

CUMULATIVE INTERFERENCE TO AIRCRAFT RADIOS FROM MULTIPLE PORTABLE ELECTRONIC DEVICES

Truong X. Nguyen, NASA Langley Research Center, Hampton, VA

Abstract

Cumulative interference effects from portable electronic devices (PEDs) located inside a passenger cabin are conservatively estimated for aircraft radio receivers. PEDs' emission powers in an aircraft radio frequency band are first scaled according to their locations' interference path loss (IPL) values, and the results are summed to determine the total interference power. The multiple-equipment-factor (MEF) is determined by normalizing the result against the worst case contribution from a single device. Conservative assumptions were made and MEF calculations were performed for Boeing 737's Localizer, Glide-slope, Traffic Collision Avoidance System, and Very High Frequency Communication radio systems where full-aircraft IPL data were available. The results show MEF for the systems to vary between 10 and 14 dB. The same process was also used on the more popular window/door IPL data, and the comparison show the multiple-equipment-factor results came within one decibel (dB) of each other.

Introduction

In dealing with PED interference with aircraft systems, multiple equipment cumulative effects should be addressed. Aggregated interference signals from the large number of devices on an airplane can be significantly higher than the power from one device.

There are many forms and paths of interference. An important form is when an interference signal enters the receiver through its antenna port, and is commonly referred to as *front-door* interference. *Back-door* interference occurs when signals enter the receiver through its wiring and apertures in the enclosure. Multiple equipment effects are of concern in all cases. In this paper, however, the scope is limited only to front-door

interference, and the measurement method reflects this fact in the process.

Approach

In simplest form, front-door cumulative effects of multiple PEDs are the ratio of cumulative PED interference powers to the interference power from just one device, all measured at receivers' antenna ports.

For non-coherent sources with equal signal strength, it is often assumed that $P'_N = N * P'_I$, where P'_N and P'_I are interference signal power at the receiver for N devices and for one device, respectively. This assumption is often valid for sources that are physically co-located (ideally), or for sources located such that contributions from all sources are nearly equal. It can also lead to an excessively high estimate for an MEF. A more reasonable approach would utilize interference path loss (IPL) measurements. IPL is a propagation loss value between the interference source location in the passenger cabin and the radio receiver's antenna port. Thus, to study the cumulative effects of multiple PEDs on "front-door" interference, aircraft IPL should be factored into the calculations.

This paper utilizes existing measured aircraft IPL data to derive a MEF. The following subsections describe the formulations for calculating MEF. Additional details concerning the topic can be found in [1].

MEF Formulation

To compute the cumulative effects from multiple devices, the spurious emission value for each device is first weighted proportional to its linear (not dB) interference coupling value. The results for all devices are summed, and normalized to the single-PED worst-case contribution to arrive at the cumulative effects. For sources of equal magnitude, the single-PED worst-case contribution is at the location with the lowest IPL value.

The interference coupling value, C_i , is computed from the IPL value at the same source location using:

$$C_i = 10^{-IPL/10} \quad (1)$$

Thus, the maximum power, in watts, coupled from seat n to the receiver is simply:

$$P_{rec}^n = P_{xmit}^n * C_i^n \quad (2)$$

Summing all P_{rec}^n and normalizing to the maximum value, P_{rec}^{max} , MEF for N devices is defined as

$$\begin{aligned} MEF &= \left(\sum_N P_{rec}^n \right) / \left(P_{rec}^n \right)^{max} \quad (3) \\ &= \left(\sum_N P_{xmit}^n * C_i^n \right) / \left(P_{xmit} * C_i \right)^{max} \end{aligned}$$

Note that $\left(P_{xmit} * C_i \right)^{max}$ is the maximum $\left(P_{xmit}^n * C_i^n \right)$ for all N values. For the devices with maximum emission located at the minimum path loss location, $\left(P_{xmit}^n * C_i^n \right)$ becomes $\left(P_{xmit}^{max} * C_i^{max} \right)$

If P_{xmit} is the same for all transmitting sources, it can be normalized out, and (3) becomes:

$$MEF = \sum_N \left(C_i^n / C_i^{max} \right); \quad n=1, \dots, N \quad (4)$$

with $C_i^{max} = \max(C_i^n)$ for all n values (or simply C_i at the minimum IPL location).

