ELECTROMAGNETIC INTERFERENCE ASSESSMENT OF CDMA AND GSM WIRELESS PHONES TO AIRCRAFT NAVIGATION RADIOS

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Abstract

To address the concern for cellular phone electromagnetic interference (EMI) to aircraft radios, a radiated emission measurement process for CDMA (IS-95) and GSM (ETSI GSM 11.22) wireless handsets was developed. Spurious radiated emissions were efficiently characterized from devices tested in either a semi-anechoic or reverberation chamber, in terms of effective isotropic radiated power. Eight representative handsets (4 GSM, 4 CDMA) were commanded to operate while varying their radio transmitter parameters (power, modulation, etc.). This report provides a detailed description of the measurement process and resulting data, which may subsequently be used by others as a basis of consistent evaluation for cellular/PCS phones, Bluetooth, IEEE802.11b, IEEE802.11a, FRS/GMRS radios, and other portable transmitters. Aircraft interference path loss (IPL) and navigation radio interference threshold data from numerous reference documents, standards, and NASA partnerships were compiled. Using this data, a preliminary risk assessment is provided for CDMA and GSM wireless phone interference to aircraft localizer, Glideslope, VOR, and GPS radio receivers on typical transport airplanes. The report identifies where existing data for device emissions, IPL, and navigation radio interference thresholds needs to be extended for an accurate risk assessment for wireless transmitters in aircraft.[·]

1 Introduction

Wireless phones and wireless LAN products have become increasingly present companions to today’s travelers. Wireless technology has brought a revolution in personal accessibility and productivity, and has created entire markets for products and services. However, this wireless revolution also presents a growing concern to airlines, the Federal Aviation Administration (FAA), and NASA for potential electromagnetic interference (EMI) to aircraft electronic systems. Although passengers are currently prohibited from using wireless phones on board aircraft during flight, it is clear that such unauthorized use is increasing.

RTCA/DO-199 [1] (published in 1988) and RTCA/DO-233 [2] (published in 1996) form a foundation for current regulatory and advisory guidance from the Federal Aviation Administration (FAA), in the United States (US) [3,4]. These reports and subsequent publications commonly agree that the potential for interference is real, but infrequent [5 to 9]. RTCA/ DO-233 contains four recommendations: 1) Prohibit all portable electronic device (PED) usage during critical flight phases, and prohibit the usage of intentionally-transmitting PEDs at all times (unless a particular device has been specifically verified to be safely operated). 2) Continue and expand radiated emissions testing from new-technology PEDs. 3) Educate the public, airline industry, and consumer electronics manufacturers regarding the potential interference hazards from PEDs. 4) Research the feasibility of using PED monitoring devices aboard commercial airplanes. Neither of the RTCA reports addressed the issue of wireless phone spurious radiated emissions into aircraft communication and

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[·] **Acknowledgements:** Special thanks is extended to the University of Oklahoma Center for Wireless Electromagnetic Compatibility, whose team members provided reference material, consultation, test equipment, operational procedures and test support at NASA Langley Research Center for controlling GSM and CDMA handsets using keypad codes, base station simulators, and a test harness interface.

The authors are also appreciative of semi-anechoic chamber facility support received from the Test and Development Branch in the Systems Engineering Competency at NASA Langley Research Center.

This work was funded in part by the FAA William J. Hughes Technical Center and in part by the NASA Aviation Safety Program, Single Aircraft Accident Prevention Project.

navigation radio frequency bands. Coincidentally, wireless voice and data radios are increasingly being integrated into multifunction packages, often making it difficult for flight crews and passengers to identify them as intentional transmitters. Thus, as the RTCA/ DO-233 recommended prohibition of portable transmitter operation during flight is becoming less enforceable, the lack of technical analysis regarding wireless phone threat to aircraft systems is becoming more critical.

This report describes the development and application of a radiated emission measurement process for CDMA (IS-95, 824-849 MHz) and GSM (ETSI GSM 11.22, 880-915 MHz) wireless phones, and provides a risk assessment for the potential interference of several units to aircraft Localizer, Glideslope, VOR, and GPS radio receivers. The goal of this work is to form a sound technical basis for assessing the potential for wireless voice and data transmitters to cause EMI to aircraft radio receivers.

2 Approach

Ideally, the most effective way to assess the potential for electronic equipment to interfere with aircraft systems is to exercise a representative unit in all modes of operation, at the location of installation, and monitor all critical and essential aircraft systems for unwanted effects during their operation. A good reference for an aircraft EMI evaluation is provided in [10]. Such in situ testing is routinely performed for aircraft equipment before regulatory approval for installation on commercial transport aircraft.

In the case of wireless phones carried aboard aircraft by passengers, this process quickly becomes impractical. Passengers routinely carry wireless handsets ranging from brand-new to over a decade old. The product design cycle for consumer electronics products is measured in periods of months. It is simply not possible to test every device, or even representative models of every device for potential EMI to all aircraft systems. In addition, wireless handsets can potentially be present in any passenger cabin or cargo bay location. It is well established that coupling loss between aircraft radios and passenger cabin locations can vary by a factor of over 100dB, depending upon location of operation. To assess the potential for wireless handsets to interfere with aircraft systems, it is necessary to separate the analysis into an elemental, rather than in-situ approach. Figure 1 graphically outlines the three required elements of any EMI problem, as they pertain to evaluating the wireless phone threat to aircraft radios. This section will address each of the three elements of the EMI threat assessment from GSM and CDMA wireless handsets. The threat power at the connector of a particular aircraft radio receiver (P_{Rcvr_Threat}, dBm), due to spurious radiated emissions from a PED (P_{PED}, dB), can be described as P_{PED}, less cable, propagation and antenna loss occurring between the PED and aircraft radio connector (Interference Path Loss, IPL, dBm). In equation form:

$$P_{Rcvr\_Threat} = P_{PED} - IPL \qquad (1)$$

To function without interference, the interference threshold power at the aircraft radio connector (P_{Rcvr_IT}, dBm) must be greater than P_{Rcvr_Threat}.

