
Radio Altimeter Test Report and Coexistence Study



Version 2
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1. Executive Summary

Bringing additional mid-band spectrum to market is essential to meet the growth in commercial wireless demand. A recent Accenture study highlighted the significant disparity in the amount of licensed spectrum for commercial use, versus unlicensed and federal spectrum allocations.¹ A Brattle Group study released in April 2023 further supported the need for additional commercial spectrum, identifying a spectrum shortfall of more than 1400 MHz of standard-power, licensed mid-band spectrum by 2032.² The spectrum deficit was similarly underscored in an earlier GSMA report identifying a need for a total of two gigahertz of mid-band spectrum to meet the International Mobile Telecommunications (IMT) wireless broadband requirements by 2030.³ With promising spectrum pipeline bands like 6 GHz already identified for low power unlicensed operations in the United States,⁴ the 3300-4200 MHz and 4400-5000 MHz bands⁵ are becoming increasingly important spectrum pipeline bands to address future wireless broadband demand. These IMT bands are immediately adjacent to the radio altimeter (RA) band of 4200-4400 MHz.

Future RA designs must be sufficiently resilient to enable the efficient use of spectrum adjacent to the RA band for full-power mobile broadband services. To understand how to achieve this coexistence, we must first understand current RA performance, and then explore the potential improvements which may be achieved through enhanced bandpass filter and transceiver design.

CTIA initiated laboratory testing of several RA models to assess the potential improvement achieved with custom bandpass filters designed to pass the RA's occupied channel and begin rolling off within the unused portion of the RA band. CTIA replicated the laboratory test environment established by the Aviation Vehicle Systems Institute (AVSI) in prior aviation industry testing. The test setup included conditions beyond worst case, similar to those employed by AVSI.

¹ Accenture, *Spectrum Allocations in the United States*, <https://www.ctia.org/news/spectrum-allocation-in-the-united-states>, September 2022.

² The Brattle Group, Coleman Bazelon and Paroma Sanyal, *How Much Licensed Spectrum is Needed to Meet Future Demands for Network Capacity?*, <https://api.ctia.org/wp-content/uploads/2023/04/Network-Capacity-Constraints-and-the-Need-for-Spectrum-Brattle.pdf>, April 17, 2023.

³ *GSMA Calls for 2 GHz of Mid-Band Spectrum to Meet UN Targets*, GSMA, <https://www.gsma.com/newsroom/press-release/gsma-calls-for-2-ghz-of-mid-band-spectrum-to-meet-un-targets/>, July 8, 2021.

⁴ *6 GHz, Satellites, and 6G Addressed at WRC-23*, LightReading, Mike Dano, <https://www.lightreading.com/6g/6ghz-satellites-and-6g-addressed-at-wrc-23>, December 15, 2023. WRC-23 harmonized 6.425-7.125 GHz globally for licensed 5G mobile operations. The United States has already introduced unlicensed operations in the band.

⁵ 3GPP TS 38.101-1 v18.1.0 (2023-03), *User Equipment (UE) radio transmission and reception, Part 1: Range 1 Standalone (Release 18)*, section 5.2, Table 5.2-1: NR operating bands in FR1, n77 3300 MHz – 4200 MHz. The 3GPP FR1 N79 band class covers 4400-5000 MHz and is a similarly important spectrum band for future IMT services.

The receiver blocking results in CTIA's initial report released in October 2023 understated the RA performance improvement seen from the addition of the new RA bandpass filters.⁶ Subsequent testing placed a band reject filter at the VSG output to lower the signal generator's unwanted emissions in the RA band. Filtering out the VSG unwanted emissions eliminated the false failures, and demonstrated the full improvement achieved with the new RA bandpass filters.

CTIA's updated test results provided herein show that RAs equipped with custom bandpass filters achieved excellent tolerance of strong signals in spectrum adjacent to the RA band. In receiver blocking tests, *all RAs showed no breakpoint*, even in the presence of an IMT signal in the adjacent channel of +25 dBm, at the RA receiver port.

The coexistence study in Section 8 drives home the benefit offered by the new bandpass filters, even under the most rigorous Physical Near-Collision Scenario employing all worst-case conditions. The receiver blocking analysis has a minimum excess margin of 12 dB relative to the +25 dBm physical limit of the test setup – *the actual margin is higher still since a breakpoint was not reached*. The *receiver desense case provides 18 dB of margin* for the Physical Near-Collision Scenario. Real world factors, not reflected in the study, would provide an additional margin of 38 dB or more.

After several years of close collaboration between the wireless and aviation industries, the tools are available for all radio altimeters to coexist with full power services in the adjacent spectrum, paving the way for future IMT expansion for 5G and beyond.

Recommendations:

- Real world factors provide additional margin not reflected in the Physical Near-Collision Scenario. Considering these real-world factors, most if not all RAs perform sufficiently well today without modification. Coexistence studies should include consideration of such real-world factors.
- If necessary, retrofit lower-performing RA installations, and/or design next generation RAs, with custom filters. The custom filters should be designed to pass the desired signal's occupied bandwidth and roll off within the unused portion of the RA band. This approach to filtering provides excellent protection from full power services in adjacent spectrum.
- Next gen RA performance may be further improved by designing the RA transmitter to emit power levels close to 30 dBm. The higher power transmitter improves the desired signal strength in all conditions.
- RA antenna design changes may further improve isolation between IMT emitters and RAs, as suggested by the difference in measured patterns for the two styles of antenna, provided in section 8.

⁶ In our October 2023 receiver blocking tests, the vector signal generator (VSG) emitted unwanted emissions within the RA band at a strong enough level to cause RA receiver desense, resulting in a premature RA failure in the blocking test.

2. Introduction

The exponential growth in wireless broadband has prompted spectrum regulators in dozens of countries to reallocate mid-band spectrum for 5G. Many countries are operating standard-power base stations within 3400-3800 MHz, with some extending operations below 3400 MHz. Other countries are expanding IMT allocations to frequencies above 3800 MHz; Canada, Australia, the United States and Korea have allocated spectrum up to 4000 MHz. Japan has 5G operations within 3600-4100 MHz and 4500-4600 MHz⁷ and is planning future allocations up to 5000 MHz. China is also using spectrum above the RA band (4800-4960 MHz), and Australia, Singapore, Vietnam, and Korea are all considering spectrum allocations above 4400 MHz.⁸

In the United States, federal government systems operate within 4400-4940 MHz and transmit with high power levels above horizon. For example, since 2002 the U.S. Navy has operated the Cooperative Engagement Capability (CEC), a communications system that integrates multiple radar sensor measurements into a single air defense view shared across a battlegroup.⁹ The CEC transceivers use 22 MHz channels with a maximum Effective Isotropic Radiated Power (EIRP) of 88 dBm,¹⁰ and are mounted on ships, aircraft, and mobile ground-based units. RAs must coexist with these military transmitters pointing toward aircraft.

The evolving spectrum landscape has prompted the consideration of coexistence between aviation's radio altimeter (RA) band at 4200-4400 MHz and nearby spectrum services. The wireless and aviation industries have worked cooperatively since 2020, participating in working groups¹¹ and industry meetings, sharing technical information, and discussing RA performance.

⁷ NTT DOCOMO 5G Initiatives for Solving Social Problems and Achieving Social Transformation, NTT Technical Review, Vol. 18, No. 12, pp. 86–96, Dec. 2020, last visited 07/20/2023 at <https://doi.org/10.53829/ntr202012fa13>. Japan operates 5G base stations up to 4100 MHz and within 4500-4600 MHz.

⁸ *Global 5G Spectrum Update and Innovations for Future Wireless Systems*, Qualcomm Research, May 2023, at <https://gsacom.com/paper/global-5g-spectrum-update-july-2023-qualcomm-paper/>.

⁹ WT Docket No. 00-32, Notice of Proposed Rulemaking, *The 4.9 GHz Band Transferred from Federal Government Use*, February 29, 2000 at 35.

¹⁰ The CEC's EIRP is nearly 10 dB higher than the C-Band rural EIRP for base stations – and the CEC antennas point above horizon at aircraft.

¹¹ As recommended by the Federal Communications Commission, wireless and aviation companies and associations formed the Technical Working Group 3 (TWG-3) work group and met regularly over a several month period, sharing wireless and radio altimeter technical information. The final TWG-3 report may be found at <https://www.fcc.gov/ecfs/document/111346743901/1>. Wireless and aviation groups also participated in the Department of Defense-led program known as the Joint Interagency Fifth Generation Radar Altimeter Interference (JI-FRAI), which successfully evaluated military radio altimeter performance through laboratory and flight testing. The only publicly available test report from JI-FRAI, NTIA Report 22-562, may be found at <https://its.ntia.gov/umbraco/surface/download/publication?reportNumber=TR-22-562.pdf>. The JI-FRAI program concluded with no further action required by the U.S. wireless carriers.

