Abstract—A program that measured the in-flight RF spectrum on 37 revenue flights of commercial aircraft cabins is described. The spectrum monitoring was performed from gate-to-gate in selected aviation critical and personal electronics frequency bands over the period from September 23 through November 19, 2003. The commercial aircraft in-flight RF environment for two critical navigation frequency bands, VOR and Global Positioning System (GPS) and four consumer electronics frequency ranges are reported. A brief analysis of the GPS band data is presented.

Keywords—RF electromagnetic environment; EME; aircraft; spectrum; cell phones; PEDs; interference

I. INTRODUCTION

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. 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.

Research efforts have been sporadic and mostly restricted to in-house efforts by aircraft manufacturers and airlines. The RTCA studies published in 1963, 1988, 1996 and 2004 [1-4] are the main influences on former and current FAA and industry policies. However, 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. More recently NASA has released a number of reports [5-8] documenting cellular phone and wireless emissions and their potential to interfere with aircraft safety, but these all have the limitation of being laboratory tests and do not approximate the variability introduced by passengers carry the latest electronic gadgets.

II. PROGRAM DESCRIPTION AND MOTIVATION

While previous measurements and analyses [5-10] 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 environment. This limitation will become more serious as we move from an era dominated by analogue devices under the direct control of users into an era dominated by ubiquitous digital devices, many with wireless features that operate without active or knowing user control.

As a consequence, decisions are being made and conclusions drawn on theory and theoretical extensions of laboratory measurements without correlation to the actual environment. 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 flight safety issues. In their writings on human factors and aviation accidents, McDonald and Johnston [11] 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."

To address this void in data a program was sponsored by Carnegie Mellon University and the FAA. The program sought to perform in-flight spectrum measurements on revenue flights [12]. Extensive consultations were conducted with the management and engineering staffs of three major US air carriers and technical staff at the FAA and FCC. The value of this effort was recommended by a recent NASA report [5].

A. Motivation

Beyond the obvious motivation of producing data where previously there was none are a number of more subtle, but important motivations.

1) Capturing In-Situ Data – The in-flight measurement program looked at the combined effects of the aircraft and passenger electronics on the RF environment over many flights. This allowed for:

- Rare events to be captured.
- In-service PED emissions to be evaluated (i.e. PEDs dropped, repaired, modified). The emissions from PEDs have been explored [1-3] [6], but these efforts concentrated on relatively new devices and had the common deficiency of a low sample size.
The use of transmitting PEDs (T-PEDs) to be evaluated. NASA has recently concluded two studies that focused on the unintentional emissions from T-PEDs [5-6], but again these were laboratory measurements only.

Previous research approaches have not analyzed effects caused by multiple PEDs or PEDs in combination with other aircraft generated emissions or the external RF EME, i.e., intermodulation.

2) 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. 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.

3) PED Detectors and Data Mining - The development of in-flight PED detection and location systems has been examined and promoted for some time [13-15]. These systems have so far been cost prohibitive and the usefulness of locators has yet to be established. However, less complex and expensive detectors could be used in conjunction with flight data recorders to search for anomalous conditions. Major airlines already routinely apply data-mining methods in order to improve operational efficiency and quality assurance [16-17]. An understanding of the in-flight RF environment will be vital to the development of any in-flight monitoring systems.

B. Frequencies of Interest

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

Four 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 L1, 1575.42 MHz. And four passenger electronics frequency ranges were selected: 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. Limited monitoring was conducted in the ILS GS band and the DME and TCAS bands due to a combination of technical difficulties and the desire to concentrate on frequencies of greater interest.

III. INSTRUMENTATION

The cooperating airlines stipulated that the instrumentation must be carry-on size 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. The instrument package consisted of an Anritsu MS2711B spectrum analyzer, Antenna Research CMA-118/A broad-band antenna, Gateway Solo Pro 9300 laptop computer, and associated cables and connectors, all housed in a conventional soft-side carry-on bag, Figure 1.
source. The instrumentation was placed in overhead compartment and under seat locations throughout the aircraft. The results demonstrated the adequacy of the 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 support previous work that suggests the reverberant nature of the aircraft cabin with gradients [19-22]. Measurements were recorded on a single maintenance flight to provide ambient levels. It was desirable to obtain additional maintenance flights, however logistics and scheduling prevented this.

