NTIA Report 17-525

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report series

U.S. DEPARTMENT OF COMMERCE • National Telecommunications and Information Administration

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DISCLAIMER

Certain commercial equipment and materials are identified in this report to specify adequately the technical aspects of the reported results. In no case does such identification imply recommendation or endorsement by the National Telecommunications and Information Administration, nor does it imply that the material or equipment identified is the best available for this purpose.

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ABBREVIATIONS AND ACRONYMS

CBRS	Citizens Broadband Radio Service
CBSD	Citizens Broadband Radio Service Device
CW	carrier wave
EIRP	effective isotropic radiated power
EMC	electromagnetic compatibility
ESC	Environmental Sensing Capability
FCC	Federal Communications Commission
FEC	forward error correction
FM	frequency modulated or frequency modulation
GAA	General Authorized Access
GaN	gallium nitride
GW	gigawatt
IRAC	Interdepartment Radio Advisory Committee
I	in-phase
ITM	Irregular Terrain Model (based on Longley Rice propagation model)
ITS	Institute for Telecommunication Sciences
LNA	low noise amplifier
LTE	Long Term Evolution
LUT	LNA under test
MMIC	monolithic microwave integrated circuit
NTIA	National Telecommunications and Information Administration
OSM	Office of Spectrum Management
P0N	simple amplitude (off–on–off carrier wave) pulse modulation emission designator
PAL	Priority Access License

PPS	pulses per second
PRR	pulse repetition rate
PW	pulse width
Q	quadrature-phase
Q3N	chirped (FM) pulse modulation emission designator
RF	radio frequency
SAS	Spectrum Access System
TSC	Technical Subcommittee
UE	user equipment
VSG	vector signal generator
µsec	microsecond

EXECUTIVE SUMMARY

The National Telecommunications and Information Administration (NTIA) and the Department of Defense worked closely with the Federal Communications Commission (FCC) to develop service rules for the Citizens Broadband Radio Service (CBRS) in the 3550–3650 MHz (“3.5 GHz”) band. The 3.5 GHz band will continue to be used by high-power shipborne and ground-based Federal radar systems. In developing the regulatory framework in the 3.5 GHz band, NTIA and the FCC recognized that high-power interference effects from the Federal radar systems could disrupt or potentially damage CBRS Device (CBSD) receivers. This report documents the results of measurements performed by NTIA’s Institute for Telecommunication Sciences (ITS) in collaboration with NTIA’s Office of Spectrum Management (OSM) to investigate non-linear interference effects for several commercially available stand-alone low-noise amplifiers (LNAs) that ITS and OSM believe to be representative of the components to be implemented in future Long-Term Evolution (LTE) 3.5 GHz CBSD receivers. The measurements documented in this report also include a small-cell LTE base station. The measurements are used to compute estimates of the maximum distances at which receiver non-linear interference effects can potentially occur.

The FCC rules for CBSD operations include Priority Access Licensed (PAL) and General Authorized Access (GAA) access points and user equipment. Both PAL and GAA CBSDs can operate in close proximity (both in frequency and distance) to 3.5 GHz Federal radars. The FCC rules also include provisions for an Environmental Sensing Capability (ESC) that continually monitors the 3.5 GHz band for the presence of radar signals. The ESC provides information regarding the presence of radar signals to associated Spectrum Access Systems (SAS) which control CBSD operations.

The CBSD and ESC monitor receivers may be susceptible to high-power, in excess of 1 gigawatt (GW), peak effective isotropic radiated power (EIRP) levels from shipborne radar transmitters that may be operated along the coasts or in close proximity as ships enter and exit harbors and ports. Such high-power radar transmissions may impair the performance of CBSD and ESC monitor receivers through various non-linear response mechanisms. Non-linear performance impairment can occur via low-noise amplifier (LNA) gain compression, intermodulation product generation, and related effects.

A second concern is physical damage referred to as burnout to CBSD receiver components, including but not limited to front-end LNAs and band-selection filters. Receiver components able to handle higher power levels (e.g., radio frequency switches) are not likely to be physically damaged by high-power radar signals. The FCC rules do not specify the power levels CBSD and ESC monitor receivers will have to accept, stating only that CBSDs must accept interference from the incumbent Federal radar systems. Burnout testing of the stand-alone LNA devices and small-cell base station was not attempted due to concerns with reflected power causing damage to the test instruments. NTIA may address concerns of LNA burnout at a later date using operational radars, not test equipment.

To investigate potential non-linear interference effects prior to the deployment of CBSDs, ITS performed measurements on commercially available equipment that CBRS operators and endusers may deploy. The commercial equipment was intentionally overloaded so as to produce non-linear output behaviors.

Prior to the testing, ITS and OSM engineers consulted with industry engineers to identify commercial, off-the-shelf LNAs to be tested. These LNAs were procured and tested against high-power simulated radar signals (both unmodulated pulsed and frequency modulated (FM) pulsed radar waveforms). A company also provided ITS with a small-cell LTE base station and an associated user equipment (UE) device for testing. The base station was used in the tests but it was not possible to physically connect the test system to the UE.

The measurements of the two stand-alone LNA devices showed that overload[1] (1 dB gain compression) occurred at received power levels of -4 and -13 dBm. For the small-cell base station prototype LTE device the 1 dB gain compression occurred at received power levels between -33 dBm and more than +5 dBm, depending on the gain state of the LNA. Because of the small-cell base station architecture, testing could not isolate the LNA; therefore the results of these tests reflect the conditions within the entire receiver and do not necessarily indicate the performance of the LNA in a stand-alone configuration.

The test results also showed that when an LNA or receiver is overloaded on just a single frequency, it will behave non-linearly (i.e., will experience overload effects) across its entire operational frequency response range. So, if a CBSD device is capable of operating in multiple bands (as expected) and it only uses a single wide-band LNA in its receiver front-end design, overload on a single frequency in the 3.5 GHz band will affect the other bands as well. Both CBSD and ESC receivers will use LNAs. Since an ESC receiver was not available for this test program, it is unknown what the actual effects of gain compression would be on an ESC's ability detect radar signals and report findings to the SAS. (Tests for an ESC's ability to operate in a non-linear state could be conducted by ITS in the future when ESCs are brought to ITS for their initial certification testing.)

OSM also performed an initial analysis to compute the separation distances necessary to preclude potential overload interference based on the stand-alone LNA and small-cell base station measurements from Radars 1 and 3.[2] The separation distance necessary to preclude potential overload interference to the stand-alone LNAs ranged from 8 kilometers to as much as 40 kilometers. The separation distances necessary to preclude potential overload interference to the small-cell base station ranged from less than 2 kilometers to 55 kilometers. Although the results of the lab tests show that the LNAs and the prototype small-cell base station are susceptible to receiver overload, other factors such as clutter loss and building loss may help to mitigate some of the effects in a real world environment. In addition, these overload events will be short lived because of the beam scanning or rotation characteristics of the radar antenna, so that the cumulative effects of the radar interference into the CBSD receiver may be mitigated by its error control coding and signal processing. In earlier NTIA work as described below the pulse

[1] Known synonymously as "saturation". Both terms refer to the same phenomena of gain compression and other non-linear amplifier behaviors. The term "overload" is used in this report.
[2] Radars 1 and 3 are identified in the Exclusion Zone Report (Drocella, E. F. Jr., J. C. Richards, R. L. Sole, F. Najmy, A. Lundy and P. M. McKenna, "3.5 GHz Exclusion Zone Analyses and Methodology," NTIA Technical Report TR-15-517, U.S. Dept. of Commerce, Jun. 2015. http://www.its.bldrdoc.gov/publications/2805.aspx) and other publications as shipborne systems.

waveform characteristics of Radar 1 and Radar 3 did not cause any significant loss in data throughput on LTE technology-based receivers (when the LTE receivers were still operating in the linear region). Assuming the CBSD systems use similar LTE technology, the results should be the same for them as well.

Another factor to consider is the recovery time of modern LNAs. In a report published in 1994, NTIA tested a 4 GHz Earth station that was experiencing high-power interference from Radar 3, and saw that its LNA was ringing[3] even after the radar pulses had ceased, causing the loss of data throughput to be extended. The LNAs tested in this report were able to quickly recover from overload and did not exhibit the same ringing effect; this behavior will help CBSD receivers to recover from the overload events.

Finally, the separation distances shown in this report are only intended to be presented to the ESC and CBSD operators as guidelines, so that as they design their systems they will have knowledge of the potential power levels that the radars will produce at their receiver LNA inputs. These distances are not exclusion zones. It is hoped that the carriers can use this knowledge of possible received radar power levels to assist in designing mitigation approaches into their receiver systems.

Additional analyses can be performed using a terrain-dependent propagation model to develop contours for specific regions of the country where Navy ships are known to operate and transit (such as near San Diego, CA, and Norfolk, VA) to give more defined regions where gain overload problems could occur. Additional testing of 3.5 GHz CBSD LNAs or prototype small-cell receivers can be performed as they become available. NTIA will work with the SAS and ESC operators to resolve any potential interference problems.

[3] Ringing is the term used to describe the oscillations in an RF or electrical circuit wherein its output, given some high-power input, varies in amplitude over time even after the input has ceased. These amplitude oscillations can cause erratic circuit behavior and reduce data throughput.

NON-LINEAR EFFECTS TESTING OF HIGH-POWER RADAR PULSES ON 3.5 GHZ LOW-NOISE AMPLIFIERS

John E. Carroll, Geoffrey A. Sanders, Frank H. Sanders,[4] Robert L. Sole, Jeffery S. Devereux and Edward F. Drocella[5]

Future spectrum sharing between high-power radars and Citizens Broadband Radio Service Device CBSD in the 3550–3650 MHz (3.5 GHz) band could expose radio frequency (RF) receiver front-end low noise amplifiers (LNAs) to high peak power radar pulse signals in the band under certain situations. In this band, radar effective isotropic radiated power (EIRP) peak levels can exceed 1 gigawatt. Previous experience with LNAs exposed to high-power radar pulses in spectrum near 3.7 GHz has shown that non-linear effects can be induced in the LNAs, leading to service interruptions. To assess the level of risk for similar LNA overload at 3.5 GHz, NTIA performed gain overload (e.g., compression) tests on two representative 3.5 GHz LNAs and a small-cell base station receiver. The tests determined the pulsed radar signal power levels that caused overload (1 dB gain compression) for these devices. Approximate distance separations that would be necessary to preclude potential overload interference effects are presented, based on the measurement results and propagation modeling.

Keywords: 3.5 GHz CBSD Band; LTE; low-noise amplifier (LNA); LNA non-linear effects; LNA overload; 47 C.F.R. Part 96; effective isotropic radiated power (EIRP); General Authorized Access (GAA); Priority Access Licensed (PAL); radar; spectrum sharing

1. INTRODUCTION

1.1 Background

The National Telecommunications and Information Administration (NTIA) identified the 3550-3650 MHz band ("3.5 GHz band") for commercial broadband use employing geographic exclusion zones to protect Federal ground-based and shipborne radar systems from interference [1]. NTIA performed a follow-on study [2] to reduce the size of the exclusion zones, maximizing the availability of the spectrum in major market areas while protecting incumbent Federal operations. The 3.5 GHz band has been identified for exploring the next generation of shared spectrum technologies, to drive greater productivity and efficiency in spectrum use [3]. NTIA

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[4] The first three authors are with the Institute for Telecommunication Sciences (ITS), National Telecommunications and Information Administration (NTIA), U.S. Department of Commerce (DoC), Boulder, Colorado 80305.
[5] The last three authors are with the Office of Spectrum Management (OSM), NTIA, U.S. DoC, Washington, DC 20230.

and the Department of Defense (DOD) have worked closely with the Federal Communications Commission (FCC) to develop service rules for the Citizens Broadband Radio Service (CBRS) in the 3.5 GHz band [4]–[6]. The 3.5 GHz band will continue to be used by high-power shipborne and ground-based Federal radar systems [7]. In developing the regulatory framework in the 3.5 GHz band, both NTIA and the FCC recognized that high-power interference effects from the Federal radar systems could disrupt or potentially damage Citizens Broadband Radio Service Device (CBSD) receivers [7].

This report documents the results of measurements performed by the NTIA's Institute for Telecommunication Sciences (ITS) in collaboration with the Office of Spectrum Management (OSM) to investigate non-linear interference effects for several commercially available stand-alone low noise amplifiers (LNAs) believed to be representative of the components to be implemented in 3.5 GHz CBSD receivers. The measurements documented in this report also include a small-cell Long-Term Evolution (LTE) base station. The measurement results were used to compute the estimated separation distances necessary to preclude potential receiver non-linear interference effects.

The DOD operates radar systems in the 3.5 GHz band for air traffic marshalling, counterfire (mortar, artillery and short-range rocket detection and tracking), and other functions. In the continental United States (CONUS), 3.5 GHz band radar operations are primarily at DOD test ranges and off-shore on Navy ships. However, the shipborne radars can operate in littoral areas close to coastlines and the ground-based systems are transportable.

The FCC rules allow for Priority Access Licensed (PAL) and General Authorized Access (GAA) devices.[6] The FCC rules also include provisions for an Environmental Sensing Capability (ESC) that continually monitors the 3.5 GHz band for the presence of radar signals. The ESC provides information regarding the presence of radar signals to associated Spectrum Access Systems (SAS) which control CBSD operations. The PAL and GAA CBSDs and ESCs can operate in close proximity (both in frequency and distance) to 3.5 GHz Federal radars.

The 3.5 GHz CBSD receivers may encounter high peak-power (in excess of 1 gigawatt (1 GW) peak EIRP) effects from radar transmitters that may impair performance. Of concern in this study is performance impairment due to non-linear effects in the communication system RF receiver front-end LNAs. These effects can include gain compression and intermodulation product generation in the LNAs. A second concern is physical damage to components, including front-end LNAs and band-selection filters. (Front end components able to handle higher power levels, e.g., RF switches, are not likely to be physically damaged.)

In two past measurement programs, NTIA, working with industry representatives, injected LTE receiver equipment with pulsed radar waveforms that encompassed the radar systems that operate in the 3.5 GHz band and in adjacent bands. Three NTIA Technical Reports [8]–[10] have been published presenting the results and showing that the LTE systems, for the most part, were

[6] PAL is a non-renewable authorization for radios to use 10 megahertz channels in a single census tract for three-years; PALs are quasi-licenses. GAA is an authorization for radios to opportunistically operate on channels that are not being used by PAL radios; GAAs provide for quasi non-licensed radio operations.

able to operate in the presence of pulsed radar interference with some loss in data throughput and an increase in block error rate. However the radar signal power levels injected into the LTE receivers in those tests were limited to levels that ensured receiver overload and burnout would not occur; such effects on the victim receivers were not evaluated.

In 1994 NTIA published a technical report [11] examining LNA overload in satellite earth station receivers by out-of-band radar emissions. The technical problem that the report addressed had developed when high peak-power EIRP DOD radars that operated at 2900–3700 MHz coupled into earth station receivers that operated in the adjacent band of 3700–4200 MHz. While the radar transmitters' emissions complied with NTIA's spectrum standards mask[7] that kept their radiated power levels in the satellite earth station band low enough to preclude direct, co-channel interference on the earth stations' tuned frequencies, the unfiltered earth station receiver RF front-end LNAs were so wideband (typically responding across a 2–6 GHz frequency range) that the radars' high-power emissions overloaded the LNAs. When the earth station LNAs overloaded on the radar frequencies *outside* the earth station band, the LNA noise figure and gain responses failed across the amplifiers' entire operational frequency range, including *within* the earth station band. This resulted in communication failures on the tuned frequencies of the earth stations, even though the actual interference coupling was occurring hundreds of megahertz away from the tuned frequencies of the earth stations. That NTIA report provided information that allowed earth station operators to develop interference mitigation techniques for their systems to protect them from adjacent-band high-power radar emissions by showing that earth station receivers needed front-end bandpass filters to protect their wideband LNAs from adjacent-band radar emissions. However, this solution devised for the earth stations in the 3.7 GHz band will not work in the 3.5 GHz band, as the CBSD devices and radars operate within the same band.

