Safety Evaluation of Bluetooth Class ISM Band Transmitters on board Commercial Aircraft

Revision 2
December 28, 2000

Mobile Architecture Lab
Technology & Research Labs

By:

Jeffrey L. Schiffer
Alan E. Waltho

Acknowledgements

The authors of this report gratefully acknowledge the support and valuable knowledge of aircraft systems provided by Mr. A (Bud) Cerino, Mr. Keith Trundle and Mr. Jens Lehne. Without their immense contribution the tests and analyses contained in this report would not have been possible.

Safety Evaluation of Bluetooth Class ISM Band Transmitters on board Commercial Aircraft

Summary

Bluetooth is a low power communications device operating in the ISM frequency band between 2.4 and 2.485 GHz. It will be incorporated into many classes of Personal Electronic Devices (PEDs) and in such form may be carried on board aircraft by passengers with the expectation of being able to use the device while in flight. Unlike the wide range of Personal Electronics Devices currently allowed to be used on aircraft during flight Bluetooth is classified as an intentional radiator. It is therefore required by the recommendations in RTCA report DO 233 to be tested to determine that it is safe for use.

This report will describe the test methods used and will show the results obtained from such tests demonstrating that Bluetooth is safe for use in flight. Furthermore, by comparing our test results with those contained in the RTCA report DO233, it will demonstrate that the spurious emissions from Bluetooth devices are significantly lower than those of existing PEDs within which the Bluetooth communications module will be installed. Therefore Bluetooth devices will not degrade the safe use of the PEDs themselves.

Measurements of path loss to external antenna from within the passenger cabin confirm the trend shown in the RTCA report DO 233 in which the propagation loss increases with frequency. Other tests on a large sample of candidate antennas have confirmed that the Bluetooth antennas are resonant at, or close to, 2.45 GHz. At the frequencies used by aircraft systems the Bluetooth antenna is very inefficient and results in a minimum of 30dB, and typically 40 to 50 dB, suppression of spurious emission products. These results were confirmed through the measurement of the Bluetooth spurious emissions.

Applying these results within the RTCA analysis methodology shows that the worst-case interference from Bluetooth devices to the VHF communications and navigation systems used by all aircraft using FAA approved VHF navigation and communications equipment is some 20 to 40 dB below the interference threshold for these systems. For the high sensitivity UHF systems, TCAS, GPS and Satcom, the Bluetooth signal is just below the interference threshold; but, considering the signal design of Bluetooth and the signal processing of these systems, the effective safety margin is more than adequate to prevent any disturbance to those systems.

The theoretical predictions from the RTCA analysis methodology were confirmed through (1) the use of empirical EMI testing with the Bluetooth Signal boosted to 1 watt, well above the level of Bluetooth radiators, and (2) the additional testing with a swept frequency CW signal also emitted at a power level of 1 watt. During these tests, the antenna of the Bluetooth and CW source were placed in close proximity to the aircraft systems and cables.

Tests were conducted on a B747, the B727 ground based test aircraft at the FAA Technical Center in Atlantic City and a Gulfstream V and to investigate the in-aircraft propagation characteristics in the frequency band 2.4 to 2.5 GHz. These wide body, narrow body and business size aircraft represent the range of propagation conditions that can be expected inside aircraft and, as there is a wide safety margin between the intended emissions from Bluetooth and the threshold of susceptibility of aircraft systems, it is reasonable to extrapolate the propagation results to other aircraft.

The propagation measurements were then used to assess the viability of this frequency band to support in-aircraft services including RFID tags and wireless communications services based on the use of the proposed open communications standard known as Bluetooth.

The results of test measurements strongly support the viability of using the frequency band 2.4 to 2.5 GHz for in–aircraft services. The propagation is shown to exhibit strong multipath components throughout the main passenger cabin. These multipath components facilitate communications even when seats, overhead luggage bins and even major obstructions such as the galley or the door to the flight deck block the direct path. Furthermore, when averaged over the frequency band, the propagation loss varies little with the polarization of the antennas

As a result of the multipath propagation deep nulls do exist at a number of spot frequencies. These nulls are very much dependent on the path geometry and could cause communications failures for systems operating on a single fixed frequency. This could be overcome by a small change in the antenna location or alternatively through the use of a diversity antenna system. For systems such as Bluetooth, the frequency-hopping mode allows communications to be supported over typically more than 80% of the band and exhibits the required diversity to support reliable communications.

Within the checked luggage compartments, propagation conditions are essentially identical to the main cabin and would clearly support the use of ground-based search for ID tags from the doorway to the baggage hold. Propagation to the checked luggage compartments from the passenger cabin is also supported, although the path loss is increased by approximately 15 dB. This would allow in flight verification of checked baggage ID tags.

For further information refer to report **"2.4 GHz Radio Propagation within Commercial Transport Aircraft."**

Conclusions

When ground-testing aircraft for interference from Bluetooth devices operated at high power levels and in worst-case locations inside the aircraft, empirical testing on both large and small aircraft has not indicated any cases of interference to the aircraft systems. Detailed analysis of the emission levels, propagation losses and aircraft system vulnerability to electromagnetic interference show that the intentional emissions and the spurious emissions from Bluetooth devices are at levels that are too low to cause interference to aircraft systems. The analyses therefore support the ground-based empirical tests and confirm that the Bluetooth device by itself does not cause interference and can therefore be considered safe for use in aircraft while in flight.

It is noted, however, that Bluetooth is designed to be incorporated into other electronic devices rather than being used as a stand-alone device. The testing of Bluetooth emission levels show that these do not degrade the emission levels of the electronic devices into which Bluetooth is likely to be installed. Based on all the testing conducted, this report concludes that Bluetooth is safe for aircraft use within other electronic devices approved for use on aircraft. This includes Laptop computers and other PEDs classed as non-intentional radiators.

Warning: Before Bluetooth is used in other electronic devices classed as intentional radiators; the intentional radiators themselves must first be shown to be safe for aircraft use.

Recommendations

It is recommended that the current policies that apply to the use of Personal Electronic Devices (PEDs), as recommended in RTCA Report DO 233, be modified to reflect the safe use of PEDs incorporating Bluetooth. It is proposed that the RTCA recommendations be revised as follows for PEDs incorporating Bluetooth devices:

1. The FAA should modify FAR 91.21 Portable Electronic Devices so that:

   a. The use of any PED, with or without Bluetooth, is prohibited in aircraft during any critical phase of flight. (The intent is that the same use prohibition that applies to any PED during all critical phases of flight also applies to Bluetooth, an intentional emitter, but would allow the use of PEDs with or without Bluetooth during non-critical phases of flight.)

   b. The use of any PED which has the capability to intentionally transmit electromagnetic energy other than that emitted by Bluetooth is prohibited in aircraft at all times unless testing has been conducted to ascertain its safe use. Note: such testing has been conducted with respect to Bluetooth and it has been determined that it is safe for aircraft use**.** Notwithstanding this fact, the use prohibition during any critical phase of flight still applies.

TABLE OF CONTENTS

Safety of Bluetooth Class ISM Band Transmitters on board Commercial Aircraft

1 Introduction

Bluetooth is a low power communications device operating in the ISM frequency band between 2.4 and 2.485 GHz. It is widely expected to be incorporated into many classes of Personal Electronic Devices (PEDs) and in such form may be carried on board aircraft by passengers with the expectation of being able to use the device while in flight. Unlike the wide range of Personal Electronics Devices currently allowed to be used on aircraft during flight, Bluetooth is classed as an intentional radiator. It is therefore required by the recommendations in RTCA report DO 233 to be tested to determine that it is safe for use onboard aircraft, see recommendation 1 b of DO 233.

This report will describe the test methods used, and the results obtained from ground tests will be used to demonstrate that Bluetooth is safe for use in flight. Furthermore, by comparing results with those contained in the RTCA report DO233, it will demonstrate that the spurious emissions from Bluetooth are significantly lower than those of the PEDs within which the Bluetooth communications module will be installed. Therefore it will not degrade the safe use of the PEDs themselves.

The Bluetooth RF design was developed for short range, near line-of-sight propagation in which interference limited conditions are assumed to apply. The test results will also show that the Bluetooth waveform will work satisfactorily in the aircraft environment using the proposed antennas with only modest degradation due to multipath fading. As such the Bluetooth communications device could find significant usage by airline flight crews as well as by passengers.

2 Background

As an intentional radiator, it is necessary to show that there is no harmful interference to aircraft systems before Bluetooth devices can be approved for use on aircraft.

Harmful interference is defined by the ITU radio Regulation No 163 as follows:

> **"Harmful Interference: interference which endangers the functioning of a radio navigation service or of other safety services or seriously degrades, obstructs, or repeatedly interrupts a radio communications service operating in accordance with these regulations"**.

Empirical evidence of interference from low power devices such as Bluetooth are not easy to observe. For this reason any empirical test aimed at demonstrating a lack of interference to aircraft systems must be supported by analysis and measurement data that verify that the probability of interference is exceedingly low or non-existent. This is achieved through the controlled and repeatable characterization of:-

the worst-case propagation losses within an aircraft,
the worst-case emissions from Bluetooth and,

the worst-case susceptibility of the aircraft systems

From the above the available interference margin, as required to avoid "harmful interference", is calculated on an extreme worst-case basis.

As an intentional radiator it is necessary to consider two classes of emissions and the various susceptibility modes by which these emissions could possibly affect the electronic systems of the aircraft.

First are the relatively high level intentional emissions. It will be shown that the intentional emissions from Bluetooth fall at precisely controlled frequencies and hence do not cause co-channel interference. It will also be seen that they are too low to cause interference to the aircraft systems via other susceptibility modes such as blocking, desensitization and receiver spurious responses.

Second are the low power spurious emissions, which can occur on almost any frequency, and have the potential to cause co-channel interference at the input of the aircraft's receiver systems. The low power spurious emissions are similar to those generated by any electrical device, including the aircraft's electronic and electrical systems and PEDs. RTCA Report DO 233 showed that co-channel interference affects can occur but, for PEDs, the probability is very low. It will be shown that the low power spurious emissions from Bluetooth devices, which are much lower than the worst-case emissions from PEDs, are sufficiently low that they will not create co-channel interference to aircraft electronics even when in the worst-case locations. From the analysis of the intentional emissions it is obvious that the low power levels of spurious emissions will not cause frequency independent interference effects such as blocking and desensitization.

.

3 Objectives

As part of the overall program, the following objectives were set:

- To assess the statistical variance in path loss between candidate Bluetooth operating locations to aircraft systems.
- To demonstrate that on the sample aircraft tested that there is a wide safety margin between the intended emissions from Bluetooth and the threshold of susceptibility of aircraft systems and that it is therefore reasonable to extrapolate the results to other aircraft.
- To demonstrate that cumulative affect of multiple Bluetooth devices does not cause interference to aircraft systems.
- To assess the statistical variance in path loss between candidate Bluetooth operating locations within large and medium size commercial aircraft and business jets.
- To assess the statistical variance in the fading bandwidth.
- To show that the safety margins are independent of the antenna polarization.

4 Approach

To permit the demonstration, and supporting analysis, that Bluetooth devices do not cause harmful interference it was determined that testing should be conducted on representative aircraft with the objective of acquiring sufficient data to support the analysis of the risk of harmful interference. This involved the following testing and data collection:

- Measuring the emissions from Bluetooth systems in a manner to allow direct comparison with other PEDs.

- Measuring and recording the path loss factor from within the cabin to the various aircraft systems on a variety of in-service commercial aircraft over a wide frequency band. In the band 50 to 1200 MHz it was considered appropriate to reuse the data reported in DO233. The Bluetooth data collection was therefore focused in the ISM frequency band 2.4 to 2.5 GHz.
- Determine, through measurement or previously documented test results, the susceptibility of avionics equipment to various modes of interference, and

- Demonstrate that high signal levels from Bluetooth, and comparable level swept CW signals, do not cause observable interference to aircraft systems.

To the extent possible, the approach used is the same as adopted in the RTCA investigation and reported in RTCA document DO 233, Portable Electronic Devices Carried On Board Aircraft. The approach considers the measured emissions from the Bluetooth devices, the worst-case propagation losses from inside the aircraft to the aircraft's antenna systems and the lowest level of desired signals received from ground based communications and navigation systems. From these various factors the worst-case interference margin is calculated. This approach allows the safety margin to be calculated and extended to other aircraft types based on easily repeated measurement data. However, it also extends the methodology to include a more empirical EMI survey of the aircraft's systems when operating in the presence of a high power Bluetooth and swept frequency CW signal.

4.1 Aircraft Measurement Methodology

The measurement methodology is divided into three segments:

a) Quantitative measurement of path loss between Bluetooth devices at various locations throughout the cabin
b) Quantitative measurement of path loss between Bluetooth devices and aircraft systems,
c) Aircraft safety demonstration

4.1.1 Measurement of path loss between Bluetooth devices

4.1.1.1 Test Equipment Used

- Spectrum Analyzer
- Power Amplifier
- Tracking Generator
- Qty 2 sleeve dipole antennas cut to center frequency of 2.45 GHz
- 10 meter lengths of double screened flexible coaxial cable with matching connectors for Tracking Generator, Spectrum analyzer and antennas

4.1.1.2 Calibration

(a) Connect spectrum analyzer input to tracking generator output via two lengths of 10 meter cable.
(b) Set spectrum analyzer to center frequency 2.45 GHz and frequency span of 100 MHz.
(c) Set tracking generator to maximum output typically +10 dBm
(d) Self calibrate spectrum analyzer to correct for cable losses or record response over the full frequency span

4.1.1.3 Seat to seat aircraft path losses

(e) Inside of the aircraft place one horizontally aligned antenna on the chair back table of the port side window seat. Place the second antenna on the chair back table of each seat in turn from the adjacent seat to the starboard window seat using the same row as the first antenna. At each location record the amplitude response over the 100 MHz frequency span.
(f) Repeat (g) with both antennas vertically aligned.
(g) Repeat (g) with one antenna vertically aligned and the other horizontally aligned
(h) Repeat (g) (h) and (i) with the second antenna one row back
(i) Repeat (g) (h) and (i) with the second antenna three rows back
(j) Repeat (g) (h) and (i) with the second antenna ten rows back
(k) Repeat (g) (h) and (i) with the second antenna at greatest range

4.1.1.4 Seat to luggage path losses(FAA B727 Aircraft only)

(l) Repeat (g) (h) and (i) with the second antenna in the overhead storage bin immediately above the transmitting antenna.
(m) Repeat (g) (h) and (i) with the second antenna located a various positions within the cargo bay.

4.2 Measurement of path loss between Bluetooth & aircraft systems

This test procedure defines the test equipment, test conditions, test locations, test set up, test monitoring and reporting form applicable to the testing of in service aircraft as used by the RTCA but amended to reflect the frequency band of Bluetooth.

4.2.1 Test Procedure

Measurements were made with all three antenna orientations each measurement being made from multiple test stations

Step by step test procedure:

Step 1	Remove aircraft receiver of the system for which path loss is to be measured.
Step 2	Set up test equipment in close proximity to the receiver of the system for which path loss is to be measured. Connect spectrum analyzer input to the cable from the aircraft's antenna in place of the receiver that has been removed.
Step 3	Connect tracking generator to dipole antenna and set tracking generator level to +0 dBm.
Step 4	Set spectrum analyzer as follows; - Freq. scan, Start 2400 MHz. Stop 2500 MHz - Resolution bandwidth, 10 kHz - Sweep duration, 10 sec - Reference level, -30 dBm
Step 5	Set spectrum analyzer to single sweep and erase trace. Trigger single sweep and record trace. Record trace number on the report form.
Step 6	Place antenna at the test locations station. Set spectrum analyzer to single sweep and erase trace. Trigger single sweep and record trace. Record trace number and seat numbers against the system orientation and test location on the report form.
Step 7	Repeat step 5 and 6 for all test locations and antenna orientations.
Step 8	Disconnect victim system antenna lead from spectrum analyzer and replace receiver.
Step 9	Test 1 through 8 were repeated for as many systems as time permitted, typically not less than the six systems considered to be the most susceptible to interference from Bluetooth.

4.2.2 Test Locations

The test locations were selected to be representative of locations in which passengers would most likely operate Bluetooth systems while also giving a low path loss to the interference susceptible antenna. These were considered to be:

- seats close to the emergency doors (locations 1&2)
- seats close to the flight deck (location 3),
- seats close to the main cabin doors (location 4),
- seats close to the interference susceptible antenna (location 5), and
- seats close to the rear bulkhead (location 6) Gulfstream only.

4.3 Aircraft Safety Demonstration

4.3.1 Objectives

To demonstrate that under high signal level conditions and with multiple active devices the cumulative signal from multiple Bluetooth devices does not cause interference to aircraft systems.

4.3.2 Test Equipment Used

- Laptop PC with Bluetooth driver (EMI emission measurements only)
- Palm Pilot with Bluetooth Driver
- Bluetooth device with ceramic antenna
- Power Amplifier
- Tracking Generator
- Sleeve dipole antennas cut to center frequency of 2.45 GHz

4.3.3 General test set up

Multiple Bluetooth devices were set to operate with 6 piconets each operating at a duty cycle of 75% or greater. This was achieved through the use of two devices per piconet each operating at a high throughput.

The devices were distributed throughout the aircraft with 50% of devices located in the forward cabin where they were closest to the aircraft's antennas and electronics. The distribution ensured a high degree of physical overlap between piconets.

Tests were conducted at power level of 0 dBm into a sleeve dipole with a gain of unity. As a further test one piconet was operated at +30 dBm.

Pico nets were operated on a non-synchronous basis so that frequency collisions between nets occurred randomly.

Aircraft tests were conducted while the aircraft was receiving weak signal levels applicable to each of the aircraft's communication and navigation systems. When available field test equipment was used to generate the test signals for the aircraft's communications. Otherwise aircraft receivers were tuned to a distant station for which the signal level was just above the minimum useable.

For the high power tests, test locations were selected to be worst-case, which are not positions in which passengers would normally be able to operate Bluetooth. These were considered to be:

- instrument panel on the flight deck
- at the front of equipment in electronics bay, and
- between cables in the electronics bay.

4.3.4 Interference Observation

With the all the aircraft's systems operating normally and the Bluetooth devices turned off, the output readings of the aircraft's navigation instruments were noted. The Bluetooth devices were then turned on and any deviations of the instruments noted as the Bluetooth antenna was placed at various locations on the flight deck and in the avionics equipment bay. No deviations were observed; see test report in appendices A and B.

The tests were repeated for all devices with one piconet being operated at +30dBm, and a swept frequency source being substituted for the Bluetooth signal. The swept source was operated at 30dBm with a sweep time of 2 minutes per sweep to allow for visual observation of instrument interference.

It is recognized that the test procedure described above only allows an assessment of harmful interference due to signals coupled via the interference susceptible system's antenna, including its feeder cable. Direct pick up into the receiver or via other associated wiring is also possible. To assess this possibility, the swept frequency measurement was extended by placing the antenna against the cable assemblies within the electronics bay.

4.4 Aircraft and Systems Tested

Using the test procedures as outlined above the aircraft and systems shown in Table 4-1 were tested.

System	Wide Body B747-400	Business jet, Gulfstream Gulf-GV
DME 1*	Yes	Yes
DME 2	Yes	Yes
ATC 1	Yes	Yes
ATC 2	Yes	Yes
TCAS 1	Yes	Yes
TCAS 2	Yes	Yes
GPS 1*		Yes

Table 4-1 Aircraft Path Loss Measurements, Aircraft & Systems Measured

5 SUMMARY OF MEASUREMENT DATA

5.1 Bluetooth Spurious Emission

The Bluetooth emission levels shown in Figure 5-1 were measured. The measurements were conducted with an unshielded Bluetooth device and antenna connected to a Laptop computer using the USB port. The Laptop was operated from battery power. The Bluetooth device was mounted on an insulated stand 1 meter in front of the measurement antenna. Other tests using a power brick were also conducted.

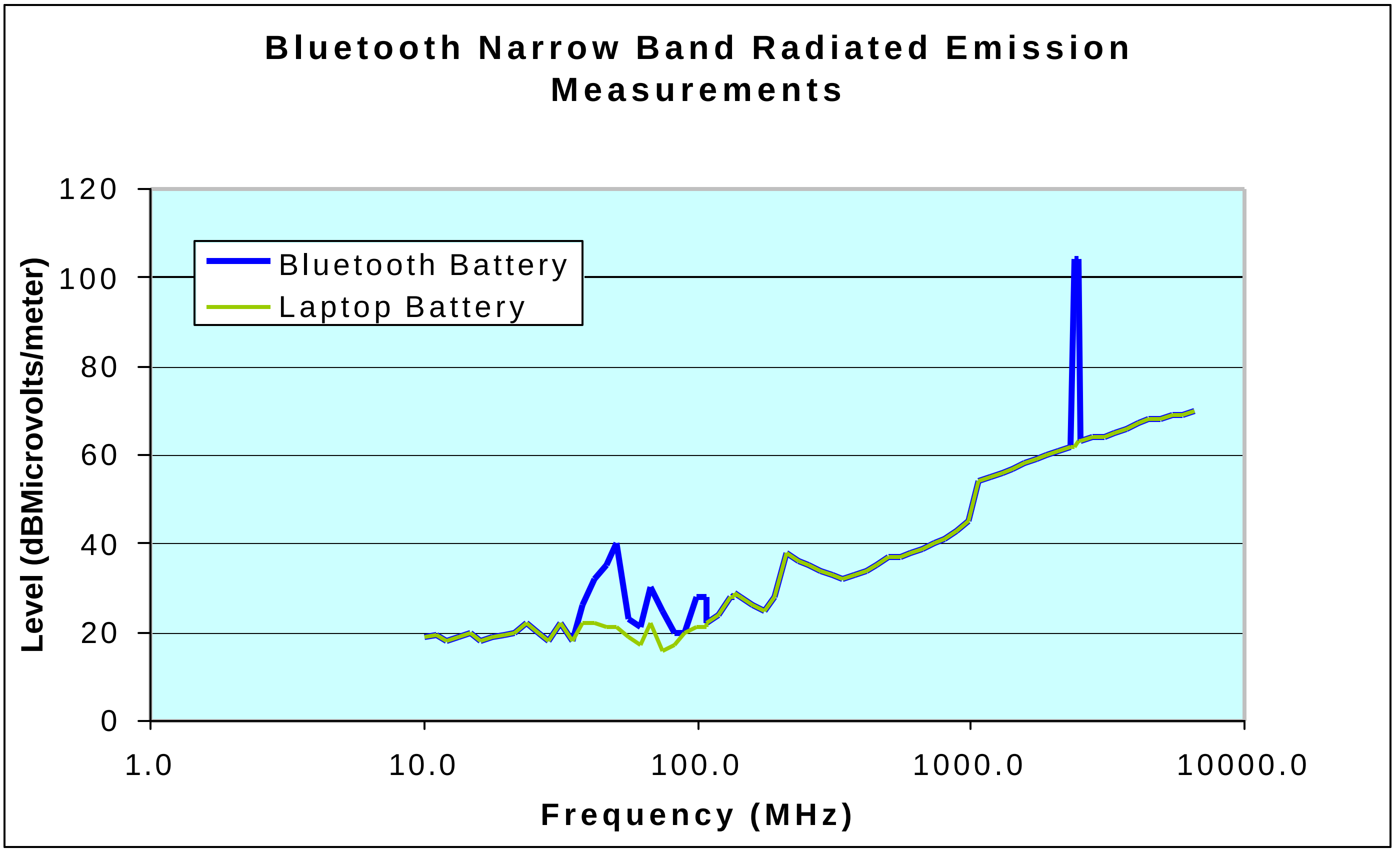


Figure 5-1 Bluetooth Emissions using Typical Aircraft EMI Test Procedures

5.2 Path Loss Data

5.2.1 Sources of Error

The test procedure used for measurement of path loss was developed for use with in-service aircraft. It includes two components of the aircraft, an antenna and interconnecting cable that are difficult to calibrate in-situ.

