gate		Taxi		In-Flight	
Frequency Band (MHz)	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	1,231	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	1,202	1:25:09
2400-2500	11	0:10:05	14	0:12:50	133	2:01:55
Totals	1,493	10:16:00	1,596	8:18:45	4,445	32:48:40
Total Traces: 7,534			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.

7.2.2 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 post-flight 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 PM. Emissions associated with this attempt were subsequently observed in the data.

The use of game electronics, CD/DVD 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 post-flight correlation to signal events.

7.2.2.1 Flight Crew Observations

The flight crews for all flights were aware of the in-flight monitoring effort. During a short post-flight 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 database, no in-flight conflicts were observed with respect to policy enforcement.

7.3 POST-FLIGHT DATA MANAGEMENT

The manually recorded information was added to the computer file of spectrum measurements during the post-flight data management phase. This included date, event times, passenger loads, instrumentation location, flight number, 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 a 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.

7.3.1 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 that did not affect the quality of subsequent recorded traces. A remedy for this situation was to “defragment” 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 7.2. 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 PM was 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 7.2: 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 recoded up to the time when the computer was powered down and thus all data were considered valid.

7.3.2 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 7.3.

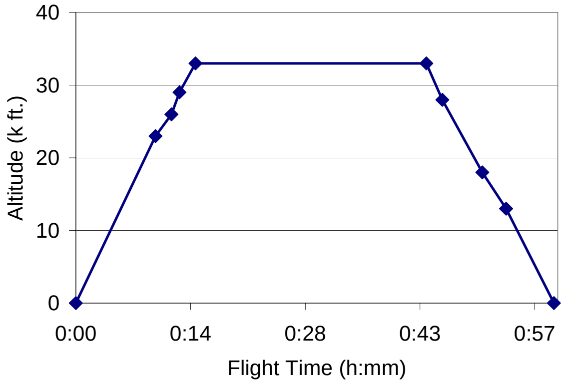


Figure 7.3: Flight #22 Estimated Altitude Profile Based on Flight Plan

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 737-800 aircraft that were equipped with telemetry systems and allowed post-flight retrieval by the airline.

While altitude information is not strictly accurate, estimated values are likely correct 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.

Chapter 8

In-Flight RF Spectrum Measurements: Results and Discussion

This chapter presents the results of the in-flight RF spectrum measurement program. The results are presented by frequency band. The instrumentation's self-generated interference prohibited valuable measurements in the ILS GS band (329 – 335 MHz). The difficultly in positively identifying ground DME station or valid TCAS signals suggested that analysis of the DME and TCAS band (960-1215 MHz) should not be pursued. Nothing notable was observed in the initial flights in the GPS L2 band (1227.5 MHz) and monitoring was discontinued. With the exception of these three frequency bands all data gathered during the in-flight RF spectrum measurement program is discussed in this chapter.

8.1 MOBILE CELLULAR

There are several mobile phone technologies utilized in the US. 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 8.1.

Table 8.1: Cellular Band Mobile Technologies

Technology	Standard	Mobile TX Frequency	Channel Bandwidth	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 utilized for cellular service such as Integrated Dispatch Enhanced Network (iDEN) 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 8.1 residing in the cellular and PCS bands accounted for over 75% of the mobile phone service in the US at the time of the 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 is 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 8.1 that displays data taken during flight #30. The wideband 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 6.6.1, 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 bandwidth (<60 kHz), high power received value (-55 dBm), and frequency band again indicate a cellular signal.

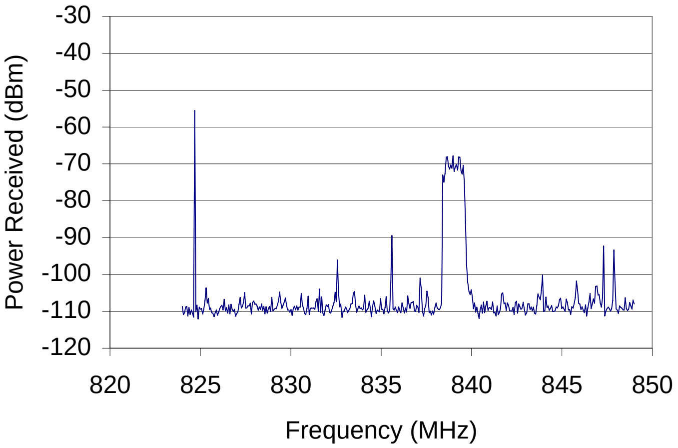


Figure 8.1: Example of Suspected CDMA and Narrowband Cellular Signals

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.

8.1.1 Description of Collected Data

As previously noted, 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 temporal protocol collected single sweeps of data. The standard collection protocol was utilized 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 bandwidth 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 six-second delay for data to be written to the computer and a new command to be issued.

Overall, there were 6,234 traces recorded in the cellular and PCS bands representing over 31 hours of monitoring. Of the 3,165 traces recorded in the cellular band, 1,720 were in-flight and represented almost 8 hours of monitoring. And, of the 3,069 traces recorded in the PCS band, 1,673 were in-flight and represented over 8 hours of monitoring. The collected data was summarized in Table 7.2.

8.1.2 General Observations

A total of 6,234 graphs were generated from the cellular and PCS bands. Clearly digesting this much data is 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 8.2 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 discussed in section 8.1. 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).

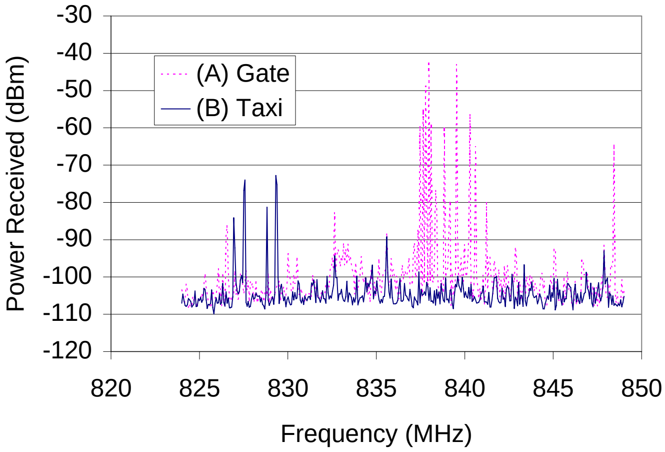


Figure 8.2: Example of the Onboard Cellular Band Environment at the Gate (A) and during Taxi (B)

A cumulative summary of the cellular band in-flight environment for standard protocol measurements is provided in Figure 8.3. 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 bandwidth 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 under-valued because the resolution bandwidth of the spectrum analyzer is smaller than the CDMA signal being measured. In the cellular and PCS range, the CDMA signals are under-valued by between 6.91 and 9.98 dB as described in section 8.1.3.3. All displayed graphics in this dissertation associated with measurements of wideband 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.

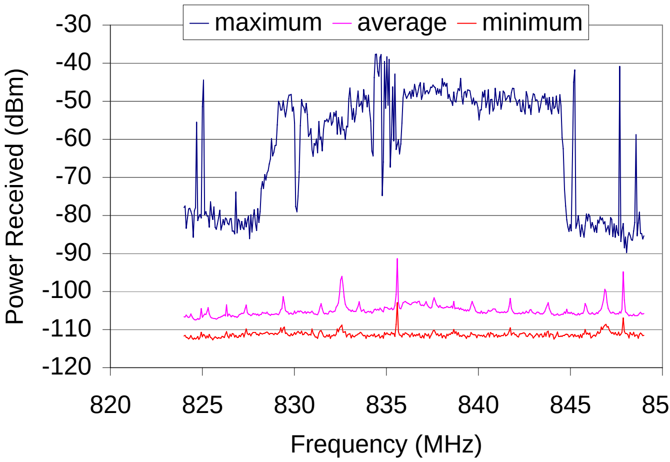


Figure 8.3: Cellular Band In-Flight Cumulative Data
(Standard Measurement Protocol)

The average trace in Figure 8.3 indicates that there is overall a low signal activity. It confirms that the instrumentation itself generates emissions as described in section 6.4 and section 7.3.1. 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 valid 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 8.4. 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.

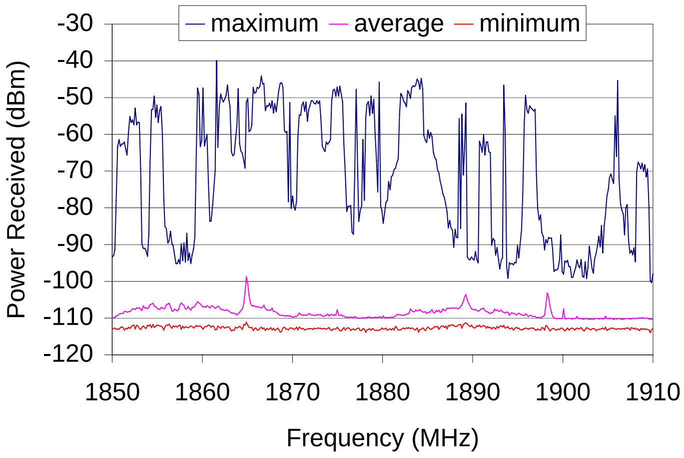


Figure 8.4: PCS Band Cumulative Data

8.1.3 Analysis Approach

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

a. Identify all cellular signals and categorize as narrowband or wideband
b. Adjust measured power received values of wideband signals
c. Determine which signals are generated from onboard sources
d. Determine if narrowband signals are registrations or calls
e. Determine the activity rates of calls and registrations

8.1.3.1 Identifying Narrowband 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. Narrowband 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 4-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 narrowband signals. This essentially identified all signals with bandwidths less than 120 kHz in the cellular band and 300 kHz in the PCS band.