Alternatively, defining the normalized coupling factor $\langle C_i^n \rangle$ and the normalized IPL $\langle IPL^n \rangle$ as

$$\langle C_i^n \rangle = C_i^n / C_i^{max}, \text{ and} \quad (5)$$

$$\langle IPL^n \rangle = IPL^n - IPL^{min}, \quad (6)$$

it can be shown that

$$\langle C_i^n \rangle = 10^{-\langle IPL^n \rangle / 10}, \text{ and} \quad (7)$$

$$MEF = \sum_N \langle C_i^n \rangle. \quad (8)$$

MEF is a power ratio. To convert to decibels,

$$MEF_{dB} = 10 \log_{10}(MEF) \quad (9)$$

Assumptions

The following simplifying and conservative assumptions are made concerning interference signals and their summing effects to establish the upperbound:

- There is one device located at each seat.
- All interference signals are of the same form, i.e. continuous-wave (CW), or similarly modulated.
- All devices transmit on the same frequency and the same emission level in the aircraft radio bands (the formulation can be easily modified to include devices having different emissions levels).
- Signals are non-coherent, and their summing effects at the radio receivers are additive in power, not in voltage (a reasonable assumption as the devices are operating independently).
- The worst-case coupling of the vertical and horizontal polarizations is used in the calculation. These two polarizations are typically used in IPL measurement.
- The worst-case IPL in the vicinity of a seat is used for that seat location.

Aircraft Interference Path Loss Measurement

Typical aircraft *minimum* IPL data are insufficient for MEF calculations since they are usually reported as a single value for each system. Full-aircraft IPL data are much more desirable as they include data for many possible PED locations within the cabin. The data are usually measured with the transmitting source located at all the windows and the seat locations, and therefore should also capture the *minimum* IPL value.

Under a recent effort between United Airlines, Eagle Wings Inc., and NASA Langley Research Center, full-aircraft IPL were collected for four systems on B737 airplanes. For each receiver system considered, measurements were conducted with approximately 160 transmit antenna locations on each airplane covering the left or right halves of

the airplanes. In addition, the transmit antennas were in vertical and horizontal polarizations.

References [2] and [3] previously reported the measurement and results for transmitting sources at the window locations. This paper repeats some of the window IPL results for the four systems for which there are full aircraft data. These data provide some insights into field coupling behavior along the length of the aircraft. In addition, full-aircraft IPL results are presented; however, the scope is limited only to details applicable to MEF analysis. The following subsections describe the measurement method and results.

Measurement Method

It is assumed that the interference source is located within the passenger cabin, and the affected systems are aircraft radio receivers. In this case, signals typically radiate through the windows or door seams, propagate along the aircraft body and into the aircraft antennas. The interference signals are then channeled back into the receivers' antenna ports to potentially cause interference if the signals are of sufficient strength.

Figure 1 illustrates typical interference coupling paths. Figure 2 illustrates a possible setup for conducting IPL measurements. This same setup was used for the data reported in [2] and [3].

Figure 2 shows a tracking source provides RF power to the transmit antenna, and a spectrum analyzer is utilized to measure the signal received by the aircraft antenna. The frequency-coupled spectrum analyzer and tracking source pair allows for frequency sweeps, resulting in more thorough measurements and reduced test time. A pair of test cables connect the instruments to the aircraft antenna cable and to the transmit antenna. An amplifier may be needed to increase the signal strength delivered to the transmit antenna, and a pre-amplifier may be used in the receive path near the spectrum analyzer for increased dynamic range. This pre-amplifier (not shown) may be internal to the spectrum analyzer.

IPL is defined to be the ratio, or the difference in dB, between the power radiated from the transmit antenna at location (1) to the power received at location (2) for most systems.