In practice the same aircraft antenna and cable are used to receive both the desired signal and receive the unwanted interfering signal from the Bluetooth device. Since the critical factor in determining whether harmful interference will affect the avionics is the relative signal to interference ratio, not the absolute level of interference, the loss or gain due to the aircraft's antenna and cable is completely cancelled out.

The path loss measurement also includes the cable loss due to the test cables. The loss due to the test cables is measured and used to correct the path loss.

5.2.2 Path Loss Calculations

A level of either +10 dBm (10 milliwatts) or +30 dBm (1Watt), at the output of the tracking generator, was used for the measurements. The path loss in dB between the source antenna and the input to the interference susceptible receiver is then calculated simply as:

> Path Loss = Output level (dBm) minus cable loss (dB) minus received power (dBm at the spectrum analyzer).

This path loss may be converted to path loss factor, as required for calculation of harmful interference with respect to the measured field strength from PEDs, by adding the antenna factor correction for the dipole antenna. The dipole antenna factor correction is supplied by the antenna manufacturer and is shown in Table 5-1.

Frequency (MHz)	Antenna Factor (dB)
30	-1.8
60	4.2
100	8.6
125	10.5
150	12.1
300	18.1
400	20.6
900	27.7
1000	28.6

Table 5-1. Antenna Factors

5.2.3 Antenna Coupling Data

The data at frequencies 100 MHz to 1000 MHz was taken from RTCA report DO 233 and is summarized in table 5-2. Test data collected during testing of Bluetooth at 2.4 to 2.5 GHz is shown in table 5-3.

	Aircraft Type	Large		Medium				Small
		B747	L1011	B737	MD80	B757	A320	Gulf G4
System	Parameter	Path Loss (dB)	Path Loss (dB)	Path Loss (dB)	Path Loss (dB)	Path Loss (dB)	Path Loss (dB)	Path Loss (dB)
VHF 1	Minimum	40.5	56.2	52.9	57.2	49.7	51.5	
	90% minima	58.0	65.0	61.0	64.0	62.0	60.0	
	Average	79.2	72.9	69.0	74.5	72.9	70.0	
	Std Deviation	12.0	6.1	7.6	9.2	9.8	8.4	
VHF 2	Minimum	63.2		58.4	64.9	38.0	62.1	
	90% Minima	73.0		62.5	71.0	55.0	70.0	
	Average	86.2		74.2	81.7	64.7	77.6	
	Std Deviation	10.8		9.3	10.0	8.7	6.7	
VHF 3	Minimum	71.5	62.2	53.2	55.2	53.0	55.6	
	90% Minima	83.0	71.0	63.0	62.0	62.0.	67.0	
	Average	92.9	77.2	76.2	81.7	79.3	76.2	
	Std Deviation	7.4	4.2	9.6	13.3	8.7	7.4	
ILS 1	Minimum	64.8	60.7	72.7		51.5	48.8	
	90% Minima	77.0	72.0	81.0		73.0	67.0	
	Average	93.9	85.2	90.7		86.1	85.7	
	Std Deviation	12.7	9.4	8.8		11.4	14.8	
VOR 1	Minimum	84.7	70.3	75.6	66.2	49.9	65	
	90% Minima	91.0	77.0	82.0	73.0	75.0	80.0	
	Average	105	79.3	90.1	87.8	90.7	91.9	
	Std Deviation	5.1	1.5					
GLS 1	Minimum	54.6	64.4	68.8	63.5	57.5	64.6	
	90% Minima	67.0	70.0	77.0	77.0	71.0	72.0	
	Average	86.2	82.6	83.1	85.4	83.0	84.2	
	Std Deviation	14.1	8.1	4.9	11.0	9.9	10.0	

Table 5-2 Summary of Aircraft Path Loss measurements

	Aircraft Type	Large		Medium				Small
		B747	L1011	B737	MD80	B757	A320	Gulf G4
DME 1	Minimum	70.7		69.1				
	90% Minima	83.0		81.0				
	Average	92.4		90.2				
	Std Deviation	7.4		12.9				
DME 2	Minimum			74.3	68.2		60.9	
	90% Minima			83.0	74.0		66.0	
	Average			88.3	78.0		79.9	
	Std Deviation			6.6	3.6		12.2	
ATC T	Minimum			67.1		61.3		
	90% Minima			75.0		69.0		
	Average			79.7		77.8		
	Std deviation			7.2		6.4		
ATC B	Minimum							
	90% Minima							
	Average							
	Std Deviation							
TCAS T	Minimum					69.1	54.8	
	90% Minima					73.0	60.0	
	Average					83.2	74.6	
	Std Deviation					7.3	11.3	
TCAS B	Minimum						63.0	
	90% Minima						70.0	
	Average						78.5	
	Std Deviation						7.1	
GPS 1	Minimum							82.4
	90% Minima							87.0
	Average							91.4
	Std Deviation							5.7

Table 5-2 Cont’d. Summary of Aircraft Path Loss measurements

	Aircraft Type	Large		Medium				Small
		B747	L1011	B737	MD80	B757	A320	Gulf G4
SATCOM	Minimum	87						
	90% Minima	90						
	Average	96.8						
	Std Deviation	5.0						
MARKER	Minimum						76.2	
	Average						106	
	Std Deviation						6.0	

Table 5-2 Cont'd. Summary of Aircraft Path Loss measurements

Victim Antenna (B747)	Average Path Loss (dB)	Victim Antenna (Gulfstream V)	Average Path Loss (dB)
VOR antenna 1dipole at window 2	52.66	ATC (lower) Door Open	65.55
VOR antenna 1, dipole outside	52.69	ATC (lower) Belly level	48.13
VOR antenna 2	52.93	ATC (Upper) Belly level	65.99
VOR antenna 3	52.56	ATC (Upper) Above door	63.06
TOP IFF with Dipole outside	38.44	ATC (Upper) door open	65.17
Top IFF with Vert dipole at window 2	52.62	DME (Front) door open	65.40
Top IFF with Hor wing Dipole 2 window 2	52.22	DME (Front) Belly Level	57.75
Lower IFF with Vert Dipole @ window 2	52.45	DME (rear) Belly Level	59.55
Lower IFF with Hor wing Dipole @ window 2	52.47	TCAS (lower) 1st Quad door open	65.50
		TCAS (lower) 3rd Quad door open	65.45
		TCAS (lower) 2nd Quad door open	65.47
		TCAS (lower) 4th Quad door open	65.62
		TCAS (lower) 4th Quad Belly	63.36
		TCAS (lower) 2nd Quad belly	64.58
		TCAS (lower) 3rd Quad Belly	65.11
		TCAS (lower) 1st Quad Belly	64.28
		TCAS (upper) 1st Quad Above door	65.62
		TCAS (upper) 3rd Quad above door	65.52
		TCAS (upper) 2nd Quad above door	65.51
		TCAS (upper) 4th Quad above door	65.56

Table 5-3 Summary of Path Loss measurements at 2.4 GHz to Aircraft Antenna

5.2.4 Seat-to-Seat Path Loss

Seat to seat path losses were measured on the FAA B727, GulfstreamV and Lufthansa B747. It was shown that the average seat-to-seat path losses across the frequency band varied closely in accordance with free space path losses although multipath fading resulted in deeper fading over approximately 10% of the frequency band. Figure 5.1 shows the path loss where the two antennas are located in adjacent seats for different co-polarizations and cross polarizations.

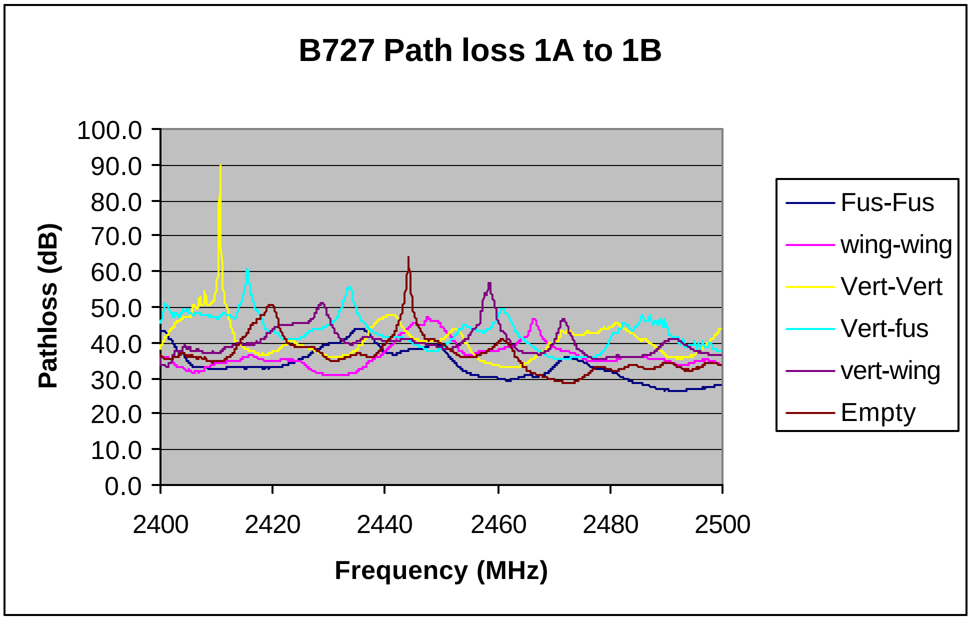


Figure 5-1 Path loss between Dipole Antennas in Adjacent Seats

The polarizations used in Figure 5-1 were:

- Co-polarized
  - Fus-fus – horizontal aligned with aircraft fuselage
  - Wing-wing – horizontal aligned with aircraft wings, and
  - Vert-vert – vertical polarization
- Cross polarized:
  - Vertical to horizontal fuselage, and
  - Vertical to horizontal wing,

All of the above were measured with an operator in the seat adjacent to the antenna. An additional measurement was made with vertical polarization with the seat adjacent to the antenna being “empty”.

From Figure 5-1 the sharp nulls due to multipath cancellation can be easily seen and are most prominent where both antennas are vertically polarized. The average values and standard deviation for each antenna orientation are shown in Table 5-4. From this it appears that on average the lowest path loss occurs when the antenna is not in very close proximity to a user or passenger. This occurs when the antenna is horizontal or the seat is empty.

Polarization	Fuselage-fuselage	Wing-wing	Vertical-vertical	Vertical Fuselage	Vertical-wing	Vertical-vertical
Other	Seat occupied	Seat occupied	Seat occupied	Seat occupied	Seat occupied	Seat empty
Average path loss	35.80	34.88	41.14	41.64	36.39	34.88
Std Deviation	4.48	3.80	5.42	4.67	3.97	5.19

Table 5-4 Average Seat-to-Seat Path Loss

However it can be seen from Figure 5-2, the average values of path loss versus separation, that there is no consistently preferred antenna orientation for all antenna separations. From this it can be concluded that Bluetooth operation inside an aircraft does not depend on antenna orientation and either co-polarized or cross polarized antennas would have an almost equal probability of working

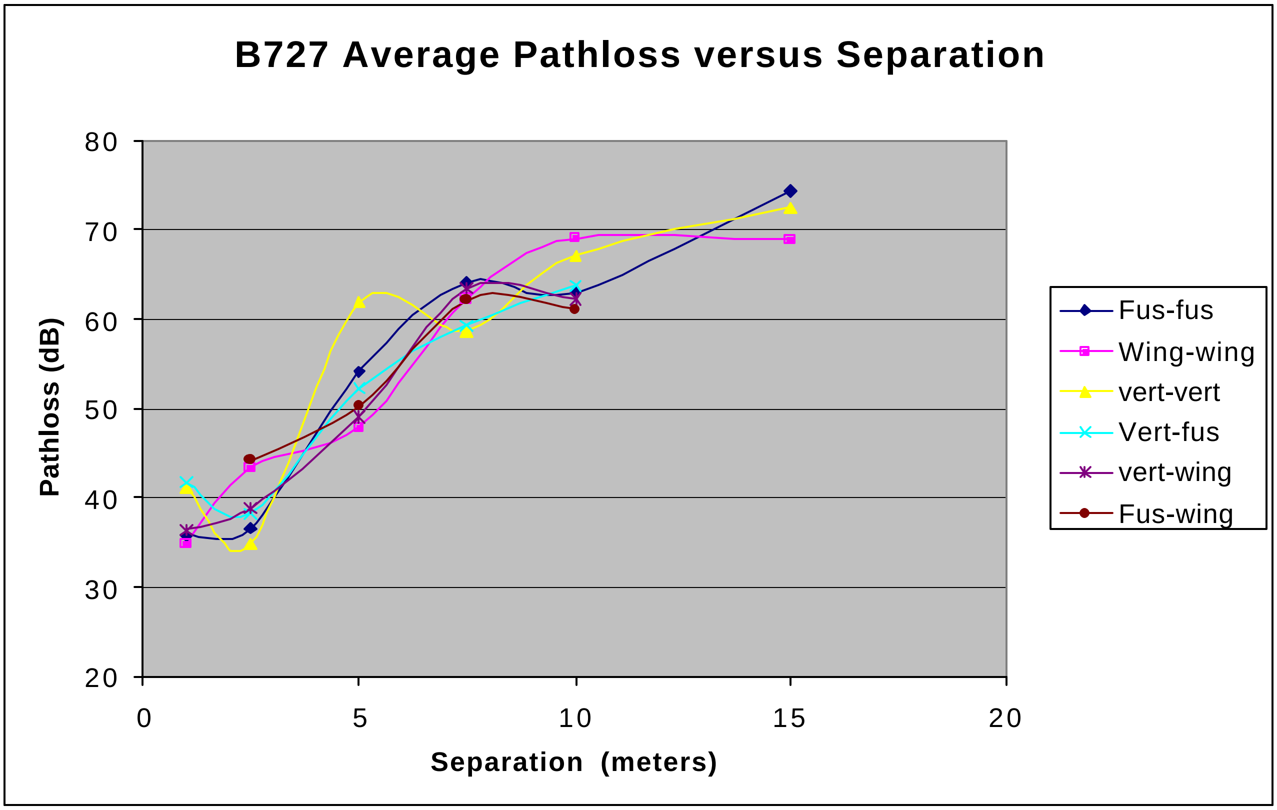


Figure 5-2 Average Path loss versus Separation Distance for Various Antenna Orientations

6 Avionics Susceptibility

6.1 Susceptibility Requirements

The Federal Aviation Authority (FAA) and International Civil Aviation Organization (ICAO) set standards that provide minimum signal levels for ground based navigation and communications transmitters throughout their intended coverage volume. The performance of navigation receivers is also specified in terms of the maximum level of in-band and out-of-band interference. For in-band interference four different thresholds are set depending on the nature and frequency of the interfering signal. These are shown for an ILS localizer receiver as follows:-

6.1.1 Interference from unmodulated carrier signals

Type I - If an unwanted signal is within the ILS localizer receiver RF pass band and beats with the localizer carrier signal to produce a difference frequency within about 0.5 Hz of the 90 Hz or 150 Hz ILS sideband signals, the unwanted RF signal field strength must be as low as 46 dB below the localizer carrier level in order not to exceed the 5 μamp limit. (5 μamp, as measured at the output of the aircraft receiver, represents the smallest observable deviation of an analog style meter on the instrument panel of an aircraft)

Type II - If an unwanted signal is within the ILS localizer receiver RF pass band and beats with the localizer carrier signal to produce a difference frequency within about 10 Hz of the 90 Hz or 150 Hz ILS sideband signals, but not within the Type I tolerance, the unwanted RF signal field strength must be as low as 26 dB below the localizer carrier level in order not to exceed the 5 μamp limit.

Type III - If an unwanted signal is within the ILS localizer receiver pass band with sufficient strength, there will be a progressive "capturing" of the receiver. In this case the unwanted signal field strength must be as low as 7 dB below the localizer carrier level in order not to exceed the 5 μamp limit.

6.1.2 Interference from a modulated carrier signal

Type IV - If an unwanted signal contains a carrier with 20% amplitude modulation by a 90 Hz or 150 Hz component, the unwanted RF signal field strength must be as low as 13 dB below the localizer carrier level in order not to exceed the 5 μamp limit.

6.1.3 Out-of band interference

For out-of-band interference, RTCA DO-160 requires that degradation due to non co-channel (out of band) interference should not occur with an interfering signal 80 dB above the wanted signal. The analyses in section 8.1 concentrates on non co-channel interference.

6.1.4 Co channel Interference

From the susceptibility levels identified above it is evident that the receivers are most susceptible to in-band interference. This is commonly referred to as co-channel interference. The analyses in section 8.2 and 8.3 concentrate on co-channel interference.

6.1.5 Forms of Co channel Interference

Several forms of co-channel interference are possible and each is considered separately. These are:

6.1.5.1 Broadband noise.

Broadband noise is uniformly distributed across a wide band and therefore, if of a sufficient level, will cause harmful interference to the interference susceptible receiver independent of the frequency to which the receiver is tuned. The probability of harmful interference due to broadband noise is therefore directly proportional to the spurious emission level emitted from the Bluetooth and inversely proportional to the path loss to the aircraft's antenna. Broadband noise causes degradation in the receiver signal to noise and hence results in a flag rather than any instrument deviation.

The effects of broadband noise due to multiple Bluetooth devices can be cumulative and for the same path losses and Bluetooth emission levels the total noise would double for each doubling of the quantity of Bluetooth devices. The aircraft tests show however that the path loss is distributed in a Rayleigh like manner. For Rayleigh distribution, cumulative broadband interference will be less than 8 dB above the mean interference for 99.9% of the time. A margin of 8 dB above the broadband noise due to a single worst-case Bluetooth broadband noise level is therefore considered as an appropriate starting point at which to perform the harmful interference probability analysis.

6.1.5.2 CW Interference.

CW emissions from Bluetooth are non uniformly distributed across the frequency band and hence, for low level CW signals, the probability of harmful interference to the avionics is dependant on the number of CW signals and the bandwidth of the avionics receiver as well as the emission levels and path loss. The frequency of the CW emissions from a variety of Bluetooth will, in general, be uncorrelated. The total number of CW signals will therefore increase as the number of Bluetooth is increased but the level of the CW signals will be independent of the number of Bluetooth devices.

Low-level CW signals could cause harmful interference to voice communication circuits or increased error rates on data circuits.

For high level CW signals, 80 dB or more above the wanted signal, broadband effects such as receiver blocking can occur but these are not applicable for the case of the intentional emissions from Bluetooth which are not high level and are modulated so that the energy is spread rather than being CW.

6.1.5.3 Modulated signals.

Several navigation receivers are dependent on measuring the phase difference between an AM modulated signal component and an FM modulated signal component. Any interfering signal that has a modulation component at the same frequency as either of the two components of the desired signal could combine with the desired signal to give an apparent shift of phase. Since the modulation component is very low in frequency, 30 Hz, 90 Hz and 150 Hz, the frequency stability of the modulation need not be high in order to obtain a steady deviation of the navigation instrument. This possible mechanism was explored in RTCA report DO 233, and, unlike the CW case, can result in a deviation of the ILS instrument. The deviation was however unstable showing that even a small difference between the modulating frequency with that of the modulation frequency of the desired signal will produce an unstable condition. This unstable condition could be recognized by the pilot or by a flight control computer. The probability of harmful interference resulting in a steady deviation rather than a flag is however likely to be extremely low. It requires the Bluetooth to generate a spectral signal at a frequency close to the frequency of the desired signal, typically within 40 Hz, for the signal level to be close to the signal level of the desired signal and for the signal to be modulated at the appropriate frequency. This is extremely improbable with a fast frequency hopping time division multiple access system such as Bluetooth.

6.1.5.4 Impulsive signals.

The energy of impulsive signals is distributed over a wide frequency band depending on the pulse width and pulse shape. The energy falling into a receiver channel is less than the energy due to an equivalent level of broadband noise or CW signal and any effect, even high level, due to a single impulse is at worst a short transient. In the event of multiple pulses due to one Bluetooth or due to multiple Bluetooths it can also be shown that the effect is will not be of concern. For non-pulsed receivers, VOR, ILS etc., the effect is the same as broadband noise and given a high enough impulse rate it could at worst result in the generation of a flag on the display so that the pilot could not use an erroneous instrument reading. It should however be noted that the DME, RADAR and ATC all generate very high levels of RF impulse and cause no problem to the VOR, ILS or GLS receivers, or to other pulse type receivers, DME, ATC or GPS. Typically the design of these systems is such that they can withstand an interfering impulse duty cycle of up to 10% without degradation. The effect of impulses due to the frequency hopping signal of Bluetooth will be much lower than due to any of these other systems.