Beginning in 2022, the Federal Aviation Administration (FAA) partnered with wireless and aviation companies to model C-Band 5G base station signals near airports and evaluate the performance of commercial and transport RA models. U.S. wireless carriers agreed to voluntary mitigations around airports until 2028.¹² The FAA issued airworthiness directives requiring installation of filters or RA upgrades to some aircraft, to complement the environment created by the voluntary mitigations.¹³

In the fall of 2022, the U.S.-based aviation standards-setting organization, RTCA, and the European Organization for Civil Aviation Equipment (EUROCAE), jointly released for public comment a draft guidance document of RA performance in the presence of IMT signals, DO-399.¹⁴ DO-399 is intended to provide one of the technical inputs to RTCA/EUROCAE’s work program developing new RA MOPS,¹⁵ which will be the first major revision to RA performance requirements since 1980 when ED-30 was released.¹⁶ Draft DO-399, at the time of the RTCA Plenary in December 2022, included best achievable performance curves for Mainline Transport (MT), Regional Group (RG), and Unmanned Aerial Systems and Rotorcraft (UR) RAs.¹⁷ Table 2-1 shows the draft DO-399 signal levels, referenced at the RA receiver port, for the Commercial/Transport RAs.¹⁸

Table 2-1: Commercial/Transport RA Receiver Blocking Thresholds (dBm/100 MHz) (Draft DO-399)

Manufacturer	3.35 GHz	3.45 GHz	3.55 GHz	3.65 GHz	3.75 GHz	3.85 GHz	3.95 GHz	4.05 GHz	4.15 GHz	4.45 GHz	4.55 GHz	4.65 GHz
Hotel	30.05	30.30	30.05	29.81	29.57	30.84	29.62	4.40			3.39	24.00
Papa	22.55	22.30	22.05	21.81	21.57	20.74	20.52				1.49	1.30
Tango 1	34.92	32.78	35.57	35.57	35.09	37.00	34.51	25.44	-5.15	-17.08	16.15	30.35
Tango 2	33.94	37.01	37.01	31.13	31.79	34.44	33.34	34.90	9.45	2.23	27.66	33.00
Whiskey	33.45	33.20	32.55	32.31	30.77	30.84	30.42	30.40	4.29	4.28	29.59	29.90

¹² Ex parte letter, AT&T Services, Inc., T-Mobile, US Cellular, and Verizon, GN Docket No. 18-122, March 31, 2023; and Agri-Valley Communications, Inc., Carolina West Wireless, New Level II L.P., Nex-Tech Wireless, and Nsight Spectrum, LLC, GN Docket No. 18-122, June 13, 2023.

¹³ FAA AD 2023-10-2, effective May 26, 2023, at <https://drs.faa.gov/browse/excelExternalWindow/FR-ADFRAWD-2023-11371-0000000000.0001>.

¹⁴ *DO-399 Guidance Document on Radar Altimeter RF Interference Rejection and Tolerance*, SC-239, RTCA, Inc., 2022.

¹⁵ The goal of the new MOPS is “to enable the efficient use of near-band spectrum by setting a standard for new radar altimeters that provide state-of-the-art near-band rejection while maintaining the current intended functions of the radar altimeters.” RTCA Paper No. 339-22/PMC-2378, *Terms of Reference, Special Committee (SC) 239 Low Range Radar Altimeter*, Revision 3, December 15, 2022, at 2.

¹⁶ *Minimum Performance Specification for Airborne Low Range Radio (RADAR) Altimeter Equipment*, ED-30, EUROCAE, March 1980.

¹⁷ As defined in the draft DO-399 document as of December 2022, Mainline Transport aircraft include “large fixed-wing aircraft used for mainline air transport applications (including both passenger air travel and air cargo)”. Draft DO-399, at 22. Other RA models are used on regional airplanes, business and general aviation airplanes, and helicopters. These other RA models will be referred to as Business/General Aviation, or BA/GA models, herein.

¹⁸ Draft DO-399 provided power flux density levels referenced to the RA antenna face and including all margins. To facilitate comparison of the RA manufacturer PFD levels to the CTIA test data, we converted the PFD values to the power level at the RA receiver port. The conversion used the manufacturer-provided antenna gain and cable loss, backed out margins to reflect DO-399 breakpoints, and then converted the power level to dBm/100 MHz.

All C/T RAs showed excellent rejection of IMT signals below 4000 MHz. Most C/T RAs showed excellent tolerance of signals in 4000-4100 MHz. One RA showed somewhat less tolerance in the nearest 100 MHz.

Table 2-2 similarly shows the signal levels from draft DO-399 for the Business and General Aviation RAs, converted to the reference point of the RA receiver port.

Table 2-2: Business/General Aviation RA Receiver Blocking Thresholds (dBm/100 MHz) (Draft DO-399)

Manufacturer	3.35 GHz	3.45 GHz	3.55 GHz	3.65 GHz	3.75 GHz	3.85 GHz	3.95 GHz	4.05 GHz	4.15 GHz	4.45 GHz	4.55 GHz	4.65 GHz
Mike	38.0	38.0	38.0	38.0	38.0	35.8	32.1	11.4	-10.8		8.4	27.5
Papa	24.6	24.3	24.0	23.8	21.6	20.7	20.5				1.5	1.3
Tango	36.5	37.3	38.8	33.6	31.1	34.0	33.6	27.2	3.0	-12.2	21.3	32.3
Whiskey 1	39.5	39.2	38.5	38.3	30.8	30.8	30.4	-9.7	-18.7	-17.7	-4.7	29.9
Whiskey 2	39.5	39.2	38.5	38.3	30.8	30.8	25.4	10.8	-33.7	-24.7	16.3	29.9

All of the BA/GA RAs showed excellent tolerance to IMT signals below 4000 MHz. Most of the BA/GA RAs showed good tolerance to IMT signals more than 100 MHz away from the RA band. Within 100 MHz of the RA band, all BA/GA RAs showed less tolerance.

Wireless industry stakeholders participating in the DO-399 Final Review and Comment process encouraged RTCA and EUROCAE to further research bandpass filter, antenna, transmitter, and receiver design to improve RA resilience to energy outside of the band.

To further support the development of a robust next generation of RAs, CTIA commissioned laboratory testing and designed proof-of-concept bandpass filters to reject energy outside of the RA band. The first test report was issued in October 2023. As discussed above, further testing has shown that the achievable improvement to RA resilience was understated in the October report. Subsequent testing, with a filter lowering the signal generator's unwanted emissions, showed no breakpoint in the presence of neighboring signals up to +25 dBm at the RA receive port, even within 100 MHz of the RA band, a notable improvement over the draft DO-399 levels.

The first step in formulating an engineering solution is to define the existing landscape. Section 3 provides an overview of the commercial RAs manufactured and flown today, along with their technical specifications. Section 4 provides specifications for bandpass filters capable of providing significant protection from energy outside of the RA band, with special consideration given to the design constraints of size, weight, and performance. Section 5 explains CTIA's laboratory test setup and inputs. Section 6 summarizes the receiver blocking test results. Section 7 summarizes the receiver desense test results. Section 8 applies the CTIA measurements in a technical study of RA coexistence with standard power IMT services in adjacent spectrum.

3. Radio Altimeter Specifications

Five RA manufacturers currently produce eleven RA models flown by civil aviation today. Key specifications are summarized in Table 3-1 below, sourced from publicly available manufacturer manuals, web sites, and FCC equipment authorization documentation.

Table 3-1: Civilian RAs Currently Produced and Flown¹⁹

Radio Altimeter Manufacturer	Country of Origin	Radio Altimeter Model	FCC EA Year	Aviation Category	Operating Bandwidth (MHz)	Transmit Power (dBm)	Frequency Range (MHz)	Source
Collins	USA	ALT-1000/4000	1995	C/T, BA, GA	100	26.5	4250-4350	Operations manual
		LRA-2100	2010	C/T	150	25.4	4225-4375	FCC test report
		LRA-900	1994	C/T	110	27.8	4245-4355	FCC equipment authorization
FreeFlight	USA	RA-4000/4500	2009	BA, GA	104	19.9	4256-4360	FCC test report
		RA-5500/6500	2022	BA, GA	102.3	26.3	4249-4351	FCC test report
Garmin	USA	GRA 55/5500	2013	BA, GA	101.9	30.5	4249-4351	FCC test report
Honeywell	USA	ALA-52B	2008	C/T	128	27.9	4235-4365	FCC test report
		KRA 405B	1996	C/T, BA, GA	100	22.0	4235-4365	Installation manual
		RT-300	1970s	BA, GA	<20	37	~4290-4310	Installation manual; measured bw
Thales	France	ERT 550	1997	C/T	123	20.8	4240-4363	FCC equipment authorization
		AHV1600	2009	C/T, BA, GA	123	19	4240-4363	FCC test report

The frequency ranges include any frequency offset applied in multi-RA installations; some manufacturers recommend offsetting the center frequency of each unit to reduce intra-system interference.

RA design characteristics that impact coexistence include transmit power, RF filter roll off, and the RA antenna pattern.²⁰ The role of transmit power in improving RA performance is evident in FreeFlight's product evolution. Aviation industry testing identified some potential weaknesses in the legacy RA-4000/4500 model. Following the release of the RTCA 2020 Report, FreeFlight developed a new RA that is resilient to C-Band 5G signals, the RA-5500/6500.²¹ This model received FCC and FAA approval in 2022 and is currently in production, along with a variant model that is a form and fit replacement for the RA-4000/4500 labeled the RA-4500 Mk II.²²

¹⁹ The table identifies RAs flown in Commercial/Transport (C/T), Business Aviation (BA) and General Aviation (GA) based on descriptions of their intended installation on the RA manufacturer web sites.

²⁰ The RA antenna pattern is not included in lab testing; the antenna rejection of energy outside of the RA band should be reflected separately in coexistence analyses, as explained further in section 8.

