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REPORT SUMMARY

VHF transceiver tests described in this report were performed at the Volpe National Transportation Systems Center under Federal Aviation Administration (FAA) sponsorship. Laboratory tests were performed on ten different panel-mount type, General Aviation (G/A) class VHF communication transceivers, and two remote-mounted Air Carrier class VHF transceivers. The goal was to measure all radio frequency (RF) emissions from the transceiver antenna port and its case that fall in the Global Positioning System (GPS) L1 band (1575.420±1.023 MHz). These tests were performed to address reported and potential problems involving VHF transceivers interfering with GPS receivers on-board aircraft, particularly in the G/A class.

Test results show that there are many more than 13 VHF communications channels in G/A transceivers that can potentially interfere with GPS receivers. The thirteen transmitter harmonics were found to be emitted from both the antenna port and the transceiver case. In addition, spurious (non-harmonic frequency) emissions as well as local oscillator harmonics were found. Emissions in the L1 band were observed from one or more units from the antenna port for a total of 198 VHF frequencies, and from their cases for 32 VHF frequencies.

The two remote-mounted air carrier class transceivers tested were found to emit only transmitter harmonics from the antenna port and case. The antenna port emissions were at or near the minimum power level that can cause interference in an aircraft installation. The case emissions were comparable to the levels measured in the G/A units.

Based on signal strength measurements, not all of the emissions are equally likely to interfere with GPS reception. However, a significant number were clearly at magnitudes that could cause interference to GPS receivers on the same aircraft. All observed antenna port emissions were in conformance with applicable TSO and FCC emission specifications regarding out-of-band radiated power. Two units, one G/A class and one air carrier class, had case emissions which did not meet FCC specifications.

It is concluded that discontinuing the use of up to 13 VHF communications channels for certain terminal area operations is not a viable solution to the VHF-GPS interference problem. The total number of channels in G/A transceivers that may interfere with GPS is unpredictable (primarily because manufacturers use different intermediate frequencies) and much larger than thirteen, making it impractical to remove them from use in terminal area operations. Additionally, it is noted that the number of interfering VHF channels increases significantly if a wider GPS bandwidth and GLONASS are considered.

The laboratory tests, especially the case emissions free-space measurements, do not necessarily correlate with what will happen when the transceiver is installed into the aircraft structure, but they do infer some suggestions that will minimize, if not eliminate, interference problems when a GPS receiver is installed in a G/A aircraft. To reduce/eliminate VHF transceiver antenna -to-GPS receiver antenna coupling, install an in-line filter at the transceiver antenna connector to attenuate signals in the GPS L1 band. To reduce/eliminate interference from transceiver case radiation: (1) do not locate the GPS antenna too close to the windshield, where it may be effectively within line of site to the transceiver; (2) mount the GPS receiver as far away from the transceiver as is practical; (3) a cable that provides shielding of at least 40 dB per foot (e.g., coaxial cable with a single copper braid) should be used for the GPS antenna cable, especially if it must be routed along side the VHF transceiver case; and (4) proper GPS operation must be tested after the installation by keying the 13 VHF communications frequencies with harmonics in or very near the GPS L1 band (see Table 1).

In terms of FAA actions, it is suggested that the VHF transceiver TSO be revised to require that all antenna port emissions in the GPS L1 band be less than -80 dBm, which would eliminate the necessity of using an external filter. It is suggested that the VHF case radiation requirement be closely examined to determine if it should be set at a lower value. Lastly, it is suggested that the FAA publish a GPS Installation Guide to aid installers.

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1.0 INTRODUCTION

1.1 BACKGROUND

Under TSO-C129 (Ref. 1), and upon approval from the FAA, Global Positioning System (GPS) receivers are authorized to be used for en route, terminal area, and non-precision approach operations under Instrument Flight Rules (IFR). However, there is concern over the potential vulnerability of GPS receivers to both intentional and unintentional interference from RF sources. Recently, it has been reported that VHF communication transceivers used in general aviation (G/A) aircraft have caused interference to on-board GPS sets. It was reported that up to thirteen frequencies in the VHF band are potential interferers, by virtue of the fact that a transmitted harmonic (either 12^{th} or 13^{th}) of the fundamental frequency falls within the GPS L1 band*. It has been suggested that a solution to this interference problem is to discontinue the use of those frequencies for certain terminal area operations.

This report describes tests that were recently completed at the Volpe National Transportation Systems Center (Volpe Center) Landing Systems Laboratory to measure the emitted signals that appear in the GPS L1 band from ten different panel-mounted G/A class and two air carrier, remote mounted transceivers. These TSO'd units are representative of what is currently in use in IFR-approved aircraft: old and relatively new units, with both 25 and 50 kHz tuning. The transceivers were manufactured by Bendix, Collins, Edo-Aire, King, Narco and Terra. No two units were alike (same manufacturer and model).

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*The term "GPS L1 band" is employed herein to describe the frequency range L1 $\pm$ 1.023 MHz, where L1 = 1575.42 MHz. This band was selected for characterizing the potential for interfering with GPS receivers because it contains most of the power in the GPS civil Standard Positioning Service (SPS) radiated signal.

1.2 TEST OBJECTIVES

The objective of these tests was to record all signals that appear at the antenna port or are emitted from the case, in the L1 $\pm$ 1.023 MHz band, when the VHF transceiver is in either transmit or receive modes.

1.3 REFERENCES

The following documents are referenced in this report.

1. Technical Standard Order TSO-C129, *Airborne Supplemental Navigation Equipment Using the Global Positioning System (GPS)*, Federal Aviation Administration, December 10, 1992.

2. ANSI C63.4-1994, *American National Standards of Methods of Measurement of Radio-Noise Emissions from Low-Voltage Electrical and Electronic Equipment in the Range of 9 kHz to 40 GHz*, American National Standards Institute, 11 West 42nd Street, New York, NY 10036.

3. Code of Federal Regulations, Title 47 (Telecommunication), 1993.

4. Technical Standard Order TSO-C37d, *VHF Radio Communications Transmitting Equipment Operating with the Radio Frequency Range 117.975 to 137.000 Megahertz*, Federal Aviation Administration, September 1992.

5 Technical Standard Order TSO-C38d, *VHF Radio Communications Receiving Equipment Operating with the Radio Frequency Range 117.975 to 137.000 Megahertz*, Federal Aviation Administration, September 1992.

6. *Minimum Operational Performance Standards for Airborne Radio Communications Equipment Operating within the Radio Frequency Range 117.975 - 137.00 MHz*, RTCA, document DO-186, January 20, 1984.

7. *Environmental Conditions and Test Procedures for Airborne Equipment*, RTCA, document DO-160C, December 1989.

8. *Airborne VHF Communications Transceiver*, Aeronautical Radio, Inc., Characteristic 716-7, July 15, 1987.

9. *VHF Data Radio*, Aeronautical Radio, Inc., Characteristic 750, January 15, 1993.

10. "GPS Antenna Interference," *The Aviation Consumer, Report To Pilots*, February 15, 1994.

11. *Minumum Operational Performance Standards for Airborne Supplemental Navigation Equipment Using Global Positioning System (GPS)*, RTCA, document DO-208, July 1991.

12. *Minumum Operational Performance Standards for Sensors Using Global Positioning System / Wide Area Augmentation System* (DRAFT 3), RTCA, paper number 485-94/SC159-578, December 1994.

1.4 STANDARDS FOR VHF TRANSCEIVER EMISSIONS IN GPS BAND

1.4.1 Avionics Standards Hierarchy

In general, there is a three-level hierarchy of avionics standards, and the applicability of these standards is cumulative. The least demanding requirements are placed on units installed in General Aviation (G/A) aircraft which are not employed for Instrument Flight Rules (IFR) operations. Typically, these units must only meet Federal Communication Commission (FCC) regulations for electronic equipment of the applicable type (e.g., intentional radiators). Avionics used during IFR operations must also meet the applicable FAA Technical Standards Order (TSO). Usually, the TSO includes by reference an associated RTCA Minimum Operational Performance Standards (MOPS) document be satisfied, with specific exceptions and additional requirements as cited. In addition to satisfying FCC and FAA requirements, air carriers' avionics normally must meet an Aeronautical Radio, Inc. (ARINC) Characteristic. While not backed by the regulatory mechanisms of the Government, ARINC Characteristics are usually more demanding than FCC Rules and FAA TSOs.

Unwanted emissions from VHF transceivers may be divided into three categories: those emanating from the antenna port, those radiated from the case, and those conducted from the unit via the power connector. Only radiated emissions are addressed in this report.

The standards applicable to transceiver case and antenna port emissions in the L1 band are summarized in Table 1 and described in the remainder of Section 1.4.

