NTIA Technical Memorandum 23-566

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U.S. DEPARTMENT OF COMMERCE

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National Telecommunications and Information Administration

April 2023
Updated May 2023

ERRATA

Table 4 was updated after initial publication to correct an error.

DISCLAIMER

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FIGURES

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ABBREVIATIONS/ACRONYMS

B_c	chirp bandwidth
CPI	coherent processing interval
CW	continuous wave
FM	frequency-modulated
GHz	gigahertz
Hz	hertz
I/Q	in-phase and quadrature
ITU-R	International Telecommunication Union Radiocommunication Sector
kHz	kilohertz
MHz	megahertz
µs	microseconds
ms	milliseconds
MXG	Keysight N5182B Signal Generator
ns	nanoseconds
NTIA	National Telecommunications and Information Administration
OOB	out-of-band
P0N	unmodulated continuous wave pulse
PRI	pulse repetition interval
PRR	pulse repetition rate
PSD	power spectral density
PW	pulse width
PXA	Keysight N9030B Signal Analyzer
Q3N	swept frequency-modulated (chirped) pulse
RF	radio frequency
RBW	resolution bandwidth
RSEC	radar spectrum engineering criteria
RSMS	radio spectrum measurement science
T_r	pulse rise time
T_f	pulse fall time
V	volt

EXECUTIVE SUMMARY

The Radio Spectrum Engineering Criteria (RSEC) in Chapter 5.5 of the National Telecommunications and Information Administration (NTIA) Manual of Regulations and Procedures for Federal Radio Frequency Management (Redbook) is a key part of ensuring that federal radar systems use spectrum efficiently and effectively. The RSEC defines emission masks based on radar waveform parameters to place limits on a radar's emission spectra. The RSEC has been used for over 40 years and has been updated over that time as radar technology has evolved and spectrum efficiency has been a goal of administrations.

The RSEC was developed when radar systems were tube-type (magnetron, traveling wave tube, klystron, cross-field amplifier etc.) driven output devices with a limited set of variables in their waveform parameters. The RSEC emission masks were based on the fact that these radars used a static waveform within a coherent processing interval (CPI) as they operated. This means that for the duration of a CPI, the waveform parameters including the modulation, pulse width, chirp bandwidth, rise time, and fall time were held constant. Many of the older systems did have the ability to change these parameters but could only do so on the next set of transmitted pulses, and the number of selectable waveforms was limited. New radar systems can generate compound waveforms within a CPI, wherein the emission spectrum is, for the purpose of this report, a combination of unmodulated pulses (P0N) and frequency modulated pulses (Q3N). The RSEC does not have any rules in place to ensure that these types of waveforms use the spectrum efficiently; therefore, the RSEC needs to be updated to address this situation.

This report is a companion to NTIA Technical Report 05-420 (TR-05-420) which gives guidelines on how to do RSEC emission spectrum measurements for conventional radar systems with single pulses within a CPI. Measurements of compound emission spectra, along with MATLAB® simulations and other works, can be used to derive the correct RSEC mask. This report investigates what the correct spectrum analyzer resolution bandwidth (RBW) should be when measuring a compound waveform's emission spectrum using a traditional spectrum analyzer following the methods described in TR-05-420. There are other methods of measuring radar emission spectra that do not rely on a spectrum analyzer, but this report specifically investigates how to choose the optimum RBW when following the measurement methods in TR-05-420.

A wide variety of compound waveforms were generated in the laboratory. Then spectrum measurements were made over a range of RBWs to ascertain the optimum bandwidth to use during RSEC compliance measurements. These measurements were also simulated to ensure accuracy. The variety of compound waveforms studied was determined in conjunction with the federal agencies in the Interdepartment Radio Advisory Committee (IRAC) Technical Subcommittee (TSC). However, these waveforms do not represent any particular radar. Instead, they comprise a parametric list of waveform parameters developed to assist research. The data used in this study is freely available and publicly accessible at DOI:10.5281/zenodo.7871632.

Based on the results of this study the following conclusions can be drawn:

1) The recommendation in TR-05-420 that the minimum calculated RBW from the component waveforms of a compound radar waveform be used to measure the spectrum is sufficient for performing radar emission measurements for RSEC certification.

2) For the most part, the compound spectrum is the maximum of the component waveform spectra. This appears to always be true through the fundamental frequency but may not be true in the out-of-band (OOB) region.

3) However, if the optimum RBW used to measure a compound radar waveform is less than the pulse repetition rate (PRR) of one of the components, then line spectrum can influence the spectrum and 2) will not be true in the OOB region of the spectrum.

4) The calculated optimum RBW does not always agree with empirically observed one. This is especially true with Q3N waveforms, which makes sense because the RBW equation for P0N (2) is only an approximation.

5) If the calculated optimum RBW for a compound radar waveform does not agree with the empirical one, then this will likely be the case for the component that is determining the optimum RBW.

6) The relative peak power of the component pulses of a compound radar waveform has a significant impact on the measured spectrum of the compound radar waveform.

7) It is important to use the correct RBW when measuring compound radar spectrum because using an RBW setting that is too high may mask the effects of one or more of the component waveforms.

8) The ratio of P0N to Q3N pulses only appears to create a difference in the spectrum if the appropriate RBW is less than the PRR of one of the components.

A potential way to update the RSEC to accommodate modern radars would be to construct the RSEC mask for the compound waveforms from the RSEC masks defined by the individual P0N and Q3N components. This would require accurately measuring the relative peak powers of the component waveforms at their fundamental frequency. With this information, the RSEC masks of the individual components could be offset by these same relative peak power levels and combined to form a single RSEC mask to apply to the compound radar waveform.

Another option is to analyze the component pulses within a compound radar individually. This would not require an update to the RSEC since mask requirements already exist for single-pulse-parameter radar waveforms. This will require new measurement techniques because those defined in TR-05-420 do not allow for analyzing pulses individually. New techniques using in-phase and quadrature (I/Q) data (time-domain) could be developed to analyze component pulses individually. NTIA and ITS are currently investigating methods using I/Q data.

NTIA and ITS will continue to work on this task and will also make emission measurements on real radar systems that use compound waveforms, so that all aspects of the task can be reviewed together. Future work would be to present this material to the ITU-R, with proposed changes to Annex 8 of Recommendation SM 1541-6. This Recommendation was developed by the U.S. and other administrations as an international version of the RSEC and it should be updated to reflect the changes as well for U.S. interests abroad.

EXAMINING THE EFFECTS OF RESOLUTION BANDWIDTH WHEN MEASURING COMPOUND RADAR WAVEFORMS

Geoffrey A. Sanders, Erik R. Hill, Frank H. Sanders,[1] Robert L. Sole,[2] Michael Ghorbanzadeh[3]

This study examines the effects of resolution bandwidth (RBW) when using the measurement methods described in National Telecommunications and Information Administration (NTIA) Technical Report 05-420 to measure the emission spectra of compound radar waveforms. This study is being conducted in support of updating the Radar Spectrum Engineering Criteria (RSEC) described in Chapter 5.5 of the NTIA Manual of Regulations and Procedures for Federal Radio Frequency Management to better accommodate modern compound radars. Many different RBW settings were used to measure the spectra of single-pulse-parameter and multi-pulse-parameter radar waveforms of both P0N and Q3N pulse types. The results of these measurements are presented in this report along with the conclusions derived from the results. The main conclusion is that the NTIA TR-05-420 recommendation to use the minimum calculated RBW for each of the component pulse types of a compound radar waveform when measuring the compound spectrum is accurate.

Keywords: ITU-R; Radar; Redbook; Resolution Bandwidth; RSEC; RSMS

1. INTRODUCTION

The Radio Spectrum Engineering Criteria (RSEC) in Chapter 5.5 of the National Telecommunications and Information Administration (NTIA) Manual of Regulations and Procedures for Federal Radio Frequency Management (Redbook) [1] is a key part of ensuring that federal radar systems use spectrum efficiently and effectively. The RSEC defines emission masks based on the waveform parameters of peak power, modulation type, pulse width (PW), pulse rise time (T_r), pulse fall time (T_f), chirp bandwidth (B_c) and pulse repetition rate (PRR) to place limits on a radar emission spectrum. The RSEC has been used and updated for over 40 years as radar technology has evolved to achieve the Administration's goal of using the spectrum more efficiently. The ITU-R has radar emission limits, like the RSEC, in ITU-R Annex 8 of Recommendation SM1541-6 [2]. Other countries have also used the RSEC as a basis for their own regulations. The U.S. administration has actively participated in ITU-R Working Parties associated with radar emission limits.

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The RSEC was developed when radar systems were tube-type (magnetron, traveling wave tube, klystron, cross-field amplifier, etc.) driven output devices with a limited set of variables in their waveform parameters. The RSEC emission masks were based on the fact that these radars used a static waveform within a coherent processing interval (CPI) as it operated. This means that for the duration of a CPI, the waveform parameters including the modulation, pulse width, chirp bandwidth, rise time, and fall time were not varied and kept to constant values. Many older radar systems did have the ability to change these parameters, but only on the next set of transmitted pulses and the number of selectable waveforms was limited.

However, modern radar systems are much more complex since they are essentially programmable vector signal generators connected to banks of amplifiers; thus, they can be (and are) programmed to transmit and receive waveforms with varying pulse characteristics within a single CPI. For example, they can change the PW and modulation on a pulse-to-pulse basis. The RSEC masks in Criteria A through D do not address this situation and Chapter 5.5 only states that such systems will be analyzed on a case-by-case basis. Because such radars are becoming more common, the RSEC should be updated to address them and thus provide radar manufacturers and designers clear goals and objectives for meeting federal rules and regulations and avoid the need for a case-by-case basis analysis of such systems.

One particular complication for the comparison of multi-pulse-parameter radar spectra, hereafter referred to as compound radars, to emission masks such as the RSEC is what measurement RBW should be selected. For single-pulse-parameter radars using unmodulated continuous wave (CW) pulses (P0N), the optimal RBW is (1/PW). Similar formulas for selecting an appropriate RBW for pulses with swept frequency modulated (FM) or chirped pulses (Q3N), are described in [3]. These formulas break down for compound radar transmissions.

NTIA's Technical Report (TR) 05-420 [4] describes measurement methods that can be used to measure radar spectra for RSEC evaluation including proper RBW selection. A new method of determining the proper RBW to be used in the measurements described in NTIA TR-05-420 should be developed for compound waveforms. This study examines the effects of changing the RBW on radar emission spectra measurements using the measurement methods described in [4] and provides recommendations for the optimal RBW to be used when measuring emission spectra of compound radars for the RSEC. Selecting the optimum RBW for this measurement method is achieved when the widest possible RBW is selected that measures total peak power in the pulse but does not distort the measured spectrum. Using the optimum RBW allows the measurement to run as quickly as possible while still producing an accurate spectrum.

2. MEASUREMENT METHODS

To determine a method for selecting the optimal RBW when measuring compound radar emissions, waveforms of P0N and Q3N types were created. The measurement techniques described in [4] were used to measure the emissions of these waveforms as single-pulse-parameter waveforms using multiple RBWs. These single-pulse-parameter waveforms were then combined to create compound radar waveforms that were measured using the same techniques at multiple RBWs. The RBWs used for the measurements were 100 Hz, 300 Hz, 1 kHz, 3 kHz, 10 kHz, 30 kHz, 100 kHz, 300 kHz, 1 MHz, 3 MHz, 6 MHz, and 8 MHz.

2.1 Test Configuration

The configuration of the measurement system used for this study is shown schematically in Figure 1. The waveforms were saved to the Keysight N5182B (MXG) signal generator and the radio frequency (RF) output of the generator was connected to the RF input of the Keysight N9030B (PXA) spectrum analyzer. The Radio Spectrum Measurement Science (RSMS) measurement control PC controlled the signal generator to load and produce the desired waveform for each test. Once the waveform was properly generated, the measurement routine described in [4] was run at multiple RBWs. The measurements at different RBWs were automated using the RSMS-5G automated measurement software running on the RSMS measurement control PC. This procedure was repeated for all of the waveforms described in Section 2.2.

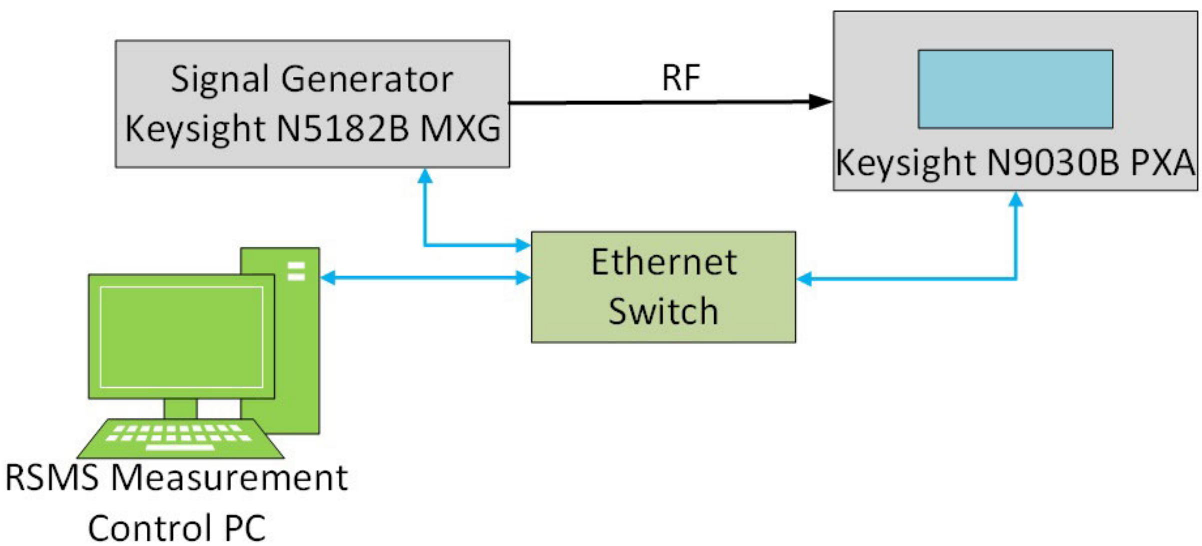

Figure 1. RBW study measurement configuration schematic.

2.2 Waveform Description

All waveforms were created using Keysight's Signal Studio for Pulse Building (Pulse Builder) software. This software allows the user to define radar waveforms and download them to a Keysight signal generator. For these tests, Keysight's N5182B (MXG) was used, and the pulse repetition interval (PRI) was set so that a 10% duty cycle was maintained for all of the waveforms. The MXG's amplitude (peak power) was set to -5 dBm for all measurements.

The waveforms were divided into three categories: unmodulated CW pulses (P0N), swept FM pulses (Q3N with a linear chirp), and compound radar waveforms which are a mixture of P0N and Q3N. For the P0N and Q3N waveforms the number of pulses in a burst was 20; but the waveform was transmitted continuously during the spectrum measurement, so these 20 pulses were repeated throughout the measurements. The compound radar waveforms were produced to test different ratios of Q3N to P0N pulses. The ratios tested were 1:1, 100:1, and 1000:1. Each waveform was given a unique waveform number.

2.2.1 Setting the Peak Power Level

Within the Pulse Builder software, it is not possible to set the peak power level of each of the pulses that make up a compound radar waveform. Instead, the peak power is set by the amplitude setting on the front panel of the MXG. It is possible to create waveforms where each of the pulses within a compound waveform are produced with different peak power levels by using what is called "power scale" (entered in dB) in the software. If the power scale is set to 0 than that pulse will have a peak power equal to the amplitude setting of the MXG. If the "power scale" is unequal to zero than the power of that pulse will have a relative peak power offset from the MXG amplitude setting equal to the input amount in dB.

Tables 1 to 5 provide a relative power for each waveform's components. This relative power is implemented using the "power scale" setting in the Pulse Builder software. The "power scale" setting is used for two cases. The first case is to observe the effects of component pulses having different peak power levels, and the second case is to maintain the same power spectral density (PSD) at the carrier (peak power/B_c) in each Q3N pulse of a compound Q3N waveform (described in Section 2.2.3).

In the first case, a compound waveform is made up of pulses with different PWs but the "power scale" input is used to simulate the component pulses having unequal peak power. The relative powers are determined based on the ratio of PW to the longest pulse.[4] Figure 2 provides an example of how this is implemented. The equal peak power case is shown in the top plot while the unequal peak power case is provided in the bottom plot. The relative powers are created using the "power scale" setting in Pulse Builder. They are determined by looking at the ratio of PWs. The ratio of the 100 µs pulse to the 1 ms pulse is 100:1000 (-10 dB) and the ratio of the 1 µs pulse to the 1 ms pulse is 1:1000 (-30 dB). The 1 ms pulse has a "power scale" of 0 dB in Pulse Builder. Compound waveforms containing components with unequal power are examined in Sections 2.2.2, 2.2.3, and 2.2.4.

[4] This was done solely to provide a formulaic way of determining relative peak power levels for testing compound waveforms with unequal peak power for each component pulse and does not represent any particular radar design.

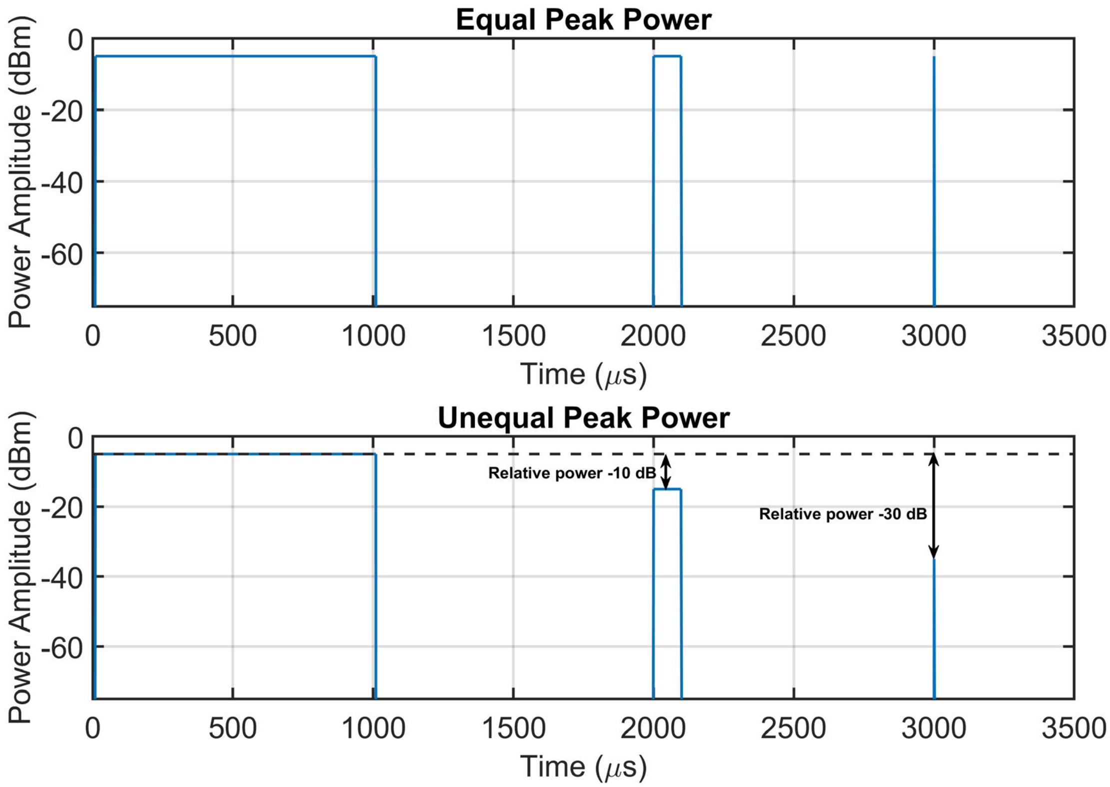

Figure 2. Example of a compound radar waveform with pulses that have different pulse widths (left to right: PW = 1 ms, 100 μs, and 1 μs) but the same peak power (top) and unequal peak power based on PW ratio (bottom).

In the second case, the "power scale" setting is used to maintain the same PSD at the carrier (peak power/B_c) for all pulses in a compound waveform with Q3N type pulses that have different chirp bandwidths. This is only relevant for a single test waveform described in Section 2.2.3 that contains three Q3N pulse types with B_c = 1 MHz, 10 MHz, and 100 MHz. To maintain the same PSD at the carrier for all the component pulse types the "power scale" input is set to reflect the ratio between these bandwidths. Using the 100 MHz pulse as the reference pulse with a "power scale" of 0 dB. The "power scales" for the other two pulses are set relative to this. The relative power of the B_c = 10 MHz pulse is set to -10 dB (10:100) and the B_c = 1 MHz pulse is set to -20 dB (1:100). Note that the compound waveforms described in Sections 2.2.2 and 2.2.4 only include one Q3N pulse type.

For all the test waveforms, the component pulse with the highest resultant peak power was chosen as the reference component. This means all the relative peak power settings presented in the following sections are negative. This was done to ensure the MXG did not try to produce a pulse with a peak power greater than its capabilities and to ensure the PXA was never overloaded. As mentioned earlier, the amplitude of the MXG was set to -5 dBm for all tests so every waveform with a "power scale" of 0 dB has a peak power of -5 dBm.

2.2.2 P0N Waveforms

This set of tests focused on examining the effect of T_r, T_f, and PW on the measured spectra for a variety of RBW settings of P0N type pulses. Each waveform was measured at RBW settings of 100 Hz, 300 Hz, 1 kHz, 3 kHz, 10 kHz, 30 kHz, 100 kHz, 300 kHz, 1 MHz, 3 MHz, 6 MHz, and 8 MHz. For each of the waveforms, one of these RBW settings corresponds to 1/PW, which is the method described in [4] for choosing the correct RBW for P0N type radars. Table 1 lists the nine waveforms produced for these tests.

Table 1. P0N waveforms.

Waveform Number	Pulse Width (μs)	Rise and Fall time (ns)	PRI (μs)	PRR (kHz)	# of pulses
1	1	50	10	100	20
2	100	100	1000	1	20
3	1000	500	10000	0.1	20
4	1	100	10	100	20
5	100	500	1000	1	20
6	1000	50	10000	0.1	20
7	1	500	10	100	20
8	100	50	1000	1	20
9	1000	100	10000	0.1	20

In addition to measuring the spectra of single P0N pulse types, mixtures of the waveforms described in Table 1 were measured. The results of these tests are compared to the individual component waveforms in Section 3.1.2. Table 2 summarizes the tests. The P0N compound waveform test case with different PWs is shown twice in Table 2: one test maintains the same peak power in every pulse type and the second uses relative peak power for each component pulse to observe the effects of pulse components with unequal peak power. The pulses created for these two test cases are shown in Figure 2, but note that the PRI is not accurate in the figure as it is only meant to demonstrate how peak powers were chosen for the equal peak power and unequal peak power test cases.

Table 2. P0N waveform test cases.