6.1.6 Interference Coupling Mechanisms

6.1.6.1 Antenna coupled interference

Potential harmful interference, i.e. interference that prevents the avionics systems from receiving and displaying the correct navigational or attitude information, could be caused due to any combination of high emission levels from a Bluetooth occurring at the frequency of the avionics receiver, low path loss from the Bluetooth to the susceptible avionics system or due to a low signal from the desired navigation ground system.

- The path loss from the Bluetooth is dependent on the location and orientation of the antenna used to represent the Bluetooth and to a lesser extent on the number and position of other movable objects or persons within the aircraft.

- The frequency and level of the wanted signal will vary according to the aircraft's location and attitude in the airspace considering the additional path loss due to shadowing by the aircraft’s fuselage or wings, see para.7.1.1.

6.1.6.2 Cable Coupled Interference

Cable coupled interference here relates to any wires or cables connecting to the receivers or associated equipments other than the antenna cables. Interference received by means of the antenna cables is already accounted for in the all-inclusive measurement of path loss to the antennas since the measurements were made at the receiver end of the antenna cables and does not need to be considered separately.

6.1.6.3 Cable Coupled Interference Thresholds

The cables of an aircraft can be segregated into some 6 categories depending on the classes of signal or power that they carry. Susceptibility to conducted interference on power lines is defined in DO 160. Susceptibility to interference on signal lines is dependent on the nature of the signal, the nature of the receiving device, the dynamic range of the system and any interference suppression devices used in the receiving circuit. The estimated worst-case interference threshold for the signal types normally found in commercial aircraft is shown in Figure 6.1. Where applicable these susceptibility thresholds have been derived from the relevant standards, e.g. Mil Std 1553 Data Bus. Elsewhere they have been derived from the typical operating levels and dynamic ranges applicable to the signal types as contained in the manufacturers data sheets, e.g. nominal audio level 0 dBm dynamic range 60 db. The in-band susceptibility threshold is assumed to be 10 dB below the noise floor and the out of band susceptibility threshold is assumed to increase at 6 dB per octave. This would be the typical reduction in gain due to increase in frequency as would apply to a circuit with no deliberate filtering.

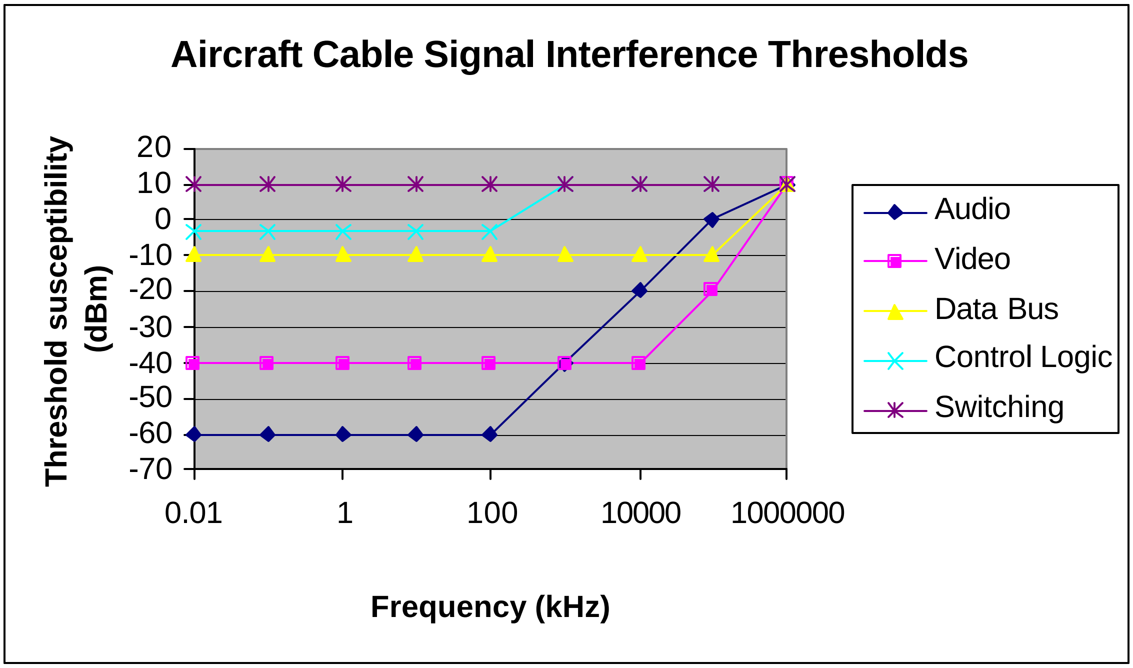


Figure 6.1 Interference Threshold on Different types of Aircraft Signal Cables

7 Desired Signal Environment

7.1 Minimum ICAO requirements

For linear receivers, as required for operation with amplitude modulated signals used in VHF navigation aids and communications, the desired signal to interference ratio is constant over a wide dynamic range independent of the desired signal level. For aircraft operating within the intended coverage volume of a navigation aids or communication transmitter the guaranteed signal level specified by the International Civil Aviation Authority (ICAO) is as shown in Table 7.1. These levels are typically 20 to 40 dB greater than the receiver threshold sensitivity, consequently it will be possible to receive the signal outside of the intended coverage volume and at such times lower level interfering signals could result in disturbance to the avionics.

The minimum signal levels for commonly used navigation and communication systems in the US and Canada are shown, together with the radius of the service volume, in Table 7.1 These signal levels and coverage volumes are in compliance with those permitted by ICAO Annex 10.

System	Guaranteed signal (dbUV/m)	Coverage Volume
ILS	+32	+/-35^o to 10 NM,+/-10^o to 18 NM
VOR	+39	System tailored with a maximum range at 30000 ft of 160 NM
GLS	+46	+/- 8^o to 10 NM
DME	+56	System tailored with a maximum range at 30000 ft of 160 NM
COMMS	+37	Extended range systems up to 150 NM
GPS	+33	Global coverage
ATC	+65	

Table 7.1 Minimum Signal Strengths and Coverage Volumes

7.1.1 Signal Strength Variation

The signal strength will vary depending on the aircraft's location with respect to the signal source. This will be most significant for local area and directional systems such as ILS and GLS. In these cases the signal strength will vary along the approach path in accordance with the well known $1/R^2$ rule. Hence for the final 50% of the approach (9 NM) the signal will be 6db or more greater than the minimum and for the final 25% (4.5 NM) the signal will be 12 dB or more greater than the minimum.

For omni directional systems such as VOR, VHF Communications and DME it is necessary to consider the coverage area. In this case 25% of the coverage area will have a signal 6 dB or more greater than the minimum and only 6.25% of the coverage area will have a signal level more than 12 dB above the minimum.

For satellite based systems there are only small differences in signal level throughout the intended coverage area.

Multipath signals can result in signal enhancement as well as cancellation. Based on Rayleigh fading probabilities significant signal enhancement will occur only very infrequently and it is considered safer to use the minimum signal levels as defined by ICAO Annex 10 as shown in table 7.1.

7.1.2 Antenna Shadowing

The signal at the receiver is the product of the field strength times the effective antenna factor. This signal may however be reduced by any shadowing loss due to the aircraft's orientation with respect to the source. During level flight the shadowing loss will be minimal for antennas mounted on the belly of the aircraft but considerable-shadowing loss could be experienced for top or vertical stabilizer mounted antennas. A maximum shadowing loss of 10 dB is used in the subsequent calculations to determine the interference susceptibility.

8 ANALYSIS OF INTERFERENCE RISK

8.1 Intentional Emissions

8.1.1 Introduction

To determine that the intentional emissions from Bluetooth do not cause interference it is appropriate to consider the specific frequencies and levels of the intended emissions. It should be noted that the intentional emissions are co-coordinated in frequency such that they should not cause interference on the receive frequency of the aircraft's avionics receivers. Therefore the subsequent analysis will focus on the frequency insensitive susceptibility due to signals coupled into avionic equipments by means of the aircraft's antenna and the aircraft's cabling.

8.1.2 Field Strength Level

Typical radiated power levels due to Class 1 Bluetooth devices is a maximum of +20 dBm (0.1 watt). To permit easy comparison with the analysis of unintentional emissions from Bluetooth this is converted to field strength in dB μvolts per meter using the following equation applicable to a short dipole antenna:

E (field strength)=(49.2*Transmitter Power)$^{0.5}$/Distance in meters.

Hence for a transmitter power of 0.1 watts the field strength at 1 meter is:

2.2 volts/meter, or
126 dBμV/meter

For a Bluetooth Class 2 device operating at 0 dBm (.001 watts) the levels at 1 meter are:

0.22 volts/meter, or
106 dBμV/meter
which agrees closely with the measurement data, see Figure 5-1

8.1.3 Antenna Coupled Interference

At 2.4 GHz the intentional emissions at a level of 106 dBμV/meter are attenuated by the path loss to the external aircraft antennas by more than 60 dB depending on distance from the Bluetooth device to the antenna. This distance is generally greater for wide body aircraft than for narrow body aircraft. The resulting signal level is therefore no greater than 46 dBμV/meter. This is 40 dB below the susceptibility to non co- channel interference as defined in DO 160. Note: The antenna factor of the receiving antenna on the aircraft is deliberately excluded since its value is unknown and any error is cancelled out when calculating the signal to interference ratio since the aircraft antenna is common to both the interference and the signal paths

8.1.4 Cable Coupled Interference

In the case of the intentional emissions they are limited to a narrow band of frequencies in the band 2.4 to 2.48 GHz. At these frequencies Figure 6-1 shows a reduced susceptibility for many of the signal types used on cables in aircraft. The results of the interference analysis when using these emission levels and susceptibility thresholds are shown in table 8.1.

Signal Type	PED Emission Level (dBμV/m)	Path Loss (dB)	Antenna Factor (dB)	Path Loss Factor (dBμV/m)	Interference Threshold (dBμV@ 50Ohms)	Margin (dB)
Audio	+145	39	26.5	65.5	+108	28.5
Video	+145	39	26.5	65.5	+104	24.5
Data Bus	+145	39	26.5	65.5	+108	28.5
Logic	+145	39	26.5	65.5	+117	37.5
Synchro	+145	39	26.5	65.5	+117	37.5

Table 8.1 Cable Coupled Interference Analysis Intentional Radiators

8.2 Equipment Case Coupled Interference

The permissible radiated susceptibility of aircraft electronics systems is defined by RTCA specification DO 160D. Various categories of susceptibility are defined depending on the criticality of the device to safe operation of the aircraft. For many older aircraft the more stringent susceptibility requirements are generally not applicable and when considering the potential interference from Bluetooth it is necessary to consider the least stringent requirements, these are defined as CAT A. The CAT A, B and C levels of susceptibility are shown in Figure 8-1. Also shown in 8-1 are the levels of Bluetooth emissions at the case of the avionics system or on its interconnecting cables as a function of distance to the Bluetooth emitter. It can be seen that distances greater than 15 cms, Bluetooth intentional emissions are below the threshold of the most susceptible device. For spurious emissions the level is below the threshold susceptibility at all distances greater than 1 cm. These separations are clearly too low to be possible for passenger operated Bluetooth devices. For later generation aircraft that are fully compliant with DO 160D there is zero risk of interference to critical systems from Bluetooth independent of the location of the Bluetooth device.

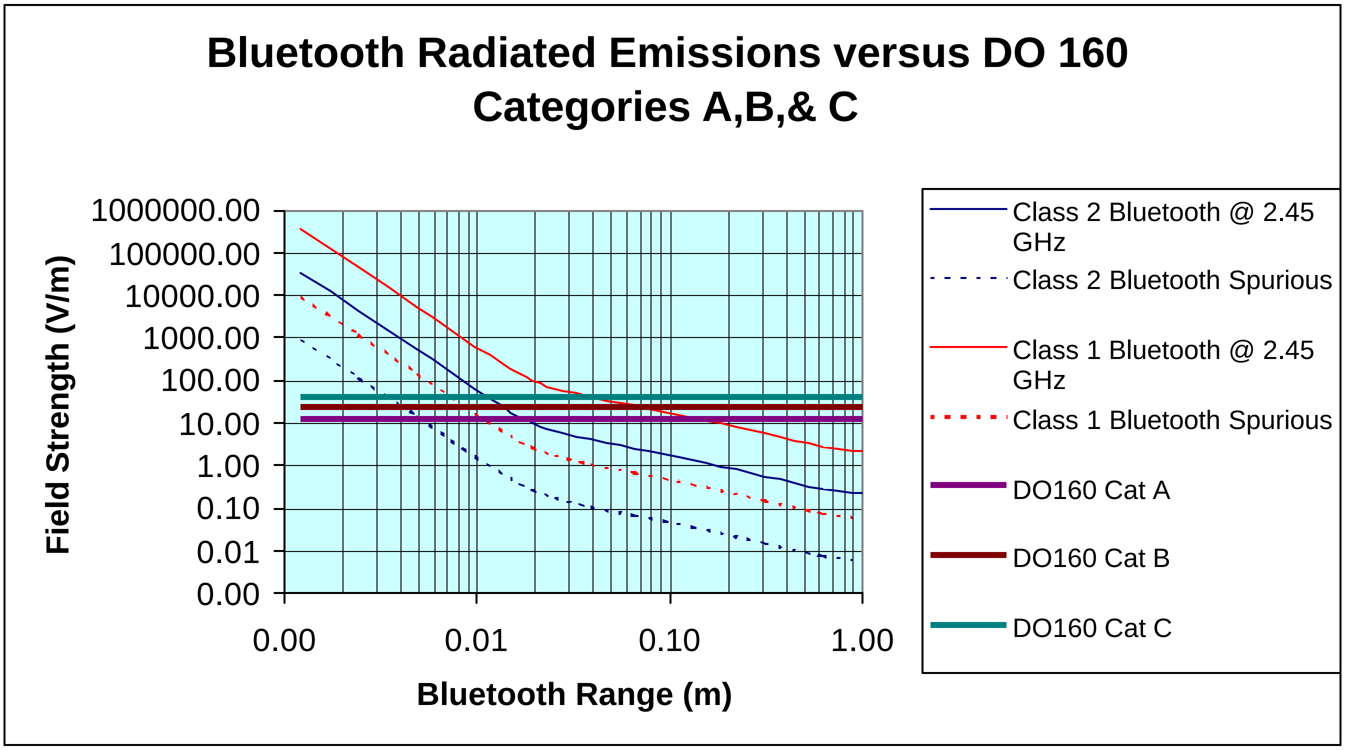


Figure 8-1 Bluetooth Radiated Emissions relative to DO 160 Susceptibility Requirements

8.2.1 Discussion of Analysis of Interference due to Intentional Emissions

It is concluded that harmful interference due to cable coupling from Bluetooth intentional emissions in the passenger cabin is sufficiently below the threshold susceptibility that interference due to Bluetooth will not occur.

For older aircraft, poor screening of a avionics system could result in direct coupling of interference levels at or close to the susceptibility level of the equipment through its case foe the unlikely case where the Bluetooth device is closer than 15 cms. For aircraft meeting DO 160 D no interference should be experienced regardless of the location of the Bluetooth device.

8.3 Interference Due to Spurious Emissions coupled Via The Aircraft's Antennas

The approach used to analyze the overall probability of harmful interference from Bluetooth is based on a worst-case analysis. The objective of this worst-case analysis is to determine which, if any, conditions could lead to possible adverse harmful interference. The worst-case analysis is conducted assuming least path loss, highest level Bluetooth emissions either CW or modulated that fall at the most susceptible frequency of the avionics receiver. It will be seen from the analysis that there is no harmful interference under the worst-case conditions for the known receiver / source locations / source configuration, and it is therefore concluded that there will be no harmful interference for all the combinations of Bluetooth devices and locations within the aircraft passenger cabin for the particular receiver system and aircraft type.

8.4 Antenna Coupled Co-Channel Interference

8.4.1 Worst-case Analysis of Antenna Coupled Interference

8.4.1.1 Methodology

The test method does not specifically measure the worst-case (least) path loss but by scanning a wide range of frequencies from a number of locations selected so as to have a low path loss, the worst-case value measured is likely very close to the true worst-case.

The path losses, which are measured as the difference in radiated and received power, are converted to path loss factors by adding the calibrated antenna factor of the source antenna used for the path loss measurements. This is necessary since signal strengths and emission levels are defined as field strengths. Hence,

Path loss factor = Path loss + Antenna factor

Note: The antenna factor of the receiving antenna on the aircraft is deliberately excluded since its value is unknown and any error is cancelled out when calculating the signal to interference ratio since the aircraft antenna is common to both the interference and the signal paths

No allowance is made for cumulative interference levels due to multiple Bluetooth since, in the worst-case, the interference due to the worst-case emissions from the worst-case location will override the interference due to any other location.

The interference level at the receiver input is deduced by subtracting the worst-case (lowest) path loss factor (in dB) from the worst-case (highest) expected Bluetooth radiated field (in dBμ V/m). Hence,

Interference level = Bluetooth Emission level - Path loss factor

.

This results in the following levels at the antennas of the most susceptible systems:

--> VHF (100-150 MHz) band: 59 dB μV/m
--> UHF (300-350 MHz) band: 57 dB μV/m
--> "L"(925-975 MHz) band: 42 dB μV/m

Note: For illustration purposes only the FCC Class B limits at 1 meter (corrected to compensate for the FCC requirement to measure the field 3 meters from the PED) are as follows:

--> *49,5 dB mV/m for the MKR band,*
--> *53 dB mV/m for the VOR, VHF and ILS bands,*
--> *55,5 dB mV/m for the GLS and DME bands.*

The analysis to determine the required signal level was performed for each aircraft type and avionics system. The calculation is based on the worst-case signal at the edge of the coverage volume using the minimum signal field strengths as defined in ICAO Annex 10. An allowance for shadowing of the aircraft antenna of either 3 dB, for belly-mounted antennas, and 10 dB (except GPS) for top mounted antennas, was included in the calculation. Hence,

Required Signal = ICAO Field Strength - Shadow Loss
and
Signal to Interference ratio = Required Signal - Interfering Signal

The safety margin is then determined by subtracting the Minimum Signal to Interference threshold, as discussed in paragraph 2.4, from the worst-case signal to noise at the receiver.

Hence,
Safety Margin = Signal to Interference - Signal to Inference Threshold

A positive value for the safety margin indicates the margin by which the signal to interference ratio exceeds the required signal to interference ratio for proper system operation. A negative value indicates the amount by which the interference exceeds the level permitted for proper system operation. The parameters used in the analysis are shown in the example Table 8-2.

8.4.2 Results of Worst-case Analysis

The results of all of the worst-case analysis are summarized in Table 8-3.

DETAIL BROADBAND INTERFERENCE WORST-CASE ANALYSIS B747									
	ANT FACTOR	PATH LOSS (dB)	Bluetooth EIRP(dBw)	Bluetooth radiated emission μV/m	ICAO Field strength (dBμv/m)	Antenna Blanking (dB)	S/I (dB)	Minimum S/I (dB)	Safety Margin (dB)
VHF 1	10.5	40.5	-108.7	0.00002	37	10	25.75	15	10.75
VHF 2	10.5	63.2	-108.7	0.00002	37	3	55.45	15	40.45
VHF 3	10.5	71.5	-108.7	0.00002	37	3	63.75	15	48.75
ILS	9	64.8	-111.2	0.000015	32	3	56.04	40	16.04
VOR	9	84.7	-111.2	0.000015	39	10	75.94	40	35.94
GLS	19	54.6	-100.79	0.00005	46	3	39.39	40	-0.6
DME	28	70.7	-88.75	0.0002	56	3	44.45	8	36.45
ATC	28	67.1	-88.75	0.0002	65	3	49.85	8	41.85
TCAS	28		-88.75	0.0002	65	3	NA	8	NA
GPS	31		-80.79	0.0005	33	0	NA	8	NA
SATCOM	31	87	-80.79	0.0005	31	0	27.79	15	12.79

Table 8-2 Example spreadsheet showing parameters used for the worst-case analysis

	Summary Interference Safety Margin Below ICAO Minimum Signal Level All Aircraft Types							
AIRCRAFT\ SYSTEM	B757	B737	L1011	MD80	A320	B747	GULF	Worst-case Over All Aircraft
VHF 1	19.95	23.15	26.45	27.45	21.75	10.75	NA	10.75
VHF 2	15.25	35.65	NA	42.15	39.35	40.45	NA	15.25
VHF 3	30.25	30.45	39.45	32.45	32.85	48.75	NA	30.25
ILS	2.75	23.95	11.95	NA	0.05	16.05	NA	0.05
VOR	1.15	26.85	21.55	17.45	43.15	35.95	NA	1.15
GLS	2.29	13.59	9.19	8.29	28.99	-0.61	NA	-0.61
DME	NA	34.85	NA	27.75	26.65	36.45	NA	26.65
ATC	36.05	41.85	NA	NA	NA	41.85	NA	36.05
TCAS	43.85	NA	NA	NA	29.55	NA	NA	29.55
GPS	4.79	NA	NA	NA	NA	NA	17.19	4.79
SATCOM	26.79	NA	NA	NA	NA	12.79	NA	12.79

Table 8-3 Results of Worst-case Interference Analysis Interference

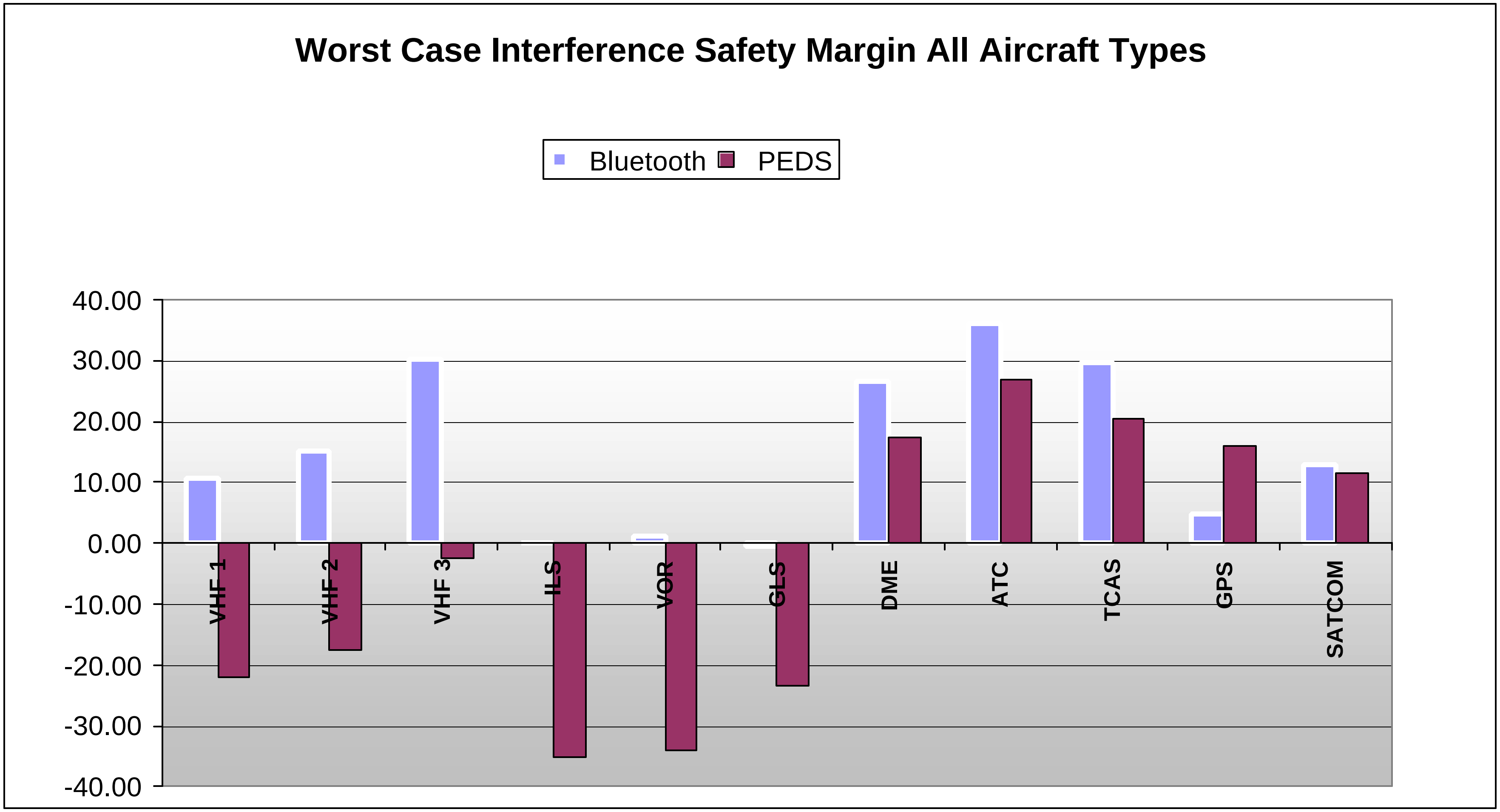


Figure 8-2 Worst-case Comparison of Interference Margin Bluetooth and PEDS

8.4.3 Safety Considerations

From a safety of flight perspective it is necessary to analyze the worst-case measurement data. If, in the worst-case analysis, there is no potential for harmful interference to the avionics, then it is reasonable to conclude that the use of Bluetooth would not be harmful to the safety of flight. However if the worst-case analysis indicates that there could be harmful interference then it is necessary to assess the probability of harmful interference and to determine the impact of such interference at various stages of the flight.