Table 1 Standards for Transceiver Emissions in GPS L1 Band

Standards Organization	Case Emissions	Antenna Port Emissions
FCC 47 (Part 15)	500 μv/m at 3 m	Unkeyed: None Keyed: -16 dBm
RTCA (DO 186)	None	Unkeyed: None Keyed: Harmonics, -16 dBm Keyed: Others, none
ARINC (Char 716, 750)	None	Unkeyed: None Keyed: Harmonics, -16 dBm Keyed: Others, -35 dBm

1.4.2 FCC Standards

Case Emissions - VHF transceivers sold in the U.S. must satisfy the FCC requirements given in Title 47 of the Code of Federal Regulations (47 CFR, Ref. 3). Part 15, Subpart C, governs unwanted emissions from transmitting equipment. Manufacturers for most of the transceivers tested during this effort assert, in the documentation and/or on the equipment case, that the unit is compliant with Part 15. These regulations require that the electric field strength for unwanted radiated emissions at frequencies greater than 900 MHz not exceed 500 microvolts per meter (μv/m) at a distance of 3 meters from the source. This limits radiations from the transceiver case. Since all emissions above 900 MHz are so limited, emissions in the GPS L1 band are limited. (Techniques for measuring case emissions are given in Ref. 2.). 500 μv/m is equal to 54 dB μv/m (the latter is employed in this report).

Antenna Port Emissions - Part 87 of 47 CFR (Ref. 3) is specifically directed at telecommunications equipment used for aeronautical and marine purposes. Unwanted emissions from the antenna port are addressed in §87.131. The wording in that paragraph is lengthy and complex and is not repeated here. It has been interpreted to mean that total emissions at frequencies outside the VHF band (a range that includes the GPS L1 band) must be less than -16 dBm.

1.4.3 FAA Standards

FAA Technical Standard Orders C37b and C38b (Refs. 4 and 5) pertain to the VHF transceivers tested during this effort. These TSOs do not contain requirements for out-of-band emissions, but reference either RTCA document DO-186 (Ref. 6) or its predecessors (DO-139, DO-156, and DO-157) as additional sources of requirements for achieving a TSO.

Case Emissions - DO-186 does not contain an explicit standard for case emissions. It states that the conducted and radiated spurious emissions shall not exceed those specified in Section 21.0 of RTCA document DO-160A, *Environmental Conditions and Test Procedures for Airborne Equipment*, predecessor to DO-160C. DO-160C places limits on narrowband and broadband emissions, both conducted and radiated. Conducted radiation limits are specified for frequencies up to 30 MHz; limits on radiated emissions are specified for frequencies up to 1,215 MHz. Thus, there are no FAA specifications for case emissions in the GPS L1 band.

Antenna Port Emissions - DO 186 places separate limits on antenna port radiations for the receive and transmit modes. For the receive mode, it requires that, when the unit is terminated in a matched impedance, spurious emissions into that load shall not exceed -57 dBm for frequencies in the range 25 kHz to 1,215 MHz. No requirement is placed on emissions in the GPS L1 band. For the transmit mode, DO 186 requires that, when the unit is terminated in a matched impedance, the level of emissions at harmonic frequencies shall not exceed -16 dBm. No standard is placed on emissions at non-harmonic frequencies.

1.4.4 ARINC Standards

ARINC has published Characteristics for two types of VHF transceivers. Characteristic 716 (Ref. 8 is the latest release) applies to "analog" radios, i.e., traditional radios capable of accepting voice and ACARS data. Characteristic 750 (Ref. 9) governs newly developed "digital" radios. In addition to the capabilities of the traditional radios, these radios support the new bit-oriented Aviation VHF Packet Communications System (AVPAC). No "digital" radios were tested during this effort.

Case Emissions - Neither ARINC Characteristic (Refs. 7 and 8) addresses case emissions.

Antenna Port Emissions - References 8 and 9 are identical insofar as emissions in the GPS L1 band are concerned. Both require that emissions on a harmonic of the transmitter carrier frequency not exceed -16 dBm, which they state is consistent with the FCC requirement. Other (non-harmonic) spurious emissions in the GPS L1 band are required to not exceed -35 dBm. Both documents state that these figures are "barely acceptable" and that the manufacturer should aim to do better.

2. TEST DESCRIPTION

2.1 ANTENNA PORT EMISSIONS

2.1.1 Equipment Setup

The strength and frequency of L1 band emissions from the antenna port were measured with the setup shown in Figure 1. The transceiver was connected to a 10 dB attenuator which allowed no more than 5 watts (damage level) into a K&L cavity type, bandpass filter. This filter greatly attenuated spectral components outside the GPS L1 band, especially the transceiver's strong fundamental frequency component when it was in the transmit mode. The port output was then boosted by 23 dB with an HP Model 87405A preamplifier and the resulting signal in the L1$\pm$1.023 MHz band was recorded with an HP8568B spectrum analyzer. A digitial image and the analyzer's settings were transferred via IEEE-488 to a computer and stored with the the following information: transceiver manufacturer, model and serial number; communications channel; operating mode (transmit or receive); and measurement type (antenna port or case radiation). The noise floor of this measurement system was -106 dBm/KHz.

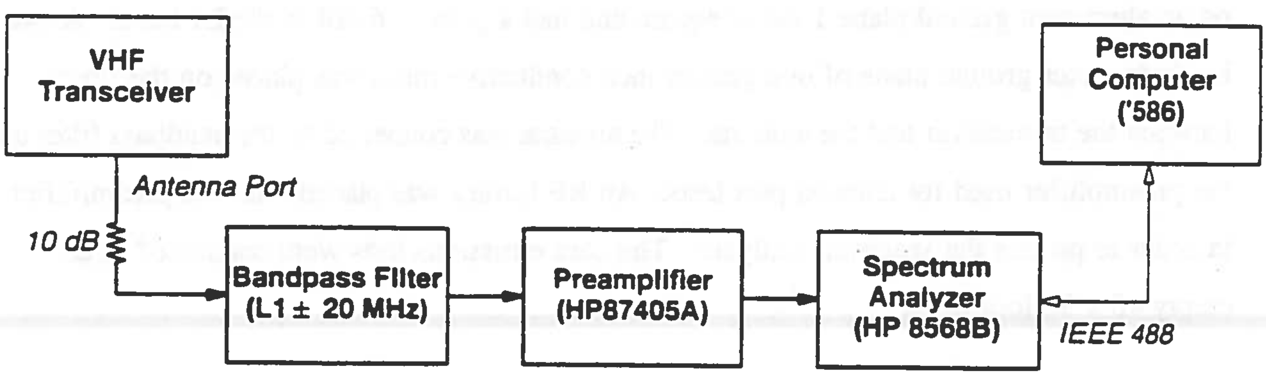


Figure 1 Antenna Port Emissions Test Setup

2.1.2 Procedure

Prior to L1 band tests, the transceiver's transmitted signal in the VHF band (118-136 MHz) was examined using the spectrum analyzer connected to the transceiver antenna port through a 50 dB attenuator. The fundamental frequency component of each transceiver had a magnitude of about 43 dBm (in compliance with the equipment specifications) and was measured at the correct communication channel frequency. The instrumentation was then configured as shown in Figure 1. Measurements were made with the spectrum analyzer set for the band L1$\pm$1.023 MHz while switching through each communications channel, for both transmit (keyed) and receive (unkeyed) modes. Results were stored in the computer when energy above the test system noise floor (-106 dBm/kHz) was detected.

2.2 CASE EMISSIONS

2.2.1 Equipment Setup

The setup used to measure transceiver case emissions (shown in Figure 2) was similar to that used to measure antenna port emissions. The transceiver was placed on a non-conductive, rotatable mounting table at a height of two meters. The transceiver's antenna port was connected to a 50 Ω terminator with a shielded, grounded cable. Signals were measured through an Antenna Research Associates (ARA) PAS-1575 patch antenna which was mounted on an aluminum ground plane 1 meter square and had a gain of 6 dBi in the L1 band. A two by three meter ground plane of one quarter inch conductive mesh was placed on the floor between the transceiver and the antenna. The antenna was connected to the bandpass filter and the preamplifier used for antenna port tests. An RF limiter was placed after the preamplifier in order to protect the spectrum analyzer. The case emissions tests were conducted in an empty 40 x 30 foot room.