The 3.5 GHz band CBSDs and radar transmitters will, at times, be operated in close proximity to each other as ships enter and exit harbors and maneuver close to shore. The current and future radar in the 3.5 GHz band will operate at peak EIRP levels exceeding 1 GW, which has the potential to cause overload and possibly even damage to RF front-ends of receivers under certain conditions. In addition, the CBSD ESC to be used for spectrum management of the 3.5 GHz band will similarly have to tolerate high power levels from the radar transmitters. The FCC rules do not specify the incident radar power levels that the CBSD and ESC monitoring receivers must tolerate.

1.2 Objective

The objective of this work was to perform measurements to investigate non-linear interference effects of commercially available devices and equipment believed to be representative of the components to be implemented in 3.5 GHz band CBSD and ESC monitoring receivers.

[7] This standard is in Section 5.5.1 of the NTIA Manual of Regulations and Procedures for Federal Radio Frequency Management (Redbook), the Radar Spectrum Engineering Criteria (RSEC). The Redbook is available at https://www.ntia.doc.gov/page/2011/manual-regulations-and-procedures-federal-radio-frequency-management-redbook.

1.3 Approach

NTIA engineers worked with industry representatives to identify commercial, off-the-shelf LNAs that are believed to be representative of the LNAs to be used by 3.5 GHz band LTE equipment. A company also provided NTIA with a small-cell LTE base station and a user equipment (UE) device for testing.

NTIA identified two types of non-linear interference modes : 1) gain compression (where the LNA performance becomes non-linear but the device still operates and eventually recovers when the interfering pulses are removed); and 2) burnout (where the LNA is exposed to up to +40 dBm (10 watts) of peak radar power levels and could be physically damaged). Burnout testing was not attempted as part of this study due to concerns with reflected power causing damage to test instruments.

NTIA developed simulated pulsed radar signals representing operational 3.5 GHz radars. These signals were used to determine the susceptibility of the stand-alone LNAs and small cell base station to overload interference effects.

The measurement results were used to compute the distance separations necessary to preclude potential gain compression interference effects in 3.5 GHz band CBSD and ESC monitoring receivers. NTIA coordinated the work, and this final report, with the Federal agency members of the Interdepartment Radio Advisory Committee (IRAC) Technical Subcommittee (TSC).

2. STAND-ALONE LNA TEST SETUP

2.1 Gain Compression (Overload) Testing

For initial testing, a vector signal generator (VSG) was configured to transmit the two radar waveforms defined by pulse width (PW) in microseconds (μsec) and pulse repetition rate (PRR) in pulses per second (PPS) in Table 1.

Table 1. Radar Pulse Waveforms Used for Testing

Waveform	PW (μsec)	PRR (PPS)	Duty Cycle (percentage)	Number of Pulses
1	1	1000	0.1	Continuous
2	100	1000	10	Continuous

From the results gathered during initial testing, additional testing with intermediate radar waveforms was deemed to be unnecessary because the tests using the upper and lower bounds on the waveforms' pulse widths and pulse repetition rates gave the same results. Due to power output restrictions of the standalone VSG, the maximum peak power transmitted into the LNA under test was +21 dBm. All tests were conducted via hardline connections. Because the LNAs recommended were surface mount package components, NTIA procured evaluation boards for the two LNAs from the respective manufacturers. Both evaluation boards were configured with subminiature assembly RF connectors.

The output of the VSG was connected to the input of the LNA under test (LUT). Due to the high compression points of both LNAs, it was not possible to simultaneously observe the LNA's noise floor response in the presence of a high-power, on-tune pulsed signal. To overcome this, NTIA engineers inserted a bandpass filter with a 3 dB bandwidth between 3500–4500 MHz, between the output of the LNA and the test equipment as shown in Figure 1. When measuring LNA output power values relative to the input power, the filter was removed.

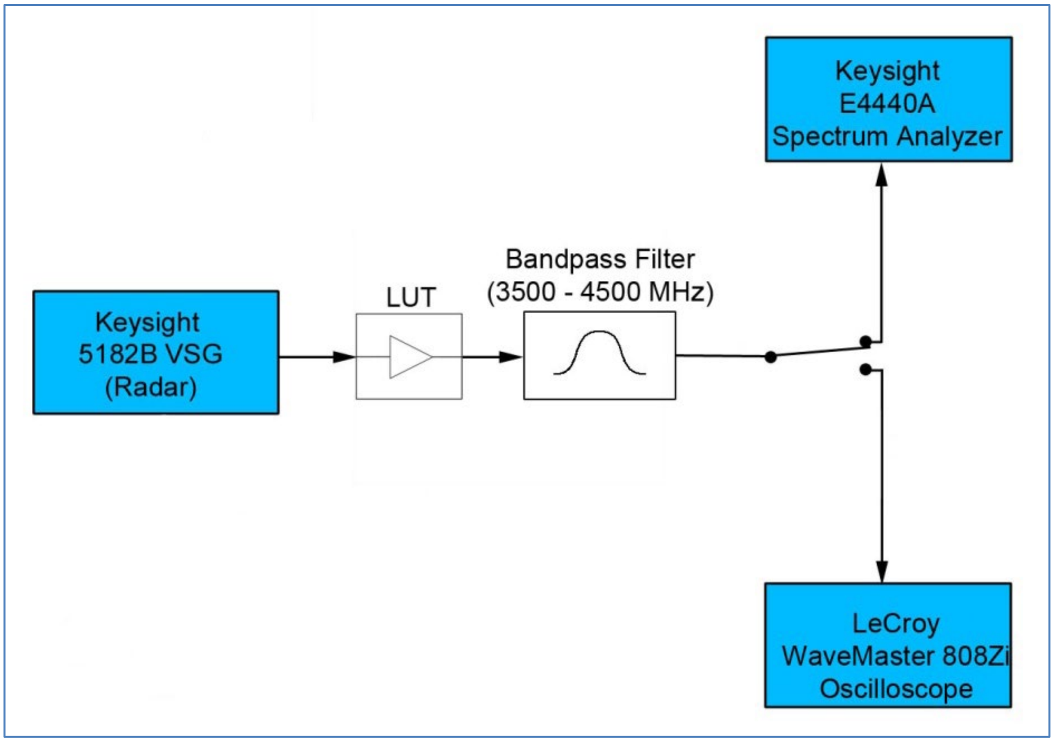

Figure 1. Test setup for overload testing.

The simulated radar signal was then transmitted at 3100 MHz, within the LNA's operational frequency range. The post-LNA filter rejects the off-tune, high-power pulsed radar signal, but allows for the observation of the LNA noise floor. As documented in [11] for multiple types of LNAs, overload of an LNA on a single frequency causes gain compression and increase in noise figure across the entire operational frequency range of the LNAs.

For high speed time-domain analysis, the LeCroy oscilloscope was used. The oscilloscope allowed for direct digitization of frequencies up to 8 GHz with a 40 billion-samples-per-second sampling rate. For frequency domain analysis, a Keysight E4440A spectrum analyzer was used, tuned to 3550 MHz. Switching between instruments was performed manually by the test operator.

3. STAND-ALONE LNA OVERLOAD RESULTS

3.1 Test LNA 1

3.1.1 LNA 1 Description

Test LNA 1[8] is a broadband LNA fabricated using gallium nitride (GaN) technology. LNA 1 has an operational frequency range from 2 to 6 GHz and typically provides a noise figure of 1.5 dB, a 1 dB compression point of +22 dBm, and a small-signal gain of 25 dB. The manufacturer claims that this LNA's performance degrades with an input power exceeding 2 watts (+33 dBm). This LNA could be used in CBSD designs and devices. The frequency response of LNA 1 was measured by ITS using a carrier wave (CW) source swept in frequency from 1 to 6 GHz and holding its power constant. The result is shown below in Figure 2. Note that the amplitude (dB value of the gain response) is normalized so that the peak response is at 0 dB. Figure 2 shows that the response of LNA 1 only varies about 3 dB from 3 to 4 GHz, and it will not filter any radar signals below 3.5 GHz.

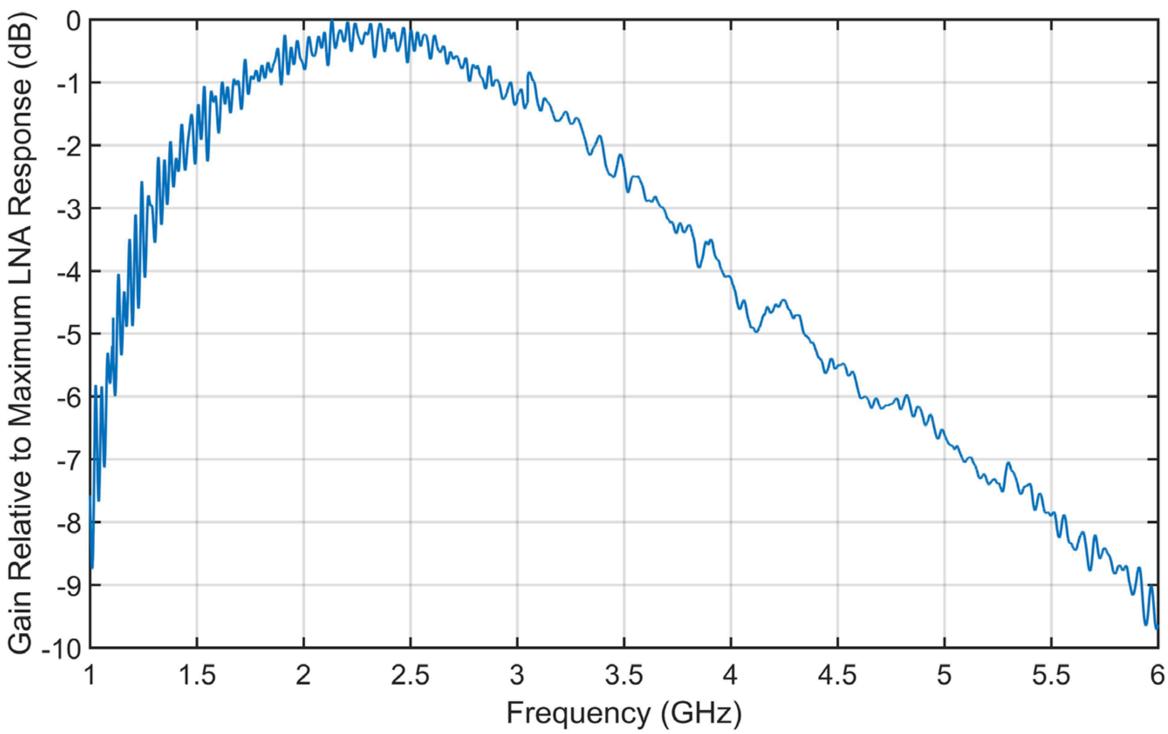

Figure 2. LNA 1 magnitude frequency response.

[8] In this report the LNAs that were tested are called LNA 1 and LNA 2. The LNA manufacturer and model identifications are available upon request.

3.1.2 LNA 1 Gain Compression Response

Using parameters for Radar Waveform 1 from Table 1, NTIA engineers examined the amplification linearity of LNA 1. Those results are shown in Table 2 and Figure 3.

Table 2. Measured Peak Power Levels (1 µsec PW, 1000 pps PRR radar waveform)

VSG Power (dBm)	**Peak Power In (dBm)**	**Peak Power Out (dBm)**	**VSG Power (dBm)**	**Peak Power In (dBm)**	**Peak Power Out (dBm)**
-12	-12.1	+12.8	**+5**	+4.9	+26.0
-11	-11.1	+13.8	**+6**	+5.9	+26.1
-10	-10.1	+14.8	**+7**	+6.9	+26.6
-9	-9.1	+15.8	**+8**	+7.9	+26.8
-8	-8.0	+16.7	**+9**	+8.9	+26.8
-7	-7.1	+17.6	**+10**	+9.9	+27.1
-6	-6.1	+18.5	**+11**	+10.9	+27.3
-5	-5.1	+19.5	**+12**	+11.9	+27.5
-4	-4.0	+20.2	**+13**	+12.9	+27.5
-3	-3.1	+21.0	**+14**	+13.9	+27.4
-2	-2.1	+21.8	**+15**	+14.9	+27.2
-1	-1.1	+22.5	**+16**	+15.9	+27.0
0	+0	+22.8	**+17**	+16.9	+26.9
+1	+0.9	+23.8	**+18**	+17.9	+26.7
+2	+1.9	+24.4	**+19**	+18.9	+26.6
+3	+2.9	+25.0	**+20**	+19.8	+26.5
+4	+3.9	+25.6	**+21**	+20.8	+26.4

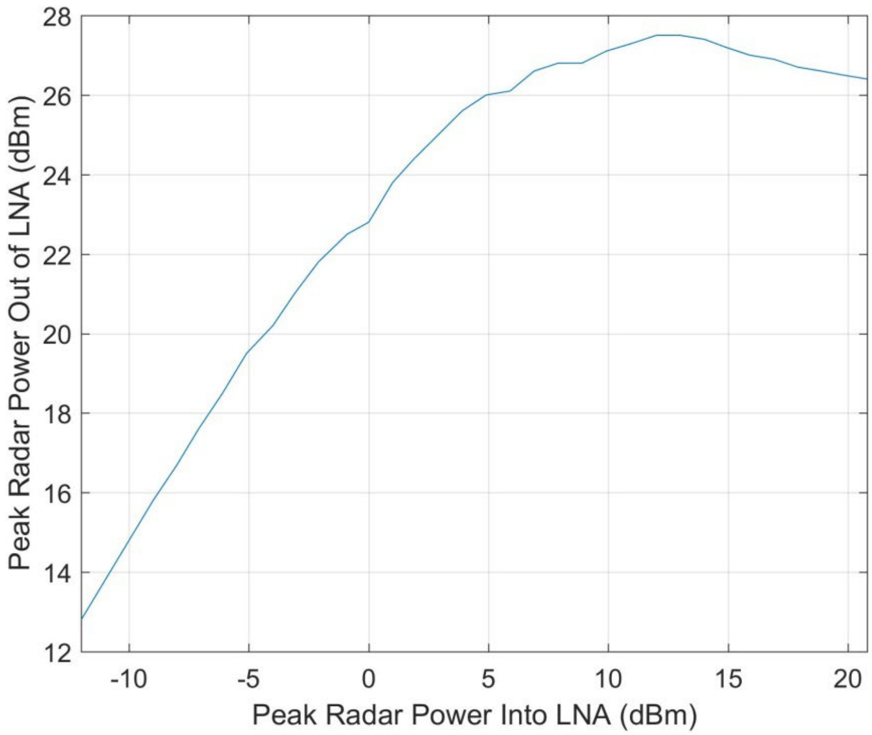

Figure 3. Relationship between input and output power for LNA 1
(1 µsec PW, 1000 pps PRR radar waveform).

The linearity of LNA 1 was then checked against the parameters for Radar Waveform 2 in Table 1. The results are shown in Table 3 and Figure 4.