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

8.1.3.2 Identifying Wideband Cellular Signals

The CDMA signals were straightforward to identify given their characteristic frequency spectrum, as seen in Figure 8.1. 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 Table D.2 and Table D.3. It is not possible to identify a CDMA signal as a call based on its frequency as is the case with the narrowband AMPS and TDMA technologies. An example of an identified CDMA signal in the raw data is provided in Figure 8.5. Note that the signal's power drops off at prescribed CDMA 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	
1873.459	-112.096	-64.079	
1873.609	-110.247	-64.640	
1873.759	-110.528	-62.020	
1873.910	-111.417	-62.722	
1874.060	-109.943	-62.183	
1874.211	-109.311	-64.313	
1874.361	-112.025	-63.611	
1874.511	-112.072	-88.134	
1874.662	-111.464	-96.277	
1874.812	-110.434	-104.584	

Figure 8.5: Example of a CDMA Signal in the Raw Data File (PCS Band)

8.1.3.3 *Identifying Onboard Signals*

The initial approach to identifying which signals had 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 (8-1).

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L} \tag{8-1}$$

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 (LOS) conditions prevailed and signals originating from the ground would be lower due to reflection, diffraction and scattering. The following parameter values were used in (8-1) to estimate a threshold to identify narrowband cellular signals originating onboard:

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

The maximum permitted mobile power output for 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 6.3 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 7.3.2 involved some modest uncertainty. Further, since altitudes are relative to sea level and all flights were over land the altitude is overestimated. 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 of 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 [47]. Thus, as a conservative approach to identifying onboard signals the result from (8-1) 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." The identified narrowband signals above the threshold were considered to be onboard signals. As described in section 8.1.4, selection of this onboard threshold value 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 (8-1) 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 bandwidth setting of the spectrum analyzer being less than the bandwidth 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 equal to 2 standard deviations below the mean plus 3 dB to account for the resolution bandwidth 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 8.2.

Table 8.2: Adjustment Values for CDMA 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 8.6 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 sideband energy.

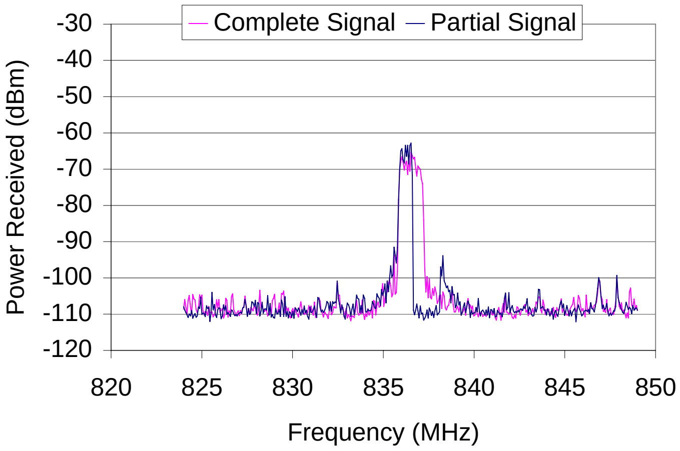


Figure 8.6: Full and Partial Capture of a CDMA Cellular Signal

8.1.4 Analysis

There were 393 signals identified as originating from onboard the aircraft. They are categorized by narrowband and wideband for the cellular and PCS bands and provided in four tables in Appendix E.

A graphical presentation of the narrowband signals observed in the cellular band is presented in terms of measured power versus altitude and is provided in Figure 8.7. 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 wideband signal were removed using the method outlined in section 8.1.3.2. 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 D.1.

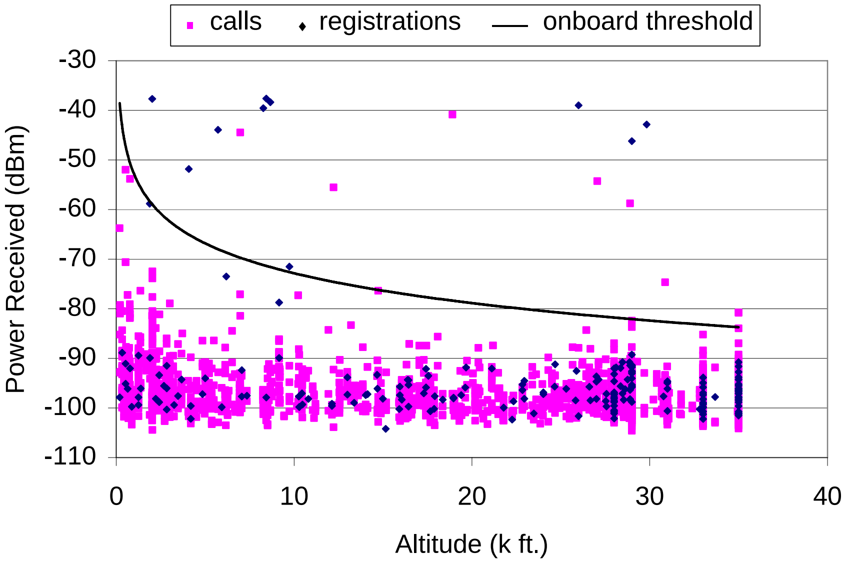


Figure 8.7: Narrowband Signals in the Cellular Band: Power Received vs. Altitude

The reverberant nature of the aircraft cabin and the inefficiency of the instrumentation make it likely that some signals originating from onboard were misidentified as originating from 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 8.7. 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 [52], 3) the instrumentation may have been shielded further by surrounding luggage and passengers, 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 indeed from the aircraft. The signals that are close to the onboard threshold, including those below the threshold, are likely in nulls created from the reverberant characteristics of the aircraft cabin.

A graphical presentation of the narrowband signals observed in the PCS band is presented in Figure 8.8. 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.

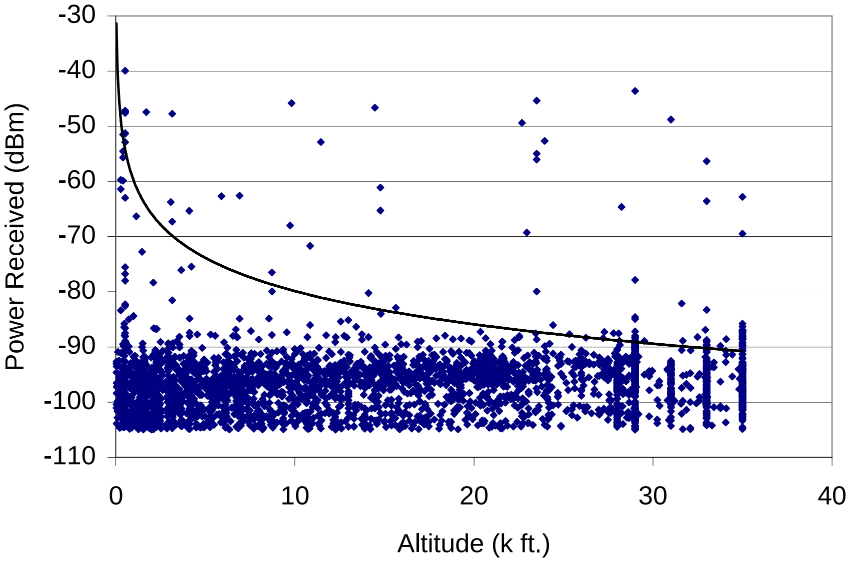


Figure 8.8: Narrowband Signals in the PCS Band: Power Received vs. Altitude

8.1.4.1 *Calls Originating from Onboard the Aircraft*

The 8 signals identified as calls originating from the aircraft in cellular band are described in Table 8.3. This considers only narrowband 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 other calls were observed, but could not be identified as such.

The large margins demonstrated by the signals in Table 8.3 suggest little ambiguity that calls are being made from the aircraft. The data further suggests that calls are being made or received during critical flight phases (low altitude) and at cruise (high altitude).

Table 8.3: In-Flight Narrowband Signals Identified as Calls

Flight #	Frequency (MHz)	Altitude (ft.)	Measured Power (dBm)	Threshold (dBm)	Margin (dB)
36	847.68	18,903	-40.84	-78.37	37.53
35	838.66	27,050	-54.28	-81.48	27.21
6	825.07	6,978	-44.45	-69.71	25.27
36	848.56	28,897	-58.77	-82.05	23.29
30	824.69	12,227	-55.51	-74.58	19.07
25	836.91	30,867	-74.68	-82.63	7.95
25	833.02	35,000	-80.76	-83.72	2.96
25	833.02	35,000	-80.83	-83.72	2.89

It is probable that calls using CDMA technologies were observed. A few signals suspected of being CDMA 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 author 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. It is also a violation of both FAA and 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 on commercial flights have now been documented.

