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Summary

This report provides an overview and results from the verification of a subset of specifications that define the operational capabilities of the airborne and ground L-band and C-band prototype Control and Non-Payload Communications (CNPC) radio. This report also provides an overview of the characteristics of the CNPC radio. Measurement results are presented to verify radio operation.

1.0 Introduction

NASA's current research in the Unmanned Aircraft Systems Integration in the National Airspace System (UAS in the NAS) project is intended to contribute design capabilities to reduce technical barriers related to the safety and operational challenges associated with routine UAS access to the NAS. The project falls under the Integrated Systems Research Program office managed by the Agency's Aeronautics Research Mission Directorate.

The UAS in the NAS project envisions performance-based routine access to all segments of the NAS for all UAS classes, once all safety-related and technical barriers are overcome. Unmanned aircraft promise new ways to increase efficiency, reduce costs, enhance safety, and save lives.

The NASA Glenn Research Center is currently researching and analyzing command and control (C2) systems in support of the UAS in the NAS project. Glenn personnel entered into a cost-sharing cooperative agreement with Rockwell Collins, Inc., to explore and develop steps to create a prototype Control and Non-Payload Communications (CNPC) system that is suitable for terrestrial UAS C2 operations. Development steps include investigating signal waveform and access techniques, developing representative CNPC radio hardware, and performing relevant verification and validation tests of the prototype system. Verification confirms that the CNPC radio specifications meet the Minimum Operational Performance Standards (MOPS) stated in RTCA DO–362 (Ref. 1).

2.0 Verification Testing

There are four primary methods of verification: inspection, demonstration, analysis, and testing. The verification method used on the prototype radio was testing. Testing verifies the operation of the radio's subsystems by using controlled input data and measurements to verify that the radio will produce the specific and predefined output as determined by the MOPS. Verification testing confirms that the radio operates according to the specified design parameters. All verification testing was conducted in Glenn's UAS communications lab.

This report verifies the design specifications of the Generation 5, Rockwell Collins prototype radio. Rockwell Collins and NASA established baseline performance requirements through an iterative process, creating five generations of the radio's prototype performance. The design specifications were defined and verification procedures were established from the baseline requirements.

Verification of a radio's specifications and performance requires developed test procedures, calibrated test equipment, and in many cases a unique custom test set that has test points at selected critical test points within the radio system. Verification testing measured data from the radio via Rockwell Collins' CNPC Manager Interface in conjunction with measured values obtained from the external radiofrequency (RF) ports.

3.0 Radio Operation Overview

This section provides an overview of the prototype radio characteristics.

3.1 Spectrum Requirements

Spectrum requirements were established with the adoption of ITU–R M.2171 (Ref. 2). This report identified 34 MHz as the maximum amount of spectrum required for a terrestrial line-of-sight (LOS) UAS. Actions taken at the International Telecommunication Union's (ITU's) World Radio Council-12 established spectrum resources to address the LOS spectrum requirement by adding a new Aeronautical Mobile (Route) Service (AM(R)S) allocation in the 5030- to 5091-MHz band combined with a portion of an existing AM(R)S allocation in the 960- to 1164-MHz band.

3.2 Recommended Tuning Ranges

The 5030- to 5091-MHz C-band frequency range is currently vacant except for the little-used Microwave Landing System. However, the 960- to 1164-MHz L-band frequency range is heavily used by preexisting systems including Distance Measuring Equipment (DME), Tactical Air Navigation (TACAN), Secondary Surveillance Radar (SSR), 1090-MHz Extended Squitter (1090ES), the Traffic Alert and Collision Avoidance System (TCAS), the Universal Access Transceiver (UAT), and the Joint Tactical Information Distribution System (JTIDS). Because of current aeronautical L-band usage, the frequencies tested in the L-band do not include those between 976 and 980 MHz or those between 1020 and 1164 MHz.

3.3 Waveform Structure

The radio uses the time division duplex (TDD) timing scheme shown in Figure 1. It also uses a bi-directional coding scheme that is different for the air-to-ground transmission link (downlink) than for the ground-to-air transmission link (uplink). The downlink uses a frequency division multiple access (FDMA) scheme, and the uplink uses a time division multiple access (TDMA) scheme.

3.4 Data Class

Information transmitted over the uplink and downlink is categorized into four different data link service structures that are common to both uplink and downlink. Throughout this report, these four data link service structures are identified as data classes 1 to 4.

The four data class structures were based on different bandwidths and symbol rates to support the required data transmission rates. Only data classes 3 and 4 were provisioned for verification and flight testing. Table I provides an overview of the specific parameters for data classes 3 and 4.

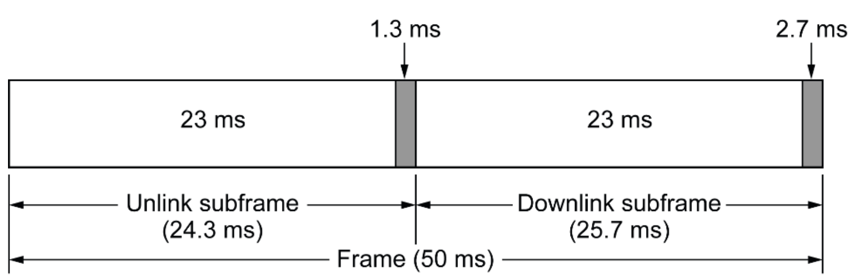


Figure 1.—Time division duplex (TDD) frame structure.

TABLE I.—SERVICE PARAMETER SUMMARIES FOR DATA CLASSES 3 AND 4

Parameter	Data class 3	Data class 4
Modulation	GMSK[a]	GMSK
Bandwidth-time product	0.2	0.2
Bits per symbol	1	1
Symbol rate, symbols per s	103,500	138,000
Data class bandwidth, kHz	90	120
Slot duration, ms	22.961	23
Total symbols[b], symbols	2376.5	3174
-Ramp up	4	4
-Acquisition	32	32
-Preamble	96	96
-Midambles[c] (32 symbols each)	96 (quantity 3)	160 (quantity 5)
-Postamble	32	32
-Ramp down	4.5	4
-Data segments	2112	2846
Data segments[d], bits	2112	2846
-Message	1280	1728
-CRC[e]	32	32
-FEC[f]	794	1062
-Fill	6	24

[a]Gaussian minimum shift keying.
[b]Sum of symbols that comprise ramp up, acquisition, preamble, midambles, postamble, ramp down, and data segments.
[c]32 symbols long and are inserted after every 512 symbols of data segment.
[d]Comprise message, CRC, FEC, and fill bits.
[e]Cyclic redundancy check.
[f]Forward error correction.

TABLE II.—CONTROL AND NON-PAYLOAD COMMUNICATIONS (CNPC) RADIO RECEIVER SENSITIVITY SPECIFICATION FOR L-BAND AND C-BAND

Data class	Link direction	Symbol rate	Occupied bandwidth, kHz	L-band sensitivity limit, dBm	C-band sensitivity limit, dBm
3	Uplink	103,500	90	–117	–114
3	Downlink	103,500	90	–118	–115
4	Uplink	138,000	120	–115	–112
4	Downlink	138,000	120	–116	–113

3.5 Modulation

The physical layer is based on a Gaussian minimum shift keying (GMSK) modulation scheme.

3.6 Transmit Power Output

The maximum allowable power at the output of the radio was determined to be 32 mW to reduce the probability of L-band interference into the incumbent airborne services in and adjacent to the CNPC-assigned frequency allocation. Low and high power limits of 100 mW and 10 W, respectively, were recommended for the C-band allocation.

3.7 Receiver Sensitivity

Sensitivity limits for the L-band and C-band receiver were based on the symbol rate and bandwidth as shown in Table II.

4.0 Prototype Radio Verification

This section contains information about the test equipment, test signals, specifications, and verification results.

4.1 Test Frequencies

Table III provides a systematic approach for selecting test frequencies for verification tests when multiple test frequencies are required.

The variables xxx, yyy, and zzz represent the low, mid, and upper test frequencies necessary when a span of frequencies is required for the CNPC radio under test.

4.2 Recommended Test Equipment

The following test systems were used in the verification process to interface with the radio for generating data messages, capturing output data, and providing overall control of the radio.

- Message generator—Generates time-varying data messages and sets the number of links simultaneously supported by the transmitter.
- Control computer—Used to send commands to the airborne or ground radio transmitter and receiver.
- Data collection computer—Collects data pertaining to bit-level information, error conditions, signal-to-interference-plus-noise ratio, power output, channel bandwidth, and receiver key performance indicators.

The following test equipment was used in the verification process. The list is not a recommendation or a promotion for the test equipment used.