$$P_{Rcvr\_IT} > P_{Rcvr\_Threat} \ ? \qquad (2)$$

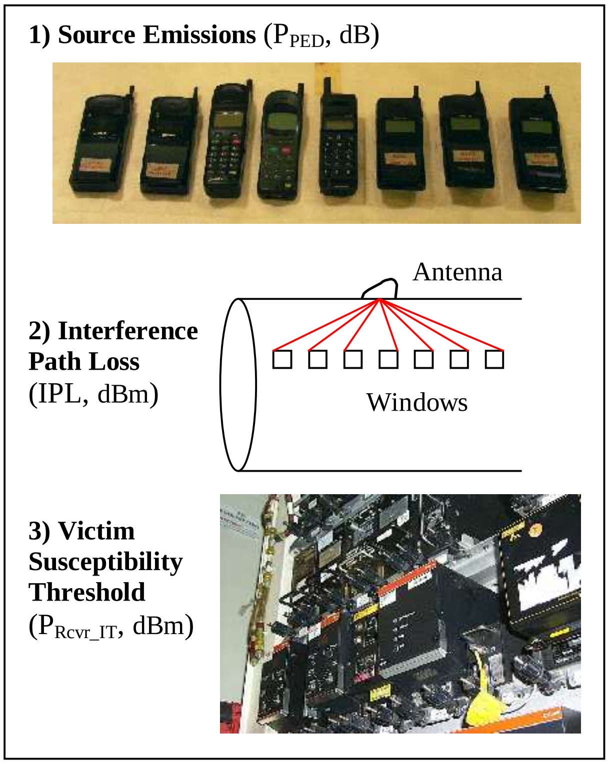

Figure 1: Three analysis elements for assessing the potential for wireless phone electromagnetic interference to aircraft radio receivers.

The analysis herein focuses upon the following flight-essential aircraft navigation radio receivers: Instrument Landing System (ILS) localizer, ILS glideslope, VOR, and GPS. The potential for interference with flight-essential VHF and satellite communications, Distance Measuring Equipment (DME), Traffic Alert and Collision Avoidance System (TCAS), Air Traffic Control Radio Beacon System (ATCRBS), transponder systems, or flight critical propulsion, flight controls and display systems is not addressed.

3 Spurious Radiated Emissions from CDMA and GSM Wireless Handsets

3.1 Regulatory Limits

In the US, the Federal Communications Commission (FCC) provides guidance for allowable signal emissions from consumer devices. These are published and available on the Internet, in the US Code of Federal Regulations (CFR), Title 47, Telecommunication. Within Title 47, there are numerous Parts and Sections that address the full range of available product types.

FCC Part 22 contains the regulations for Public Mobile Services, and Subpart H provides guidance for Cellular Radiotelephone Service. 47CFR22.917 provides the emission limitations for cellular handsets, with graduated emissions masks depending upon the frequency offset from the unmodulated carrier frequency. In summary, on any frequency removed from the carrier frequency more than 90 kHz, the mean power of emissions must be attenuated below the mean power of the unmodulated carrier (P) by at least 43 + 10logP dB. Thus, for a 1 watt unmodulated carrier frequency, a 47CFR22.917 compliant cellular handset could radiate 0.05 milliwatts (or -13dBm) in any aircraft communication or navigation radio frequency band. It should be noted that 47CFR22.925 specifically prohibits airborne operation of cellular telephones. This regulation applies as soon as the aircraft is no longer touching the ground, and is intended to prevent interaction with multiple cell base stations and possible interference with other calls.

FCC Part 24 contains the regulations for Personal Communications Services. 47CFR24.238 provides the simple emission limit statement in paragraph (a) "On any frequency outside a licensee's frequency block, the power of any emission shall be attenuated below the transmitter power (P) by at least 43+10log(P) dB. Thus again, for a 1 watt unmodulated carrier frequency, a 47CFR22.238 compliant cellular handset could radiate 0.05 milliwatts (or -13dBm) in any aircraft communication or navigation radio frequency band. It should be noted that 47CFR22.925 does NOT apply. 47CFR24.2 lists the other FCC rule parts that are applicable to licensees in the personal communications services, but specifically excludes any reference to Part 22. Thus, there is no FCC prohibition from airborne operation of PCS telephones.

3.2 Measurement Process for Spurious Radiated Emissions

3.2.1 Semi-Anechoic Chamber

The measurement process was based directly upon the RTCA/DO-233 procedure [2], except the DO-233 procedure did not require absorber lining for the shielded enclosure. NASA's semi-anechoic chamber meets normalized site attenuation (NSA) requirements as specified in ANSI C63.4-1992, EN 50147-2, and CISPR16-1993, as well as field uniformity requirements as specified in IEC 61000-4-3. As with the DO-233 procedure, a non-conductive table support was used, 0.8 meters from the conductive floor, with a 1-meter antenna-to-device separation distance. All antenna factor data was verified to be current, and within 1-meter calibration standards specified by SAE ARP-958-1997.