Based on the measurement data obtained, a worst-case analysis, see Table 8-3 and Figure 8-2, shows that potentially harmful interference DOES NOT OCCUR IN ANY CIRCUMSTANCES.

8.5 Discussion of Worst-case Analysis Results

The worst-case analysis indicates that:

1 DME, ATC and TCAS CANNOT be disturbed by Bluetooth emissions, whatever the location of the PED inside the aircraft. Taking into account worst Bluetooth emission levels, worst coupling configurations and the highest susceptibility level of the receivers, a safety margin greater than 20 dB has been demonstrated. This result is due to a combination of the high path loss and low emission levels at the higher frequency ranges applicable to DME, ATC and TCAS.

2 The typical worst-case results for the ILS-Localizer, VOR and GLS show a 11 to 43 dB safety margin. However specific results for certain aircraft types exhibit a reduced margin of –0.6 to 1.15 dB. However this interference frequency must fall in a very narrow band at the modulation frequencies. When the necessary signal to interference ratio is adjusted to reflect the ICAO required susceptibility at the full RF pass bandwidth of the receivers, i.e. 7 dB (from ICAO Annex 10), the resulting signal to interference ratio is strongly positive and harmful interference cannot occur.

3 VHF Communications also exhibit a large safety margin of 10 to 30 dB over all aircraft types measured.

4 There is insufficient data available to provide conclusive evidence for the potential of harmful interference to GPS but the combination of higher path loss and lower PED emissions at the L band frequencies together with the specific data available for the Gulf G4 indicates that a margin of greater than 10 dB should exist.

8.6 Cable Coupled Interference

8.6.1 Cable Coupling

Annex E illustrates the typical variation of path loss to an 8 meter unshielded wire laid on the cabin floor. The three curves represented different polarizations of the source antenna. It can be seen that on average the path loss is only loosely dependent on polarization.

The worst-case coupling to representative cables inside the aircraft is shown in table 8-4.

Location	Frequency (MHz)	B757		A320	
		2 meter Unshielded	8 meter Unshielded	8 meter Unshielded	8 meter Shielded
L1	100-150	58 dB	48 dB		
L2	100-150	34 dB	36 dB	39 dB	62 dB
L3	100-150	72 dB	53 dB	64 dB	91 dB
L1	300-400				
L2	300-400			41 dB	52 dB
L3	300-400			67 dB	73 dB
L1	925-975		56 dB		
L2	925-975		39 dB	43 dB	58 dB
L3	925-975		77 dB	71 dB	84 dB

Table 8.4 Cable Coupling

From Table 8-1 it can be seen that the worst-case path loss is strongly dependent on the location of the source antenna but shows only a small variation with frequency and cable length. The average path loss within each frequency band is however dependent on cable loss and shows a decrease of 6 dB when the cable length is shortened from 8 to 2 meters. The effect of screening is greatest at low frequencies where the path loss is increased by 22 dB. At 400 MHz the additional path loss is only 11 dB

8.6.2 Cable Coupled Interference Analysis

The potential for harmful interference to be coupled to the avionics via cables is determined through the following analysis.

Emission Level - Path Loss Factor - Interference Threshold = Margin (+ve or -ve)

The results of the worst-case analysis for emissions at a frequency of 100 MHz are shown for representative aircraft signal types in Table 8.5

Signal Type	PED Emission Level (dBμV/M)	Path Loss (dB)	Antenna Factor (dB)	Path Loss Factor (dBμV/M)	Interference Threshold (dBμV@ 50Ohms)	Margin (dB)
Audio	+60	35	10.5	45.5	+47	32.5
Video	+60	35	10.5	45.5	+67	52.5
Data Bus	+60	35	10.5	45.5	+97	82.5
Logic	+60	35	10.5	45.5	+117	102.5
Synchro	+60	35	10.5	45.5	+117	102.5

Table 8.5 Cable Coupled Interference Analysis

8.6.3 Discussion of Results of Cable Coupled Interference

It can be seen from Table 8.5 that there are significant safety margins with respect to each category of signal. It is noted that the worst-case analysis assumes unshielded cables and very little reduction in susceptibility as for interfering frequencies outside normal frequency band of the signals. In actual systems the safety margins will usually be significantly greater.

It is concluded that harmful interference due to cable coupling from Bluetooth is not likely to occur.

9 Conclusions

When testing aircraft for interference from Bluetooth Class devices operated at high power levels and in worst-case location empirical testing on both large and small aircraft has not indicated any cases of interference to the aircraft systems. Detailed analysis of the emission levels, propagation losses and aircraft system vulnerability to electromagnetic interference show that the intentional emissions and the spurious emissions from Bluetooth devices are at levels that cannot cause interference to aircraft systems. The analyses therefore support the empirical test and confirm that Bluetooth by itself is safe for use in aircraft while in flight.

It is noted however that Bluetooth is designed to be incorporated into other electronic devices rather than being used as a stand-alone device. The testing of Bluetooth emission levels show that these do not degrade the emission levels of the electronic devices into which Bluetooth is likely to be installed. It is therefore concluded that Bluetooth is safe for on aircraft use within other electronic devices approved for use on aircraft. This includes Laptop computers and other PEDs classed as non-intentional radiators. Before Bluetooth is used in other electronic devices classed as intentional radiators the intentional radiators themselves must be shown to be safe for aircraft use.

10 Recommendations

It is recommended that the current policies that apply to the use of Personal Electronic Devices (PEDs), as recommended in RTCA Report DO 233, be modified to reflect the safe use of PEDs incorporating Bluetooth. It is proposed that the RTCA recommendations be revised as follows for PEDs incorporating Bluetooth devices:

2. The FAA should modify FAR 91.21 Portable Electronic Devices so that:

    a. The use of any PED, with or without Bluetooth, is prohibited in aircraft during any critical phase of flight. (The intent is that the same use prohibition that applies to any PED during all critical phases of flight also applies to Bluetooth, an intentional emitter, but would allow the use of PEDs with or without Bluetooth during non-critical phases of flight).

    b. The use of any PED which has the capability to intentionally transmit electromagnetic energy other than that emitted by Bluetooth is prohibited in aircraft at all times unless testing has been conducted to ascertain its safe use. Note: such testing has been conducted with respect to Bluetooth and it has been determined that it is safe for aircraft use. Notwithstanding this fact, the use prohibition during any critical phase of flight still applies.

Annex A - Gulfstream EMI Test Report

GROUND TEST REPORT

G-V

INTEL® BLUETOOTH EMI TESTING

REPORT NO:

REPORT

AIRCRAFT S/N: 590

SYSTEMS TEST: K. Trundle DATE: 30 May, 2000

FAA/DAS TEST: N/A DATE: N/A

REVISIONS

REV LVL	REV BY	APPROVAL	DATE	REVISIONS AND/OR ADDITIONS

TABLE OF CONTENTS

1 INTRODUCTION:

The purpose of this test was to determine if the Bluetooth technology would function inside the cabin of the Gulfstream and if the devices or the frequencies would interfere with the GV avionics. We tested the interference possibilities using both, a Bluetooth device and a sweep generator at the frequency span of the Blue Tooth devices, either, connected to a power amplifier transmitting to avionics in the Right Electrical Equipment Rack (REER), with the cover off and to the Flight Deck. The testing was accomplished in Savannah, GA on 11 May, 2000 at the Gulfstream facility, the west ramp of the service center by the entrance to the airport Taxiway B.

2 TEST EQUIPMENT/PERSONNEL:

2.1 Personnel:
Keith Trundle – Gulfstream
Larry Wilson – Gulfstream
Joseph Ramirez – Gulfstream
Jeff Schiffer – INTEL
Al Bettner – INTEL
Travis Bonifield – INTEL
Alan Waltho – INTEL (contractor)
Margo Lynch – Teledyne
Tong Chen – Teledyne

2.2 Test Equipment: Hewlett Packard Spectrum Analyzer ESA Series E4402B

3 TESTING:

Using the APU setup and began propagation measurements.

Charts are attached as Appendix I (Plot Report.doc), to this document. No perceived propagation anomalies were noted. Due to the spectrum analyzer setup there were no readings below –70dBm to show the actual noise floor versus the Bluetooth Signal.

4 EMI TESTING:

Started both engines and applied normal aircraft power per G-V maintenance manual procedures. See the EMI Matrix charts at the end of this section for the standard report pages.

Swept from 2.4 to 2.5 GHz at +20 dBm in cockpit using HP tracking generator + pre-amp + 3ft sma cable into dipole. Dipole antenna moved throughout cockpit.

#1 FMS CDU,
Pilot Audio, CP Audio
#1 FMS CDU, #2 FMS CDU
Standby instruments
Center Overhead
Overhead CB panel center
HUD system
Autopilot engaged radiating adjacent to the Flight Guidance Panel, (FGP).

Removed covers from RH Radio Rack REER.

Swept from 2.4 to 2.5 GHz at +20 dBm in the REER using Hp tracking generator + pre-amp + 3ft sma cable into dipole. Dipole antenna moved throughout radio rack radiating.

Transponder, NAV, DME
COM, ADF, Audio (Two sweeps)
Right radio, back harnessed, back shelf
Between RH fault warning symbol generator
Ground Prox and IAC (Two sweeps)
Anti Skid Controller and APU Generator Controller
Cabin Press ECU and MDAU
Right Generator and Right Buss Power Control Unit
Right Hand Radio CB Panel
Cabin CB panel
Third shelf, RH Radio Rack outboard wiring harness
Fourth shelf, RH Radio Rack outboard wiring harness
Above main entrance door (Three sweeps)

Now using actual Bluetooth signal into preamp.
Marginal signal inside,
Level from generator is –73.5 dBm, breaking squelch. Bluetooth

transmitting outside (by cabin door) +20 dB. No noted interference
Bluetooth transmitting next to top antenna and bottom antenna of aircraft, no interference noted.

4.1 Engine interference Tests

Tests to determine if Bluetooth or CW signals 2.4 to 2.5 GHz have any effect on engine operation

Tests using CW signal 2.4 to 2.5 GHz at +20dBm
Baggage compartment EER
Top shelf
Flap controller
Security system battery pack
Emergency Light Battery
APU Electronic Control Unit
No Interference was noted.

Tests using Bluetooth signal.
Baggage compartment EER.
Flap controller
Security system battery pack
Emergency Light Battery
APU Electronic Control Unit
No Interference noted.

Tested throttle quadrant for interference placing the antenna around the throttle quadrant using 20dBm swept 2.3 to 2.5 GHz CW signal.
Gust lock right of throttle
Middle between the two throttles
Left side throttle
Middle advanced throttle
Horizontal to the throttle
Left throttle horizontal wing
Vertical middle throttle
Forward vertical
No Interference noted.

Tested Nose Wheel Steering using 20dBm swept 2.3 to 2.5 GHz CW signal.
No Interference noted.

Tested throttle handle interference placing the antenna around the throttle quadrant using 20dBm Bluetooth signal.
Gust lock right of throttle

Middle between the two throttles
Left side throttle
Middle advanced throttle
Horizontal to the throttle
Left throttle horizontal wing
Vertical middle throttle
Forward vertical
No Interference noted.

Also tested Nose Wheel Steering using 20dBm Bluetooth signal.
No Interference noted.

4.2 Magnastar Interference Tests:

The Magnastar was not transmitting or receiving due to the lack of a ground station at this location. The RSS values of the Magnastar were acceptable. No anomalies were noted.

A/C 590 5-11-00

Gulfstream GV

EMI MATRIX CHART

SOURCE EQUIPMENT		MONITOR EQUIPMENT (VICTIM)				REMARKS
				(1) LOSS OF FUNCTION (2) OBSCURING FUNCTION (3) ANNOYING (4) MINOR (5) OTHER (6) NO EFFECT		USE WHENEVER NECESSARY AND ALWAYS WHEN CODE (5) IS USED.
SOURCE EQUIP.	FUNCTION/ FREQUENCY	VICTIM EQUIP.	FREQUENCY/ MHz	AUDIO	VISUAL	All Checked w/ Track Gen And Panel II w/BTooth + Ampd +20dBm
PCM CARD	2.4GHz	VHF COMMS	120.02 124.00 128.025 132.025 151.975	6	6	
		HF COMMS	2.4218(*11) 4.8437(*10) 9.6875(*9) 10.0450*(8) 19.3750(*7)	6	6	
		UHF COMMS	223.20 275.25 310.00(*3) 370.75 395.00	6	6	
		RADAR	ON/OFF	6	6	Watch for false or charging targets during radiated testing of PCM CARD
		SATCOM	CALL IN PROGRESS	—	—	Not Commissioned
		IFF	OFF	6	6	
		TACAN	ON LOCAL CHANNEL	6	6	No DME Displayed
		MAGNASTAR	CALL IN PROGRESS	—	—	No Gnd Station
		UHF SATCOM	CALL IN PROGRESS	—	—	No Channel Allocated
		VHF NAVS	~~CALL IN PROGRESS~~ Local VOR	6	6	
HF COMM		PCM CARD	OPERATING			
		RADIO ALTIMETER	OPERATING	6	6	

SOURCE EQUIPMENT		MONITOR EQUIPMENT (VICTIM)				REMARKS
				(1) LOSS OF FUNCTION (2) OBSCURING FUNCTION (3) ANNOYING (4) MINOR (5) OTHER (6) NO EFFECT		USE WHENEVER NECESSARY AND ALWAYS WHEN CODE (5) IS USED.
		ADF	151.367KHz(*15) 302.734 KHz(*14) 605.469 KHz(*13) 1210.938 KHz(*12)	6	6	
		AFGCS		6	6	
		STALL BARRIER	ON	6	6	
		FLAP STSAB CONTROLLER	10°	6	6	
		FLIGHT CONTROL FAILURE DETECTION		6	6	
		FADEC		6	6	ENG RUN START 1830
		NOSE WHELL STEERING		6	6	
		EDS		6	6	
		MADC		6	6	
			* NO PROBLEMS NOTED DURING BLUE TOOTH RADIATION @ +20dBm			
			* NO PROBLEMS NOTED DURING SWEEP TESTING IN THE CABIN OR CKPT AREAS			

5

1. Tested preamp (HP8449B) 30 db gain. 25’ cable has 5 db loss. 3’ cable has 1 db loss. It has +20dbm output before saturation.

2. Configuration: 10 db / 6 db atten to tee then to preamp to ant. Then Ant. on analyzer. BT at other end of the atten.

3. Set tracking gen to –5 dbm 5 db cable loss connected to the preamp. Preamp output to dipole and sweep in cockpit. Freq. Range 2.4 – 2.5 GHz.

4.+20 dBm in cockpit using Hp tracking generator + pre-amp + 3ft SMA cable into dipole. Dipole antenna moved throughout cockpit.

Tests:

LH FMS CDU,
Left Audio, Right Audio
Right FMS, Left FMS
Standby instruments
Center Overhead
Overhead CB panel center
HUD system
Autopilot

5.1 Take covers off of radio rack

Transponder, NAV, DME
COM, ADF, Audio (Two sweeps)
Right radio, back harnessed, back shelf
Between RH fault warning symbol generator
Ground prox and IAC (Two sweeps)
Anti Skid and APU gen
Cabin press control and MDAU
Right generator and right buss power control unit
Right hand radio XCD control panel
Cabin CD panel
Circuit Breaker
Third shelf, RH radio rack outboard harness
Fourth shelf, outboard
Above main entrance door (Three sweeps)

Now use actual Bluetooth signal into preamp

Marginal signal inside,
Level from generator outside aircraft is –73.5 dBm, breaking squelch;
Bluetooth transmitting outside (by cabin door) +20 dB. No noted interference
BT transmitting next to top antennae and bottom antennae of aircraft

Path Loss Measurements

Two cables (one for each antenna) back to back.
File name tst00049.csv.

Dipoles @ 6 inches apart in center cabin.
Filename is tst00051.csv (00050 is scrap)

Vertical to vertical cockpit to front cabin center (window 2) 00052
Horizontal wing to cockpit 00053
Horizontal fusilage to cockpit 00054

Vertical to vertical cockpit to rear cabin center (window 4-5) 00055
Horizontal wing 00056
Horizontal fusilage 00057

Path loss (cont)
Vertical vertical cockpit to rear of cabin 00060 (00058 bad)
Horiz Horiz parallel to wing cockpit to rear of middle cabin 00061(00059 bad)
Horiz Horiz pointing to front &parallel to fusalage 00062

Vertical vertical cockpit to rear of aircraft 00063
Horiz Horiz parallel to wing cockpit to rear of aircraft 00064
Horiz Horiz pointing to front &parallel to fusilage 00065

5.2 Path loss msmts from dipole to actual aircraft antennas

Vertical dipole in front cabin window to Nav receiver (coax #1) 00066
Vertical dipole outside bottom of aircraft to Nav (coax #1) 00067
Same test as above but with coax #2 00068
Same test as above but with coax #3 00069

IFF receive/transmit antenna top 00070 (with dipole outside)
Same as above but dipole in seat 2 vertical 00071
Same as above but dipole horizontal pointing forward 00073

IFF lower antenna with dipole in seat 2 vertical 00074
Same as above but dipole horizontal pointing forward 00075

Did not do DME since it would likely be the same (antennas nearly the same)qaqq

Could not get multiple Bluetooth devices to continue operation inside the aircraft. Needs further investigation to determine whether there are multipath effects, interference from aircraft systems or a software problem in the Palm Pilot

Engine interference tests

Tests to determine if BT or CW signals 2.4 to 2.5 GHz have any effect on engine operation.