²¹ See *FreeFlight RA-5500™ – Terrain Series Radar Altimeter*, https://www.freeflightsystems.com/avionics/radar-altimeters/ra-5500/?utm_term=ra%205500&utm_campaign=Radar+Altimeters&utm_source=adwords&utm_medium=ppc&hsa_a_cc=6563803196&hsa_cam=12575460361&hsa_grp=126387955824&hsa_ad=507525930657&hsa_src=g&hsa_tgt=kwd-540131968490&hsa_kw=ra%205500&hsa_mt=p&hsa_net=adwords&hsa_ver=3&gclid=Cj0KCQiAxbefBhDfARIsAL4XLRqcQFeoFJ-3iCFw38pxTVxetAe883F0wWf4W9i9nGTUsJ2g8BZ3IN8aAsZ_EALw_wcB.

²² See *RA-4500™ MK II – Terrain Series Radar Altimeter*, <https://www.freeflightsystems.com/avionics/radar-altimeters/ra-4500-mk-ii/>.

One of the design changes in the RA-5500/6500 was to increase the RA transmitter power by 6.4 dB.²³ A higher transmitter power level increases the desired signal level at the receiver, directly improving the RA performance under all conditions, including in the presence of strong out-of-band signals. Thus, it would appear beneficial for future RA designs to target higher transmitter power close to 30 dBm to improve performance under all operating conditions, as well as employing custom bandpass filters with enhanced isolation from signals outside of the band.

²³ From Table 3-1, $26.3 - 19.9 = 6.4$ dB. Source: FCC equipment authorization test reports.

4. Bandpass Filter Design

Since the less well-performing receivers are flown in Business and General Aviation, we will focus on those models. The amount of spectrum used by each RA is well documented in FCC equipment authorization reports and operations manuals. The frequency separation between the edge of the RA transmission channel and the RA band edge of 4200 MHz ranged from 35 to 90 megahertz, as observed in Table 3-1 above.

CTIA procured four custom-built RF bandpass filters with different passband sizes to cover the range of occupied bandwidth of the BA/GA RAs.²⁴ These examples of filter designs could be integrated by the RA manufacturer into new RA products or could be retrofitted into existing aircraft configurations by installing an RF filter in line with the coaxial cable, near the RA receiver port. The first two filters procured, 20782 and 20783, were over-designed, with an overly wide passband and greater rejection of signals outside the band than necessary. The third filter, 20926, was closely tailored for the pulse altimeter's smaller occupied bandwidth and achieved a smaller form factor. The fourth filter, 21043, was optimized for the Frequency Modulated Continuous Wave (FMCW) RAs with a tailored passband and a smaller size than the first two filters. The CTIA-procured filter specifications are provided in Table 4-1.

Table 4-1: RF Bandpass Filter Specifications

RF Filter ID	Filter Passband (MHz)	Measured Insertion Loss (dB)	Measured Attenuation at 4180 MHz (dB)	Size (in.)
20782	4230-4370	0.91	49.7	9.85 x 1 x 1
20783	4250-4365	0.96	66.2	11 x 1 x 1
20926	4280-4320	1.5	78.4	4.8 x 1 x 0.75
21043	4235-4365	1.4	47.1	5 x 1 x 0.75

The smaller filter, 21043, weighs 0.65 lbs. The Microwave Filter Company is willing to work with RA manufacturers to further optimize filter designs for each RA model. The expected price for a filter similar to 21043 would be around \$600 for volume sales of 500 units, and \$350 for a volume of 5,000 units.

The below figures provide the bandpass filter frequency response curves.

²⁴ CTIA contracted the Microwave Filter Company to design custom-built bandpass filters with low in-band ripple, low insertion loss, and high rejection of energy outside of the RA band. Microwave Filter Company, Inc. is a leader in the design, development and manufacture of high-quality filter products since 1967. <https://microwavefilter.com>

Figure 4-1: MFC 20782 Filter Response Curve

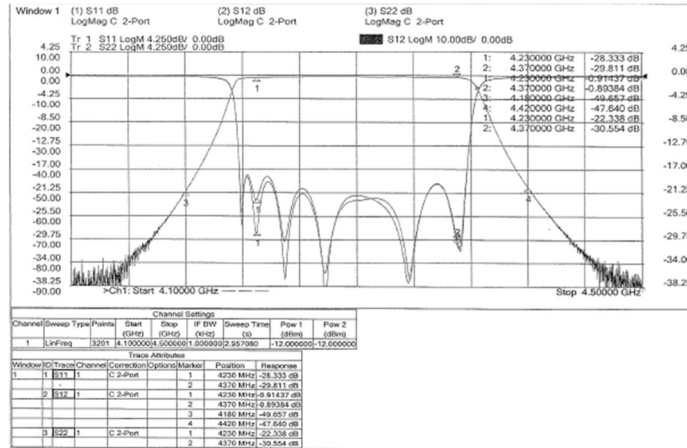


Figure 4-2: MFC 20783 Filter Response Curve

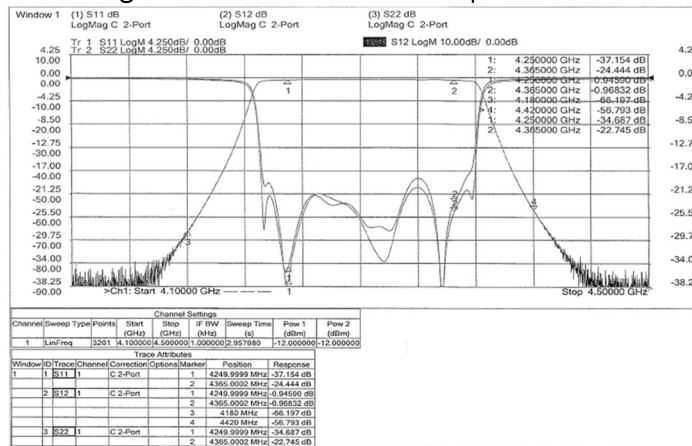


Figure 4-3: MFC 20926 Filter Response Curve

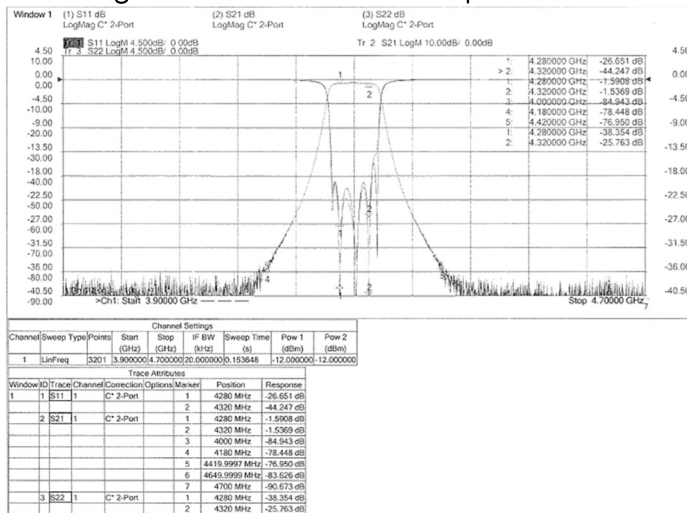


Figure 4-4: MFC 21043 Filter Response Curve

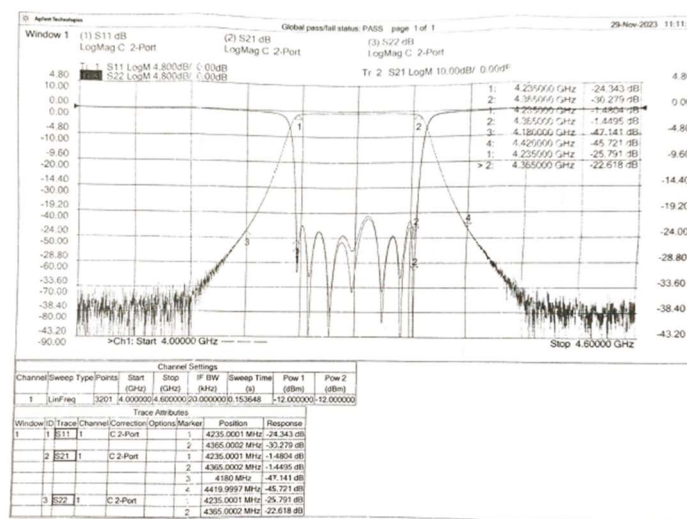


Figure 4-5 illustrates the smaller form factor achieved with Filter 21043.

Figure 4-5: MFC Filter 21043



5. RA Laboratory Test Setup and Inputs

CTIA established an RA test environment to evaluate coexistence with C-Band 5G fundamental and spurious emissions. The testing followed a “box-level” approach, applying external stimuli to the RA under test and observing the reported height accuracy relative to baseline conditions, in the absence of other emissions. This approach mirrored that employed by AVSI;²⁵ no model-specific information was required beyond that provided by the manufacturers in the publicly available installation and operation manuals. We also tested the addition of an RF bandpass filter to evaluate potential resiliency improvements to RA receiver blocking performance.

CTIA commissioned DEKRA, an FCC OET Accredited Test Firm, to perform the laboratory testing of C-Band 5G coexistence with RAs. The lab test setup, inputs, and other background information are provided below.

5.1 DEKRA Facility

DEKRA employs more than 45,000 specialists worldwide focused on increasing safety in all areas of life, including vehicle inspection, expert appraisals, claims services, industrial and building inspections, safety consultancy, and testing and certification of products and systems, as well as training courses.