Table 3. Measured Peak Power Levels (100 µsec PW, 1000 pps PRR radar waveform)

VSG Power (dBm)	**Peak Power In (dBm)**	**Peak Power Out (dBm)**	**VSG Power (dBm)**	**Peak Power In (dBm)**	**Peak Power Out (dBm)**
-12	-12.1	+12.8	**+5**	+4.9	+26.1
-11	-11.1	+13.8	**+6**	+5.9	+26.4
-10	-10.1	+14.8	**+7**	+6.9	+26.6
-9	-9.1	+15.8	**+8**	+7.9	+26.8
-8	-8.0	+16.8	**+9**	+8.9	+27.0
-7	-7.1	+17.8	**+10**	+9.9	+27.1
-6	-6.1	+18.8	**+11**	+10.9	+27.3
-5	-5.1	+19.5	**+12**	+11.9	+27.4
-4	-4.0	+20.4	**+13**	+12.9	+27.4
-3	-3.1	+21.0	**+14**	+13.9	+27.2
-2	-2.1	+21.9	**+15**	+14.9	+27.0
-1	-1.1	+22.5	**+16**	+15.9	+16.8
0	+0	+23.2	**+17**	+16.9	+26.6
+1	+0.9	+24.0	**+18**	+17.9	+26.4
+2	+1.9	+24.2	**+19**	+18.9	+26.1

VSG Power (dBm)	Peak Power In (dBm)	Peak Power Out (dBm)	VSG Power (dBm)	Peak Power In (dBm)	Peak Power Out (dBm)
+3	+2.9	+25.2	**+20**	+19.8	+26.0
+4	+3.9	+25.7	**+21**	+20.8	+26.0

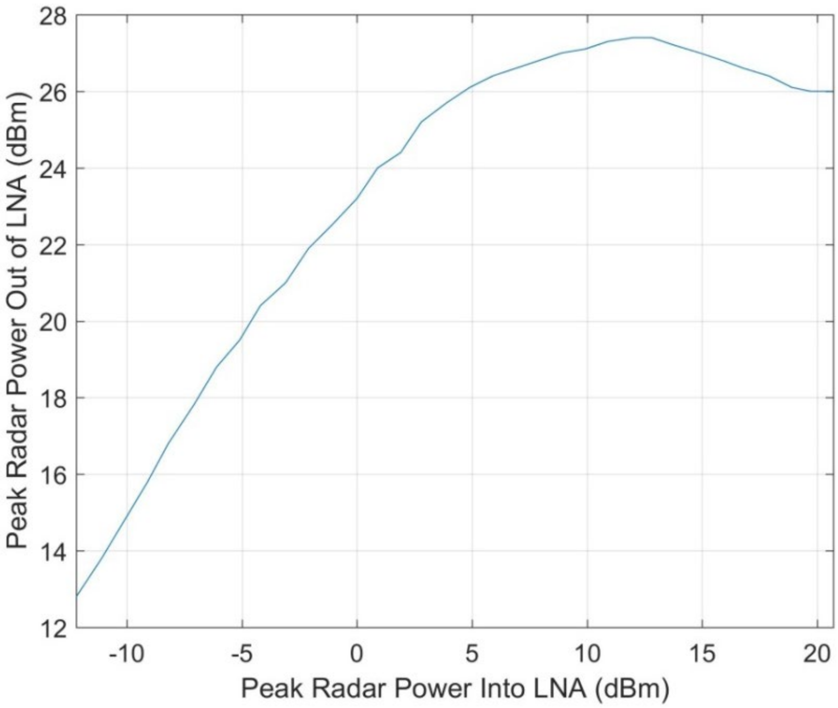

Figure 4. Relationship between input and output power for LNA 1 (100 µsec PW, 1000 pps PRR radar waveform).

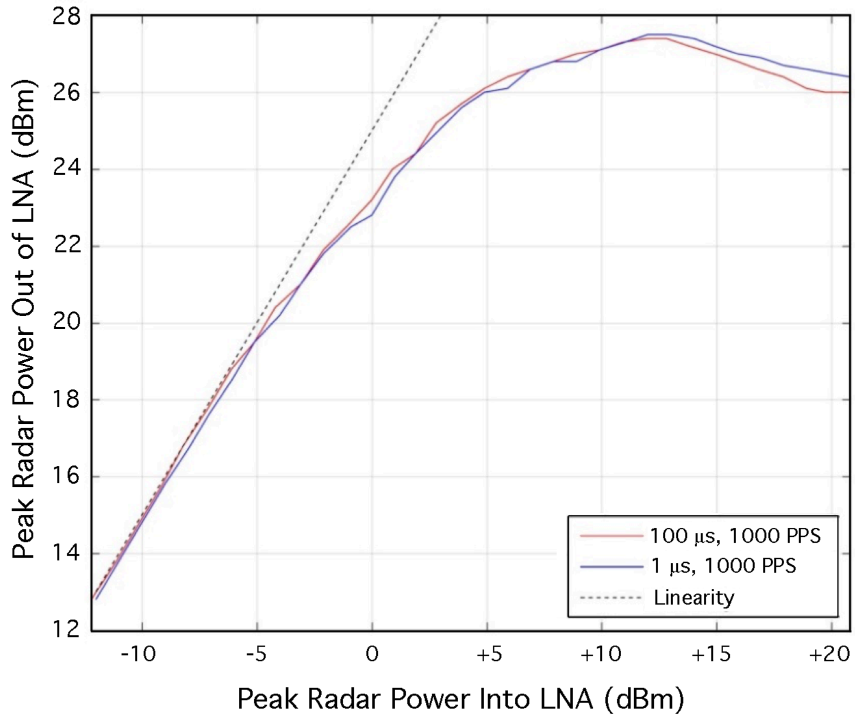

Figure 5. Comparison between input and output powers for LNA 1 for both simulated radar test waveforms. The 1 dB compression input power level is -4 dBm.

Figure 5 shows the comparison between the LNA 1 linearity responses for the two simulated radar waveforms in Table 1. Figures 6 and 7 show time-domain captures of the end of the 1 µsec and 100 µsec pulses, respectively. During testing with pulsed radar waveforms, no increase in LNA 1 noise figure after transmission of the radar pulses was observed. (This represents a performance improvement over the test results that were documented for an earlier generation of LNAs in [11].)

In Figure 5 the 1 dB compression point for LNA 1 occurs where the measured output power diverges from the linear-operation projection (dotted line) by one decibel. This divergence from linearity is at an input power level of -4 dBm.

To investigate whether an increase in noise figure occurred, a carrier wave (CW) signal was injected at 3100 MHz at three different power levels as shown in Figure 8. The amplifier output level was measured across 3500–3700 MHz as a function of CW input power level and any change in LNA 1 noise figure (manifested as a reduction in gain) was observed. It is unknown why the +5 dBm CW signal decreased the LNA noise figure; non-linear behavior means, by definition, that outputs do not linearly follow inputs. In any event, the largest change from the nominal gain value of 25 dB was 6 dB downward, to a gain level of 19 dB.

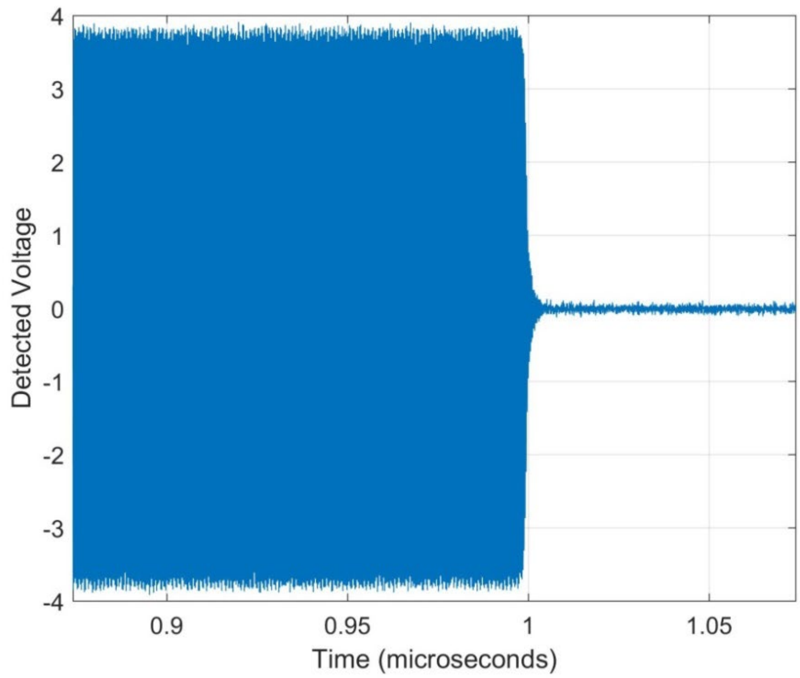

Figure 6. Time-domain behavior of the 1 μsec PW radar pulse.

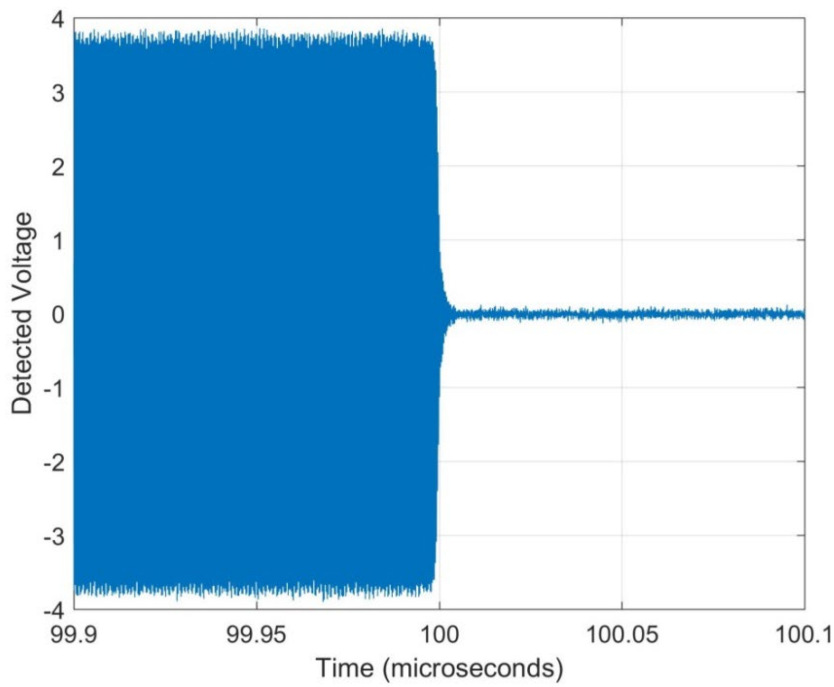

Figure 7. Time-domain behavior of the 100 μsec PW radar pulse.

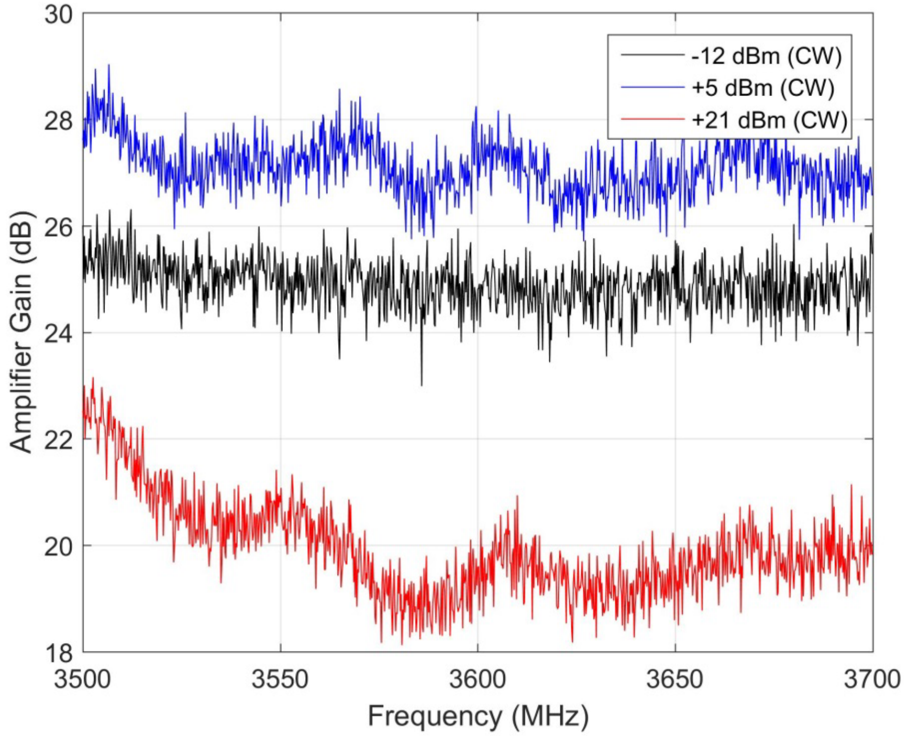

Figure 8. LNA 1 gain change for three CW input power levels. The largest change from the manufacturer's specified gain of 25 dB is 6 dB downward, to about 19 dB.

3.2 LNA 2

3.2.1 LNA 2 Description

LNA 2 is a custom broadband amplifier with an operational frequency range of 2 to 6 GHz. It typically provides a noise figure of 1.5 dB, a 1 dB compression point of +13 dBm and a small signal gain of 28 dB. However, during testing LNA 2 was found to provide a small signal gain of 17 dB. Two identical LNA 2 units were tested and both provided similar gain values. It is unknown why the deviation from the manufacturer specification occurred. The frequency versus gain response of LNA 2 was measured by ITS using a CW source swept in frequency from 1 to 6 GHz and holding its power constant. The result is shown below in Figure 9. Note that the amplitude (dB value of the gain response) is normalized so that the peak response is at 0 dB. Figure 9 shows that the gain response of LNA 2 varies about 10 dB from 3 to 4 GHz.

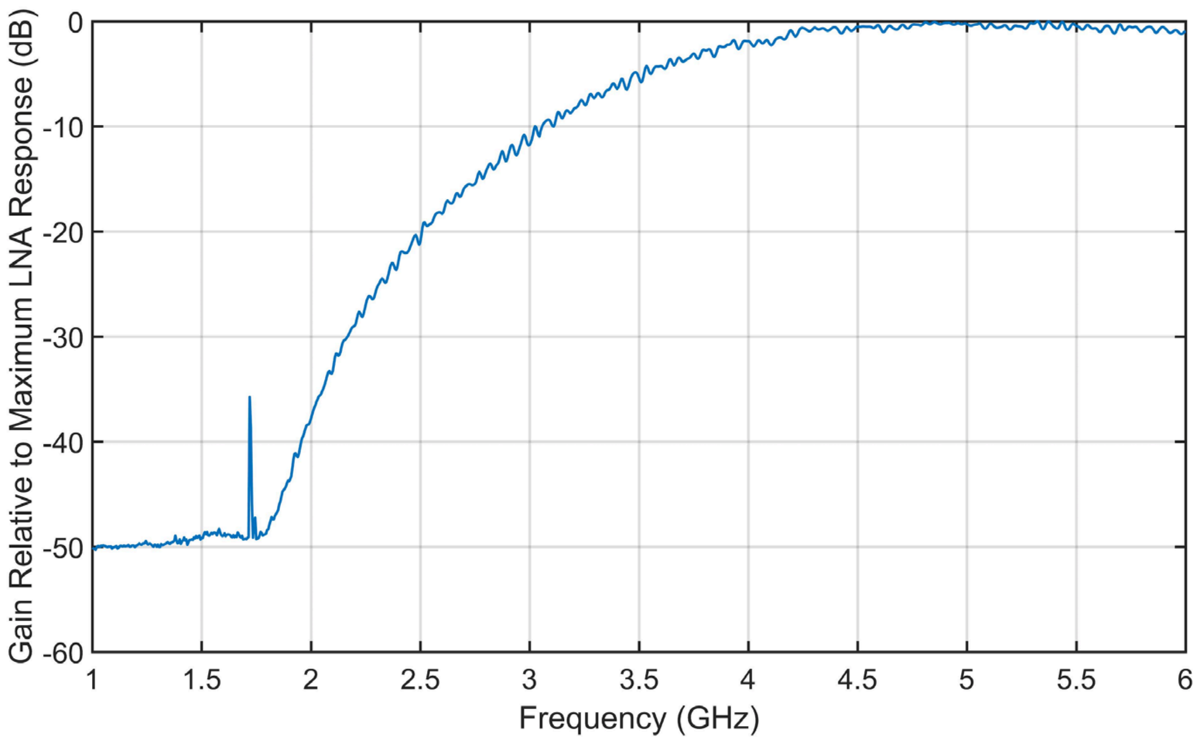

Figure 9. LNA 2 magnitude frequency response. (Spur at 1750 MHz is a measurement artifact.)

3.2.2 LNA 2 Compression Response

Using the parameters for radar waveforms from Table 1, NTIA engineers examined the amplification linearity of LNA 2. The results are shown in Tables 4 and 5 and Figures 10 and 11 for Radar Waveforms 1 and 2, respectively.