- Spectrum analyzer—Keysight (formally Agilent) PXA N9030A or equivalent
- Vector signal analyzer (VSA) software—Agilent 89600 or equivalent
- Average power sensor—Rohde & Schwarz NRP–Z31 or equivalent
- Vector signal generator (VSG)—Keysight E8267D or equivalent
- Various fixed attenuators—Pasternack® or equivalent
- TDD/RF pulse synchronization timing system—Symmetricom® or equivalent
- 50-Ω termination—Bird Technologies® or equivalent
- Resistive four-way power splitter/combiner—Mini-Circuits® ZFRSC–4–842 or equivalent
- High-power attenuators:
  - Bird Technologies®, 50-W, 30-dB attenuation, or equivalent
  - Bird Technologies®, 50-W, 20-dB attenuation, or equivalent
  - Bird Technologies®, 50-W, 10-dB attenuation, or equivalent
  - RF Lambda, 50-W, 40-dB attenuation, or equivalent
  - RF Lambda, 50-W, 50-dB attenuation, or equivalent

TABLE III.—CONTROL AND NON-PAYLOAD COMMUNICATIONS (CNPC) LINK TRANSMITTER/RECEIVER TEST FREQUENCIES

Transmitter/receiver test frequencies, MHz		
Lower L-band	Upper L-band	C-band
960.xxx, 968.yyy, 975.zzz	980.xxx, 1000.yyy, 1019.zzz	5030.xxx, 5060.yyy, 5090.zzz

4.3 Standard Test Signals

The standard test signals are defined as follows:

(1) Standard L-band test signal—The L-band RF carrier input is encoded and modulated by the manufacturer-specified modulation and encoding technique. The user input data rates associated with the encoding and modulation rates are also specified by the manufacturer. The standard test signal is generated by inputting a block of user data (test message) to the L-band radio transmitter in accordance with Section 4.4. The CNPC Transmitted Test Signal is synchronized to the TDD frame structure specified in the NASA–Rockwell Collins CNPC radio waveform.

(2) Standard C-band test signal—The C-band RF carrier input is encoded and modulated by the manufacturer-specified modulation and encoding technique. The user input data rates and the associated encoding and modulation rates are also specified by the manufacturer. The standard test signal is generated by inputting a block of user data (test message) to the C-band radio transmitter in accordance with Section 4.4. The Transmitted Test Signal is synchronized to the TDD frame structure specified in the NASA–Rockwell Collins CNPC radio waveform.

(3) Minimum desired power level—The minimum power of the desired signal applied to the receiver will be $S_{\min}$, where $S_{\min}$ is the manufacturer-defined sensitivity level of the receiver. If the receiver supports multiple user data rates, the manufacturer will define the sensitivity level for each user data rate.

4.4 Test Message Size and User Data Rate

Test messages contain pseudorandom user message bits that vary for each successive transmitted burst (pulse). The number of bits are equal to the number of user bits per subframe specified by the manufacturer for the specific user data rates of the radio receiver/transmitter under test.

The relationship between the number of user bits per subframe and the user data rate is defined as the number of user bits per subframe (bits/50 ms).

4.5 Statistical Sample Size and Pass/Fail Criteria

The message generator transmits 10,000 test messages to get a sufficient sample to generate the following pass/fail criteria for the receiver message reception:

- If 10 or fewer messages are not received (lost by the radio receiver) or are received with errors (do not pass the cyclic redundancy check (CRC)), then the receiver subsystem passes the test. This is less than or equal to a message failure rate of 0.1 percent.
- If 11 or more messages are not received (lost by the radio receiver) or are received with errors (do not pass CRC), then the receiver subsystem fails the test. This is greater than or equal to a message failure rate of 0.1 percent.

4.6 Airborne and Ground Radiofrequency (RF) Output Power

This section verifies the output power specified for the L-band and C-band transmitters.

4.6.1 Radiofrequency (RF) Output Power Specification

The L-band airborne radio transmitter will produce an average power of 32 mW or less. The C-band airborne radio transmitter will produce an average power of 100 mW or less in the low-power mode and an average power of 10 W or less in the high-power mode. Output power levels will be within 10 percent, measured at the antenna interface port over a 1-s interval. These specifications apply to all data classes as shown in Table IV.

4.6.2 Radiofrequency (RF) Output Power Verification

This test procedure verifies the transmit output power measured at the radio unit under test (UUT) antenna interface port. The test procedure will enable the UUT to transmit messages for 10 s. The transmit output power is measured by a power meter as the average power over the full transmit cycle. In addition, the transmit duty cycle must be accounted for when a final measurement number is calculated. The transmit duty cycle is 23-ms ON and 27-ms OFF in a 50-ms window and equates to a 46-percent duty cycle.

The test procedure for RF output power verification is as follows:

(1) Connect the equipment as shown in Figure 2.
(2) Calibrate the power meter according to the manufacturer's specification, and include the measured total path loss from the output connector of the UUT to the input of the power meter.
(3) Enter the offset level required to negate the losses in the test configuration.
(4) Use a 50-ms aperture to configure the power meter to measure the average power over 10 s.
(5) Configure the UUT to transmit messages using every time slot.
(6) Command the UUT to enable the transmit function.
(7) Using the power-stepping function in the UUT, raise or lower the number of steps to achieve as close to the required output as possible while maintaining the limits listed in the Specification row in Table IV.
(8) On the power meter, initiate power measurements. Wait at least 10 s before recording the power meter measurement.
(9) The average power for the L-band radio should be 32 mW or less. The average power for the C-band radio at the low-power setting should be 100 mW or less and at the high-power setting is 10 W or less.
    (a) Pass: RF power output was within the requirements in step 9
    (b) Fail: RF power output was not within the requirements in step 9.
(10) Command the UUT to disable the transmit function. Verify that the meter reads negligible output power.

TABLE IV.—SPECIFICATIONS AND MEASURED RADIOFREQUENCY (RF) AVERAGE OUTPUT POWER FOR L-BAND AND C-BAND

	L-band power (average)	C-band power (average low)	C-band power (average high)
Specification	≤32.0 mW	≤100.0 mW	≤10.0 W
Measured	27.0 mW	76.0 mW	9.29 W

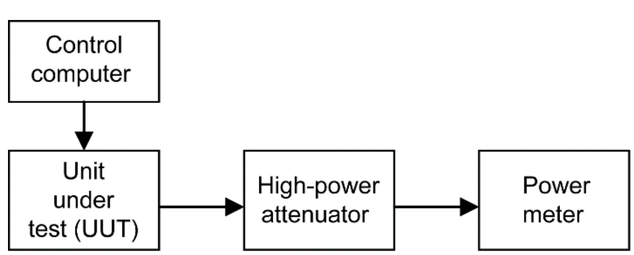


Figure 2.—Radiofrequency (RF) output measurement test setup.

4.6.3 Radiofrequency (RF) Output Power Results

Table IV shows the measured RF output power for the L-band and C-band in comparison to the specifications. The radio interface did not allow for exact power settings. So, the measured values are the result of using a fixed number of steps to come as close as possible to the Specification limits.

4.7 Signal Modulation Verification

This section verifies the precoding, rate, and distortion of the modulation processes.

4.7.1 Signal Modulation Specifications

The airborne radio transmitter uses a GMSK modulation scheme with a modulation index of 0.5 and a bandwidth-time, *BT*, product of 0.2.

4.7.1.1 Modulation and Precoding

The modulation bit stream is precoded according to the rules and information in Table V. The first bit is numbered B_0. Entering a logic "1" into the modulator produces a positive phase rotation, and entering a logic "0" into the modulator produces a negative phase rotation. The value passed into the modulator for each of the bits is defined in Table V.

4.7.1.2 Modulation Rates

The modulation symbol rate is shown in Table VI for each of the supported data classes.

4.7.1.3 Modulation Distortion

The modulation distortion must not exceed 5° root mean square (RMS) or 20° peak. The mean frequency error across the burst must not exceed 0.05 ppm.

TABLE V.—MODULATION PRECODING

Bits	Logic value of current bit, B_n	Logic value of previous bit, B_{n-1}	Value passed into modulator for bit *n*
Even (B_0, B_2, B_4, etc.)	1	1	0
		0	1
	0	1	1
		0	0
Odd (B_1, B_3, B_5, etc.)	1	1	1
		0	0
	0	1	0
		0	1

TABLE VI.—SYMBOL RATES FOR DATA CLASSES

Data class	Symbol rate, kilosymbols/second
1	34.5
2	69.0
3	103.5
4	138.0

4.7.2 Signal Modulation Verification

This procedure verifies that the transmitter uses a GMSK modulation waveform as defined in Section 4.7.1. This procedure also verifies the modulation precoding, rate, and distortion. A VSA demodulates the waveform, recovers the channel symbols, and searches for a sync pattern. The channel symbols are remodulated within the VSA by using a reference GMSK waveform created within the VSA and are compared against the input signal to measure vector distortion.