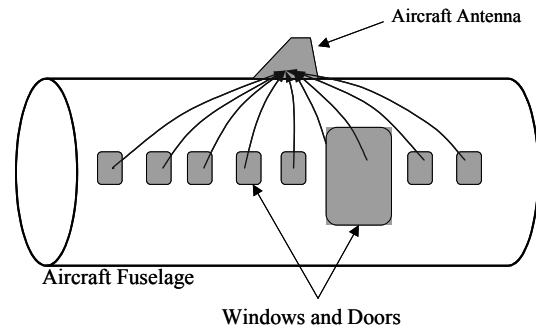


Figure 1. Receiver front-door interference paths

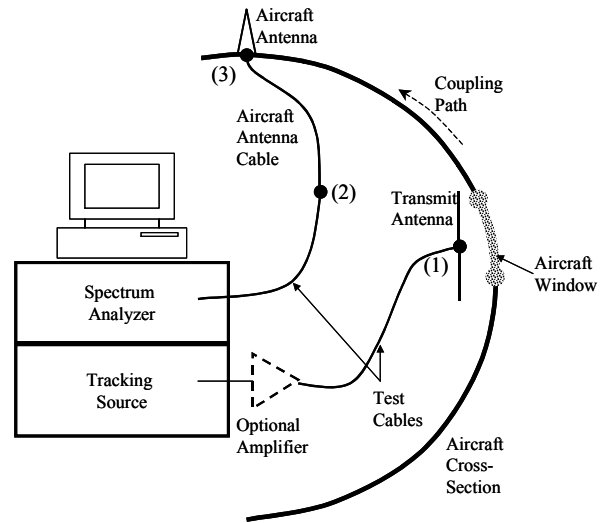


Figure 2. Typical IPL measurement setup

$$IPL = P^T(1) - P^R(2) \quad , \quad (10)$$

where $P^T(1)$ is power *transmitted* at point (1), and $P^R(2)$, is power *received* at points (2).

Figure 3 shows the Boeing 737-200 airplanes on which the IPL data were measured. Figure 4 shows a measurement being conducted with the transmit antennas radiating at windows, and the computer and software used for data acquisition. Instruments and computers were located within the passenger cabin.

The transmit antennas used in this measurement include dipoles for frequencies in the Glide Slope (GS) band and below, and a dual-ridge horn antenna for the frequencies in the TCAS band

and above. No corrections to the IPL data were made to account for the transmit antenna gain. The close proximity between the transmit antenna and nearby internal structures (such as walls, windows and passenger seats) could significantly alter the gain, and the free-space values may not be appropriate. Figure 4 shows examples of the antennas used and their proximity to aircraft seats and aircraft airframe.

For the MEF calculations, however, antenna-gain correction is not necessary since the same factor exists in all measurements. These antenna-gains are removed in the normalization in Equation (3).



Figure 3. Boeing 737-200 aircraft used in IPL measurement



Figure 4. IPL measurement on aircraft

Full-aircraft data were collected with the transmit antenna:

- Positioned at all window locations
- Scanned along door seams
- Positioned in all seat locations, at window level
- Positioned in armrest locations, at window level
- Positioned in the aisle, one per row of seats, at window level
- Include vertical and horizontal polarizations

For the Boeing 737-200, full-aircraft IPL data were collected for four systems, Very High Frequency –Communication (VHF-Com), Localizer (LOC), Glide-Slope (GS) and Traffic Collision Avoidance System (TCAS). Table 1 shows details concerning spectrum and measurement range used.

Table 1. Systems with Full-Aircraft IPL Data

Systems	Aircraft Antenna Location	Meas. Freq. (MHz)	Spectrum (MHz)
VHF-Com	Top	116-138	118 – 137
LOC/VOR	Tail	108-118	108.1–111.95 108-117.95
GS	Nose	325-340	328.6–335.4
TCAS	Top	1080– 1100	1090

Representative IPL Measurement Results

Two-dimensional graphical presentations of some of the available full-aircraft data have been previously reported in [4]. In addition, window IPL data previously reported in [2] and [3] are repeated here in Figures 5 to 8 for the four systems in consideration.