Table 4. Measured Peak Power Levels (1 µsec PW, 1000 pps PRR radar waveform)

VSG Power (dBm)	Peak Power In (dBm)	Peak Power Out (dBm)	VSG Power (dBm)	Peak Power In (dBm)	Peak Power Out (dBm)
-22	-22.1	-4.8	-6	-6.1	+6.5
-21	-21.1	-3.7	-5	-5.1	+6.2
-20	-20.1	-2.7	-4	-4.1	+6.6
-19	-19.1	-1.7	-3	-3.1	+6.6
-18	-18.1	-1.2	-2	-2.1	+6.9
-17	-17.1	+0.1	-1	-1.1	+6.6
-16	-16.1	+0.9	+0	-0.1	+6.4
-15	-15.1	+1.5	+1	0.9	+6.7
-14	-14.1	+1.8	+2	1.8	+6.6
-13	-13.2	+3.1	+3	2.9	+6.6
-12	-12.1	+3.4	+4	3.9	+6.3

VSG Power (dBm)	Peak Power In (dBm)	Peak Power Out (dBm)	VSG Power (dBm)	Peak Power In (dBm)	Peak Power Out (dBm)
-11	-11.1	+4.0	+5	4.9	+5.7
-10	-10.1	+4.5	+6	5.9	+4.6
-9	-9.1	+4.8	+7	6.9	+3.0
-8	-8.1	+5.8	+8	7.9	+2.0
-7	-7.1	+6.2			

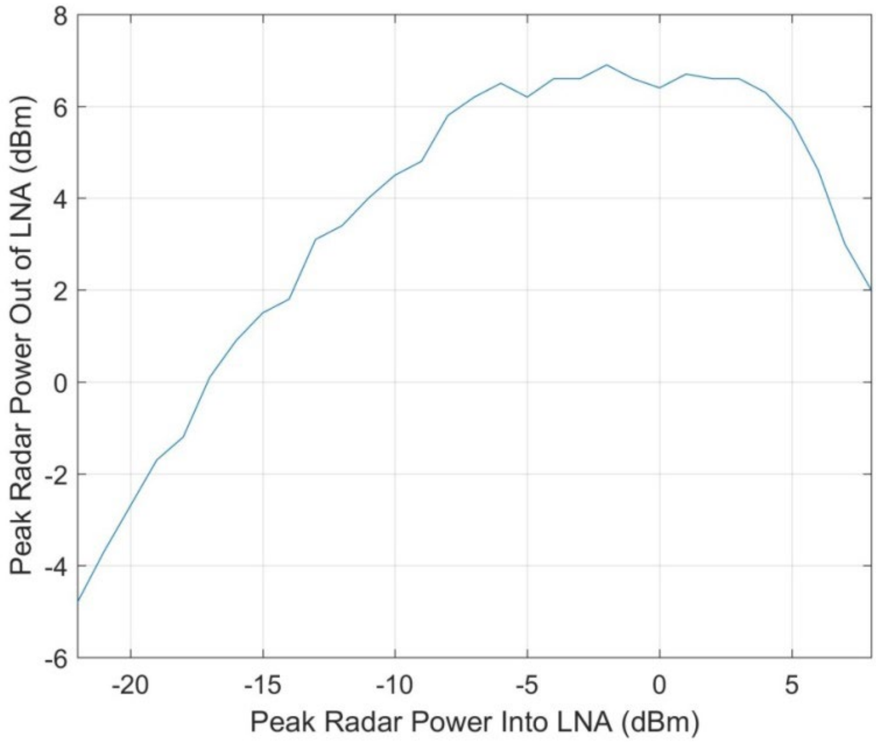

Figure 10. Relationship between input and output power for the custom MMIC LNA 2 (1 µsec PW, 1000 PRR).

Table 5. Measured Peak Power Levels (100 µsec PW, 1000 pps PRR radar waveform)

VSG Power (dBm)	Peak Power In (dBm)	Peak Power Out (dBm)	VSG Power (dBm)	Peak Power In (dBm)	Peak Power Out (dBm)
-22	-22.1	-4.9	-6	-6.1	+6.4
-21	-21.1	-3.8	-5	-5.1	+6.5
-20	-20.1	-2.8	-4	-4.1	+6.5
-19	-19.1	-2.1	-3	-3.1	+6.6
-18	-18.1	-1.4	-2	-2.1	+6.4
-17	-17.1	-0.1	-1	-1.1	+6.6
-16	-16.1	+0.6	+0	-0.1	+6.6
-15	-15.1	+1.3	+1	0.9	+6.5

VSG Power (dBm)	Peak Power In (dBm)	Peak Power Out (dBm)	VSG Power (dBm)	Peak Power In (dBm)	Peak Power Out (dBm)
-14	-14.1	+2.0	+2	1.8	+6.6
-13	-13.2	+2.8	+3	2.9	+6.5
-12	-12.1	+3.4	+4	3.9	+6.1
-11	-11.1	+4.0	+5	4.9	+5.6
-10	-10.1	+4.4	+6	5.9	+4.6
-9	-9.1	+5.0	+7	6.9	+3.3
-8	-8.1	+5.4	+8	7.9	+2.1
-7	-7.1	+6.0			

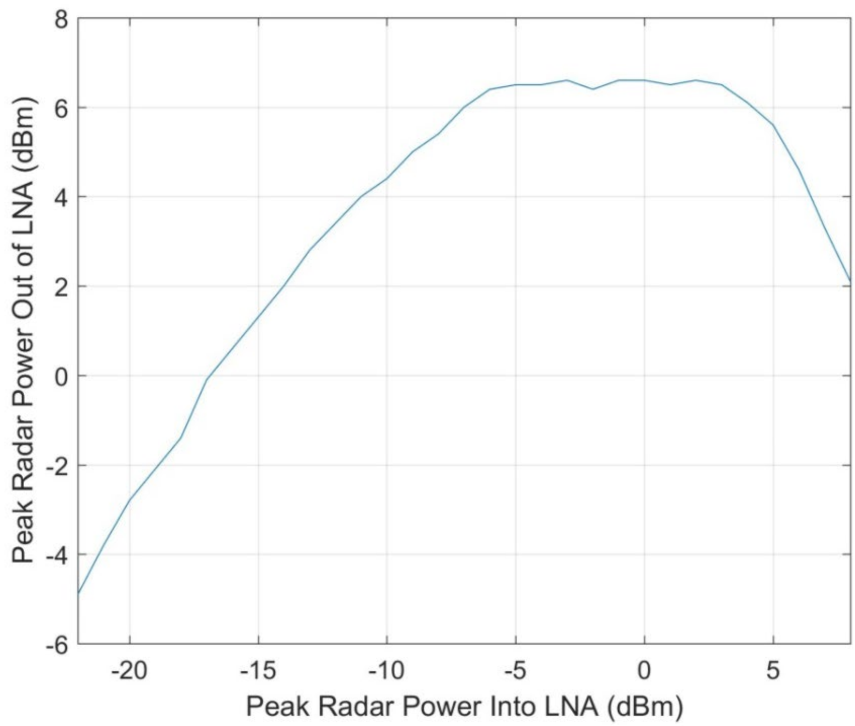

Figure 11. Relationship between input and output power for the custom MMIC LNA 2 (100 µsec PW, 1000 PRR).

Figure 12 shows the comparison between the LNA linearity responses for the two simulated radar waveforms in Table 1. The 1 dB compression input power level is -13 dBm.

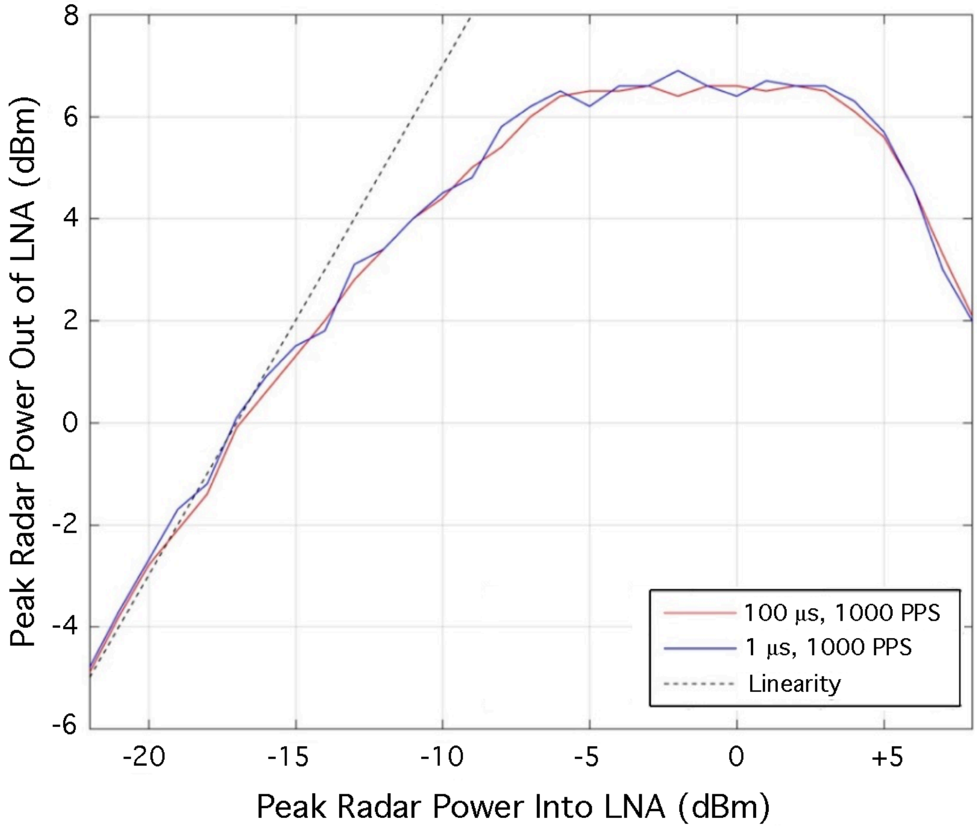

Figure 12. Comparison between input and output powers for the custom MMIC LNA 2 for both simulated radar waveform types.

Figures 13 and 14 show time-domain captures of the end of the 1 µsec and 100 µsec pulses, respectively. During testing with simulated pulsed radar waveforms, no increase in LNA 2 noise figure after transmission of the radar pulses was observed. As already noted for LNA 1, this represents a performance improvement over the behavior that was observed for LNAs in the early 1990s [11].

To investigate whether an increase in noise figure manifested as a reduction in gain occurred, a CW signal was injected at 3100 MHz at three different power levels as shown in Figure 15. The amplifier output level was measured across 3500–3700 MHz as a function of CW input power level and any change in LNA 2 noise figure (manifested as a reduction in gain) was observed. The largest change in that figure from the nominal gain of 17 dB is about 12 dB downward, to about 5 dB.

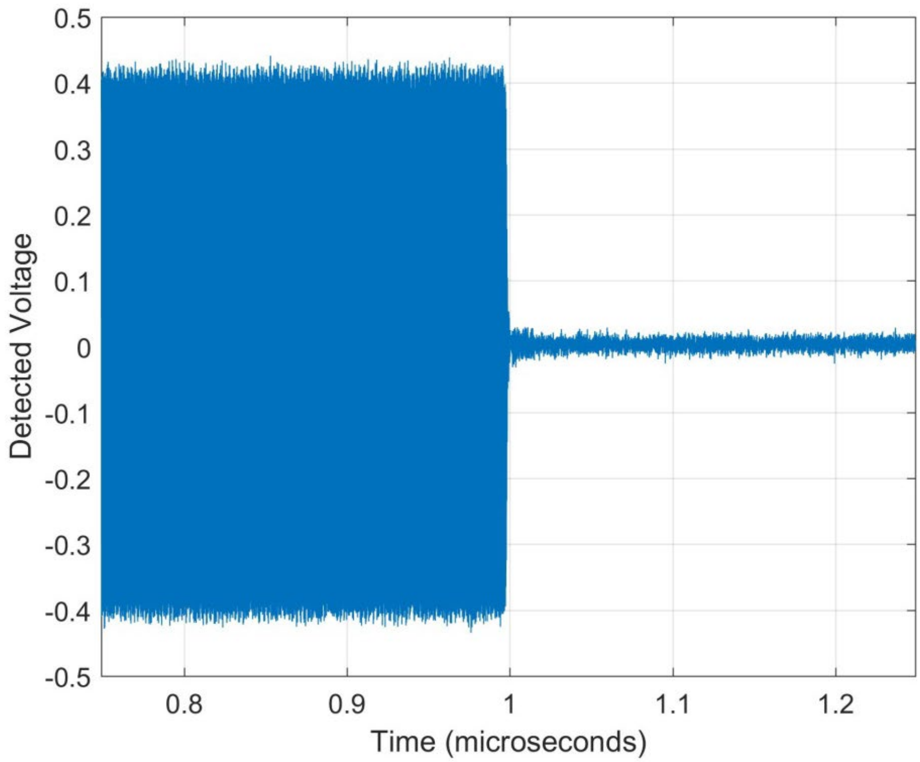

Figure 13. Time-domain behavior of the 1 µsec radar pulse for LNA 2.

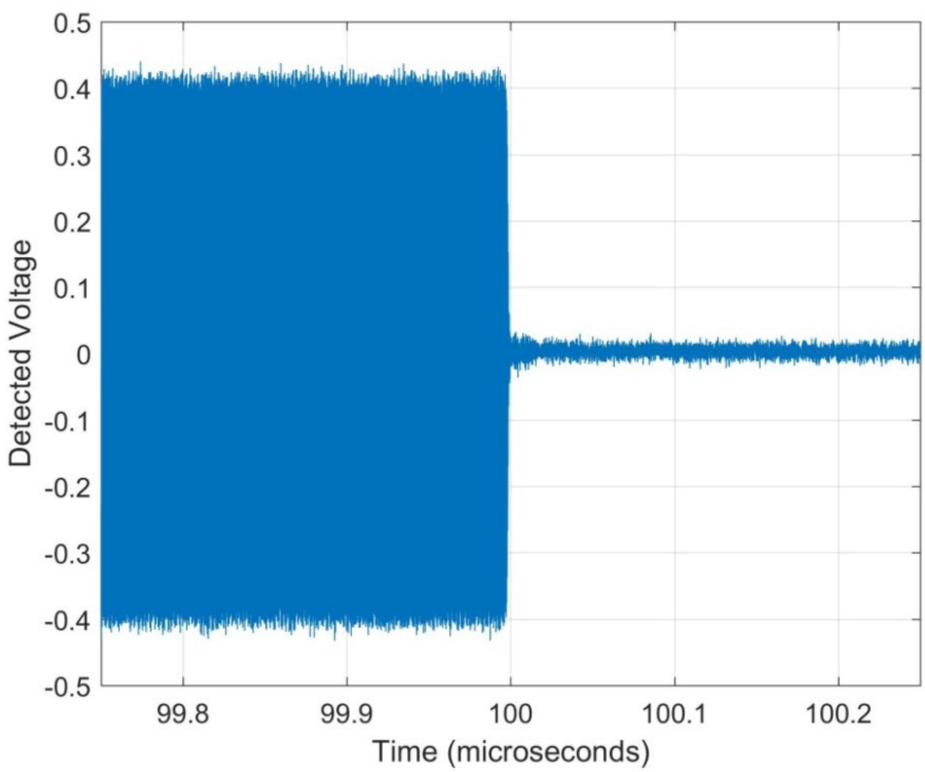

Figure 14. Time-domain behavior of the 100 µsec radar pulse for LNA 2.

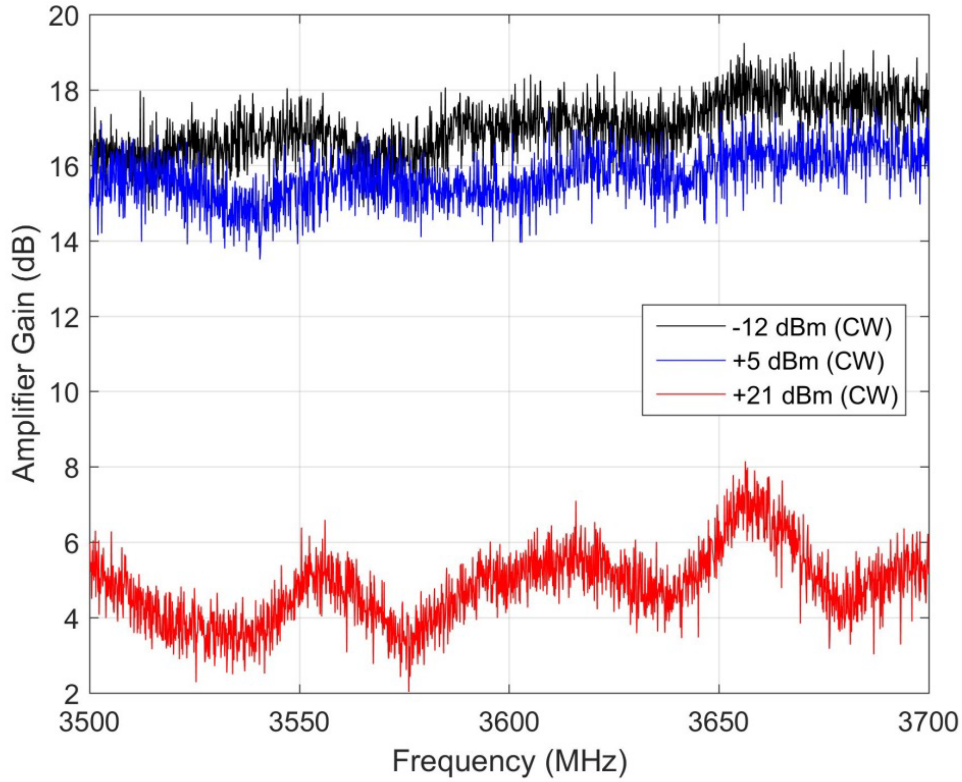

Figure 15. LNA 2 gain change for three CW signal levels. The largest change from the nominal gain of 17 dB is about 12 dB downward, to about 5 dB.