The test procedure for signal modulation verification follows:[1 2]

(1) Connect the equipment as shown in Figure 3 with enough attenuation to present a signal at the VSA with a pulse power of 15±5 dBm.
(2) Configure the VSA according to the digital demodulation settings listed in Table VII.
(3) Command the transmitter to transmit at maximum power.
(4) Command the message generator to transmit messages containing pseudorandom user message bits that vary for each successive transmitted burst (pulse).
(5) Verify that the constellation diagram has a constant envelope with 12 well-defined constellation points as shown in Figure 4(a), and verify that the synchronization pattern is detected in the symbol table, for all subframes, as shown in Figure 4(b) (first 32 symbols in inverted text).
(6) Pass/fail criteria:
  (a) Pass: A valid synchronization pattern was detected and displayed.
  (b) Fail: A valid synchronization pattern was not detected and displayed.

4.7.3 Signal Modulation Results

The modulation verification procedure was performed for data class 3 and 4 data rates (data classes 1 and 2 were not implemented in the Generation 5 radio). The verification measurement data, constellation diagrams, and symbol table/error summaries were captured as shown in Figure 5 and Figure 6. The measurement data were compared against each pass/fail criteria, and the results are summarized in Table VIII, Table IX, and Table X.

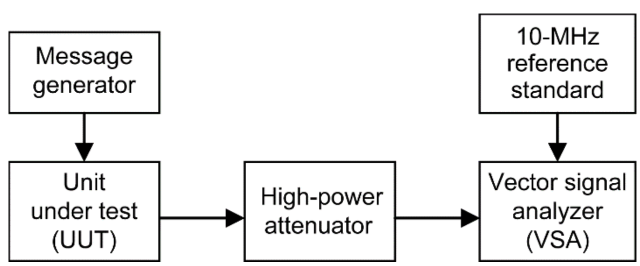
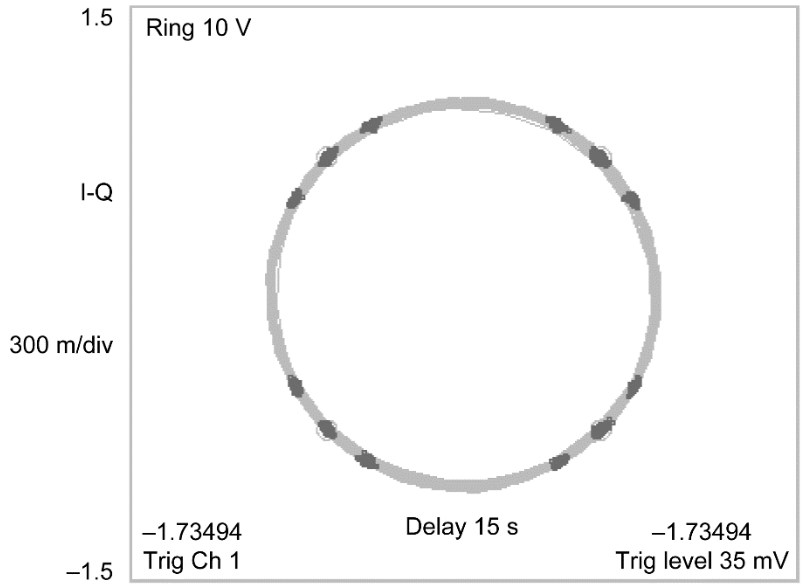


Figure 3.—Signal modulation measurement test configuration.

[1]These settings are specific to the Keysight 89600 VSA and will serve as a guide if other VSA analysis software is used.

[2]Alternative procedures and test equipment may be used if the equipment manufacturer can show that they provide at least equivalent measured performance.



(a)

C: Ch1 MSK2 Syms/Errs

RMS:100

EVM	= 2.0866	%rms	6.9726	% pk at	sym	2849
Mag Err	= 859.77	m%rms	-4.4050	% pk at	sym	5
Phase Err	= 1.0581	deg	3.9974	deg pk at	sym	2849
Freq Err	= -8.8011	Hz				
IQ Offset	= -49.349	dB	Amp Droop = -2.615	udB/sym		
Quad Err	= 164.59	mdeg	Gain Imb = 0.002	dB		

```
  0 11001101 01100001 01101010 10010111 10010011 11010010 01101101 00010000
 64 01000110 10001110 11101100 01001010 11100011 00111111 01000100 10000101
128 11000100 11111001 11100010 10111000 01111111 11000000 11010011 10001010
192 00100101 11100010 01110100 01011111 11011111 11011100 11110000 10000011
256 11110011 10111000 10000010 11011011 10010001 01001110 00100010 10010110
320 10111011 11111011 10100001 11101001 01000001 01111011 00110101 01111101
384 10110001 10000101 10011110 01011001 10001011 10010111 11011110 11011000
448 11011101 00110011 10110011 01000011 11101101 10111001 11010001 10101011
512 00010110 01000010 10100011 01000101 11010001 01111010 10111010 10010000
576 00000100 11110001 11111011 11010011 11100101 00101010 10101000 11010101
640 00111101 10111010 11000100 10001010 00000010 11011100 00011001 00011011
704 10111101 00001010 01010101 01101110 01010011 00111010 10110100 00000110
```

(b)

Figure 4.—Digital demodulation. (a) Trace A constellation diagram. (b) Trace C symbol table/error summary.

TABLE VII.—VECTOR SIGNAL ANALYZER (VSA) DIGITAL DEMODULATION CONFIGURATION

Demodulation parameter	Setting
Preset	Press to preset VSA
Input analog range	Pulse power + 2 dBm
Center frequency	Channel center frequency under test
Span	–60-dBc bandwidth points
Measurement type	Digital demodulation
Format	Minimum shift keying (MSK) type 2
Symbol rate	Symbol rate under test
Points per symbols	5
Result length, symbols	See Table VIII
Measurement filter	None
Reference filter	Gaussian
Reference filter bandwidth-time, *BT*	0.2
Pulse search	Off
Constellation sync search	On
Sync search pattern	
Hexadecimal	CD616A97
Binary	11001101011000010110101010010111
Sync search length	23 ms
Trigger style	Intermediate frequency (IF) magnitude
Trigger level	25 mV
Average	On
Average count	100
Average type	Root mean square (RMS) exponential
Trace A measurement data	In-phase/quadrature (IQ) measured time
Trace A trace format	IQ
Trace B measurement data	IQ measured time
Trace B trace format	Eye diagram
Trace B digital demodulation/eye length	Three symbols
Trace C measurement data	Symbol table/error summary