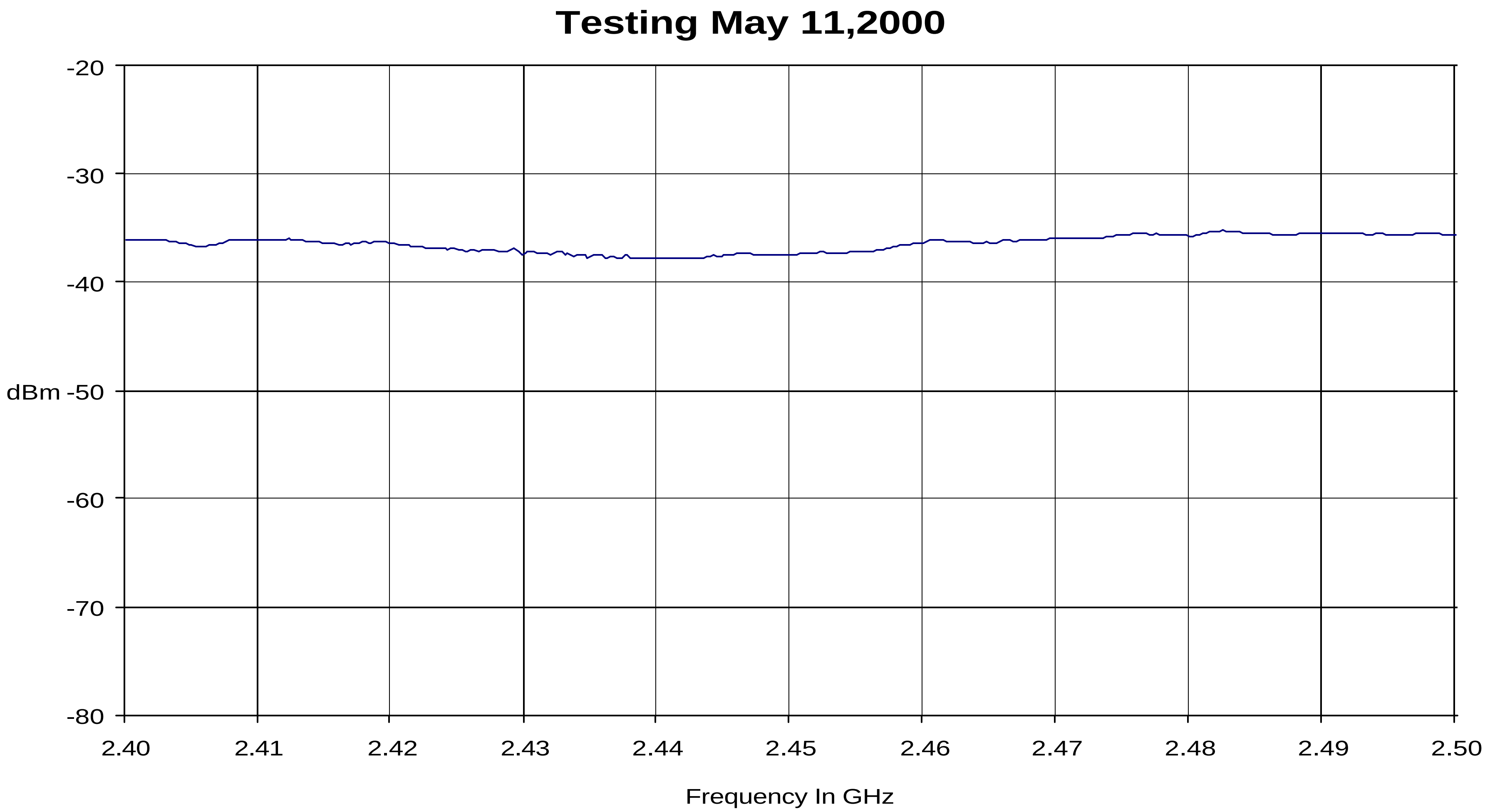
Tests using CW signal 2.4 to 2.5 GHz at +20dBm
Back of the airplane
Top shelf
Flap controller
Security system battery pack
Emerg Light Battery
APU Elec Control Unit

Tests using BT signal
Back of the airplane: APU
Top shelf
Flap controller
Security system battery pack
Emerg Light Battery

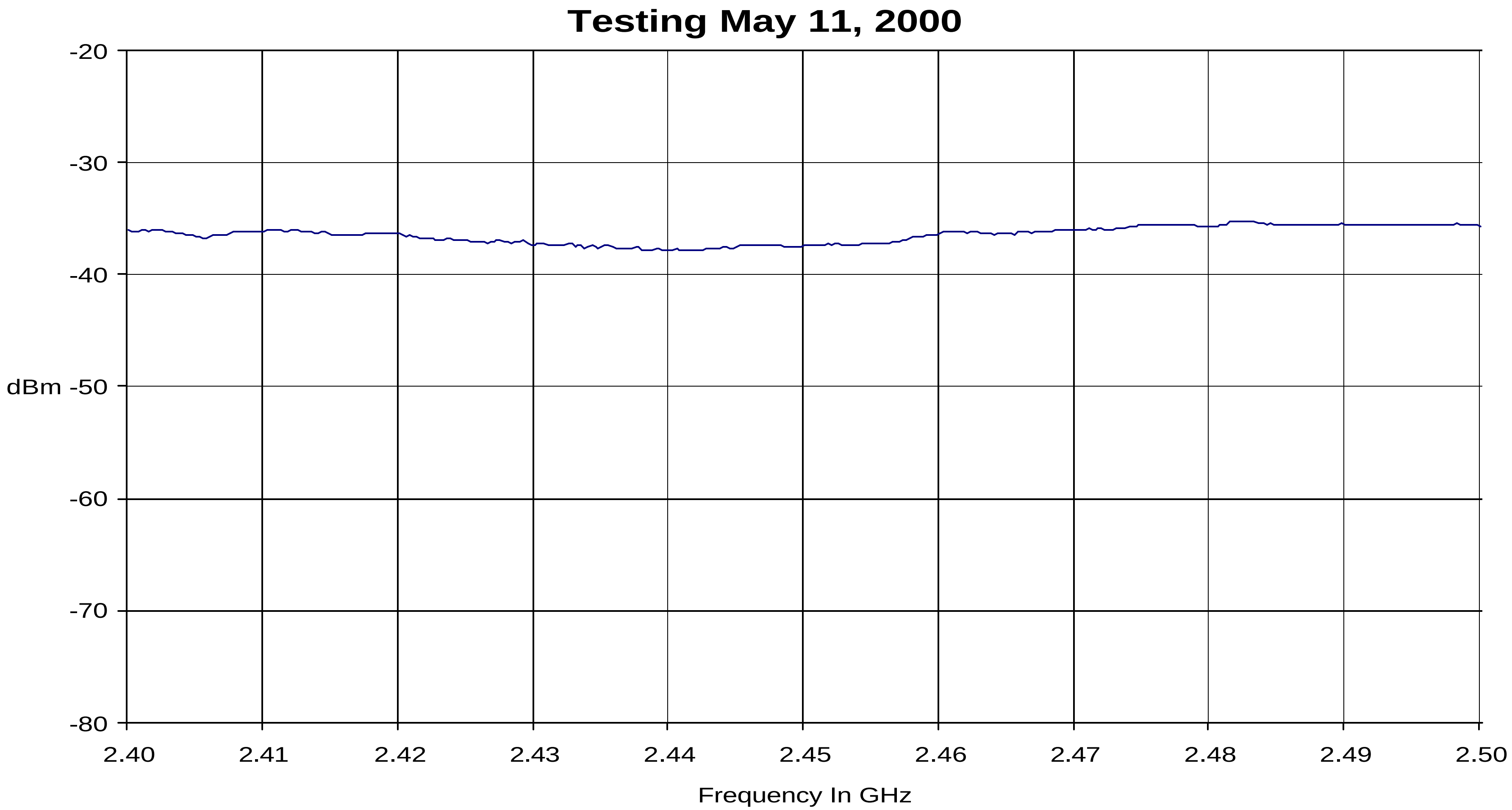
APU Elec Control Unit

Did Magnastar tests: No effect

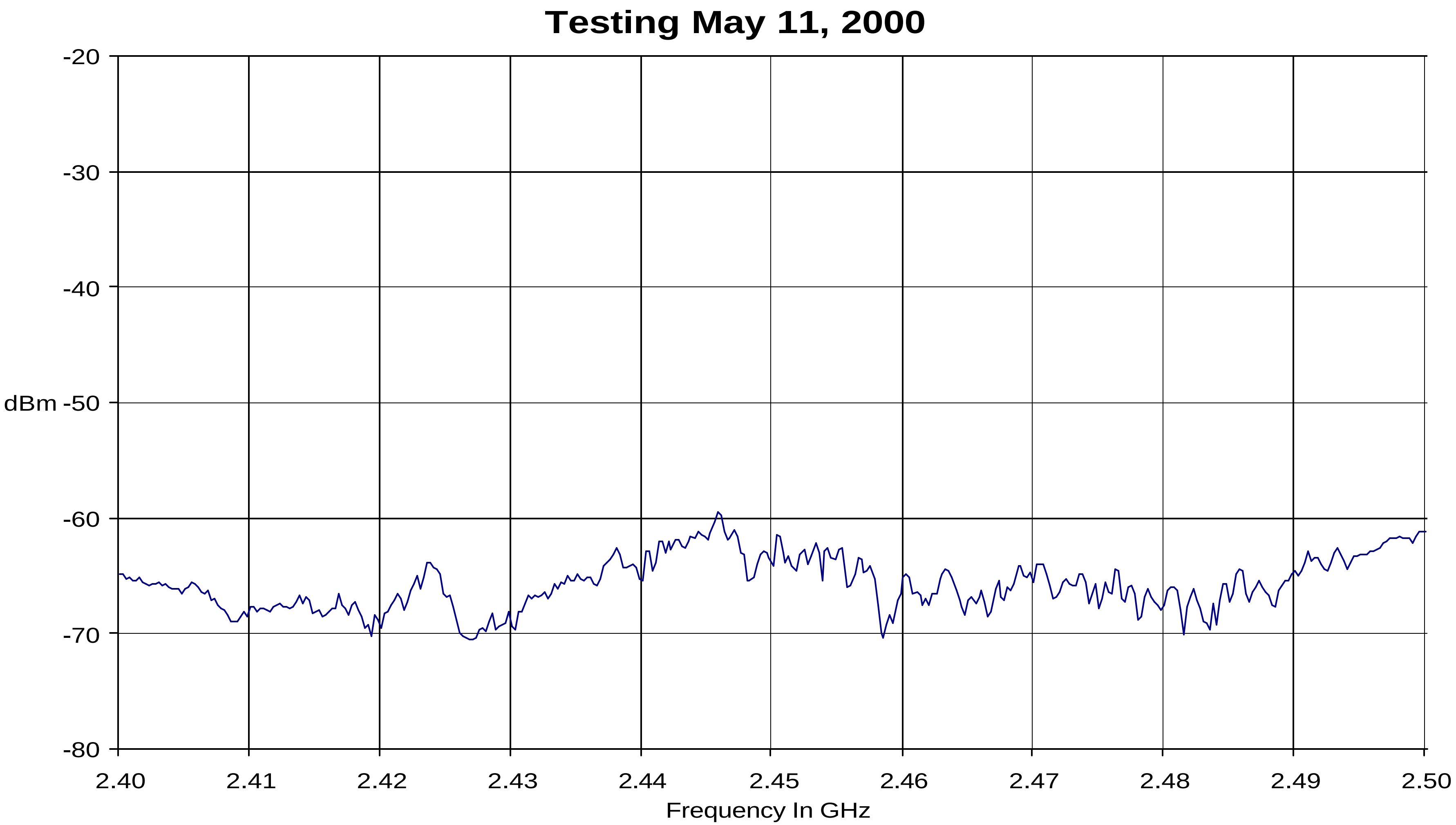
Tested front area engine interference using 20dBm CW signal
Tested front area engine interference using 20dBm BT signal
Gust lock right of throttle
Middle between the two throttles
Left side throttle
Middle advanced throttle
Horizontal to the throttle
Left throttle horizontal wing
Vertical middle throttle
Forward vertical
Left console and moved steering



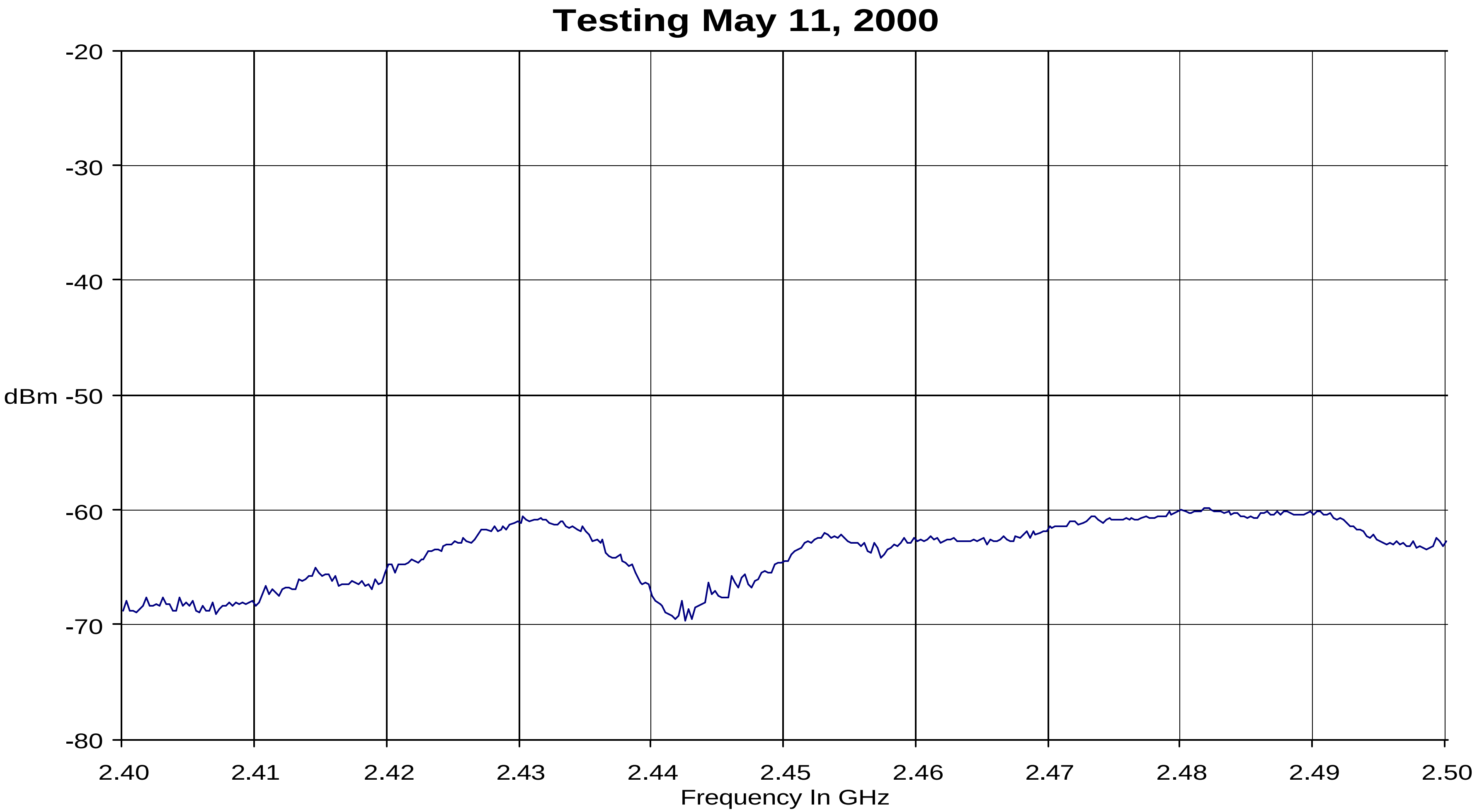
File 51.csv – Dipoles 6” apart in fwd center of the cabin.



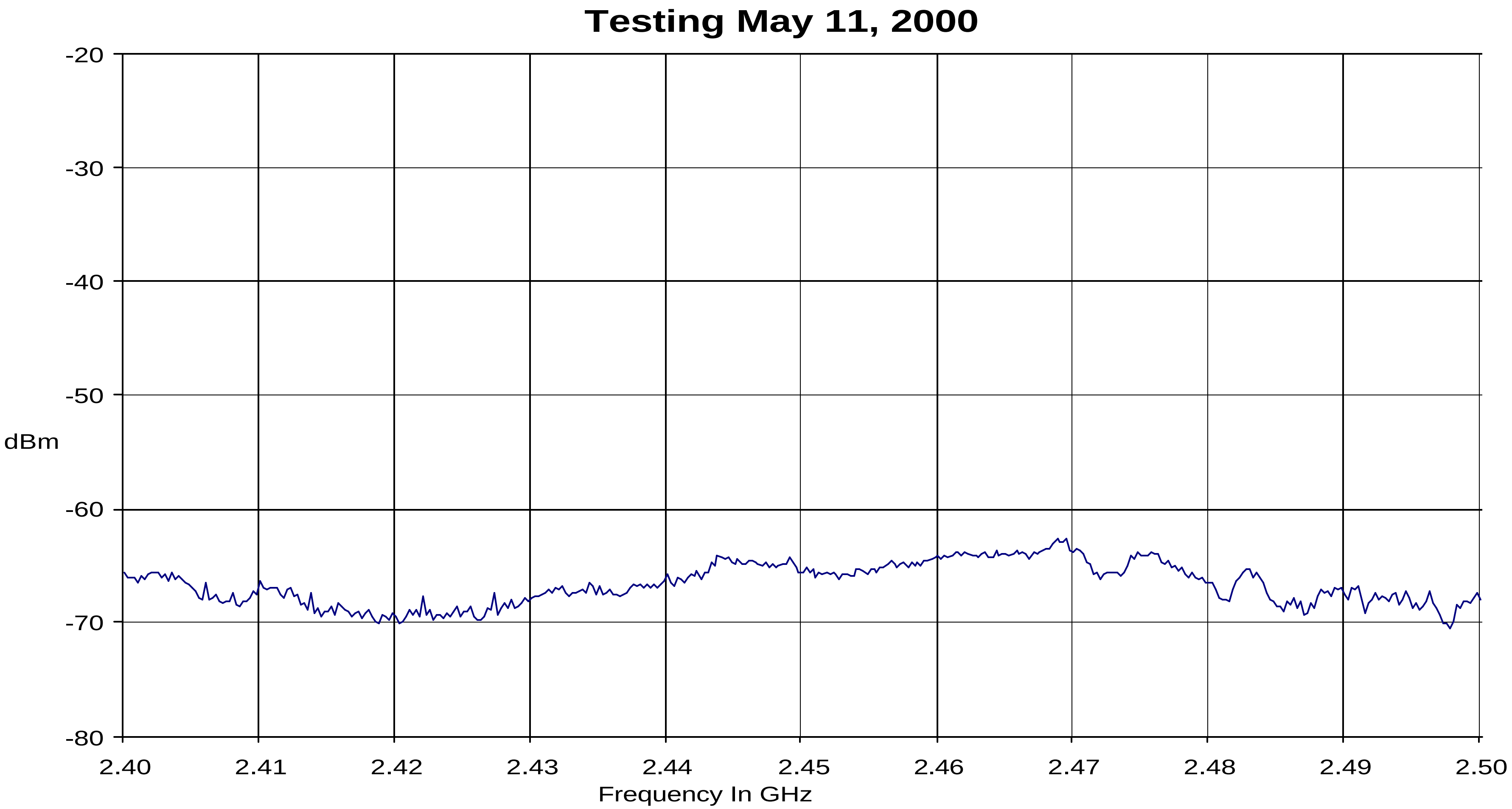
File 32.csv – Flight deck (aft pedestal area), antenna vertical polarity transmit to the Fwd cabin center, window #2 antenna receive, vertical polarity.



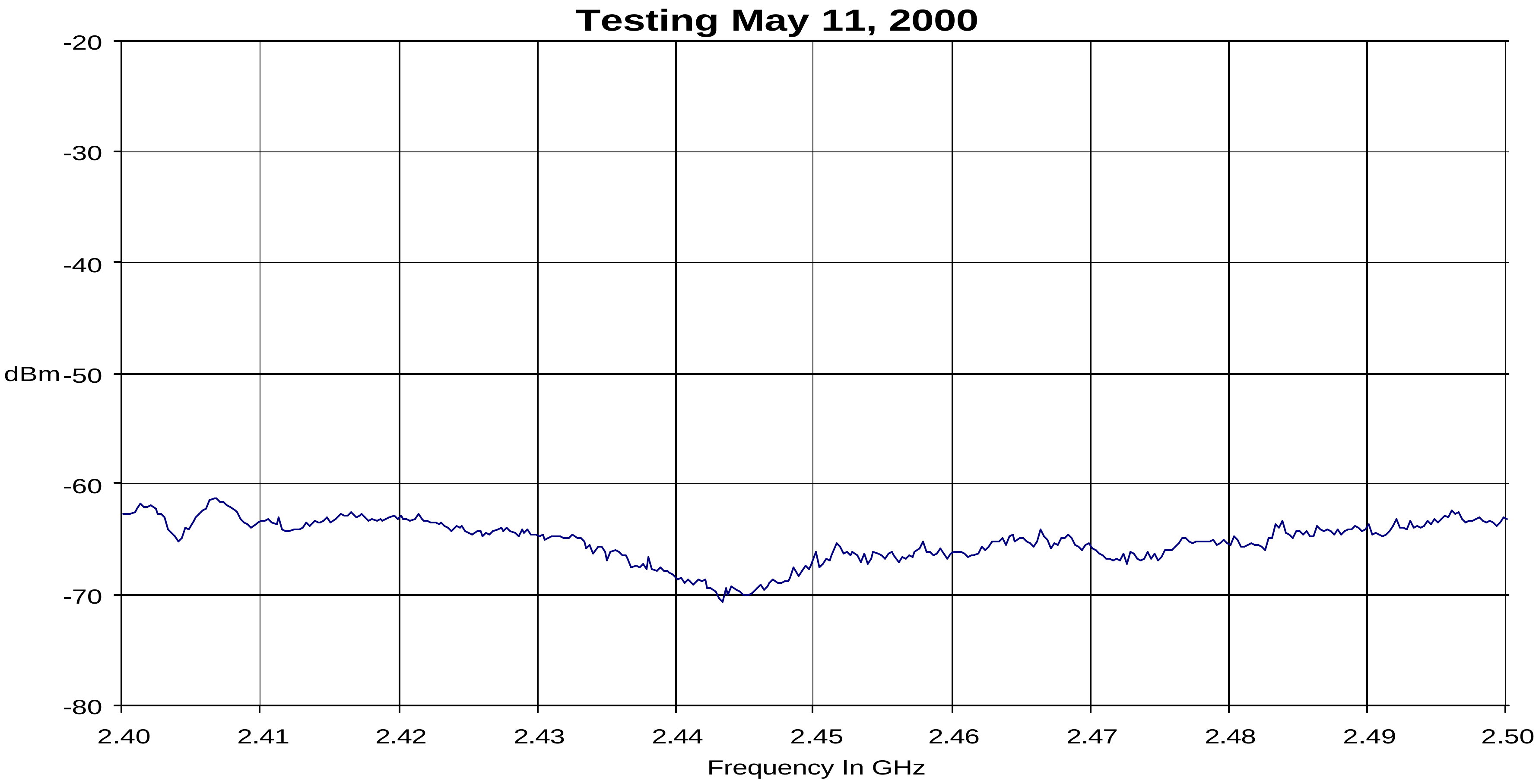
axis along the wing.