On these plots, IPL data for each receiver system on each aircraft are represented by two traces for vertical and horizontal polarizations of the transmit antennas. The window locations are simply labeled as the n^{th} side window starting from the cockpit. The door locations are labeled as “L1” and “L2” for left side doors; and “EE” for emergency exits. At the doors, a sweep was

typically conducted with the transmit antenna scanning along the door seam. A door sweep at L1 is labeled as “L1 Dr Swp”. The legend shows the aircraft tail numbers associated with the data. The individual data points, representing the measurements at the window and door locations along the length of the aircraft, are connected with straight lines to help resolving separate data sets.

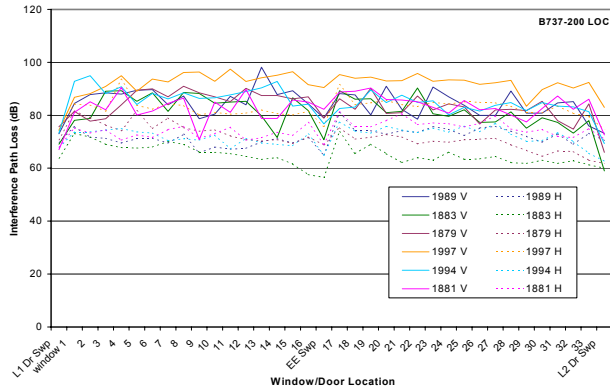


Figure 5. B737-200 LOC/VOR (Tail) IPL

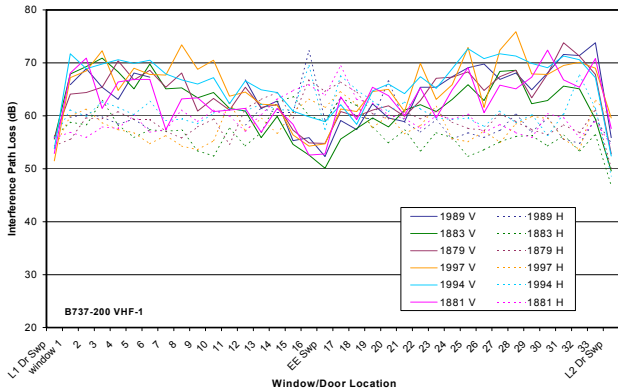


Figure 6. B737-200 VHF-1 Com. IPL

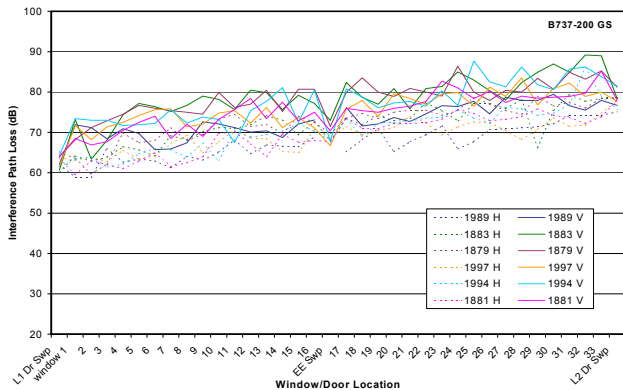


Figure 7. B737-200 GS (nose) IPL

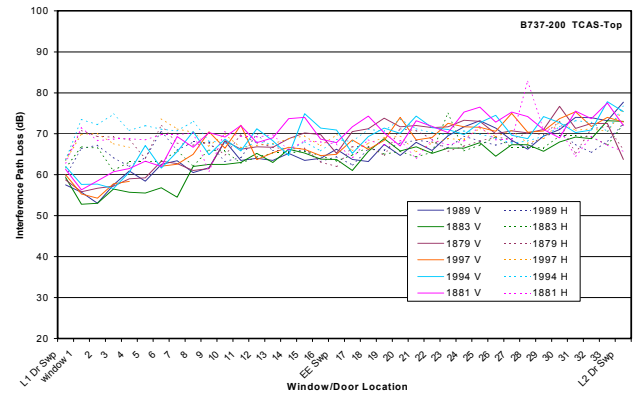


Figure 8. B737-200 TCAS (Top) IPL.