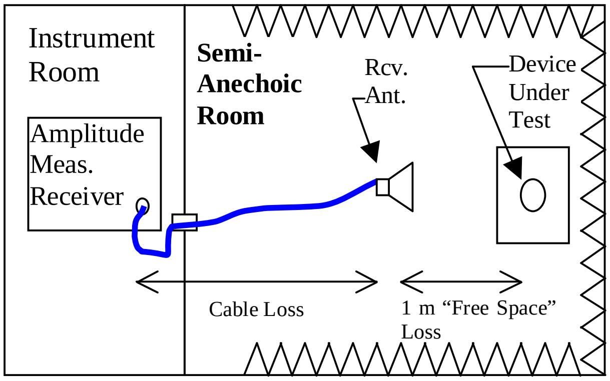

Figure 2: Diagram of Semi-Anechoic Chamber radiated emission measurement setup.

Standard radiated emission measurements collected in open area test sites, shielded rooms, and semi-anechoic chambers produce data in terms of electric field intensity. This is a point of significant concern when applying the data to devices that are not typically used in such controlled environments. The authors of DO-233 recognized this, and proposed that measured field intensity be converted to units of power, by approximating the PED as an isotropic radiator. This was considered conservative because an electrically-large PED could focus more power toward the measurement antenna than elsewhere, thus producing an artificially high measurement result. Ideally, the device should be re-oriented when measured at each frequency, such as to provide maximum power transfer to the measurement antenna at all frequencies. The isotropic approximation is certainly more valid in a semi-anechoic room than the passenger cabin of an airplane, and allows radiated emission data to be more accurately applied to the measured path-loss data between passenger cabin and aircraft radio receiver antenna.

To calculate effective isotropic radiated power (EIRP, in dBm) of a PED, at a given frequency, the following formula was applied to the measured data:

$$P_{PED} = P_{Meas} + \alpha_{RcvPath} + (AF + 2.23) \qquad (3)$$

where:

P_{Meas}= Power measured at amplitude measurement receiver. [dBm]

$\alpha_{RcvPath}$= Cable loss from Rcv. antenna connector to amplitude measurement receiver.

AF = Antenna Factor from Manufacturer relating field intensity at antenna to voltage measured at antenna connector (free-space input relative to 50 Ω output at 1 meter) [dB]

2.23= Factor including conversion from dBμV to dBm (107) at amplitude measurement receiver (assuming 50 ohm impedance) and Antenna Factor conversion from dBμV/m to dBm (-104.77) from isotropic source.

Derivation and documentation of Equation (3) can be found in [11]

3.2.2 Reverberation Chamber

Radiated emission measurements in reverberation chambers produce data in terms of EIRP, so the isotropic radiator approximation is not required. A peak-radiated-power measurement is particularly useful when evaluating the EMI potential of devices that may be used in multiple locations that are electromagnetically complex. This situation is certainly applicable to wireless phones used in aircraft passenger cabins. The measurement process utilized the same amplitude measurement receiver and antennas as those used in the semi-anechoic chamber. NASA LaRC's reverberation chambers have been characterized for field uniformity by the National Institute of Standards and Technology (NIST). Details regarding their performance may be found in [12].

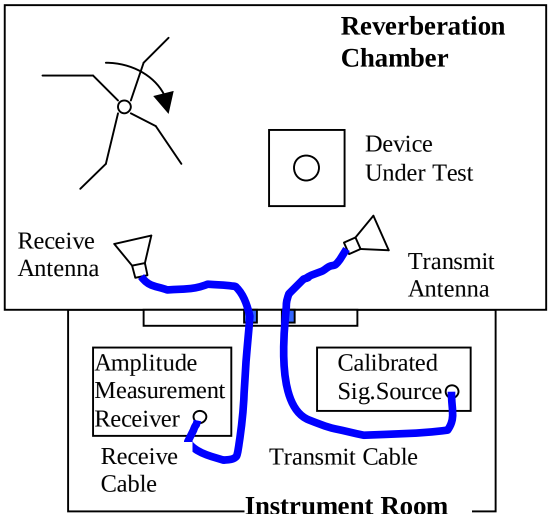

Figure 3: Diagram of Reverberation Chamber radiated emission measurement setup.

The standard formula for measuring PED EIRP (dBm) in a reverberation chamber is:

$$P_{PED} = P_{Meas} + \alpha_{Cbr} + \alpha_{RcvCbl} \qquad (4)$$

where:

P_{Meas} = Power measured at amplitude measurement receiver.

α_{RcvCbl} = Cable loss from Rcv. antenna terminals to amplitude measurement receiver.

α_{Cbr} = Chamber Loss, described below.

α_{Cbr} describes the relationship between the power transmitted into the reverberation chamber and the power coupled out through the receive antenna connector. This definition includes the power lost as the signal travels through the chamber, reflecting off the walls and paddle-wheel, and coupling to and re-radiating from anything else contained within the chamber. It also includes reflection and resistive loss contributed by the receive antenna. It is important to note that α_{Cbr} varies with paddle-wheel position. For the testing described herein, all measurements were obtained with the paddle-wheel rotating continuously. This is often referred to as "mode-stirred" testing. All values in Equation (4) are maximum values obtained over at least one entire paddle-wheel rotation. The paddle wheel should be rotated fast enough to complete at least one rotation during each measurement period, but slow enough for the measurement receiver to complete each frequency sweep over a small fraction of the paddle wheel rotation. The rotation rate should not be a multiple of the frequency sweep time. The typical default for NASA's reverberation chambers is 5 revolutions per minute, and the measurement time is adjusted based upon spectrum analyzer sweep time to provide adequate sampling as to capture the maximum radiated emissions from the device under test. Derivation, documentation and application of Equation (4) can be found in [11]

3.3 Interactive Control of CDMA and GSM Handsets

Measurement of radiated emissions from wireless phones is significantly more complex than from other PEDs. Unlike PDAs, laptop computers, music players, televisions, games and CB/FRS radios, wireless phones require physical-layer interaction with a base station in order to exercise the breadth of their functionality. This interaction allows control of handset transmit parameters likely to influence the spurious radiated emissions from the device. In the laboratory, transmitter control can be accomplished either with base station simulators, proprietary keypad entry codes (supplied by the manufacturer), or a proprietary cable interface that connects between the phone and a programming device.