DEKRA is an industry leader in testing and certification, offering turnkey product certification services in nearly 200 countries and territories. DEKRA established an RA test bed at its facility in Sterling, VA. Testing was conducted in a shielded chamber providing more than 80 dB of isolation from external signals.

5.2 Radio Altimeters Tested

CTIA procured five BA/GA RAs currently produced and flown in the United States, consisting of one pulse altimeter and four FMCW RAs.²⁶ The RA identities were anonymized as in prior testing by the aviation industry.

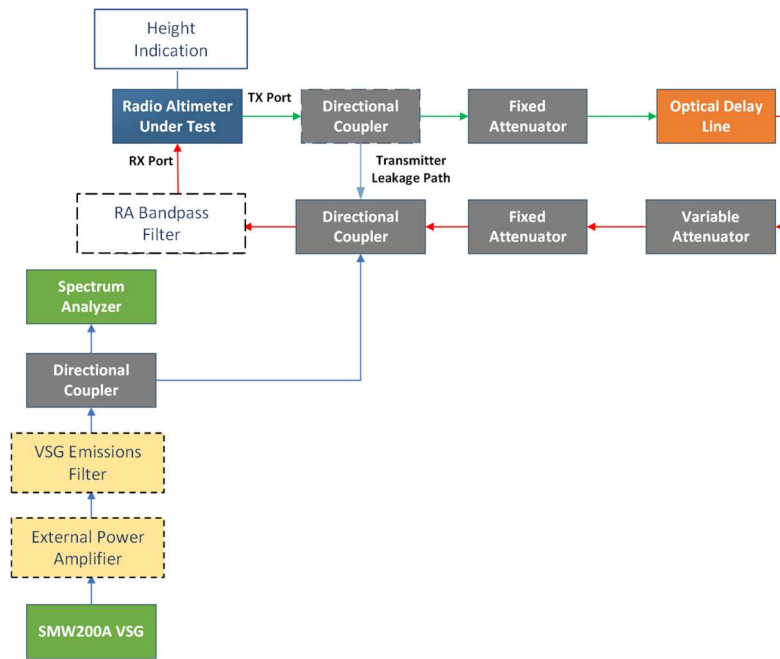
5.3 Test Setup

The laboratory test setup is illustrated in Figure 5-1 below.

²⁵ “This testing does not make use of proprietary design information concerning the specific receiver features and performance for each RA that was tested. Such information was not provided to AVSI. As a result, this “black box” testing does not allow determination of specific failure mechanisms causing the reported height errors or NCDs that were observed on the standard output.” See *AVSI Volume I* report, at 1-3.

²⁶ RAs in the Commercial/Transport category were not available for purchase in the secondary market without an aircraft installation.

Figure 5-1: RA Laboratory Test Setup



The unit under test was connected to fixed and variable attenuators to emulate the targeted loop loss corresponding to the height under test. The test height was emulated by passing the RA transmit signal through optical delay lines to replicate the time delay corresponding to the height above ground. The CTIA/DEKRA test setup was identical to that employed by AVSI,²⁷ except for the inclusion of transmitter leakage as discussed below. The C-Band 5G fundamental and spurious signals were formed by a VSG and coupled into the RA receive path, with the VSG signals verified via a spectrum analyzer.

The CTIA test setup also included an external power amplifier. The amplifier increased the magnitude of the 5G signal being injected into the test setup to +25 dBm at the RA receiver port.

The RA measured height was determined by recording the digital or analog output from the RA, as done in prior testing by the aviation industry.

²⁷ *Radio Altimeter Tolerance of Wireless Avionics Intra-Communications Systems*, MSEE thesis, Joshua Ruff, Texas A&M University, May 2019, section 2.2.2. The thesis describes the test setup employed by AVSI in WAIC and subsequent C-Band coexistence testing.

5.4 RA Transmitter Leakage

EUROCAE ED-30 required the test setup to couple RA transmitter leakage from the transmit port to the receive port to emulate imperfect antenna isolation on the aircraft, “down to 70 dB”.²⁹ In an aircraft installation, a radio altimeter is installed with one transmit antenna and one receive antenna, generally separated by 18 to 36 inches. The amount of leakage from the transmit to the receive antenna depends on their separation distance, the type of antenna, and the number of RAs installed. Each RA introduces another set of transmit and receive antennas, potentially lowering the achievable isolation among them.

AVSI Volume I and II testing did not include transmitter leakage in the laboratory test setup. AVSI Volume III included transmitter leakage, but with a wide variance in the assumed level, as noted in Table 5-2.³⁰

Table 5-2 AVSI Volume III Transmitter Leakage in Laboratory Testing

RA Category	RA Model	Tx Leakage (dB)
MT	F	51
	L	55
	T	75
	U	88
	X	80
BA/GA	A	88
	S	80
	V	90
	W	88
	Z	75

CTIA employed a transmitter leakage level of 75 dB, a lower level of leakage than that indicated by ED-30 but an approximate midpoint in the values shown in Table 5-2.

5.5 Test Pass/Fail Criteria

The test pass/fail criteria for RA height accuracy employed the EUROCAE ED-30 guidance for automatic landing as shown in Table 5-3.³¹

Table 5-3: EUROCAE ED-30 RA Height Accuracy

System Type	Height Range	Altimeter output
Automatic Landing (ED-30 Table 1)	3 to 100 feet	+/- 3 feet
	100 to 500 feet	+/- 3%
	500 feet to maximum of the scale	+/- 5%
Ground Proximity Warning (ED-30 Table 2)	3 to 100 feet	+/- 5 feet
	Above 100 feet	+/- 5%

²⁹ EUROCAE ED-30, at 18.

³⁰ AFE 76s2 Report Derivation of Radar Altimeter Interference Tolerance Masks Volume III: Manufacturer-Provided Test Results, AVSI, Doc ID 76s2-REP-05, Apr 2022.

³¹ ED-30, Table 1 at 11, Table 2 at 12.

5.6 Test Heights and Loop Loss

The October 2023 test report assessed the same three aircraft heights above ground as the AVSI testing summarized by RTCA: 200, 1000, and 2000 feet above ground level.³² This report focuses on the 200 ft height given the aircraft's closer physical proximity to IMT emitters.

The treatment of loop loss has been much debated between the aviation and wireless industries. Loop loss is the round-trip path loss incurred as the signal traverses the distance from the RA to the ground, where a portion of the signal reflects off of the ground surface back toward the aircraft, and that reflected signal traverses the distance back to the RA. The loop loss will vary depending on factors including the reflectivity of the surface material – for instance, paved surfaces will reflect more energy than would a meadow with long grass. The loop loss also increases as the RA height above the surface increases since the RF propagation path loss increases with distance. A brief recap of the loop losses employed in prior public studies is summarized in 5.6.1, followed by an explanation of the loop loss used in the CTIA testing.

5.6.1 Loop Losses in Aviation Industry Studies

Prior aviation industry studies employed a range of loop losses as summarized in Table 5-4.

Table 5-4: Loop Losses in Aviation Industry Testing³³

Loop Loss Comparison at 200 ft (dB)			
RA Model	DO-155	Vol. I/II	Vol. III
Model A	88	96	104*
Model I			N/A
Model V			99
Model W			99

The DO-155 value of 88 dB, shown in Table 5-4, assumes an RA antenna with a 3 dB beamwidth of 45 degrees.³⁴ AVSI Volume I and II testing employed loop losses that were 8 dB more lossy than the DO-155 guidance, using a 60-degree beamwidth antenna and adding 6 dB of cable loss, 3 dB for the transmitter-to-antenna cable and 3 dB for the antenna-to-receiver cable. Loop losses in Volume III testing were further degraded from the Volume I and II testing, with 11 dB more loss than the DO-155 guidance.

³² RTCA Report, at 36.

³³ Model A was tested at 250 ft, not 200 ft. Therefore, the loop loss at 200 ft would have been 102 dB, correcting for the difference in free space path loss.

³⁴ Most civilian radio altimeter antennas employ a microstrip design dating to the 1980s. Examples of this antenna design are the Sensor Systems Inc. antennas, commonly flown on most BA/GA aircraft. See <https://www.sensorantennas.com/>. Sensor Systems antennas employ a 3 dB beamwidth of 45 degrees, which would correspond to the use of DO-155 Appendix B, Figure 4 for determining the appropriate loop loss at a given height above ground. The RTCA 2020 report, at 37, assumed a 60-degree beamwidth antenna, and used DO-155 App. B Figure 5, resulting in 2 dB worse loop loss relative to that applicable to the Sensor System antennas.

5.6.2 Loop Losses in CTIA Testing

In CTIA’s prior technical studies,³⁵ CTIA cited DO-155’s loop loss requirements and that document’s stated characterization that such loop loss, based on the scattering cross section of 0.01, “if actually met in reality, has proven extremely reliable over a wide spectrum of terrain, and for pitch and roll maneuvers within the half power beamwidths of the antennas.”³⁶ It follows that employing larger loop losses, more stringent than the DO-155 requirements under which the RAs were certified, would place the RA receiver in a disadvantaged state in which it would be more susceptible to external signals.

Nevertheless, CTIA’s testing followed the aviation industry’s approach of employing a worse loop loss to accommodate cable losses above and beyond the DO-155 loop loss, summarized in Table 5-5.