8.1.4.2 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 further defines how commonly cellular calls are made, how often phones are left in standby and the resulting signal activity rate.

All of the identified onboard signals in the cellular and PCS band are summarized in Appendix F, Table F.1 through Table F.12. The summary is broken down by the standard and high resolution measurement protocols and narrowband versus wideband 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 resolution 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 F.3. It can be taken as a lower limit and the high resolution measurement protocol total rate given in Table F.2 is likely a more realistic rate. Using the high resolution measurement protocol total rate given in Table F.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 Table F.4 through Table F.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 Table F.7 through Table F.12.

Given that cellular phone use onboard aircraft is strictly prohibited, these rates demonstrate either passenger disregard for policies or a lack of successful communication of the policies. If cellular phones have the potential to interfere with ILS approaches [21], 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:

$$Actual\ Calls = (Observed\ Calls)\frac{T_{Total}}{T_{Observed}} \tag{8-2}$$

$$Actual\ Calls = (12)\frac{2644\,\text{min}}{993\,\text{min}} = 32\ calls \tag{8-3}$$

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 8 calls identified using these technologies in the cellular band imply that 24 calls were active in the cellular and PCS bands during the monitored period. Again, using (8-2) 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 scheduled commercial aircraft in the Eastern U.S. are occurring at a rate of 1-4 calls per flight.

8.1.4.3 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 -34.69 dBm. This occurred in the PCS band and the signal was wideband. The maximum received measurements for the narrowband and wideband signals in the cellular and PCS band are provided in Table 8.4. The values are all relatively similar. 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 8.4: Maximum Power Received Measurements In the Cellular and PCS Bands

Signal Type	Cellular Band	PCS Band
Narrowband	-37.64 dBm	-39.93 dBm
Wideband	-34.69 dBm	-36.69 dBm

8.1.5 Summary of Mobile Cellular Bands

This section has shown that calls are accomplished from onboard commercial aircraft in the Eastern U.S. at a rate greater than once 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.

8.2 GLOBAL POSITIONING SYSTEM

This section presents a brief overview of how the Global Positioning System (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 the GPS bands is summarized and used to calculate safety margins for commercial aircraft.

8.2.1 GPS 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 MHz 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 1 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 [53] are used. The GPS Gold codes have excellent cross-correlation properties at the expense of causing the auto-correlation 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 that nulls every 1023 kHz. There are certain “strong” lines caused by the auto-correlation of the Gold codes adversely affecting the co-channel rejection in the GPS receiver. In most cases, a 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 [54]. It has been demonstrated in theory [55] and practice [56] that a 1 Watt 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 [57]. The impact of both CW and pulsed interference sources are discussed below.

8.2.2 CW Interference Sources

A CW interference signal can prevent or disrupt a GPS receiver's ability to generate a valid navigation solution. Early assessments found that narrowband and wideband CW interference affected GPS performance [58]. 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 [59]. The ability of an interference signal to not only jam, but to "spoof "or provide deceiving information to the GPS receiver is of great concern. This becomes critical as the commercial aviation community heads towards GPS as a sole-means navigation system [57] and utilization of GPS in landing systems. The general aviation community already uses GPS for approaches.

The immunity of GPS receivers to the effects of pulsed interference has been shown to be considerably more robust than to CW interference [57]. 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 general aviation pilots and avionics installers that Samsung SPH-N300 phones caused their GPS navigation systems to lose satellite lock. Subsequent analysis by NASA has shown that these phones have significant emissions in the GPS L1 band [19].

8.2.3 GPS Band Data

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 6.4, 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 8.9. 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 (30%). The instrumentation utilized was not capable of detecting the low-level GPS signals from satellites and the frequency band is protected and not utilized for any other purpose. Thus, all of the observed signals are notable. Because the spectrum analyzer recorded traces using a maximum hold protocol the duration of each identified signal is not known.

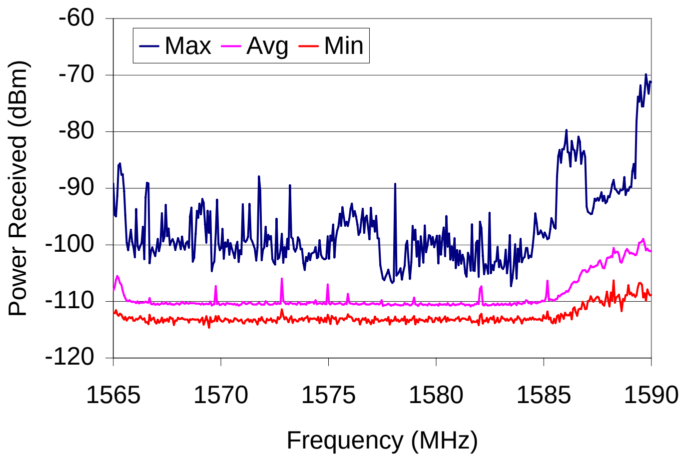


Figure 8.9: Summary of In-Flight GPS L1 Band Measurements

Assessment of the instrumentation package in an anechoic chamber[19] indicated that there was an increased system noise floor above 1585 MHz as well as some narrowband discrete signals between 1565 and 1585 MHz. The instrumentation emissions can be clearly seen in Figure 8.9. The discrete signal activity is observed in the average of the cumulative result and the wideband 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, RTCA DO-160, category M and H, this study revealed onboard signal content within the L1 band.

Of course, the presence of signals within the GPS band does not automatically mean that there will be interference. As discussed previously, pulsed interference is not likely to cause problems unless it contains significant power. None of the observed signals contained sufficient power to raise concern, 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 [55], [56], [58], [59], [60], [61]. The results of these analyses have produced industry specifications based on theory and validated in practice. The RTCA DO-235A [62] 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 bandwidth and center frequency. A threshold was developed for each signal using the information in DO-235A, Appendix F. That information specifies the RF interference environment at

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[19] An anechoic chamber is a shielded room lined with RF absorbing material. The chamber used for this test was the AATF at the Naval Air Warfare Center in Patuxent River, MD. Typical

and around GPS L1 receivers. The threshold was developed by first using the BW of the potential interference signals and Figure F-2 and then adjusting the threshold using the center frequency of the potential interference signals and Figure F-1. The observed signals and derived thresholds are provided in Table 8.5. The wideband signals in have been adjusted to account for under-valuing due to the 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 8.5 all have more power than the derived thresholds, however this does not account for path loss to the aircraft GPS antennas.

The expected path loss for signals transmitted from within an aircraft cabin to the GPS antenna port is assessed in RTCA DO-233 and defined as the IPL. According to NASA report TP-2003-212438 [18] in the GPS band the minimum IPL (MIPL) is 41 dB for medium size aircraft (i.e. 737, 727, etc) and the average IPL is 64.4 dB. This NASA report includes data recently measured and from RTCA 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 is calculated using (8-4) and the results are provided in Table 8.5 for observed signals in the GPS band.

$$Margin = P_{Threshold} - (P_{Signal} - MIPL) \tag{8-4}$$

The worst-case signal listed in Table 8.5 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 8.10 at the far right of the trace. This signal was observed 9 minutes earlier on the same flight, (second entry in Table 8.5), indicating that the signal was present for an extended period of time. The signal was not observed on the other 4 traces taken during the flight.

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shielding from the external environment is 80 dB or greater at the frequencies of interest.

Table 8.5: Safety Margin for Signals Observed in the GPS (L1) Band Using Minimum IPL for Medium Transport Aircraft

Flight #	Altitude	Center Frequency (MHz)	Bandwidth (MHz)	Measured Power (dBm)	Threshold (dBm)	Margin (dB)
25	35,000	1,589.56	0.75	-59.07	-100.50	-0.43
25	23,031	1,589.56	0.75	-60.87	-100.50	1.37
3	26,000	1,576.28	2.25	-77.16	-112.98	5.17
25	35,000	1,586.24	1.38	-67.46	-101.42	7.04
25	35,000	1,576.65	0.94	-83.23	-114.50	9.73
3	26,000	1,579.85	2.00	-79.87	-108.00	12.87
19	12,818	1,565.25	0.63	-75.61	-103.50	13.11
19	12,818	1,569.14	0.75	-81.09	-108.50	13.59
6	29,000	1,571.77	0.13	-84.91	-112.25	13.66
22	33,000	1,578.10	0.06	-89.23	-114.51	15.72
19	35,000	1,573.21	0.06	-93.52	-115.51	19.00
6	12,195	1,571.33	0.13	-89.76	-111.70	19.06
19	35,000	1,566.57	0.19	-84.28	-105.00	20.28
19	5,182	1,577.09	0.06	-95.74	-116.11	20.63
25	28,767	1,585.43	1.81	-80.65	-100.92	20.73
25	35,000	1,571.02	0.06	-92.81	-112.01	21.80
19	35,000	1,572.58	0.06	-95.41	-114.31	22.10
30	29,000	1,566.63	0.13	-86.15	-105.00	22.15
9	33,000	1,568.63	0.13	-90.39	-107.75	23.64
22	33,000	1,572.08	0.06	-96.82	-113.51	24.30
11	28,000	1,573.21	0.06	-98.64	-115.01	24.63
19	5,182	1,585.68	0.06	-88.77	-104.51	25.25
19	5,182	1,582.48	0.06	-94.34	-108.51	26.82
19	12,818	1,581.67	0.06	-96.37	-110.01	27.36
23	10,479	1,582.04	0.06	-95.88	-109.31	27.57
6	29,000	1,581.92	0.13	-96.24	-108.00	29.24
22	33,000	1,566.07	0.06	-93.68	-105.31	29.37
30	29,000	1,584.61	0.06	-94.43	-105.81	29.62
19	28,281	1,566.38	0.13	-93.78	-104.70	30.08
21	33,000	1,567.44	0.06	-97.78	-107.51	31.26
19	5,182	1,568.01	0.06	-98.80	-108.01	31.79
11	23,902	1,584.86	0.06	-97.47	-106.01	32.46
6	29,000	1,565.75	0.06	-99.20	-105.51	34.69