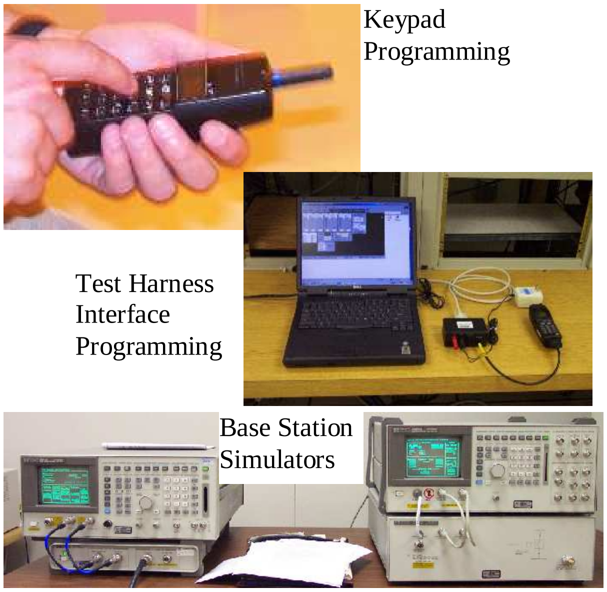

Figure 4: Three Methods of Wireless Handset Control for Radiated Emissions Measurement.

The University of Oklahoma (U of OK) Wireless EMC Center has a partnership with wireless phone manufacturers, service providers, test instrumentation providers, which allows access to these tools. The U of OK Wireless EMC Center had completed preliminary radiated emission measurements for the FAA prior to becoming involved with this effort. NASA LaRC contracted with the U of OK to evaluate and report CDMA and GSM handset physical layer parameters that can influence spurious radiated emissions, and can be controlled in a laboratory. The U of OK Wireless EMC Center provided an operating modes analysis with a standard protocol for spurious radiated emissions testing [13]. The University of Oklahoma provided 8 wireless handsets to support experimental testing. The U of OK Wireless EMC Center provided procedures and instrumentation to control RF Power output level, Puncture Rate, and VOCODER Rate for CDMA handsets. Keypad entry codes were limited in their ability to control puncture rate and VOCODER rate. The CDMA Base Station Simulator could control the handset RF transmit power level by initiating a call in a closed-loop mode, whereby the handset transmit power would automatically increase with a specified decrease in simulator transmit power. The test harness interface could control all three parameters, with RF power control based upon a numerical entry into a proprietary software package running on a personal computer, and issuing commands via a RS232 serial bus. It was necessary to experimentally determine equivalent handset transmit power levels depending upon base station simulator versus test harness interface commands.The U of OK Wireless EMC Center provided procedures and instrumentation to control RF Power output level, Discontinuous Transmit (DTX), Discontinuous Reception (DRX), and Speech CODEC Rate for GSM handsets. Keypad entry codes were limited in their ability to control DRX and Speech CODEC rate. The GSM Base Station Simulator could control the handset RF transmit power level by commanding a "TX Level" parameter, with values from 1 to 15. There was no test harness interface available for the GSM handsets.

Table 1: Programming Methods for 8 Wireless Handsets

Handset Designation	Manufacturer /Model	Programming Type
CDM1	A/1	Keypad
CDM2	A/1	Base Station, Keypad
CDM3	B/1	Base Station
CDM4	B/2	Test Harness
GSM1	C/1	Keypad
GSM2	A/2	Base Station, Keypad
GSM3	A/2	Base Station, Keypad
GSM4	A/2	Base Station, Keypad
AMPS1	D/1	Keypad

3.4 Radiated Emission Measurement Data

Radiated spurious emission data was measured for wireless handsets, as affected by operating mode, programming method, antenna retraction & extension, handling & manipulation, battery charge level, and interactions (intermodulation) with other transmitting handsets. Nearly all data was acquired using the reverberation chamber measurement process to gain advantages of reduced time and lower noise floors. Reverberation versus semi-anechoic chamber measurement comparability was established by operating a particular wireless phone in the same operational mode, when measured in each facility.

3.4.1 Operating Mode Data

A primary objective for the measurement project was to determine which operating modes can be described as "worst-case", in terms of wireless handset spurious radiated emissions. Each handset was operated in extensive combinations of operating modes using available command capability, to gain insight into configurations resulting in highest emissions.