Test	Waveform(s) from Table 1	Relative Peak Power (dB)
Single-pulse-parameter P0N	1	N/A
Single-pulse-parameter P0N	2	N/A
Single-pulse-parameter P0N	3	N/A
Single-pulse-parameter P0N	4	N/A
Single-pulse-parameter P0N	5	N/A
Single-pulse-parameter P0N	6	N/A
Single-pulse-parameter P0N	7	N/A
Single-pulse-parameter P0N	8	N/A
Single-pulse-parameter P0N	9	N/A

Test	Waveform(s) from Table 1	Relative Peak Power (dB)
Pulse Width–Equal Peak Power	1, 6, 8	0,0,0
Pulse Width–Unequal Peak Power	1, 6, 8	-30,0,-10
Rise and Fall Time	2, 5, 8	0,0,0

2.2.3 Q3N Waveforms

This set of tests focused on examining the effect of PW and B_c on the measured emission spectra for a variety of RBW settings of Q3N type pulses. Each waveform was measured using the same RBW settings as the P0N test cases. One of these RBW settings was approximately equal to $\sqrt{B_c/PW}$, the standard estimate of the proper RBW to use for Q3N type radar pulses as described in [4]. Pulse rise and fall times were set to 50 ns for all of these tests. Table 3 lists the nine single Q3N type waveforms that were produced for these tests.

Table 3. Q3N waveforms.

Waveform Number	Pulse Width (μs)	Chirp BW (MHz)	PRI (μs)	PRR (kHz)	Number of Pulses
10	1	1	10	100	20
11	100	10	1000	1	20
12	10000	100	100000	0.1	20
13	1	10	10	100	20
14	100	100	1000	1	20
15	10000	1	100000	0.1	20
16	1	100	10	100	20
17	100	1	1000	1	20
18	10000	10	100000	0.1	20

In addition to measuring the spectra of single Q3N pulse types, mixtures of the waveforms described in Table 3 were measured. Two of these compound Q3N test cases were examined. The first combined three of the pulses from Table 3 that all had the same pulse parameters except PW. The second contained pulses with all the same parameters except B_c. The results of these tests are compared to the individual component waveforms in Section 3.2.2.

Table 4 summarizes the test cases that were examined. Each of the compound Q3N waveform tests were performed twice. For the PW test, one test maintained the same peak power in every pulse type and the second had unequal peak powers for each component pulse.

For the first B_c test, the peak power in each of the component pulses was held constant. For the second test, the PSD was held constant by adjusting the power relative to waveform 14 with B_c = 100 MHz. This second test is described in detail at the end of Section 2.2.1.

Table 4. Q3N waveform test cases.

Test	Waveform(s) from Table 3	Relative Peak Power (dB)
Single-pulse-parameter Q3N	10	N/A
Single-pulse-parameter Q3N	11	N/A
Single-pulse-parameter Q3N	12	N/A
Single-pulse-parameter Q3N	13	N/A
Single-pulse-parameter Q3N	14	N/A
Single-pulse-parameter Q3N	15	N/A
Single-pulse-parameter Q3N	16	N/A
Single-pulse-parameter Q3N	17	N/A
Single-pulse-parameter Q3N	18	N/A
Pulse Width–Equal Peak Power	12,14,16	0, 0, 0
Pulse Width–Unequal Peak Power	12,14,16	0, -20, -40
B_c - Equal Peak Power	11, 14, 17	0, 0, 0
B_c - Equal PSD	11, 14, 17	-10, 0, -20

2.2.4 Compound Waveforms with Both P0N and Q3N Pulse Types

Several compound radar waveforms were generated by combining waveforms from Table 1 (P0N) and Table 3 (Q3N). Each compound radar waveform consists of a single P0N pulse followed by the number of Q3N pulses required to achieve the designated Q3N:P0N ratio shown in Table 5. Only four of the waveforms were measured with ratios other than 1:1. These test cases were not given a unique waveform number. Instead, they have the same waveform number as the 1:1 test case followed by the ratio of its test case. The PRI for each component is maintained from the relevant table in each compound waveform, meaning the P0N component could have a different PRI than the Q3N component. The PRIs for each component are provided in Table 1 (P0N) and Table 3 (Q3N). Each of these waveforms were measured using RBW settings of 100 Hz, 300 Hz, 1 kHz, 3 kHz, 10 kHz, 30 kHz, 100 kHz, 300 kHz, 1 MHz, 3 MHz, 6 MHz, and 8 MHz.

Table 5. Compound radar waveform test cases.

Waveform Number	P0N Waveform	Q3N Waveform	P0N PW (μs)	Q3N PW (μs)	Q3N B_c (MHz)	Ratio	Relative Peak Power (dB) (P0N,Q3N)
19	1	10	1	1	1	1	0, 0
20	1	17	1	100	1	1	0, 0
21	1	17	1	100	1	1	-20, 0
22	1	15	1	10000	1	1	0, 0
23	1	15	1	10000	1	1	-40 ,0
24	1	16	1	1	100	1	0, 0
24-100	1	16	1	1	100	100	0, 0
24-1000	1	16	1	1	100	1000	0, 0

Waveform Number	P0N Waveform	Q3N Waveform	P0N PW (μs)	Q3N PW (μs)	Q3N B_c (MHz)	Ratio	Relative Peak Power (dB) (P0N,Q3N)
25	1	14	1	100	100	1	0, 0
26	1	14	1	100	100	1	-20, 0
27	1	12	1	10000	100	1	0, 0
28	1	12	1	10000	100	1	-40, 0
29	8	10	100	1	1	1	0, 0
30	8	10	100	1	1	1	0, -20
31	8	17	100	100	1	1	0, 0
32	8	15	100	10000	1	1	0, 0
33	8	15	100	10000	1	1	-20, 0
34	8	16	100	1	100	1	0, 0
35	8	16	100	1	100	1	0, -20
36	8	14	100	100	100	1	0, 0
37	8	12	100	10000	100	1	0, 0
38	8	12	100	10000	100	1	-20, 0
39	6	10	1000	1	1	1	0, 0
39-100	6	10	1000	1	1	100	0, 0
39-1000	6	10	1000	1	1	1000	0, 0
40	6	10	1000	1	1	1	0, -40
40-100	6	10	1000	1	1	100	0, -40
40-1000	6	10	1000	1	1	1000	0, -40
41	6	17	1000	100	1	1	0, 0
42	6	17	1000	100	1	1	0, -10
43	6	15	1000	10000	1	1	0, 0
44	6	16	1000	1	100	1	0, 0
45	6	16	1000	1	100	1	0, -40
46	6	14	1000	100	100	1	0, 0
47	6	14	1000	100	100	1	0, -10
48	6	12	1000	10000	100	1	0, 0
49	6	12	1000	10000	100	1	-10, 0
50	6	15	1000	10000	1	1	-10, 0

2.3 Data Collection and Analysis

The emission spectra of each of the waveform test cases described in section 2.2 were measured using the stepped measurement algorithm described in [4] using RBW settings of 100 Hz, 300 Hz, 1 kHz, 3 kHz, 10 kHz, 30 kHz, 100 kHz, 300 kHz, 1 MHz, 3 MHz, 6 MHz, and 8 MHz. In order to make the figures more intelligible only 10 of the 12 RBWs are plotted. Typically, either the two lowest RBW settings (100 and 300 Hz) or the two highest RBW settings (6 and 8 MHz) are omitted.

The data collected were used to investigate two main features of the emission spectra. The first was how the pulse parameters and complexity of the waveform affect what RBW should be used when measuring radar spectra. The second was to investigate how individual pulse parameters affect radar spectra. The parameters investigated for this second feature were PW, T_r, and T_f, for the compound P0N test cases; PW and B_c for the compound Q3N test cases; and Q3N:P0N ratio for the compound test cases containing both types of pulses.

2.3.1 Effects of Pulse Parameters on RBW

To investigate how pulse parameters affect which RBW setting should be used when conducting a radar emission measurement as described in [4], the spectra collected at multiple RBW settings were plotted together. There are two ways to determine proper RBW when conducting these types of measurements. The first is to simply use the equations provided in [4] for P0N pulses (1) and for Q3N pulses (2). A complete derivation for (2) is provided in [3]. This formula is an approximation as there is no closed-form solution for the Q3N pulsed radar type. For each of the waveform test cases these equations were used to calculate the appropriate RBW for that test case. The RBW equation for unmodulated CW radar pulses (P0N) is:

$$RBW = \frac{1}{PW} \tag{1}$$

where RBW is the optimum resolution bandwidth to use for the measurement and PW is the pulse width (this is also referred to as τ).

The RBW Equation for swept FM (chirped) radar pulses (Q3N) is:

$$RBW = \sqrt{\frac{B_c}{PW}} \tag{2}$$

where RBW is the approximate optimum resolution bandwidth to use for the measurement, B_c is the FM Chirp bandwidth, and PW is the pulse width (also referred to as τ).

The second method for determining the appropriate RBW is empirical and is determined by looking at the measured power in the emission spectra at the fundamental at several RBW settings, starting from an RBW less than the one calculated using (1) or (2) and then increasing the RBW. The measured peak power at the fundamental will increase linearly with the increase in RBW at first, but at some RBW value it will stop increasing linearly.[5] The RBW reached when the power at the fundamental stops increasing linearly is the empirically observed optimum RBW. For each of the waveform test cases, this method is also used to determine the appropriate RBW from the measured emission spectra. This result is then compared to the calculated RBW value.

[5] If the starting RBW is too small, an increase in power may not be observed as the RBW is increased. The RBW must be greater than the pulse repetition rate (PRR) or else there will not be enough spectral lines within the RBW to get an accurate measurement of peak power [5].

To demonstrate the effect of RBW on measured pulsed radar spectra, the emission spectra of each waveform test case at all RBW settings are plotted in the same figure. The calculated and measured RBW spectra are highlighted in the plots with solid lines and greater thickness. For the P0N and Q3N test cases shown in Tables 2 and 4, respectively, there are at most only two highlighted spectra (calculated and measured, and in many cases these are the same). For the compound radar test cases provided in Table 5, there are typically no more than four highlighted. The highlighted spectra will include the measured and calculated RBW spectra for each of the P0N and Q3N components, for a total of four possible. Since there is no optimum RBW equation for compound radar waveforms containing both P0N and Q3N pulses, only the spectrum with the empirically derived RBW is also highlighted for the compound waveform test cases for a potential total of five highlighted RBWs.

Additionally, for all of the compound radar test cases the spectrum measured at the empirically derived RBW is displayed with the individual component spectra measured with the same RBW setting. This provides a good representation of how the component parts affect the compound radar spectra. The compound test cases from Table 5 contain three spectra: the compound spectrum and each of the Q3N and P0N component spectra. For the compound waveforms with only P0N or Q3N pulse types, this includes four spectra in each plot because these compound test cases contain three component parts.

2.3.2 Effects of Pulse Parameters on the Spectrum

To examine the effects of pulse parameters on radar emission spectra, the test cases were constructed such that the pulse parameters varied for each test case. The compound P0N test cases were chosen so that the effects of PW, T_r, and T_f could be observed. The compound Q3N test cases were chosen to examine the effects of PW and B_c on the emission spectrum. Finally, different Q3N to P0N ratios were measured for some of the compound radar test cases to observe the effect.

These effects are shown by plotting the spectra collected at the empirically observed RBW setting for all the test cases with the same parameters except the one of interest. Doing so makes it possible to look at the differences between the spectra to see how the individual parameter changes it. For all the tested parameters, this results in three spectra being displayed together.

3. MEASUREMENT RESULTS

3.1 P0N Waveform Results

This section provides the results of measuring the emission spectra for the P0N test cases. First, the data collected for the single-pulse-parameter test cases from Table 2 are presented, followed by the compound P0N test cases with their component parts. Finally, the data showing the effects of rise and fall times, and pulse width on the measured radar emission spectra are provided.

3.1.1 P0N Emission Measurements for Single-Pulse-Parameter Radar Waveforms

Figure 3 provides the results of measuring waveform number 6 from Table 1 using multiple RBW settings. The pulse parameters for this waveform are PW = 1 ms, $T_r = T_f = 50$ ns, and PRI = 10 ms. Using (1), the calculated RBW to use for this measurement when using the stepped measurement algorithm described in [4] is 1 kHz, and this optimal RBW setting is highlighted in Figure 3.

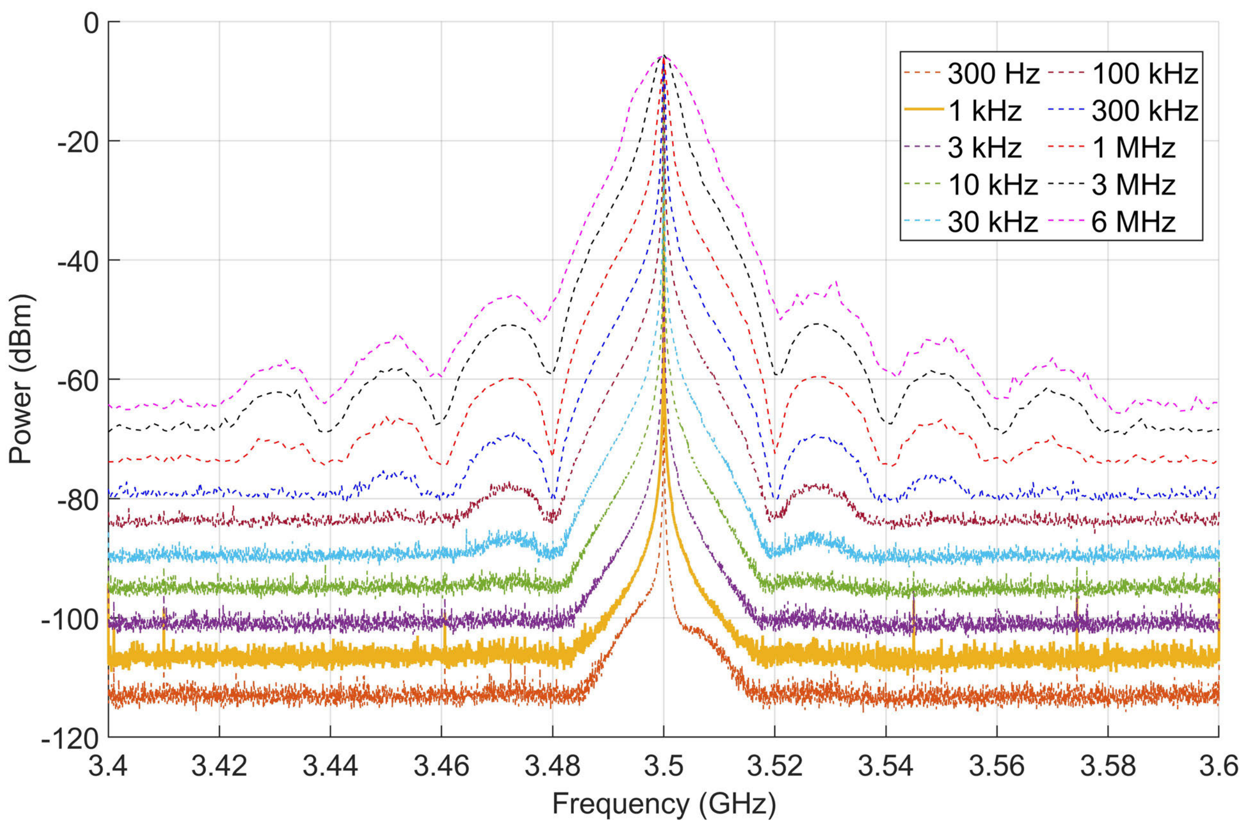

Figure 3. Spectrum emission measurements at multiple RBW settings for waveform 6. RBW = 1 kHz is the calculated optimum RBW and is also the empirically derived optimum RBW to use for this measurement.

Looking at the data more closely, as shown in Figure 4, it can also be seen empirically that RBW = 1 kHz is the optimum. To determine the optimum RBW empirically, observe the increase in power at the fundamental (3.5 GHz) as the RBW is increased. When the power stops increasing linearly because the peak power of the pulse is being measured, the optimum RBW has been reached. In the case shown in Figure 4, the power at the fundamental stops increasing after RBW = 1 kHz. Using an RBW greater than 1 kHz will make the spectrum appear to be worse than it actually is; that is, the emission levels in the out of channel and out-of-band (OOB) regions will be shown to be artificially high, which could make the radar fail the RSEC and system certification. This is because the fundamental frequency no longer increases in power, but the power in the OOB emissions do continue to increase. RBW settings less than 1 kHz could be used for this measurement, but doing so would increase the time the measurement takes.

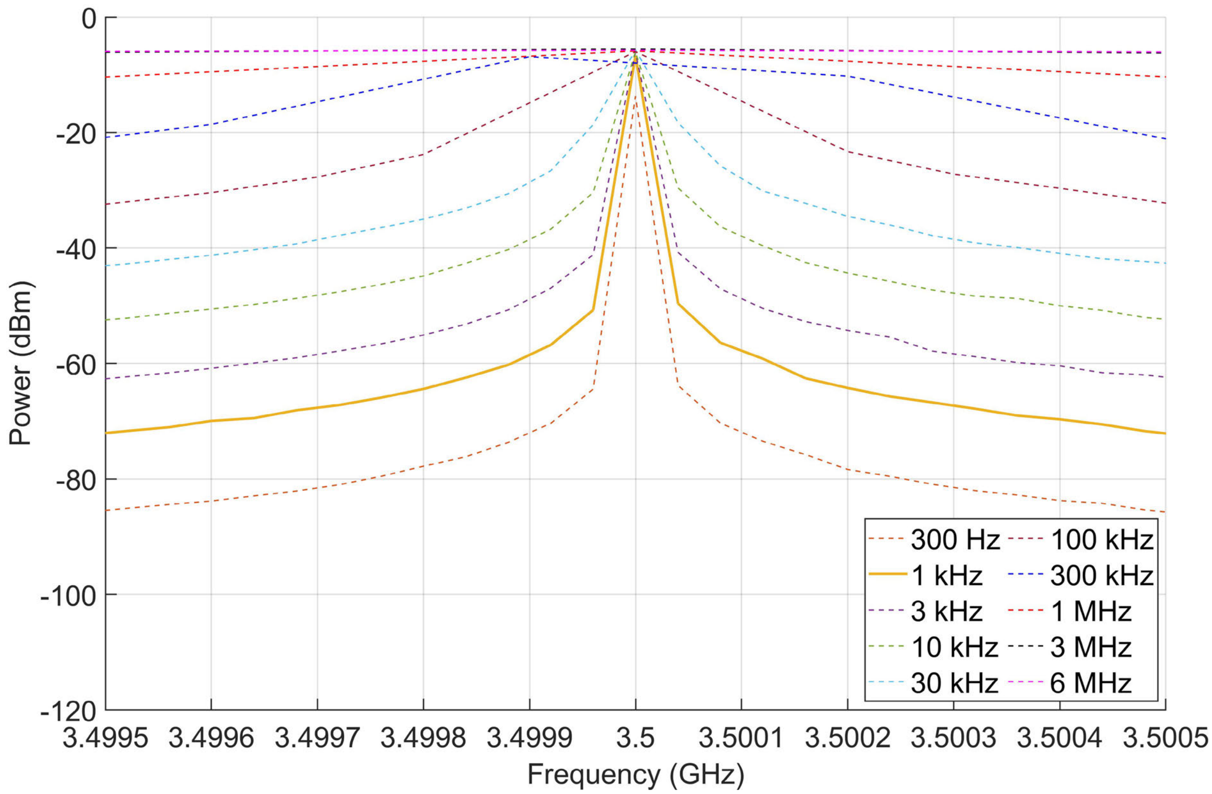

Figure 4. Zoom of Figure 3 showing that RBW = 1 kHz is the optimum RBW when measuring radar emission spectra for a radar with the same pulse parameters.

Figure 5 provides the results of measuring waveform number 4 from Table 1 using multiple RBW settings. The pulse parameters for this waveform are PW = 1 µs, $T_r = T_f$ = 100 ns, and PRI = 10 µs. Using (1), the calculated RBW to use for this measurement when using the stepped measurement algorithm described in [4] is 1 MHz. In this test case, the empirical optimum RBW setting is the same. The remainder of the results from the P0N waveforms described in Table 1 can be found in Section A.1.

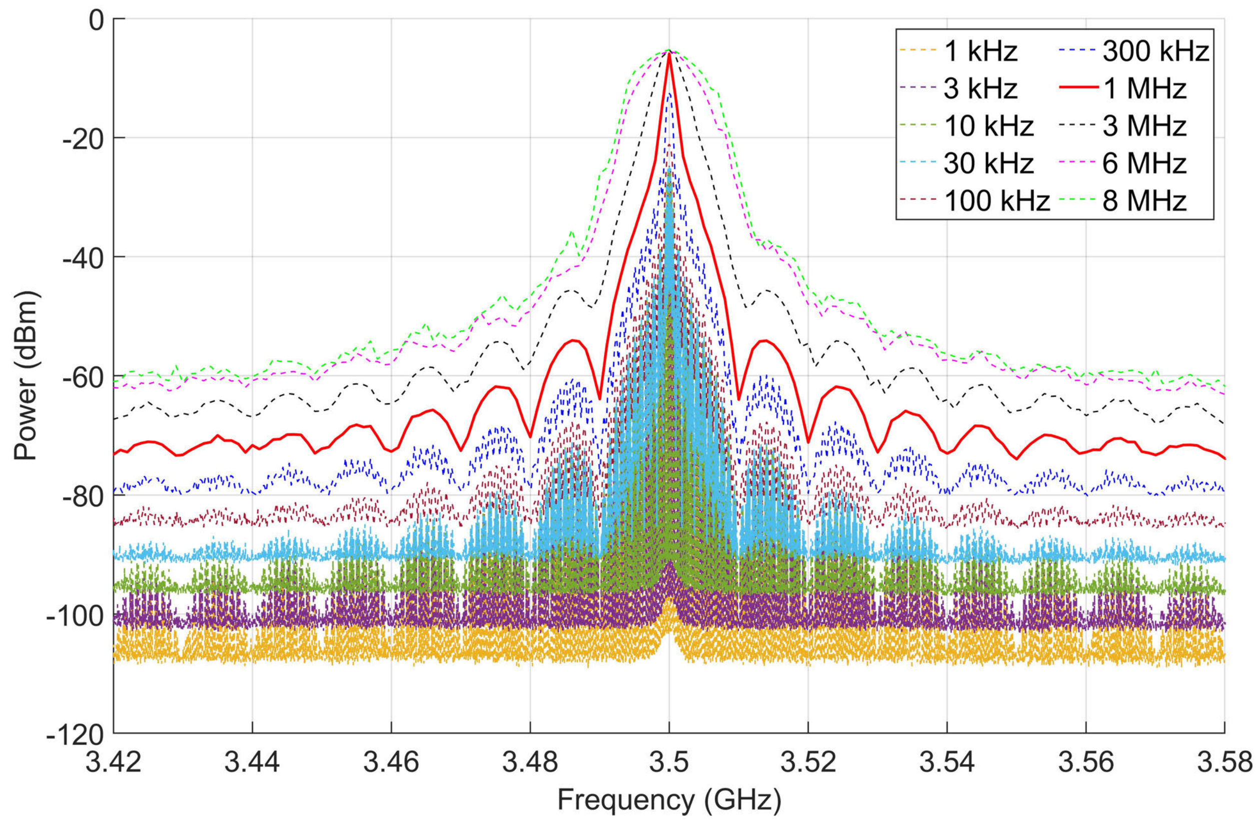

Figure 5. Spectrum emission measurements at multiple RBW settings for waveform 4. RBW = 1 MHz is the optimum from calculation and empirically for this measurement.

Table 6 provides a summary of the calculated and empirical RBW values for the P0N waveforms described in Table 1 and the first nine test cases listed in Table 2. For all the P0N test cases, the calculated optimal RBW is the same as the empirically observed one. This may not always be the case, as will be shown in Section 3.2.1 for the Q3N test cases.

Table 6. Summary of calculated and empirical RBW for the P0N waveforms.