TABLE VIII.—DIGITAL DEMODULATION RESULTS

Data class	Symbols
1	782
2	1576
3	2368
4	3166

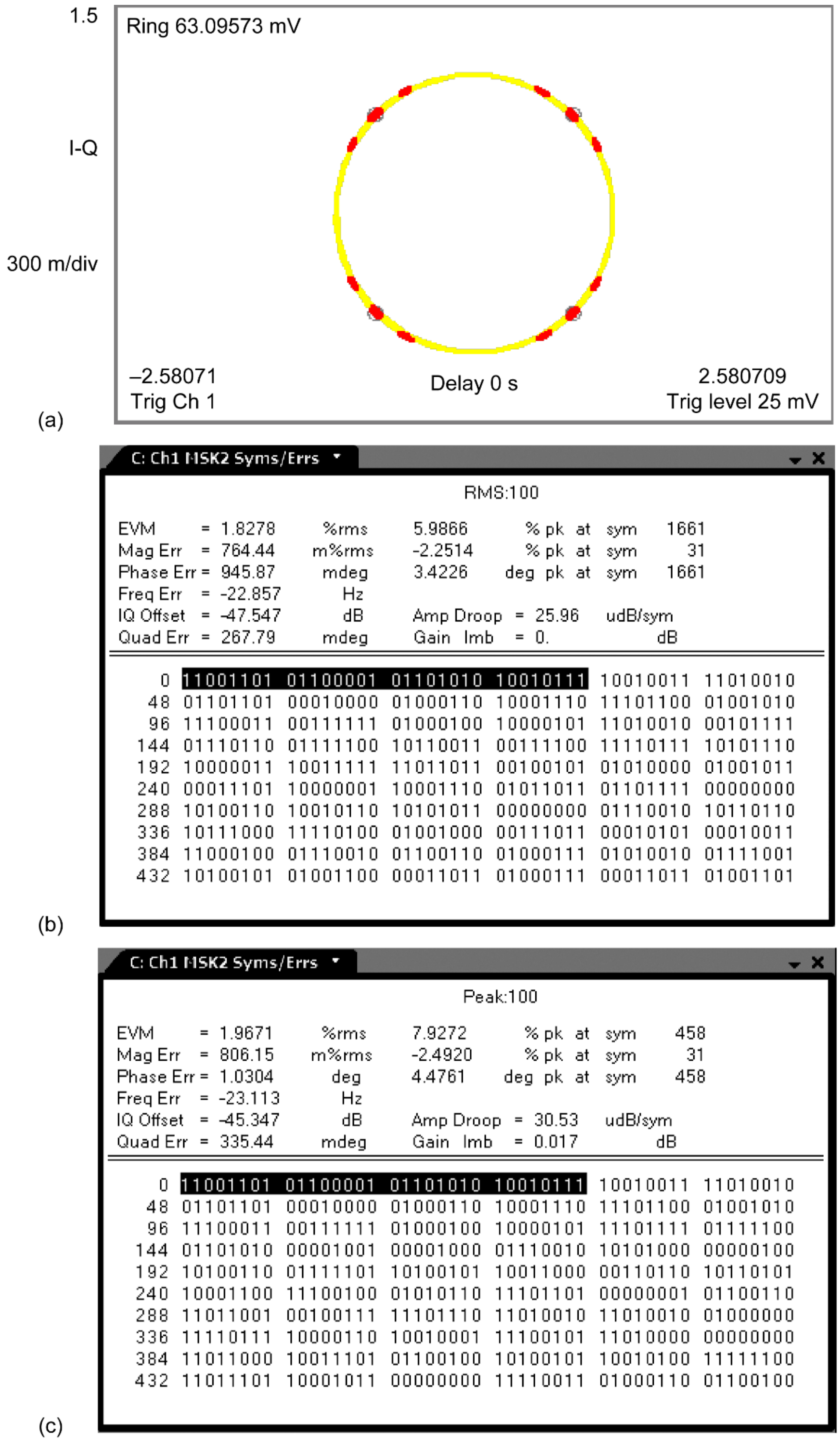
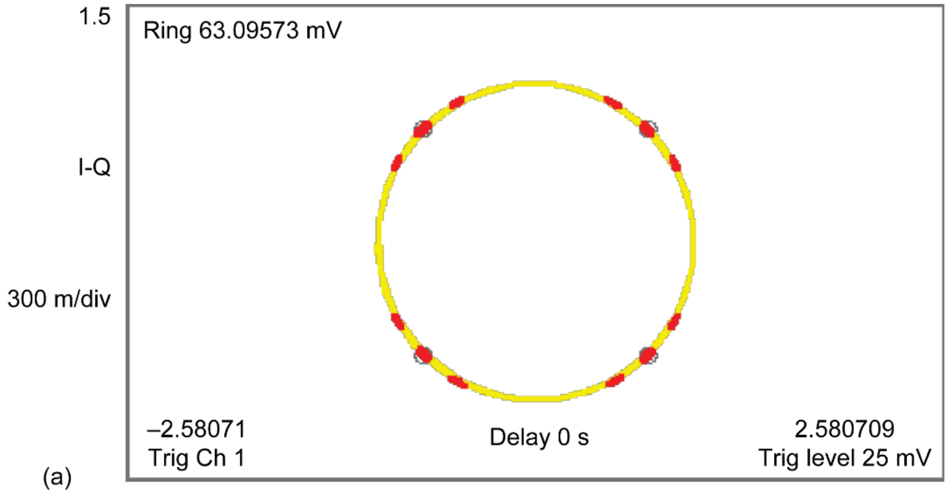


Figure 5.—Data class 3 digital demodulation. (a) Trace A constellation diagram. (b) Trace C symbol table/error summary (RMS, root mean square). (c) Trace C symbol table/error summary (peak).



(a)

C: Ch1 MSK2 Syms/Errs

RMS:100

EVM	= 1.8416	%rms	6.2837	% pk at	sym	2778
Mag Err	= 775.49	m%rms	-2.4036	% pk at	sym	31
Phase Err	= 952.02	mdeg	-3.5809	deg pk at	sym	2778
Freq Err	= -22.522	Hz				
IQ Offset	= -47.469	dB	Amp Droop = 19.03	udB/sym		
Quad Err	= 267.42	mdeg	Gain Imb = -0.001	dB		

0	11001101	01100001	01101010	10010111	10010011	11010010
48	01101101	00010000	01000110	10001110	11101100	01001010
96	11100011	00111111	01000100	10000101	10100001	10001010
144	01011100	11100111	01011111	01100010	11111001	01101000
192	01001110	00100110	10111001	11000110	01010010	00001011
240	11000000	11100000	11001010	10011100	10111100	11010011
288	10000011	11101011	11001100	10011000	10001011	11001101
336	01001100	10110111	10100010	00001011	10000001	11011011
384	10001001	10000011	11100001	11011000	01101110	11100100
432	01100011	11110111	01011101	10110001	00111000	10000111

(b)

C: Ch1 MSK2 Syms/Errs

Peak:100

EVM	= 2.0470	%rms	7.7454	% pk at	sym	969
Mag Err	= 799.93	m%rms	-2.4967	% pk at	sym	31
Phase Err	= 1.0825	deg	4.4389	deg pk at	sym	969
Freq Err	= -22.640	Hz				
IQ Offset	= -45.712	dB	Amp Droop = 23.66	udB/sym		
Quad Err	= 316.37	mdeg	Gain Imb = 0.016	dB		

0	11001101	01100001	01101010	10010111	10010011	11010010
48	01101101	00010000	01000110	10001110	11101100	01001010
96	11100011	00111111	01000100	10000101	11111111	01110100
144	01000010	10000011	10110011	00100100	10010110	01001000
192	11101100	00010111	01010111	00010101	10110100	01001101
240	11110001	00001000	00101100	10111011	00111000	11111111
288	11100100	00001110	01111000	01010111	01111101	11100011
336	11011110	10101101	00011110	01111010	00110110	10110111
384	10010011	01111000	10001011	00011001	10101000	01011011
432	01000011	01010000	01111011	00001110	01111010	10101110

(c)

Figure 6.—Data Class 4 digital demodulation. (a) Trace A constellation diagram. (b) Trace C symbol table/error summary (RMS, root mean square). (c) Trace C symbol table/error summary (peak).

TABLE IX.—MODULATION RESULTS

Data class	Sync pattern detected for all subframes?	Result
3	Yes	Pass
4	Yes	Pass

TABLE X.—MODULATION SYMBOL PHASE ERROR RESULTS

Data class	Root mean square (RMS)		Peak	
	Degrees	Results	Degrees	Results
3	0.946	Pass	4.48	Pass
4	.952	Pass	4.44	Pass

4.8 Power Spectral Density (PSD)

This section verifies the transmitter's specified PSD limits given various antenna gains and system installation losses for the L-band and C-band transmitters.

4.8.1 Power Spectral Density (PSD) Specification

This test verifies that the density of the spectral output power of the radio transmitter is within the PSD mask specifications set by RTCA DO–362. Channel width, as used in Figure 7 to Figure 14, is defined as a positive integer multiple of 5 kHz and as C in the spectral-density masks shown in these figures. PSD measurements include the worst-case conditions of transmitter frequency inaccuracy and Doppler shift when the information bits being transmitted consist of a pseudorandomly generated sequence of 0's and 1's.

4.8.1.1 L-Band Airborne Radio Transmitter Power Spectral Density (PSD) Limits: Antenna Gain Minus System Installation Loss of 3 dBi or Less

For systems in which the antenna gain minus system installation loss is 3 dBi or less, the PSD of any L-band airborne radio transmitter with a channel that is C kHz wide must fit in the mask envelope shown in Figure 7.

4.8.1.2 L-Band Airborne Radio Transmitter Power Spectral Density (PSD) Limits: Antenna Gain Minus System Installation Loss Greater Than 3 dBi

For systems in which the antenna gain minus system installation loss is greater than 3 dBi, the PSD levels of any L-band airborne radio transmitter with a channel that is C kHz wide will be reduced to ensure compliance at all azimuth and elevation angles with the effective isotropically radiated power spectral density (EIRPSD) mask shown in Figure 8.

4.8.1.3 L-Band Ground Radio Transmitter Power Spectral Density (PSD) Limits: Antenna Gain Minus System Installation Loss of 18 dBi or Less

For systems in which the antenna gain minus system installation loss is 18 dBi or less, the PSD levels of any L-band ground radio transmitter with a channel that is C kHz wide must fit in the mask envelope shown in Figure 9.