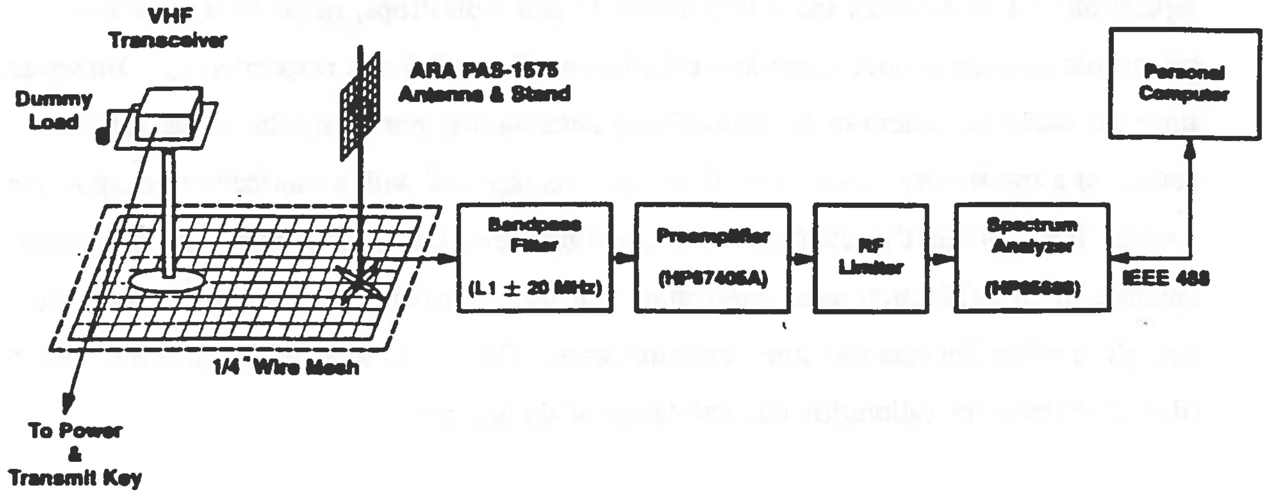


Figure 2 Case Emissions Test Setup

2.2.2 Calibration and Test Site Validation

An HP 8657B Signal Generator connected to a patch antenna was used as a source to calibrate the test system and validate the test site. The signal generator was setup (replacing the transceiver) to transmit a -20 dBm, CW tone at 1575.420 MHz through the patch antenna. This signal was measured at distances of 1, 2 and 3 meters from the antenna in the test setup. They measured -58, -65, and -68 dBm, respectively. Those measurements were repeated three times with identical results. These results are within 2 dB of calculated results, assuming plane wave propagation.

Test site validation addressed two issues that can corrupt the measurements: the ambient RF environment and reflected signals. The ambient environment was monitored before and after the case emissions tests and no signals were detected above 900 MHz. The site calibration tests indicate that no reflections corrupted the measurements, because the signal strength decrease as seen with the spectrum analyzer when the antenna was moved from a separation of 1 to 2 meters and 2 to 3 meters (7 and 3 dB drops, respectively) were in reasonable agreement with space-loss calculations (6 and 3.5 dB, respectively). However, since the radiation pattern of the transmitting antenna may not be similar to the radiation pattern of a transceiver's case, the calibration was repeated with a transceiver acting as the source. It was found that the case emissions signal level decreases agreed with the results obtained in the calibration tests, confirming that reflections at the test site were not large enough to affect the case radiation measurements. These tests were based on ANSI C63.4 (Ref. 2) criteria for calibration and validation of the test site.

Measurements were performed with the antenna one meter from the transceiver (the far-field for the L1 band when measured through a PAS-1575 antenna) rather than 3 meters referred to in the FCC specification in order to increase measurement sensitivity. The noise floor of the spectrum analyzer was -106 dBm/kHz and the propagation loss at one meter is 36 dB. Thus the noise floor of the test system at one meter was -70 dBm/kHz equivalent omnidirectional source power which is equivalent to 25 dB μvolts/meter at 3 meters (compare with the FCC specification that states a maximum of 54 dB μvolts/meter at 3 meters). See Appendix D for the conversion of equivaent source power (dBm) to field strength at 3 meters (dB μvolts/meter).

2.2.3 Procedure

Initially (as part of the antenna port measurements), uncalibrated measurements of transceiver case emissions in the L1 band were made using a simple antenna-like probe attached to the spectrum analyzer and placed nearly in contact with the transceiver case (sampling the near field). The transceiver was switched through every communications channel, in both transmit (keyed) and receive (unkeyed) modes. For calibrated case emissions tests, the transceiver channels that were tested were chosen from the results of the uncalibrated measurements. Typically, for each transceiver, one channel was selected for each of the following interference types: 12^{th} and 13^{th} transmitter harmonic, 11^{th} and 12^{th} local oscillator harmonic, and spurious emissions (in some cases two channels were used for spurious emissions). The same peak power level of interference was found on each channel in a "group", so that only one measurement was necessary for a group. For example, during the uncalibrated case emissions tests, unit 1 showed six channels grouped in the 119 MHz range that produced local oscillator harmonics; only one channel (119.22 MHz) was selected and tested during the calibrated emissions tests.

The transceivers, which were provided by the FAA Technical Center, were mounted on test pallets with metallic structures that could effect the measurements. Most units were therefore removed from their pallets before testing. However, one of the units (number 6) could not be removed from its pallet without extensive rewiring and therefore was not tested for case emissions.

Each transceiver was placed on the turntable in the normal, bottom-side down position and rotated through 360 degrees. The highest signal strength and the corresponding angular position were recorded and then this process was repeated for each channel group. Two additional power measurements were made for the channel group with the highest measured power; bottom-side down with the front panel facing the the antenna (0 degrees) and then with the unit on its right edge rotated to the angle with the highest signal strength. All of the case emissions data are presented in Appendix C.

2.3 POTENTIAL INTERFERING VHF CHANNELS

VHF transceivers can interfere with GPS reception via three mechanisms emanating from both the transceiver's antenna port and case. These mechanisms are transmitter harmonics, local oscillator harmonics, and spurious emissions, and are discussed more fully in the following paragraphs.

When a transceiver is transmitting (keyed), the 12[th] and 13[th] harmonics of the VHF fundamental fall in the GPS L1 band. The channels which produce such harmonics are listed in Table 2 (total of 13 with harmonics in L1±1.023 MHz).

Table 2 . VHF Channels with Transmitter Harmonics in the Band f_{L1} ± 1.023 MHz (All Frequencies in MHz)

VHF Frequency f_{VHF}	Harmonic Number N	Harmonic Frequency $N \times f_{VHF}$	Frequency Difference $N \times f_{VHF} - f_{L1}$
121.125	13	1574.625	-0.795
121.150	13	1574.950	-0.470
121.175	13	1575.275	-0.145
121.200	13	1575.600	0.180
121.225	13	1575.925	0.505
121.250	13	1576.250	0.830
131.200	12	1574.400	-1.020
131.225	12	1574.700	-0.720
131.250	12	1575.000	-0.420
131.275	12	1575.300	-0.120
131.300	12	1575.600	0.180
131.325	12	1575.900	0.480
131.350	12	1576.200	0.780

The second mechanism listed above occurs when the transceiver is in receive mode (un-keyed). The 11[th] and 12[th] harmonics of the local oscillator can fall in the GPS L1 band. The transceivers available for this work had a variety of intermediate frequencies (I.F.s), resulting in local oscillator (L.O.) frequencies that are different for units tuned to the same VHF channel. Table 3 lists the tuning increment, intermediate frequency, and channels with 11[th] and 12[th] local oscillator harmonics in the L1 band. Each transceiver is identified by a unit number, not manufacturer and model; units 1-10 are G/A-class sets and units 11 and 12 are the air carrier units.

Table 3 VHF Channels of Units Tested with L.O. Harmonics in the Band $f_{L1} \pm 1.023$ MHz (All Frequencies in MHz)

Unit No.	Tuning (kHz)	I.F. (MHz)	VHF Channels w/ 11th L.O. Harmonic in L1 Band	VHF Channels w/ 12th L.O. Harmonic in L1 Band	Total
1	25	12.0	131.150-131.300	119.200-119.350	14
2	25	11.4	131.750-131.900	119.800-119.950	14
3	50	20.0	123.150-123.300		4
4	25	10.5	132.650-132.800	120.700-120.850	14
5	50	9.9	133.250-133.400	121.300-121.450	8
6	25	9.8	133.350-133.500	121.400-121.550	14
7	50	8.6	134.550-134.700	122.600-122.750	8
8	25	8.6	134.550-134.700	120.600-120.750	14
9	25	10.7	132.450-132.600	120.500-120.650	14
10	50	11.4	131.750-131.900	119.800-119.950	8
11	25	10.0	133.150-133.300	121.200-121.350	14
12	25	20.0	123.150-123.300		7

For all 12 units, the L.O. frequency was greater than the tuned frequency by the I.F. It can be seen that if the I.F. is known, channels that can emit L.O. harmonics that fall into the GPS L1 band can be predicted. However, even different models from the same manufacturer had different intermediate (hence L.O.) frequencies. It will be seen in Section 3 that this fact increases the number of transceiver channels that emit local oscillator harmonics in the GPS L1 band (over the number for a single I.F. frequency).

The third mechanism by which transceiver emissions can fall in the GPS L1 band is spurious emissions. It is not possible to identify the VHF channels that, for a specific model, will emit spurious emissions in the GPS band.

3. TEST FINDINGS

3.1 ANTENNA PORT EMISSIONS

3.1.1 General Aviation Units

Appendix A contains sample spectrum analyzer plots of calibrated measurements of VHF transceiver antenna port emissions in the L1 band. One example is presented for each mechanism by which a transceiver was found to generate observable energy in the L1 band (transmitter harmonics, transmitter spurs, and local oscillator harmonics). Appendix B contains all of the antenna port data from the spectrum analyzer measurements. These tables identify: the communications channels that produced emissions in the bands L1 ± 1.023 MHZ and L1 ± 0.5 MHZ; the associated signal strengths; and the interference generation mechanism. Figure 3 is a plot of the emissions from all ten G/A-class transceivers.