It is seen in Figures 6, 7 and 8 that the lowest IPL is observed when the measurement transmit antenna is closest to the aircraft antenna along the length of the aircraft. In this direction, the VHF-Com antenna is mounted close to the emergency exit, the GS antenna in the nose, and the TCAS antenna near the front on top of the cockpit. The exception to this observation is LOC, where its antenna is mounted at the top of the vertical tail, away from the body of the aircraft. Additional data and findings can be found in [2].

MEF Based on IPL Measurements

As a result of the full-aircraft IPL measurements, there were more data points collected than there were seats. This happened since data were taken at every window (there are more windows than there are number of rows), at every seat, at every armrest position, and also in the aisle. For MEF calculations, the number of data points needs to be reduced to the same number of seats, since it was assumed that there is one PED per seat. To achieve that goal, each seat’s IPL is chosen to be the lowest IPL value (maximum coupling) for the vicinity locations. This action provides a conservative IPL value for each of the seats. Referring to Figure 9, the specifics on the data reduction approach are listed below:

1. Seat-A Data: the IPL value is chosen to be the lowest among the Location Set A. Location Set A includes locations: 1) seat A; and 2) nearest windows and doors. There may be more than one window considered.
2. Seat-B Data: the lowest IPL among the Location Set B. Location Set B includes locations:

1) in middle of seat B; and 2) arm-rest between seats A and B.

3. Seat-C Data: the lowest IPL among the Location Set C. Location Set C includes locations: 1) armrest between seats B and C; 2) in the middle of seat C; and 3) the armrest next to the aisle.

4. Aisle Data: the IPL measured in the center of the aisle.

5. No First Class Seats: While data were collected on an airplane with first class seating (2 seats per row), this section assumes there are three seats per row for ease of data arrangement in the table format. This is reasonable since many configurations do not include first class seats.

6. All measurement points were considered only once. If a window data point was considered in an earlier row, the same data point cannot be considered in any other row.

Data points near a seat were compared and the minimum IPL (maximum coupling) is chosen and assigned for that seat.

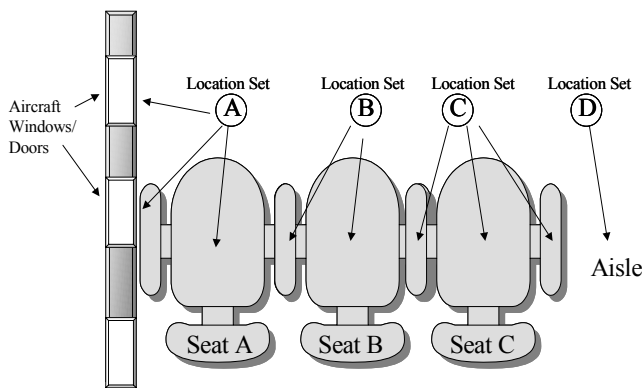


Figure 9. Seat and measurement locations relationship

Results of MEF Calculations

The minimum IPL for the four aircraft systems are reported in Table 2. In addition, the IPL are normalized according to Equation 6, and the results are tabulated in Tables 3 to 6. In these tables, the number of IPL data points is approximately equal to the number of aircraft seats.

The reporting of *normalized* IPL helps to overcome the problem of different definitions of IPL, whether transmit antenna gains are included.

Regardless of the actual IPL definitions, the normalized IPL values in the tables remain the same, while the minimum IPL may be scaled to conform to different definitions.

It is also noted that the full-aircraft IPL can also be computed from the normalized values in Table 3 to 6, the minimum IPL in Table 2, and Equation 6. The transmit antenna gains are also provided in Table 2, which are useful in converting the data between different definitions of IPL where antenna gain may be a factor.

In determining MEF, the data in the Tables 3 to 6 can also be used for interference sources at different locations having different emission levels. In this report, however, only sources having the same emissions level are assumed for simplicity.