C. Data Collection Routines

The spectrum analyzer settings used are summarized in Table I. The settings were chosen to meet the overall objective of determining a first general characterization of the RF environment in commercial aircraft cabins and more specific objectives such as capturing in-flight “calls.”

<table>
<thead>
<tr>
<th>Table I</th>
<th>SPECTRUM ANALYZER SETTINGS</th>
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<tbody>
<tr>
<td>Band</td>
<td>Frequency Range (MHz)</td>
</tr>
<tr>
<td></td>
<td>Resolution BW</td>
</tr>
<tr>
<td></td>
<td>Video BW</td>
</tr>
<tr>
<td>VOR</td>
<td>108 - 118</td>
</tr>
<tr>
<td></td>
<td>10 kHz</td>
</tr>
<tr>
<td>Cellular</td>
<td>824 - 849</td>
</tr>
<tr>
<td></td>
<td>30 kHz</td>
</tr>
<tr>
<td>ISM</td>
<td>902 - 928</td>
</tr>
<tr>
<td></td>
<td>30 kHz</td>
</tr>
<tr>
<td>GPS</td>
<td>1565 - 1590</td>
</tr>
<tr>
<td></td>
<td>30 kHz</td>
</tr>
<tr>
<td>PCS</td>
<td>1850 - 1910</td>
</tr>
<tr>
<td></td>
<td>30 kHz</td>
</tr>
<tr>
<td>ISM</td>
<td>2400 - 2485</td>
</tr>
<tr>
<td></td>
<td>1 MHz</td>
</tr>
<tr>
<td></td>
<td>300 kHz</td>
</tr>
</tbody>
</table>

The data were obtained using two sweep protocols. The “standard” protocol collected approximately 1-minute of data using maximum hold and positive detection. This measurement approach is similar to that used by NTIA in their spectrum utilization assessments [23]. The “high resolution” protocol collected single sweeps of data. The standard collection protocol was utilized exclusively except in 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. The high resolution protocol records more data, but results in a lower time monitored percentage due to the delay each time data are written to the computer and a new command is issued. During some flights the cellular and PCS bands were monitored exclusively using the high resolution protocol.

The instrumentation did not support parallel recording of frequency bands. Thus, a sequential order was determined for each flight by prioritizing according to flight phase.

IV. COLLECTED DATA

Measurements were made on 38 flights in late 2003. All flights were revenue flights except for one maintenance flight. All flights were on Boeing 737 model aircraft except for one flight on an Airbus 320. Two airlines participated in the in-flight study with 29 flights on one airline and 9 flights on the other. 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.

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, etc.) was random. There was no attempt to control what objects (luggage, handbags, boxes, etc.) were placed in proximity to the instrumentation.

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.

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. The manually recorded information including altitude information was added to the raw data during the post-flight data management phase. The altitude information for most flights was derived from flight plans provided by the airlines the day following a flight. Actual altitude information was obtained for two flights involving 737-800 aircraft that were equipped with telemetry systems.

While altitude information was 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 were accurately known.

No real-time monitoring of the spectrum was permitted because of the established agreements with the airlines. This reduced the possibility of correlating a passenger’s electronics use with a signal event. To the extent possible, passengers’ electronics use was noted. For example, a passenger was observed making an in-flight cellular call and this was subsequently observed in the data at the noted time.

The flight crews were aware of the in-flight monitoring program and debriefed after the flights. 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 author’s flying experience.

V. RESULTS AND DISCUSSION

The results and discussion are provided in two parts. The first part provides summary data to allow the reader an introduction to the commercial aircraft in-flight environment. The second part provides an approach to evaluating the data and determining the implications on flight safety.

A. Summary Data

This section provides summary data to allow the reader an introduction to the commercial aircraft in-flight environment. The description of RF electromagnetic environments is often given as field strength (V/m). 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 commercial aircraft in-flight environment, this was not viewed as a major limitation. Thus, the data is in terms of power received (dBm) by the spectrum analyzer. All data in Figures 2-6 used the standard measurement protocol and represent the maximum-average-minimum recorded values for all in-flight collected data.