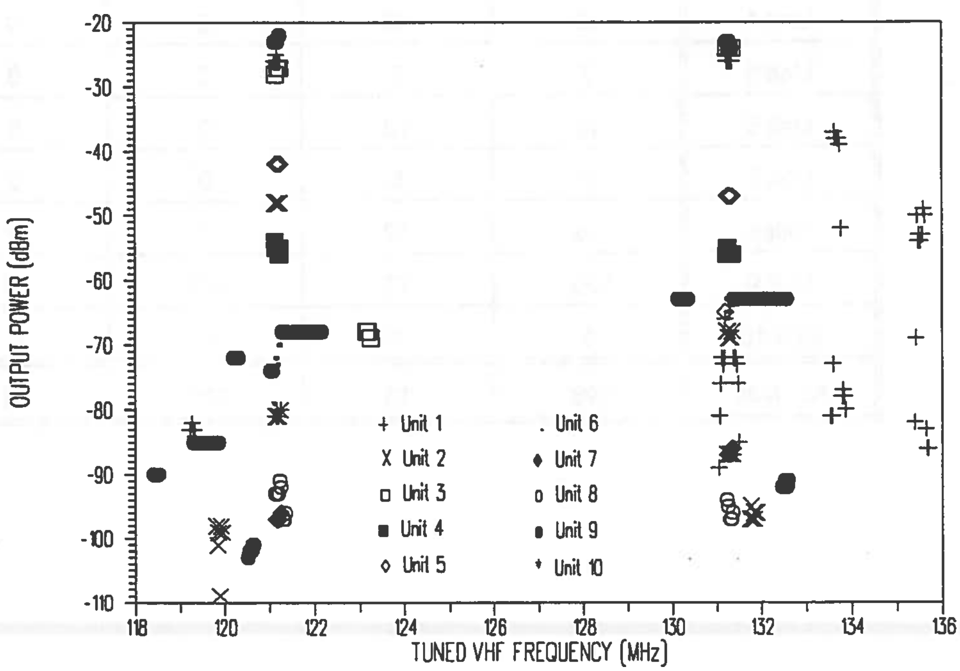


Figure 3 Antenna Port Emissions from All Panel-Mounted Transceivers

Tables 4 and 5 summarize the information contained in the tables in Appendix B. Table 4 shows the number of frequencies, with emissions levels greater than -105 dBm in the L1 ± 1.023 MHz band for each interference mechanism. Table 5 shows, for the individual units and all units taken together, the number of frequencies for which the peak power is greater than the threshold level given in the left-hand column.

Table 4 Count of Panel-Mounted Transceiver VHF Channels with Measurable Interference in the GPS L1 Band at the Antenna Port

Unit Number	All Mechanisms	Transmitter Harmonics	Transmitter Spurs	L.O. Harmonics
Unit 1	58	12	40	13
Unit 2	25	12	0	13
Unit 3	9	6	0	3
Unit 4	12	12	0	0
Unit 5	7	7	0	0
Unit 6	12	12	0	0
Unit 7	6	6	0	0
Unit 8	15	12	3	0
Unit 9	155	12	136	13
Unit 10	6	6	0	0
All Units	198	13	170	42

Table 5 Count of Panel-Mounted Transceiver VHF Channels with Power in the GPS L1 Band at the Antenna Port Exceeding a Given Threshold

Power Threshold (dBm)	Number of Frequencies with Power Exceeding Threshold										
	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6	Unit 7	Unit 8	Unit 9	Unit 10	All Units
-20	0	0	0	0	0	0	0	0	0	0	0
-30	12	0	6	0	0	0	0	0	12	0	12
-40	18	0	6	0	0	0	0	0	12	0	18
-50	21	6	6	0	6	0	0	0	12	0	21
-60	27	6	6	12	6	0	0	0	12	0	27
-70	29	12	9	12	7	8	0	0	109	0	129
-80	43	12	9	12	7	12	0	0	118	1	147
-90	58	12	9	12	7	12	3	1	148	6	188
-100	58	23	9	12	7	12	6	15	149	6	191
-110	58	25	9	12	7	12	6	15	155	6	198

The results of antenna port tests for G/A transceivers indicate the following. If VHF and GPS antennas are separated by one meter (reasonable for small aircraft) their isolation can be as low as 30 dB. Reference 11 (the MOPS associated with TS0-C129) requires GPS receivers to operate properly in the presence of interference less than -120 dBm. Laboratory tests at the Volpe Center indicate that some GPS receivers can lose lock with CW interference at approximately -110 dBm. Thus, using the less stringent -110 dBm as the immunity level, transceiver emissions in the L1 band that may cause interference to GPS receivers can be as small as -80 dBm. Looking at the threshold values in Table 5, it is seen that nearly 150 VHF channels produced enough energy in the L1± 1.023 MHz band to potentially interfere with a GPS receiver.

3.1.2 Air Carrier Units

Two air carrier remote-mounted transceivers were tested. These units emitted only transmitter harmonics (no local oscillator harmonics and no spurious emissions), and the maximum power level was -80 dBm. These emissions would not be expected to cause a problem with GPS reception.

3.2 CASE EMISSIONS

Table 6 summarizes data from the calibrated case emissions. Complete data are provided in Appendix C, where the emission levels from the front panels are given together with the levels and angular directions where the maximum signal strengths were measured. The results of all of the field strength measurements presented in this report are quantified in terms of the power (dBm) radiated by an equivalent omnidirectional source. (Appendix D provides the calculations for converting between equivalent source power and field strength.) The FCC specification for intentional radiators states that, *for frequencies above 960 MHz, the field strength not exceed 500 μvolts/meter at 3 meters from the source*, which is equivalent to a -41 dBm omnidirectional source.

The initial, uncalibrated measurements of transceiver case emissions made by using a simple antenna-like probe placed nearly in contact with the transceiver case revealed that there were considerably more emissions in the L1 band than are indicated in Table 6. These emissions were below -70 dBm/kHz, which was the noise floor of the test system.

Table 6 Case Emissions: Equivalent Source Power in dBm

CHANNEL GROUP	UNIT NUMBER										Total Channels
	1	2	3	4	5	7	8	9	10	12	
12th Transmitted Harmonic	-47	-49		-50	-43	-43	-48	-33	-54	-35	7
13th Transmitted Harmonic	-52	-46	-48	-50	-42	-44	-41	-29	-44	-40	6
11th L.O. Harmonic	-56		-62								14
12th L.O. Harmonic	-52	-68									14
Spurs								-68			1
											Total 32

Front Panel	-54	-62	-50	-50	-50	-59	-56	-34	-51	-48

Note: Instrumentation sensitivity level was -70 dBm/kHz equivalent source power 47 CFR, Part 15 limit is -41 dBm. Also, the total number of channels is not equal to the sum because some transmit and L.O. harmonics are on the same channel.

3.2.1 General Aviation Units

Calibrated case emissions measurements were made on nine G/A transceivers. All units exhibited transmitter harmonics case emissions. Unit 9 was seen to have the largest; its worst-case transmitter harmonics were equivalent to an omnidirectional source of -29 dBm, or approximately 10 dB in excess of the FCC limit. The remaining units met the FCC standard, although, in the cases of units 5 and 8, only by a small margin.

One third of the units tested (three sets) produced measurable local oscillator harmonic emissions. Unit 1 had the largest such emissions, equivalent to -52 dBm omnidirectional source and 5 dB less than the largest transmitter harmonic for that unit. One unit was observed to have transmitter spurious emissions, at an equivalent power of -68 dBm. Case radiated emissions above the -70 dBm equivalent power sensitivity level were found on 32 VHF channels.

3.2.2 Air Carrier Units

Calibrated case emissions tests were performed on one air carrier, remote-mounted transceiver (unit 12 in Table 5). The maximum measured case emission was -35 dBm equivalent power at the source, which exceeds the FCC limit. No local oscillator harmonics or spurious emissions were seen.

3.2.3 Observations with GPS Receivers

The behavior of a hand-held GPS receiver with its antenna placed close to the transceiver case was observed during the antenna port tests. Live satellite data were acquired through a roof-mounted antenna connected to the GPS receiver through a coupler. The other input to the coupler came from an antenna placed close to the transceiver case. When the communications channels were being incremented, the GPS receiver signal quality would decrease at VHF channels which had harmonics or spurs close to the GPS band. The GPS receiver always lost lock when emissions in the L1 band were detected with the spectrum analyzer. This behavior is consistent with reports in the literature of interference to GPS reception by a hand-held receiver in the cockpit of a G/A aircraft (Ref.10).