4.8.1.4 L-Band Ground Radio Transmitter Power Spectral Density (PSD) Limits: Antenna Gain Minus System Installation Loss Greater Than 18 dBi

For systems in which the antenna gain minus system installation loss is greater than 18 dBi, the PSD levels of any L-band ground radio transmitter with a channel that is C kHz wide will be reduced to ensure compliance at all azimuth and elevation angles with the EIRPSD mask shown in Figure 10.

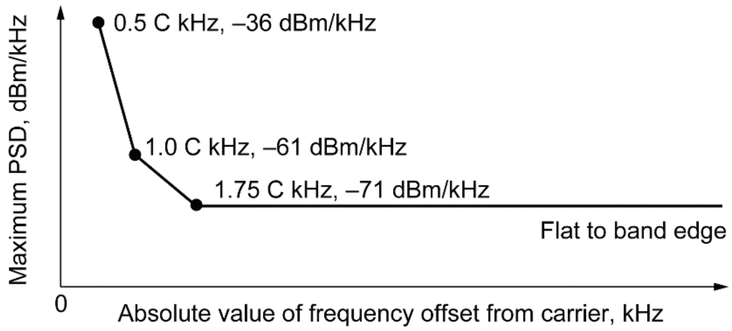


Figure 7.—L-band airborne radio transmitter power spectral density (PSD) mask.

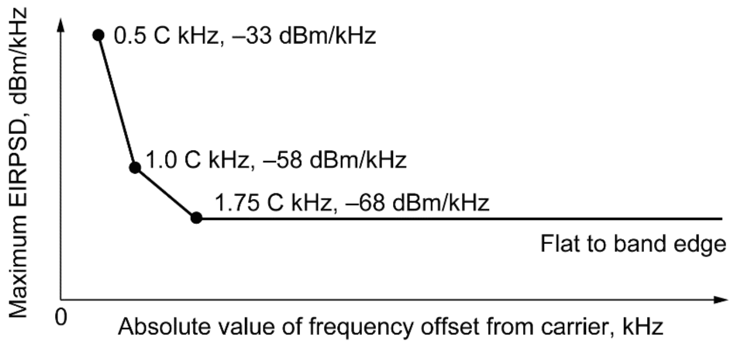


Figure 8.—L-band airborne radio system transmitter effective isotropically radiated power spectral density (EIRPSD) mask.

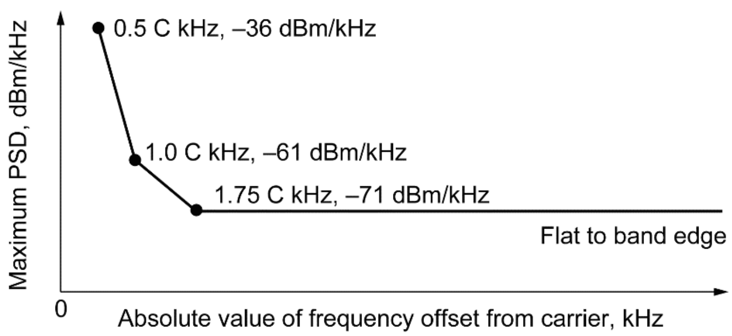


Figure 9.—L-band ground radio power spectral density (PSD) mask.

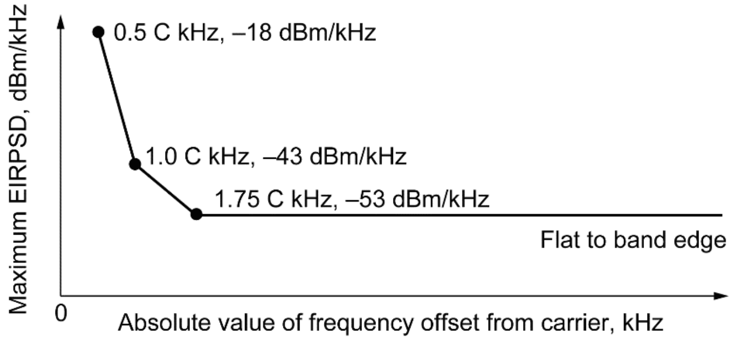


Figure 10.—L-band ground radio system transmitter effective isotropically radiated power spectral density (EIRPSD) mask.

4.8.1.5 C-Band Airborne Radio Transmitter Power Spectral Density (PSD) Limits: Antenna Gain Minus System Installation Loss of 3 dBi or Less

For systems in which the antenna gain minus system installation loss is 3 dBi or less, the PSD levels of any C-band airborne radio transmitter with a channel that is C kHz wide must fit in the mask envelope shown in Figure 11.

4.8.1.6 C-Band Airborne Radio Transmitter Power Spectral Density (PSD) Limits: Antenna Gain Minus System Installation Loss Greater Than 3 dBi

For systems in which the antenna gain minus system installation loss is greater than 3 dBi, the PSD levels of any C-band airborne radio transmitter with a channel that is C kHz wide will be reduced to ensure compliance at all azimuth and elevation angles with the EIRPSD mask shown in Figure 12.

4.8.1.7 C-Band Ground Radio Transmitter Power Spectral Density (PSD) Limits: Antenna Gain Minus System Installation Loss of 24 dBi or Less

For systems in which the antenna gain minus system installation loss is 24 dBi or less, the PSD levels of any C-band ground radio transmitter with a channel that is C kHz wide must fit in the mask envelope shown in Figure 13.

4.8.1.8 C-Band Ground Radio Transmitter Power Spectral Density (PSD) Limits: Antenna Gain Minus System Installation Loss Greater Than 24 dBi

For systems in which the antenna gain minus system installation loss is greater than 24 dBi, the PSD levels of any C-band ground radio transmitter with a channel that is C kHz wide will be reduced to ensure compliance at all azimuth and elevation angles with the EIRPSD mask shown in Figure 14.

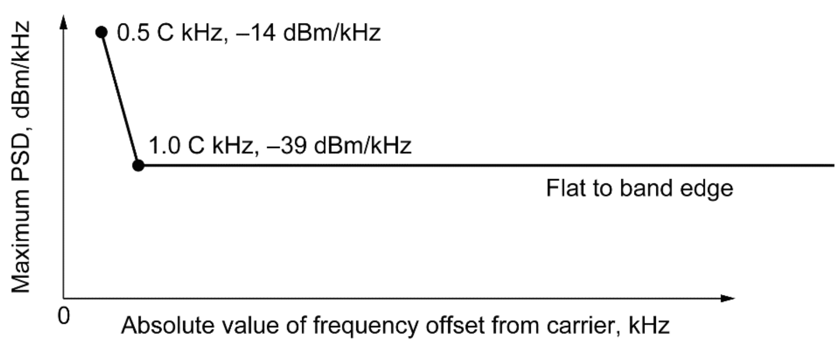


Figure 11.—C-band airborne radio system power spectral density (PSD) mask.

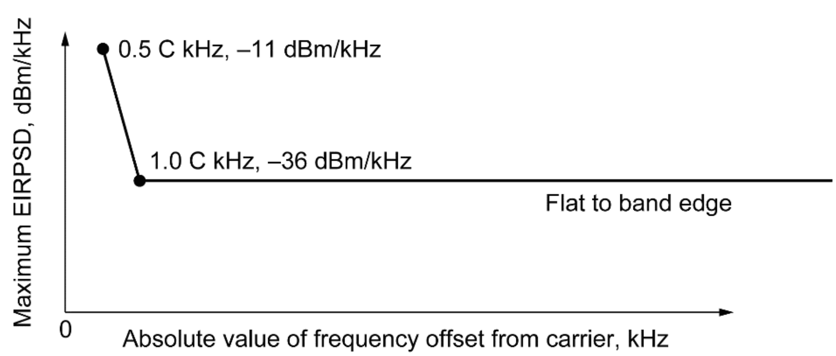


Figure 12.—C-band airborne radio system transmitter effective isotropically radiated power spectral density (EIRPSD) mask.

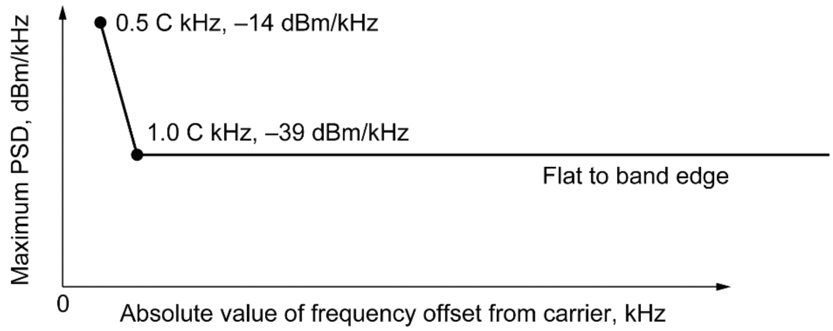


Figure 13.—C-band ground radio transmitter power spectral density (PSD) mask.