Table 5-5: Loop Losses in CTIA Testing (200 ft)³⁷

RA Model	Loop Loss (dB)	Excess Loss Beyond DO-155
India	97	9
Kilo	97	9
Alpha	97	9
Zulu	97	9
Victor (October 2023)	90	2
Victor (March 2024)	86	-2
DO-155 Requirement	88	N/A

CTIA employed loop losses 1 dB worse than the AVSI Volume I and II reports to account for the insertion loss from the external bandpass filter, the transmit and receive cable losses, and the worst case RA antenna assumed by AVSI. This loop loss target is 9 dB worse than the levels required by DO-155.

During testing, loop losses for the RA model Victor were reduced below the target of 97 dB, due to the performance of the RA in baseline testing (with no IMT signals or unwanted emissions present). The Victor RA experienced further degradation over the course of weeks of testing, with the baseline loop loss degrading from 90 dB to 86 dB by March 2024. A second Victor unit procured from an aviation component repair facility performed even less well in baseline testing. We completed testing with the original Victor RA.

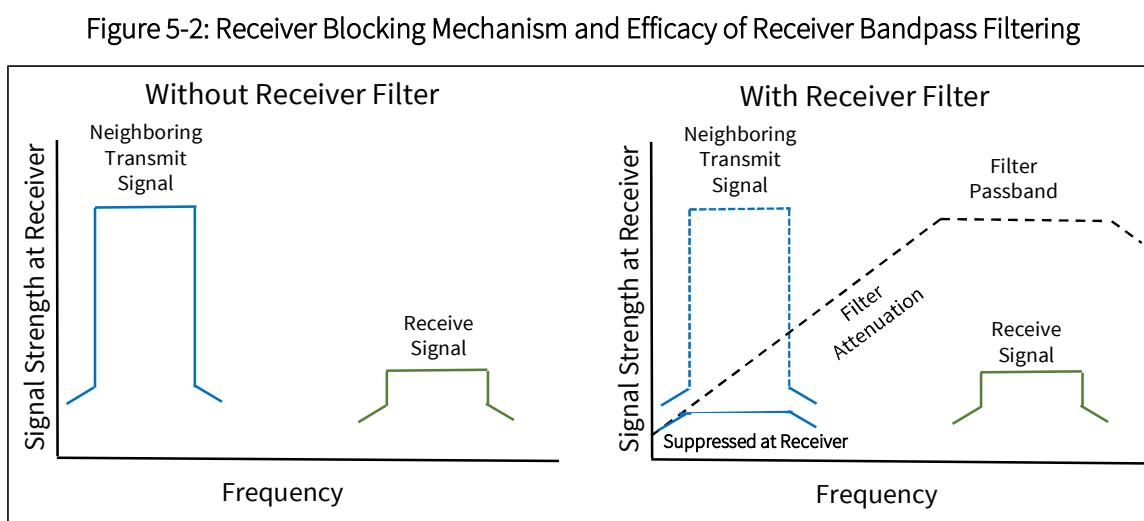
³⁵ CTIA 5G-Aviation Technical Annex, ex parte presentation, GN Docket No. 18-122, sections 4.1 and 4.2.

³⁶ DO-155, Appendix C, at 13.

³⁷ CTIA anonymized the RA test results.

5.7 Receiver Blocking Test Inputs

As background, receiver blocking, or overload, is a receiver's loss in sensitivity due to strong signals outside of a receiver's channel.⁴⁰ A bandpass filter placed between the antenna and the receiver front end components will prevent receiver blocking.⁴¹ This situation is shown in the left side of Figure 5-2; the receiver is exposed to a strong signal outside of the receive band, and the unfiltered incoming power compresses the first stage amplification in the receiver, impairing its ability to detect weak desired signals. The solution to receiver blocking is to design a receiver with components limiting the external power entering the front end, and to include a bandpass filter sufficient to reject strong signals in other spectrum bands, as illustrated by the right side of Figure 5-2.



The receiver blocking test places 5G NR signals in the adjacent spectrum to the RA band, as shown in Figure 5-3.

Figure 5-3: Receiver Blocking Test Center Frequencies

3650 MHz	3750 MHz	3850 MHz	3930 MHz	4030 MHz not tested	4130 MHz	RA Band: 4200-4400 MHz
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⁴⁰ *Analysis of Electromagnetic Compatibility Between Radar Stations and 4 GHz Fixed-Satellite Earth Stations*, NTIA Report 94-313, F.H. Sanders, R.L. Hinkle, and B.J. Ramsey, U.S. Department of Commerce, July 1994, at 11, “Receiver front-end overload coupling occurs when energy from the fundamental frequency of an undesired signal saturates the receiver front-end (e.g., low-noise amplifier, or LNA), resulting in gain compression (reduction in output signal level) of the desired signal sufficient to degrade performance. Receiver front-end overload generally occurs from high power signals in adjacent bands.”

⁴¹ *Analysis and Resolution of RF Interference to Radars Operating in the Band 2700–2900 MHz from Broadband Communication Transmitters*, NTIA Report 13-490, F.H. Sanders, R.L. Sole, J.E. Carroll, G.S. Secrest, and T.L. Allmon, Department of Commerce, October 2012, “Front-end overload occurs when the LNA in a receiver RF front end is not adequately protected (de-coupled) from high-power out-of-band energy by a front-end bandpass filter between the receiver antenna and the LNA’s input. Conversely, the presence of a front-end bandpass filter in front of an LNA in a receiver should automatically prevent the possibility of front-end overload of a receiver’s LNA.”

The test channels of 100-megahertz bandwidth⁴² were placed at center frequencies of 3650, 3750, 3850, 3930, and 4130 MHz, to evaluate the RA receiver’s blocking susceptibility. The VSG settings for the receiver blocking tests are provided in Table 5-6.

Table 5-6: 5G NR VSG Settings for the Receiver Blocking Test

Test Input	Parameter
5G NR Channel Bandwidth	100 MHz
Waveform	NR-FR1-TM 1.1
Modulation	QPSK
Subcarrier Spacing	30 kHz
TDD Downlink Tx Time	70%

The TM1.1 settings fully load the base station radio frame in the downlink transmission time slots, which occupy 70% of the radio frame. The remaining 30% of the time slots per frame are allocated to mobile transmissions back to the base station.

The C-Band 5G fundamental emissions were introduced at a low signal level and increased in 1 dB increments until the height accuracy pass/fail criteria were no longer met, or until the maximum power of the test setup was reached. The 5G signal level corresponding to this breakpoint was identified as the receiver blocking threshold.

5.7.1. VSG Unwanted Emissions

The test setup required an external power amplifier to increase the IMT power level at the RA receiver port to +25 dBm. The external amplifier also increased the power level of the VSG’s unwanted emissions falling within the RA band. The October 2023 test results showed a premature failure of the receiver blocking test, which in further testing, we determined was caused by the elevated levels of unwanted emissions in-band to the RA receiver.

We worked with the Microwave Filter Company to build filters to reduce the VSG unwanted emissions in the RA band to enable accurate receiver blocking measurements.

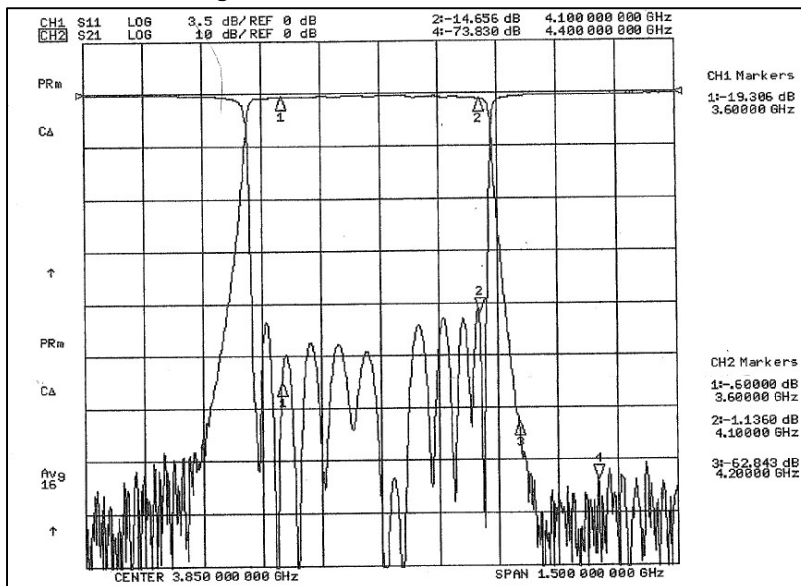
5.7.2. VSG Filter Design

The challenge to a successful receiver blocking test is to design a filter that can pass the IMT signal in the test channels outside of the RA band, while rolling off quickly enough to provide attenuation of the unwanted energy falling within the RA occupied bandwidth. This challenge increases as the IMT test channel closely approaches the RA band edges.

⁴² The channel bandwidth of 100 megahertz represents the largest channel size defined by 3GPP for 5G NR mid-band spectrum. 3GPP TS 38.104, v17.3.0, (2021-09), Third Generation Partnership Project; Technical Specification Group Radar Access Network; NR; *Base Station (BS) Radio Transmission and Reception* ((Release 17), Table 5.3.2-1. As an example, the center frequency of 3850 MHz defines a channel consisting of 3800-3900 MHz. Operating base stations may employ smaller than 100-megahertz channels depending on the amount of spectrum within each wireless provider’s license.