4. SMALL-CELL BASE STATION

NTIA engineers worked with engineers from a private sector company that are developing LTE devices for use in the 3.5 GHz band at their company's laboratory located in Boulder, Colorado. Conducted electromagnetic compatibility testing was performed on a small-cell base station (also called an eNodeB station) using simulated high-power radar signals. Transmitted power levels of the simulated radar signals were limited to prevent permanent damage to the small-cell base station and test equipment; that is to say, only LNA overload conditions were examined. Because of the small-cell base station system's architecture, the testing could not isolate the LNA and the results of these tests reflect the conditions within the entire receiver, and do not necessarily indicate how the LNA would have performed in a stand-alone configuration. The small-cell base station was configured to provide diagnostic data to the operator, via a control port, with information such as received power and block error rates. The UE device could not be tested because it proved to be impossible to mechanically connect it to the test system. The test diagram for the small-cell base station is shown in Figure 16.

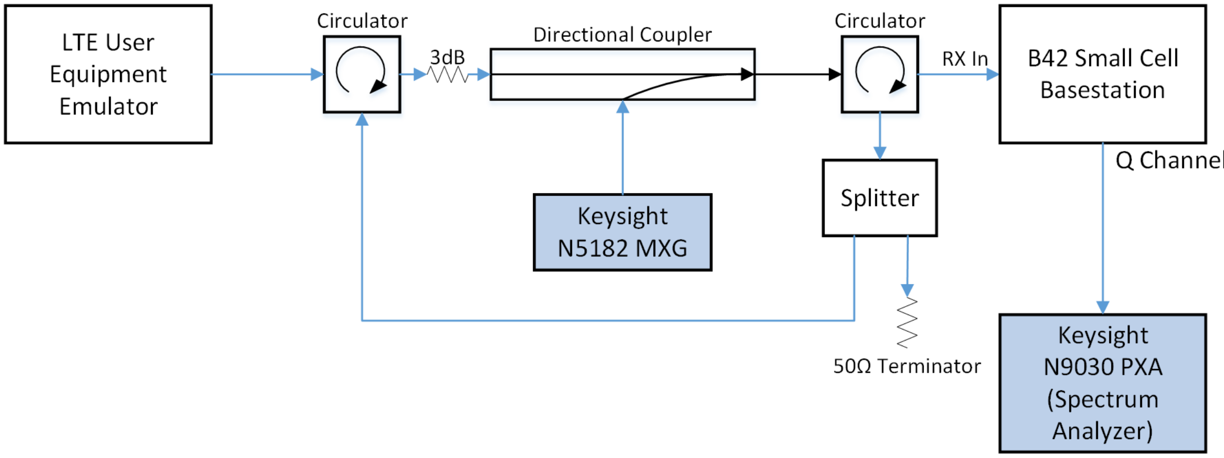

Figure 16. Small-cell base station test setup. Only the Q channel data channel output from the base station was recorded.

Since the small-cell station had to be tested in its entirety and not as a stand-alone LNA, an expanded set of radar waveforms was used to ensure that its responses were thoroughly characterized. Furthermore, the base station provided more detailed data in its output than could be obtained from the stand-alone LNAs, which was another reason to expand the range of input pulse parameters. Tables 6 and 7 contain the technical characteristics of simple pulsed (P0N) and frequency-modulated (FM) chirp (Q3N) radar waveforms that were used for these tests.

Table 6. P0N (CW) Pulsed Radar Interference Waveforms

Duty Cycle (percent)	PRR = 1000 PPS	Number of Pulses
0.1	PW = 1 μsec (P0N-1)	Continuous
1	PW = 10 μsec (P0N-4)	Continuous
3	PW = 30 μsec (P0N-7)	Continuous
10	PW = 100 μsec (P0N-10)	Continuous

Table 7. Q3N (FM Chirp) Pulsed Radar Interference Waveforms

Duty Cycle (percent)	**Chirped Pulse Group 2**		**Number of Pulses**
	PW (μsec)	PRR (pps)	
1	1	10,000 (Q3N-2)	Continuous
10	10	10,000 (Q3N-5)	Continuous
20	20	10,000 (Q3N-8)	Continuous
30	30	10,000 (Q3N-11)	Continuous

5. SMALL-CELL BASE STATION OVERLOAD RESULTS

The small-cell base station was tested by fixing its LNA gain to specific “Gain State” values (ranging from one to seven)[9] via a software interface at a control port. Radar waveforms were injected at Gain States 0, 3 and 7. Gain State 0 was the most sensitive and Gain State 7 was the least sensitive. Although the small-cell gain was fixed in these states by the test engineer while radar waveforms were injected, the small-cell base station would dynamically change its gain state to prevent overload during actual operations. Figures 17–19 show the gain curves for each state that was tested. Gain compression occurs where the traces flatten.

The small-cell base station has in-phase (I) and quadrature-phase (Q) channel data outputs that are equivalent. The small-cell Gain State 0 gain compression curves for the Q channel data are shown in Figure 17.

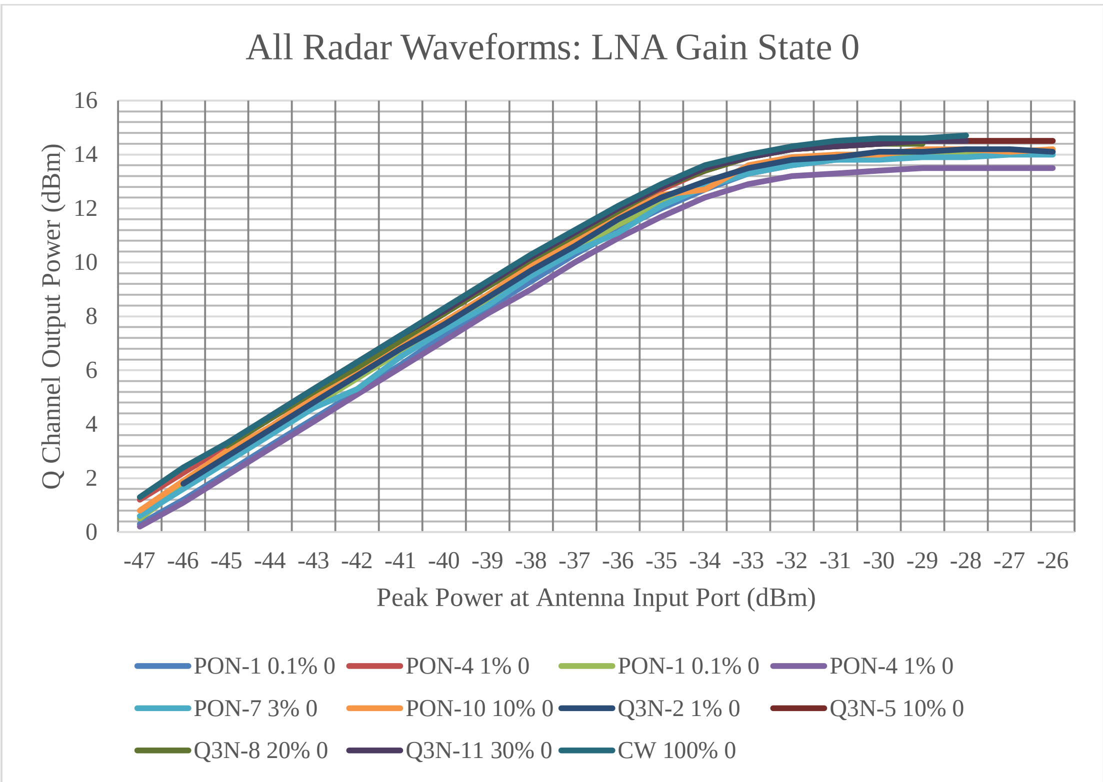

Figure 17. Small-cell Gain State 0 gain compression curves.

[9] Gain state is the ability of the LTE base station receiver to change its sensitivity to protect itself from overload conditions due to high-power signals. For the tests, it was manually fixed to some value. In an operational system the gain state level may be changed automatically. Since this was a prototype system, those features are assumed to still be under development. It is not known how fast a base station receivers will be able to switch their gain states in an auto-ranging mode.

Figure 17 shows that the 1 dB compression (overload) point occurs at approximately -33 dBm input power, with slight variation depending on the duty cycle of the radar signal. All curves flatten out at approximately -31 dBm input power.

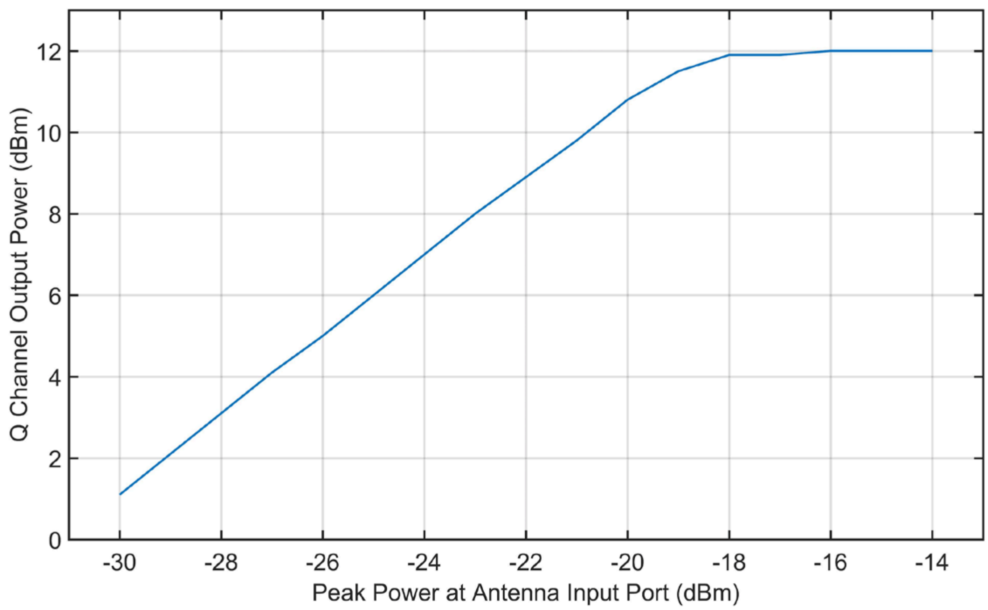

Figure 18. Small-cell Gain State 3 gain compression curve. 1 dB compression input power level is at -18.5 dBm.

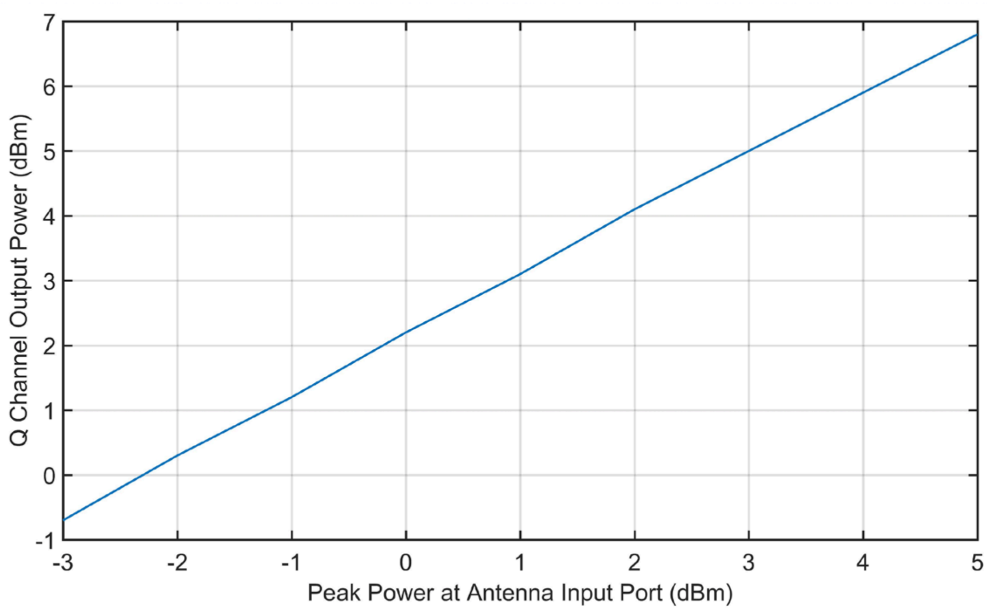

Figure 19. Small-cell Gain State 7 gain compression curve. Performance is linear up to at least +5 dBm input power level.

Gain State 3 was only tested against waveform P0N-1; in this case, the signal generator had sufficient output power to drive the small-cell base station into gain compression. Figure 18 shows linear operation up to an input signal power of -18.5 dBm. Gain State 7 was only tested against one waveform, P0N-1, because the VSG used to simulate the radar signals lacked sufficient output power to drive the small-cell base station into gain compression. Figure 19 shows linear operation up to an input signal power of at least +5 dBm.

6. ANALYSIS: PREDICTED OVERLOAD DISTANCES FROM RADARS

6.1 Predicted Received Power Levels of Radars 1 and 3 as a Function of Distance

The received power levels from radars operated in and adjacent to the 3550–3650 MHz band are computed in this section. The Irregular Terrain Model (ITM) was used to compute the received power levels for different shipborne radar operational scenarios. The ITM parameters used for the analyses are shown below in Table 8.

Table 8. Parameters Used for ITM Area Mode Propagation Loss Calculation

ITM Parameter	Value
Surface Refractivity	301 N-units
Conductivity of Ground	0.005 S/M
Dielectric Constant of Ground	15
Delta h (Terrain Roughness Factor)	0 meters
Polarization	Vertical
Mode of Variability	Broadcast
Percent Confidence	50 %
Percent Time	50 %
Percent Location	50 %
Frequency	3550 MHz
Ship Location Relative to Coast	1, 5, and 10 km
Radar Mainbeam EIRP	Radar 1: 122 dBm Radar 3: 138 and 140 dBm
Radar Sidelobe EIRP	Radar 1: 102 dBm Radar 3: 118 and 120 dBm
Radar Transmitter System/Insertion Losses	2 dB
Radar Transmitter Antenna Height	50 meters
CBSD Receiver Antenna Height	6 meters
CBSD Receive Mainbeam Antenna Gain	6 dBi
ESC Receive Mainbeam Antenna Gain	0 dBi
ESC Receive Antenna Height	10 meters
CBSD/ESC Receiver System/Insertion Losses	2 dB
Site Criteria Radar Transmitter	Random
Site Criteria CBSD/ESC Receiver	Careful
Radio Climate	Maritime Temperate

The equation below was used to calculate the received power of the radar at the LNA input of an ESC and small-cell base station receiver.[10]

$$P_R = EIRP + G_R - L_T - L_R - L_P - L_C - L_B$$

where:

P_R = received radar power level at input of the CBSD/ESC receiver LNA (dBm)
$EIRP$ = radar mainbeam/sidelobe effective isotropically radiated power (dBm)
G_R = CBSD/ESC receive mainbeam antenna gain (dBi)
L_T = radar transmitter insertion/system losses (dB)
L_R = CBSD/ESC receiver insertion/system losses (dB
L_P = propagation loss (dB)
L_B = building attenuation loss (dB)
L_C = clutter loss (dB)

In the analysis for CBSD receivers a nominal value of 15 dB was used to represent building attenuation loss and 5 dB for clutter loss.[11] The analysis assumes that ESC receivers are located to avoid the effects of building attenuation and clutter losses, so those terms are given a value of 0 dB when using the equation. The results of the radar received power calculations for mainbeam antenna coupling are shown in Tables 9 and 10 and for sidelobe antenna coupling in Tables 11 and 12. If an entry is red, then the compression value is exceeded. Appendix A contains received radar power versus distance curves for the mainbeam and sidelobe coupling for Radar 1 and Radar 3. These curves were used to match the LNA and small-cell compression values for each radar; they generate the values provided in Tables 9–13.