Table 2. IPL Normalization Factors (Minimum IPL) for Tables 3 to 6

System	Xmit Ant. Type	Xmit Ant. Gain (dBi)	Minimum IPL value (dB)
LOC/VOR	Dipole	0.9	65
VHF-Com	Dipole	2.1	51.5
TCAS	Dual-Ridge-Horn	7.4	54.3
GS	Dipole	1.9	61.7

Figures 10-13 show the statistical cumulative distribution as the number of locations (seats) is increased. This process involves first sorting then incrementally summing the normalized IPL, starting from the worst case IPL. Equations 8 and 9 are used on the incremental sums. Note that the numbers of seats/windows are for both sides of the aircraft for the purpose of calculating MEF. Actual number of data points measured is only half if performed on only one side.

Table 3. LOC/VOR (Tail) Normalized IPL

Row	Seat-A	Seat-B	Seat-C	Aisle
1	4.8	16	14.2	15.5
2	4.5	17.7	16.5	17.5
3	6.2	19.2	18.3	17.7
4	4.5	17.2	15.3	16.7
5	0.8	11.8	13.5	13.2
6	2.2	8	13.5	17.5
7	5	13.7	14.3	16
8	6.2	12.2	14	14.8
9	4.5	9.8	13.5	13
10	6.3	11.5	15	14.2
11	0	17.8	17	16
12	9.3	15.7	15.7	15.7
13	7.8	20.7	17.2	17
14	9.2	17.2	16.8	18.8
15	8.5	18.3	14	16.7
16	7.3	15.5	15.2	15.5
17	4.8	10	11	15.5
18	4	11.5	12.8	11.1

Table 4. VHF-Com Normalized IPL

Row	Seat-A	Seat-B	Seat-C	Aisle
1	0	13.2	11.8	10
2	5.9	15.7	13.6	16.7
3	3.2	16.3	13.3	12.2
4	2.8	16.8	13.9	15.4
5	2.1	15.9	12.8	12.1
6	5.7	13.7	11.9	13
7	8	14.4	12	11.1
8	4.9	10.8	13	15.4
9	2.8	9.5	9.8	13.8
10	3.2	14.9	10.7	12.5
11	9.3	13.5	10.8	11.2
12	6.2	14	14	12.4
13	5.1	12.9	11.7	15.9
14	6.7	15.3	13.1	17.7
15	3.6	13.2	9.9	14.3
16	5.7	15.1	14.1	15.7
17	3.5	16.6	13.8	16.8
18	8.4	15.2	13.6	13.5
19	4.2	12.1	12.7	16.7
20	2.1	10.3	6.2	13.3
21	8.1	9.9	6.1	9.6

Table 5. GS (Nose) Normalized IPL

Row	Seat-A	Seat-B	Seat-C	Aisle
1	0	4	8.7	4.1
2	1	3.1	4.3	6.6
3	1.6	6.8	6	6.3
4	5.6	7.2	5	5.9
5	3.2	5.3	5.8	7.2
6	6.9	6.6	8.1	8.9
7	5.3	7.4	6.7	
8	3.3	7	9.2	14.5
9	5	10.7	9	6.8
10	9.8	7.2	7.6	8.4
11	6.3	9.3	6.3	10.3
12	8.6	11.2	6.9	9.7
13	12.3	11.1	11	12.2
14	6.2	9.9	11.5	15.7
15	9.7	11.9	13.5	14.3
16	9.9	11.3	12.1	12.9
17	6.5	15.8	12	14.3
18	9	12.1	13.2	16.8
19	9.8	12	15.2	13.9
20	10.1	15.3	14.9	14.5
21	13	14.9	14.7	15.3

Table 6. TCAS (Top) Normalized IPL

Row	Seat-A	Seat-B	Seat-C	Aisle
1	1	11	13.2	15.4
2	0	9	9.7	12.8
3	7.8	10.3	8.8	14.6
4	8.3	13.1	13.9	13.8
5	12.2	12.9	11.4	19.2
6	9.4	13.6	11.8	17
7	11.1	14.7	13.6	14.9
8	12.4	14.3	13.4	16.1
9	9.5	13.6	13	16.3
10	10.4	13.6	16.2	15.8
11	10.7	13.3	14.8	19.4
12	11.9	14.8	15.7	18
13	12.7	16.3	16.3	13.8
14	11.3	16.3	15.1	17.7
15	13.5	11.3	17.2	18.8
16	14.4	17.3	16.9	19.9
17	15	16.3	19.2	23
18	13.4	16.5	18	16.1
19	14.6	16.4	17	17.5
20	16.6	19.4	20.2	21.1
21	16.9	16.3	19.7	21.2
22	14.8	18.6	17.1	20.3