Additional bench tests were performed with a TSO'd GPS receiver (without a filter connected to the transceiver antenna port) and transceiver number 1. Again live satellite data were acquired through a roof mounted antenna whose gain was adjusted so that the signal level was comparable to an aircraft installation. A single braid, copper shielded cable (RG-58/59) was used as the GPS antenna cable. *Receiver operation (signal-to-noise ratio) was not effected when the two cases were placed in contact in a variety of positions*. When the GPS antenna cable was routed along side the VHF transceiver and its antenna cable (which was terminated into a dummy load) minor degradation in signal-to-noise ratio could be seen, but the GPS receiver maintained track. This seems to indicate that *the predominant VHF transceiver interference mechanism to GPS is due to the transceiver case-to-GPS antenna or GPS antenna cable coupling (if a poorly shielded cable is used).*

4. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

4.1 SUMMARY

VHF transceivers can radiate emissions in the GPS L1 band via three mechanisms through both the transceiver's antenna port and case. There are 13 VHF channels which generate 12^{th} and 13^{th} transmitter harmonics which fall in the L1$\pm$1.023 MHz band. Also, for a given transceiver there are up to 14 channels which generate 11^{th} and 12^{th} local oscillator harmonics which fall in the L1 band. The specific channels will vary from unit to unit, because the intermediate frequency used in transceivers is not standardized. Lastly, spurious emissions can occur, and the frequencies of these emissions are not predictable.

4.1.1 Antenna Port Emissions

For the ten G/A class units tested, antenna port emissions in the L1$\pm$1.023 MHz band were found on 198 channels, and can be summarized as follows:

- 13 channels exhibited transmitter harmonics (12th and 13th) as high as -22 dBm
- 42 channels exhibited local oscillator harmonics as high as -67 dBm.
- 179 transmitter spurious emissions occurred, on 170 different frequencies, with power levels as high as -37 dBm (one third of the units tested exhibited spurs).

FCC specifications limit the antenna port emissions in the L1 band to -16 dBm. All units tested met this specification.

4.1.2 Case Radiated Emissions

Equivalent omnidirectional point source emissions exceeding -70 dBm were found in the L1 band on 32 channels, as follows:

- 13 channels exhibited transmitter harmonics (12^{th} and 13^{th}) as high as -29 dBm

- Three units (one third of the units tested) exhibited local oscillator harmonics on an additional 23 channels, with the maximum level being -52 dBm.

- One unit exhibited a transmitter spurious emission of -68 dBm.

FCC specifications limit case emissions to 500 μVolts/meter at 3 meters (equivalent to a source power of -41 dBm). Two units, one G/A class and one air carrier class, had transmitter harmonics which did not meet this specification.

4.2 CONCLUSIONS

4.2.1 Antenna Port Emissions

Transceiver antenna-port emissions in the L1 band that exceed approximately -80 dBm can disrupt GPS reception through antenna-to-antenna coupling. During testing, approximately 150 VHF channels were found to have emissions greater than -80 dBm. Moreover, it is likely that other units in the fleet will have additional channels with emissions greater than this threshold, since the channels on which spurs and local oscillator harmonics occur are dependent on the transceiver design, and a relatively small subset of the models in service were tested. Consequently, discontinuing the use of up to 13 VHF frequencies is not a viable solution to the antenna-to-antenna interference problem for currently available TSO'd GPS sets. It will be even less effective in the future, when GPS receivers which utilize a wider signal bandwidth (e.g., narrow correlator technology) and/or GLONASS become approved for IFR service.

4.2.2 Case Radiated Emissions

Due to the large variations in aircraft configurations, it is difficult to make definitive statements concerning the impact of transceiver case-radiated emissions on GPS reception. However, VHF transceiver case-radiated power levels observed in the laboratory clearly have the potential to disrupt GPS reception. Whether such disruption actually occurs depends upon the amount of isolation between the VHF case and the GPS antenna, cable, and case that is achieved in the aircraft. The FCC limits case radiation to -41 dBm equivalent source power, while the largest transmitter harmonic power observed was -29 dBm at the case. Since TSO'd GPS receivers can only withstand about -110 dBm of interference, even for compliant VHF sets a total of 70 dB of isolation must be provided by physical separation and shielding. The highest local oscillator harmonic power observed was -52 dBm, so 58 dB of isolation must be provided by the aircraft, to protect against this mechanism.

Limited laboratory testing indicates that GPS case shielding and cables using single copper braid are adequate, but other cables that may be in use may not provide sufficient isolation. Shielding for the GPS antenna must be provided by its location, which has to be removed from any electromagnetic energy paths from the VHF set case. Such energy paths can occur through a line-of-sight or "near line-of-sight" relationship between the source and GPS antenna. Line-of-sight paths - either directly from the VHF set case or from metallic secondary radiators (e.g., windshield housing) - must be avoided. "Near line-of-sight" situations occur when energy reaches the GPS antenna through diffraction (e.g., around the edges of a windshield), and must also be avoided.

It is concluded that eliminating the use of 13 VHF channels for certain terminal area operations is a not a viable approach to reducing interference to GPS from the transceiver case. First, local oscillator harmonics can disrupt GPS reception, and this situation would remain if the 13 VHF channels in question were placed in a restricted status. Second, utilization of a wider navigation satellite signal bandwidth is becoming a reality. For example, the WAAS MOPS (Ref. 12) released in December 1994 provides for protection of a 20 MHz band centered on L1. Multiplying the signal bandwidth used in receiver processing by ten will (approximately) multiply the number of VHF channels which can cause interference by ten, that is, 130 transmitter harmonics plus additional local oscillator harmonics. Restricting the use of so many channels would be totally unacceptable. Similarly, introduction of GLONASS would significantly increase the number of interferers and require restricting the use of an additional number of VHF channels.

4.3 RECOMMENDATIONS

4.3.1 Antenna Port Emissions

It is recommended that a filter be installed in the VHF transceiver antenna connector to attenuate signals (from the antenna port) in the L1 band when a GPS receiver is installed in general aviation aircraft. The Garmin 155 TSO receiver Installation Manual identifies such an in-line filter by part number. That filter, which is only slightly larger than a BNC T-connector, has an attenuation greater than 50 dB at L1, is inexpensive, and effectively eliminates the antenna port emissions problem. Its placement at the transceiver antenna connector also reduces potential transceiver cable-to-GPS antenna cable coupling of transmitter harmonics.

4.3.2 Case Radiated Emissions

The following steps are recommended to reduce/eliminate interference from transceiver case radiation: (1) do not locate the GPS antenna too close to the windshield, where it may be effectively within line of sight to the transceiver; (2) mount the GPS receiver as far away from the transceiver as is practical; (3) use a GPS antenna cable that provides shielding of at least 40 dB per foot (e.g. coaxial cable with a single copper braid), especially if it must be routed along side the VHF transceiver case; and (4) proper GPS operation must be tested after the installation by keying the 13 VHF communications frequencies identified in Table 2.

If proper GPS reception still can not be achieved, other possible interference sources should be checked, such as re-radiation of VHF harmonics from the Emergency Locator Transmitter (ELT), a poor ground connection of the transceiver cable, or a VHF transceiver that is out of specification.

4.3.3 Revision of Specifications

It is suggested that the VHF transceiver TSO (Ref. 5) be revised to require that all antenna port emissions in the GPS L1 band be less than -80 dBm, which would eliminate the need for an external filter. With antenna port emissions limited to -80 dBm and with a reasonable level of 30 dB of antenna-to-antenna isolation (separation distance of one meter), in-band transceiver-emitted interference will be less than -110 dBm at the GPS antenna and will not disrupt GPS receiver operations. For transceiver units 7 and 8, all antenna port emissions in the L1 $\pm$ 1 MHz band were less than -85 dBm, suggesting that the recommended limit can be achieved with current design and manufacturing techniques.

4.3.4 GPS Installation Support

Since a wide variation of aircraft are in service, and wide variations in the physical layout of avionics equipment and aircraft structure will inevitably arise, some occurrence of interference to GPS are to be expected. To aid installers in addressing such situations, it is recommended that the FAA prepare a GPS Installation Guide. The guide would describe troubleshooting techniques (including test equipment) and would itemize installation problems previously found and their associated solutions.

It is also recommended that the FAA identify installation specialists in each region that have both the experience and equipment required to resolve electromagnetic interference problems with onboard GPS receivers. Those specialists can provide assistance where an installer encounters an interference problem that cannot be easily solved.