Table 9. ESC Monitor Receiver Gain Compression Analysis Mainbeam Antenna Coupling

Ship Location Relative to Coast (km)	**EIRP Mainbeam (dBm)**	**G_R (dBi)**	**L_T (dB)**	**L_R (dB)**	**L_P (dB)**	**P_R (dBm)**	**Measured 1 dB Gain Compression Point (dBm)**	**Amount 1 dB Gain Compression Point is Exceeded (dB)[b]**
Radar 1 3550–3650 MHz								
1	122	0	2	2	103.5	14.5	-4	**19.5**
5	122	0	2	2	117.4	0.6	-4	**5.6**
10	122	0	2	2	123.4	-5.4	-4	-0.4
1	122	0	2	2	103.5	14.5	-13	**27.5**
5	122	0	2	2	117.4	0.6	-13	**13.6**
10	122	0	2	2	123.4	-5.4	-13	**7.6**

[10] The equation has no frequency dependent rejection (*FDR*) term. The LNA frequency response ranges were wider than the emissions of any of the radars in the band. *FDR* would be zero decibels for this condition.
[11] In the 3.5 GHz exclusion zone analysis [2] building attenuation losses ranged between 10 dB and 20 dB. The clutter loss varied depending on the region (urban, suburban, rural).

Ship Location Relative to Coast (km)	EIRP Mainbeam (dBm)	G_R (dBi)	L_T (dB)	L_R (dB)	L_P (dB)	P_R (dBm)	Measured 1 dB Gain Compression Point (dBm)	Amount 1 dB Gain Compression Point is Exceeded (dB)[b]
Radar 3 3100–3500 MHz								
1	138	0	2	2	103.5	30.5	-4	**35.5**
5	138	0	2	2	117.4	16.6	-4	**21.6**
10	138	0	2	2	123.4	10.6	-4	**15.6**
1	138	0	2	2	103.5	30.5	-13	**43.5**
5	138	0	2	2	117.4	16.6	-13	**29.6**
10	138	0	2	2	123.4	10.6	-13	**23.6**
Radar 3 3100–3500 MHz[a]								
46	140	0	2	2	157	-21	-4	-16
46	140	0	2	2	157	-21	-13	-8
Note a: These entries are for the radar's high-power mode. The frequency authorization for this operating mode is limited to distances beyond 25 nmi (46 km) from the coast. High-power mode is 2 dB more than low power mode. **Note b:** Positive values shown in red exceed the measured 1 dB gain compression point.								

Table 10. CBSD Receiver Gain Compression Analysis Mainbeam Antenna Coupling

Ship Location Relative to Coast (km)	EIRP Main-beam (dBm)	G_R (dBi)	L_T (dB)	L_R (dB)	L_P (dB)	L_C (dB)	L_B (dB)	P_R (dBm)	Measured 1 dB Gain Compression Point (dBm)	Amount 1 dB Gain Compression Point is Exceeded (dB)[b]
Radar 1 3550–3650 MHz										
1	122	6	2	2	103.5	15	5	0.5	-33	**33.5**
5	122	6	2	2	117.4	15	5	-13.4	-33	**19.6**
10	122	6	2	2	123.4	15	5	-19.4	-33	**13.6**
1	122	6	2	2	103.5	15	5	0.5	-18	**18.5**
5	122	6	2	2	117.4	15	5	-13.4	-18	**4.6**
10	122	6	2	2	123.4	15	5	-19.4	-18	-1.4
1	122	6	2	2	103.5	15	5	0.5	5	-4.5
5	122	6	2	2	117.4	15	5	-13.4	5	-18.4
10	122	6	2	2	123.4	15	5	-19.4	5	-24.4
Radar 3 3100–3500 MHz										
1	138	6	2	2	103.5	15	5	16.5	-33	**49.5**
5	138	6	2	2	117.4	15	5	2.6	-33	**35.6**
10	138	6	2	2	123.4	15	5	-3.4	-33	**29.6**
1	138	6	2	2	103.5	15	5	16.5	-18	**34**
5	138	6	2	2	117.4	15	5	2.6	-18	**20.6**
10	138	6	2	2	123.4	15	5	-3.4	-18	**14.6**

Ship Location Relative to Coast (km)	EIRP Main-beam (dBm)	G_R (dBi)	L_T (dB)	L_R (dB)	L_P (dB)	L_C (dB)	L_B (dB)	P_R (dBm)	Measured 1 dB Gain Compression Point (dBm)	Amount 1 dB Gain Compression Point is Exceeded (dB)[b]
1	138	6	2	2	103.5	15	5	16.5	5	**11.5**
5	138	6	2	2	117.4	15	5	2.6	5	-2.4
10	138	6	2	2	123.4	15	5	-3.4	5	-8.4
Radar 3 3100–3500 MHz[a]										
46	140	6	2	2	157	15	5	-40	-33	-2
46	140	6	2	2	157	15	5	-40	-18	-17
46	140	6	2	2	157	15	5	-40	5	-30

Note a: The frequency authorization for this operating mode is limited to outside of 25 nautical miles (46 kilometers) from the coast.
Note b: Positive values shown in red exceed the measured 1 dB gain compression point.

Table 11. ESC Monitor Receiver Gain Compression Analysis Sidelobe Antenna Coupling

Ship Location Relative to Coast (km)	EIRP Sidelobe (dBm)	G_R (dBi)	L_T (dB)	L_R (dB)	L_P (dB)	P_R (dBm)	Measured 1 dB Gain Compression Point (dBm)	Amount 1 dB Gain Compression Point is Exceeded (dB)[b]
Radar 1 3550-3650 MHz								
1	102	0	2	2	103.5	-5.5	-5	-0.5
5	102	0	2	2	117.4	-19.4	-5	-14.4
10	102	0	2	2	123.4	-25.4	-5	-20.4
1	102	0	2	2	103.5	-5.5	-13	**7.5**
5	102	0	2	2	117.4	-19.4	-13	-6.4
10	102	0	2	2	123.4	-25.4	-13	-12.4
Radar 3 3100-3500 MHz								
1	118	0	2	2	103.5	10.5	-5	**5.5**
5	118	0	2	2	117.4	-3.4	-5	**1.6**
10	118	0	2	2	123.4	-9.4	-5	-4.4
1	118	0	2	2	103.5	10.5	-13	**23.5**
5	118	0	2	2	117.4	-3.4	-13	**10.4**
10	118	0	2	2	123.4	-9.4	-13	**3.6**
Radar 3 3100-3500 MHz[a]								
46	120	0	2	2	157	-41	-5	**-36**
46	120	0	2	2	157	-41	-13	**-28**

Note a: The frequency authorization for this operating mode is limited to outside of 25 nautical miles (46 kilometers) from the coast.
Note b: Positive values shown in red exceed the measured 1 dB gain compression point.

Table 12. CBSD Receiver Gain Compression Analysis Sidelobe Antenna Coupling

Ship Location Relative to Coast (km)	EIRP Side-lobe (dBm)	G_R (dBi)	L_T (dB)	L_R (dB)	L_P (dB)	L_C (dB)	L_B (dB)	P_R (dBm)	Measured 1 dB Gain Compression Point (dBm)	Amount 1 dB Gain Compression Point is Exceeded (dB)[b]
Radar 1 3550-3650 MHz										
1	102	6	2	2	103.5	15	5	-19.5	-33	**13.5**
5	102	6	2	2	117.4	15	5	-33.4	-33	-0.4
10	102	6	2	2	123.4	15	5	-39.4	-33	-6.4
1	102	6	2	2	103.5	15	5	-19.5	-18	-1.5
5	102	6	2	2	117.4	15	5	-33.4	-18	-15.4
10	102	6	2	2	123.4	15	5	-39.4	-18	-21.4
1	102	6	2	2	103.5	15	5	-19.5	5	-14.5
5	102	6	2	2	117.4	15	5	-33.4	5	-28.4
10	102	6	2	2	123.4	15	5	-39.4	5	-34.4
Radar 3 3100-3500 MHz										
1	118	6	2	2	103.5	15	5	-3.5	-33	**29.5**
5	118	6	2	2	117.4	15	5	-17.4	-33	**15.6**
10	118	6	2	2	123.4	15	5	-23.4	-33	**9.6**
1	118	6	2	2	103.5	15	5	-3.5	-18	**14.5**
5	118	6	2	2	117.4	15	5	-17.4	-18	**0.6**
10	118	6	2	2	123.4	15	5	-23.4	-18	-5.4
1	118	6	2	2	103.5	15	5	-3.5	5	-8.5
5	118	6	2	2	117.4	15	5	-17.4	5	-22.4
10	118	6	2	2	123.4	15	5	-23.4	5	-28.4
Radar 3 3100-3500 MHz[a]										
46	120	6	2	2	157	15	5	-60	-33	-22
46	120	6	2	2	157	15	5	-60	-18	-37
46	120	6	2	2	157	15	5	-60	5	-60

Note a: The frequency authorization for this operating mode is limited to outside of 25 nautical miles (46 kilometers) from the coast.
Note b: Positive values shown in red exceed the measured 1 dB gain compression point.

Table 13. Computed 1 dB LNA Compression vs. Separation Distances for Radars 1 and 3, from Prediction Curves Shown in Appendix A, Figures A-1 through A-12

LNA No.	Radar No.	CBSD/ESC coupling	CBSD/ESC antenna coupling mode to radar signal	Computed separation distance (km) for 1 dB compression	Comments
1	1	CBSD	mainbeam	1.5	
1	1	CBSD	sidelobe	< 1	
1	1	ESC	mainbeam	8.1	
1	1	ESC	sidelobe	< 1	
1	3	CBSD	mainbeam	9	
1	3	CBSD	sidelobe	< 1	
1	3	ESC	mainbeam	34.5	Largest distance for any radar for LNA 1
1	3	ESC	sidelobe	5	
2	1	CBSD	mainbeam	4.8	Largest CBSD distance for Radar 1
2	1	CBSD	sidelobe	< 1	
2	1	ESC	mainbeam	24.4	Largest ESC distance for Radar 1
2	1	ESC	sidelobe	2.5	
2	3	CBSD	mainbeam	28.7	Largest CBSD distance for Radar 3
2	3	CBSD	sidelobe	3.8	
2	3	ESC	mainbeam	40	Largest ESC distance for Radar 3
2	3	ESC	sidelobe	15	

6.2 Stand-Alone LNA Summary of Results

As previously discussed, when the input signal to the LNA is large, the LNA overloads, hence clipping or distorting the output signal. When the strength of the input signal is further increased, the output signal power becomes constant. At this point the LNA output is said to be in an overload condition. When an LNA is compressed the data throughput through the receiver may be reduced. The received power levels from the radars that operate in and adjacent to the 3550–3650 MHz band are shown in Tables 9 and 10 for different shipborne radar operational scenarios. As shown in Tables 9 and 10, depending on the operational scenario, the received power from the shipborne radar can significantly exceed the measured LNA 1 dB gain compression point.

Because ESC receivers have higher antenna gain the CBSD receivers in our analysis, the largest separation distances in Table 13 are for mainbeam coupling to ESC receivers. In summary, the largest separation distances for each of the radars and for each of the LNAs is for ESC mainbeam coupling. This is due to the ESC antenna gain being higher than the CBSD antenna gain. These distances are:

- Radar 1: 8.1 km for LNA 1
- Radar 1: 24.4 km for LNA 2
- Radar 3: 34.5 km for LNA 1
- Radar 3: 40 km for LNA 2

Although the analyses predict the LNA and small-cell receiver overload to occur at various distances that may disrupt the LTE and ESC operations, there are three time varying parameters that may help mitigate the effects: radar waveform duty cycle, the amount of time the CBSD or ESC receiver is in any radar antenna mainbeam, and the recovery speed of each LNA. Each one is discussed in more detail in the following paragraphs. Any one of these will help mitigate the compression effects and when all three are combined, they will help even more.

6.3 Small-Cell Base Station Summary of Results

Referring to the same gain state compression curves and the propagation prediction curves of Appendix A, because ESC receivers have higher antenna gain the CBSD receivers in our analysis, the largest separation distances in Table 13 are for mainbeam coupling to ESC receivers. In summary, from the gain state compression curves and the propagation prediction curves of Appendix A, the largest separation distances for each of the radars is for ESC mainbeam coupling. This is due to the ESC antenna gain being higher than the CBSD antenna gain. These distances are:

- Radar 1: Less than 2 km for Gain State 7
- Radar 1: 30 km for Gain State 0
- Radar 3: 19 km for Gain State 7
- Radar 3: 55 km for Gain State 0

The results from the small-cell base station testing cannot be solely attributed to the LNA performance since the LNA was tested within an integrated system.

6.4 Consideration of Radar Duty Cycle on Receiver Compression Effects

The effect of LNA gain compression also has a time component that is related to the duty cycle and pulse width of the interfering radar signal. The radar duty cycle, expressed in terms of PW and PRR, determines the fraction of time that a system is in an “active” state, the amount of time the radar signal is transmitted. The duty cycles considered in the LNA gain compression measurements were 0.1 percent and 10 percent, corresponding to Radar 1 and Radar 3. In [8] and [9] the LTE receivers did not experience a major loss of data throughput when they were tested against the waveforms of Radar 1 and Radar 3, as long the power was below overload levels. If a few resource blocks are lost in an interference event, the forward error correction (FEC) and coding of the LTE system should help mitigate the effects.

6.5 Consideration of Radar Antenna Scanning on Receiver Compression Effects

The amount of time a CBSD or ESC receiver experiences mainbeam coupling is determined by the radar's antenna beamwidth and antenna scan rate or dwell time. The radars operating in and adjacent to the 3550–3650 MHz band have beamwidths of less than 2 degrees with dwell times of less than 0.1 seconds, further reducing the time the mainbeam is directed at CBSD and ESC receivers (with typically 20 pulses/beam). The combination of the radar's duty cycle and the time the CBSD or ESC receiver is in its mainbeam can be compared to the measured LNA recovery times. Since the measured LNA recovery times are instantaneous, the effects of gain compression should be minimal even in cases where the radar received power level exceeds the measured 1 dB gain compression point. Gain-compression exceedance events are only expected to happen for brief intervals, on the order of 20 ms or less, due to small radar beamwidths. Intervals between such exceedance events are expected to equal or exceed 4 seconds due to radar beam scanning behaviors. This effect was observed in [9].

6.6 Consideration of LNA Recovery Time on Receiver Compression Effects

The LNAs tested in the report were able to recover from the compression effects faster than could be measured by the test equipment. In past studies [11] the LNAs were not able to recover for many milliseconds even after the pulse had ceased. The extension of the interference effects, even after the interference is gone, is called ringing in RF or electrical circuits. The ringing in the LNA studied in [11] caused loss of data throughput after the pulse had ceased. However, modern LNAs are not expected to suffer such an extension of the duration of any interference compression event.

7. SUMMARY AND CONCLUSIONS

7.1 Stand-Alone LNAs

Two LNAs from two different manufacturers were tested against two types of pulsed radar emissions, with a 0.1 percent and 10 percent duty cycles, respectively, as well as a CW signal. The results are summarized in the following subsections.

7.1.1 LNA 1

- The 1 dB gain compression input power level is -4 dBm. Table 13 shows distances at which this level could be exceeded. The largest distances are 8.1 km and 34.5 km for Radar 1 and 3, respectively, with ESC mainbeam coupling.

- Gain compression performance was the same for 0.1 percent and 10 percent duty cycle radar pulses.