Waveform Number	Calculated RBW (kHz)	Empirical RBW (kHz)
1	1000	1000
2	10	10
3	1	1
4	1000	1000
5	10	10
6	1	1
7	1000	1000
8	10	10
9	1	1

3.1.2 P0N Emission Measurements for Compound Radar Waveforms

The compound P0N waveforms described as the last three test cases in Table 2 were measured in the same way as the single-pulse-parameter test cases. Since these cases are compound waveforms, there is not a single set of parameters from which to calculate the optimum RBW setting. In this case, [4] states that the smallest of the calculated RBW for each component should be used. The optimum RBW can also be determined empirically. This is done in the same way as described in the previous section.

Figure 6 provides the results of measuring the pulse width–equal peak power test case from Table 2. This compound P0N waveform is made up of three different P0N pulses with different PWs. In this test case, the peak power was the same for all three pulses. The PWs of the three pulses were 1 µs, 100 µs, and 1 ms. The calculated optimum RBW for each of these PWs are 1 MHz, 10 kHz, and 1 kHz, respectively. Following [4], an RBW setting of 1 kHz would be the correct RBW to use for this measurement. Figure 7 shows a close-up of the fundamental frequency from Figure 6 which demonstrates that an RBW setting of 1 kHz is also empirically observed as optimal.

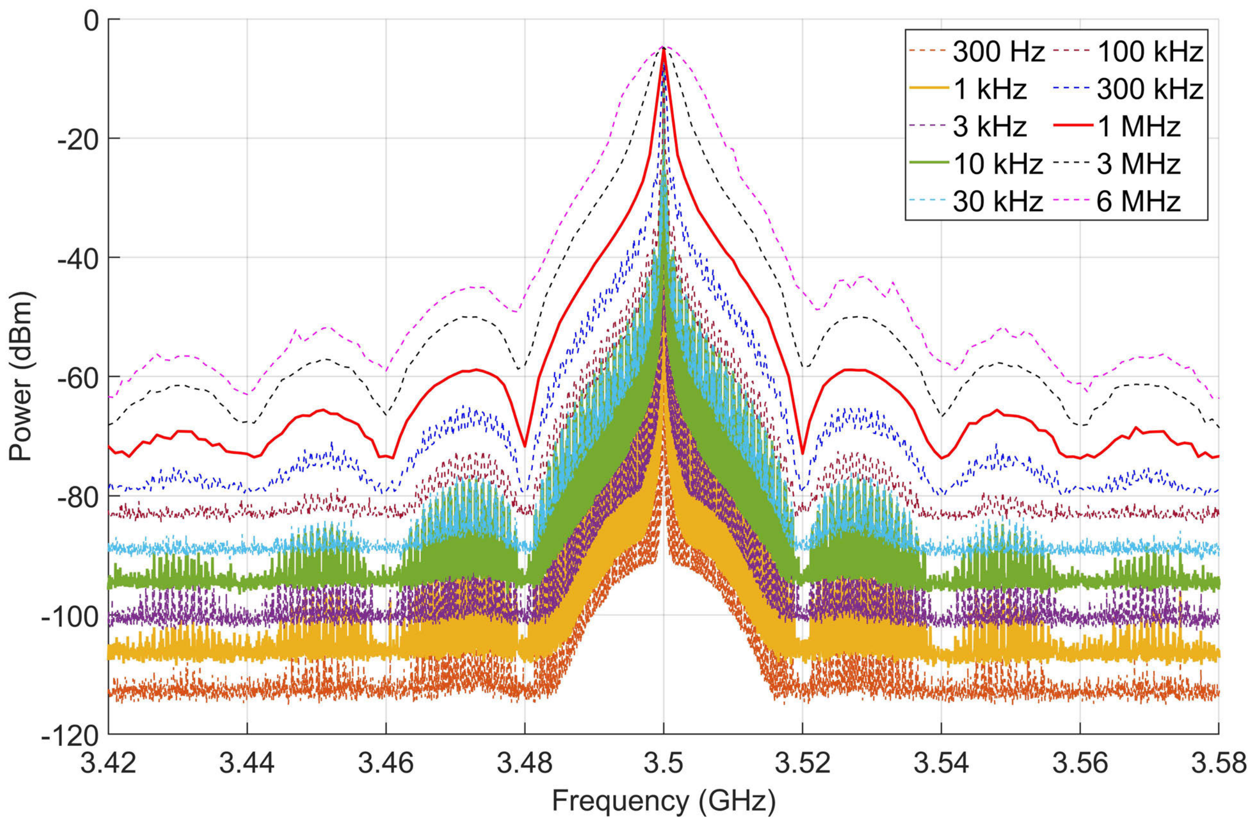

Figure 6. Spectrum emission measurements at multiple RBW settings for the pulse width–equal peak power test case from Table 2. RBW = 1 kHz, 10 kHz, and 1 MHz are the calculated optimum RBW settings for each of the three components. Empirically and from calculation, 1 kHz is the optimum RBW setting.

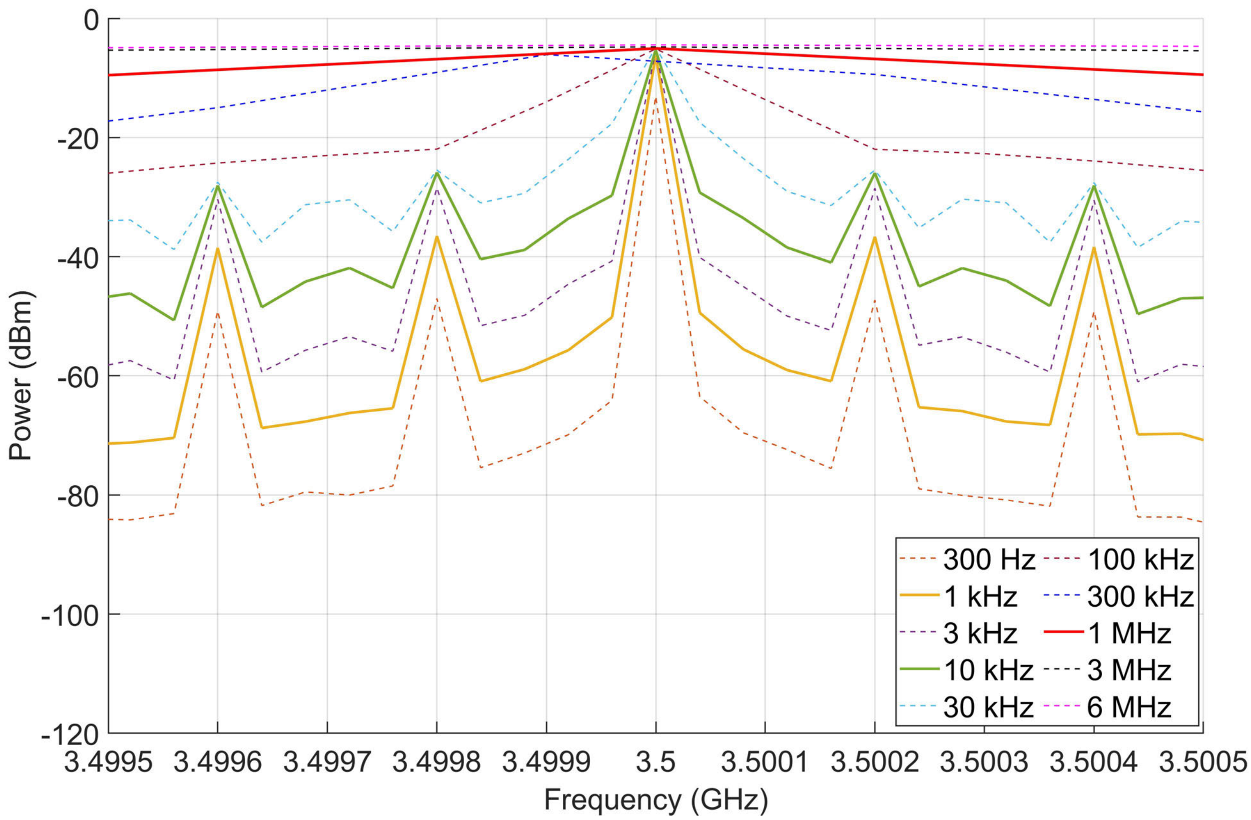

Figure 7. Zoom of the fundamental from Figure 6 showing that RBW = 1 kHz should be used when measuring this compound radar emission spectrum.

Once the optimum RBW setting has been determined, it is possible to look at the emission spectrum of the compound radar with its component parts to get a better understanding of the selection. This is shown in Figure 8. The spectrum of the compound P0N radar signal appears to follow whichever of the component spectra has the greatest measured power at each point through the fundamental. In this case, the fundamental is dominated by the PW = 1 ms component and so the compound spectrum matches it. Figure 9 shows a close-up of the fundamental so that it is easier to see this phenomenon.

In the roll-off region of the spectrum, the PW = 1 µs spectrum influences the compound spectrum. The spiky behavior of the PW = 1 µs spectrum is due to the RBW setting (1 kHz) being less than the PRR (100 kHz). This results in the appearance of spectral lines that create the spikes observed in the PW = 1 µs spectrum. While the power of the compound spectrum does not match the power of these spikes, it is certainly influenced by them. For a greater explanation of spectral lines and what causes them see [5].

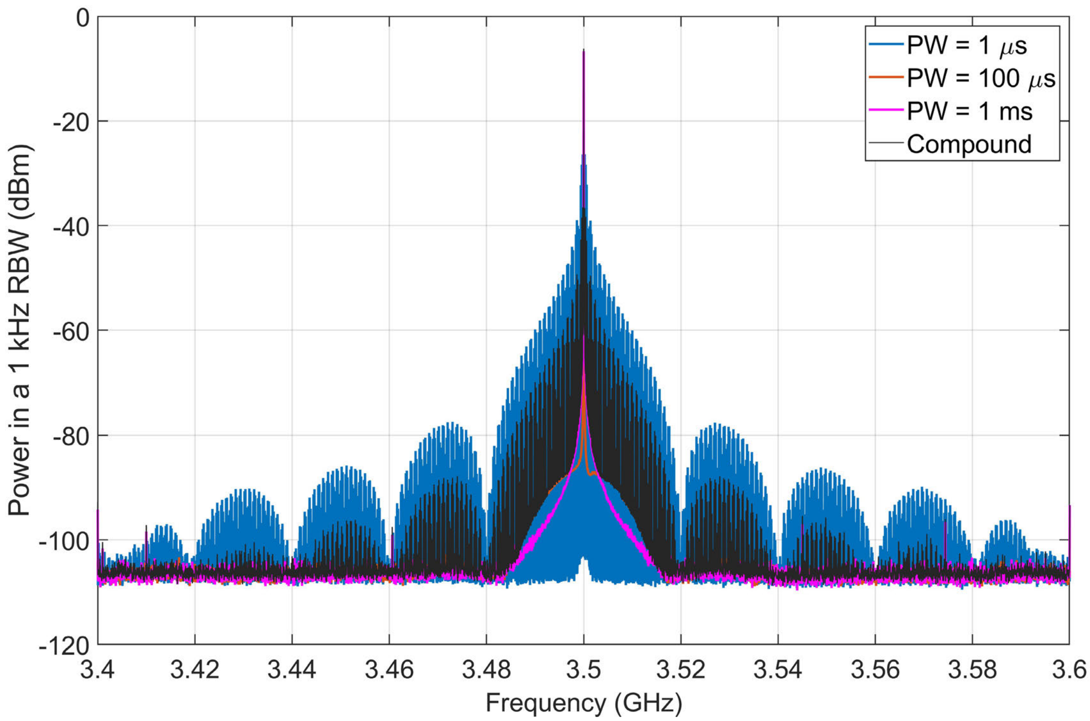

Figure 8. Test case pulse width–equal peak power with its single-pulse-parameter components at RBW = 1 kHz.

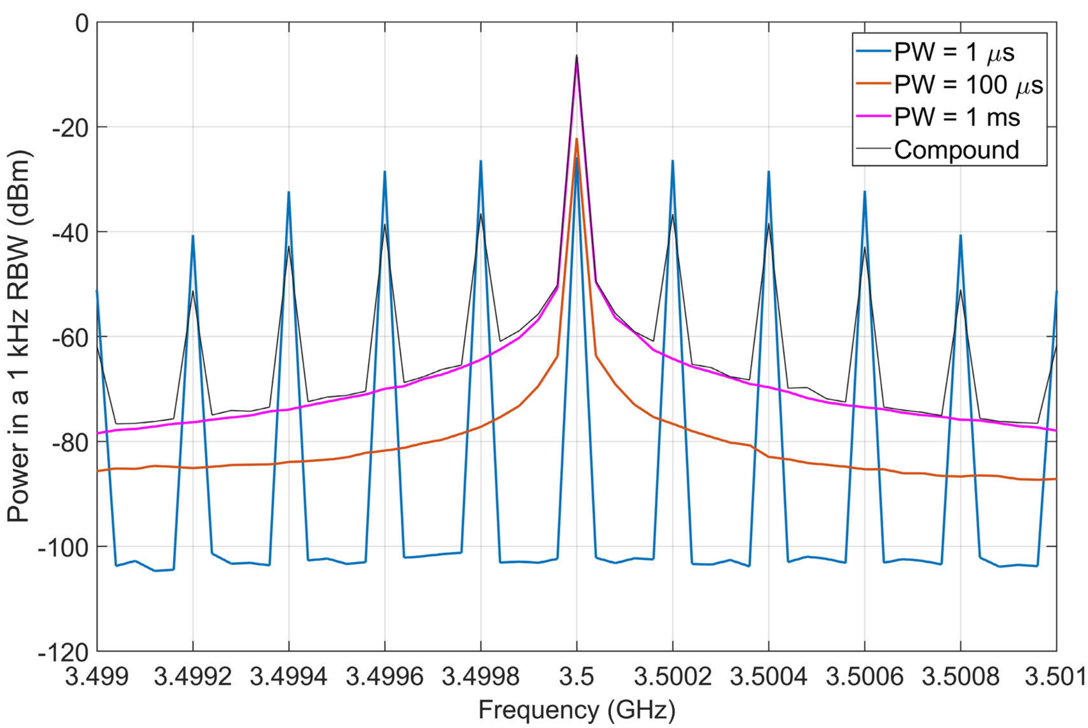

Figure 9. Close-up view of the fundamental from Figure 8 showing that the compound spectrum follows along with the maximum power of the component single-pulse-parameter spectra at the fundamental. The influence of the spectral lines from the PW = 1 μs spectrum can also be seen.

Next, Figure 10 provides the results of conducting spectrum emission measurements on the pulse width–unequal peak power test case from Table 2 at multiple RBW settings. As for the test case with equal power, the calculated optimum RBW settings for this test case are 1 MHz, 10 kHz, and 1 kHz because this test case uses the same PWs. As with the previous test case, the empirical optimum RBW is 1 kHz, which is the smallest of the three calculated values.

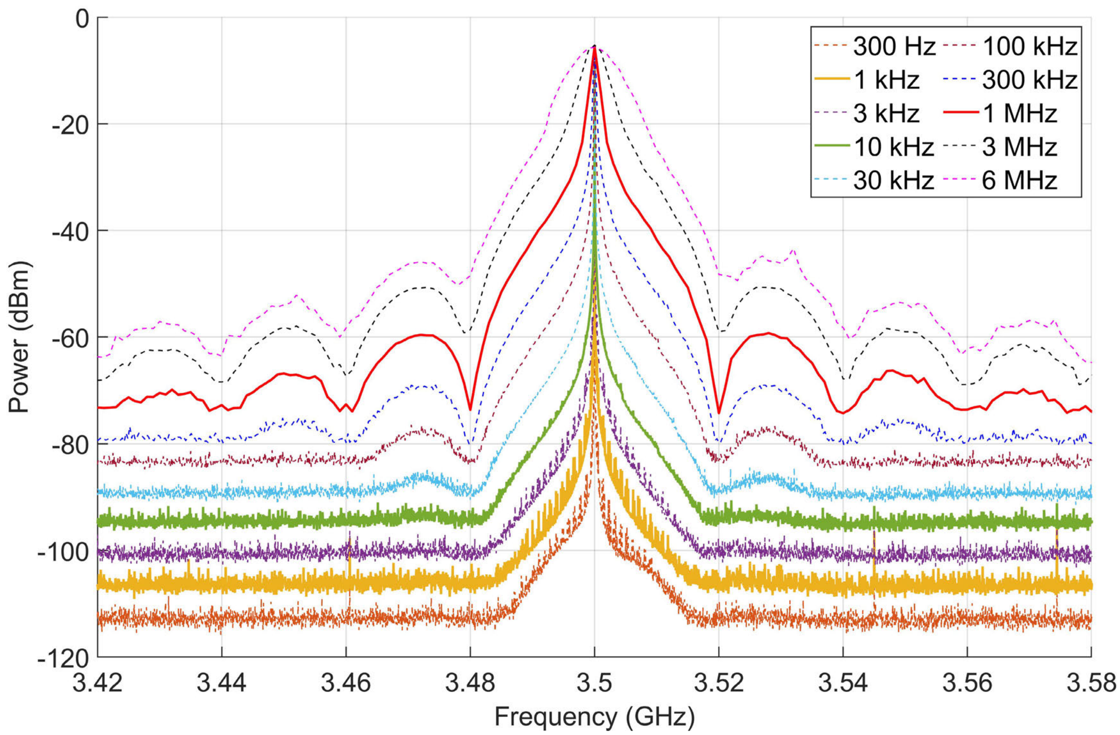

Figure 10. Spectrum emission measurements at multiple RBW settings for the pulse width–unequal peak power test case from Table 2. RBW = 1 kHz, 10 kHz, and 1 MHz are the calculated optimum RBW settings for each of the three components. Empirically, 1 kHz is the optimum RBW setting.

Next, Figure 11 shows the emission spectrum of the compound waveform described in the pulse width–unequal peak power test case along with the spectra of its component parts all measured at the empirical optimum RBW setting of 1 kHz.[6] The 1 ms PW has 30 dB more peak power than the 1 µs pulse and the 100 µs PW has 20 dB more peak power than the 1 µs PW. This difference in power means that the 1 µs PW and 100 µs components do not contribute to the compound spectrum at all at the fundamental. Figure 12 provides a close up of the fundamental frequency so this effect can be seen more clearly. The spectral lines of the PW = 1 µs waveform do contribute to the compound spectrum in the roll-off region, but in the OOB region beyond the roll-off region the two waveforms with less peak power do not influence the compound spectrum.

[6] The noise floors of each component appear at different levels because all of the individual component waveforms were measured with the same MXG output power level. To simulate the difference in peak power, each component spectrum's power was adjusted using the same relative peak power settings provided in Tables 2, 4, and 5. This applies to all the unequal peak power test cases in this report.

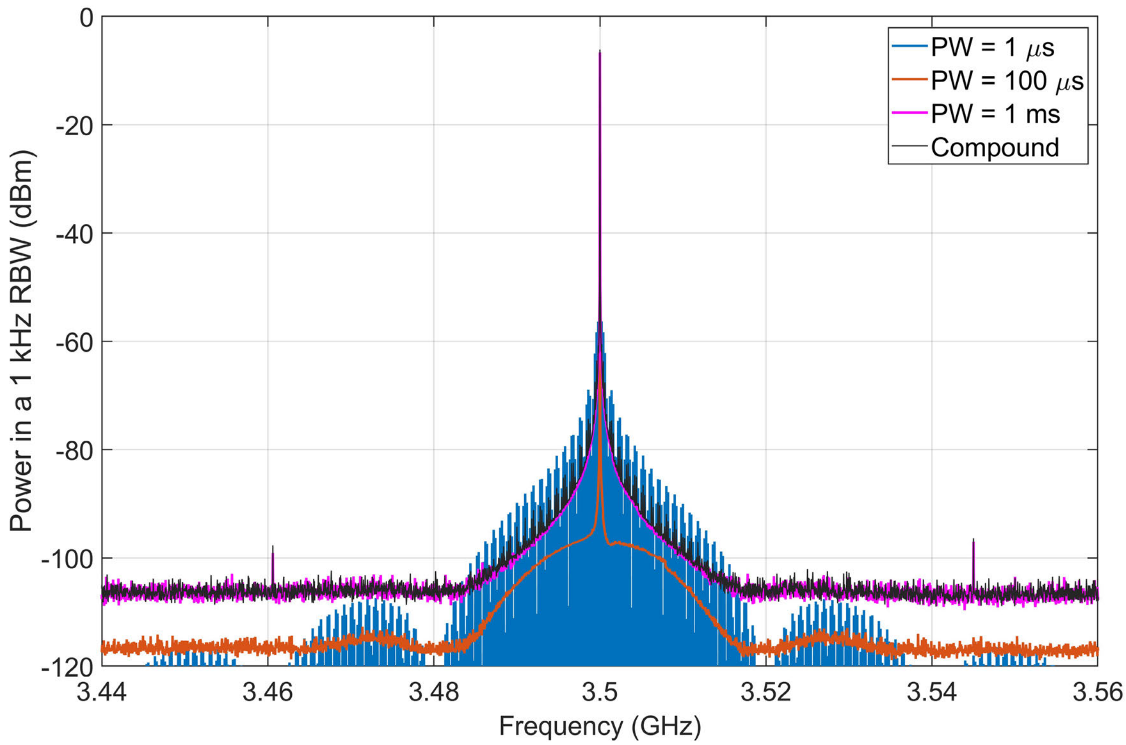

Figure 11. Test case pulse width–unequal peak power with its single-pulse-parameter components at RBW = 1 kHz.

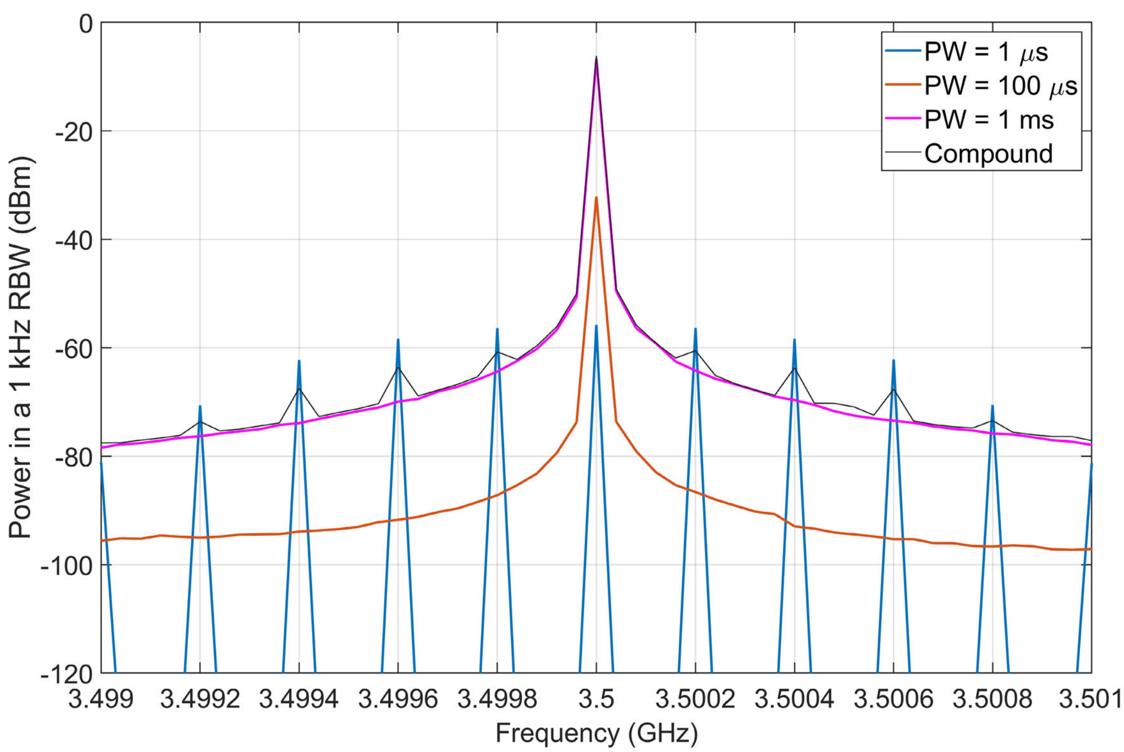

Figure 12. Close-up view of the fundamental from Figure 11 showing that the greatest PW with the greatest peak power determines the compound spectrum at the fundamental.