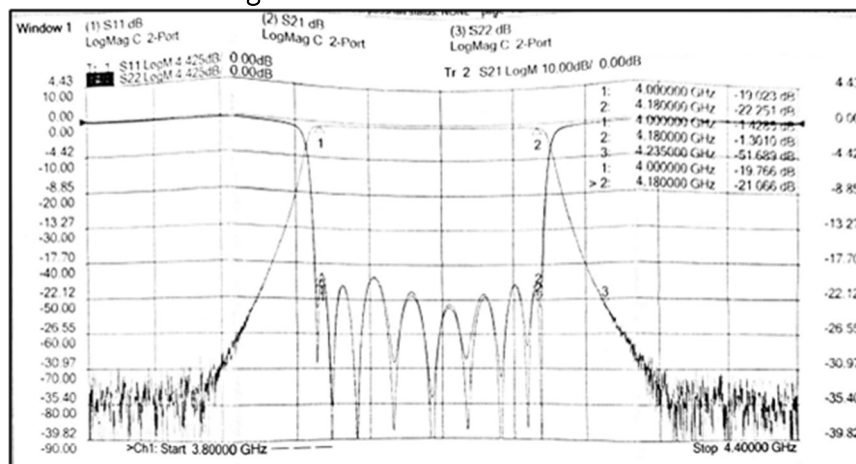
We built one filter passing the IMT test frequencies of 3600-4100 MHz, achieving 62 dB of attenuation within 4200-4400 MHz. This filter was used in testing the IMT channels below 4000 MHz. The filter frequency response is shown in Figure 5-4.

Figure 5-4: VSG Filter 3600-4100 MHz



We built a second filter passing 4000-4180 MHz and providing more than 51 dB of rejection above 4235 MHz. This filter reduced the VSG unwanted emissions for the closest IMT test channel of 4130 MHz. The second VSG filter response curve is shown in Figure 5-5.

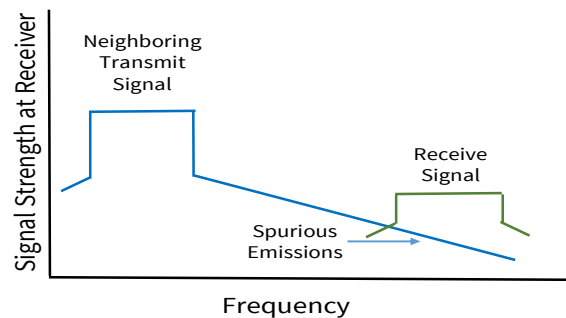
Figure 5-5: VSG Filter 4000-4180 MHz



5.8 Receiver Desense Test Inputs

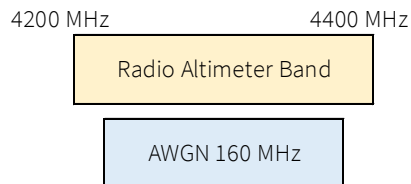
Transmitters are designed to emit nearly all their power within their intended channel. Small amounts of energy leak into nearby spectrum, with the energy level generally decreasing as a function of increasing frequency separation, as shown in Figure 5-6.

Figure 5-6: Spurious Emissions Place Small Amounts of Energy in the Receiver's Channel



If sufficiently strong, spurious emissions may elevate the receiver's noise floor, and prevent the detection of weak desired signals. This is termed receiver desense. The receiver desense test places an Additive White Gaussian Noise (AWGN) transmission with 160 megahertz bandwidth within the RA band, as shown in Figure 5-7, completely overlapping the occupied bandwidth of the RA under test.

Figure 5-7: Receiver Desense Test



The amplitude of the AWGN signal was increased in 1 dB increments until the RA's height accuracy no longer met the pass/fail criteria. This signal level was recorded as the receiver desense exceedance threshold.

6. Receiver Blocking Test Results

The receiver blocking test results at the test height of 200 ft are provided in Table 6-1, with and without the external bandpass filter. The power levels shown are dBm within a 100-megahertz bandwidth IMT signal for test channels from 3650 to 4130 MHz. The power levels shown in Table 6-1 are measured at the RA receiver port. The numbers in the table represent the 5G C-Band signal strength at which the error in reported height exceeded the pass/fail criteria. The letters NB stand for “no breakpoint” - meaning the maximum transmit power in the test setup was reached with no observed effect on the RA performance – passing all criteria.

Table 6-1: CTIA Receiver Blocking Test Results

RA Model Tested	IMT Center Frequency Under Test										Filter Model
	3650 MHz		3750 MHz		3850 MHz		3930 MHz		4130 MHz		
	No Filter	Filter	No Filter	Filter	No Filter	Filter	No Filter	Filter	No Filter	Filter	
India	-28	NB	-31	NB	-27	NB	-27	NB	-31	NB	21043
Kilo	NB	NB	NB	NB	NB	NB	0	NB	-27	NB	21043
Alpha	8	NB	10	NB	10	NB	6	NB	-13	NB	21043
Zulu	9	NB	6	NB	3	NB	-7	NB	0	NB	21043
Victor	-23	NB	-9	NB	-11	NB	-18	NB	-42	NB	20926

With the bandpass filter present, all RAs performed with no breakpoint – meeting all test criteria for the maximum power level of +25 dBm at the RA receiver port. The Kilo RA, recently introduced as a replacement for the India model, exhibited good resilience below 4000 MHz, but still benefited from the external filter to improve rejection of high power IMT signals in the adjacent channel.

7. Receiver Desense Test Results

The receiver desense test placed unwanted energy within 4220-4380 MHz and increased the power level in 1 dB increments until the RA height accuracy exceeded the pass/fail criteria. The receiver desense test results are provided in Table 7-1 for the three test heights. The power levels are in dBm per 1 MHz measurement bandwidth.

Table 7-1: CTIA Receiver Desense Test Results

RA Model Tested	200 ft	1000 ft	2000 ft
India	-94	-91	-86
Kilo	-52	-54	-49
Alpha	-66	-66	-75
Zulu	-77	-86	-82
Victor	-78	-90	-99

The recently released Kilo RA performed much better than all other RA models and showed a large improvement over its predecessor, India. As further studied in section 8 below, the worst-performing RA, Victor, has more than sufficient excess margin even in the Physical Near-Collision Scenario.

8. IMT/RA Coexistence Study: Physical Near-Collision

RTCA and EUROCAE's draft DO-399 document proposed coexistence scenarios between an aircraft equipped with a radio altimeter and ground-based IMT emitters. DO-399 also included estimates of the best achievable RA performance thresholds for receiver blocking and desense, as provided by the RA manufacturers.

The worst-case coexistence scenario involved an aircraft flying in close proximity to a tower, called the Physical Near-Collision Scenario. In light of CTIA's test results, we will revisit DO-399's Physical Near-Collision Scenario to understand the extent to which the addition of the new RF bandpass filters facilitate IMT/RA coexistence. The next sections derive the key modeling inputs.

8.1 Aircraft Pitch and Roll Angle

An important modeling input is the amount of pitch or roll that an aircraft may experience when near a structure with an IMT emitter. The pitch and roll angles determine the RA antenna gain pointing toward the emitter, affecting the IMT signal level at the RA receiver. Several aviation regulatory and industry documents describe the maximum limit of roll angles that aircraft may experience, for the aircraft height of 200 ft that we are assessing. Expected RA performance over pitch and roll angles is also an important question.

FAA regulations specify the radio altimeter performance criteria to be met under pitch angles of zero to plus or minus 5 degrees and roll angles of zero to 20 degrees in either direction.⁴³ At steeper roll angles, the RA performance will be impacted and eventually unlock, as more and more of the antenna pattern is pointed away from the terrain underneath the aircraft.

Some RA manufacturer installation manuals include stated limitations to roll angle. The FreeFlight RA-5500/6500 states that an excessive roll attitude may cause the RA to unlock, recommending a bank angle limit of 30 degrees below 1500 ft.⁴⁴ The Garmin GRA-5500 states full accuracy over roll angles of +/- 20 degrees, and accuracy within 20% for angles between +/- 20 to 30 degrees.⁴⁵

FAA Advisory Circular (AC) 61-98C recommends a bank angle not exceeding 15 degrees on final approach for general aviation.⁴⁶ The FAA further requires takeoff clearances of at least 300 feet horizontally outside

⁴³ CFR Title 14, Chapter I, Subpart F, Appendix A to Part 91—Category II Operations: Manual, Instruments, Equipment, and Maintenance, 3 c.

⁴⁴ RA-6500/5500 Series Radar Altimeter Installation Manual, Doc. No. 88222 Rev 2, FreeFlight Systems, 2021.

⁴⁵ GRA-5500 Installation Manual, Doc No. 190-01277-00 Rev. A, Garmin Ltd., Table 1-3.

⁴⁶ FAA Advisory Circular 61-98C "Currency Requirements and Guidance for the Flight Review and Instrument Proficiency Check", 11/20/15 at 6.