- No increase in LNA noise figure was observed for either radar pulse type.

- Increase in LNA noise figure was observed for a CW input signal. This implies that the noise figure increases due to the radar pulses as well. However, the recovery times from pulsed-signal overload seem to fall within the durations of the radar pulses themselves.

- For the CW signal case, a +5 dBm input (well inside the compression regime) resulted in a decrease of noise figure. It is unknown why this occurred but LNA behavior when performance is in the non-linear region is erratic.

- As shown in Figure 8 and described in Section 3.1.2, the maximum increase in noise figure is approximately 6 dB. This can also be thought of as a reduction in LNA gain when equated to an equivalent amount of performance degradation.

7.1.2 Custom MMIC LNA 2

- The 1 dB compression input power level of -13 dBm makes LNA 2 more susceptible to high-power signals than LNA 1. Table 13 shows distances at which this level could be exceeded. The largest distances are 24.4 km and 40 km for Radars 1 and 3, respectively, with ESC mainbeam coupling.

- Compression performance was the same for 0.1 percent and 10 percent duty cycle radar pulses.

- No increase in LNA noise figure was observed for either radar pulse type.

- Increase in LNA noise figure was observed for a CW input signal. This implies that the noise figure does increase after the transmission of the radar pulses, however, the recovery time is shorter than the time it takes for the radar pulse to decay.

- As shown in Figure 15 and described in Section 3.2.2, the maximum increase in noise figure is approximately 12 dB. This can also be thought of as a reduction in LNA gain when equated to an equivalent amount of performance degradation.

7.2 Small-Cell Base Station Results

- For the small-cell base station, 1 dB gain compression input power level is -33 dBm in Gain State 0 and exceeds +5 dBm in Gain State 7. For the highest receiver coupling factor (ESC mainbeam), the largest separation distances at which these levels are predicted to be exceeded for Radars 1 and 3 range from less than 2 km to 30 km for the two gain states for Radar 1 and are 19 km and 55 km for the two gain states for Radar 3.

7.3 Possible Further Work

NTIA believes that additional work can be done on this topic to ensure greater success as the 3.5 GHz CBSD systems and their infrastructure are developed and deployed:

- Perform follow-up testing of stand-alone LNAs to determine at what power level and duration physical damage (burnout) occurs. This could be done by using the shore based systems of Shipboard Radars 1 and 3 via joint testing with the Navy.

- Use a terrain-dependent propagation model and other factors such as clutter loss to generate contour maps for specific areas such as the San Diego or Virginia Beach where CBSD and ESC monitor receivers might experience overload conditions.

- Perform additional overload measurements on other makes and models of 3.5 GHz LNAs when such LNAs become available.

7.4 Possible Operational Impact of Overload on CBSD and ESC Receivers

The data show that the LNAs can be overloaded by radar pulses and be in that condition across their entire operational frequency range when it happens. Designers of the CBSDs and ESC monitor receivers should note that even if an SAS commands CBSD devices to vacate the 3.5 GHz band, if these devices are designed to be multi-band operational (i.e., they also operate at 2.4 GHz and 5 GHz for Wi-Fi and AWS-1, -2, -3) and are using a single LNA to cover their entire operational frequency ranges they may experience overload in all of their bands if the common-band LNAs are overloaded at 3.5 GHz. (This effect is further described in [11].) The only way to mitigate this effect would be to use multiple, band-limited (e.g., band filtered) LNAs in the CBSD and ESC monitor receivers.

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APPENDIX A POWER VERSUS DISTANCE CURVES FOR RADARS 1 AND 3

The figures in this Appendix show received power versus distance curves for Radar 1 and Radar 3 to ESC and CBSD receivers using Table 8 propagation model parameters.

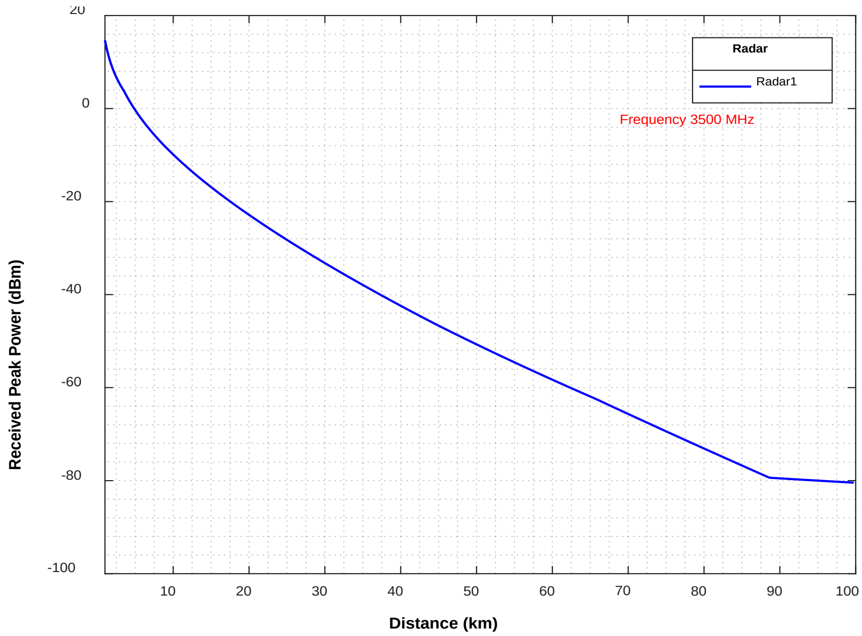

Figure A-1. Radar 1 power versus distance for ESC receiver, mainbeam coupling.

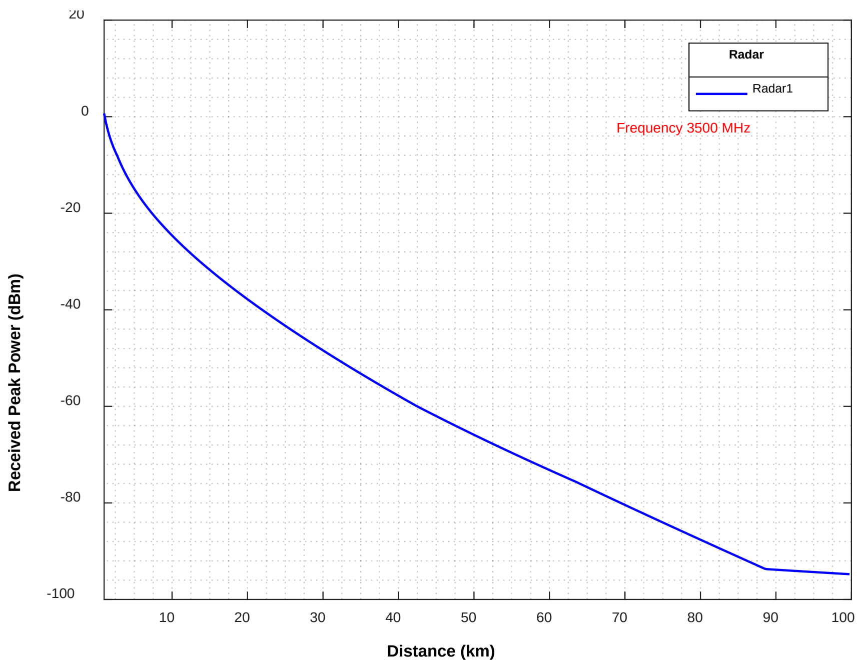

Figure A-2. Radar 1 power versus distance for CBSD receiver, mainbeam coupling.

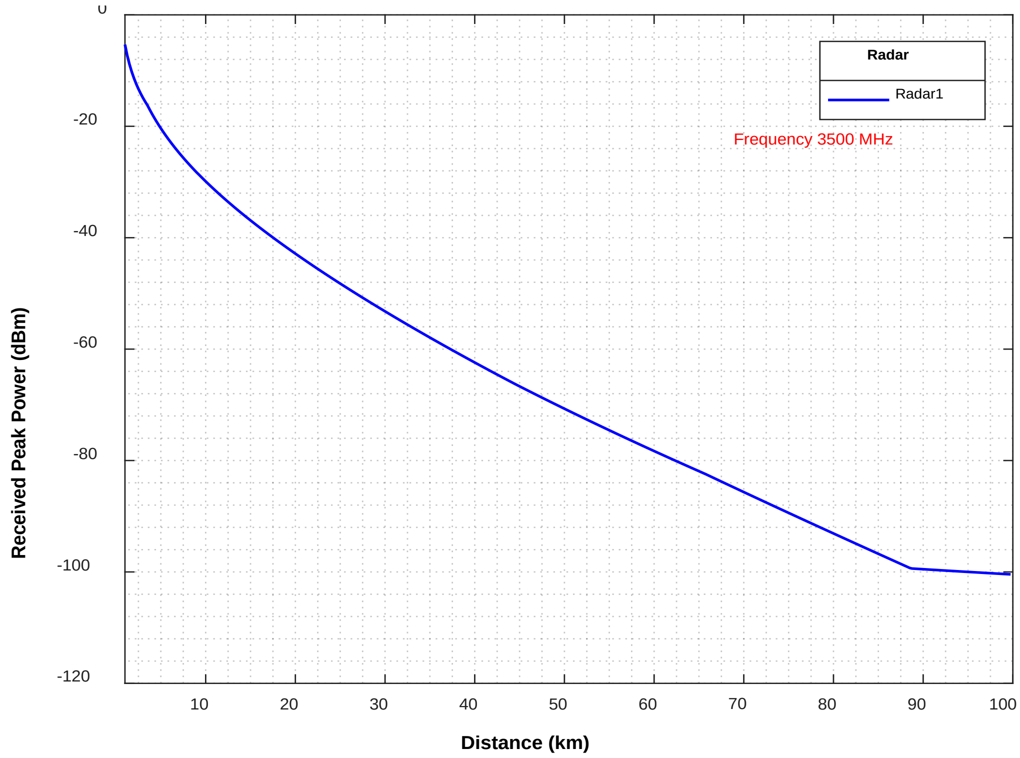

Figure A-3. Radar 1 power versus distance for ESC receiver, sidelobe coupling.

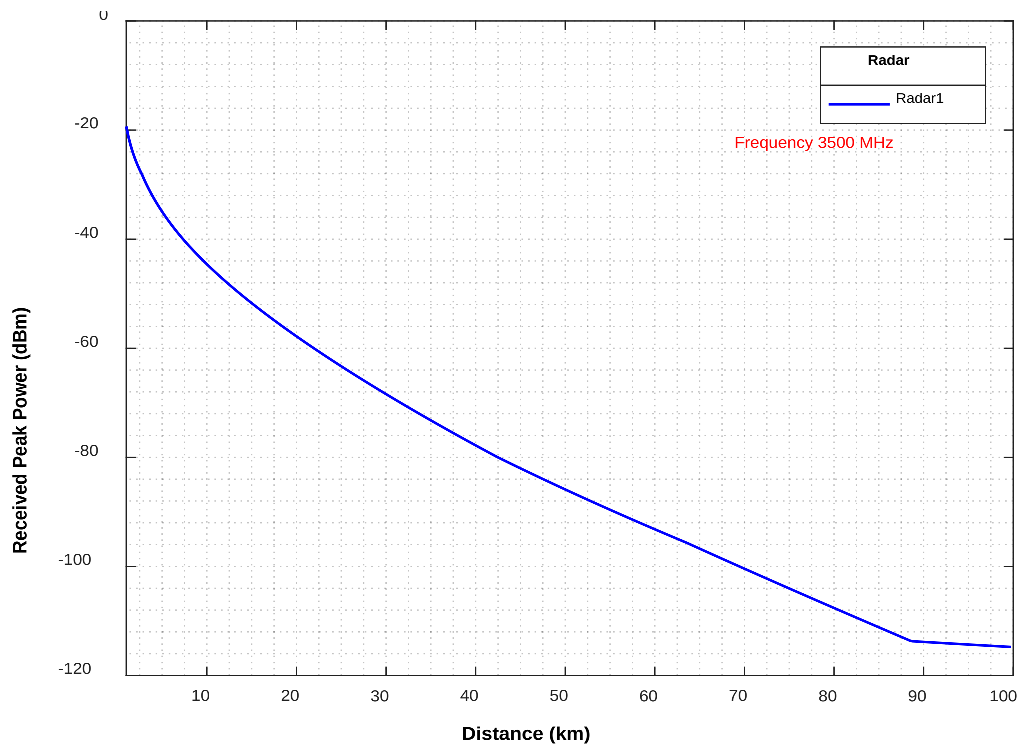

Figure A-4. Radar 1 power versus distance for CBSD receiver, sidelobe coupling.

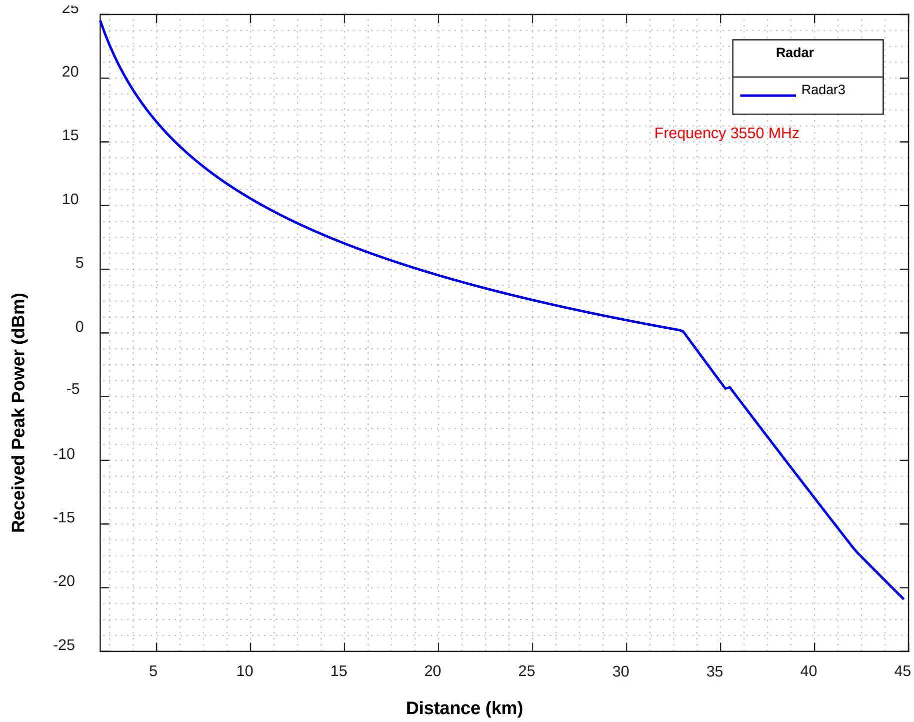

Figure A-5. Radar 3 power (lower EIRP) versus distance for ESC receiver, mainbeam coupling.

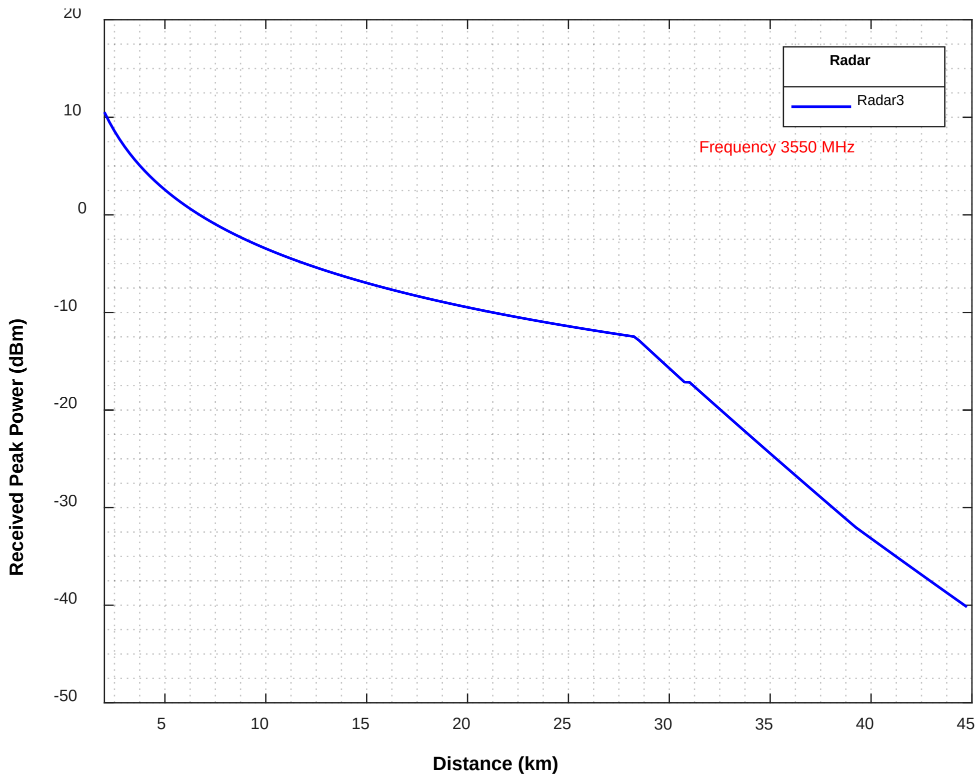

Figure A-6. Radar 3 power (lower EIRP) versus distance for CBSD receiver, mainbeam coupling.