Figure 13 provides the results of conducting spectrum emission measurements on the rise and fall time test case from Table 2 at multiple RBW settings. Since the PW is the same for all three components of this test waveform, the calculated optimum RBW setting is 10 kHz. Empirically, the optimum RBW setting is also 10 kHz, which agrees with what was seen for the single-pulse-parameter test cases seen in Section 3.1.1 that make up the individual components of this compound waveform.

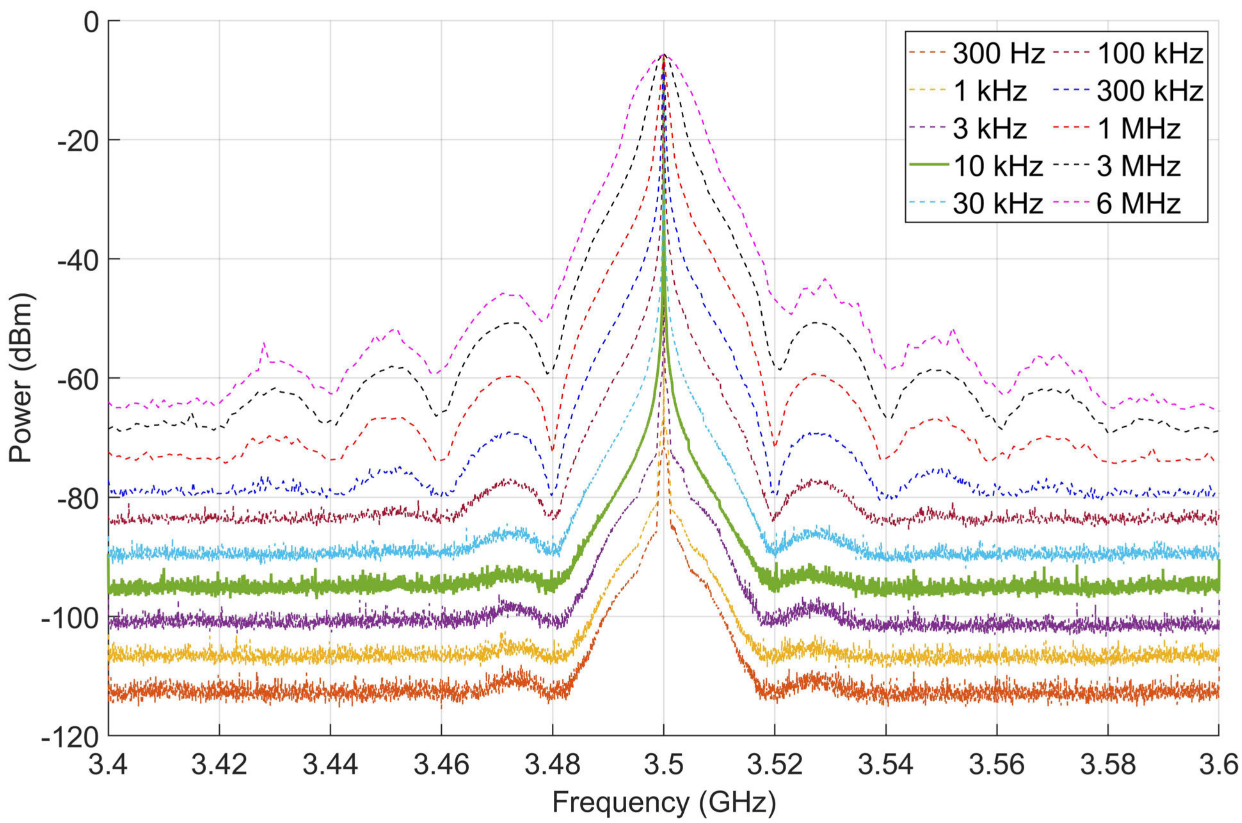

Figure 13. Spectrum emission measurements at multiple RBW settings for the rise and fall time test case from Table 2. RBW = 10 kHz is both the calculated and the empirically observed optimum RBW setting for all three components.

Next, Figure 14 shows the emission spectrum of the compound P0N test case rise and fall time along with the individual single-pulse-parameter components of this waveform all measured at RBW = 10 kHz. In this test case, the entire compound spectrum follows the maximum of the component spectra. In this case, the compound spectrum follows the single-parameter-pulse with $T_r = T_f = 50$ ns, because this component is almost always the maximum.

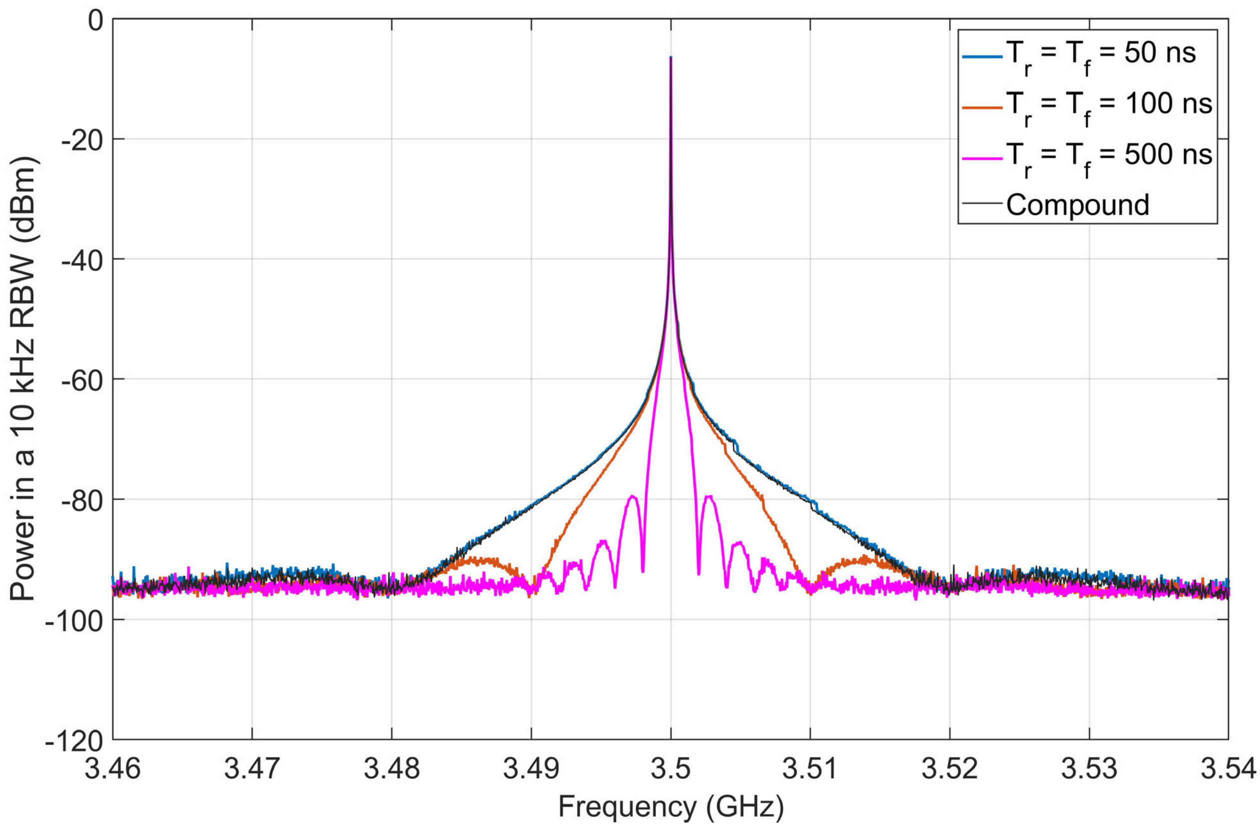

Figure 14. Test case rise and fall time with its single-pulse-parameter components at RBW = 10 kHz.

3.1.3 Effects of Pulse Parameters on P0N Emission Spectrum

The effects of T_r and T_f on the emission spectrum of a pulsed signal are noticeable in the roll-off region of the spectrum as seen in Figure 14. As T_r and T_f increase, the roll-off becomes steeper. The frequency separation from the fundamental to the first null when $T_r = T_f = 50$ ns is 20 MHz. The separation when $T_r = T_f = 100$ ns is 10 MHz and when $T_r = T_f = 500$ ns, it is 2 MHz. This effect is why T_r and T_f are taken into consideration when computing the RSEC mask for radar emissions.

3.2 Q3N Waveform Results

This section provides the results of measuring the emission spectra for the Q3N test cases. First, the data collected for the single-pulse-parameter test cases from Table 4 are presented, followed by the compound Q3N test cases with their component parts. Finally, the data showing the effects of chirp bandwidth and pulse width on the measured radar emission spectra are provided.

3.2.1 Q3N Emission Measurements at Several RBW Settings

Figure 15 provides the results of measuring waveform number 11 from Table 3 using multiple RBW settings. The pulse parameters for this waveform are PW = 100 µs, $T_r = T_f$ = 50 ns, B_c = 10 MHz, and PRI = 1 ms. Using (2), the calculated RBW to use for this measurement when using the stepped measurement algorithm described in [4] is approximately 300 kHz (316.2 kHz). RBW settings of 100 kHz and 300 kHz are highlighted in Figure 15 because RBW = 100 kHz is the optimal RBW to use for this measurement based on empirical evidence.

The empirical optimum RBW setting can be seen by following the bandwidth progression and observing the power at the fundamental frequency does not increase linearly with the RBW when the RBW is increased from 100 kHz to 300 kHz. The increase in power due to the increase in RBW should be $20 \cdot \log_{10}$(300 kHz / 100 kHz) = 9.5 dB.[7] Instead, the power increase is measured to be 6.2 dB. In the OOB region the measured power has increased by more than 6.2 dB, meaning the measured spectrum is less likely to pass the RSEC. Using the 1-3-10 RBW progression is convenient when measuring radars because the linear increase in power at the fundamental should always be approximately 10 dB ($20 \cdot \log_{10}(100/30)$ = 10.5 dB).

In this test case, 100 kHz is the optimum RBW only if the spectrum analyzer being used has RBW settings that are limited to the 1-3-10 RBW progression used in this study. Many modern spectrum analyzers have more RBW settings available. For the case shown in Figure 15, the true optimum RBW is closer to, but less than, 300 kHz. If more RBW settings are available, the BW progression measurement could be conducted between 100 and 300 kHz to find the RBW where the peak power in the pulse is measured at the fundamental, but the spectrum is not distorted because the RBW is too wide. The spectrum becomes distorted when the power measured at the fundamental ceases to increase but the power in the OOB region continues to increase. Using a narrower RBW than the optimum will still produce an accurate spectrum, but the measurement time when using the stepped measurement method described in [4] will increase.

[7] The power increase goes as $20 \cdot \log_{10}$ instead of $10 \cdot \log_{10}$ because of the peak detector used for these measurements as described in [4].

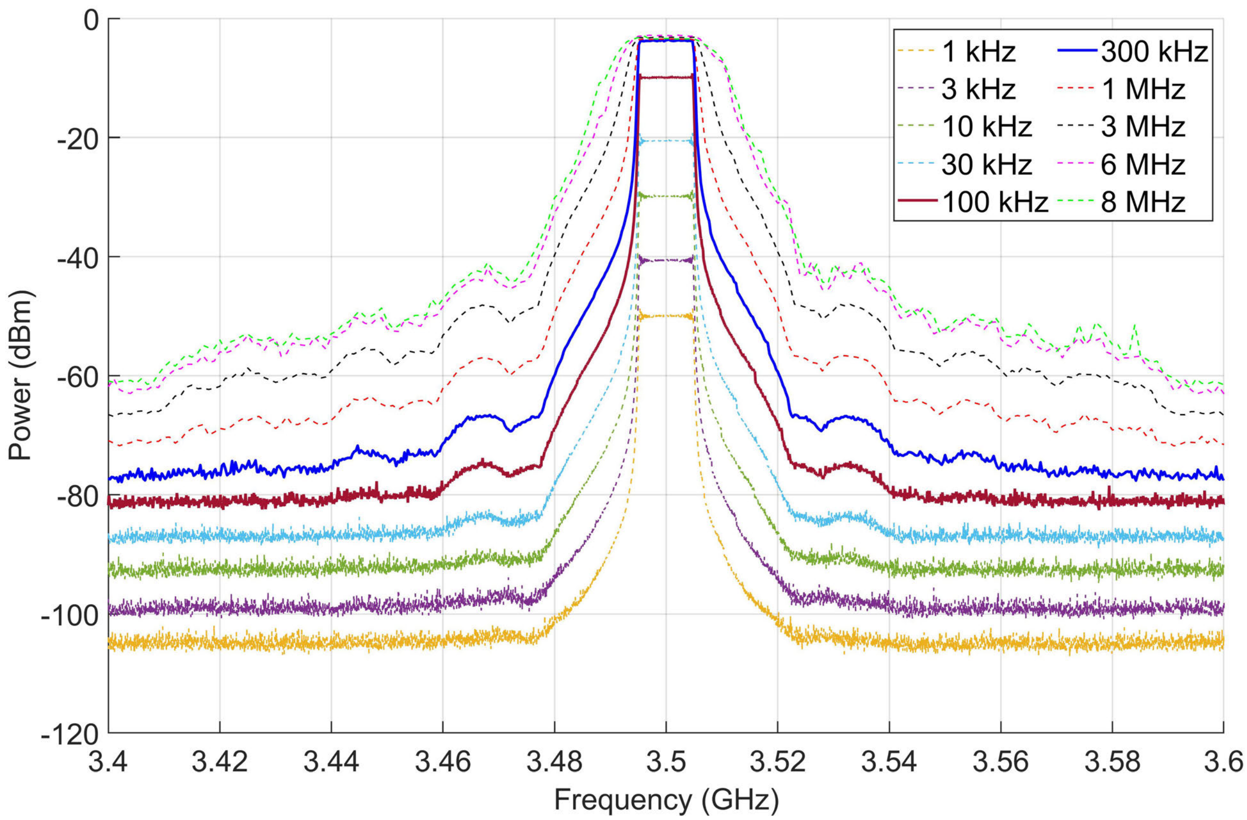

Figure 15. Spectrum emission measurements at multiple RBW settings for waveform 11. RBW = 300 kHz is the calculated optimum RBW while RBW = 100 kHz is the empirically observed optimum RBW to use for this measurement.

Figure 16 provides the results of measuring waveform number 15 from Table 3 using multiple RBW settings. The pulse parameters for this waveform are: PW = 10 ms, $T_r = T_f$ = 50 ns, B_c = 1 MHz, and PRI = 10 µs. Using (2), the calculated RBW to use for this measurement, when using the stepped measurement algorithm described in [4], is 10 kHz. This is also the optimum RBW setting empirically. Figure 17 provides a close-up of the fundamental frequency so that it is easier to see that RBW = 10 kHz is the optimum RBW.

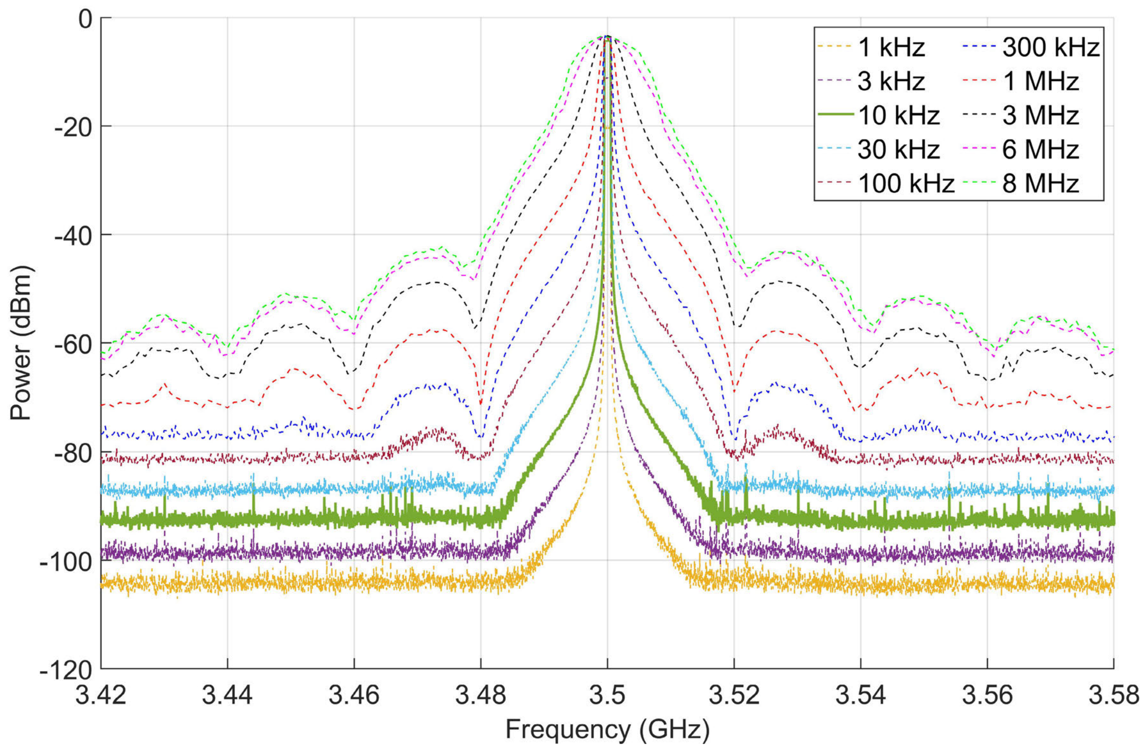

Figure 16. Spectrum emission measurements at multiple RBW settings for waveform 15. RBW = 10 kHz is the optimum RBW empirically and calculated for this measurement.

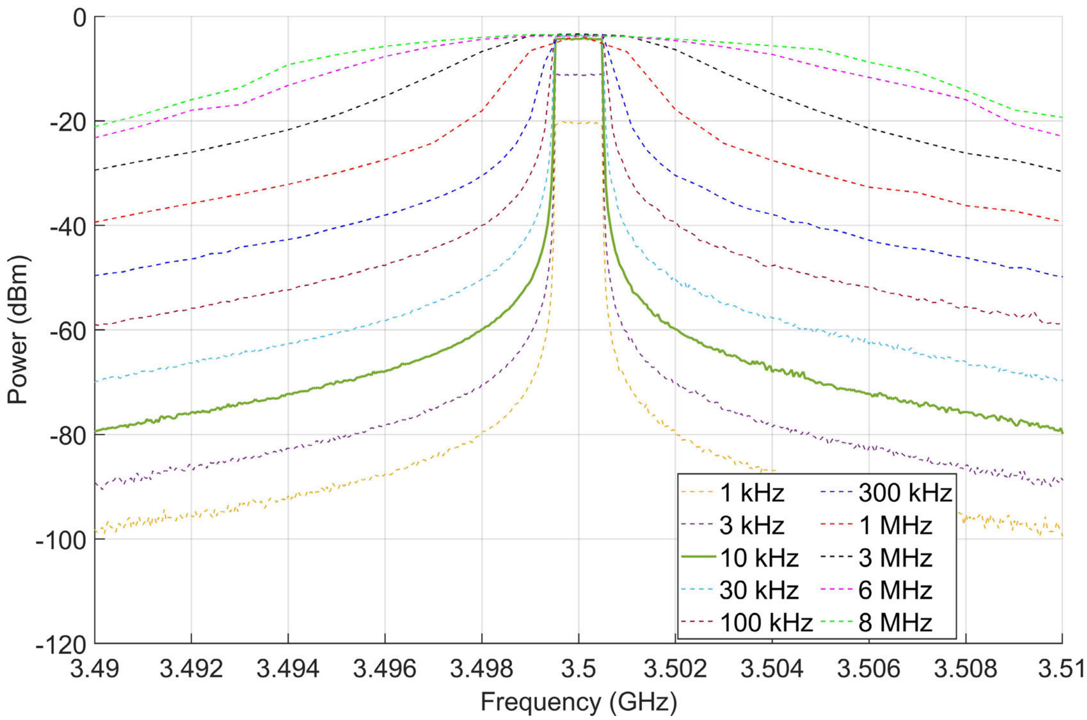

Figure 17. Close-up view of the fundamental from Figure 16 showing that RBW = 10 kHz should be used when measuring radar emission spectra for this test case.

Figure 18 provides the results of measuring waveform number 14 from Table 3 using multiple RBW settings. The pulse parameters for this waveform are: PW = 100 µs, $T_r = T_f = 50$ ns, $B_c = 100$ MHz, and PRI = 1 ms. Using (2), the calculated RBW to use for this measurement, when using the stepped measurement algorithm described in [4], is 1 MHz. Empirically, the optimum RBW setting is 300 kHz, but the improvement is minimal. Performing the RBW progression between 300 kHz and 1 MHz would show that the true optimum RBW, where the peak power is measured and the spectrum is not distorted, would be close to, but less than, 1 MHz. The remainder of the results from the single-pulse parameter Q3N waveforms described in Table 3 can be found in Section A.2.