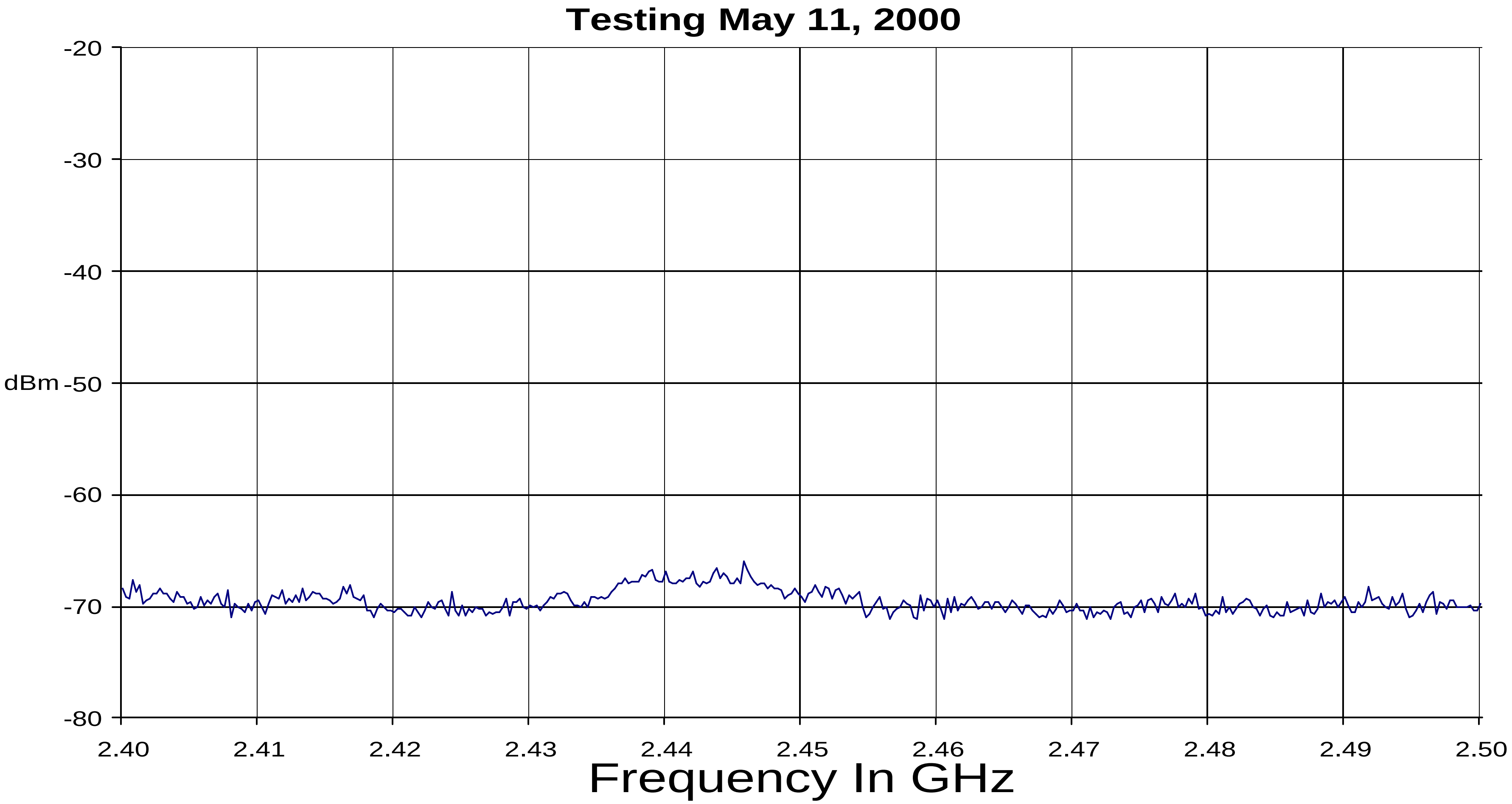
axis along the fuselage.



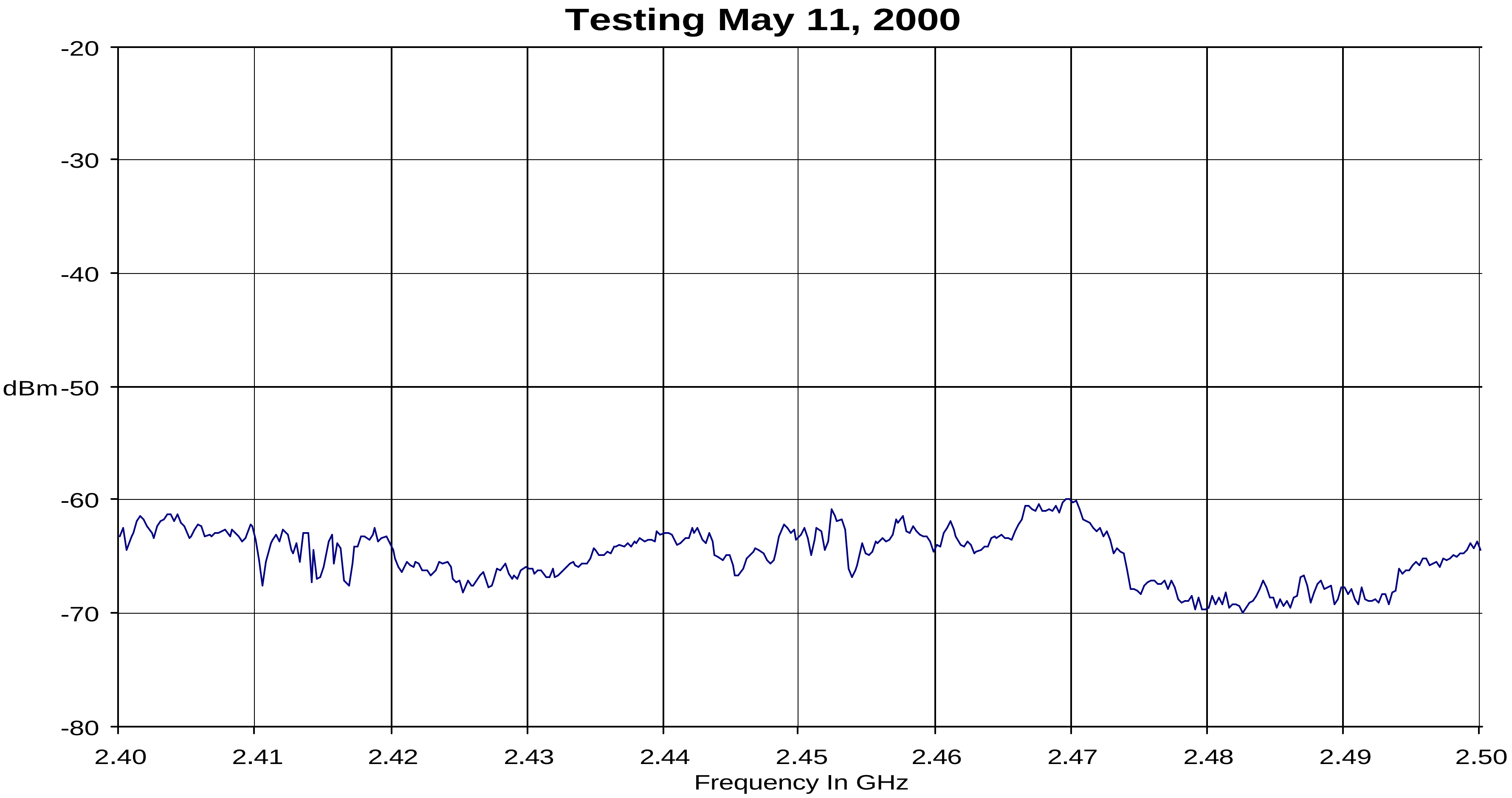
File 55.csv – Flight deck (aft pedestal area), antenna vertical polarity transmit to the Middle cabin center, window #4-5 antenna receive, vertical polarity.



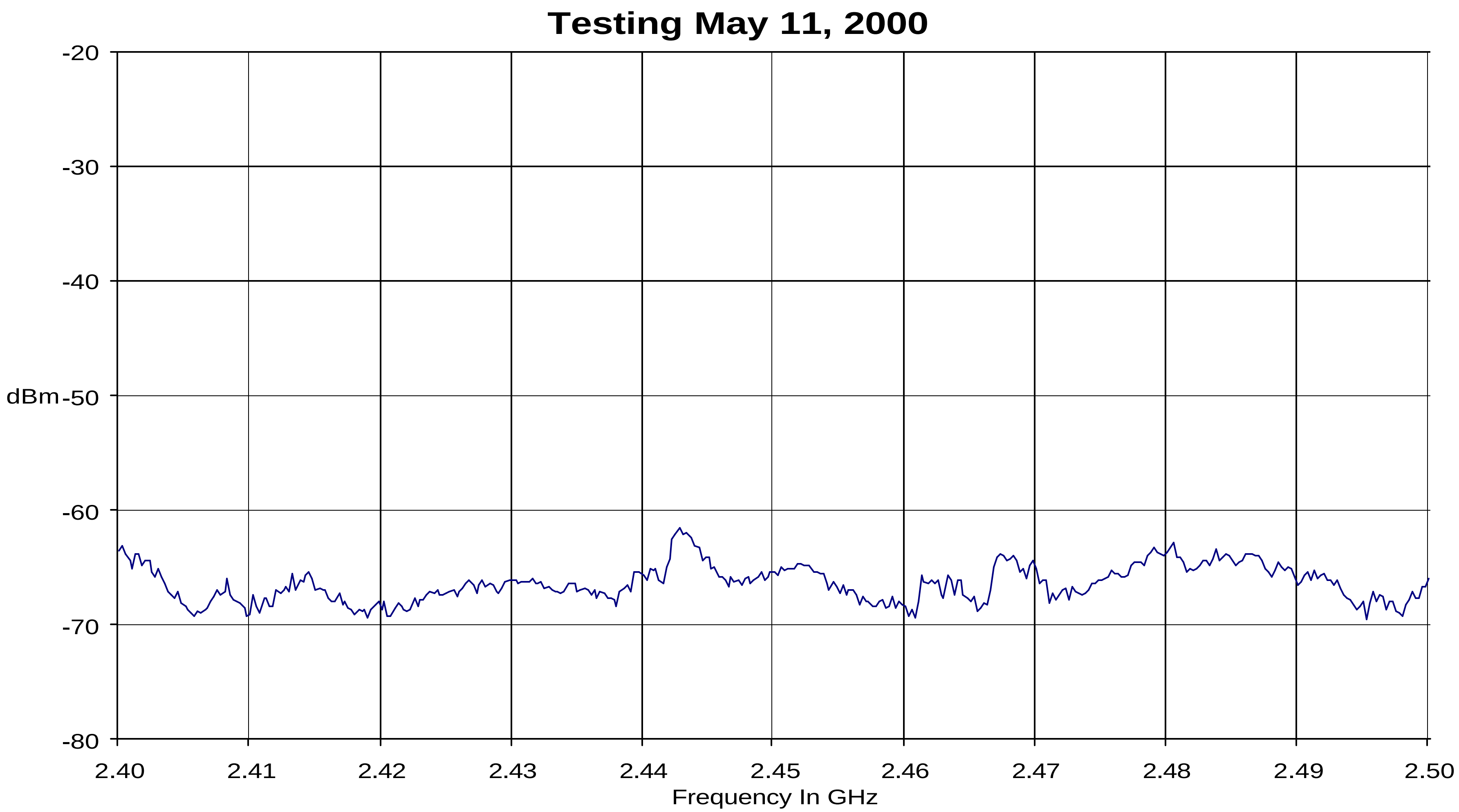
polarity, axis along the wing.



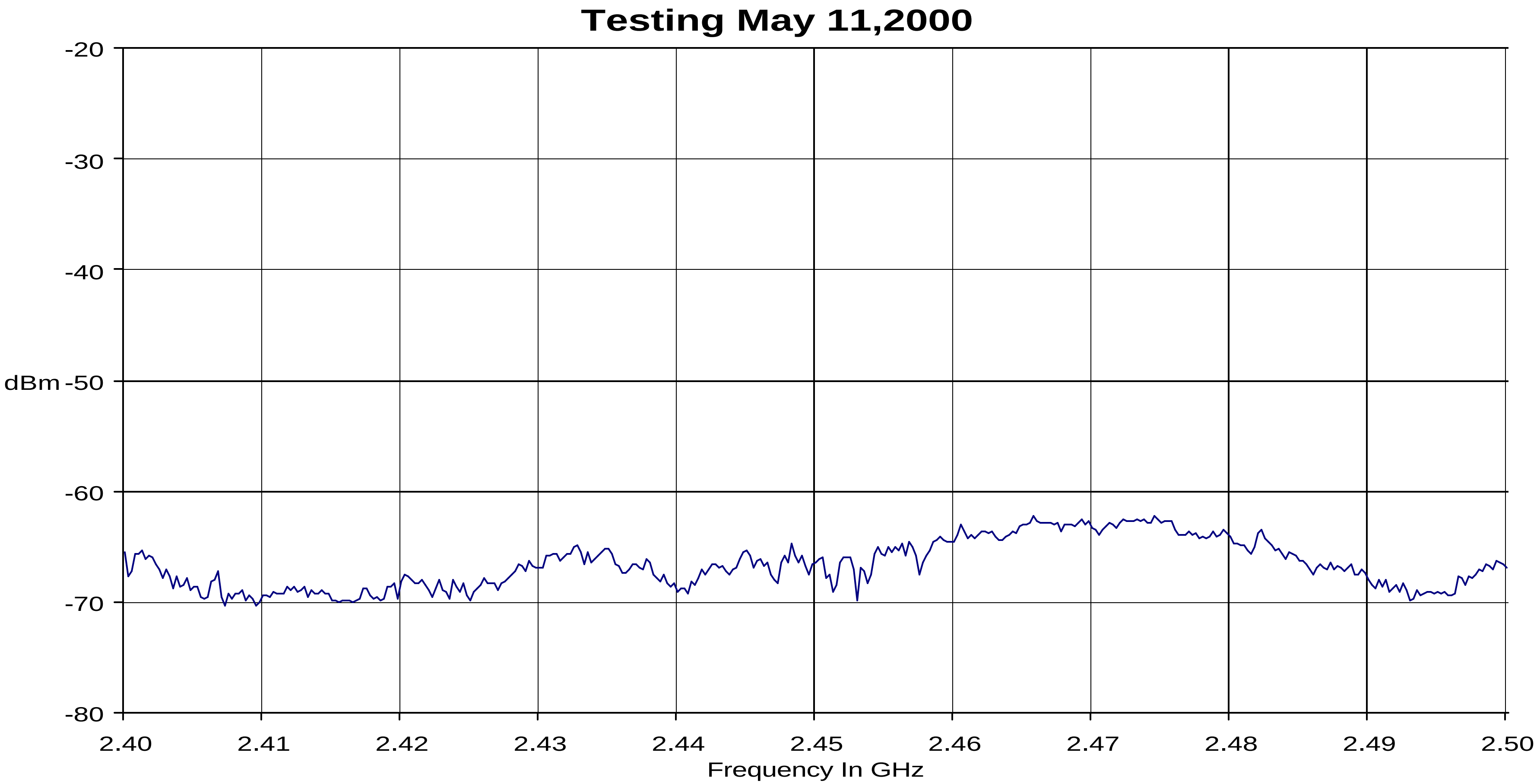
File 57.csv – Flight deck (aft pedestal area), antenna vertical polarity transmit to the Middle cabin center, window #4-5 antenna receive, horizontal polarity, axis along the fuselage.



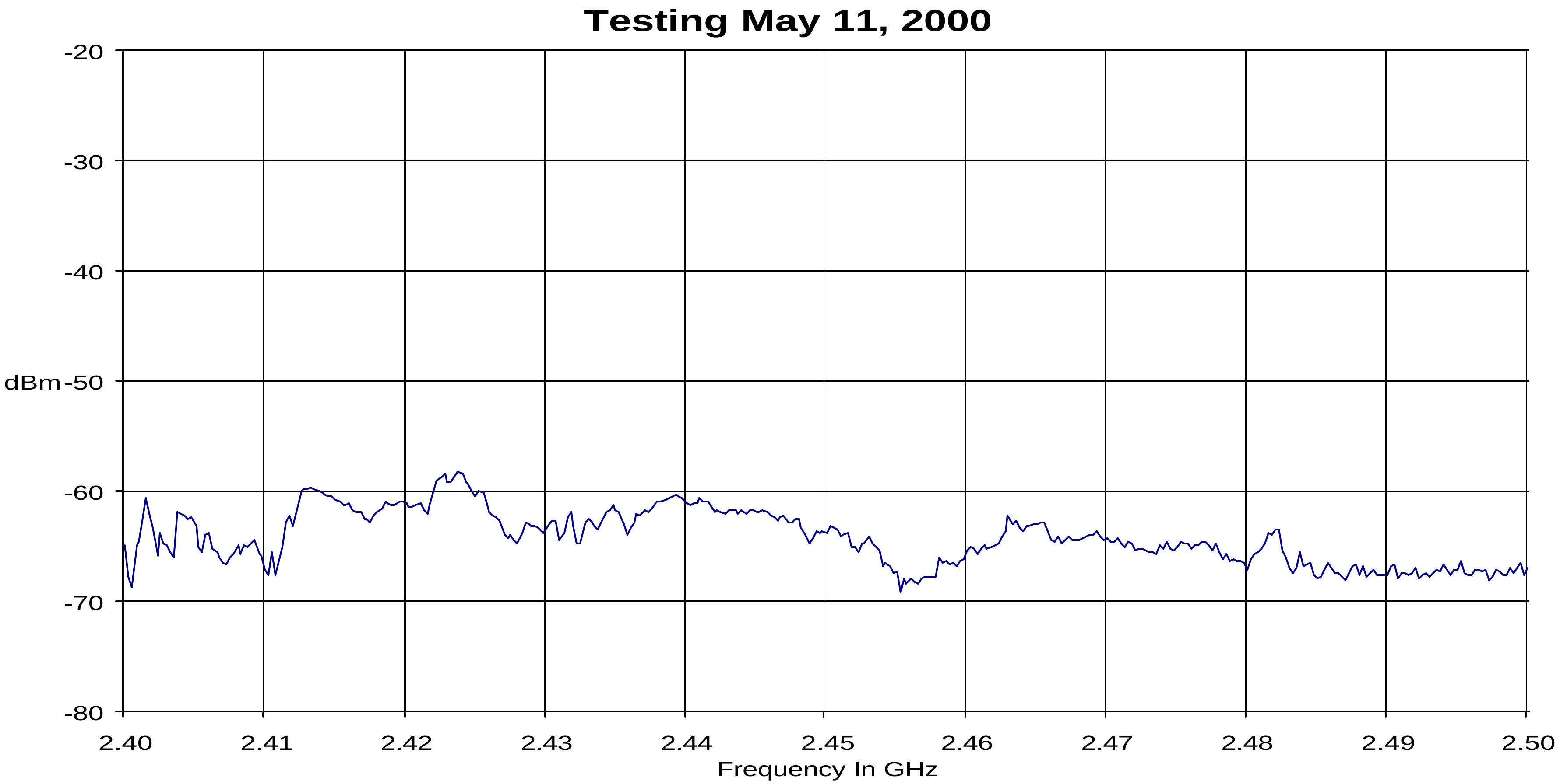
File 60.csv – Flight deck (aft pedestal area), antenna vertical polarity transmit to the Aft cabin center, antenna receive, vertical polarity.


Testing May 11, 2000
dBm
-20
-30
-40
-50
-60
-70
-80
2.40
2.41
2.42
2.43
2.44
2.45
2.46
2.47
2.48
2.49
2.50
Frequency In GHz

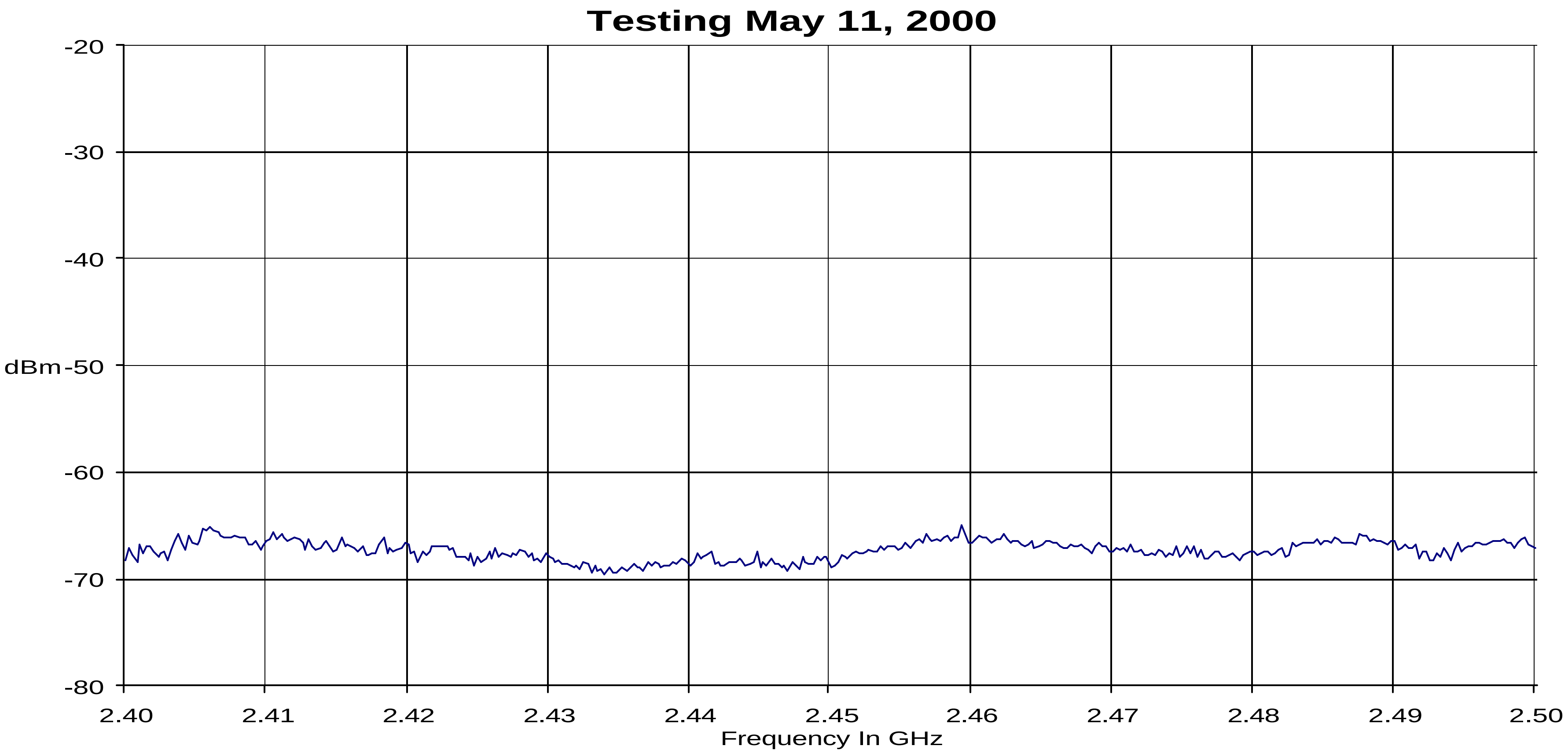
the wing.