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

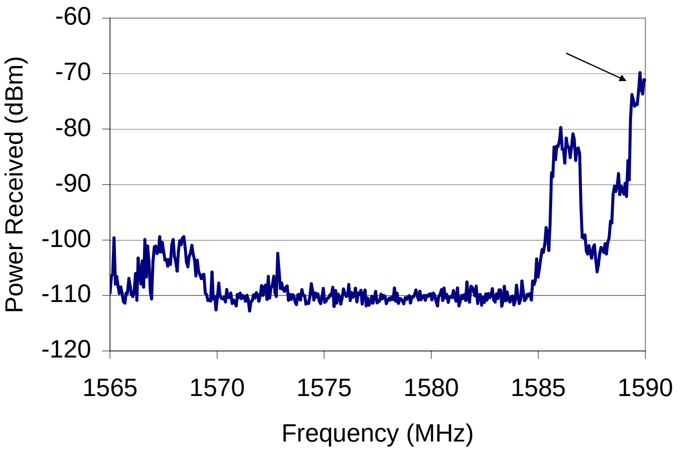

Figure 8.10: Potential Interference Signals in the GPS L1 Band

The third entry in Table 8.5 was observed during flight #3 and is presented in Figure 8.11. 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 8.5, it must be noted that the locations of the signals are not known. The data in Appendix C and [47] suggest that gradients exist for signals in an aircraft cavity. Furthermore, given the reverberant nature of the aircraft cabin the possibility that the recorded signals were observed in a null cannot be eliminated. Thus, some of the values provided in Table 8.5 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 5 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.

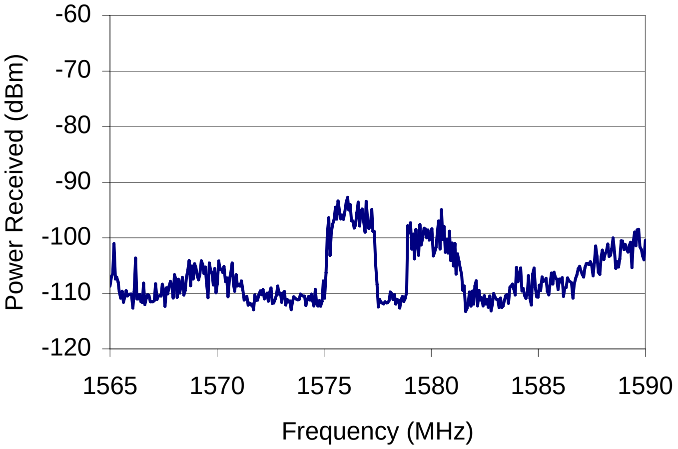

Figure 8.11: Signals of Interest in the GPS L1 Band

It is unknown from what source the potentially interfering signals originated. However, current data indicates cellular phones as one potential source [19]. Given the demonstrated high activity level of cellular phone use onboard it possible that the detected signals are coming from these devices.

8.2.4 GPS Band 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 [57]. This includes navigation in the en route, terminal area, approach/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 [60].

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.

8.3 INDUSTRIAL, SCIENTIFIC AND MEDICAL

As the name implies, the industrial, scientific and medical (ISM) 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.[20]

The 2.4 GHz ISM band is heavily used in today's electronics and computer markets. The products found using this frequency band employ 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 utilized these bands are and at which flight phases was desirable.

8.3.1 900 MHz Band

There were 127 data charts taken during 30 revenue flights. This represents approximately 2 hours of in-flight monitoring. There were 4 data charts taken during the 1 non-revenue maintenance flight (no passengers). The cumulative summary of the 900 MHz ISM band is provided in Figure 8.12. Notice that the average value is somewhat elevated above the minimum values indicating some consistent activity level.

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[20] Securaplane ST3000 Smoke Detection System.

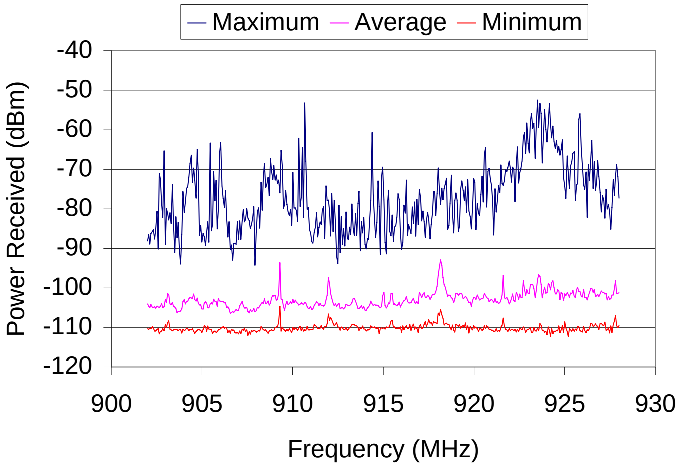

Figure 8.12: 900 MHz ISM Band Summary

There was activity observed during all flights. The right hand side of Figure 8.12 shows that around 924 MHz was the most active part of the 900 MHz ISM spectrum. 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 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 narrowband.

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

8.3.2 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 4 data charts taken during the 1 non-revenue maintenance flight (no passengers). The maintenance flight was unremarkable.

The cumulative summary of the 2.4 GHz ISM band is provided in Figure 8.13. The maximums are composed of 802.11 and Bluetooth signals. The maximum received signal was -44.26 dBm.

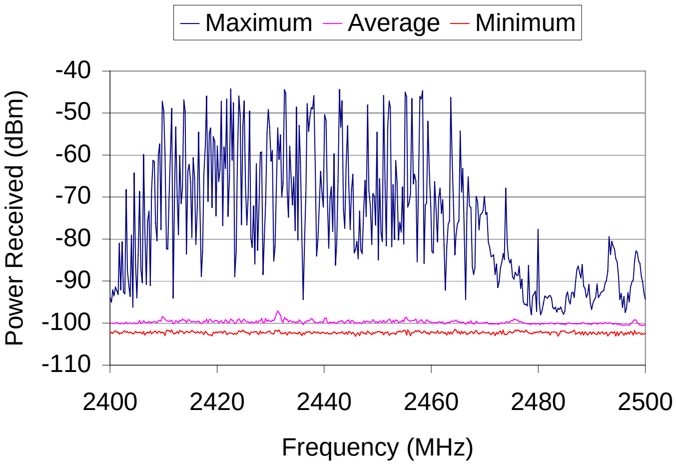

Figure 8.13: 2.4 GHz ISM Band Summary

There was activity observed on 11 of 30 flights. In the 11 flights with observed activity, there were only 2 data charts where activity was observed during a PED use prohibited time period. A summary of the observations is provided in Table 8.6. Activity during an approved PED use time period was seen 20% of the time. This largely derives from observations on 11 flights where activity was observed throughout the PED approved period. This finding suggests that passengers are using wireless devices during all flight phases with some appreciable regularity.

Table 8.6: 2.4 GHz ISM Band Summary of Activity (30 Flights)

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. It also may indicate that they are unaware that the wireless devices are transmitting. No activity was observed during takeoff and climb out. Generally, the data support the conclusion that passengers are complying with airline policies to not turn on electronic devices until they have reached cruising altitude. This conclusion does not extend to cellular phone use as described in section 8.1.

8.4 VOR AND ILS FREQUENCY BANDS

The 108 – 118 MHz and 329 – 335 MHz bands are utilized by commercial and general aviation for VOR and ILS navigation. VOR is the primary navigation aid used in commercial and general aviation today and operates on frequencies between 108.00 – 117.95 MHz. It provides heading information to a selected VOR station. The ILS has two components, the localizer (LOC) and glide slope (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 frequency band has been determined to be unusable for this evaluation.

There were 242 data charts taken during 30 revenue flights. This represents almost 4 hours of in-flight monitoring. There were 4 data charts taken during the 1 non-revenue maintenance flight (no passengers). The 108-118 MHz band produced three observations.

8.4.1 Narrowband Signals

Most in-flight traces contained only a few narrowband 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 narrowband signals was difficult except in the immediate vicinity of the airfield. The task of identifying the signals also proved to be time consuming. No further analysis was performed on the narrowband signals.