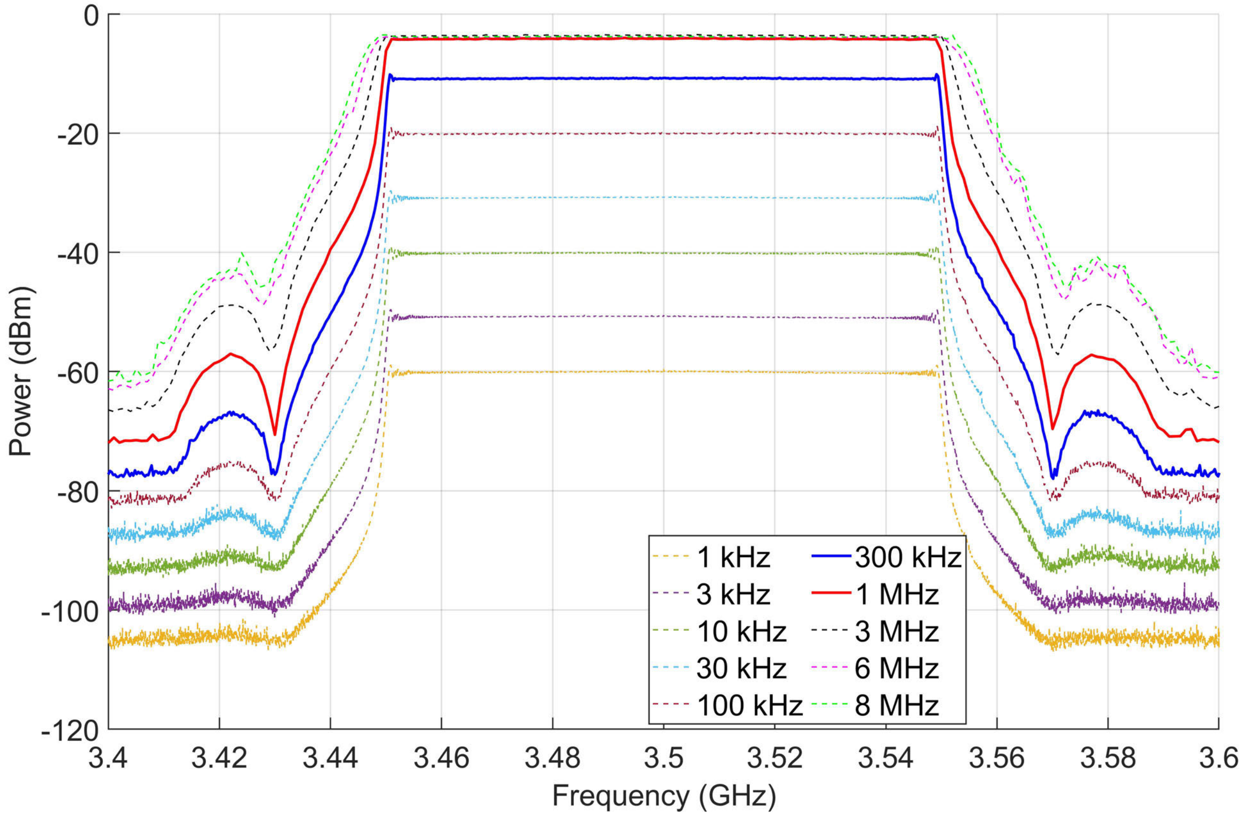

Figure 18 Spectrum emission measurements at multiple RBW settings for waveform 14. RBW = 1 MHz is the calculated optimum RBW setting, but empirically the optimum RBW setting for this measurement is 300 kHz.

Table 7 provides a summary of the calculated and empirical RBW settings for the Q3N waveforms described in Table 3 and the first nine test cases described in Table 4.

Table 7. Summary of calculated and empirical RBW for the Q3N waveforms.

Waveform Number	Calculated RBW (kHz)	Empirical RBW (kHz)
10	1000	1000
11	316.2	100
12	100	100

Waveform Number	Calculated RBW (kHz)	Empirical RBW (kHz)
13	3162	1000
14	1000	300
15	10	10
16	10000	8000 (Max used in this study)
17	100	30
18	31.62	30

3.2.2 Spectra of Compound Q3N Waveforms with Component Spectra

The compound Q3N waveforms described as the last four test cases in Table 4, were measured in the same way as the single-pulse-parameter test cases. Since these cases are compound waveforms, there is no single set of parameters from which to calculate the optimum RBW setting. In this case, [4] states that the smallest of the calculated RBWs for each component should be used. The optimum RBW setting can also be determined empirically. This is done in the same way as described in Section 2.3.1.

Figure 19 provides the results of measuring the pulse width–equal peak power test case from Table 4. This compound Q3N waveform is made up of three different Q3N pulses with different pulse widths. In this test case the relative peak power was set to 0 so that the peak power of all three pulse types were equal. The PWs of the three pulses were 1 µs, 100 µs, and 10 ms. The calculated optimum RBW for each of these PWs is 10 MHz (the PXA had a maximum RBW of 8 MHz), 1 MHz, and 100 kHz, respectively using (2). Following [4], an RBW setting of 100 kHz would be the correct RBW to use for this measurement. The chirp BW is 100 MHz and $T_r = T_f = 50$ ns for all three component pulses. Figure 19 shows that RBW = 100 kHz is the correct RBW to use empirically as well.

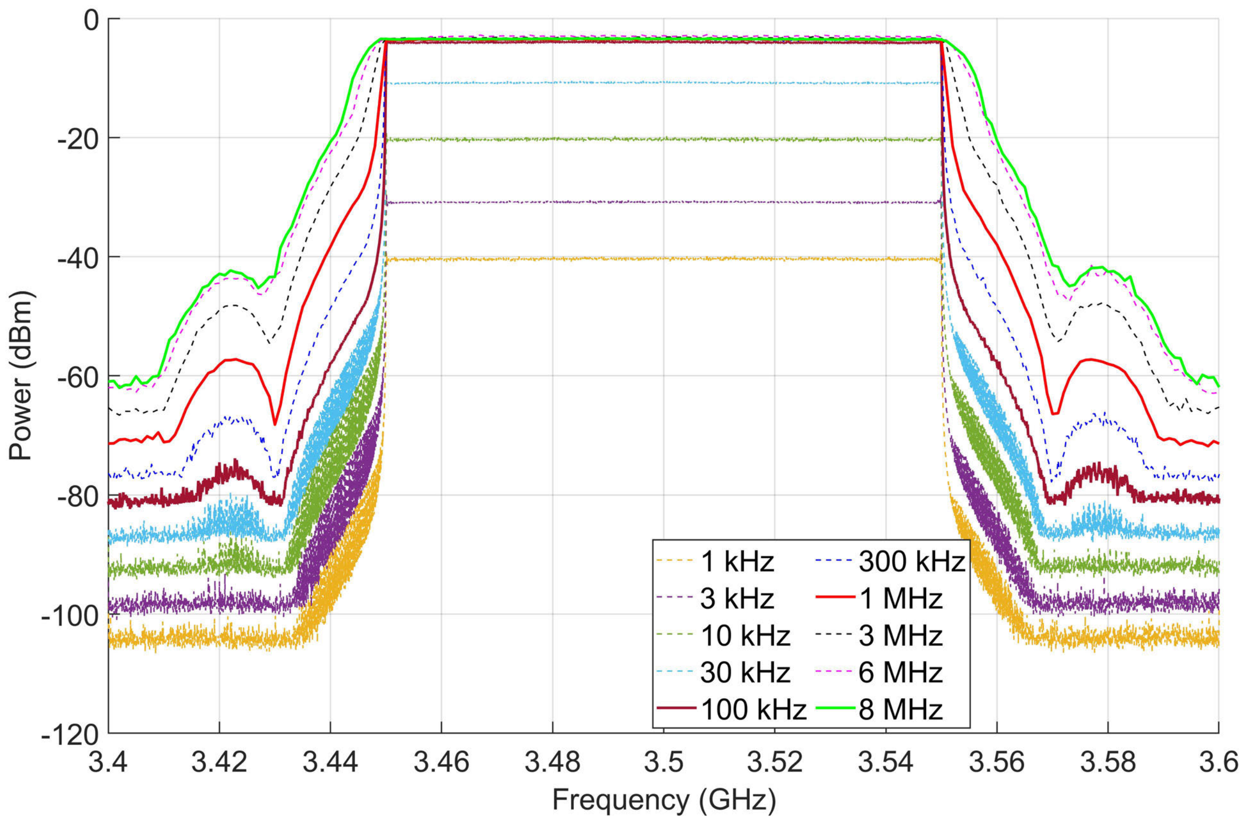

Figure 19. Spectrum emission measurements at multiple RBW settings for the pulse width–equal peak power test case from Table 4. RBW = 100 kHz, 1 MHz, and 10 MHz are the calculated optimum RBW settings for each of the three components. Empirically, 100 kHz is the optimum RBW setting.

Next, Figure 20 shows the emission spectrum of the compound waveform described in the pulse width–equal peak power test case from Table 4 along with the spectra of its component parts all measured at the empirical optimum RBW setting of 100 kHz. Through the fundamental frequency, the compound spectrum follows the PW = 10 ms spectrum. The PW = 100 µs and PW = 1 µs spectra appear to have lower power because RBW = 100 kHz is less than the optimum RBW for either of them.

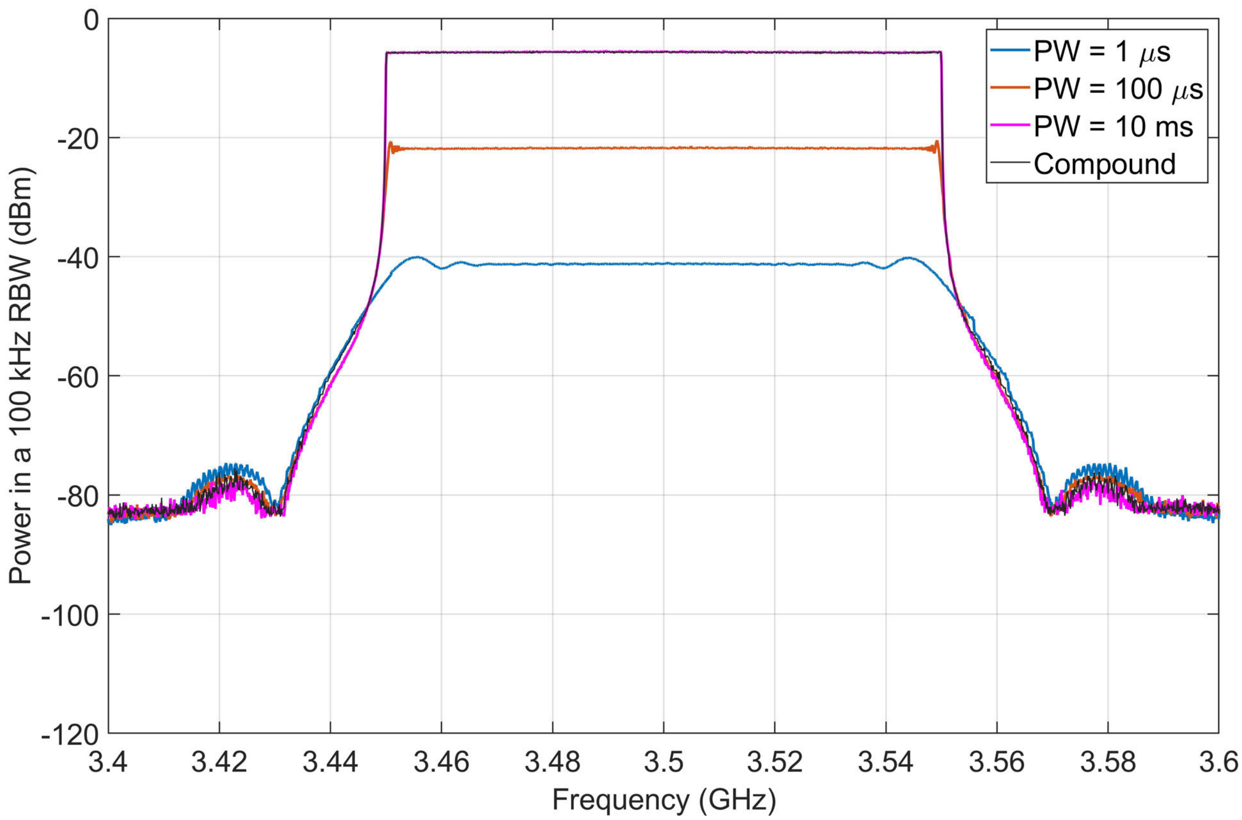

Figure 20. Test case pulse width–equal peak power from Table 4 with its single-pulse-parameter components at RBW = 100 kHz.

The spectra of the pulse width–unequal peak power test case from Table 4 measured at multiple RBW settings are shown in Figure 21. In this case, the relative peak power is adjusted such that each pulse type has a different peak power. The pulse with PW = 10 ms has 40 dB more peak power than the pulse with PW = 1 μs while the pulse with PW = 100 μs has 20 dB more peak power. The empirically observed optimum RBW for this test case is 100 kHz, corresponding to the pulse with the highest peak power.

Next, Figure 22 provides the spectrum of the pulse width–unequal peak power test case from Table 4 with the spectra of its component waveforms. In this case, the difference in peak power of each component pulse results in the PW = 1 μs and PW = 100 μs components not contributing to the compound spectrum at all. The compound spectrum is the same as the PW = 10 ms spectrum.

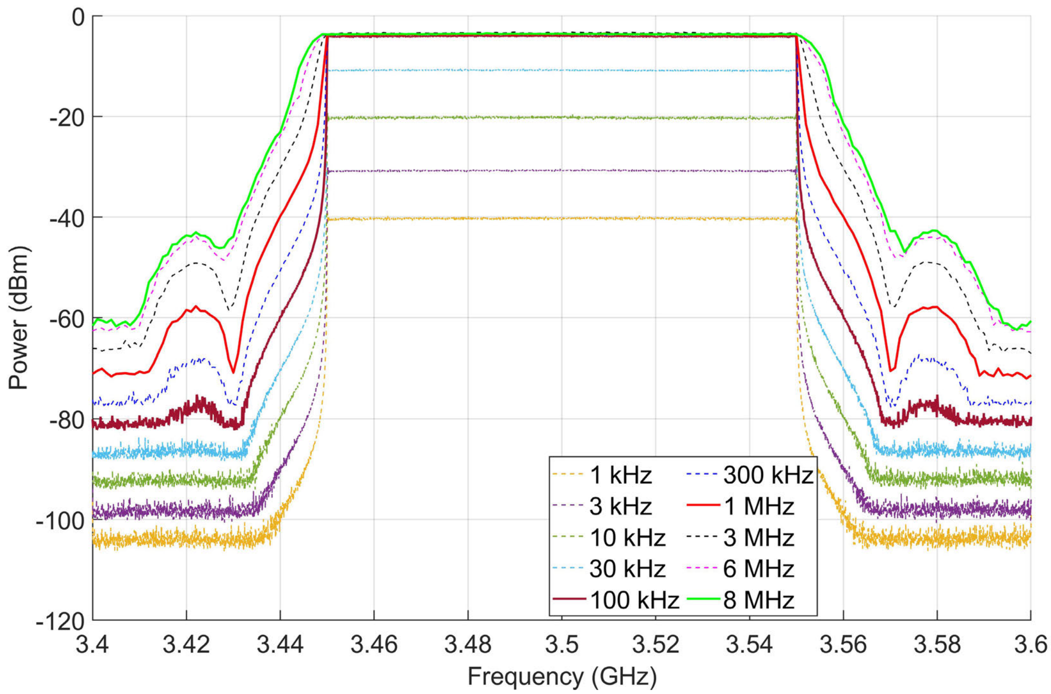

Figure 21. Spectrum emission measurements at multiple RBW settings for the pulse width–unequal peak power test case from Table 4. RBW = 100 kHz, 1 MHz, and 10 MHz are the calculated optimum RBW settings for each of the three components. Empirically, 100 kHz is the optimum RBW setting.

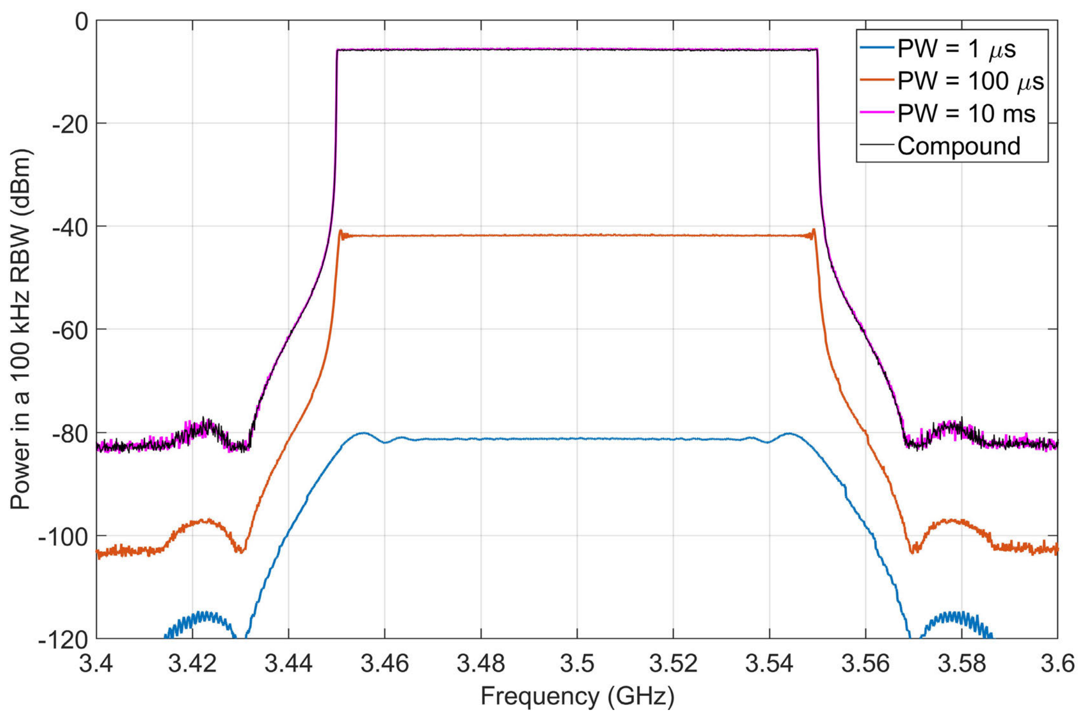

Figure 22. Test case pulse width–unequal peak power from Table 4 with its single-pulse-parameter components at RBW = 100 kHz.

The results from the chirp BW–equal peak power test case from Table 4 are shown in Figure 23. In this test case the PW is held constant and B_c is varied. For the component waveform with B_c = 1 MHz (waveform 17), the calculated optimum RBW is 100 kHz. The optimum RBW for the component waveform with B_c = 10 MHz (waveform 11) is 300 kHz and for the component waveform with B_c = 100 MHz (waveform 14), it is 1 MHz. Empirically, the correct RBW to use for this measurement is 30 kHz which agrees with what was seen for the individual component with B_c = 1 MHz.

In this test case, it is possible to see the contribution of each component with the three different B_c values. This is because of the way the peak power is spread out over the BW of the signal, or PSD (power/B_c). Because the component pulses contain the same peak power, they appear at different power levels because they have different PSDs. For waveform 17, all the power in the pulse is spread out over 1 MHz. The power in waveform 11 is spread out over 10 MHz, which is 10 times wider than 1 MHz and which is why there is a 10 dB reduction in power from waveform 17. B_c increases by 10 times again going from waveform 11 to waveform 14, so there is another 10 dB reduction in power.

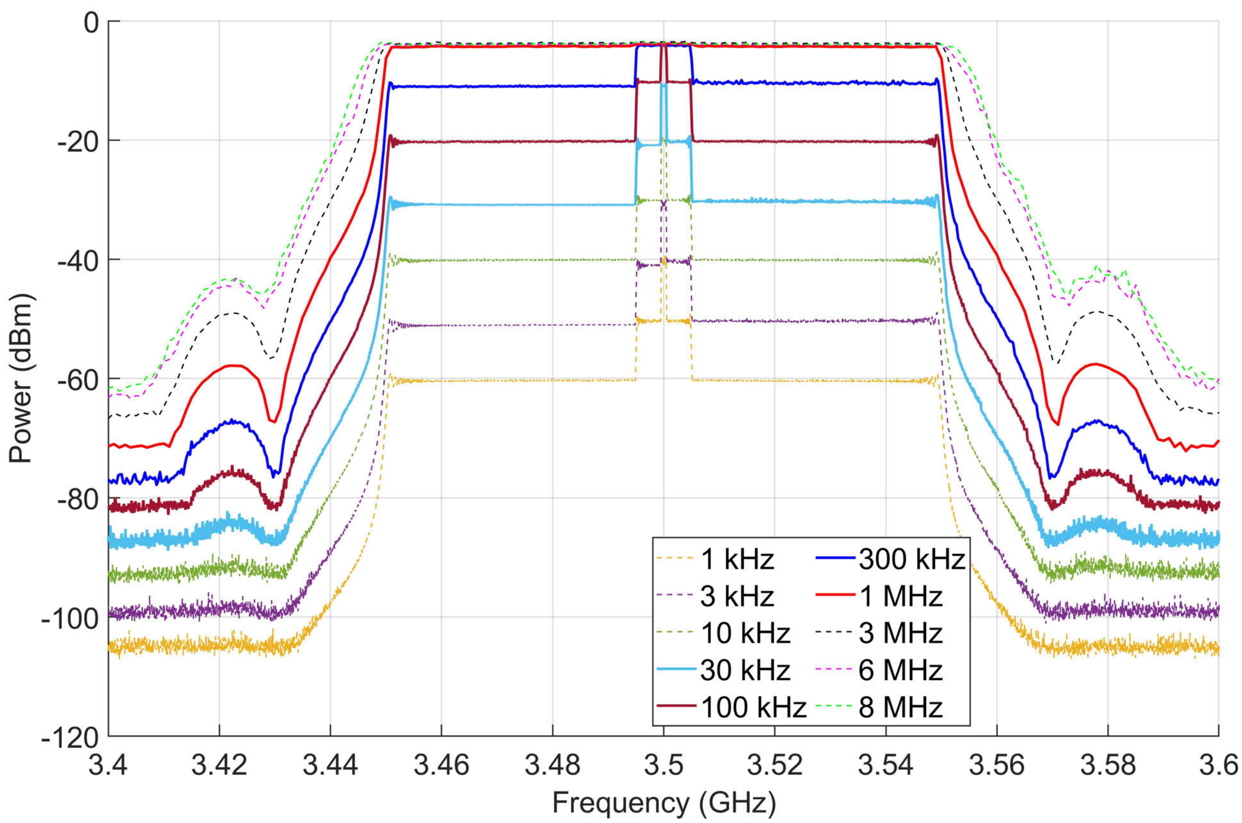

Figure 23. Spectrum emission measurements at multiple RBW settings for the chirp BW–equal peak power test case from Table 4. RBW = 100 kHz, 300 kHz, and 1 MHz are the calculated optimum RBW settings for each of the three components. Empirically, 30 kHz is the optimum RBW setting.

Next, Figure 24 shows the compound spectrum with its components measured in a 30 kHz RBW. In this figure, it is clear how each of the components contributes to the compound spectrum. As seen before, the compound spectrum follows the maximum of the three components through the fundamental and across the chirp BW.