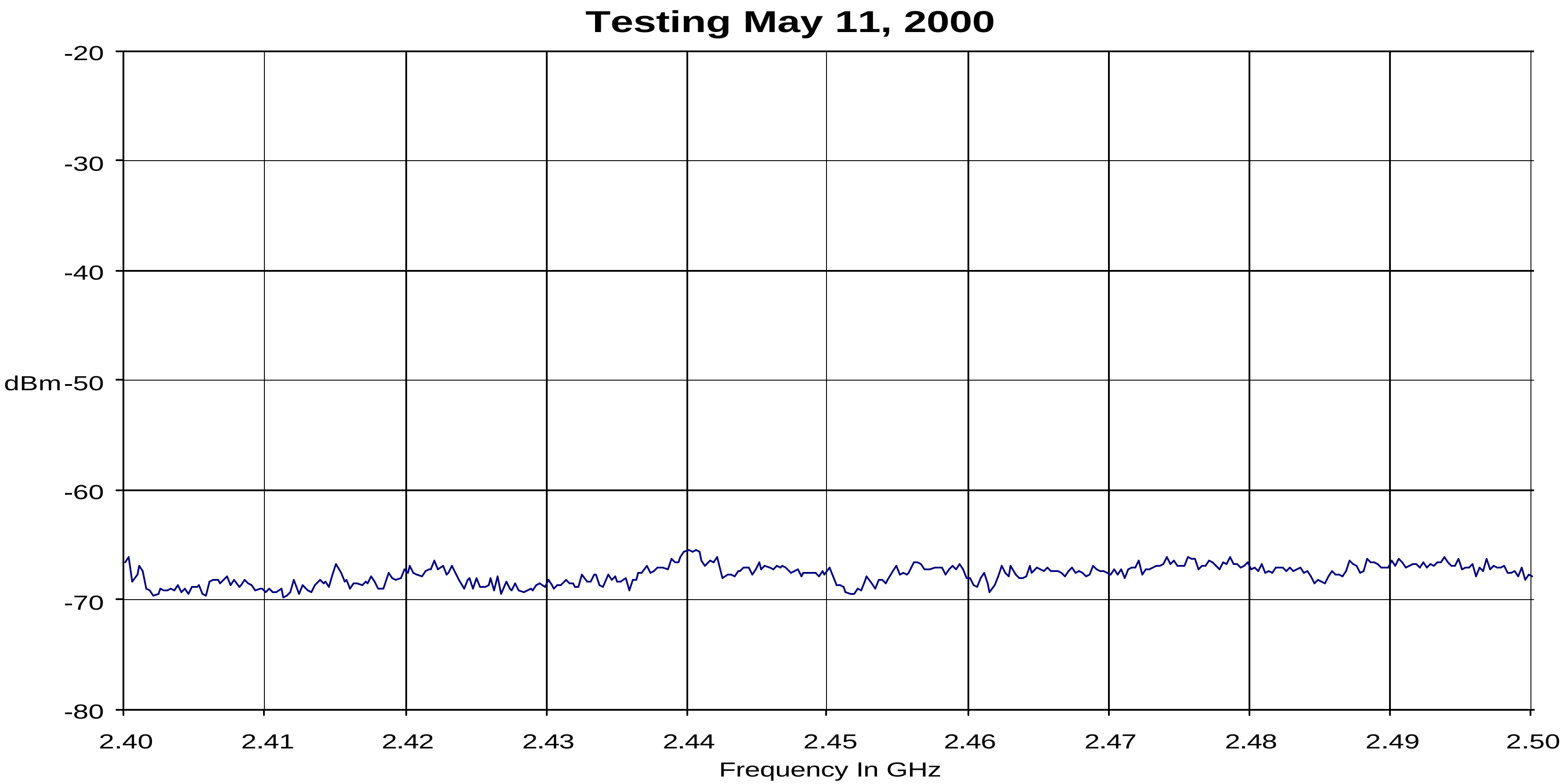
the fuselage.



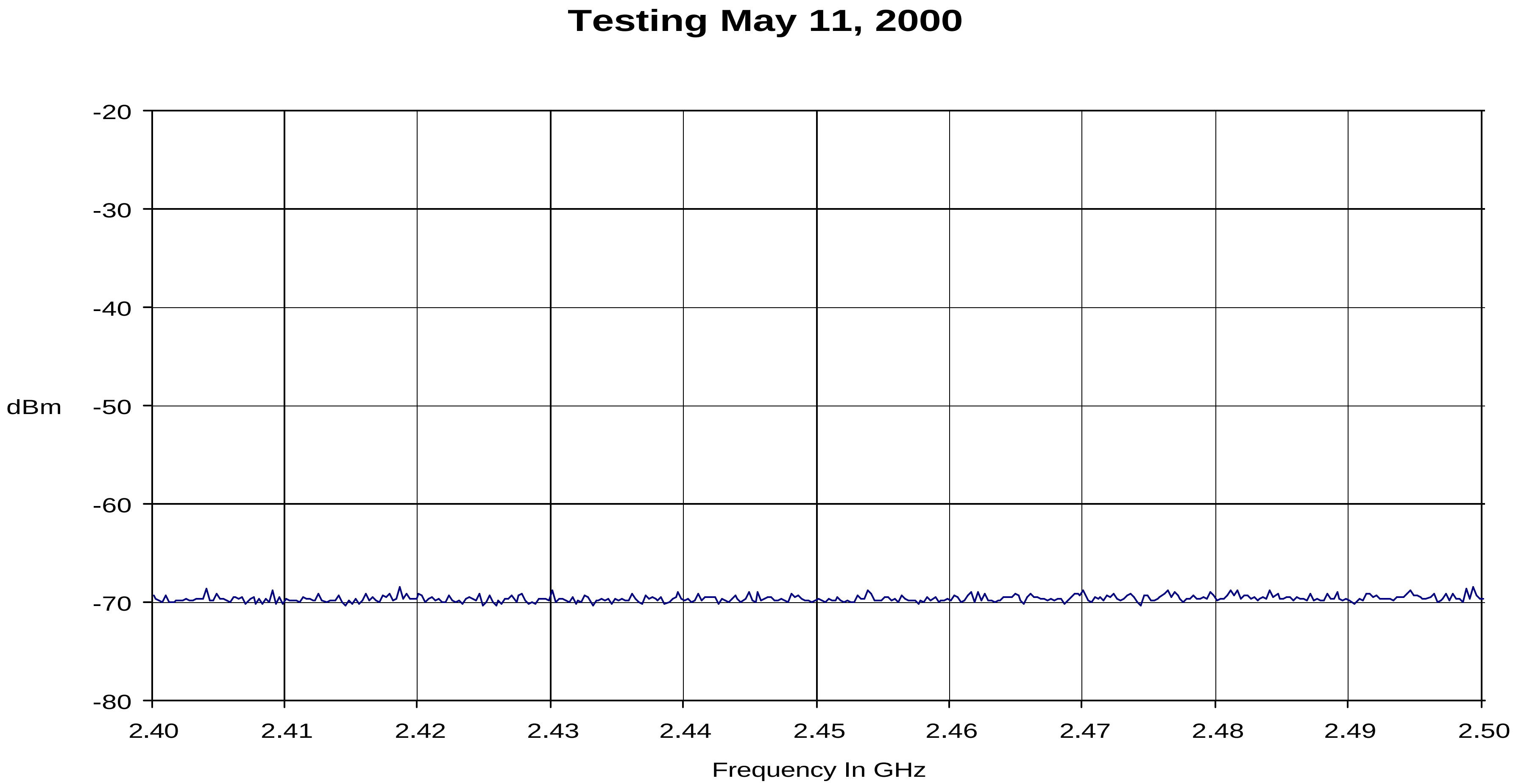
File 03.csv – Flight deck (aft pedestal area), antenna vertical polarity transmit to the Baggage compartment center, antenna receive, vertical polarity.



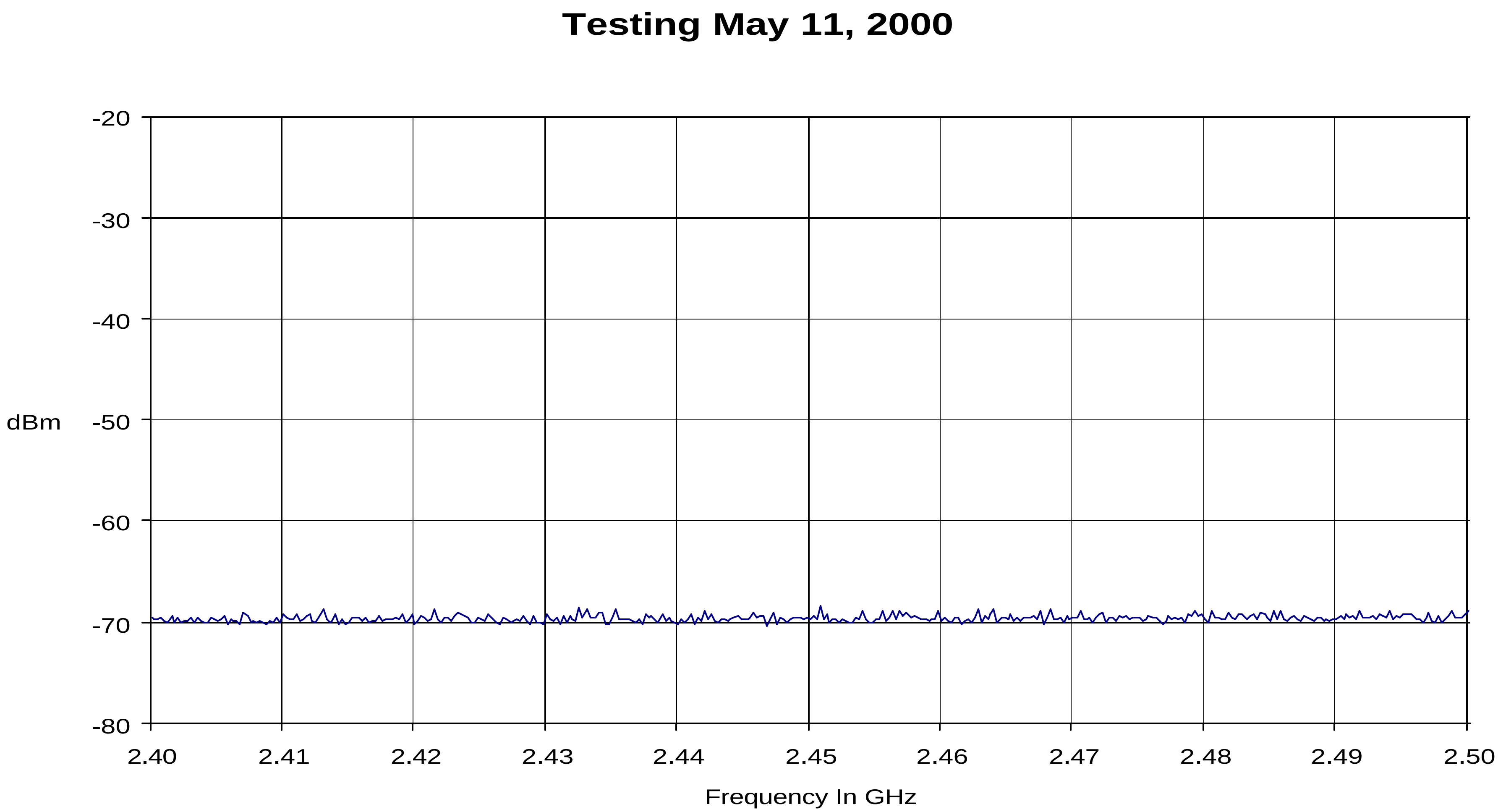
File 64.csv – Flight deck (aft pedestal area), antenna vertical polarity transmit to the Baggage compartment center, antenna receive, horizontal polarity, axis along the wing.

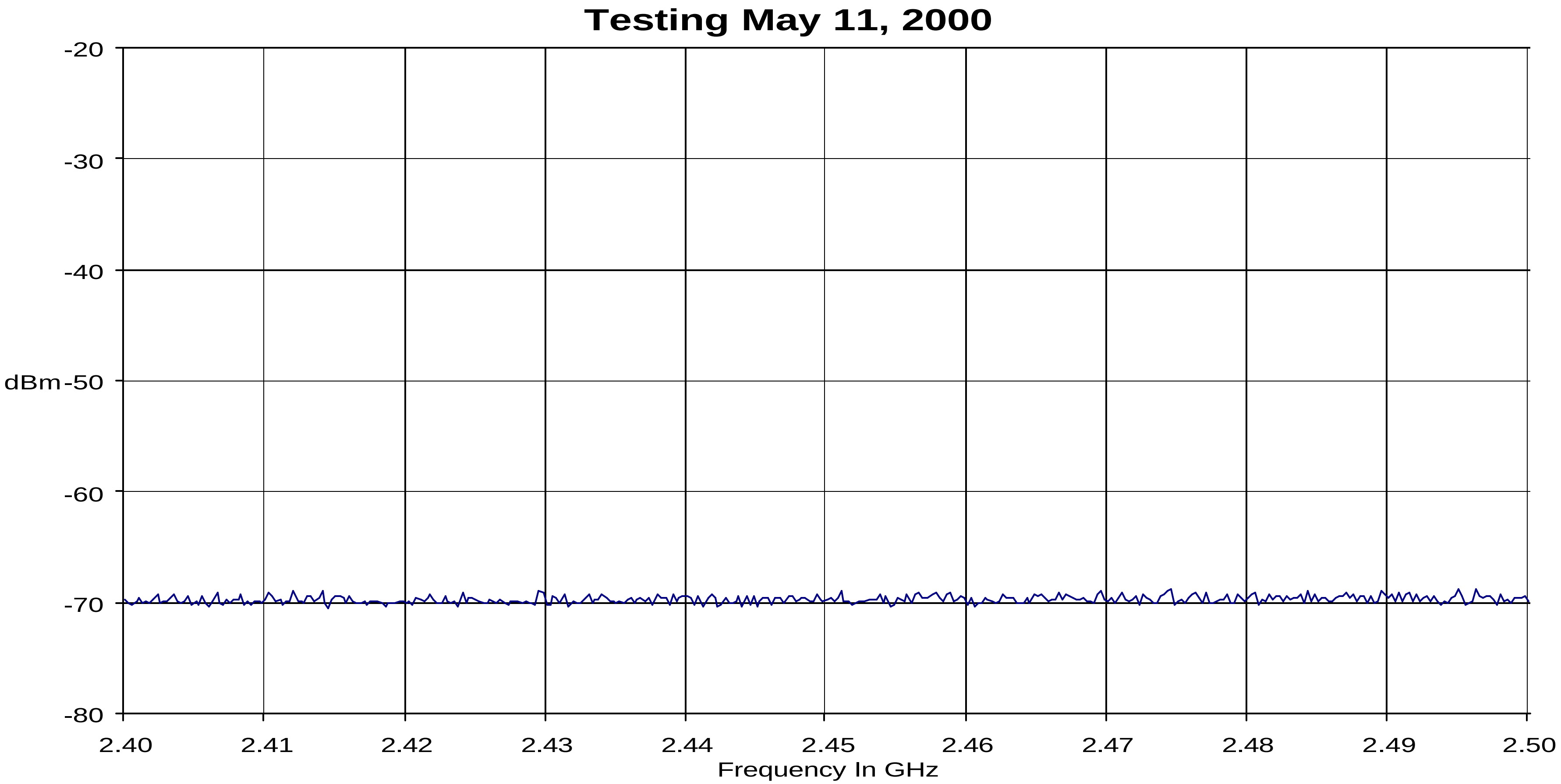


File 65.csv – Flight deck (aft pedestal area), antenna vertical polarity transmit to the Baggage Compartment, antenna receive, horizontal polarity, axis along the fuselage.

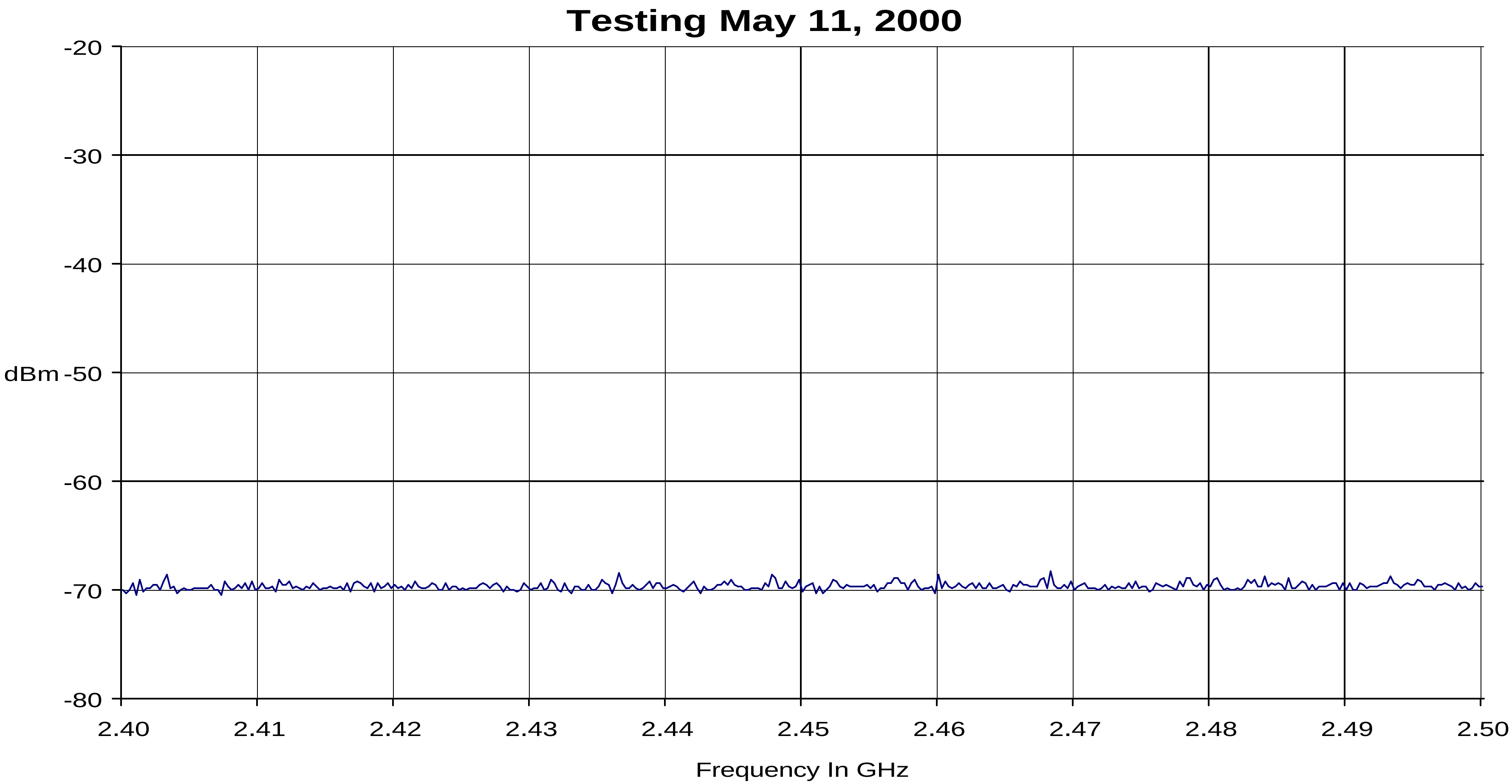


located in the Right Electrical Equipment Rack (REER) with the receiver removed and the analyzer connected to the #1 coaxial insert.