A summary chart of the VOR band would not be useful; however two observations are helpful in understanding this in-flight environment.

- Most in-flight traces contained only a few narrowband signals. The ground VOR stations were identifiable, however exact aircraft locations were not known so correlation to specific narrowband signals was difficult except in the immediate vicinity of the airfield.

- 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. Figure 7 demonstrates 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 not suspected that the noise increase was from PEDs.
B. Brief Analysis of the GPS Band and Implications

This section introduces an analysis method and provides a summary. The details are too lengthy for this paper and will be published in the future. There were a total of 196 traces collected on 31 flights. This represents approximately 3 hours of in-flight monitoring. None of the aircraft on which measurements were made were GPS equipped.

While the avionics community specifically attempts to avoid emissions in this band, this study revealed onboard signal activity. There were signals observed on 58 of 196 traces and creates the potential for interference. As future dependence on GPS grows, i.e. precision approaches, the threat posed by such interference will become more serious. Thus, any observed signals should raise concern.

Of course, the presence of signals within the GPS band does not automatically create interference and the duration of each identified signal is not known because of the spectrum analyzer settings. The susceptibility of GPS receivers has been thoroughly explored [24-29]. Pulsed interference is not likely to cause problems unless it contains significant power and none of the observed signals contained sufficient power. However, if the signals were CW in nature, then there is some potential to cause interference to commercial GPS receivers.

The RTCA DO-235A [30] defines the likelihood of interference for GPS receivers and is based on theory and validated in practice. 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. The worst-case observed signals and derived thresholds are provided in Table II. The threshold provided is for acquisition-mode, the time period when a GPS receiver is acquiring signals and has not established a navigation solution. The table includes 41 dB of path loss as reported by NASA [6], the minimum path loss for medium size aircraft (i.e. 737, 727, etc).

<table>
<thead>
<tr>
<th>Altitude</th>
<th>Frequency (MHz)</th>
<th>BW (MHz)</th>
<th>Measured Power (dBm)</th>
<th>Threshold (dBm)</th>
<th>Margin (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>35,000</td>
<td>1,589.6</td>
<td>0.75</td>
<td>-59.07</td>
<td>-100.50</td>
<td>-40.43</td>
</tr>
<tr>
<td>23,031</td>
<td>1,589.6</td>
<td>0.75</td>
<td>-60.87</td>
<td>-100.50</td>
<td>1.37</td>
</tr>
<tr>
<td>26,000</td>
<td>1,576.3</td>
<td>2.25</td>
<td>-77.16</td>
<td>-112.98</td>
<td>5.17</td>
</tr>
</tbody>
</table>

The worst-case signal listed in Table II has a negative safety margin and could prevent a GPS receiver from acquiring a navigation solution. The margins will be worse on smaller commuter and general aviation aircraft. The worst-case signal is shown in Figure 8 at the far right. This signal was also observed earlier on the same flight indicating that the signal was present for an extended period of time.

In considering the safety margins presented in Table II, it must be noted that the locations of the signals are not known and given the reverberant nature of the aircraft cavity with gradients the signals could be undervalued (i.e. located far from the instrumentation or recorded in a null).

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 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.

It is unknown from what source the potentially interfering signals originated. However, current data indicates cellular phones as one potential source [7]. Furthermore, this in-flight measurement program determined cellular phone activity rates of 1-4 calls per flight and detected cellular activity at a rate higher than 1 signal per minute [31]. This demonstrated high activity level loans well to the possibility that the detected signals are cellular.

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 [32]. This includes navigation in the en route, terminal area, approach/landing, and surface operating regimes. 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 [28]. The observed signal with a negative safety 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.

VI. RECOMMENDATIONS

This paper provides the first reported characterization of the commercial in-flight RF environment. The results indicate that the environment is more active than previously believed. Furthermore, the observed emissions in aircraft critical navigation bands increase the potential for aircraft interference. This coupled with the now documented passenger use of cellular phones in-flight and passenger non-compliance with in-flight electronics use policies leads to cautionary signs that need further investigation. This first look at the in-flight spectrum has been illuminating, but is nowhere thorough enough to end the issue. A longer-term in-flight monitoring program with more sophisticated instrumentation that allows monitoring of bands simultaneously is in order.

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REFERENCES