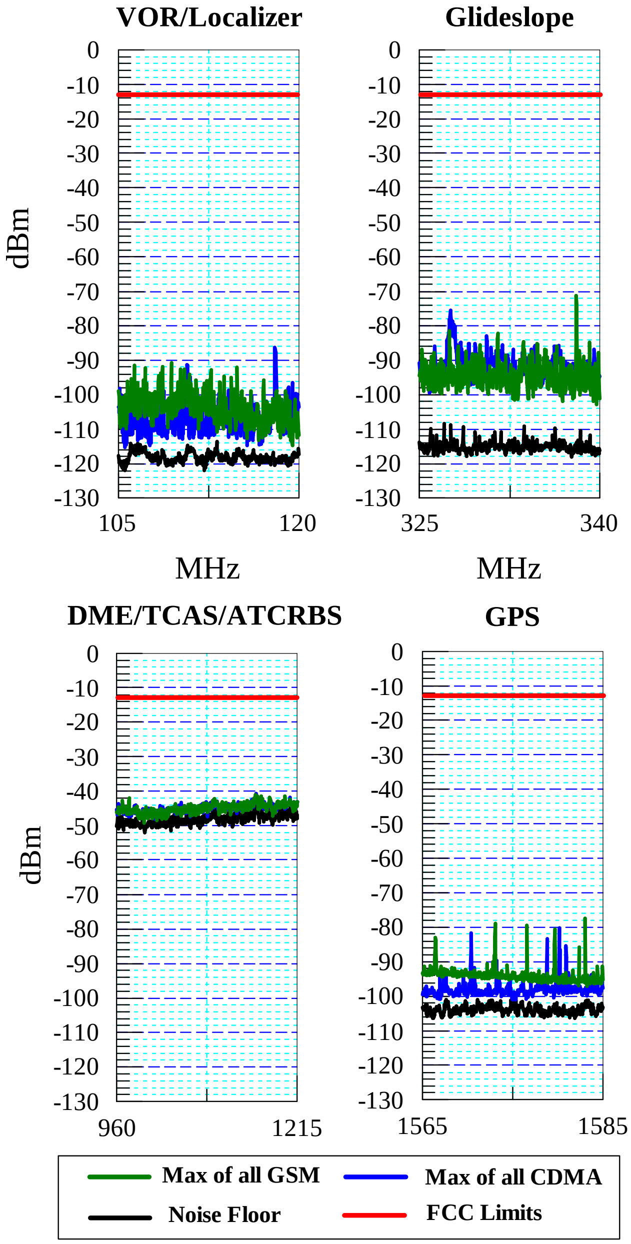

Figure 5: Maximum spurious radiated emissions from all CDMA and GSM wireless handsets operated in all modes. Also shown is the noise floor, and the FCC allowable limits assuming 1 watt transmitter power output.

CDMA handsets were commanded to multiple power output levels, puncture rate settings, and vocoder rate settings. GSM handsets were commanded to multiple power output levels, discontinuous transmit (DTX) and discontinuous receive (DRX), and speech CODEC settings. An exhaustive compilation of radiated emission measurements for all operating modes of each handset is provided in [11]. While the operating mode often resulted in discernable differences in the spurious radiated spectrum, dominant spectral components did not vary appreciably due to mode changes. Figure 5 shows a summary plot of maximum spurious radiated emissions from individual CDMA and GSM wireless handsets operated in all modes as tested at NASA LaRC. Also shown is the noise floor, and the FCC allowable limits assuming 1 watt transmitter power output. Maximum radiated emissions measured during hours of extensive testing in all operational modes on all 8 handsets, resulted in levels far below those allowed by FCC regulations. Operating mode did not appear to result is significant differences in emissions in the aircraft RF navigation frequency bands.

For comparison, each handset was turned ON and OFF repeatedly, for a 120-second measurement duration. The ON-OFF testing did not require any keypad codes, base station interaction or test harness interface. ON-OFF testing data is also included in [11]. Interestingly, repeatedly turning the handset power on-and-off caused the most significant changes in the spurious radiated spectrum, however these changes did not impact the highest emission levels.

3.4.2 Programming Method Data

Section 3.3 describes how the operating modes of CDMA and GSM handsets were controlled via keypad entry codes, base station simulator, and test harness interface. This approach was based upon the assumption that the handsets would respond the same regardless of which control method was used. To validate this assumption, spurious radiated emission data was obtained for two handsets having dual control capability.

CDM2 was the only CDMA handset capable of being operated by both keypad entry code and base station simulator control. Nearly identical spurious radiated emissions were observed for CDM2 handset in the ILS glideslope frequency band. CDM2 emissions were of the same amplitude in the GPS frequency band, but with peaks at different frequencies, it was difficult to resolve whether the differences could be attributed to the different puncture rate settings.

The GSM3 handset was also operated by keypad entry code and base station simulator control. For the VOR/Localizer and Glideslope frequency bands, the handsets clearly radiated 10-15dB higher emission levels when commanded by the base station simulator, versus keypad entry codes. For GPS frequency band, there was no discernable difference between the two techniques.

3.4.3 Phone Handling and Manipulation Data

All spurious radiated emissions measurements discussed so far were obtained with the wireless handset antennas extended (except GSM1, whose antenna did not extend), with the unit placed upon a Styrofoam dielectric support, 80 cm in height, with no objects touching the unit during operation (Free Standing). In practice, however, people need to handle their devices in order to operate them. It is conceivable that specific signals may radiate more or less to the surrounding environment depending upon electromagnetic interaction with the user. Data was collected for the following three operating conditions for each of the 8 handsets, in each of the 4 frequency bands:

a) Handset Free Standing, with Antenna Extended
b) Handset Free Standing, with the Antenna Retracted
c) Handset Manipulated by User for 30 seconds in each of four states (total 120 seconds) with antenna extended. The four states included pushing buttons on the keypad, normal conversation position, holding the handset away from the body, and touching the keypad.

Emission levels tended to increase about 5 to 10 dB for the VOR/Localizer frequency band and tended to decrease about 2 to 5 dB for the GPS frequency band, when manipulating the GSM and CDMA handsets. However, when comparing the levels with the overall worst-case radiated emissions, handling and manipulation only provided about a 3 dB enhancement from all CDMA handsets. The same 3 dB enhancement was roughly true for the GSM handsets, except that the ON-OFF testing spurious emissions exceeded other handling and manipulation cases by up to 10 dB in the VOR/LOC frequency band.