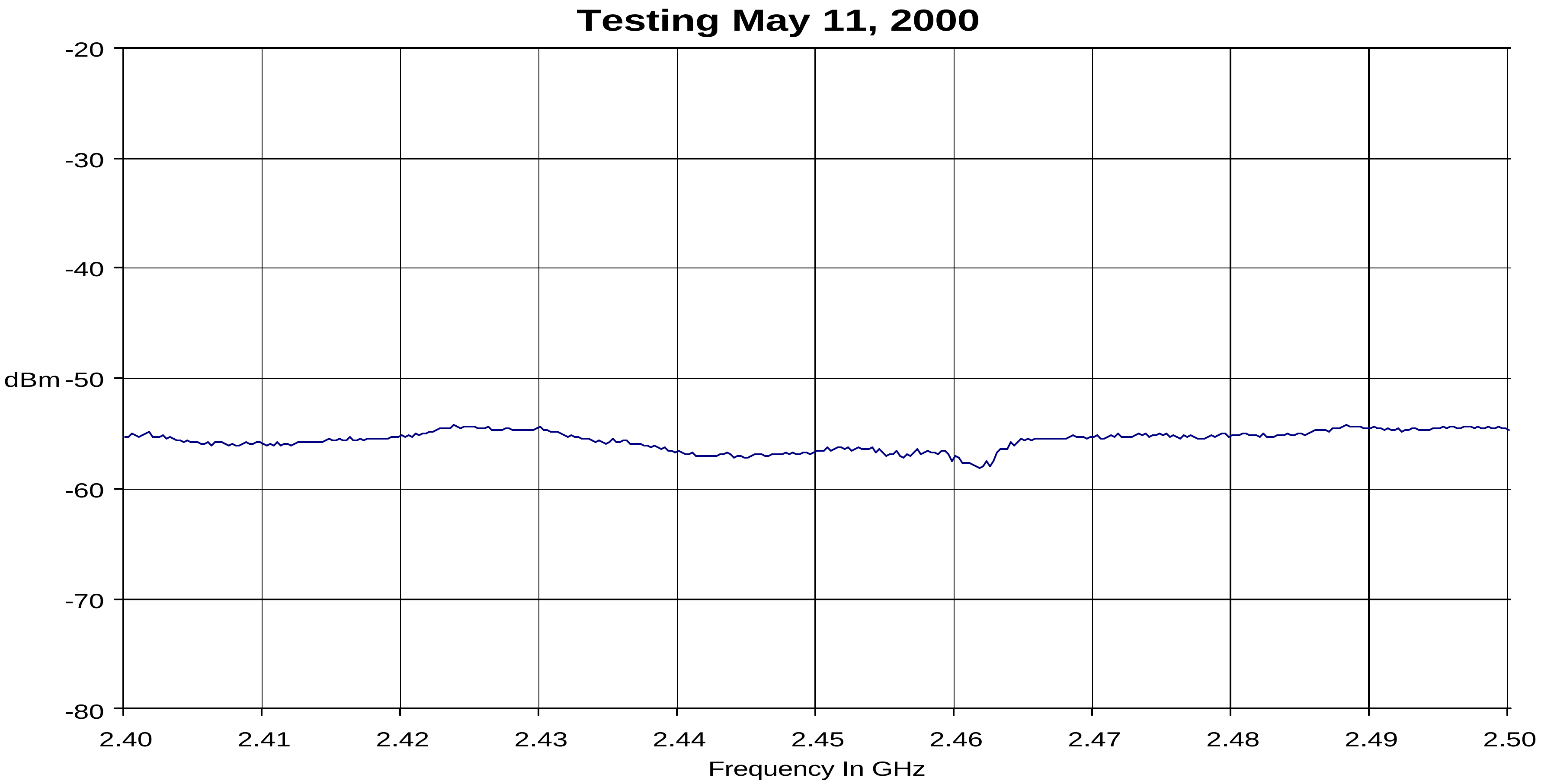

Testing May 11, 2000
dBm
-20
-30
-40
-50
-60
-70
-80
2.40
2.41
2.42
2.43
2.44
2.45
2.46
2.47
2.48
2.49
2.50
Frequency In GHz

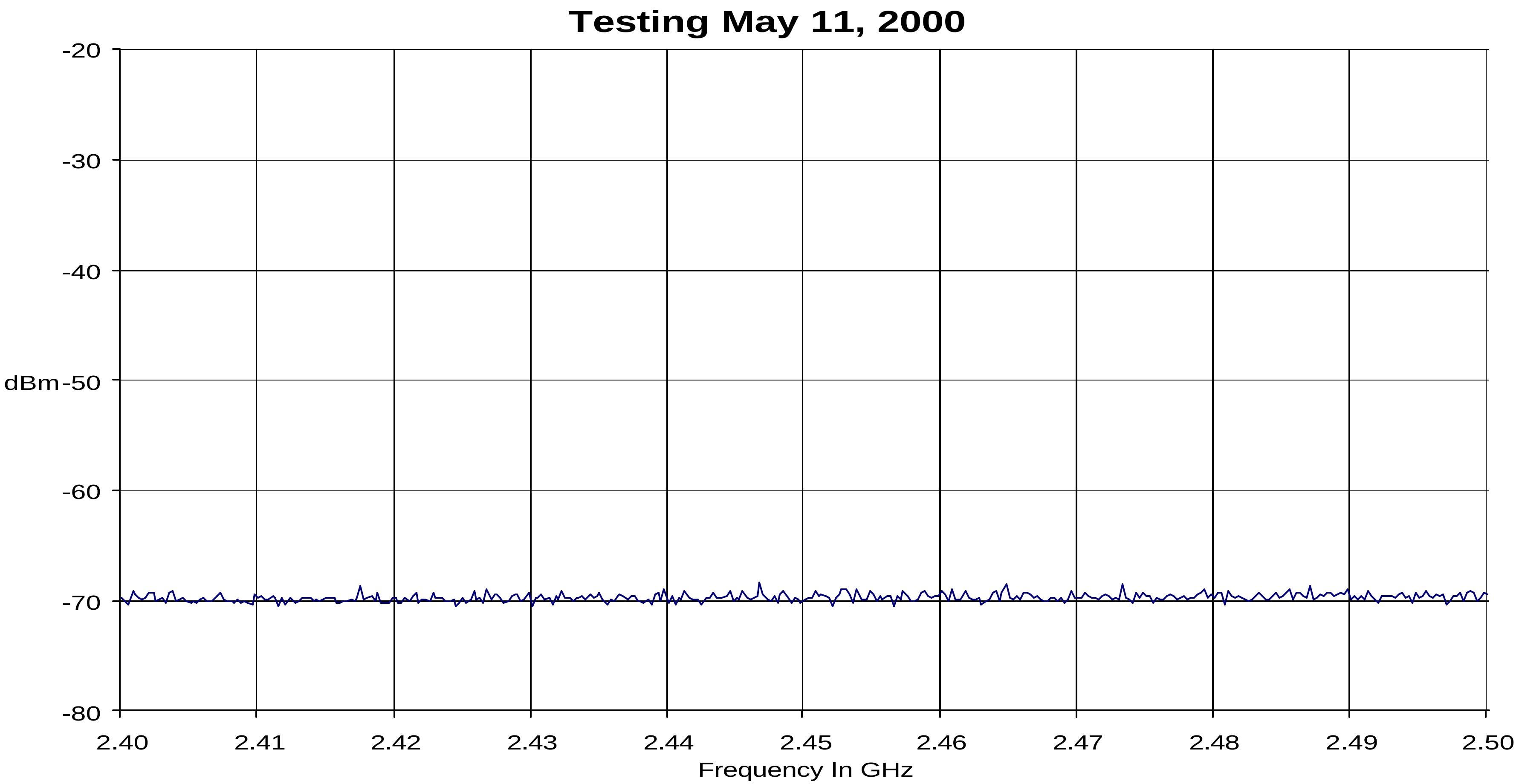


File 68.csv – Transmitting antenna located out side the aircraft, adjacent to the main cabin door, positioned vertically. Receive path is from the #2 VHF NAV RX #2 located in the Right Electrical Equipment Rack (REER) with the receiver removed and the analyzer connected to the #2 coaxial insert.

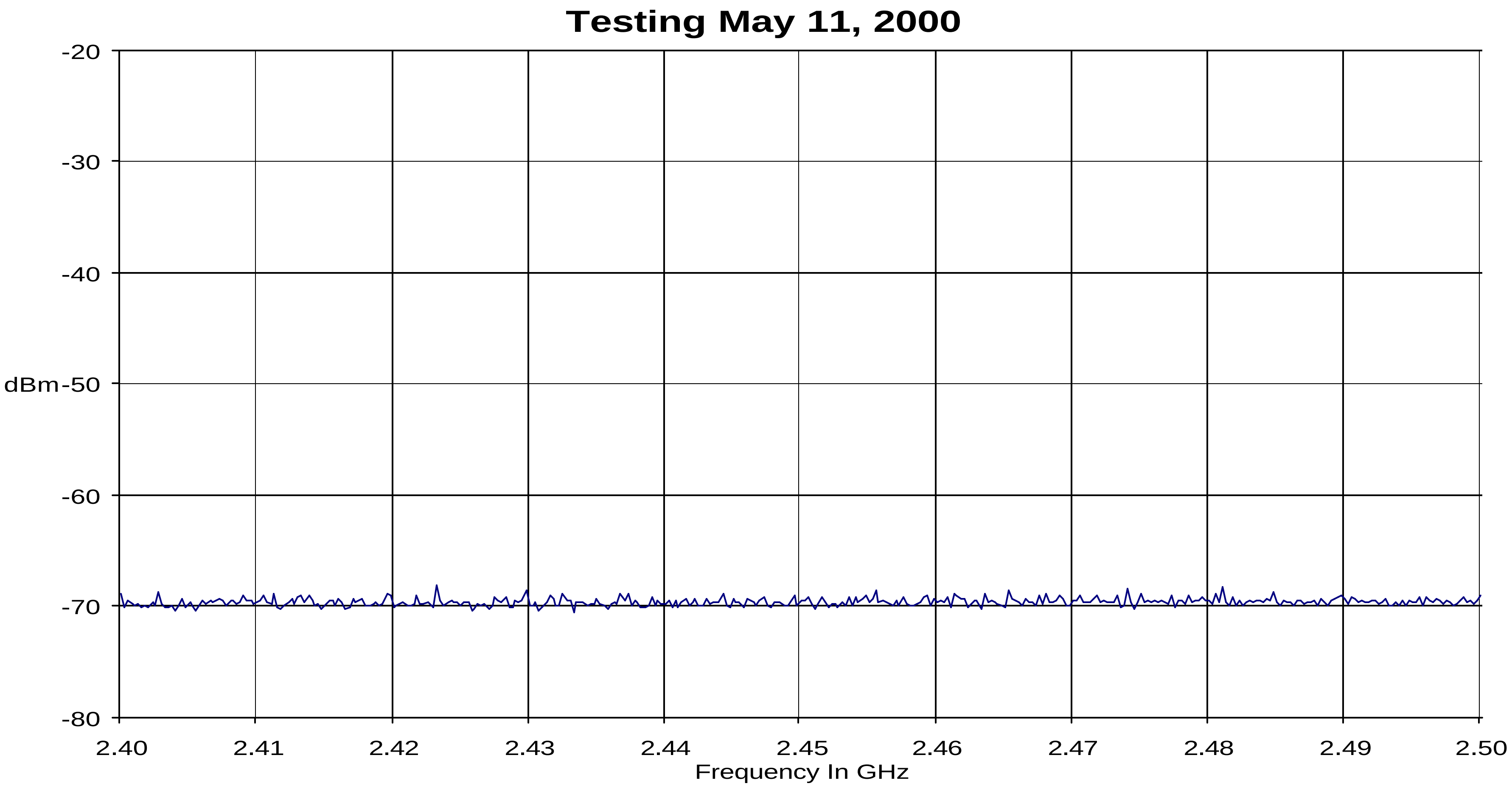


VHF NAV RX #2 located in the Right Electrical Equipment Rack (REER) with the receiver removed and the analyzer connected to the #2 coaxial insert.

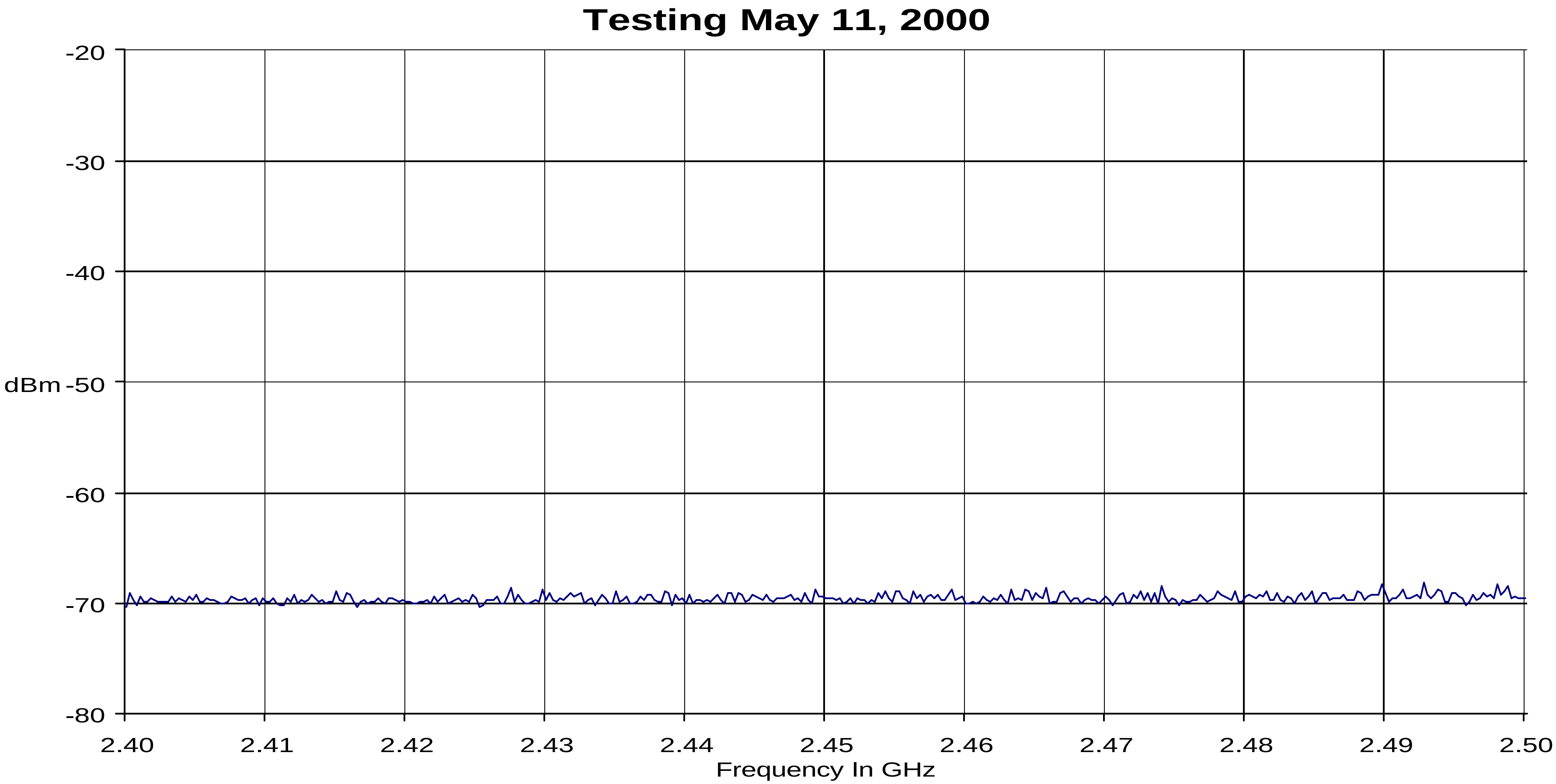

Testing May 11, 2000
-20
-30
-40
dBm -50
-60
-70
-80
2.40
2.41
2.42
2.43
2.44
2.45
2.46
2.47
2.48
2.49
2.50
Frequency In GHz



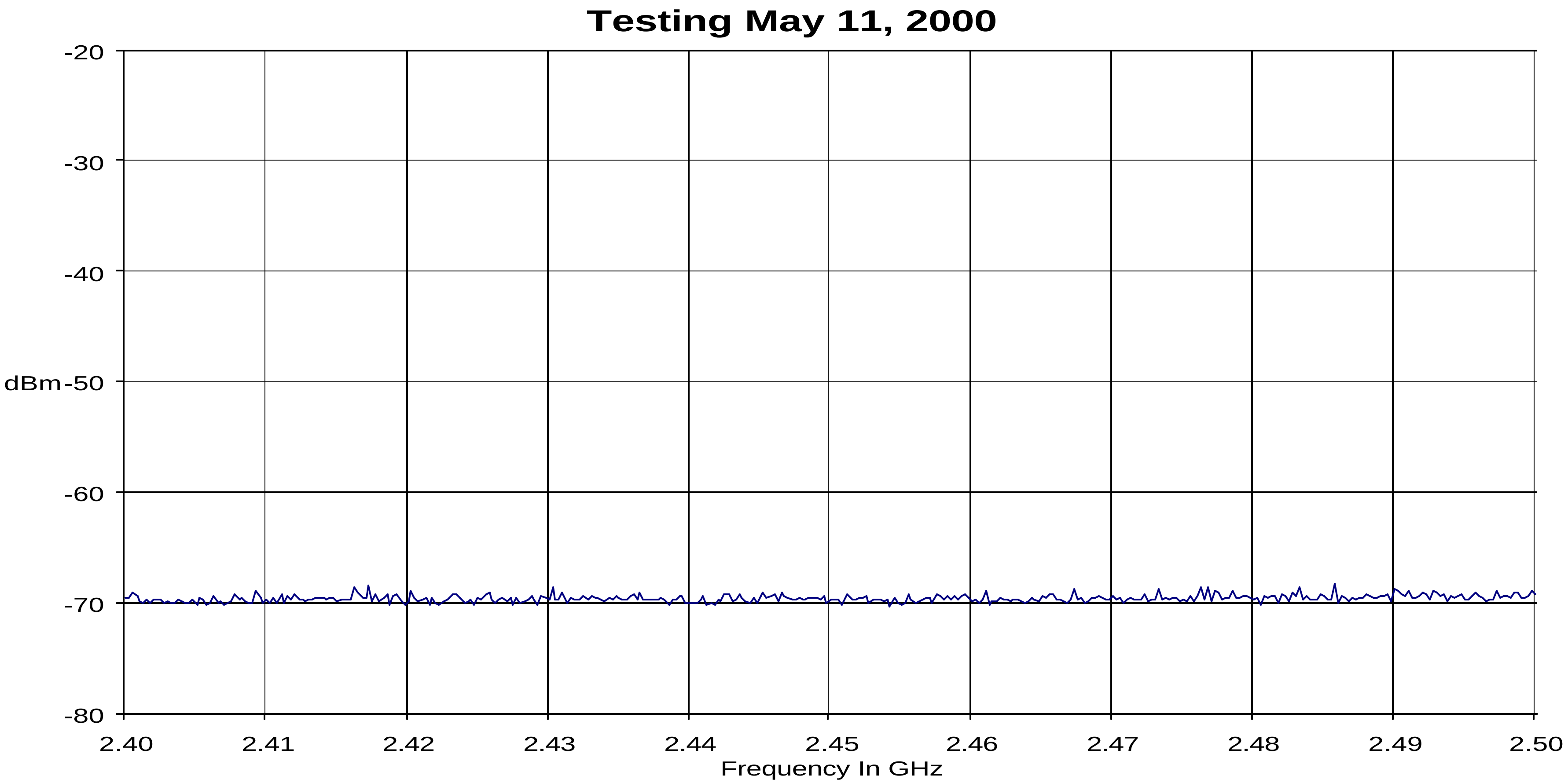
File 71.csv – Transmit antenna at # ?/H Seat #2 by the window positioned vertically. Receive Path is from the IFF top antenna.



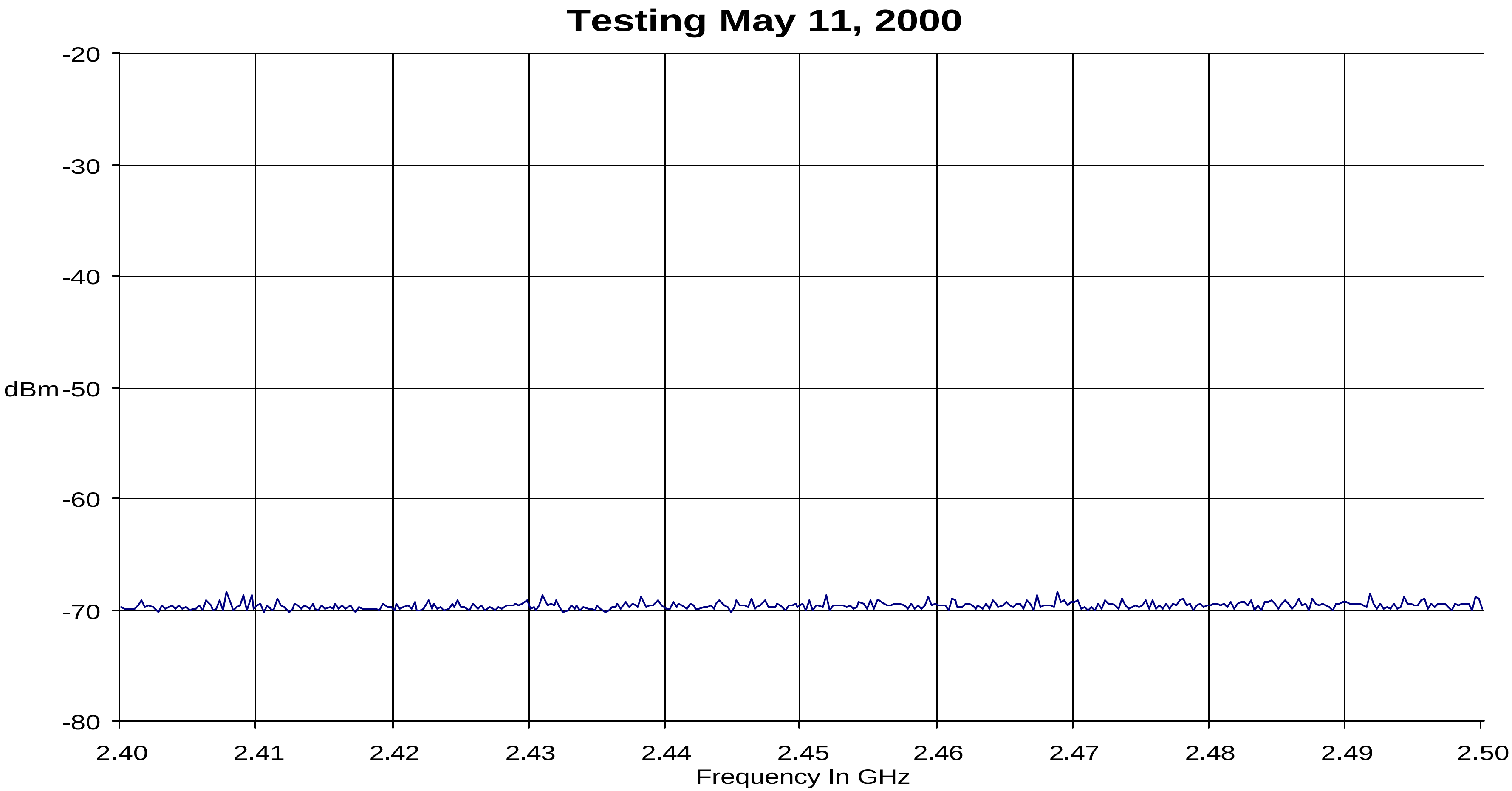
File 72.csv – No entry for sweep.



File 73.csv – Transmit antenna at # ?/H Seat #2 by the window positioned horizontally axis aligned with the fuselage, pointing foward. Receive Path is from the IFF top antenna.



File 74.csv – Transmit antenna at # ?/H Seat #2 by the window positioned vertically. Receive Path is from the IFF Bottom antenna.



is from the IFF Bottom antenna.