APPENDIX A

SAMPLES OF SPECTRUM ANALYZER DISPLAYS

This appendix contains plots of selected spectrum analyzer snapshots observed during testing of the VHF transceivers:

- Unit one's transmitter 12th harmonic at 1574.7 MHz, observed at antenna port, when set is tuned to 131.225 MHz
- Unit one's transmitter 13th harmonic at 1575.6 MHz, observed at antenna port, when set is tuned to 121.200 MHz
- Unit one's transmitter spurious emission at 1575.11 MHz, observed at antenna port, when set is tuned to 133.675 MHz
- Unit one's local oscillator 12th harmonic at 1575.28 MHz, when set is tuned to 119.275 MHz

Figure A-1 Unit 1 Emissions through Antenna Port in the L1 ± 1 MHz Band (Transceiver Tuned to 131.225 MHz and Keyed; Transmitter 12th Harmonic Observed)

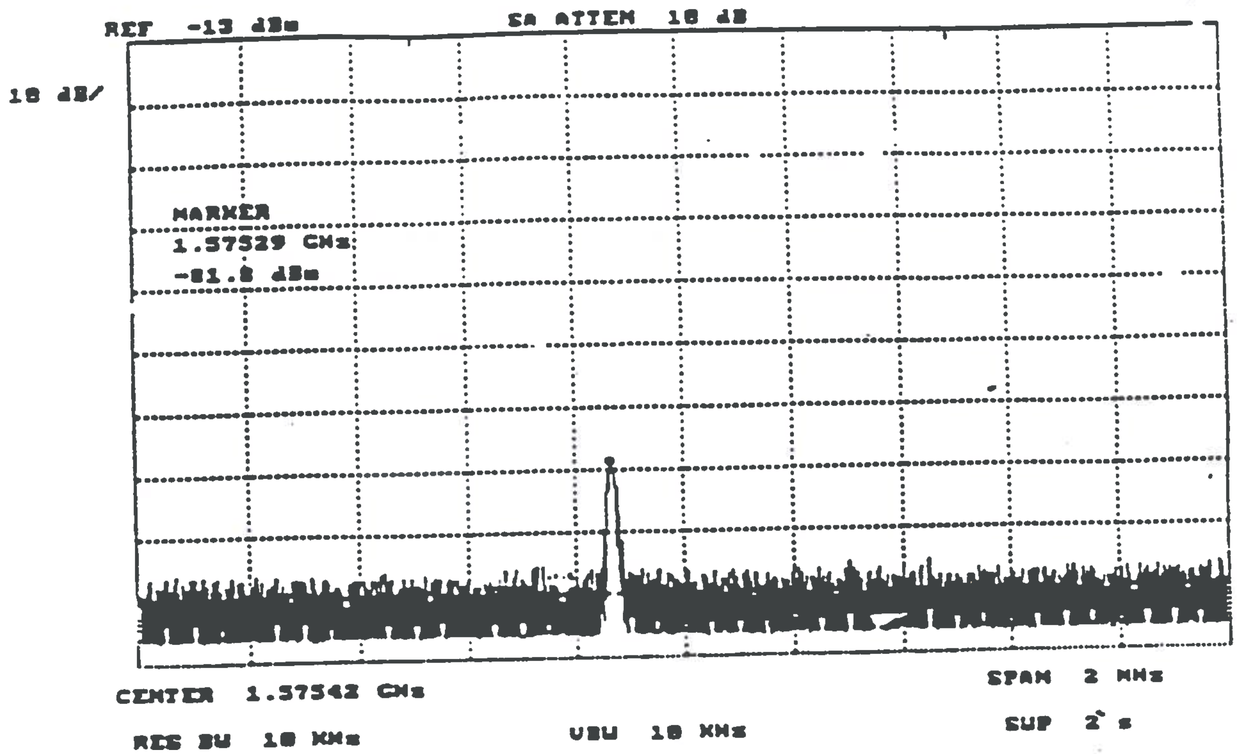


Figure A-2 Unit 1 Emissions through Antenna Port in the L1 ± 1 MHz Band (Transceiver Tuned to 121.200 MHz and Keyed; Transmitter 13th Harmonic Observed)

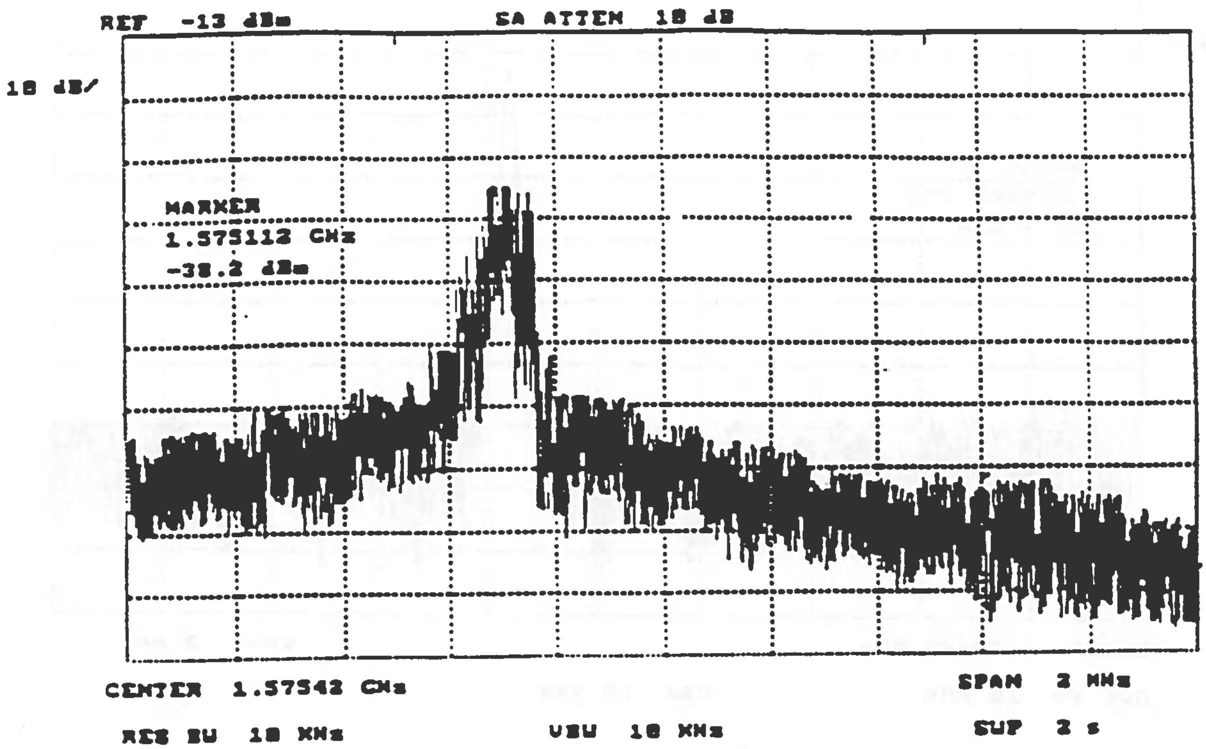


Figure A-3 Unit 1 Emissions through Antenna Port in the L1 ± 1 MHz Band (Transceiver Tuned to 133.675 MHz and Keyed; Transmitter Spur Observed)