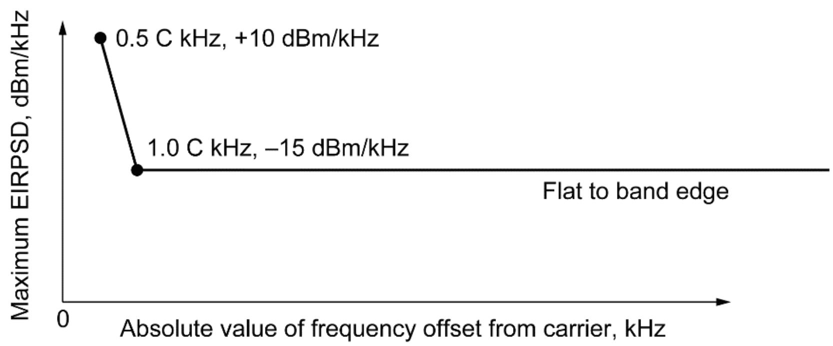


Figure 14.—C-band ground radio system transmitter effective isotropically radiated power spectral density (EIRPSD) mask.

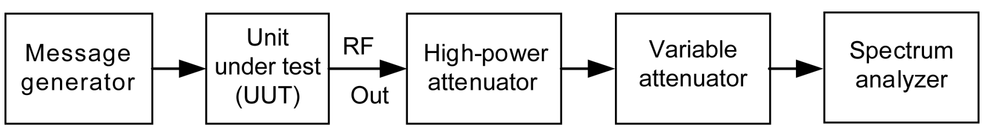


Figure 15.—Transmitter power spectral density (PSD) limits test setup. RF, radiofrequency.

4.8.2 Power Spectral Density (PSD) Verification

The following test procedure verifies each transmitter mask to ensure that the spectral output power will not impact adjacent channels. The masks defined in Section 4.8.1 are absolute PSD measurements, thus losses between the RF output port and the spectrum analyzer will have to be taken into account. The RF output power of the radio transmitter UUT is safely dissipated in the high-power attenuator, which also provides a proper standing wave ratio match to the transmitter. The variable attenuator optimizes the spectrum analyzer input level for best measurement accuracy.

The test procedure for PSD verification follows:

(1) Connect the equipment as shown in Figure 15.
(2) Adjust the variable attenuator to ensure the maximum input level without causing signal distortion.
(3) Preset the spectrum analyzer.
(4) For each data rate supported by the UUT, perform the following steps:
   (a) Apply the following spectrum analyzer settings:
      (i) Set the spectrum analyzer reference level offset to the total path loss from the output of the transmitter port to the input of the spectrum analyzer.
      (ii) Set the span to approximately five times the channel bandwidth and set the number of points to approximately span/1000. These settings will ensure a bucket size of 1 kHz and will capture the inband and first two adjacent channels.
      (iii) Set the detector type to Sample.

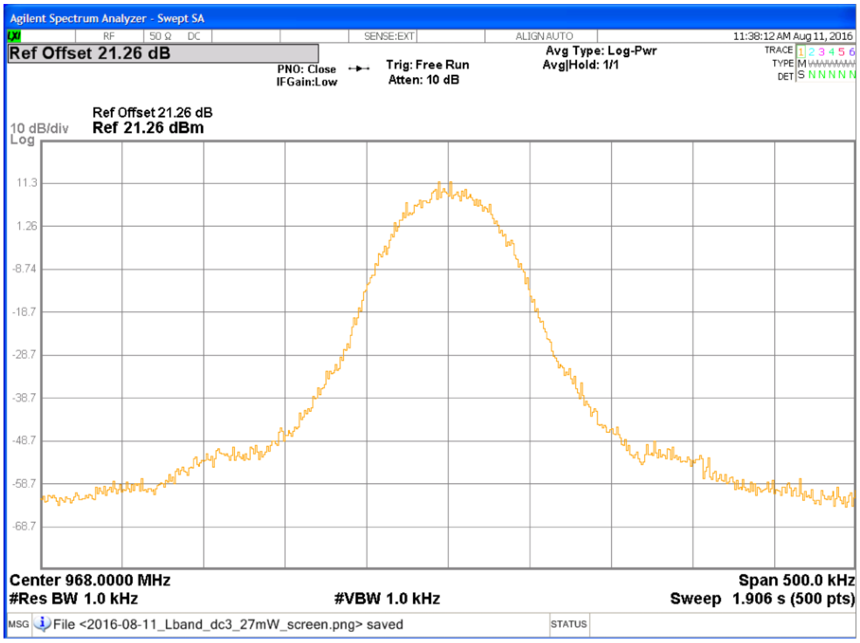
(iv) Set the resolution bandwidth (RBW) to 1 kHz. The RBW filter should be Gaussian with –3 dB points equal to RBW.
(v) Set the video bandwidth (VBW) to 1 kHz.
(vi) Set the trace type to Max Hold.
(b) Tune the UUT transmit to the middle channel of the frequency band under test.
(c) Set the spectrum analyzer center frequency to the same frequency.
(d) Command the message generator to transmit messages containing pseudorandom user message bits that vary for each successive transmitted burst (pulse).
(e) Command the UUT to transmit at maximum output power.
(f) Reset the trace measurement.
(g) After 10 min, stop the message generator.
(h) Command the UUT transmitter off.

(5) Verify the transmitter mask requirements used in Sections 4.8.1.1 to 4.8.1.8.
(a) For L-band airborne systems complying under antenna gain minus system installation loss of 3 dBi or less, use Section 4.8.1.1.
(b) For L-band airborne systems complying under antenna gain minus system installation loss greater than 3 dBi, use Section 4.8.1.2.
(i) New PSD mask value = old PSD mask value (Figure 7) + 3 dBi – (new antenna gain – new installation loss)
(c) For L-band ground systems complying under antenna gain minus system installation loss of 18 dBi or less, use Section 4.8.1.3.
(d) For L-band ground systems complying under antenna gain minus system installation loss greater than 18 dBi, use Section 4.8.1.4.
(i) New PSD mask value = old PSD mask value (Figure 9) + 18 dBi – (new antenna gain – new installation loss)
(e) For C-band airborne systems complying under antenna gain minus system installation loss of 3 dBi or less, use Section 4.8.1.5.
(f) For C-band airborne systems complying under antenna gain minus system installation loss greater than 3 dBi, use Section 4.8.1.6.
(i) New PSD mask value = old PSD mask value (Figure 11) + 3 dBi – (new antenna gain – new installation loss)
(g) For C-band ground systems complying under antenna gain minus system installation loss of 24 dBi or less, use Section 4.8.1.7.
(h) For C-band ground systems complying under antenna gain minus system installation loss greater than 24 dBi, use Section 4.8.1.8.
(i) New PSD mask value = old PSD mask value (Figure 13) + 24 dBi – (new antenna gain – new installation loss)

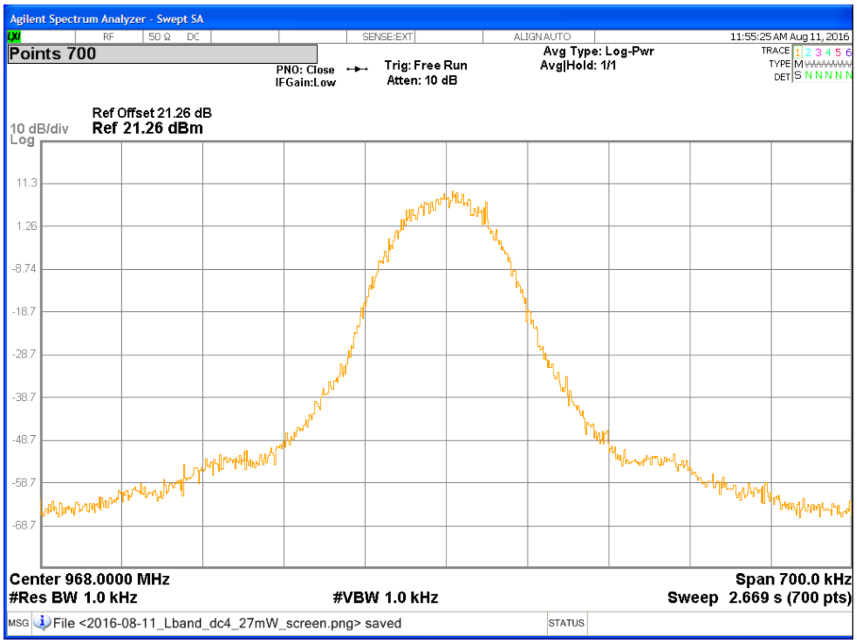
(6) Pass/fail criteria:
(a) Pass: All trace measurement points are at or below the transmitter mask.
(b) Fail: Trace measurement points appearing above the transmitter mask indicate noncompliance with the requirement.