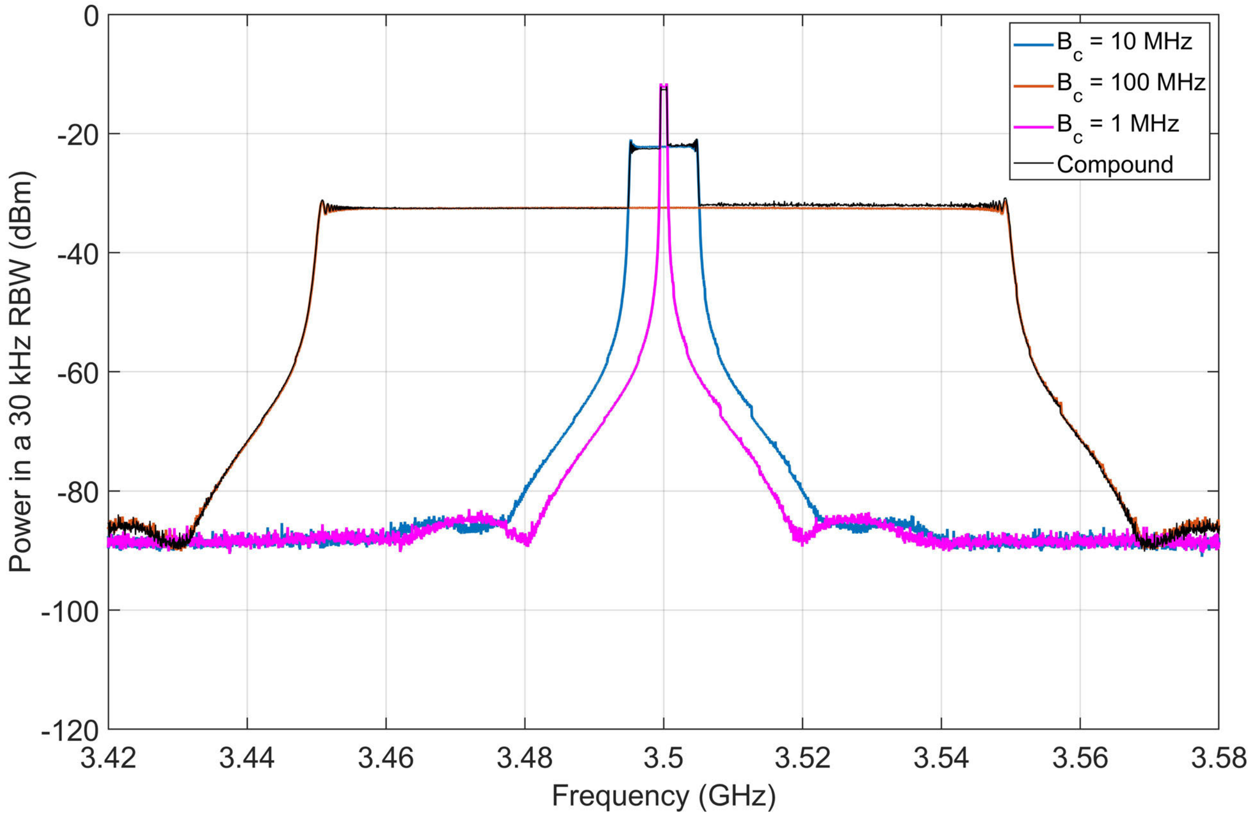

Figure 24. Test case chirp BW–equal peak power from Table 4 with its single-pulse-parameter components at RBW = 30 kHz.

For the final test case in Table 4, the same waveforms from the previous case were used except the relative peak power of the pulses was adjusted such that the PSD was equal for all three waveform components at the carrier. The spectra of the resultant compound waveform at multiple RBW settings are shown in Figure 25. The calculated optimum RBW settings are the same for this test case as for the previous one.

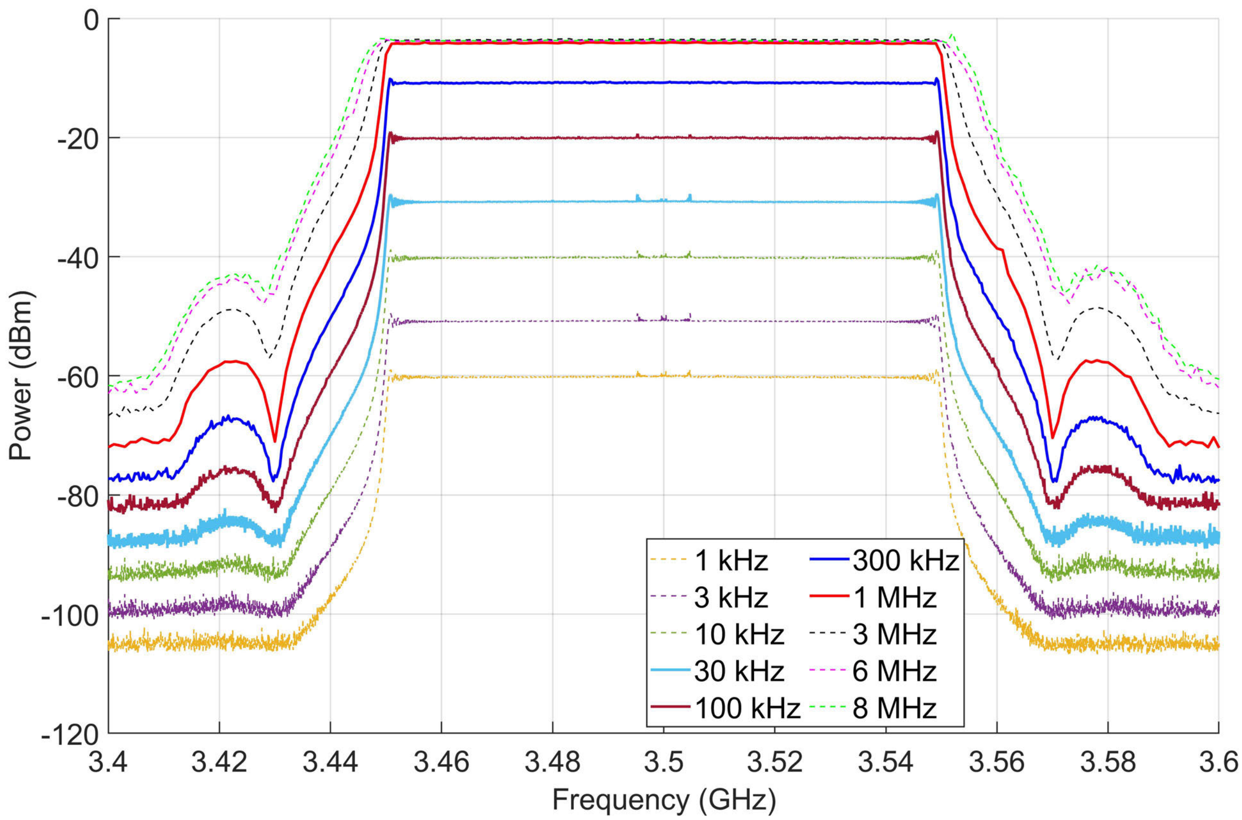

Figure 25. Spectrum emission measurements at multiple RBW settings for the chirp BW–equal PSD test case from Table 4. RBW = 100 kHz, 300 kHz, and 1 MHz are the calculated optimum RBW settings for each of the three components.

This test case presents a dilemma when determining the optimum RBW empirically. If nothing were known about this waveform and a bandwidth progression measurement were performed, it would appear that 300 kHz, or even 1 MHz, would be the optimum RBW empirically. Since the waveform parameters are known and 30 kHz was the optimum empirical RBW for the previous test case, the compound waveform with its component waveform spectra are presented in Figure 26 at RBW = 30 kHz. Using this RBW does present some small features created by the components with smaller chirp BWs near the center of the compound spectrum. Figure 27 shows the compound spectrum with its component waveforms measured with RBW = 300 kHz. If this RBW is used, then the spectra of the Bc = 10 MHz and Bc = 1 MHz components no longer contribute to the spectrum of the compound waveform at all.

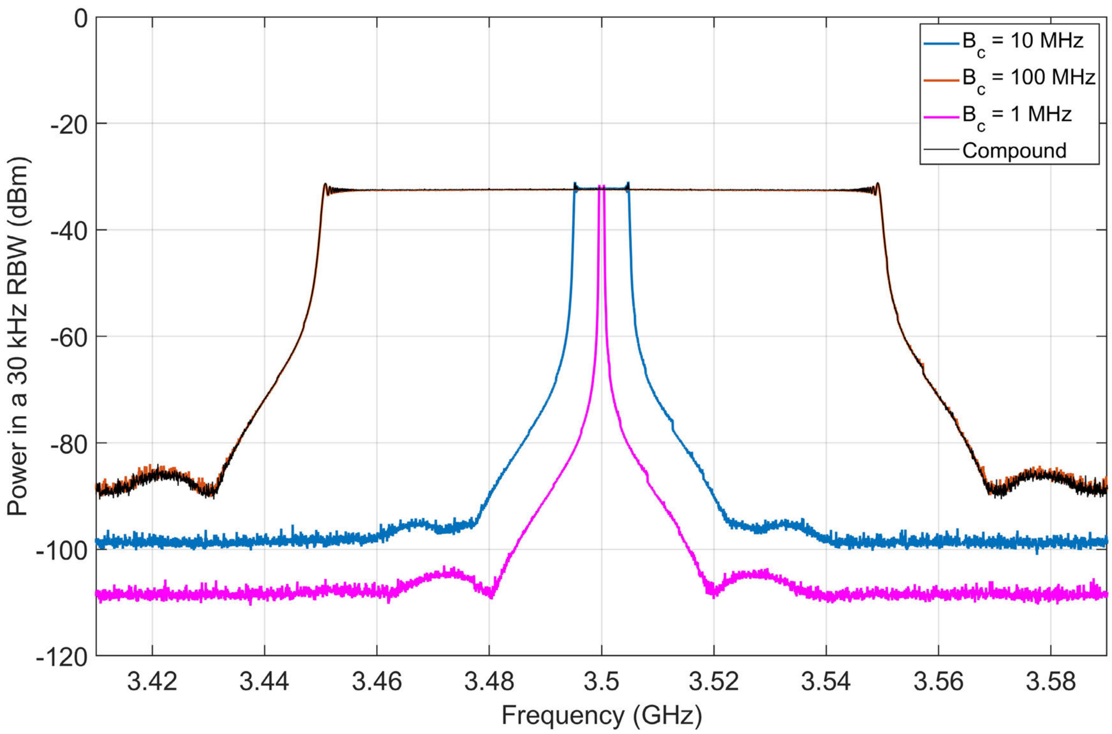

Figure 26. Test case chirp BW–equal PSD from Table 4 with its single-pulse-parameter components at RBW = 30 kHz.

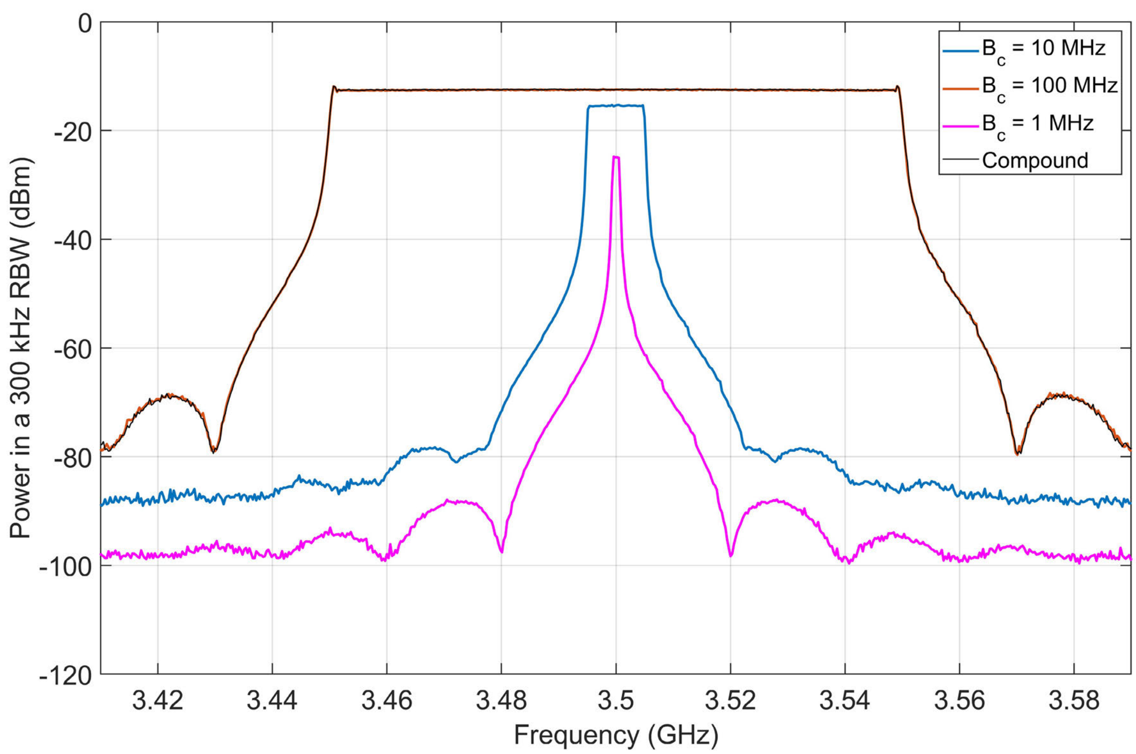

Figure 27. Test case chirp BW–equal PSD from Table 4 with its single-pulse-parameter components at RBW = 300 kHz.

3.2.3 Effects of Pulse Parameters on Q3N Emission Spectrum

The effects of B_c on the spectrum have been demonstrated throughout Section 3.2. The larger the B_c, the wider the measured spectrum is across the center. One thing to note is that the relative peak power in the components of the compound waveform can have a significant effect on the compound spectrum. Depending on the peak power in the component waveforms, the compound spectrum may exhibit characteristics from all the components or only one if there is one component that has significantly higher peak power than the others. This can be seen when comparing Figure 22 to Figure 24.

The primary effect PW has when measuring spectrum is on choosing the optimal RBW setting. The shorter the PW, the greater the RBW setting, can be as seen in (2). The full derivation and explanation of the approximation that (2) provides can be found in [3].

3.3 Compound Waveform Results Both P0N and Q3N Component Pulses

Compound waveforms containing a P0N pulse followed by a Q3N pulse were created by combining pulses from Tables 1 and 3. The only difference from these tables is that the bursts do not contain 20 pulses. Instead, the number of pulses is determined by the ratio provided in Table 5, which lists all the combinations that were chosen to create the compound waveforms. In all cases, there is only a single P0N pulse followed by the number of Q3N pulses shown in the ratio column of Table 5. For most cases the ratio is 1:1. This pattern is repeated continuously throughout the entire spectrum measurement.

This section provides the results of measuring the spectra of these multi-pulse-type compound waveforms at multiple RBW settings, making it possible to empirically determine the optimum RBW. The compound waveform is then presented at its optimum RBW with its individual P0N and Q3N components. Finally, the effect of the ratio of Q3N to P0N pulses is examined.

3.3.1 Compound Waveform Emission Measurements at Several RBWs

The compound radar waveforms described in Table 5 were measured at multiple RBW settings. The results of these measurements are presented here. Like the results in the previous sections, the calculated optimum RBW settings of the components and the empirically observed optimum RBW of the compound waveform are highlighted in the figures. Only some of the compound waveforms are presented here. The remainder of the results are provided in Section B.1. For all the compound radar waveforms presented in this section $T_r = T_f = 50$ ns and the PRI is set such that the duty cycle is 10%.

The results of measuring waveform 19 from Table 5 are provided in Figure 28. This combines waveform 1 (PW = 1 µs) and waveform 10 (PW = 1 µs, B_c = 1 MHz) to create a compound radar waveform. The peak power of each component is the same for this waveform. In this case the calculated optimum RBW setting for both components is 1 MHz. This is the empirical optimum RBW as well.

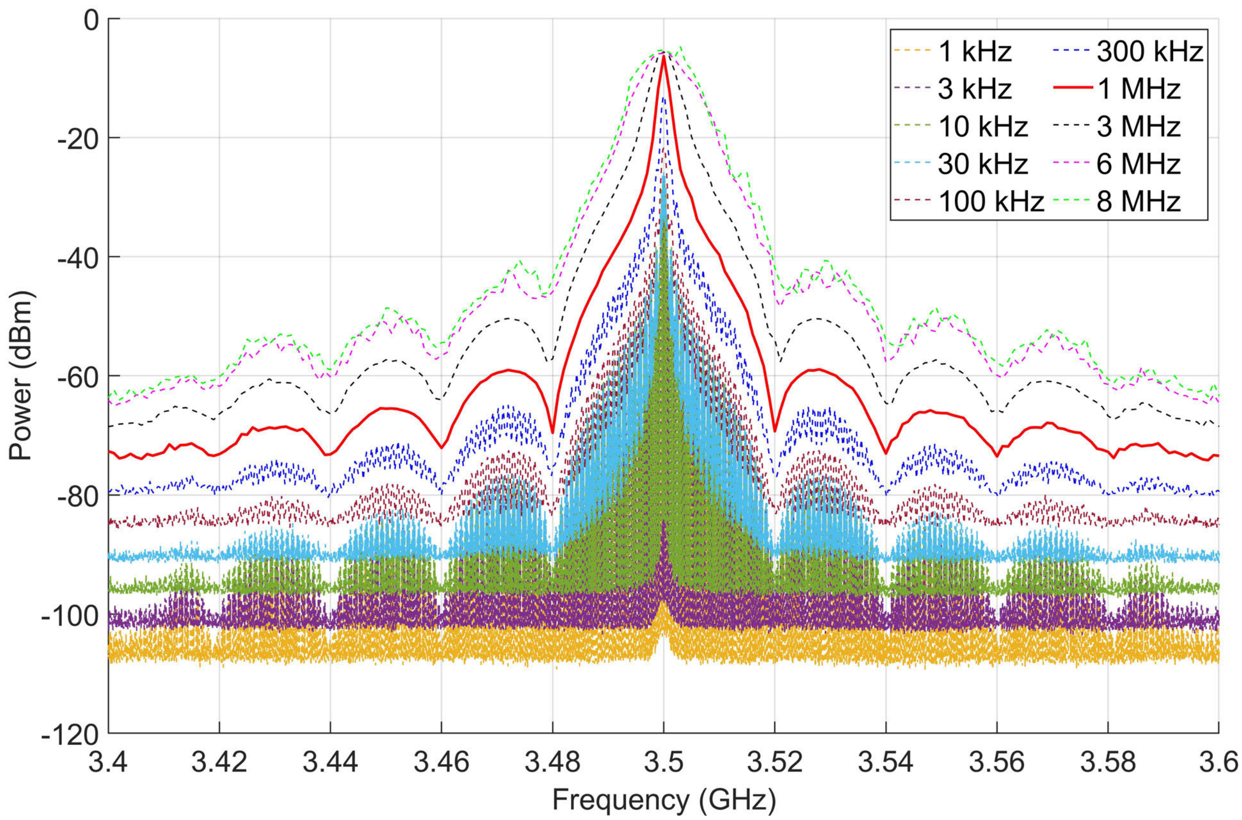

Figure 28. Spectrum emission measurements at multiple RBW settings of waveform 19 (equal peak power) from Table 5. RBW = 1 MHz is the calculated optimum RBW setting for each component and the compound waveform.

The results of measuring waveform 24 from Table 5 are provided in Figure 29. This combines waveform 1 (PW = 1 µs) and waveform 16 (PW = 10 µs, B_c = 100 MHz) to create a compound radar waveform. The peak power of each component is the same for this waveform. In this case, the calculated optimum RBW for the P0N component is 1 MHz and it is 10 MHz for the Q3N component. The PXA has a maximum RBW of 8 MHz, so this is what is highlighted in Figure 29. The empirical optimum RBW is 1 MHz. In this case, the P0N component can clearly be seen extending out of the Q3N spectrum at the center frequency, 3.5 GHz.

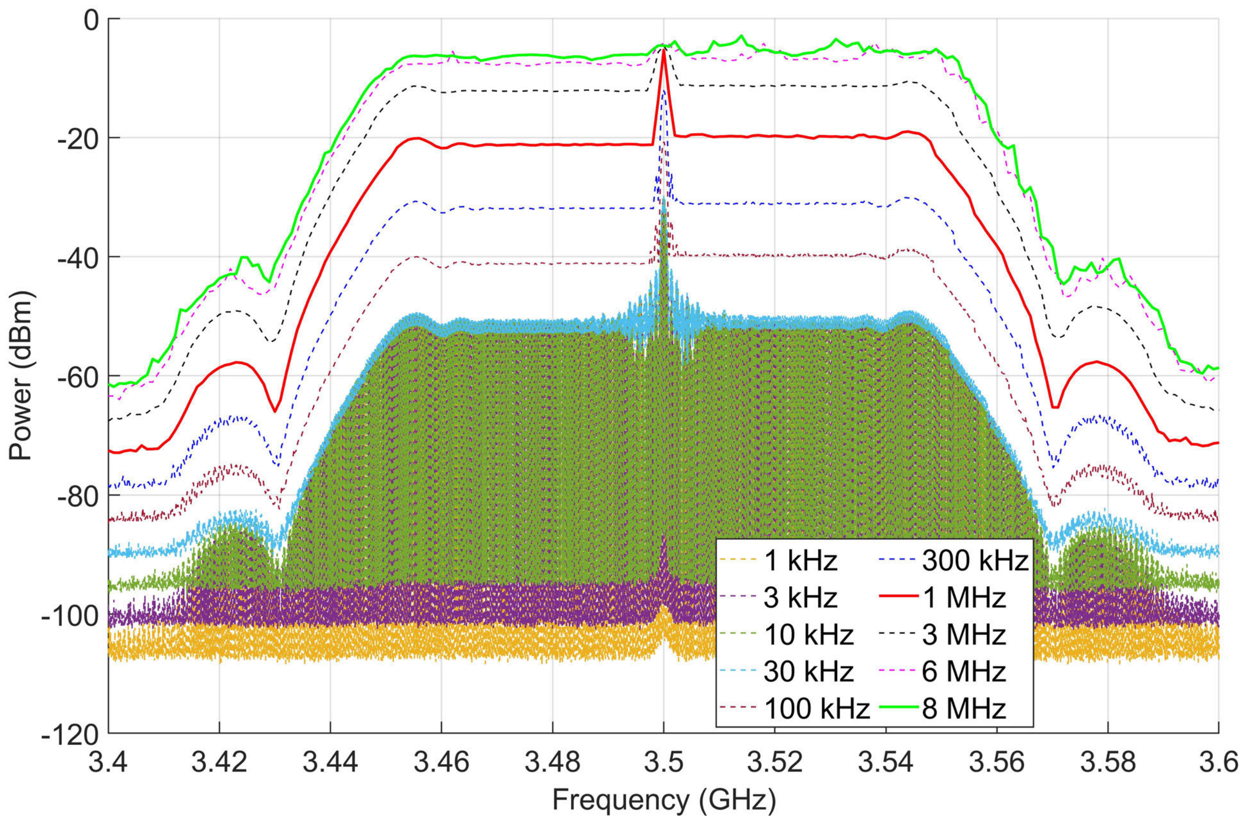

Figure 29. Spectrum emission measurements at multiple RBW settings of waveform 24 (equal peak power) from Table 5. RBW = 1 MHz is the calculated optimum RBW setting for the P0N component and RBW = 10 MHz for the Q3N component. The empirical optimum RBW is 1 MHz.

The results of measuring waveform 27 from Table 5 are provided in Figure 30. This combines waveform 1 (PW = 1 μs) and waveform 12 (PW = 10 ms, B_c = 100 MHz) to create a compound radar waveform. The peak power of each component is the same for this waveform. In this case, the calculated optimum RBW for the P0N component is 1 MHz and it is 100 kHz for the Q3N component. The empirical optimum RBW is 100 kHz. In this case, the P0N component does not appear to influence the compound radar spectrum at all.