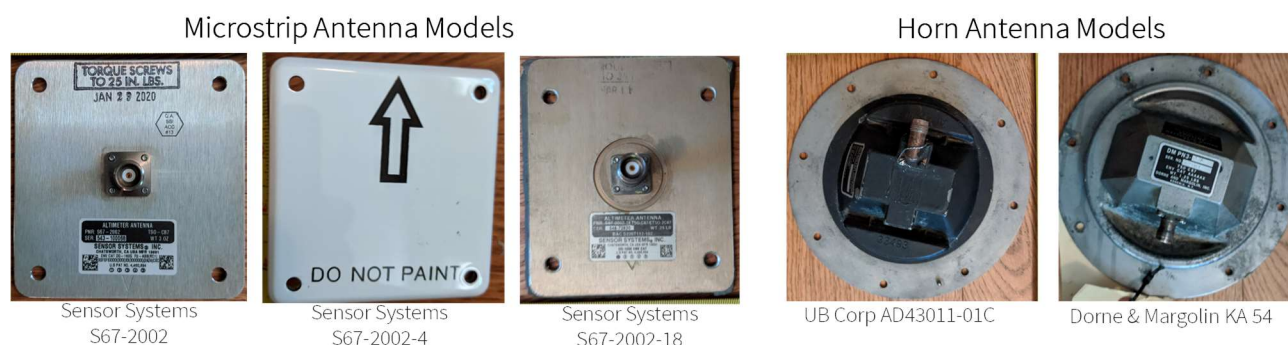
of the airport boundaries, without banking more than 15 degrees.⁴⁷ And FAA AC 120-91A states a maximum bank angle of 20 degrees for aircraft heights of 100 to 400 feet.⁴⁸

The aircraft location relative to the IMT emitter also plays a role in defining the signal's final angle of arrival at the RA antenna. An aircraft RA at the same height as the emitter would have an angle of arrival coincident with the horizon, at 90 degrees from the RA antenna's boresight direction. If the aircraft is above the emitter, then the angle from the IMT emitter to the RA must also be accounted for in determining the RA antenna gain to use in the coexistence study.

8.2 Radio Altimeter Antenna Pattern Measurements

RA antennas flown by BA/GA aircraft generally include two design types: the older horn-style antenna and the newer microstrip antenna design. CTIA procured several models of each style of antenna design and measured their in-band and out-of-band antenna patterns in an anechoic chamber. Figure 8-1 shows the units tested.

Figure 8-1: RA Antenna Models Tested



We tested three models of microstrip antenna, the antenna design used in most BA/GA RA installations. We also tested two models of the horn-style antenna, commonly installed with older RA models such as the Collins ALT-50. All units except the S67-2002-4 were removed from aircraft after years of service – ensuring a realistic capture of environmental factors impacting antenna performance.

The tests were conducted in an anechoic chamber, with the unit under test mounted on a curved ground plane to emulate the aircraft fuselage, as shown in Figure 8-2. An Agilent signal generator produced the test signal, radiated over-the-air using a Satimo dual ridge horn antenna.

⁴⁷ Part 121.177 (a) (3); 121.189 (f); 135.367 (a) (3); 135.379 (f); 135.398 (e).

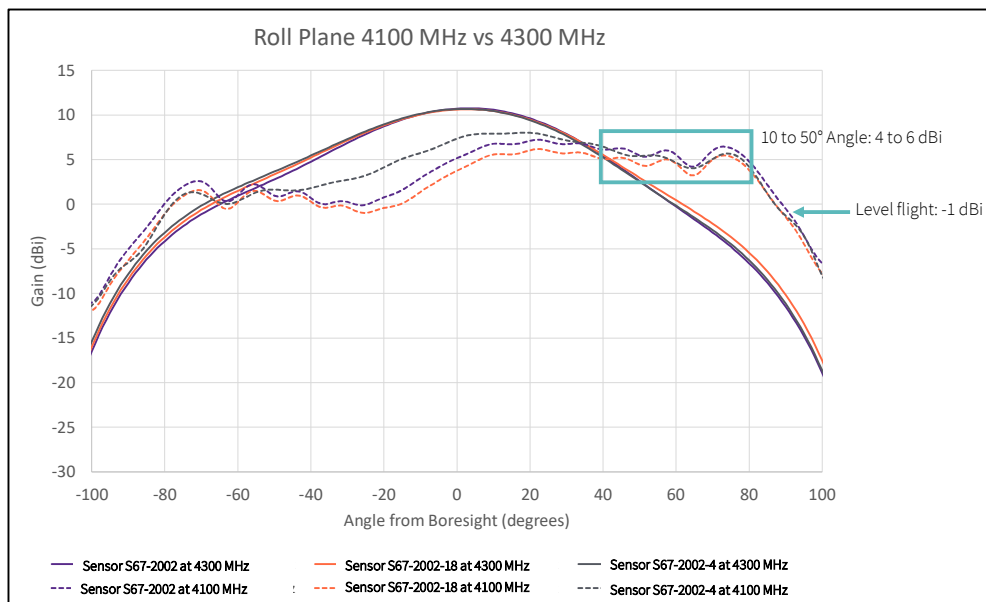
⁴⁸ FAA AC 120-91A “Airport Obstacle Analysis”, January 13, 2020, Table 1, p. 12.

Figure 8-2: Horn Antenna Mounted on Curved Ground Plane



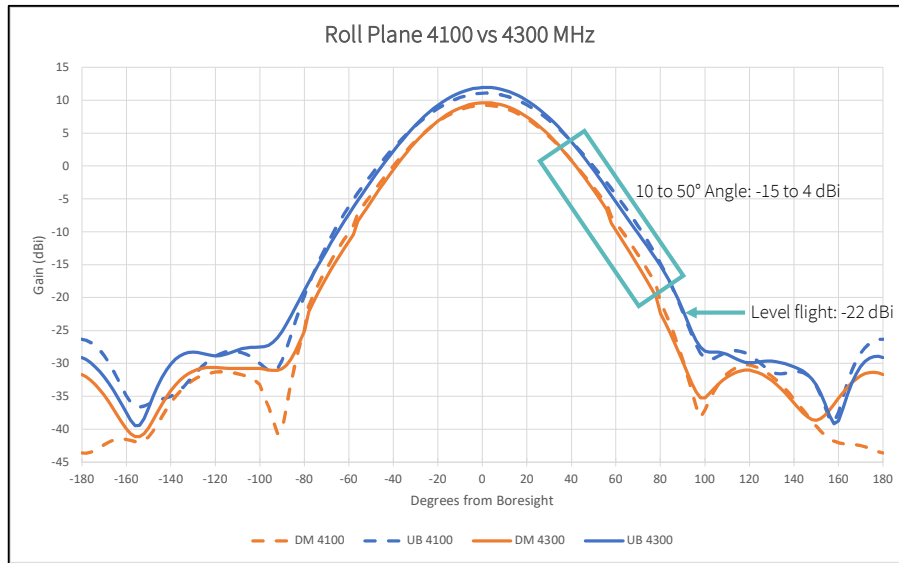
The measurement results for the microstrip antennas are provided in Figure 8-3, comparing the in-band antenna gain at 4300 MHz to the adjacent channel antenna gain at 4100 MHz. The green box highlights RA antenna pattern gains for the sum of the roll angle plus the arrival angle for values ranging from 10 to 50 degrees, relative to horizon. The antenna gain over this range varies from 4 to 6 dBi. If the sum of both angles is less than 10 degrees, then the RA antenna gain would be lower.

Figure 8-3: Microstrip Antenna Patterns



The measurement results for the horn-style of antennas are shown in Figure 8-4. The antenna patterns for the adjacent channel were relatively consistent with the in-band pattern. At shallow arrival angles, the horn antennas provide 21 dB more rejection of IMT signals than the microstrip antennas.

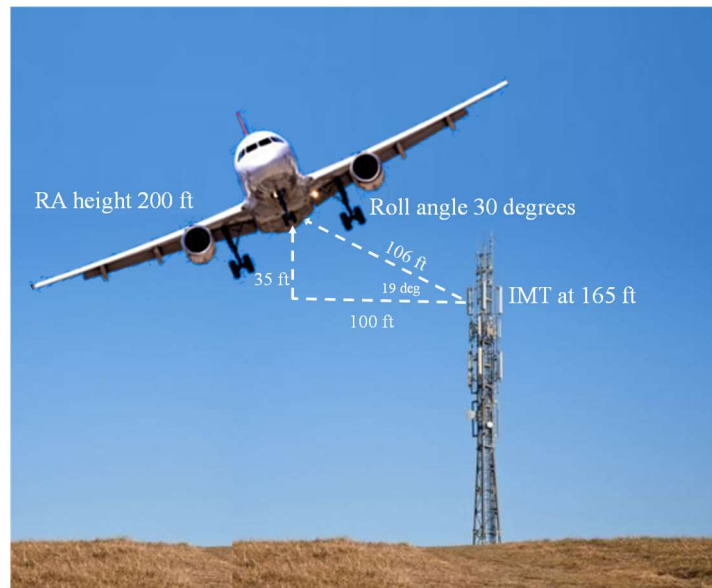
Figure 8-4: Horn Antenna Patterns



8.3 Physical Near-Collision Scenario

The most challenging coexistence example in the draft DO-399 document was termed the Physical Near-Collision Scenario. This scenario assumed that an aircraft could approach an IMT emitter with either a 100 ft lateral distance or a 35 ft vertical separation and combined the two physical separation distances into a single model.⁵¹ This scenario is illustrated in Figure 8-5, in which we consider an extreme case of a 30-degree roll angle at an RA height above ground of 200 ft.

Figure 8-5: Physical Near-Collision Scenario



⁵¹ DO-399 at 73. The combination shown here is the worst case; an aircraft 35 ft directly above a base station would be in the base station's antenna pattern null, with much lower energy toward the aircraft. And an aircraft at 100 ft horizontal distance would have a lower RA antenna gain toward the IMT emitter, with a similar path loss.