3.4.4 Antenna Retraction and Extension Data

To evaluate the extent to which antenna position influenced spurious radiated emissions in aircraft radio frequency bands, spurious radiated emission data was compared with antennas extended and retracted (with the handsets free-standing upon a Styrofoam support). For the most part, emission variations due to antenna position were only a few dB. Such small variations were considered to be within the expected measurement uncertainty.

Some additional measurements were obtained in the handset transmit frequency bands also (820-960MHz). This data included test cases with the antenna extended versus retracted, with the handset free standing versus next to the operators head. The data is currently being evaluated as a basis for further testing to better understand how to reduce transmitted signal coupling to an operators head.

3.4.5 Battery Charge Level Data

The functionality of the data acquisition software was extended to allow unattended measurement of emissions at specified time intervals. This allowed periodic sampling of handsets configured to transmit continuously until their battery was completely discharged. To accomplish the test, handsets were set to operate with a freshly charged battery at the maximum transmit power setting, and left in the test chamber overnight. During the three-week period of the measurement program, most of the 8 handsets were tested in each of the 4 frequency bands. Data for this test is still in the process of being evaluated, and will be included in a subsequent NASA Technical Publication.

3.4.6 Intermodulation Data

To identify whether signals from multiple handsets could potentially interact to produce additional spurious radiated emissions, all phones were simultaneously set to simultaneously radiate at maximum power in the reverberation chamber. Significant additional spurious radiated emissions occurred. A series of additional tests revealed that nearly any combination of GSM (880-915 MHz) and CDMA or AMPS (824-849 MHz) handsets resulted in intermodulation products, particularly in the DME/ATC/TCAS and GPS frequency bands. An example chart, showing GSM and AMPS handset intermodulation is shown in Figure 6. A much more detailed analysis can be found in [14].

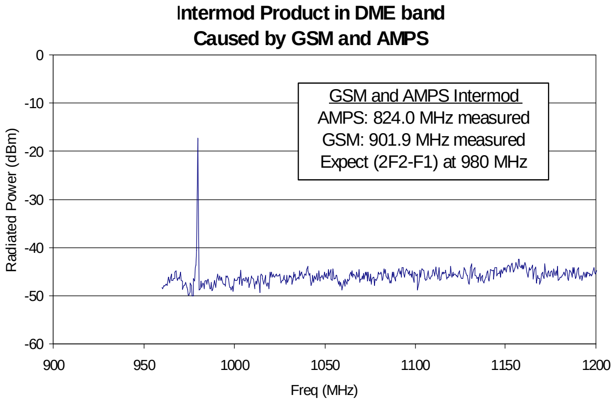

Figure 6: Intermodulation Product in DME/ATC/TCAS Frequency Band caused by GSM combined with AMPS handset signals.

4 Aircraft Interference Path Loss

In order to approximate a PED radiating spurious signals in a particular aircraft radio frequency band, the test setup shown schematically in Figure 7 was described in RTCA/DO233 as a standard technique for assessing the threat to communication and navigation radio receivers. In Figure 7, IPL is defined as the loss between a reference antenna (approximating the PED) and a particular aircraft radio receiver terminal connector. (The aircraft radio needs to be removed to allow connection of the measurement receiver to the aircraft antenna.) This can alternately be described as the loss between a calibrated signal source and measurement receiver, less any test cable losses. In equation form:

$$\begin{aligned} \text{IPL} &= \alpha_{Rad} + \alpha_{AC} \\ &= P_T - \alpha_{TC1} - \alpha_{TC2} - P_R \qquad (5) \end{aligned}$$

In Equation (5),

P_T= RMS power amplitude transmitted by the CW signal source. (dBm)

P_R= RMS power amplitude measured at the test receiver (spectrum analyzer). (dBm)

α_{Rad}= Radiated path loss between the test antenna connector and the aircraft antenna connector. This term includes the characteristic antenna gains and any associated path factors (ie. multipath, separation distance and electric/ magnetic field coupling to, conduction upon, and re-radiation from the surrounding environment nearby). (dB)

α_{AC}= Aircraft cable loss. (dB)

α_{TC1}= Loss of Test Cable #1, between the signal source and reference antenna connector. If an active device, such as a RF amplifier is present, this factor may be negative. (dB)

α_{TC2}= Loss of Test Cable #2, between the aircraft radio receiver rack location and the measurement receiver. If an active device, such as a RF pre-amplifier is present, this factor may be negative. (dB)

Data published in previous reports was compiled and is summarized in Table 2. To perform a statistical risk assessment, it would be best to generate a probability distribution for the IPL to be below a certain value for certain classes of airplanes. Many references do not report any statistical information regarding IPL data, like standard deviation and number of samples.

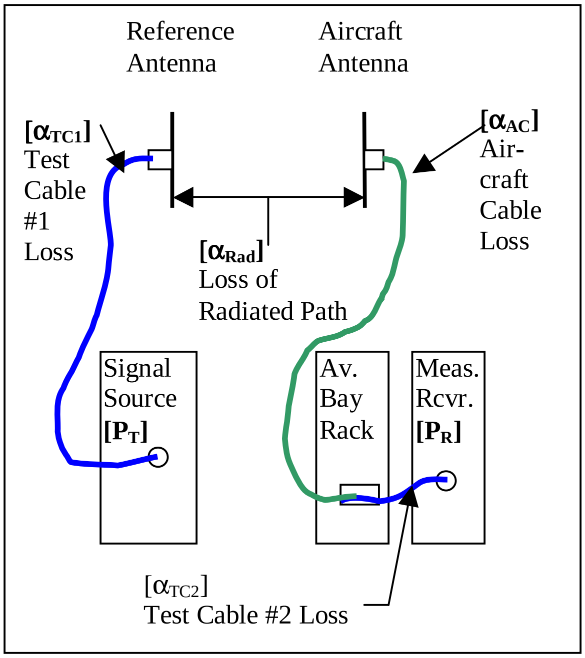

Figure 7: Schematic diagram of IPL measurement variables.