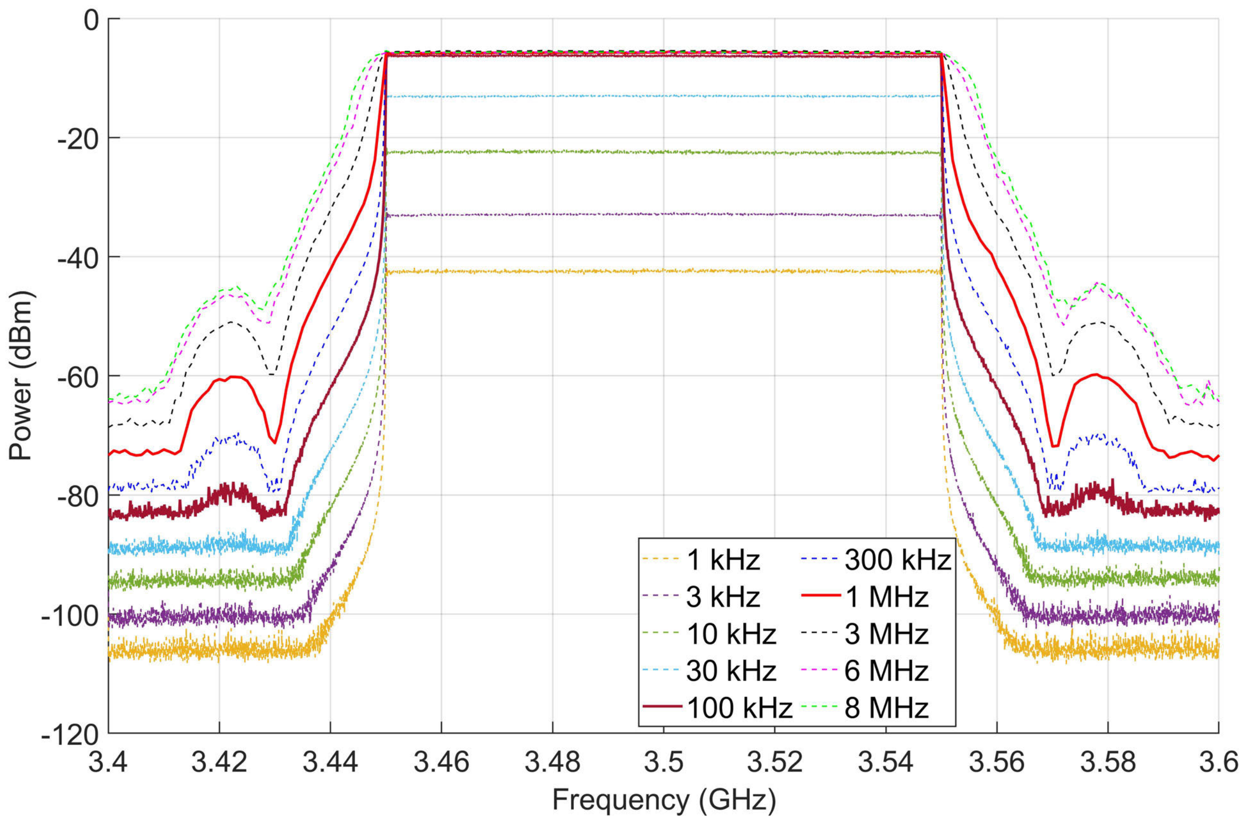

Figure 30. Spectrum emission measurements at multiple RBW settings of waveform 27 (equal peak power) from Table 5. RBW = 1 MHz is the calculated optimum RBW setting for the P0N component and RBW = 100 kHz for the Q3N component. The empirical optimum RBW is 100 kHz.

The results of measuring waveform 31 from Table 5 are provided in Figure 31. This combines waveform 8 (PW = 100 μs) and waveform 17 (PW = 100 μs, B_c = 1 MHz) to create a compound radar waveform. The peak power of each component is the same for this waveform. In this case, the calculated optimum RBW for the P0N component is 10 kHz and it is 100 kHz for the Q3N component. The empirical optimum RBW is 10 kHz. A close-up of the spectra around the fundamental is provided in Figure 32. The P0N Component can be seen extending out of the Q3N component at 3.5 GHz. If the optimum RBW for the Q3N component (100 kHz) were used for this measurement, the P0N component would not be visible at all.

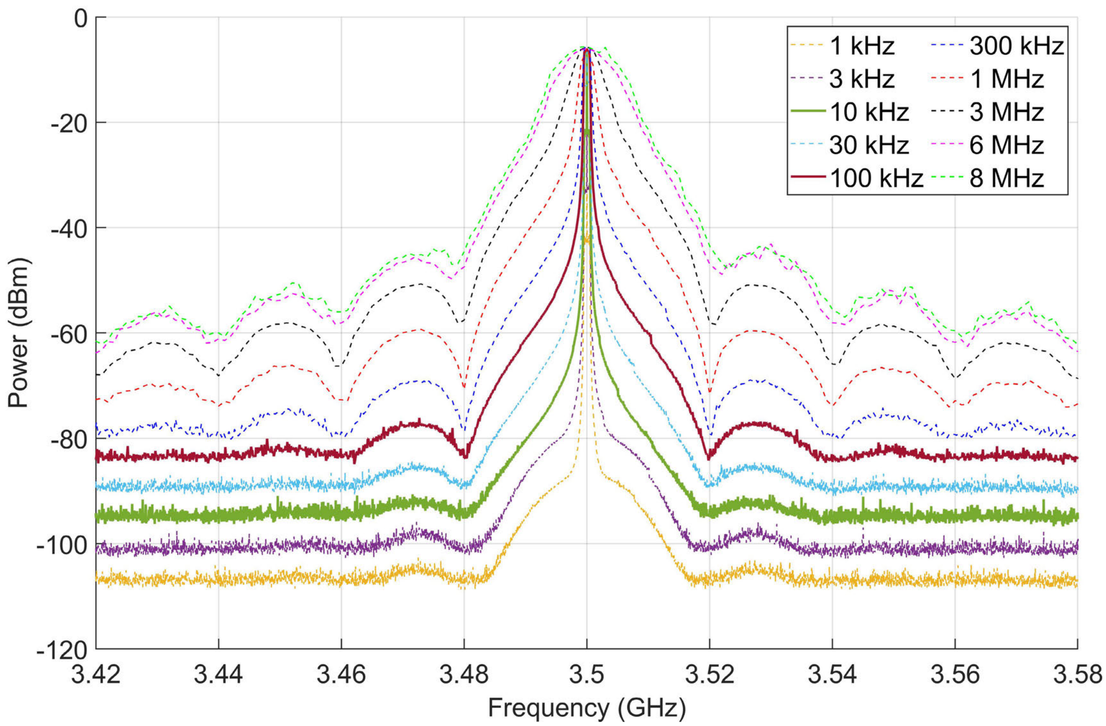

Figure 31. Spectrum measurements at multiple RBW settings of waveform 31 (equal peak power) from Table 5. RBW = 10 kHz is the calculated optimum RBW for the P0N component and RBW = 100 kHz for the Q3N component. The empirical optimum RBW is 10 kHz.

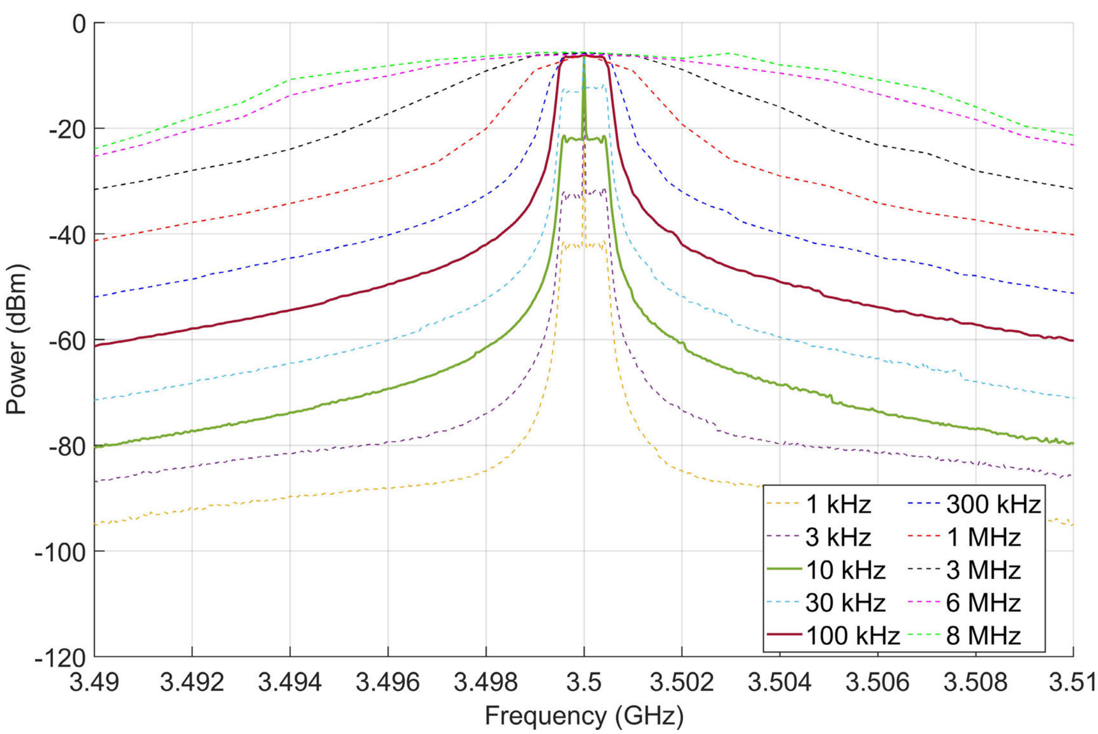

Figure 32. Close-up of the spectra from Figure 31 near the fundamental so that the features can be seen more clearly.

The results of measuring waveform 32 from Table 5 are provided in Figure 33. This combines waveform 8 (PW = 100 µs) and waveform 15 (PW = 10 ms, B_c = 1 MHz) to create a compound radar waveform. In this case, the calculated optimum RBW for both the P0N and Q3N components is 10 kHz. The empirical optimum RBW is also 10 kHz. A close-up of the spectra around the fundamental is provided in Figure 34. For this test case, the peak power of each component is the same. In the next case that is presented, the same components are used but the peak power of each of the components is not the same.

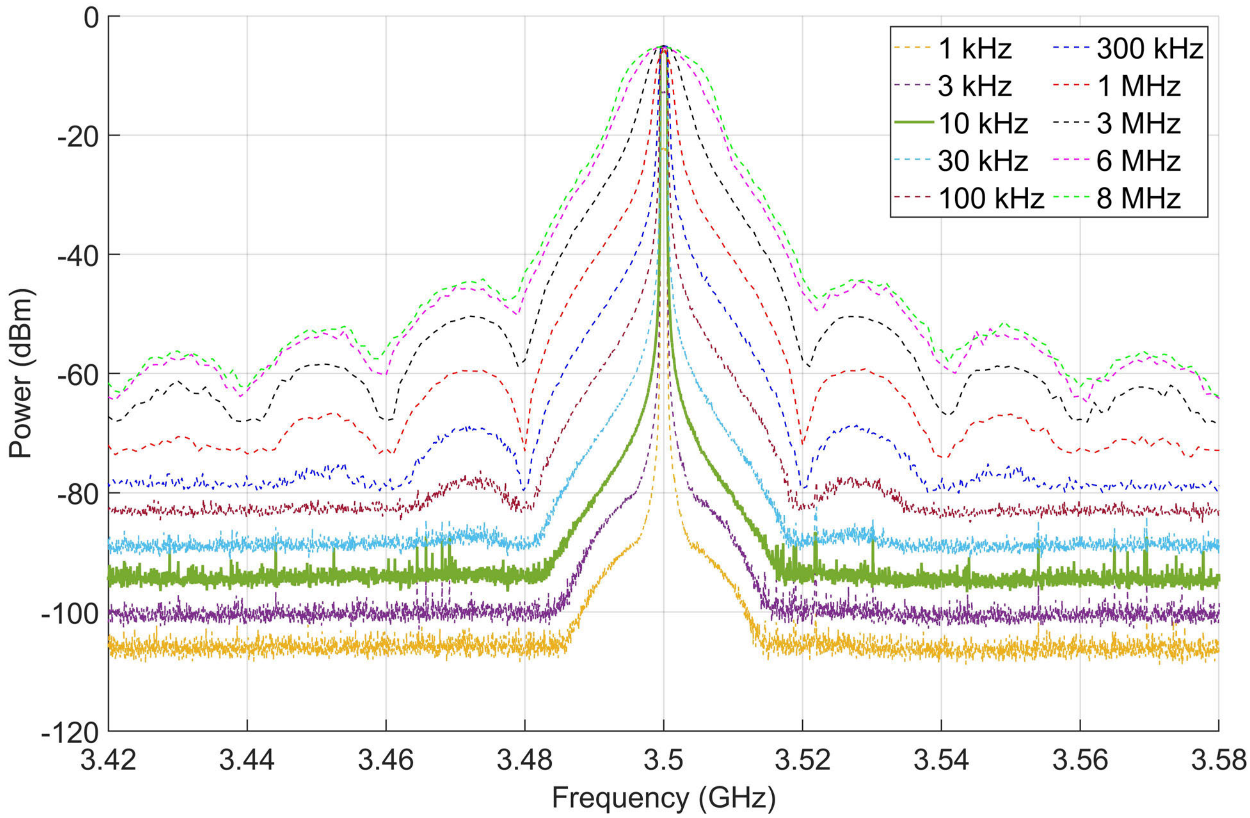

Figure 33. Spectrum emission measurements at multiple RBW settings of waveform 32 (equal peak power) from Table 5. RBW = 10 kHz is the calculated optimum RBW setting for the P0N component and RBW = 100 kHz for the Q3N component. The empirical optimum RBW is 10 kHz.

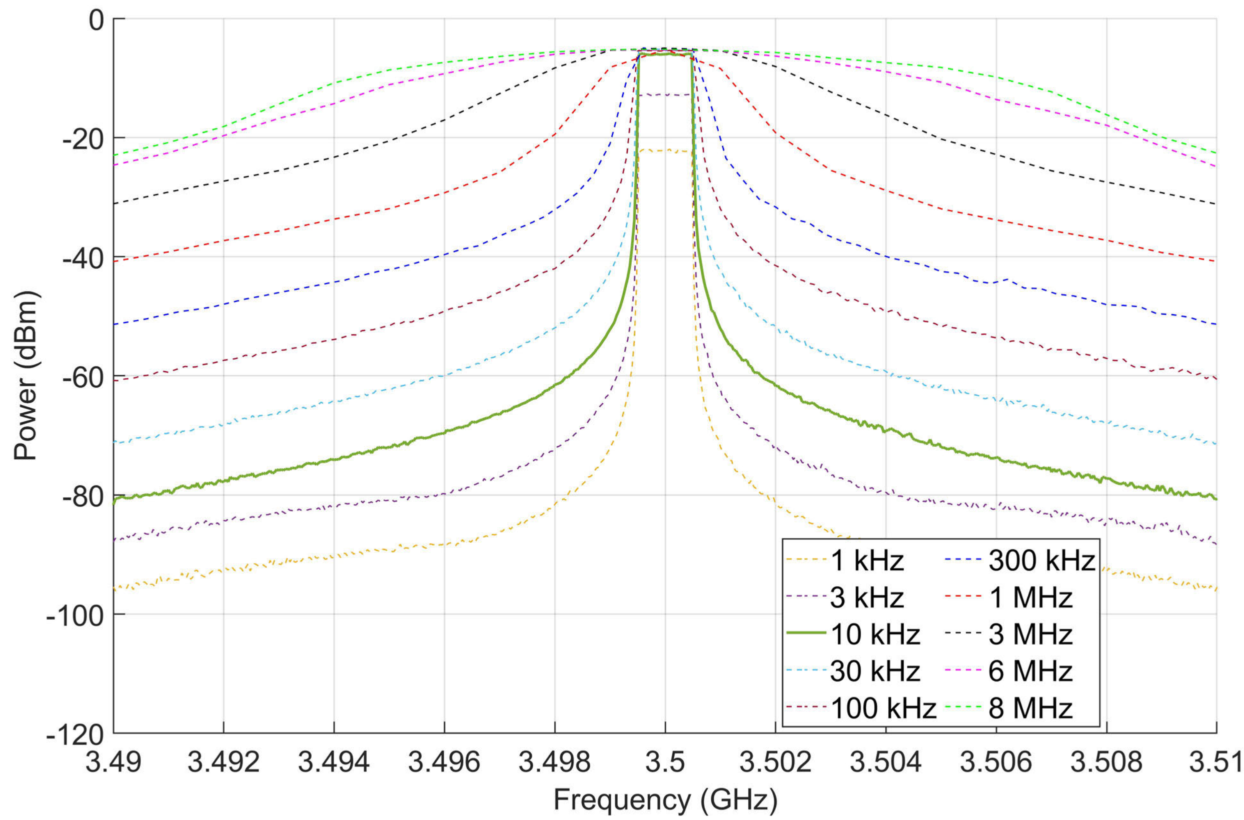

Figure 34. Close-up of the spectra from Figure 33 near the fundamental so that the features can be seen more clearly.

The results of measuring waveform 33 from Table 5 are provided in Figure 35. This combines waveform 8 (PW = 100 µs) and waveform 15 (PW = 10 ms, B_c = 1 MHz) to create a compound radar waveform. These are the same component waveforms used to create waveform 32, but in this case, the peak power of each component is not the same. Following the methods described in Section 2.2.1 the Q3N component has 20 dB more peak power than the P0N component.

Like the previous case, the calculated optimum RBW for both the P0N and Q3N components is 10 kHz. The empirical optimum RBW is also 10 kHz. A close-up of the spectra around the fundamental is provided in Figure 34. When comparing waveform 33 to 32, it does not appear that the difference in peak power in the pulses changes the spectrum. Figure 36 provides a close-up of the fundamental to provide more detail.

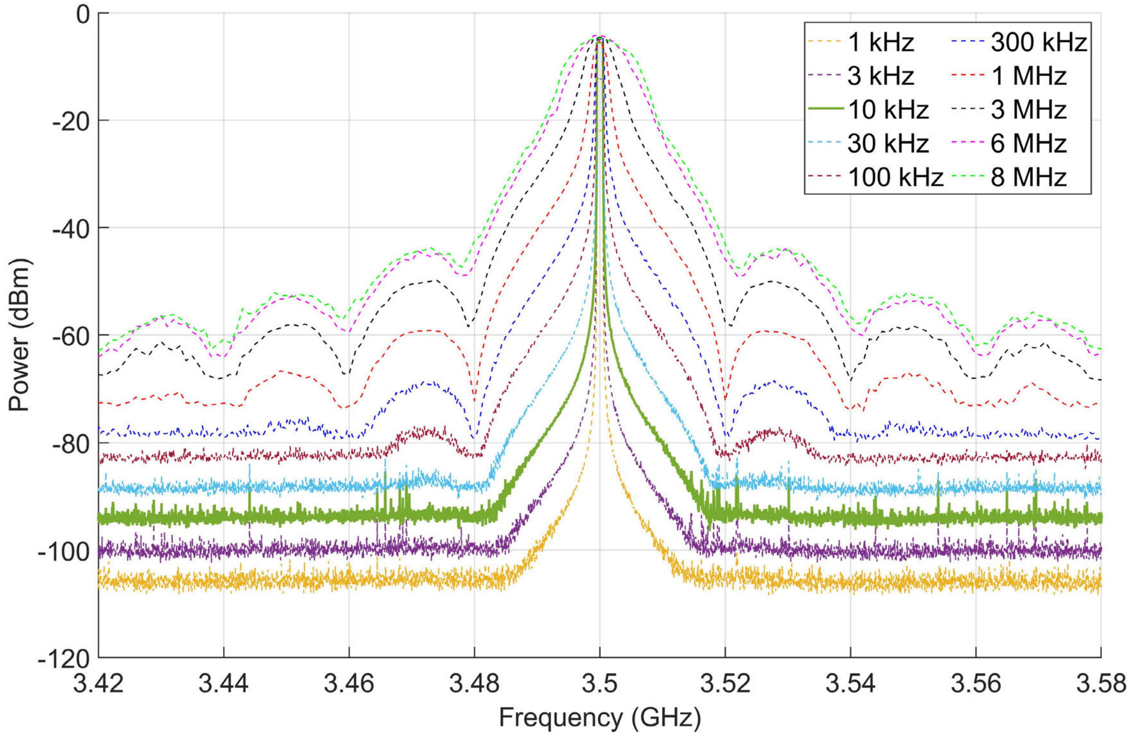

Figure 35. Spectrum measurements at multiple RBW settings of waveform 33 (unequal peak power) from Table 5. RBW = 10 kHz is the calculated optimum RBW for the P0N component and RBW = 100 kHz for the Q3N component. The empirical optimum RBW is 10 kHz.

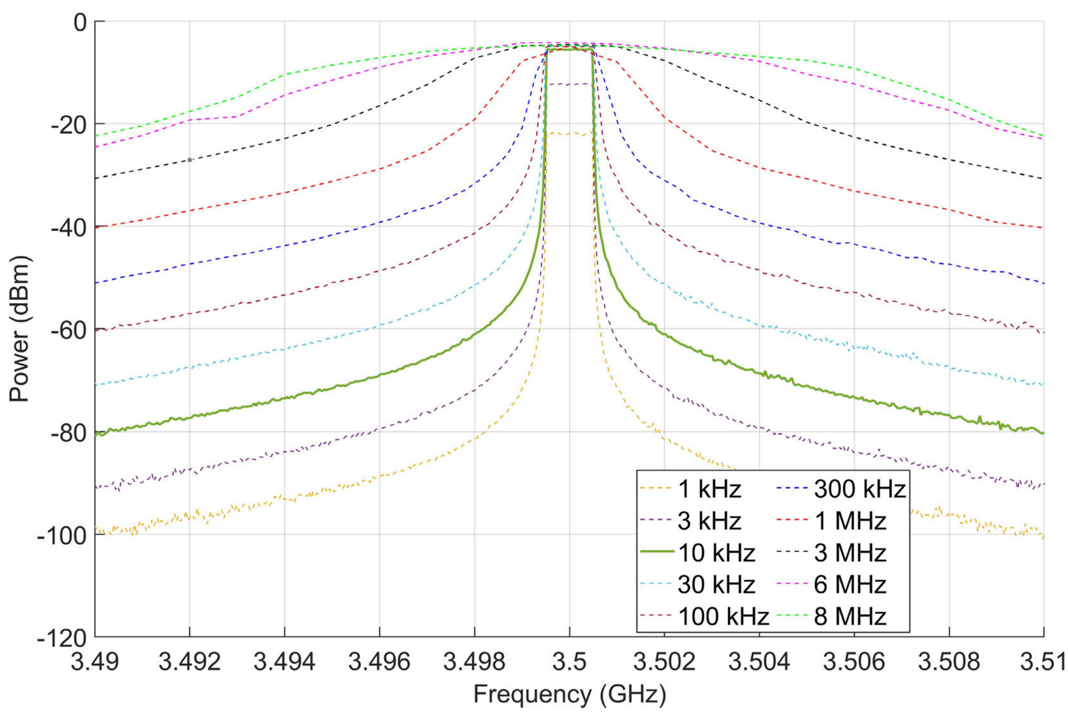

Figure 36. Close-up of the spectra from Figure 35 near the fundamental so that the features can be seen more clearly.

The results of measuring waveform 42 from Table 5 are provided in Figure 37. This combines waveform 6 (PW = 1 ms) and waveform 17 (PW = 100 μs, B_c = 1 MHz) to create a compound radar waveform. The P0N pulse has 10 dB more peak power than the Q3N pulse. In this case, the calculated optimum RBW for the P0N component is 1 kHz and it is 100 kHz for the Q3N component. The empirical optimum RBW is 1 kHz for the compound waveform. The empirical optimum RBW for the Q3N component is 30 kHz. In the close-up of the fundamental frequency shown in Figure 38, the P0N spectrum extends out of the Q3N spectrum at 3.5 GHz.