8.4.2 Elevated Measurement Floor

Many flights showed an elevated measurement floor. Generally, this was observed for an entire flight and did not correlate to say low vs. high altitude. Two in-flight charts are compared in Figure 8.14 to demonstrate an elevated measurement floor. The indication is that particular aircraft may have characteristic emissions or instrumentation location 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. It is not suspected that the noise increase is generated from PEDs.

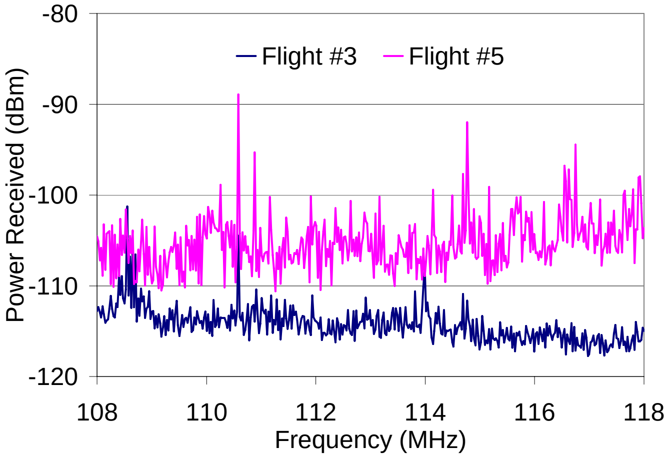

Figure 8.14: Example of Flights with and without an Elevated Measurement Floor

8.4.3 Distinct Noise Pattern

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 8.15.

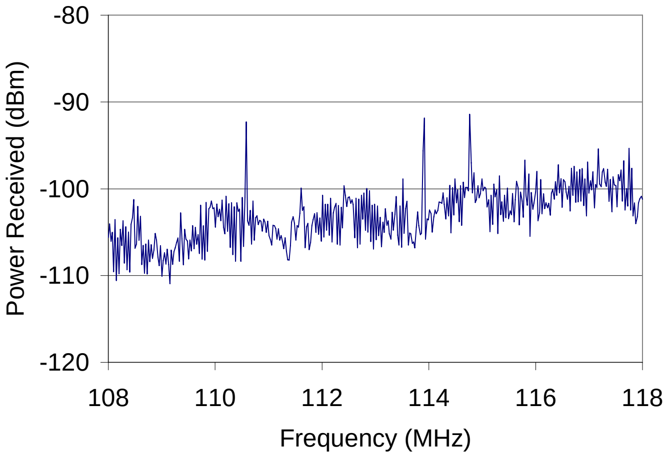

Figure 8.15: Example of an Unidentified Noise Pattern
Observed on Three Flights

8.5 SUMMARY OF THE IN-FLIGHT RF SPECTRUM MEASUREMENTS

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

1. Cellular phone calls were observed in all phases of flight at a rate conservatively estimated to be 1-4 calls per flight for Eastern U.S. flights.
2. Onboard cellular telephone activity was detected on all flights at a rate of approximately 1 signal per minute.
3. Considerable onboard RF activity was observed in the GPS L1 band, some of which appeared to have field strengths that, under appropriate circumstances, could result in interference with aircraft GPS equipment. Because of the likely growing future dependence on GPS for commercial aircraft navigation and precision approach, these emissions observed in the GPS band are the most troubling. It is very likely that many of these emissions are associated with the use of cellular phones.
4. Elevated broadband noise was observed on many occasions in the VOR and 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.
5. 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 PEDs prohibited cabin announcement.

8.5.1 Recommendations

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 ASRS 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.

The indications for the general aviation community are also that controlling emissions is prudent. However, a strategy of limiting and prohibiting use of PEDs during flight will be easier to implement if awareness and education are stressed.

Chapter 9

Managing the Problem

9.1 MANAGEMENT STRATEGIES

This dissertation has established that PED interference is occurring with a frequency that deserves concern. It has been demonstrated that PED interference events create hazardous situations. While the nature of the risks is different this conclusion applies to both commercial and general aviation. There are no documented cases of a fatal aircraft accident caused by PED interference; however the dissertation shows that PED interference could have been an unrecognized factor in some accidents. The RF environment in commercial aircraft cabins has been shown to be more active than previously believed. Some of this activity is in aircraft critical frequency bands and at levels that are high enough to be of concern. Finally, passenger disregard of rules and policies has been demonstrated.

Safety purists might argue that airlines should simply ban the use of all consumer electronic devices in aircraft cabins under the authority they already have through existing FAA regulations. The FAA specifies, "No person may operate...any portable electronic device on any...aircraft" unless an airline has determined that use of the device "will not cause interference with the navigation or communication system of the aircraft on which it is to be used." It is unlikely, however, that airlines will issue such a ban. Competitive pressures among airlines are large and growing. Business travelers, who are the most likely to want to stay connected and networked, are also the most profitable group of customers. There will be enormous pressure to introduce new services as airlines search for sources of comparative advantage. As long as one major airline allows or supports a service, there will be pressure on others to do the same. Further, since some of these technologies carry clear productivity and other benefits, it would be inappropriate to restrict their use through an overly precautionary policy if more balanced risk management solutions could be developed.

Instead, there are a number of management and control actions that parties on all sides of the issue can take to help improve air safety. For one thing, airlines, aircraft and equipment manufactures, and regulators can do more in using the classic tools of risk analysis to examine the problem of RF interference. Clearly, such analysis, which has been largely overlooked, is urgently needed. But this will by no means be enough. Given the enormous diversity and complexity of the systems involved, the constantly changing aircraft environment, and the limited analytical resources, such conventional studies will not be sufficient for identifying and assessing all important potential accident sequences. Greater progress can be made through five broad strategies that will foster adaptive management and control, listed below in approximate order in terms of importance and feasibility.

9.1.1 Joint Industry-Government Co-operation

It will be important to pay careful attention to the issues of RF interference, aircraft equipment design and certification and to quality control in maintenance. Obviously, airlines should maintain due vigilance regarding their existing equipment and systems. Moreover, airlines should move with great caution as they proceed to consider new aircraft systems. The potential for problems associated with emerging wireless systems is probably large. Since individual airlines may not have the resources to adequately evaluate all systems under development, a joint effort is indicated, and in the interests of public safety, some federal money should be provided to augment airline resources. FAA budgets have long been tight, and today they are stretched even thinner by the demands imposed in the aftermath of the 2001 terrorist attacks. The FAA, FCC, NTSB, airlines, and equipment manufacturers should form a joint industry-government cooperative program to perform evaluation and testing and promote better communication to aviation professionals and the public. Congress should appropriate funds to support the federal contribution to this undertaking. The RTCA committees on

PEDs have served the purpose, but have convened too infrequently to be effective. In addition to expanding the extent and quality of analysis and testing, such a program also would help to reduce redundant testing efforts across the industry. And since participation would be mandatory for all airlines, it would improve information sharing and eliminate free riding. Today, because of competitive considerations, airlines that have invested heavily in interference testing are sometimes understandably reluctant to share results with other lines that have invested less heavily. From a societal perspective this is clearly not desirable.

9.1.2 ASRS Database Augmentation

The Aviation Safety Reporting System should be augmented to again support statistically meaningful time series event analysis. The system has become a cornerstone of aviation safety. It has been used to identify many safety issues. The ASRS has issued more than 4,000 safety alerts and outside researchers have drawn on the database to produce at least 60 safety related reports and papers. Because of budget cuts, the practice of including an identifiable random sample was dropped in 2001. Thus, ASRS can no longer be used to do full, statistically valid time series studies of all types of incidents, including those involving PED interference. Clearly, Congress should provide budgetary support to reinstate the random sample entries. Given the diminished emphasis on NASA's role in aerospace, at some stage in the future it may become necessary to reconsider who should manage the database.

9.1.3 Continue In-Flight RF Spectrum Measurements

Improving characterization and analysis of the RF environment onboard aircraft will yield many benefits. This dissertation has served as a first exploration of the in-flight RF environment on commercial revenue flights.

Such measurements could be made a routine function on all flights. Modern flight data recorders—the familiar "black boxes" that serve as tools for investigating aircraft crashes—have hundreds of channels for recording data. Major airlines now routinely apply data-mining methods to the records from each flight in order to improve operational efficiency and quality assurance and to search for anomalies that may be indicative of problems [44], [45]. It would be relatively straightforward to install in aircraft cabins a set of RF detectors that would continuously monitor field strength in several spectral bands and record the data in the black box. Analysts could then include an examination of the cabin electromagnetic environment in their search for anomalous conditions.

9.1.4 Real-Time Monitoring

The development and deployment of simple real-time tools to help flight crews detect RF emissions would reduce risks. If airline cabins were equipped with RF detectors, then flight crews could take corrective action when strong electromagnetic emissions occurred. The utility of equipping flight crews with easy-to-use hand-held RF detectors also warrants investigation. If such observations ultimately identify particular types of electronic devices that are seriously troublesome, then legal or other mechanisms should be available to keep them off of airliners in the future. Currently, there is no systematic way to keep offending devices off of flights. A further benefit would be that flight crews would be aware of the presence of the high-level emissions. This would enable them to monitor their avionics closely for any anomalies.