Table 2: Summary of published IPL data for VOR, Localizer, Glideslope and GPS aircraft nav. Systems.

			VOR					LOC					GS					GPS			
Measured Airplane	Min.	Avg.	Std. Dev.	# of Pts.	1m Loss	Min.	Avg.	Std. Dev.	# of Pts.	1m Loss	Min.	Avg.	Std. Dev.	# of Pts.	1m Loss	Min.	Avg.	Std. Dev.	# of Pts.	1m Loss	**Ref.**
B747 (DO-233)	85	105	5			65	94	13			55	86	14								[2]
B747 (EWI/UAL)	76	80	3	8	21	55	61	2	38	28	53	71	8	36	35						[17]
L1011 (DO-233)	70	79	2			61	85	9			64	83	8								[2]
B737 (DO-233)	76	90	5			73	91	9			69	83	5								[2]
MD80 (DO-233)	66	88	9								64	85	11								[2]
DC10 (DO-199)	80	89		20		82	91		10		77	91		24							[1]
B757 (DO-199)	42	49		20		23	45		30		22	38		28							[1]
B757 (DO-233)	50	91	10			52	86	11			58	83	10								[2]
B757 (Delta)	46	66	7	113	16	56	75	10	104	16	59	72	6	106	32						[15]
A320 (DO-233)	65	92	9			49	86	15			65	84	10								[2]
A320 (Aerospatiale)	59	84				54	75				56	70									[2]
B727 (DO-199a)	70	74		6		63	67		6		68	76		12		71	77		12		[1]
B727 (DO-199b)	30	56		86		35	53		86												[1]
B727 (DO-199c)	71	76		6																	[1]
B727 (RTCA SC177)	75	90				72	90				68	83									[2]
CV-580 (Veda/FAA)	45										64					41					[16]
Gulf G4 (DO-233)																82	91	6			[2]
Canadair RJ (Delta/ASA)	58	72	7	28	28	58	72	7	28	28	52	60	3	28	30	43	54	6	28	18	[15]
Emb 120 (Delta/ASA)	42	56	5	22	28	42	56	5	22	28	46	52	2	20	28						[15]
ATR72 (Delta/ASA)	64	72	4	50	24	64	72	4	50	24	58	68	5	53	38						[15]
Column Avg.	62					56					59					59					
Minimum																					

In Table 2, minimum IPL values for each system are highlighted in yellow. It is suspected that the minimum values set by RTCA/DO-199 studies are biased low due to the technique of computing isotropic radiated power from field strength measurements acquired in airplanes. For these measurements, the high multipath environment was likely to have resulted in better coupling than the free-space isotropic approximation would indicate. If not for these cases, the minimum IPL values would clearly be set by smaller, regional aircraft (which is more reasonable). On the other hand, some minimum IPL values are unrealistically high. For example, the variation between minimums for B727 VOR systems is 45dB. A column average of minimum values is highlighted in green. In the absence of adequate data for a probabilistic description of IPL, it was decided to perform an average-of-minimum IPL values for the risk assessment described in this report. This is not a very conservative approach, and it is likely that future assessments of expected IPL will be significantly lower.

Detailed review of the previous reports referenced in Table 2 reveals a number of useful observations and conclusions from previous analyses, which are summarized here:

1. Larger aircraft generally have higher IPL, except for special situations such as multiple floor levels and exit/door seams close to antennas. [1] (Appx A, 1.0a), [15], [17]
2. VHF signals (below 300MHz) do not propagate well through windows, but propagate freely through window and door exits on typical aircraft, presumably because of larger electrical apertures. UHF and L-Band frequencies (300MHz and up) propagate well through aircraft windows, window exits, and door apertures. [15]
3. Close proximity of PED to aircraft antennas tends to be a primary factor for minimum IPL. [1] (Appx A, 1.0b), [15]
4. Window seat locations provide much higher coupling than aisle seat locations. [1] (RTCA No. 238-84/SC156-26), [15].
5. Ground versus in-flight IPL measurements can vary by up to 10dB at a specific measurement location. [1] (Appx. A)
6. At VHF frequencies, opening one of the front aircraft doors was observed to decrease IPL values by about 10 to 20dB. [2] (Sec. 2.4.4.1)
7. Stirring (Reverberation) has little effect when compared to direct path measurements of IPL. [16]

5 Aircraft Radio Receiver Interference Thresholds

A significant part of the threat assessment was to determine the minimum interfering signal power, delivered to the RF connector of each aircraft navigation radio that would be required to cause unacceptable performance. A detailed analysis of aircraft ILS, VOR and GPS interference thresholds based upon ICAO and RTCA reference documents and manufacturer's data was performed. For GPS, the available reference documents are very consistent with one another. For this analysis, the RTCA DO-229B narrow band enroute interference threshold for GPS/WAAS was used (-126.5dBm) [18]. It was found that an enormous degree of variability exists for the ground beacon systems' (VOR, ILS localizer and ILS glideslope) susceptibility thresholds, depending upon the frequency relationship between the desired and interfering signals, and the expected amplitude of the desired signal. Details are provided in [12] and the results are summarized in Table 3, below.