In addition, Figures 10 to 13 also show the MEF computed using only the window/door IPL data for the same aircraft. The window/door IPL data, previously shown in Figures 5 to 8, were measured with the transmit antennas located near aircraft windows, or scanning along door seams. It is suspected that there are possible relationships between the MEF using the seats data and the MEF using only the window data. After all, interference signals are assumed to pass through window/door-seams as they propagate to aircraft receiver antennas.

The comparisons show that the MEF calculated using seat-IPL data and window-IPL data are within one dB of one another.

While there are significantly higher numbers of seats than windows, the similar MEF values can be explained: 1) There are more windows than number of rows of seats; and 2) Coupling data at the windows are significantly higher than the same data for the inside seats.

It is also of interest to determine the incremental effects of the seat locations. Using seat-A as the base line, Tables 7 to 10 compute the incremental effects as all seat-B data and all seat-C data are added. Incremental effects are also shown as the aisle data are added. This inclusion of the aisle data simulates the effect of adding another seat, and is relevant in simulating larger airplane with higher number of seats. In this case the aisle data are counted only once per row, rather than doubled as the seat data.

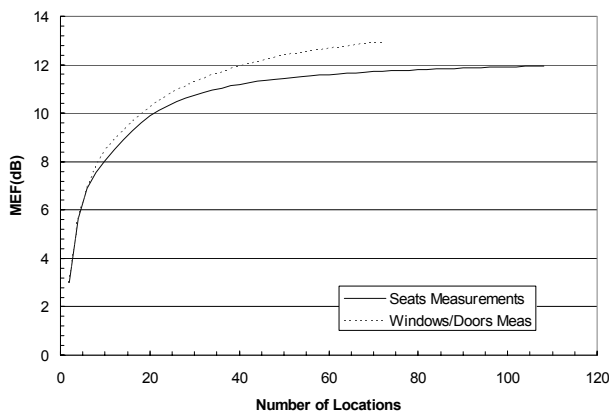


Figure 10. MEF for LOC

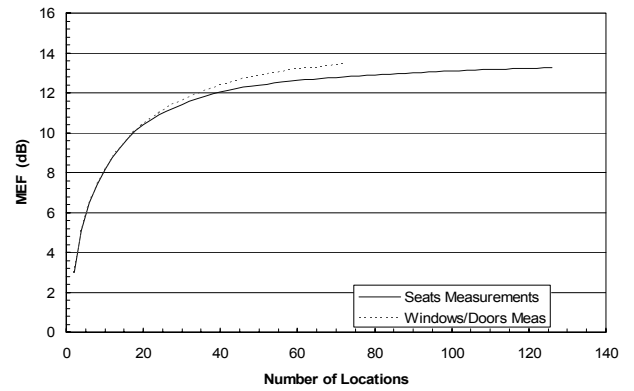


Figure 11. MEF for VHF-Com

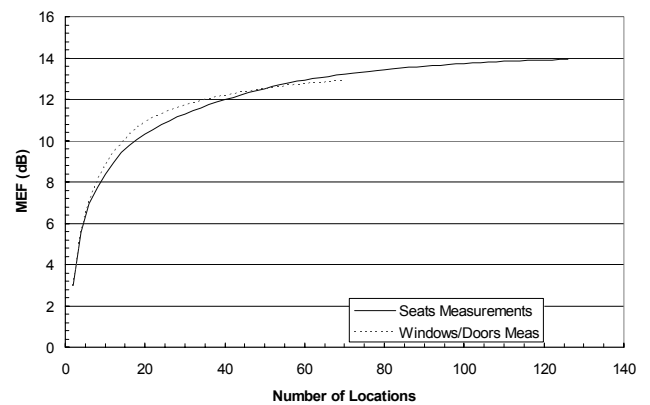


Figure 12. MEF for GS

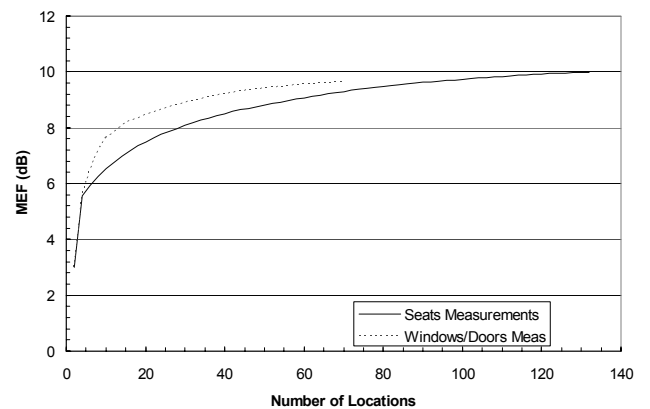


Figure 13. MEF for TCAS

As expected, the effects on MEF decrease as the seats are further inward from the windows. The addition of aisle data implies that each additional seat column only adds no more than 0.4 dB to the total MEF, with decreasing effects further

inside. For large airplane, this implies that only outside seats should be considered, and that further inside seats contribute little to the overall MEF.

Table 7. Incremental Effects on MEF due to Additional Seats – LOC/VOR

Seat Locations Included	MEF (dB)	Incremental Effects (dB)	No. of Locations
Seat-A	11.02	0	36
Seat-A and Seat-B	11.57	0.55	72
Seat-A, Seat-B and Seat-C	11.94	0.37	108
Seat-A, Seat-B, Seat-C and Ailse	12.09	0.15	126