The angle of arrival for the IMT signal at the aircraft is 19 degrees, based on the physical separation distances shown above, and as defined in DO-399 for the Physical Near-Collision Scenario. From the RA antenna perspective, the aircraft roll angle and the IMT arrival angle are combined to determine the antenna gain applicable to this scenario. The antenna pointing direction in this example becomes $(90-30-19) = 41$ degrees from the RA antenna boresight. This corresponds to an RA antenna gain of 6 dBi at 4100 MHz, and 5 dBi at 4300 MHz, for the worst-performer of the RA antenna patterns.

8.4 Real World Factors Not Considered in the Physical Near-Collision Scenario

Many real-world factors would alter the assumptions and inputs used in the Physical Near-Collision Scenario, providing further margins of safety:

- As noted in section 8.1, aircraft maintain larger separation distances than those contemplated in the Physical Near-Collision Scenario. Aircraft maintain a separation distance of 300 feet from obstructions outside of the airport boundaries.⁵² Over congested areas, the pilot should maintain a vertical separation of 1,000 ft above all obstacles within 2,000 ft of the aircraft. In non-congested areas, the pilot maintains a distance of 500 ft above the surface, and 500 ft from all structures.⁵³ A larger separation distance would increase the RF path loss from the IMT emitter to the RA antenna. For example, a distance of 300 feet would reduce the IMT signal by an additional 9 dB relative to the near-collision distance.
- An IMT arrival angle at the RA antenna of less than ten degrees would experience up to 7 dB greater RA antenna discrimination, reducing the IMT emitter signal level at the RA receiver.
- The IMT base station would be serving customers on the ground or in nearby buildings and would not be directing its peak energy above the horizon toward the aircraft, a power reduction of 10 dB or more.
- IMT base stations form beams to several users at once, diffusing the energy in several directions, lowering the energy toward the aircraft's RA antenna.⁵⁴ Four simultaneous beams would lead to a 6 dB power reduction in any given direction.
- IMT base station loading - the traffic levels being served - impact the total energy emitted, with no power transmitted in unused resource blocks. The maximum EIRP level used in the Physical Near-Collision Scenario, corresponding to a fully loaded channel, is a low probability occurrence.⁵⁵ A 50% traffic load would reduce the average power by 3 dB.

⁵² Part 121.177 (a) (3); 121.189 (f); 135.367 (a) (3); 135.379 (f); 135.398 (e).

⁵³ CFR Title 14, Part 91.119 (b) and (c).

⁵⁴ *Advanced Antenna Systems for 5G*, 5G Americas White Paper, August 2019, at 52. Figure 15-2 illustrates multiple beams being formed to multiple users per sector, dividing the total energy over the coverage area resulting in lower power than the maximum in each beam. <https://www.5gamericas.org/wp-content/uploads/2019/08/5G-Americas-Advanced-Antenna-Systems-for-5G-White-Paper.pdf>

⁵⁵ Network operators engineer network traffic to remain well below 70% utilization in the busy hour to ensure that all customers receive a satisfactory experience. Capacity is increased through the addition of more spectrum and increasing cell site density over time. Measurements on a mature LTE network noted channel utilization levels of up to 20% for a 1900 MHz channel, and a maximum of 53% for a 700 MHz channel. *On the impact of network load on CQI*

- The IMT EIRP level used in the coexistence study is the FCC limit for rural areas. Base stations in non-rural areas, where many airports are located, are limited to 3 dB less power.
- The Physical Near-Collision Scenario is a dynamic situation, with the aircraft in motion and the base station dynamically scheduling traffic in different directions and times, increasing the isolation between the base station and the aircraft in operations. The lab testing is a static environment, creating the worst conditions in a persistent manner.

The above considerations provide more than 38 dB of protection not modeled in the Physical Near Collision Scenario, relative to an operational situation.

Nonetheless, we will assess the coexistence case of an aircraft with the DO-399 Physical Near-Collision Scenario assumptions - the extreme closeness to a rural IMT base station at full power, with all its energy directed at the aircraft, to verify that the beyond-worst-case-possible situation still has spare margin.

8.5 Physical Near-Collision Receiver Blocking Study

Under the beyond-worst-case conditions of the Physical Near-Collision Scenario, *the new RA filters provide at least 12 dB of excess margin, for the maximum test power level of +25 dBm, which was not a breakpoint*. The actual margin delivered in this scenario is greater than 12 dB since a breakpoint had not occurred – and the other real-world factors would add more than 38 dB of additional margin.

Table 8-1 provides the calculations for the case of receiver blocking.

Table 8-1: Physical Near-Collision Receiver Blocking Study

Parameter	Value	Unit	Notes
Lateral Distance	100	ft	a (section 8.3)
Vertical Separation	35	ft	b (section 8.3)
Slant Distance	106	ft	$c = a^2 + b^2$
Free Space Path Loss	75	dB	$d = 32.45 + 20 \cdot \log(f_{\text{MHz}}) + 20 \cdot \log(d_{\text{km}})$
IMT Rural EIRP	85	dBm/100 MHz	e (FCC limit for rural areas)
IMT Signal at Aircraft	10	dBm/100 MHz	$f = e - d$
RA Antenna Gain	6	dBi	g (section 8.2 4100 MHz curve, 41 deg from boresight)
RA Receive Cable Loss	3	dB	h (AVSI Vol I and II receive cable loss)
IMT Signal at RA Receiver	13		$i = f + g - h$
RA Verified Threshold	25	dBm/100 MHz	j (section 6 CTIA receiver blocking measurements, NB)
Minimum Excess Margin	12	dB	$k = j - i$

The custom bandpass filters enable RA coexistence with full-power IMT emitters in the spectrum adjacent to the RA band.

reporting and Link Adaptation in LTE systems, Tomic, Davidovich, et al,
https://www.etrn.rs/2021/zbornik/Papers/124_TEI_1.1.pdf

A GSMA report summarizing network measurements described sites with 40-60% utilization as heavily loaded. 4G/5G Network Experience Evaluation Guide, GSMA, at 15, <https://www.gsma.com/futurenetworks/wp-content/uploads/2020/02/4G5G-Network-Experience-Evaluation-Guideline-GSMA.pdf>

8.6 Physical Near-Collision Receiver Desense Study

In the receiver desense coexistence study, the worst-performing RA tested by CTIA showed 18 dB of margin under the Physical Near-Collision Scenario assumptions and inputs. Again, the other real-world factors described in section 8.3 would add 38 dB or more of additional margin.

Table 8-2 provides the calculations for the RA receiver desense study. The IMT spurious radiated emissions level was calculated as the conducted base station emissions of -30 dBm/MHz plus the Advanced Antenna System (AAS) element gain of 7 dBi for a rural array, as was assumed in RTCA/EUROCAE's draft DO-399 document.⁵⁶

Table 8-2: Physical Near-Collision Receiver Desense Study

Parameter	Value	Unit	Notes
Lateral Distance	100	ft	a (section 8.3, and per draft DO-399)
Vertical Separation	35	ft	b (section 8.3, and per draft DO-399)
Slant Distance	106	ft	$c = a^2 + b^2$
Free Space Path Loss	75	dB	$d = 32.45 + 20 \cdot \log(f_{\text{MHz}}) + 20 \cdot \log(d_{\text{km}})$
IMT Spurious Radiated Emissions	-23	dBm/MHz	e (-30 dBm/MHz + 7 dBi element gain, DO-399)
IMT Signal at Aircraft	-98	dBm/MHz	$f = e - d$
RA Antenna Gain	5	dBi	g (section 8.2 4300 MHz curve, 41 deg from boresight)
RA Receive Cable Loss	3	dB	h (AVSI Vol I and II receive cable loss)
IMT Signal at RA Receiver	-96	dBm/MHz	$i = f + g - h$
Worst RA Desense Threshold	-78	dBm/MHz	j (section 7 CTIA receiver desense measurements, Victor)
Excess Margin	18	dB	$k = j - i$

⁵⁶ Consistent with the IMT emissions employed in draft DO-399, Figure 5-12.

9. Conclusions

CTIA measured the performance of five BA/GA RA models in a laboratory setup identical to that employed in aviation industry testing, and under worst-case test conditions. With custom bandpass filters added inline to the RA receiver port, *all RA receiver blocking tests showed no impairment*, up to the maximum power level of +25 dBm at the RA receiver port.

CTIA's receiver desense tests verified the desense threshold for the five BA/GA RAs. The *receiver desense measurements showed good resilience* to IMT unwanted emissions within the RA band.

CTIA's coexistence studies employed the receiver blocking and receiver desense measurements to assess the worst-case Physical Near-Collision Scenario proposed in the draft DO-399 document. The worst-case conditions did not include real world factors that would provide additional margin of 38 dB or more. *The coexistence studies showed significant excess margin for both the receiver blocking and desense cases, verifying successful coexistence with future full power IMT services in spectrum adjacent to the RA band.*

Recommendations:

- Real world factors provide additional margin not reflected in the Physical Near-Collision Scenario. Considering these real-world factors, most if not all RAs perform sufficiently well today without modification. Coexistence studies should include consideration of such real world factors.
- If necessary, retrofit lower-performing RA installations, and/or design next generation RAs, with custom filters. The custom filters should be designed to pass the desired signal's occupied bandwidth and roll off within the unused portion of the RA band. This approach to filtering provides excellent protection from full power services in adjacent spectrum.
- Next gen RA performance may be further improved by designing the RA transmitter to emit power levels close to 30 dBm. The higher power transmitter improves the desired signal strength in all conditions.
- RA antenna design changes may further improve isolation between IMT emitters and RAs, as suggested by the comparison of measured antenna patterns in section 8.