Table 3: Summary of Interference Thresholds (P_{Rcvr_IT}) required to cause unacceptable performance of aircraft navigation radios.

	VOR (dBm)	**LOC (dBm)**	**GS (dBm)**
Reasonable Sensitivity	-93	-86	-76
Reasonable Margin	-13	-26	-26
Reasonable Minimum Threshold (P_{Rcvr_IT})	**-106**	**-112**	**-102**
Minimum Sensitivity	-113	-113	-99
Maximum Margin	-46	-46	-46
Absolute Minimum Threshold (P_{Rcvr_IT})	**-159**	**-159**	**-145**

In Table 3, "Reasonable Minimum" interference threshold was taken to be the RTCA DO-192 [19], DO-195 [20] and DO-196 [21] specified minimum receiver sensitivities, with a

26dB required signal to interference ratio for localizer and glideslope receivers. (Defined as “Type 2” in RTCA DO-233. DO-233 provided data only for the localizer receiver, but the ratio is assumed to be the same for glideslope due to similarities between the two systems.) For VOR, the “Reasonable Minimum” signal to interference ratio was 13 dB, as published in DO-199. “Absolute Minimum” interference threshold was taken as the minimum sensitivity of a known commercial radio receiver, with a 46dB required signal to interference ratio for localizer and glideslope. (Defined as “Type 1” in RTCA DO-233. Again, DO-233 only provided data for the localizer receiver, but the ratio is assumed to be the same for glideslope due to similarities between the two systems.) For VOR, the "Absolute Minimum" signal to interference ratio was measured as 46 dB, published in DO-199.

6 Results and Conclusions: CDMA/GSM Mobile Unit Threat Assessment

The NASA / University of Oklahoma team demonstrated a viable process for measurement of spurious radiated emissions of CDMA and GSM wireless handsets, in both semi-anechoic and reverberation chamber test facilities. The process can easily be extended to measure spurious radiated emissions from all existing and emerging wireless voice and data devices. None of the 4 CDMA and 4 GSM wireless handsets tested would individually be likely to interfere with aircraft VOR, LOC, GLS, or GPS navigation radios. Tables 4 and 5 illustrate safety margins using measurement data.

If a CDMA or GSM wireless handset radiated spurious signals equal to the maximum allowable FCC limits, it would result in LARGE NEGATIVE safety margins, even when considering “reasonable minimum” radio receiver interference thresholds. See Table 6.

Each handset was commanded according to an extensive matrix of operational modes, while spurious radiated emissions were measured. CDMA handsets were commanded to multiple power output levels, puncture rate settings, and vocoder rate settings. GSM handsets were commanded to multiple power output levels, discontinuous transmit (DTX) and discontinuous receive (DRX), and speech CODEC settings. While the operating mode often resulted in discernable differences in the spurious radiated spectrum, dominant spectral components did not vary appreciably due to mode changes. Interestingly, repeatedly turning the handset power on-and-off caused the most significant changes in the spurious radiated spectrum.

Table 4: CDMA (IS-95, 824-849 MHZ) Handset Threat Assessment

	VOR	**LOC**	**GLS**	**GPS**
P_{Rcvr_IT} [dBm] (reasonable min /absolute min)	-106/ -159	-112/ -159	-102/ -145	-126.5
+ IPL (average of fleet minimums) [dB]	62	56	59	59
- P_{PED} (CDMA measured max.) [dBm]	-86	-86	-76	-80
= Safety Margin (reasonable min / absolute min) [dB]	**+42/ -11**	**+30/ -17**	**+33/ -10**	**+12.5**

Table 5: GSM (ETSI GSM 11.22, 880-915 MHz) Handset Threat Assessment

	VOR	**LOC**	**GLS**	**GPS**
P_{Rcvr_IT} [dBm] (reasonable min /absolute min)	-106/ -159	-112/ -159	-102/ -145	-126.5
+ IPL (average of fleet minimums) [dB]	62	56	59	59
- P_{PED} (GSM measured max.) [dBm]	-91	-91	-71	-78
= Safety Margin (reasonable min / absolute min) [dB]	**+47/ -6**	**+35/ -12**	**+28/ -15**	**+10.5**

Table 6: Threat Assessment for Cellular/PCS (FCC 22.917/24.238) Limits

	VOR	**LOC**	**GLS**	**GPS**
P_{Rcvr_IT} [dBm] (reasonable min /absolute min)	-106/ -159	-112 - 159	-102/ -145	-126.5
+ IPL (average of fleet minimums) [dB]	62	56	59	59
- P_{PED} (FCC Limits for 1 Watt Xmitter) [dBm]	-13	-13	-13	-13
= Safety Margin (reasonable min / absolute min) [dB]	**-31/ -84**	**-43/ -90**	**-30/ -73**	**-54.5**

It was demonstrated that intermittent spurious radiated emissions would sometimes increase up to 10 dB when touching the keypad, touching the antenna, or retracting the antenna on the test handsets. However, when compared to the highest emission levels in all operating modes, these manipulations resulted in only a 3 dB increase for the highest emission levels.

It was demonstrated that GPS and DME band emissions occur, due to intermodulation between GSM and other wireless handset types, when the handsets were placed in close proximity to one another. It was identified that other combinations of common passenger transmitters could potentially produce intermodulation products in aircraft communication and navigation radio frequency bands.

It was identified that the FCC does not restrict airborne use of 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 by the FCC (47CFR22.925).

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