9.1.5 Better FAA-FCC Co-operation

Paying greater attention to managing the RF emissions of consumer electronics is an essential element of a control strategy. The FCC currently does not confer with the FAA when establishing RF emission standards for consumer devices. Such coordination should occur. Recently, the Consumer Electronics Association in co-operation with RTCA Special Committee 202 created a voluntary guideline for indicating whether a T-PED transmitter is disabled [63]. This type of industry co-operation is admirable, but the regulatory bodies need to also be involved.

In addition, the national debate over the management of the electromagnetic spectrum and wireless technology should pay greater attention to the consequences that different policies will have for the aircraft environment. If the expected growth of wireless technology leads to interference problems that are sufficiently grave, then it may prove necessary to adopt more aggressive control measures. For example, the FCC could require manufacturers to include override capability in wireless devices so that they could be turned off by a centrally transmitted control signal during critical phases of flight, such as take off and final approach. Such a “silencing” capability might also prove beneficial in other critical settings, such as hospital critical care facilities, as well as in such social settings as theaters, restaurants, and library reading rooms. This type of regulation, however, would raise important questions of civil liberties, social vulnerability, and the potential for “common-mode failure” in important communications systems, and such a requirement should not be imposed without careful analysis and a balancing of risks, costs, and benefits.

Taken together, these actions will enable regulators and the airline industry to better characterize, and adaptively manage, the risk that RF interference from consumer electronics poses to aviation safety. In an industry that has eliminated or is effectively managing most large and obvious sources of risk, such persistent risks increasingly warrant attention.

9.2 CODA

The use of passenger electronics onboard commercial aircraft should continue to be limited. The many reasons why this is prudent have been outlined. It seems unlikely that this arrangement will be followed though. However, as this dissertation goes to print major decisions are in the balance. The FCC is exploring whether to allow cellular phones in-flight [12]. Conventional wisdom, as reflected in a New York Times article of 10 December 2004, is that this is “inevitable” [64]. Economic pressures on the airlines and electronics manufacturers will make it difficult, if not impossible to change course. The burden will fall on the FAA to address the situation. Traditionally, the FAA has given great leeway to the aviation industry to self-regulate. In this situation it would be asking for trouble. This situation calls out for a different approach.

A foundation of effective public policy must be the ability to use information to be proactive rather than reactionary. It must also strive to ensure that the data to make decisions is available. The management strategies of centralized research efforts, a standing oversight committee, and monitoring tools will help create those data sets needed to better understand the issue. The FAA must take the lead in this effort. If it does not, Congress should direct it to do so - and provide the needed resources.

The issue of PED interference can no longer be discussed in terms of anecdotal stories. There is clear data that PEDs do interfere with avionics and they do so at a measurable rate. Ultimately, the risk to the flying public can only be minimized by mitigating the hazards posed by PED interference. This will include strategies that prohibit certain electronic devices from powering on or transmitting at certain points in flight. It will also require industry wide acknowledgement of the problem so that the flying public will understand the issue on its merits. Both of these efforts will take time, which leaves limiting the use of passenger electronics onboard commercial aircraft as the only method available to ensure the near-term safety of the flying public.

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Appendix A

ASRS Narratives

ASRS #440557:

LOCATION 116.1 PZD VORTAC, GA. I HAVE HEARD S80 PLTS DESCRIBE NAV INTERFERENCE FROM PAX USING THE NEW DVD MOVIE PLAYERS. ON THIS FLT WE HAD A 30 DEG DIFFERENCE BTWN THE #1 AND #2 FOR NEEDLES WHEN TUNED TO 116.1. DME AND CDI DISPLAYS FOR CAPT AND FO WERE BOTH IN AGREEMENT WITH GFMS INFO AND THE #1 FOR NEEDLE. WHEN WE ASKED THE PAX IN SEAT XX TO TURN OFF HIS DVD PLAYER, THE #2 VOR NEEDLES ON BOTH RMI'S RETURNED TO CORRECT INDICATIONS. WHEN THE PAX TURNED THE DVD BACK ON, THE #2 NEEDLE DIVERGED 30 DEGS R AGAIN. WITH VOR 114.1 SELECTED, THE #2 NEEDLE WOULD WAVER BUT NOT DIVERGE WHILE THE DVD WAS ON. WITH VOR 116.5, NO EFFECT WAS NOTICED. CALLBACK CONVERSATION WITH RPTR REVEALED THE FOLLOWING INFO: THE PLT IS AN INSTRUCTOR AT HIS ACR FLT ACADEMY. HE HAS HEARD STORIES FROM MD80 CREWS OF INTERFERENCE CAUSED BY DVD PLAYERS ON THAT ACFT. BECAUSE OF THIS HE THOUGHT TO CHK THE CABIN FOR PAX OPERATED ELECTRONIC DEVICES. ON THIS PARTICULAR CASE, ONLY THE RMI NEEDLE ON THE #2 VOR WAS AFFECTED. BOTH THE CAPT'S AND FO'S #2 RMI NEEDLES SHOWED ERRONEOUS READINGS. THE HSI DISPLAY WAS NORMAL. TURNING THE DVD PLAYER OFF RETURNED THE RMI NEEDLES TO NORMAL, AND TURNING THE DVD BACK ON CAUSED THE RMI NEEDLES TO BECOME ERRONEOUS AGAIN. THEY DID NOT TRY MOVING THE PAX TO ANOTHER SEAT. NO MAINT DISCREPANCY WAS WRITTEN UP ON THE ACFT. IT IS NOT KNOWN WHETHER THIS PARTICULAR ACFT HAD FAULTY WIRE SHIELDING OR NOT.

ASRS #274861

WHILE IN CRUISE FLT, NAVING BY VOR ON J2, WE NOTICED THAT THE COURSE DEV INDICATOR (CDI) WAS DEFLECTING ERRATICALLY. AS THIS OCCURRED THERE WAS NOT ANY ASSOCIATED OFF FLAG. THE DEVS WERE IN BOTH DIRECTIONS AND IN VARYING DEGS. THE ACFT WAS WITHIN 30 NM OF THE VOR, IN CLR AIR AND THERE WAS NOT ANY LIGHTNING WITHIN 50 NM. I ASKED A FLT ATTENDANT IF ANYONE WAS USING AN ELECTRONIC DEVICE ONBOARD. SHE RPTED THAT A FAMILY WAS PLAYING WITH 2 'GAMEBOYS' WHICH WERE CONNECTED BY A CORD. THEY WERE SEATED IN THE FIRST 2 ROWS OF THE CABIN. AFTER SHE

RELAYED MY REQUEST TO TURN OFF THE DEVICES TO THE PAX THE DISTURBANCES CEASED. LATER SMALLER CDI DEVS OCCURRED AND WE FOUND 1 GAMEBOY IN USE, SEPARATELY, WITHOUT THE CONNECTING CORD ATTACHED. THE PAX WERE COOPERATIVE WHEN ASKED, THEN, TO TURN OFF AND PUT AWAY THE GAMEBOYS. AFTER THAT NO OTHER LIKE INCIDENTS WERE NOTED
ASRS #239173

IN CRUISE FLT AT FL310 25 NM W OF THE DFW VOR, THE #1 COMPASS SUDDENLY PRECESSED 10 DEGS TO THE R. I ASKED THE FIRST FLT ATTENDANT IF ANY PAX OPERATED ELECTRONIC DEVICES WERE IN OP IN THE CABIN. SHE SAID THAT A PAX IN SEAT X HAD JUST TURNED ON HIS LAPTOP COMPUTER. I ASKED THAT THE PAX TURN OFF HIS LAPTOP COMPUTER FOR A PERIOD OF 10 MINS, WHICH HE DID. I SLAVED THE #1 COMPASS, AND IT RETURNED TO NORMAL OP FOR THE 10 MIN PERIOD. I THEN ASKED THAT THE PAX TURN ON HIS COMPUTER ONCE AGAIN. THE #1 COMPASS IMMEDIATELY PRECESSED 8 DEGS TO THE R. THE COMPUTER WAS THEN TURNED OFF FOR A 30 MIN PERIOD DURING WHICH THE #1 COMPASS OP WAS VERIFIED AS NORMAL. IT WAS VERY EVIDENT TO ALL ON THE FLT DECK THAT THE LAPTOP COMPUTER OP WAS ADVERSELY AFFECTING THE OP OF THE #1 COMPASS. I BELIEVE THAT THE OP OF ALL PAX OPERATED ELECTRONIC DEVICES SHOULD BE PROHIBITED ON AIRLINES UNTIL THE SAFE OP OF ALL OF THESE DEVICES CAN BE VERIFIED. CALLBACK CONVERSATION WITH RPTR REVEALED THE FOLLOWING INFO: RPTR REITERATED THE INCIDENT AND ADDED THAT HE HAS SENT IN ANOTHER RPT ON A SIMILAR INCIDENT. HE IS A SAFETY COMMITTEE MEMBER AND CLAIMS THAT MANY CASES HAVE BEEN RPTED AND THAT HE IS CONVINCED THAT MANY LAPTOP COMPUTERS DO AFFECT HDG AND NAV INSTS. HE IS EXTREMELY CONCERNED WITH THE POSSIBLE FUTURE AFFECTS ON FLY-BY-WIRE ACFT. COMPUTER WAS AN IMPORTED PC CLONE.