Windows/ Doors Only	12.90		72

Table 8. Incremental Effects on MEF due to Additional Seats – VHF-Com

Seat Locations Included	MEF (dB)	Incremental Effects (dB)	No. of Locations
Seat-A	12.02	0	42
Seat-A and Seat-B	12.54	0.52	84
Seat-A and Seat-B and Seat-C	13.26	0.72	126
Seat-A and Seat-B and Seat-C and Ailse	13.46	0.2	147
Windows/ Doors Only	13.41		72

Table 9. Incremental Effects on MEF due to Additional Seats – GS

Seat Locations Included	MEF (dB)	Incremental Effects (dB)	No. of Locations
Seat-A	10.87	0	42
Seat-A and Seat-B	12.72	1.85	84
Seat-A and Seat-B and Seat-C	13.93	1.21	126
Seat-A and Seat-B and Seat-C and Ailse	14.33	0.4	146
Windows/ Doors Only (All)	12.9		70

Table 10. Incremental Effects on MEF due to Additional Seats – TCAS

Seat Locations Included	MEF (dB)	Incremental Effects (dB)	No. of Locations
Seat-A	8.02	0	44
Seat-A and Seat-B	9.15	1.13	88
Seat-A and Seat-B and Seat-C	9.98	0.83	132
Seat-A and Seat-B and Seat-C and Ailse	10.19	0.21	154
Windows/ Doors Only (All)	9.64		70

Observations

Several observations can be made from the data:

- MEF determined using the windows-only IPL data are within one dB of the MEF determined using full-aircraft seat data. This is significant in that only window IPLs are needed for the purpose of estimating the MEF. Window IPL data are readily available, while full-aircraft data are more difficult and expensive to collect, especially for large aircraft.
- The cumulative distribution curves can help in estimating the minimum number of measurements to make for the purpose of MEF calculations.
- The conservative estimates of the bounds for MEF for the systems measured are between 10 dB and 14 dB, depending on systems.
- The additional seat effects on the MEF diminish rapidly as the seat locations moved away from windows/doors. At the worst case, the addition of seat-B contributes only 2 dB to the MEF. Seat-C and aisle (simulating another column of seats) contribute even less.

Conclusions

An approach was developed to provide an estimate of the reasonable bound on the front-door interference effects of multiple devices in the passenger cabin. Applications on real aircraft path

loss data resulted in a multiple equipment factor of 10-14 dB for the four systems. Extension of the work is desired to include more aircraft systems and types.

Acknowledgements

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