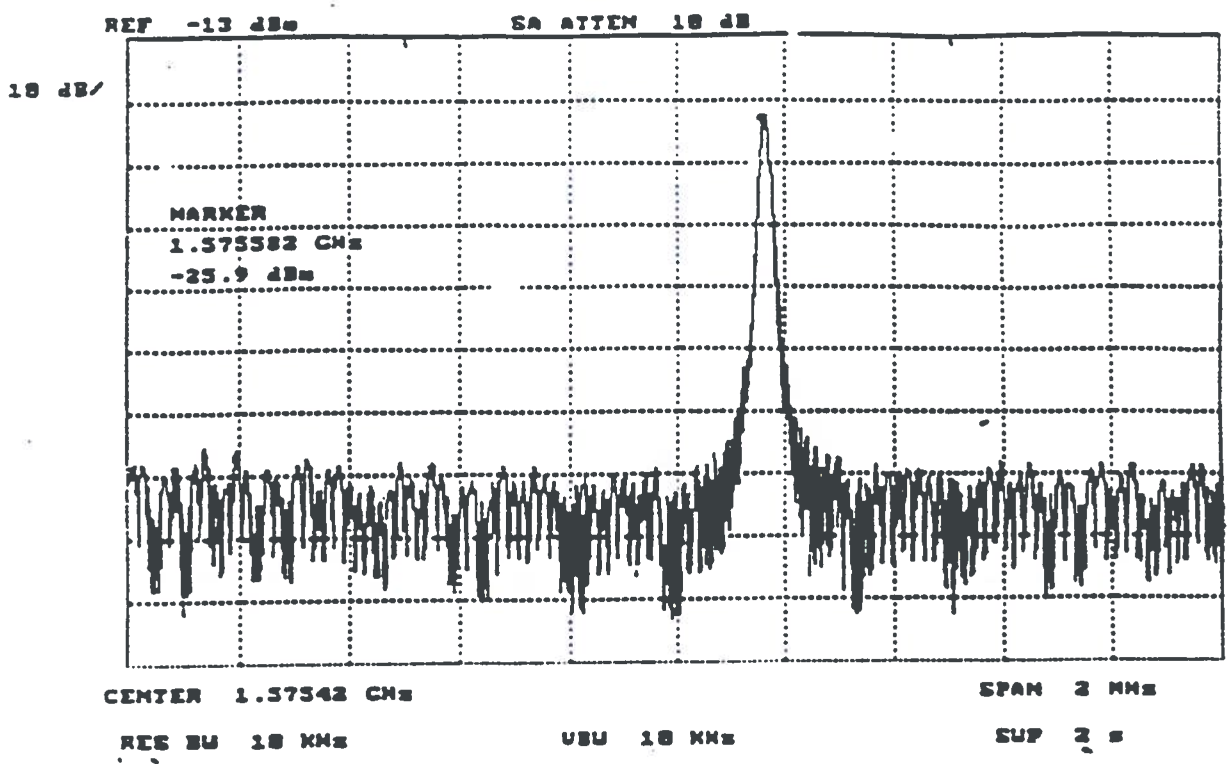
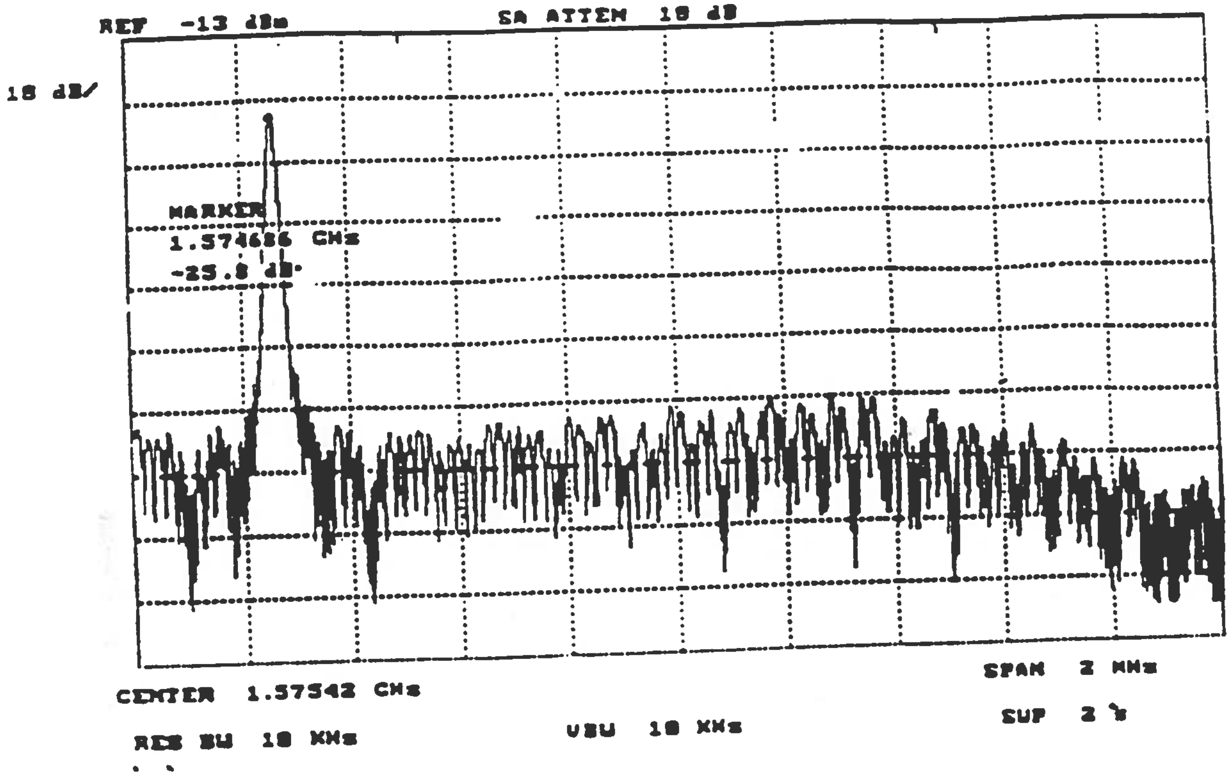


Figure A-4 Unit 1 Emissions through Antenna Port in the L1 ± 1 MHz Band (Transceiver Tuned to 119.275.675 MHz and Unkeyed; L.O. Harmonic Observed)



APPENDIX B

TABLES OF ANTENNA PORT EMISSIONS FOR EACH TRANSCEIVER

This appendix contains tables of data collected from the VHF sets' antenna ports. There is one table for each unit (in some cases spanning two pages), and tables are in ascending order. Units numbered 1 through 10 are G/A-class, panel-mounted sets. Units 11 and 12 are commercial-class remote-mounted sets.

Table B-1 Antenna Port Emissions: Unit 1
L1 ± 1 MHz (± 0.5 MHz shaded)

Channel (MHz)	Transmit Peak (dBm)/Harmonic	Receive Peak (dBm)/Harmonic
119.225		-83/12
119.250		-83/12
119.275		-82/12
119.300		-83/12
119.325		-83/12
119.350		-84/12
121.125	-26/13	
121.150	-26/13	
121.175	-25/13	
121.200	-26/13	
121.225	-26/13	
121.250	-26/13	
131.050	-89*	
131.075	-81*	
131.100	-76*	
131.125	-72*	
131.150	-73*	-83/11
131.175	-72*	-82/11
131.200	-66*	-75/11
131.225	-25/12	-76/11
131.250	-26/12	-78/11
131.275	-26/12	-78/11
131.300	-26/12	-79/11
131.325	-26/12	
131.350	-26/12	
131.375	-72*	
131.400	-72*	
131.425	-72*	
131.450	-73*	
131.475	-78*	
131.500	-85*	

* Spurious Emission

Table B-1 Antenna Port Emissions: Unit 1 (con't)
L1 ± 1 MHz (± 0.5 MHz shaded)

Channel (MHz)	Transmit Peak (dBm)/Harmonic	Receive Peak (dBm)/Harmonic
133.550	-81*	
133.575	-81*	
133.600	-73*	
133.625	-37*	
133.650	-38*	
133.675	-38*	
133.700	-38*	
133.725	-38*	
133.750	-39*	
133.775	-52*	
133.800	-78*	
133.825	-77*	
133.850	-78*	
133.875	-80*	
135.400	-82*	
135.425	-69*	
135.450	-50*	
135.475	-54*	
135.500	-53*	
135.525	-54*	
135.550	-53*	
135.575	-53*	
135.600	-49*	
135.625	-50*	
135.650	-83*	
135.675	-86*	
135.700	-86*	

* Spurious Emission

Table B-2 Antenna Port Emissions: Unit 2
L1 ± 1 MHz (± 0.5 MHz shaded)

Channel (MHz)	Transmit Peak (dBm)/Harmonic	Receive Peak (dBm)/Harmonic
119.825		-98/12
119.850		-101/12
119.875		-99/12
119.900		-109/12
119.925		-98/12
119.950		-99/12
121.125	-48/13	
121.150	-48/13	
121.175	-48/13	
121.200	-48/13	
121.225	-48/13	
121.250	-48/13	
131.225	-68/12	
131.250	-68/12	
131.275	-69/12	
131.300	-69/12	
131.325	-69/12	
131.350	-68/12	
131.750		-97/11
131.775		-95/11
131.800		-97/11
131.825		-96/11
131.850		-97/11
131.875		-96/11
131.900		-96/11

Table B-3 Antenna Port Emissions: Unit 3
L1 ± 1 MHz (± 0.5 MHz shaded)

Channel (MHz)	Transmit Peak (dBm)/Harmonic	Receive Peak (dBm)/Harmonic
121.150	-28/13	
121.200	-27/13	
121.250	-27/13	
123.150		-68/11
123.200		-68/11
123.250		-69/11
131.250	-24/12	
131.300	-24/12	
131.350	-24/12	

Table B-4 Antenna Port Emissions: Unit 4
L1 ± 1 MHz (± 0.5 MHz shaded)

Channel (MHz)	Transmit Peak (dBm)/Harmonic	Receive Peak (dBm)/Harmonic
121.125	-54/13	
121.150	-55/13	
121.175	-55/13	
121.200	-55/13	
121.225	-56/13	
121.250	-55/13	
131.225	-56/12	
131.250	-55/12	
131.275	-56/12	
131.300	-56/12	
131.325	-56/12	
131.350	-56/12	

Table B-5 Antenna Port Emissions: Unit 5
L1 ± 1 MHz (± 0.5 MHz shaded)

Channel (MHz)	Transmit Peak (dBm)/Harmonic	Receive Peak (dBm)/Harmonic
121.150	-42/13	
121.200	-42/13	
121.250	-42/13	
131.200	-65/12	
131.250	-47/12	
131.300	-47/12	
131.350	-47/12	

The frequencies for this unit appeared to be slight "off-tune." As a result, the twelfth harmonic of 131.200 MHz was observed to be in L1 ± 1 MHz although it should not fall in that band (see Table 1).