Appendix B

Passenger Electronics Use: Survey Results

Responses: 39 of 100

1. When do you believe that it is *permissible* to use a cell phone on an airplane?

2. When do you believe that it is *safe* to use a cell phone on an airplane?

3. Have you, or anyone you know, ever forgotten to turn off power to your cell phone when you got on an airplane and later found that it had been on for the duration of the flight?
Yes: 12
No: 23

4. Have you ever used a cell phone while in the air?
Yes: 1
No: 34

5. Have you ever seen anyone else use a cell phone on an airplane while in the air?
Yes: 10
No: 23

6. Who do you believe is responsible for the rule against cell phone use in the air?
Airlines: 2
FAA: 25
FCC: 3
Other: 0
Don’t know: 8

7. Why do you think there is the rule to limit the use of cell phones in airplanes?
Because use in the air might interfere with the operation of aircraft electronics: 32
Because use in the air might disrupt the operation of the cell phone system: 2
Because cell phone use would undermine the profitability of air phone service: 8
Other: 0

8. Do you believe there is a serious safety risk from using cell phones on airplanes?

Yes: 14
No: 18

9. If there were a safe and legal way to use your cell phone on an airplane, would you use it?
Yes: 23
No: 9

10. If you were allowed to use your cell phone in the air, roughly how often would you use it?

Only rarely: 20
Once every two to three flights: 7
One to three times during most flights: 3
More than three times during most flights: 1

11. Why do airlines require laptop computers to be put away during take-off and landing?

To keep the cabin clear for rapid evacuation: 9
To prevent passengers' attention from being diverted from crew instructions: 5
To prevent interference with the operation of aircraft electronics: 20
To secure heavy objects that might become projectiles: 16
Other: 0

12. Laptop computers, electronic games, and other electronic devices are now able to talk to each other using wireless radio links. When this capability becomes more readily available, will you want to use it to communicate with others who fly with you? If so, how often might you do this?

Only rarely: 30
Every two or three flights: 1
During most flights: 1

13. Was your most recent air trip for business or pleasure?

Business: 22
Pleasure: 13

14. Roughly how many miles a year do you fly?

Less than 25,000: 16
Between 25,000 and 50,000: 15
More than 50,000: 4

Appendix C

Instrumentation Performance Results Onboard A 737-300 Aircraft

The instrumentation in its final configuration was tested onboard a Boeing 737-300 aircraft parked 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 Hewlett Packard signal generator. Line losses were minimal, but were accounted for.

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

The influence of instrumentation orientation was minimal and the figures below demonstrate that there are gradients. The signal attenuation approximately follows free-space losses (n = 2). The previous research suggests that directionality and polarization effects are minimized by the reverberant characteristics of the aircraft cabin and that gradients exist [47], [48], [49], [50]. The results are in agreement with these previous findings. The deviations from the free-space model are likely due to absorption losses (seats, floors, etc.), losses due to window apertures and data points recorded in the reverberant cavity nulls.

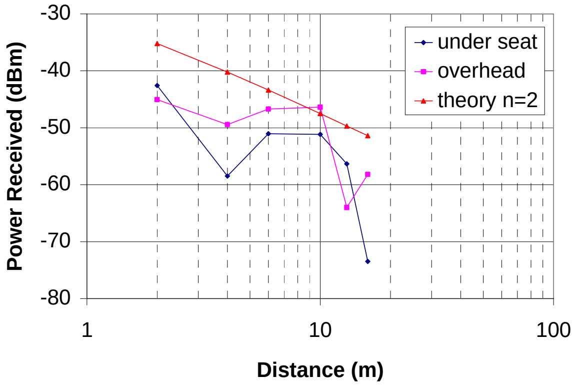

Figure C.1: Data Taken on a B737 at 113 MHz

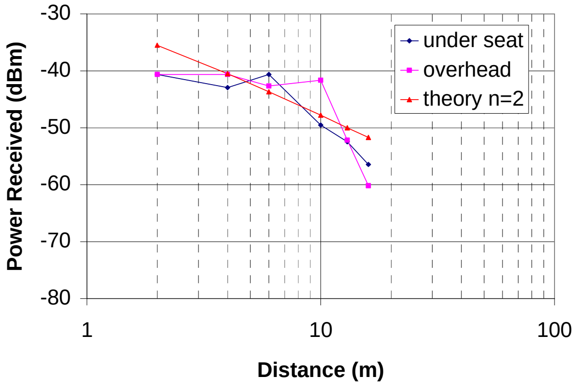

Figure C.2: Data Taken on a B737 at 332 MHz

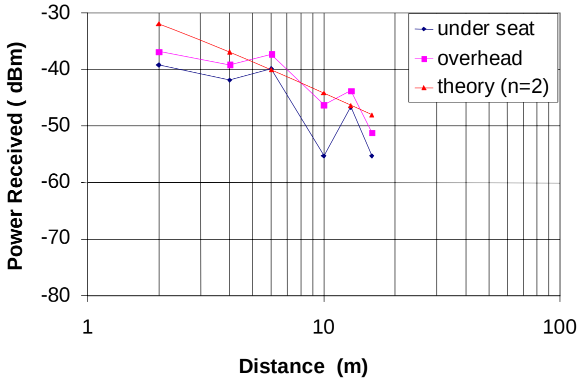

Figure C.3: Data Taken on a B737 at 836 MHz

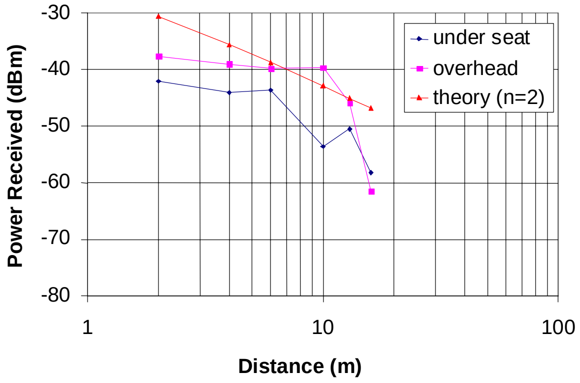

Figure C.4: Data Taken on a B737 at 915 MHz

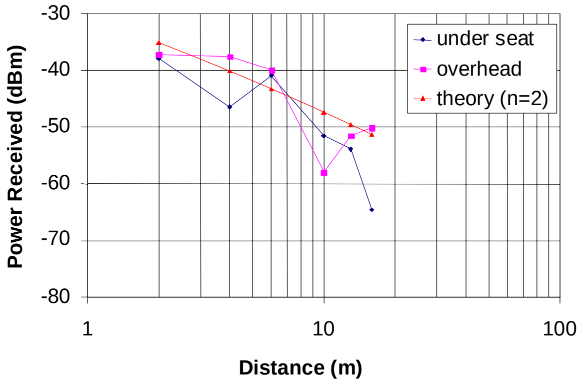

Figure C.5: Data Taken on a B737 at 1227 MHz

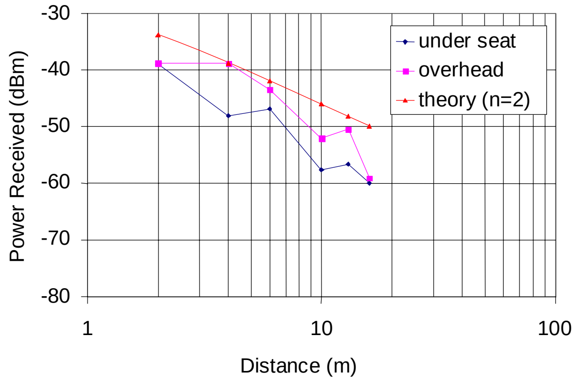

Figure C.6: Data Taken on a B737 at 1577 MHz

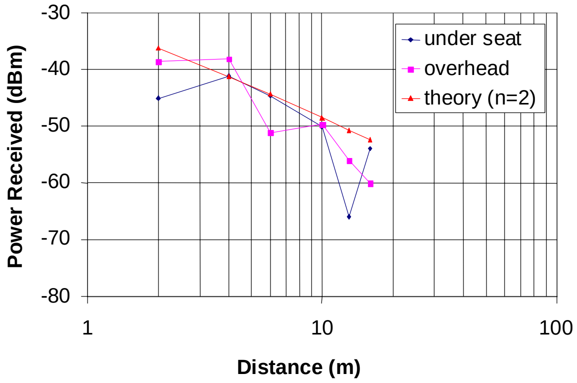

Figure C.7: Data Taken on a B737 at 1880 MHz

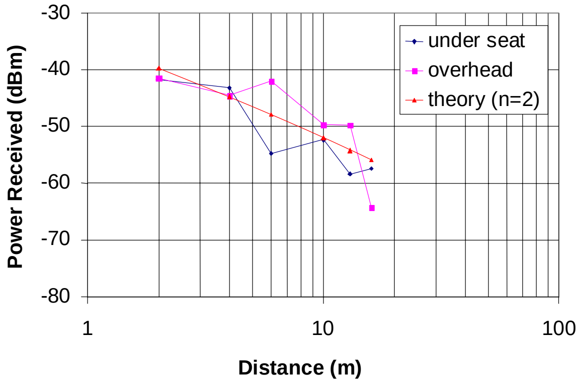

Figure C.8: Data Taken on a B737 at 2450 MHz

Appendix D

Cellular Phone Channels

The tables presented in this appendix provide information on the cellular channels in the cellular and PCS bands. The information in Table D.1 was used to identify calls verses registrations in the cellular band. The information in Table D.2 and Table D.3 was used to identify CDMA signals. Finally, the GSM channels used in the PCS band are provided in Table D.4, but this information was not specifically used in the analysis.