4.8.3 Power Spectral Density (PSD) Results

PSD verification tests were performed using a prototype C-band radio and a prototype L-band radio. The C-band radio was tested in high-power mode (≤10-W average power) and low-power mode (≤100-mW average power). The L-band radio was tested at a single transmit output power level (≤32-mW average power). Both radios used data classes 3 and 4 data rates; data classes 1 and 2 were not implemented by the prototype radios. Total path loss, power attenuator loss, and cable loss were measured from the transmitter output port to the test equipment, and the correction was applied to the power meter and spectrum analyzer reference offset. The output power was adjusted to be close as possible to the maximum level while not exceeding the requirement. The captured PSD measurement results are shown in Figure 16 to Figure 18. For each test, the measured data were compared against the appropriate mask to determine the pass/fail result. The results are summarized in Table XI.

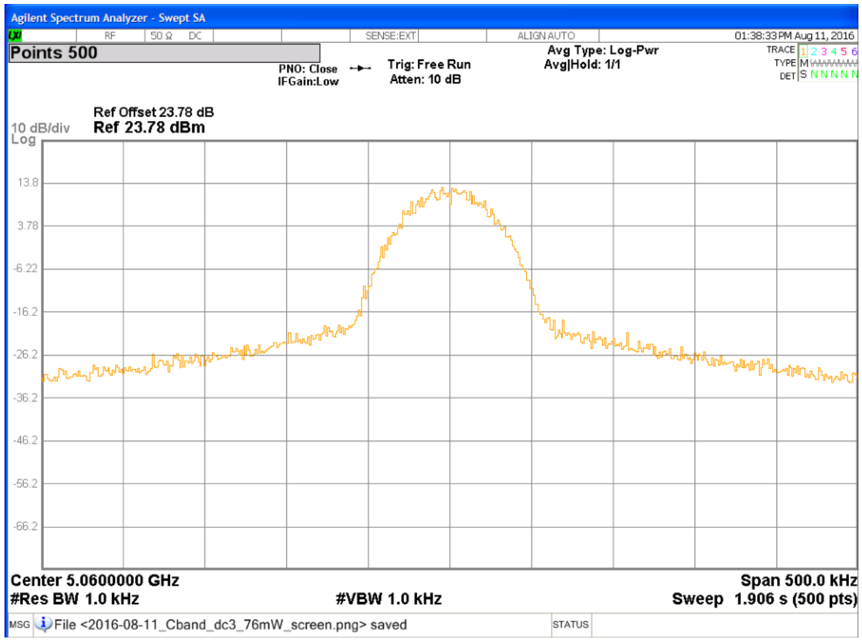


(a)

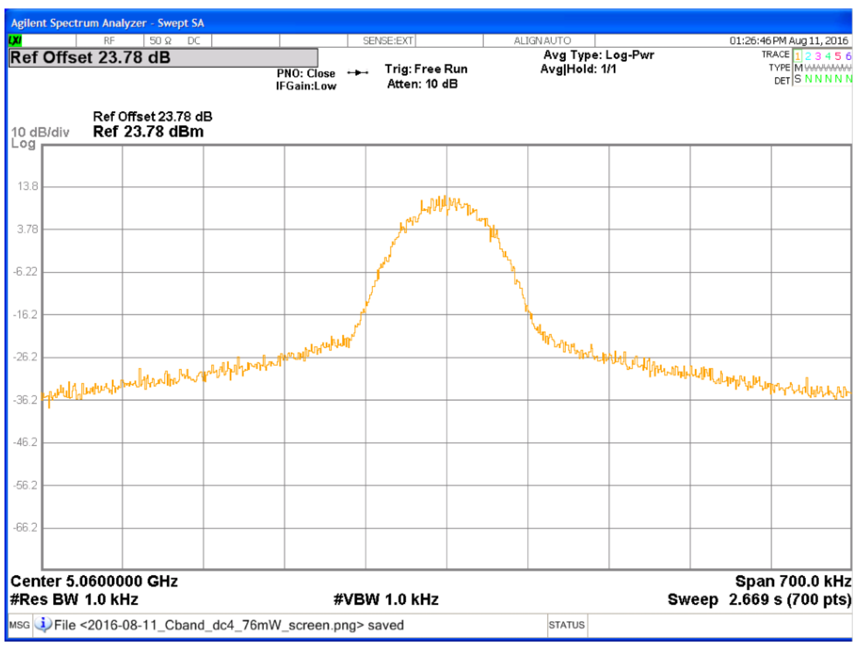


(b)

Figure 16.—L-band—27-mW average output power—power spectral density (PSD). (a) Data class 3. (b) Data class 4.

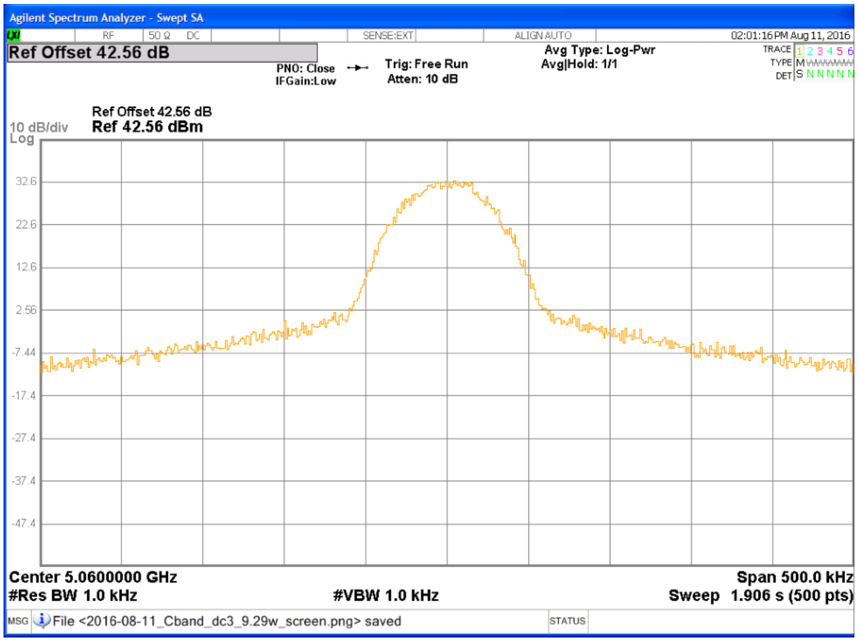


(a)

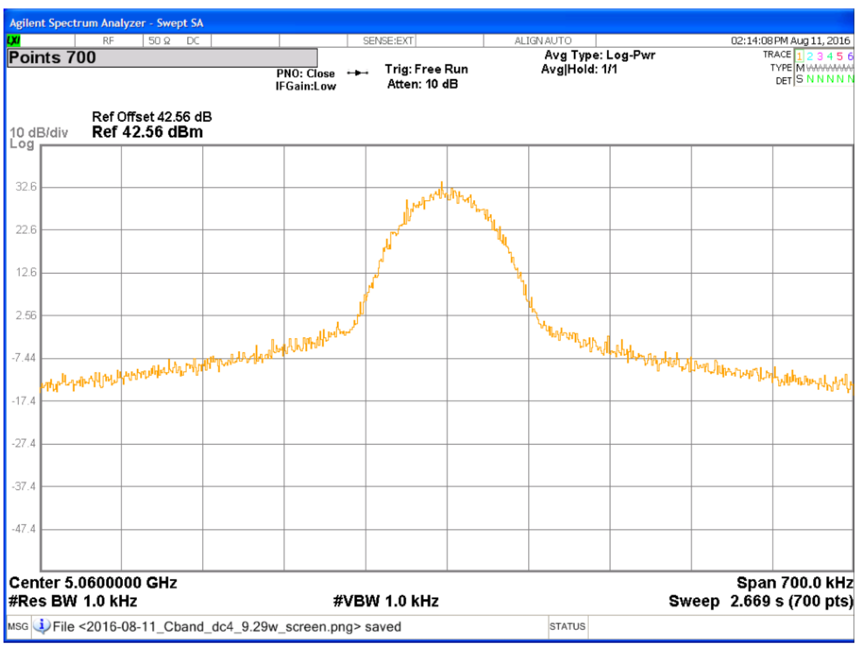


(b)

Figure 17.—C-band—76-mW average output power—power spectral density (PSD). (a) Data class 3. (b) Data class 4.