Table B-6 Antenna Port Emissions: Unit 6
L1 ± 1 MHz (± 0.5 MHz shaded)

Channel (MHz)	Transmit Peak (dBm)/Harmonic	Receive Peak (dBm)/Harmonic
121.125	-79/13	
121.150	-72/13	
121.175	-72/13	
121.200	-73/13	
121.225	-70/13	
121.250	-70/13	
131.225	-63/12	
131.250	-66/12	
131.275	-65/12	
131.300	-65/12	
131.325	-64/12	
131.350	-64/12	

Table B-7 Antenna Port Emissions: Unit 7
L1 ± 1 MHz (± 0.5 MHz shaded)

Channel (MHz)	Transmit Peak (dBm)/Harmonic	Receive Peak (dBm)/Harmonic
121.150	-97/13	
121.200	-97/13	
121.250	-96/13	
131.250	-87/12	
131.300	-87/12	
131.350	-86/12	

Table B-8 Antenna Port Emissions: Unit 8
L1 ± 1 MHz (± 0.5 MHz shaded)

Channel (MHz)	Transmit Peak (dBm)/Harmonic	Receive Peak (dBm)/Harmonic
121.125	-93/13	
121.150	-93/13	
121.175	-93/13	
121.200	-93/13	
121.225	-91/13	
121.250	-92/13	
121.300	-97 *	
121.325	-97*	
121.350	-96*	
131.225	-94/12	
131.250	-95/12	
131.275	-87/12	
131.300	-97/12	
131.325	-97/12	
131.350	-96/12	

* Spurious Emission

Table B-9 Antenna Port Emissions: Unit 9
L1 ± 1 MHz (± 0.5 MHz shaded)

Channel (MHz)	Transmit Peak (dBm)/Harmonic	Receive Peak (dBm)/Harmonic
120.525		-103/12
120.550		-102/12
120.575		-102/12
120.600		-102/12
120.625		-101/12
120.650		-101/12
121.125	-23/13	
121.150	-23/13	
121.175	-23/13	
121.200	-23/13	
121.225	-22/13	
121.250	-22/13	
131.225	-23/12	
131.250	-23/12	
131.275	-24/12	
131.300	-23/12	
131.325	-24/12	
131.350	-24/12	
132.450		-92/11
132.475		-92/11
132.500		-92/11
132.525		-91/11
132.550		-91/11
132.575		-92/11
132.600		-91/11

Table B-9 Antenna Port Emissions: Unit 9 (con't)
L1 ± 1 MHz (± 0.5 MHz shaded)

Channels (MHz)	Transmit Peak (dBm)	Number of Channels
118.400 - 118.525	-90*	6
119.300 - 120.175	-85*	24
120.200 - 121.325	-72*	6
121.025 - 121.100	-74*	3
121.275 - 122.200	-68*	37
130.125 - 130.400	-63*	11
131.375 - 132.600	-63*	49

* Spurious Emission

Spurious emissions were found on virtually every frequency in the ranges shown in the left-hand column. Some were time-varying, with power levels varying between the peak level shown in the center column and significantly lower levels. Others had steady power, with the level given in the center column. The count of those with steady levels in each band is shown in the right-hand column.

Table B-10 Antenna Port Emissions: Unit 10
L1 ± 1 MHz (± 0.5 MHz shaded)

Channel (MHz)	Transmit Peak (dBm)/Harmonic	Receive Peak (dBm)/Harmonic
121.150	-81/13	
121.200	-81/13	
121.250	-80/13	
131.250	-87/12	
131.300	-87/12	
131.350	-87/12	

Table B-11 Antenna Port Emissions: Unit 11
L1 ± 1 MHz (± 0.5 MHz shaded)

Channel (MHz)	Transmit Peak (dBm)/Harmonic	Receive Peak (dBm)/Harmonic
121.125	-81/13	
121.150	-82/13	
121.175	-82/13	
121.200	-80/13	
121.225	-79/13	
121.250	-79/13	
131.225	-83/12	
131.250	-81/12	
131.275	-81/12	
131.300	-82/12	
131.325	-85/12	
131.350	-84/12	

Table B-12 Antenna Port Emissions: Unit 12
L1 ± 1 MHz (± 0.5 MHz shaded)

Channel (MHz)	Transmit Peak (dBm)/Harmonic	Receive Peak (dBm)/Harmonic
121.125	-83/13	
121.150	-84/13	
121.175	-83/13	
121.200	-83/13	
121.225	-83/13	
121.250	-83/13	
131.225	-84/12	
131.250	-84/12	
131.275	-83/12	
131.300	-84/12	
131.325	-84/12	
131.350	-84/12	

APPENDIX C

TABLE OF CASE EMISSIONS FOR EACH TRANSCEIVER

This appendix contains a table that summarizes data collected for the VHF sets' case emissions. This table lists each channel that was tested, the type of interference (Mode), the power measured out of the front panel, the maximum power and corresponding angle when the unit is resting on its bottom (Normal Position), and the maximum power and corresponding angle when the unit is resting on its right side (On Right Edge). Units numbered 1 through 10 are G/A-class, panel-mounted sets. Unit 12 is an air carrier-class remote-mounted set.

Table C-1 Case Emissions

Unit	Channel (MHz)	Mode[1]	Front Panel 0° Angle[2] Power[3] (dBm)	Normal Position Power, Angle (dBm) (°)	On Right Edge Power Angle (dBm) (°)
Unit 1	119.22	L		-52 (90°)	
	121.12	T		-52 (90°)	
	131.25	L		-56 (90°)	
	131.27	T	-54	-47 (90°)	-48 (0°)
	133.45	Ts		NO (90°)	
	135.65	Ts		NO (90°)	
Unit 2	119.9	L		-68 (45°)	
	121.15	T	-62	-47 (45°)	-46 (45°)
	131.22	T		-49 (45°)	
	131.9	L		NO (45°)	

Table C-1 Case Emissions (continued)

Unit	Channel (MHz)	Mode[1]	Front Panel 0° Angle[2] Power[3] (dBm)	Normal Position Power, Angle (dBm) (°)	On Right Edge Power Angle (dBm) (°)
Unit 3	121.2	T	-50	-49 (45°)	-48 (180°)
	123.25	L		-62 (45°)	
	131.25	L		NO (45°)	
Unit 4	121.15	T		-50 (315°)	-51 (100°)
	126	Ts		NO (315°)	
	131.32	T	-50	-50 (315°)	
Unit 5	121.2	T		-42 (150°)	
	125	Ts		NO (150°)	
	128.8	Ts		NO (150°)	
	131.35	T	-50	-43 (150°)	-45 (45°)
Unit 7	121.15	T	-59	-50 (30°)	-44 (70°)
	122.3	L		NO (30°)	
	126	Ts		NO (30°)	
	131.25	T		-43 (30°)	
	135	L		NO (30°)	
Unit 8	121.25	T	-56	-41 (330°)	-43 (45°)
	122.35	L		NO (330°)	
	126.07	Ts		NO (330°)	
	131.22	T		-48 (330°)	
	135.05	L		NO (330°)	

Table C-1 Case Emissions (continued)

Unit	Channel (MHz)	Mode[1]	Front Panel 0° Angle[2] Power[3] (dBm)	Normal Position Power, Angle (dBm) (°)	On Right Edge Power Angle (dBm) (°)
Unit 9	120.52	L		NO (270°)	
	121.2	T	-34	-30 (270°)	-29 (315°)
	123.05	Ts		NO (270°)	
	130.12	Ts		-68 (270°)	
	131.22	T		-33 (270°)	
	132.57	L		NO (270°)	
Unit 10	119.9	L		NO (90°)	
	121.2	T	-51	-48 (90°)	-44 (315°)
	131.25	T		-54 (90°)	
	131.75	L		NO (90°)	
Unit 12	121.125	T	-48	-40 (330°)	
	131.225	T		-38 (330°)	-35 (210°)

1. T - transmitted harmonic, Ts - transmitted spur, L - local oscillator harmonic.
2. Front panel is 0° reference, rotation is clockwise viewed from above.
3. Minimum detected signal at case ≈ -70 dBm.
4. Blank entries indicate that measurement was not made.
5. "NO" indicates either no signal present or it was below the test system detection threshold.

APPENDIX D

CONVERSION OF EQUIVALENT SOURCE POWER TO FIELD STRENGTH

The Code of Federal Regulations, Title 47 Telecommunications, Section 15 Subpart C-Intentional Radiators, contains the radiated emission limits for VHF transceivers. It states that the emitted field strength as determined at a distance of 3 meters for frequencies above 960 MHz shall not exceed 500 µvolts/meter. In this report, the results of emissions tests are quantified in terms of the power radiated by an equivalent source power. The following calculations relate the equivalent source power (dBm) to field strength (V/m).

The Power Density at 3 meters can be stated as :

$PD_3 = (E_3)^2 / 377$

where E_3 = Field Strength at 3 meters

377 = free space impedance

Assuming an omnidirectional source, the power density is also given by

$P_o / 4\pi r^2 = P_o / 36\pi = (E_3)^2 / 377$

where P_o = equivalent omnidirectional source power

Converting to dB, the last equation becomes

$P_o\,(dBW) = 10\log(36\pi/377) + 20\log E_3$ (1)

$P_o\,(dBW) = P_o\,(dBm) - 30$

$10\log(36\pi/377) = -5.2$

$20\log E_3 = -120 + E_3(dB\ \mu Volts/meter)$

By replacing terms in Equation (1), the electric field strength at three meters can be related to the equivalent power at the source by the following equation:

$$P_o\,(\text{dBm}) = E_3(\text{dB}\,\mu\text{V/m}) - 95$$

The FCC limit of 500 μV/m (or 54 dB μV/m) at 3 meters is thus:

$$P_o\,(\text{dBm}) = 54 - 95 = -41 \text{ dBm omnidirectional source power}$$