Table D.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 D.2: Cellular Band CDMA Channel Assignments

	AMPS/TDMA Channel		Frequency (MHz)	
CDMA Channel	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

Table D.3: PCS Band CDMA Channel Assignments

Block	CDMA Channels[1]	Frequency (MHz) Start	Frequency (MHz) 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 D.4: PCS Band GSM Channel Assignments

GSM Channel	Frequency (MHz) Start	Frequency (MHz) 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*(ARFCN-512)
2. Channel Width = 200 kHz

Appendix E

Identified Onboard Cellular Signals

The tables in this appendix identify all of the observed onboard signals as determined by the analysis described in section 8.1. The column titled “Margin” refers to the measured level above the “onboard threshold” described in section 8.1.3.3. Received power is at the instrumentation and “Adjusted” accounts for measurement under-valuing of wideband (CDMA) signals.

Table E.1: Narrowband Signals in the Cellular Band

Flight #	Frequency (MHz)	Altitude (ft)	Received Power (dBm)	Onboard Threshold (dBm)	Margin (dB)	Signal Type
36	847.68	18,903	-40.84	-78.37	37.53	call
35	838.66	27,050	-54.28	-81.48	27.21	call
6	825.07	6,978	-44.45	-69.71	25.27	call
36	848.56	28,897	-58.77	-82.05	23.29	call
30	824.69	12,227	-55.51	-74.58	19.07	call
25	836.91	30,867	-74.68	-82.63	7.95	call
25	833.02	35,000	-80.76	-83.72	2.96	call
25	833.02	35,000	-80.83	-83.72	2.89	call
3	835.15	26,000	-39.00	-81.14	42.14	registration
38	835.47	29,827	-42.83	-82.33	39.50	registration
6	835.34	29,000	-46.20	-82.09	35.88	registration
14	834.46	8,437	-37.64	-71.36	33.72	registration
23	835.03	8,665	-38.34	-71.59	33.25	registration
15	834.90	8,267	-39.56	-71.18	31.63	registration
8	834.53	5,718	-43.91	-67.98	24.07	registration
14	834.40	2,025	-37.68	-58.97	21.28	registration
14	834.96	4,082	-51.84	-65.06	13.21	registration
24	834.53	29,000	-75.76	-82.09	6.33	registration

Table E.2: Wideband Signals in the Cellular Band

Flight #	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
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

Table E.2 (Cont.)

Flight #	CDMA Channel	Altitude (ft)	Max P_r[1] (dBm)	Adjusted[2] (dBm)	Onboard Threshold (dBm)	Margin (dB)
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
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

Table E.2 (Cont.)

Flight #	CDMA Channel	Altitude (ft)	Max P_r[1] (dBm)	Adjusted[2] (dBm)	Onboard Threshold (dBm)	Margin (dB)
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
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. Adjustment to account for measurement set-up under-value.

Table E.3: Narrowband Signals in the PCS Band

Flight #	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
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

Table E.3 (Cont.)

Flight #	Frequency (MHz)	Altitude (ft.)	Power Received (dBm)	Onboard Threshold (dBm)	Margin (dBm)
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
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

Note: * High Resolution Protocol Data

Table E.4: Wideband Signals in the PCS Band

Flight #	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
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

Table E.4 (Cont.)

Flight #	CDMA Channel	Altitude (ft.)	Max P_r[1] (dBm)	Adjusted[2] (dBm)	Onboard Threshold (dBm)	Margin (dB)
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
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

Table E.4 (Cont.)

Flight #	CDMA Channel	Altitude (ft.)	Max P_r[1] (dBm)	Adjusted[2] (dBm)	Onboard Threshold (dBm)	Margin (dB)
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
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

Table E.4 (Cont.)

Flight #	CDMA Channel	Altitude (ft.)	Max P_r[1] (dBm)	Adjusted[2] (dBm)	Onboard Threshold (dBm)	Margin (dB)
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 F

In-Flight Mobile Cellular Activity Rates

Table F.1: In-Flight Cellular Band Activity Rate (Standard Resolution Measurement Protocol)

	Signals Detected	Analyzer Sweeps (approximate)	Monitored Time (sec)	Rate (signals/min)
Narrowband	18	14,081	26,895	0.04
Wideband	87	14,081	26,895	0.19
Total	105	14,081	26,895	0.23

Table F.2: In-Flight Cellular Band Activity Rate (High Resolution Measurement Protocol)

	Signals Detected	Analyzer Sweeps (approximate)	Monitored Time (sec)	Rate (signals/min)
Narrowband	1	1,230	2,349	0.03
Wideband	45	1,230	2,349	1.15
Total	46	1,230	2,349	1.17

Table F.3: In-Flight Cellular Band Activity Rate (Overall)

	Signals Detected	Analyzer Sweeps (approximate)	Monitored Time (sec)	Rate (signals/min)
Narrowband	19	15,311	29,244	0.04
Wideband	132	15,311	29,244	0.27
Total	151	15,311	29,244	0.31

Table F.4: Low Altitude Cellular Band Activity Rate (Standard Resolution Measurement Protocol)

	Signals Detected	Analyzer Sweeps (approximate)	Monitored Time (sec)	Rate (signals/min)
Narrowband	8	2,591	4,949	0.10
Wideband	17	2,591	4,949	0.21
Total	25	2,591	4,949	0.30

Table F.5: Low Altitude Cellular Band Activity Rate (High Resolution Measurement Protocol)

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

Table F.6: Low Altitude Cellular Band Activity Rate (Overall)

	Signals Detected	Analyzer Sweeps (approximate)	Monitored Time (sec)	Rate (signals/min)
Narrowband	8	2,961	5,656	0.08
Wideband	28	2,961	5,656	0.30
Total	36	2,961	5,656	0.39

Table F.7: In-Flight PCS Band Activity Rate (Standard Resolution Measurement Protocol)

	Signals Detected	Analyzer Sweeps (approximate)	Monitored Time (sec)	Rate (signals/min)
Narrowband	73	6,095	25,904	0.17
Wideband	103	6,095	25,904	0.24
Total	176	6,095	25,904	0.41

Table F.8: In-Flight PCS Band Activity Rate (High Resolution Measurement Protocol)

	Signals Detected	Analyzer Sweeps (approximate)	Monitored Time (sec)	Rate (signals/min)
Narrowband	9	1,202	5,109	0.11
Wideband	57	1,202	5,109	0.67
Total	66	1,202	5,109	0.78

Table F.9: In-Flight PCS Band Activity Rate (Overall)

	Signals Detected	Analyzer Sweeps (approximate)	Monitored Time (sec)	Rate (signals/min)
Narrowband	82	7,297	31,012	0.16
Wideband	160	7,297	31,012	0.31
Total	242	7,297	31,012	0.47

Table F.10: Low Altitude PCS Band Activity Rate (Standard Resolution Measurement Protocol)

	Signals Detected	Analyzer Sweeps (approximate)	Monitored Time (sec)	Rate (signals/min)
Narrowband	12	1,035	4,399	0.16
Wideband	18	1,035	4,399	0.25
Total	30	1,035	4,399	0.41

Table F.11: Low Altitude PCS Band Activity Rate (High Resolution Measurement Protocol)

	Signals Detected	Analyzer Sweeps (approximate)	Monitored Time (sec)	Rate (signals/min)
Narrowband	3	378	1,607	0.11
Wideband	23	378	1,607	0.86
Total	26	378	1,607	0.97

Table F.12: Low Altitude PCS Band Activity Rate (Overall)

	Signals Detected	Analyzer Sweeps (approximate)	Monitored Time (sec)	Rate (signals/min)
Narrowband	15	1,413	6,005	0.15
Wideband	41	1,413	6,005	0.41
Total	56	1,413	6,005	0.56

Appendix G

Current FAA Policy on PEDS: 14 CFR 91.21

Sec. **91**.**21** Portable electronic devices

(a) Except as provided in paragraph (b) of this section, no person may operate, nor may any operator or pilot in command of an aircraft allow the operation of, any portable electronic device on any of the following U.S.-registered civil aircraft:
  (1) Aircraft operated by a holder of an air carrier operating certificate or an operating certificate; or
  (2) Any other aircraft while it is operated under IFR.
(b) Paragraph (a) of this section does not apply to--
  (1) Portable voice recorders;
  (2) Hearing aids;
  (3) Heart pacemakers;
  (4) Electric shavers; or
  (5) Any other portable electronic device that the operator of the aircraft has determined will not cause interference with the navigation or communication system of the aircraft on which it is to be used.
(c) In the case of an aircraft operated by a holder of an air carrier operating certificate or an operating certificate, the determination required by paragraph (b)(5) of this section shall be made by that operator of the aircraft on which the particular device is to be used. In the case of other aircraft, the determination may be made by the pilot in command or other operator of the aircraft.