(a)



(b)

Figure 18.—C-band—9.29-W average output power—power spectral density (PSD). (a) Data class 3. (b) Data class 4.

TABLE XI.—POWER SPECTRAL DENSITY (PSD) VERIFICATION RESULTS

Band	Average output power	Data class	Masks used to determine pass or fail	Result
L	27 mW	3	Figure 7 and Figure 9	Fail
		4		Fail
C	76 mW	3	Figure 11 and Figure 13	Fail
		4		Fail
	9.29 W	3		Fail
		4		Fail

4.9 Receiver Sensitivity Verification

This section verifies the sensitivity specification for the L-band and C-band receivers.

4.9.1 Receiver Sensitivity Specification

Ground and airborne receiver sensitivity is achieved by measuring the lowest input signal level (in decibel-milliwatts (dBm)) that meets the pass/fail criteria in Section 4.5.

4.9.2 Receiver Sensitivity Verification Procedure

The test procedure for receiver sensitivity verification follows:

(1) Connect the equipment as shown in Figure 19.
(2) Determine the cable and connector losses in the test configuration prior to any low-signal-level receiver sensitivity evaluation so that accurate VSG outputs can be measured.
(3) Configure the VSG RF output to the lowest channel assignment in the first set of test frequencies shown in Table III.
(4) Load the waveform configuration file for data class 3 into the VSG. This file contains the necessary parameters to simulate the CNPC data class being tested using the appropriate frequency-band-dependent standard test signals from Section 4.1 and the text message size and user data rate from Section 4.4.
(5) Configure the data collection computer to process the message error rate that meets the pass/fail criteria in Section 4.5.
(6) Set the output level of the VSG for the data class 3 receiver sensitivity limit shown in Table XII for an airborne or ground radio receiver under test. (It is recommended that a level of –80 dBm be used initially to validate the test configuration. There should be no dropped messages at this level.)
(7) Initialize the previously loaded waveform configuration file.
(8) Use the spectrum analyzer to confirm that the input signal has the expected bandwidth and amplitude for the data class being tested.
(9) Observe the number of successfully received and dropped messages on the data collection computer and note the pass/fail criteria.
(10) Repeat steps 2 to 9 running the waveform configuration file for data class 4 messages. Note: Data class 4 is not required if the receiver under test will be used in an airborne radio configuration.
(11) Repeat steps 2 to 9 for the remainder of the channels identified in Table III, running the appropriate data class configuration files for each one.
(12) If any radio data class fails, the receiver fails the sensitivity verification test.
(13) The pass/fail criteria are based on the percentage of messages successfully received at the minimum input levels shown in Table XII.
    (a) Pass: The receiver had a message failure rate of 0.1 percent or less at less than or equal to the sensitivity (dBm) input values in Table XII.
    (b) Fail: The receiver had a message failure rate of greater than 0.1 percent at less than or equal to the sensitivity (dBm) values in Table XII.

4.9.3 Receiver Sensitivity Results

Table XII shows the maximum receiver sensitivity specifications for L-band and C-band in both airborne and ground configurations for data classes 3 and 4, and the measured (actual) receiver sensitivity results gathered using repeated tests with varying levels approaching receiver specifications.

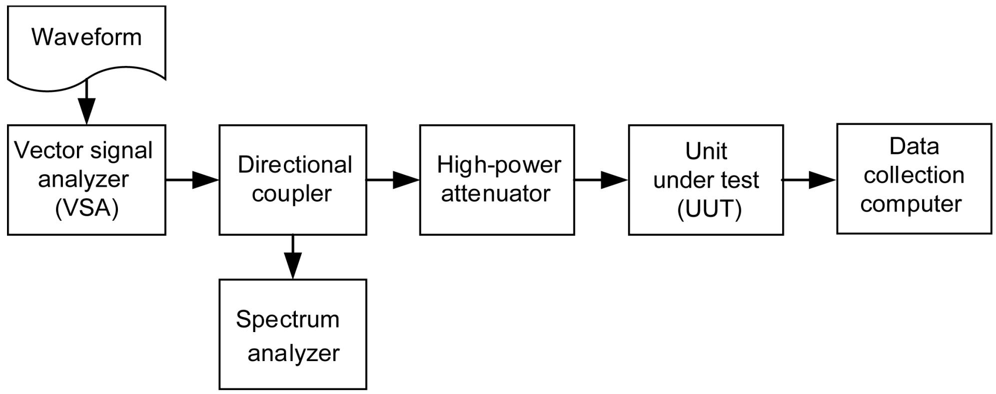


Figure 19.—Radio receiver sensitivity test configuration.

TABLE XII.—RADIO RECEIVER SENSITIVITY SPECIFICATION AND RESULTS FOR L-BAND AND C-BAND

Data class	Receiver location	Symbol rate	Occupied bandwidth, kHz	L-band sensitivity, dBm		C-band sensitivity, dBm	
				Specification	Measured	Specification	Measured
3	Airborne	103,500	90	≤–117.0	–115.0	≤–114.0	–115.0
3	Ground	103,500	90	≤–118.0	–115.0	≤–115.0	–115.0
4	Ground	138,000	120	≤–116.0	–113.8	≤–113.0	Not measured

5.0 Conclusions

The Control and Non-Payload Communications (CNPC) prototype radio design specifications were developed through five generations, resulting in the verification results discussed in this report. Some of the specifications for the prototype radio were easily met, while others fell short, as should be expected in the early stages of prototype radio development.

The radiofrequency (RF) power output specifications were easily met for both L-band and C-band using the transmit power output adjustment function in the CNPC prototype radio interface.

The modulation specification was met for L-band but not C-band. The vector signal analyzer (VSA) successfully demodulated the L-band Gaussian minimum shift keying (GMSK) waveform. The sync-pattern was detected for all subframes, and the error vector magnitude was within a reasonable amount of error (<2.5 percent). Because of the basic demodulation technique used in the VSA and the excessive phase noise of the CNPC transmitter, the VSA was unable to demodulate a C-band GMSK waveform.

The power spectral density (PSD) specification was not met by the prototype CNPC radio for either the L-band or C-band. The PSD verification failed because the Minimum Operational Performance Standards (MOPS) were defined after the last generation of the prototype radio used in the verification was developed.

The L-band receiver section of the CNPC radio under test did not meet any of the maximum prototype CNPC radio sensitivity specifications. A production radio should be able to meet these specifications. The C-band receiver section of the CNPC radio under test met both prototype CNPC radio airborne and ground maximum sensitivity specifications for data class 3.

Appendix—Abbreviations, Acronyms, and Symbols List

1090ES	1090-mHz Extended Squitter
AM(R)S	Aeronautical Mobile (Route) Service
C2	command and control
CNPC	Control and Non-Payload Communications
CRC	cyclic redundancy check
DME	Distance Measuring Equipment
EIRPSD	effective isotropically radiated power spectral density
FDMA	frequency division multiple access
FEC	forward error correction
GMSK	Gaussian minimum shift keying
IF	intermediate frequency
IQ	in-phase/quadrature
ITU	International Telecommunication Union
JTIDS	Joint Tactical Information Distribution System
LOS	line-of-sight
MOPS	Minimum Operational Performance Standards
MSK	minimum shift keying
NAS	National Airspace System
PSD	power spectral density
RBW	resolution bandwidth
RF	radiofrequency
RMS	root mean square
SSR	Secondary Surveillance Radar
TACAN	Tactical Air Navigation
TCAS	Traffic Alert and Collision Avoidance System
TDD	time division duplex
TDMA	time division multiple access
UAS	Unmanned Aircraft Systems
UAT	Universal Access Transceiver
UUT	unit under test
VBW	video bandwidth
VSA	vector signal analyzer
VSG	vector signal generator

Symbols

B_n	logic value of current bit
B_{n-1}	logic value of previous bit
BT	bandwidth-time
n	value passed into modulator
$S_{\min}$	manufacturer-defined sensitivity level of the receiver

References

1. Command and Control (C2) Data Link Minimum Operational Performance Standards (MOPS) (Terrestrial). RTCA DO−362, 2016. http://www.rtca.org/store_product.asp?prodid=1256 Accessed Nov. 14, 2016.
2. Characteristics of Unmanned Aircraft Systems and Spectrum Requirements To Support Their Safe Operation in Non-Segregated Airspace by the International Telecommunication Union Radiocommunication Sector (ITU−R). Standard ITU−R Report M.2171, 2009. http://standards.globalspec.com/std/1404570/itu-r-report-m-2171 Accessed Nov. 14, 2016.