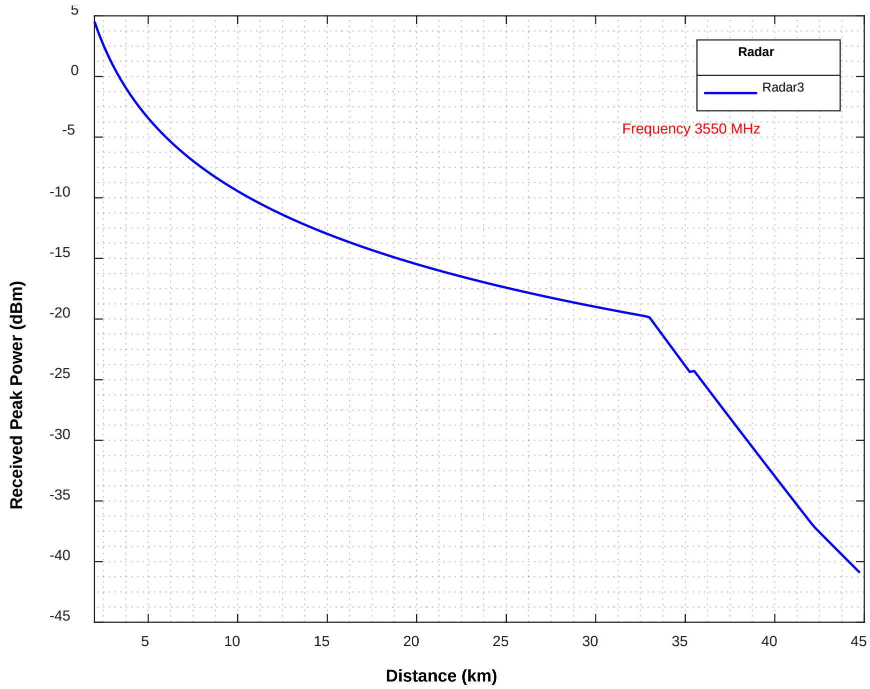

Figure A-7. Radar 3 power (lower EIRP) versus distance for ESC receiver, sidelobe coupling.

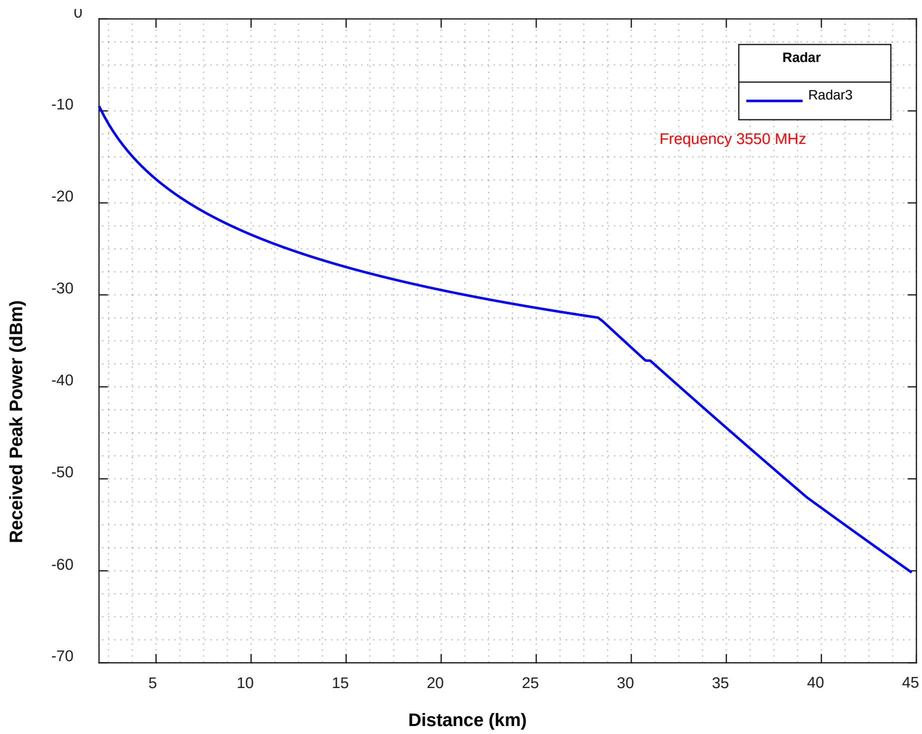

Figure A-8. Radar 3 power (lower EIRP) versus distance for CBSD receiver, sidelobe coupling.

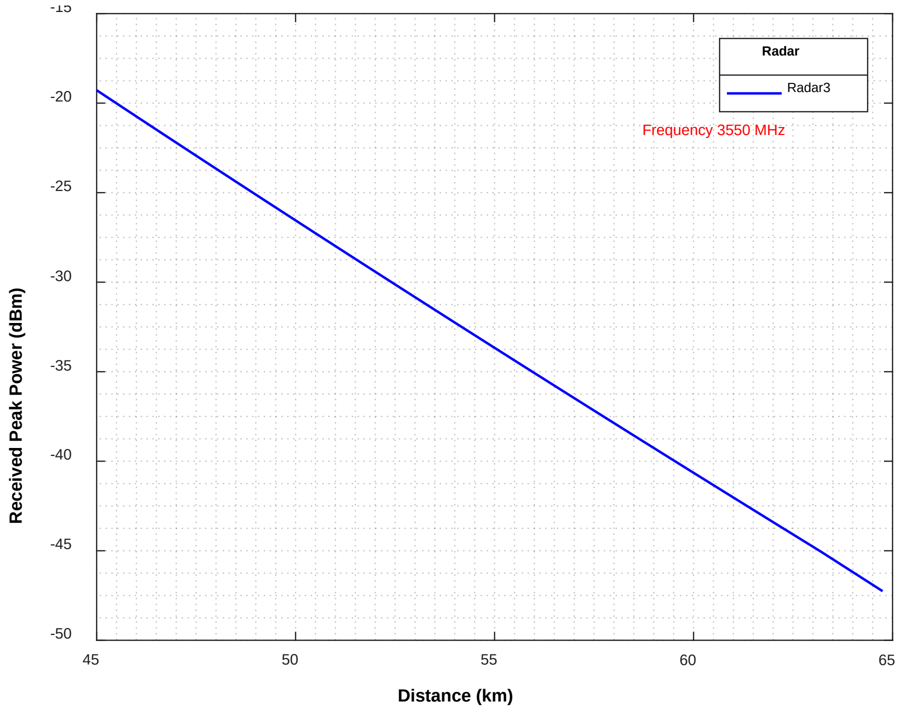

Figure A-9. Radar 3 power (higher EIRP) versus distance for ESC receiver, mainbeam coupling.

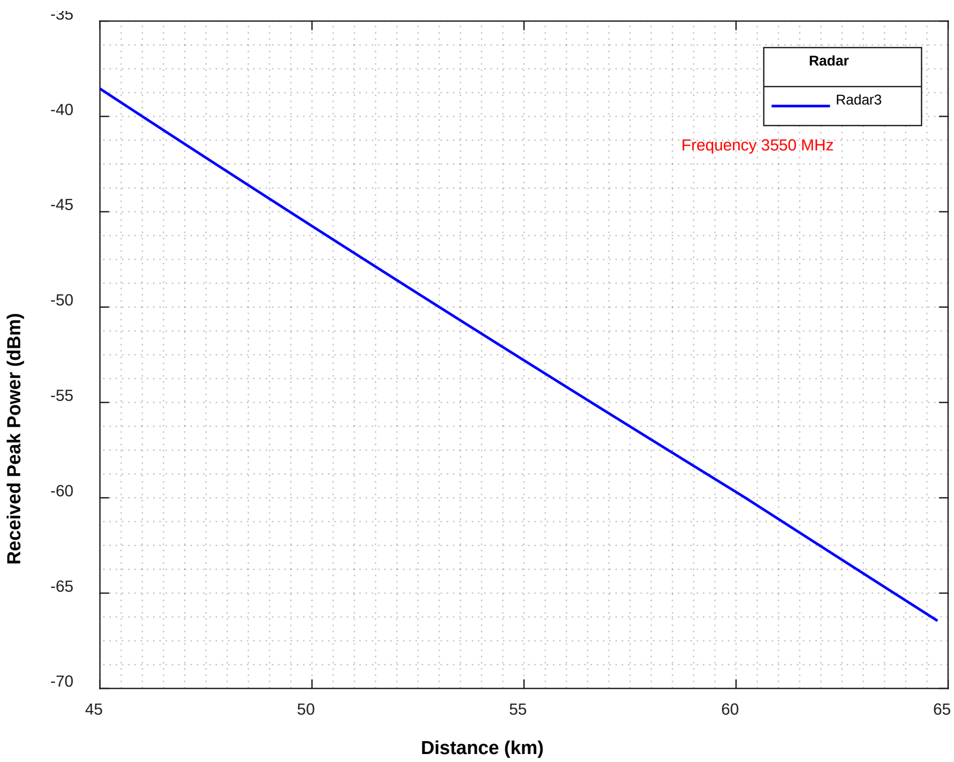

Figure A-10. Radar 3 power (higher EIRP) versus distance for CBSD receiver, mainbeam coupling.

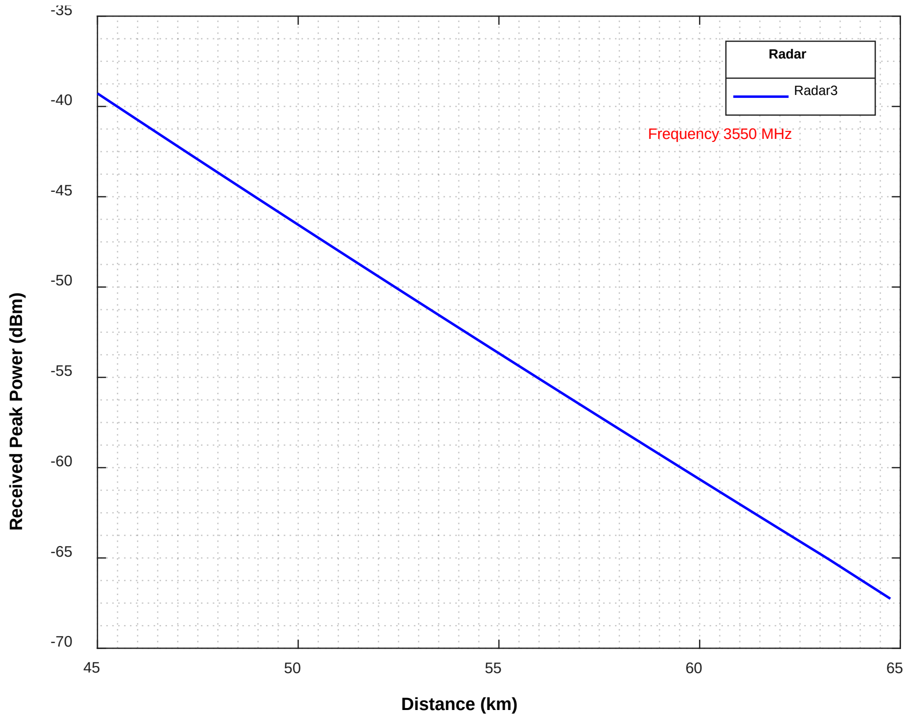

Figure A-11. Radar 3 power (higher EIRP) versus distance for ESC receiver, sidelobe coupling.

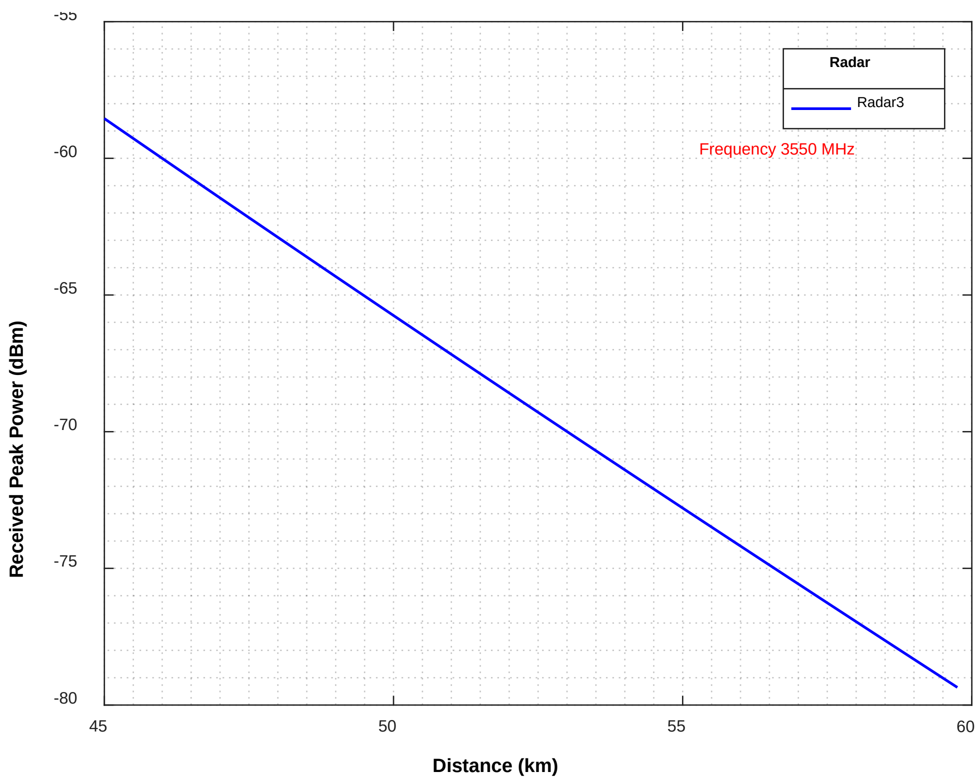

Figure A-12. Radar 3 power (higher EIRP) versus distance for CBSD receiver, sidelobe coupling.

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14. SUPPLEMENTARY NOTES

15. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

Future spectrum sharing between high-power radars and Citizens Broadband Radio Service Device CBSD in the 3550–3650 MHz (3.5 GHz) band could expose radio frequency (RF) receiver front-end low noise amplifiers (LNAs) to high peak power radar pulse signals in the band under certain situations. In this band, radar effective isotropic radiated power (EIRP) peak levels can exceed 1 gigawatt. Previous experience with LNAs exposed to high-power radar pulses in spectrum near 3.7 GHz has shown that non-linear effects can be induced in the LNAs, leading to service interruptions. To assess the level of risk for similar LNA overload at 3.5 GHz, NTIA performed gain overload (e.g., compression) tests on two representative 3.5 GHz LNAs and a small-cell base station receiver. The tests determined the pulsed radar signal power levels that caused overload (1 dB gain compression) for these devices. Approximate distance separations that would be necessary to preclude potential overload interference effects are presented, based on the measurement results and propagation modeling.

16. Key Words (Alphabetical order, separated by semicolons)

3.5 GHz CBSD Band; LTE; low-noise amplifier (LNA); LNA non-linear effects; LNA overload; 47 C.F.R. Part 96; effective isotropic radiated power (EIRP); General Authorized Access (GAA); Priority Access Licensed (PAL); radar; spectrum sharing

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