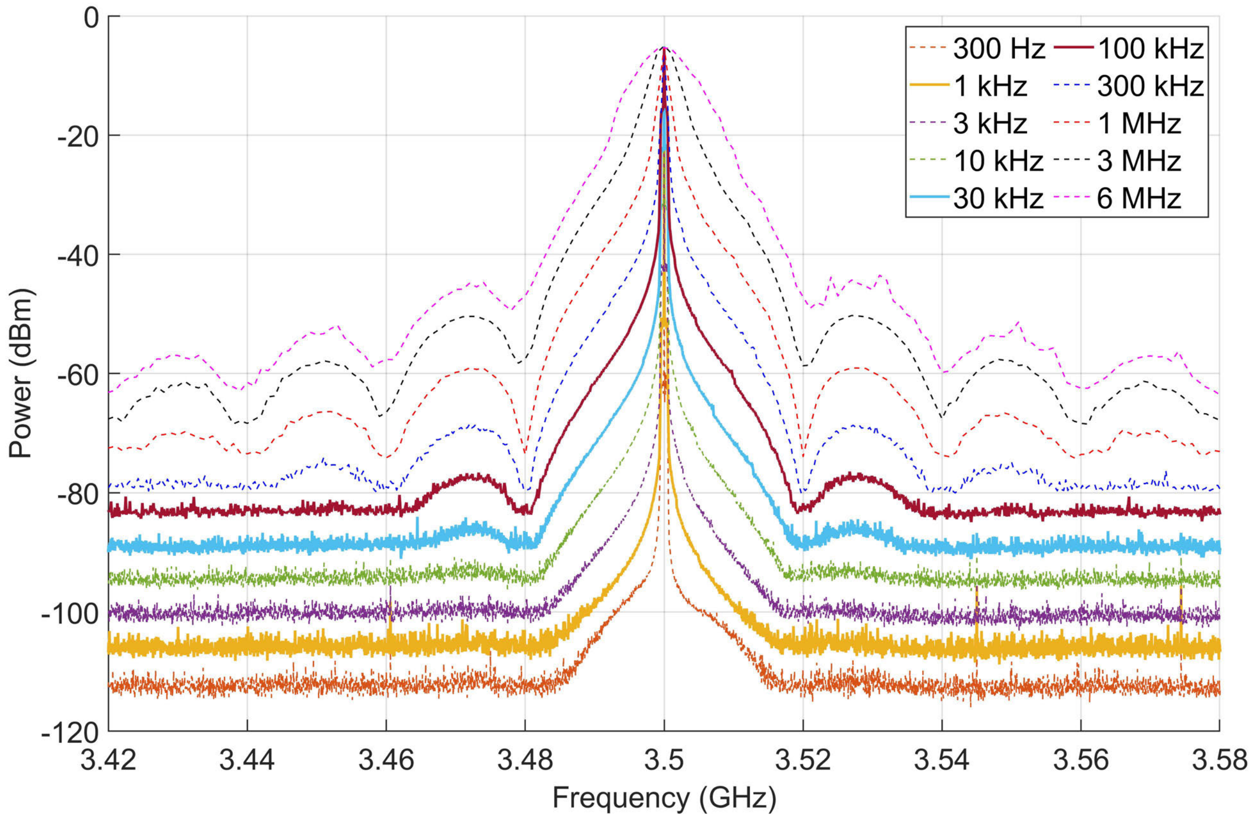

Figure 37. Spectrum emission measurements at multiple RBW settings of waveform 42 (unequal peak power) from Table 5. The calculated optimum RBW setting for the P0N component is 1 kHz and it is 100 kHz for the Q3N component. The empirical optimum RBW is 1 kHz.

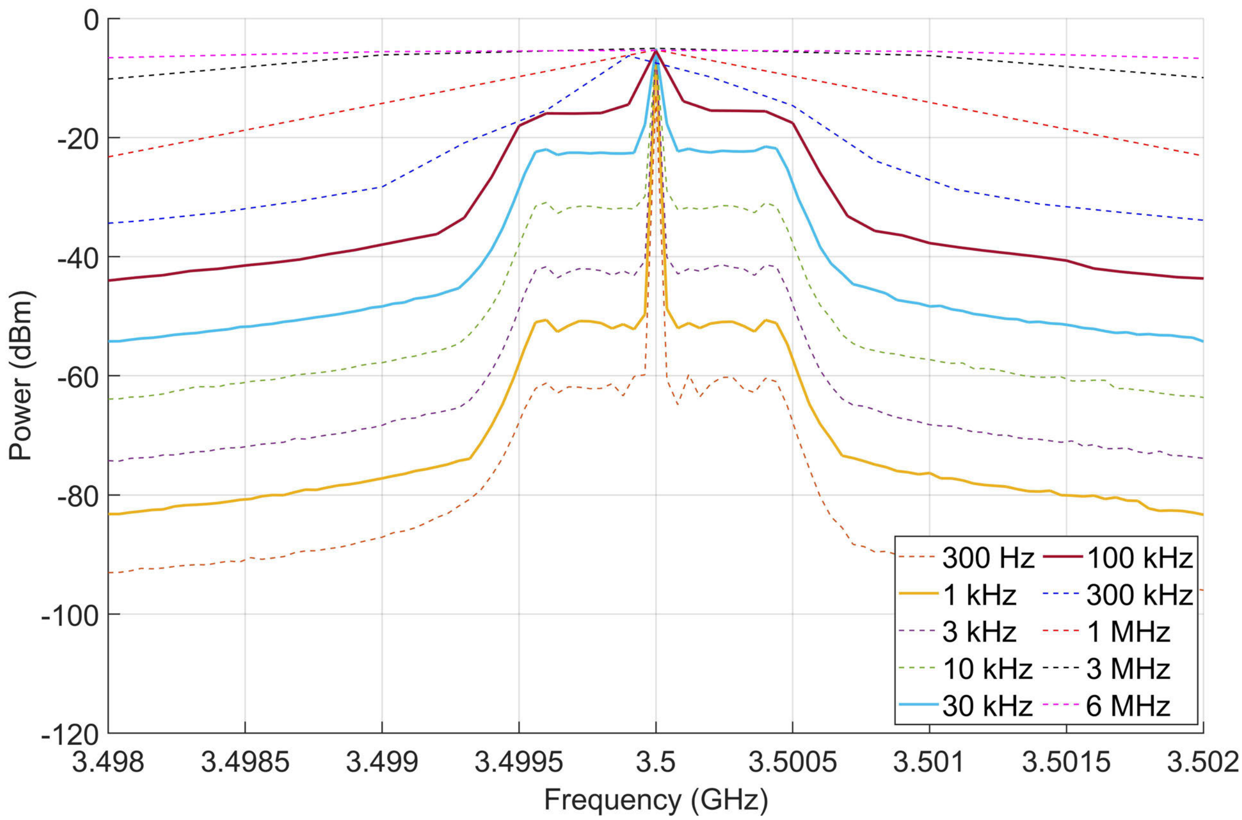

Figure 38. Close-up of the spectra from Figure 37 near the fundamental so that the features can be seen more clearly.

The results of measuring waveform 46 from Table 5 are provided in Figure 39. This combines waveform 6 (PW = 1 ms) and waveform 14 (PW = 100 µs, B_c = 100 MHz) to create a compound radar waveform. In this case, the calculated optimum RBW for the P0N component is 1 kHz and 1 MHz for the Q3N component. The empirical optimum RBW is 1 kHz for the compound spectrum. The empirical optimum RBW for the Q3N component is 30 kHz. For this test case, the peak power of each component is the same. In the next case that is presented, the same P0N and Q3N components are used but the peak power of each of the components is not the same.

The spectrum of the P0N component can be seen extending out of the Q3N spectrum at 3.5 GHz. A close-up of the spectra near the fundamental is provided in Figure 40. This close-up shows that 1 kHz is the optimum RBW, empirically.

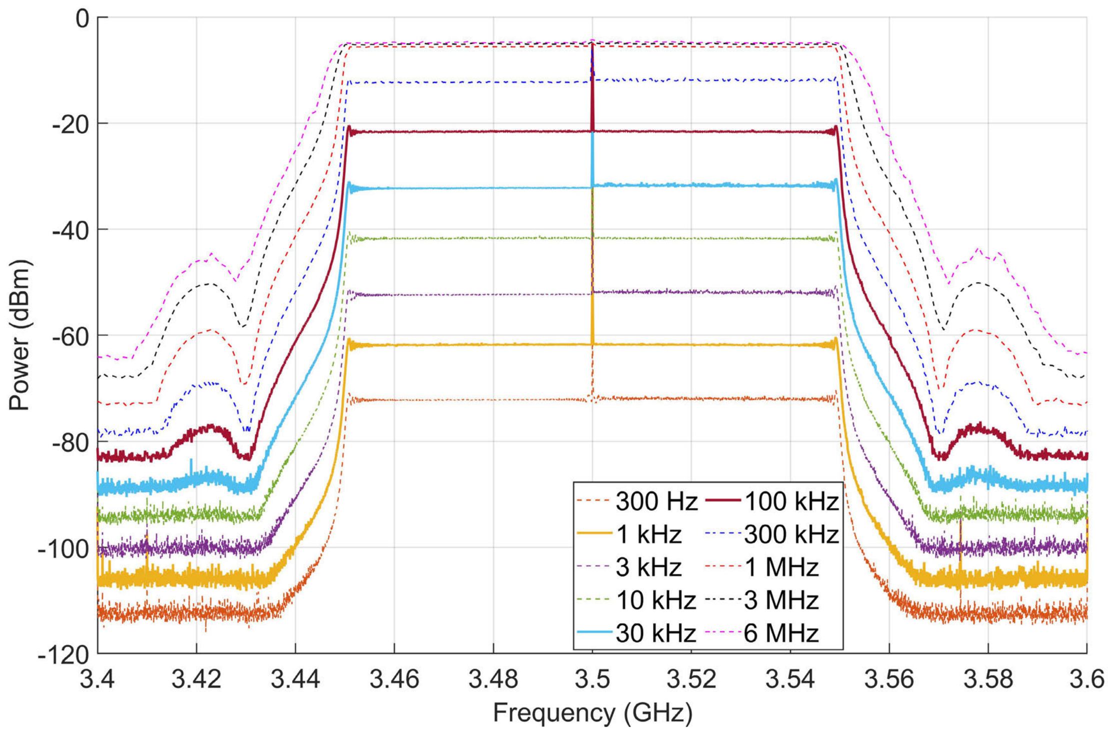

Figure 39. Spectrum emission measurements at multiple RBW settings of waveform 46 (equal peak power) from Table 5. The calculated optimum RBW setting for the P0N component is 1 kHz and it is 1 MHz for the Q3N component. The empirical optimum RBW is 1 kHz.

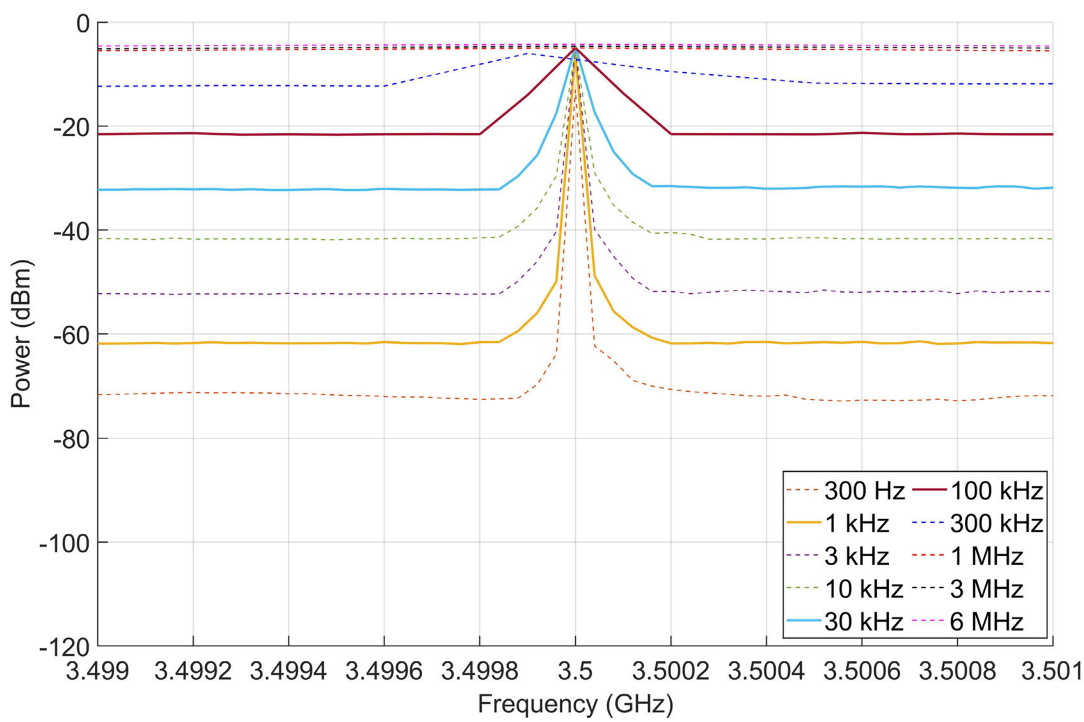

Figure 40. Close-up of the spectra from Figure 39 near the fundamental so that the features can be seen more clearly.

The results of measuring waveform 47 from Table 5 are provided in Figure 41. This combines waveform 6 (PW = 1 ms) and waveform 14 (PW = 100 μs, B_c = 100 MHz) to create a compound radar waveform. These are the same component waveforms used to create waveform 46, seen previously, but in this case the peak power of each component is not the same. TheP0N component has 10 dB more peak power than the Q3N component.

Like the previous case, the calculated optimum RBW for the P0N component is 1 kHz and for the Q3N component it is 1 MHz. The empirical optimum RBW is also 1 kHz for the compound waveform. When comparing waveform 46 to 47, the P0N spectrum is more prevalent in waveform 47. The P0N component is present in the spectrum no matter what RBW is used for waveform 47 (Figure 41). At RBW settings more than or equal to 1 MHz, the influence of the P0N component on the compound spectrum is barely noticeable for waveform 46 (Figure 39).

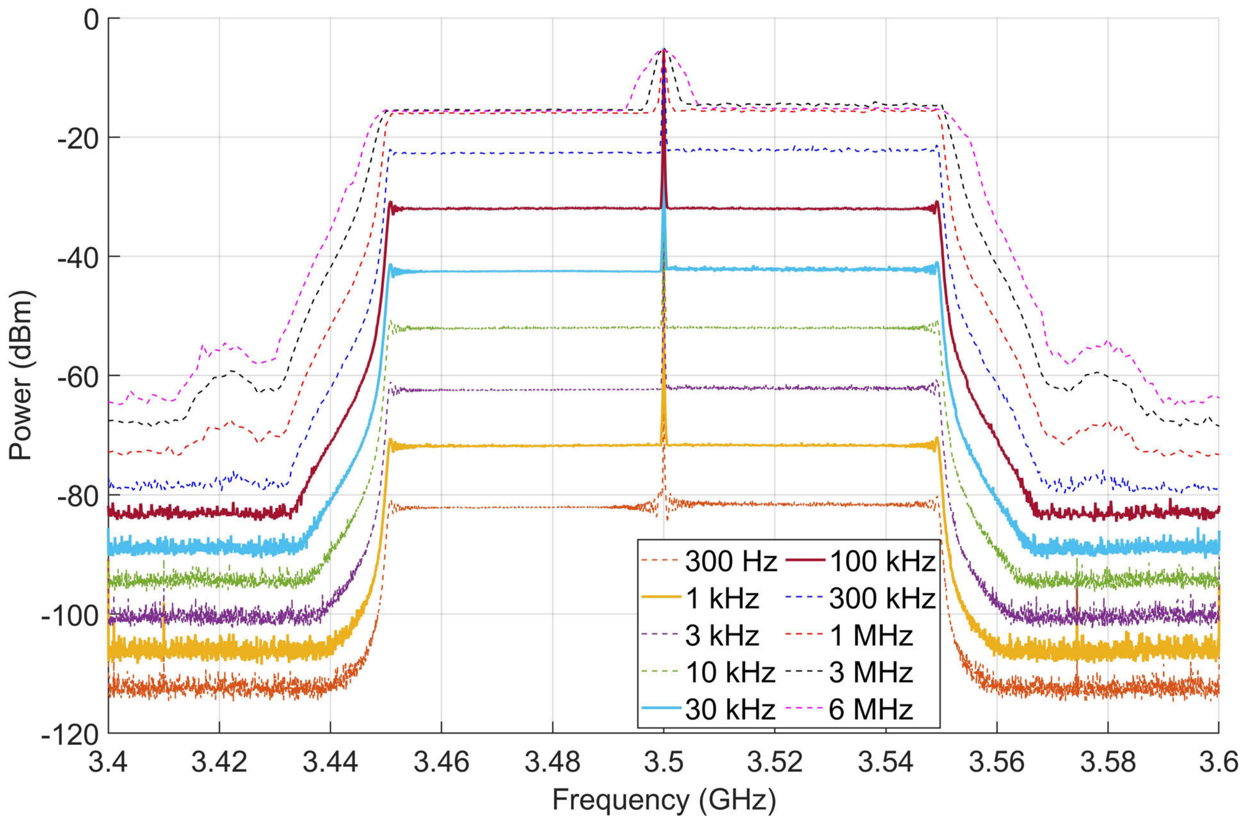

Figure 41. Spectrum emission measurements at multiple RBW settings of waveform 47 (unequal peak power) from Table 5. The calculated optimum RBW setting for the P0N component is 1 kHz and it is 1 MHz for the Q3N component. The empirical optimum RBW is 1 kHz.

Next, Table 8 provides the calculated and empirical optimum RBW settings for each of the component waveforms and the empirical optimum RBW for the compound spectrum resulting from those components. In every case the correct RBW to use to measure the compound spectrum is the minimum optimum RBW of its components. The remainder of the compound test cases measured at multiple RBW settings can be found in Section B.1.

Table 8. Summary of optimum RBW settings for the compound waveforms described in Table 5.

Waveform	P0N Component (kHz)	Q3N Component (kHz)		Compound (kHz)	Peak Power
	Calculated/Empirical	Calculated	Empirical		
19	1000	1000	1000	1000	Equal
20	1000	100	30	30	Equal
21	1000	100	30	30	Not Equal
22	1000	10	10	10	Equal
23	1000	10	10	10	Not Equal
24	1000	10000	8000*	1000	Equal
25	1000	1000	300	300	Equal
26	1000	1000	300	300	Not Equal
27	1000	100	100	100	Equal
28	1000	100	100	100	Not Equal
29	10	1000	1000	10	Equal
30	10	1000	1000	10	Not Equal
31	10	100	30	10	Equal
32	10	10	10	10	Equal
33	10	10	10	10	Not Equal
34	10	10000	8000*	10	Equal
35	10	10000	8000*	10	Not Equal
36	10	1000	300	10	Equal
37	10	100	100	10	Equal
38	10	100	100	10	Not Equal
39	1	1000	1000	1	Equal
40	1	1000	1000	1	Not Equal
41	1	100	30	1	Equal
42	1	100	30	1	Not Equal
43	1	10	10	1	Equal
44	1	10000	8000*	1	Equal
45	1	10000	8000*	1	Not Equal
46	1	1000	300	1	Equal
47	1	1000	300	1	Not Equal
48	1	100	100	1	Equal
49	1	100	100	1	Not Equal
50	1	10	10	1	Not Equal
* The PXA has a maximum RBW setting of 8 MHz so it was not possible to measure at RBW = 10 MHz.					

3.3.2 Spectra of Compound Waveforms with P0N and Q3N Components

In this section, the waveforms from the previous section are presented again measured at the empirically observed RBW along with their component parts. Figure 42 shows waveform 19 with its P0N and Q3N components measured with a RBW setting of 1 MHz. In this case, all three spectra are very similar.

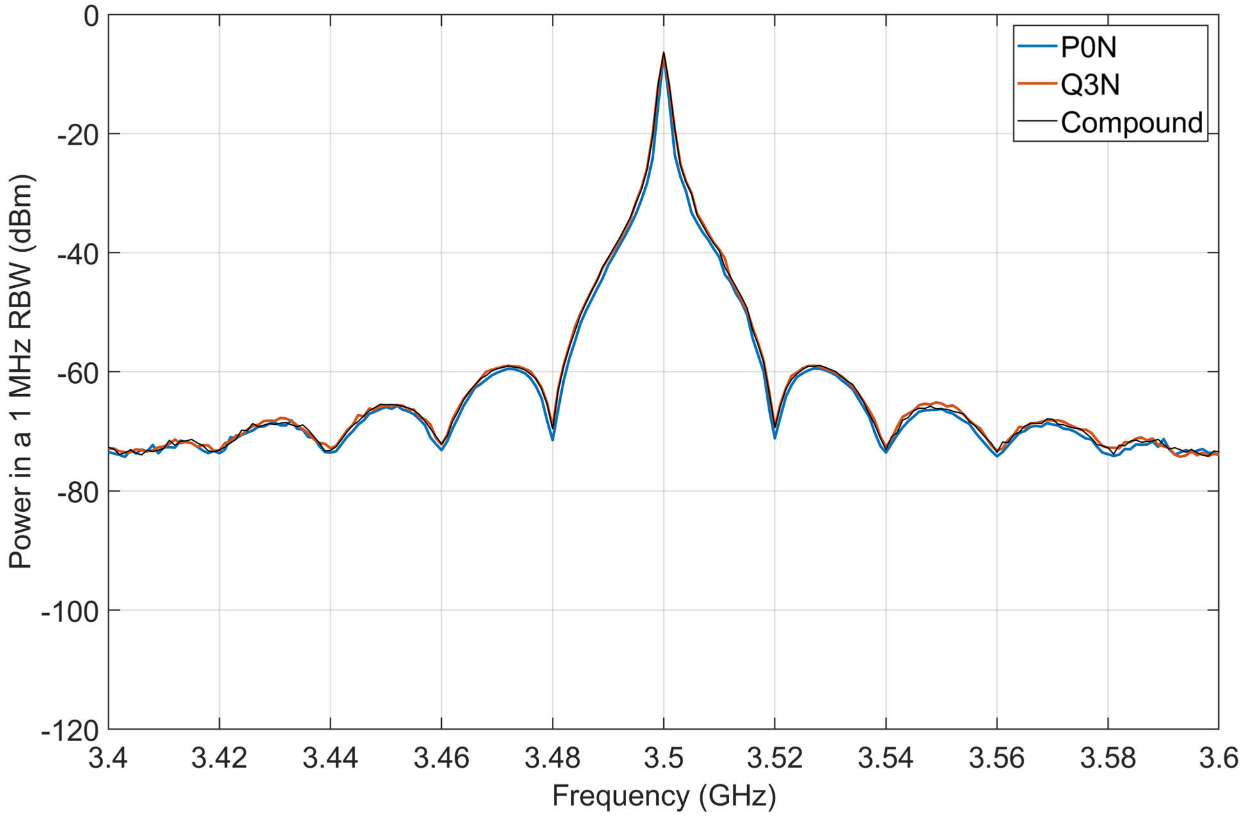

Figure 42. Spectrum measurement of waveform 19 (equal peak power) with its P0N and Q3N components at RBW = 1 MHz.

Figure 43 shows waveform 24 with its P0N and Q3N components measured with a RBW setting of 1 MHz. In this case, the compound spectrum follows the maximum of the component spectra. Near the fundamental the compound spectrum is shaped by the P0N component while everywhere else it follows the Q3N spectrum.[8]

[8] Note: the slight difference in the measured power of the compound spectrum from that of the Q3N spectrum above 3.5 GHz is an artifact of the automated measurement routine that was used to collect the data. More attenuation than was needed was applied above 3.5 GHz, allowing the noise of the measurement system to contribute to the measured power.

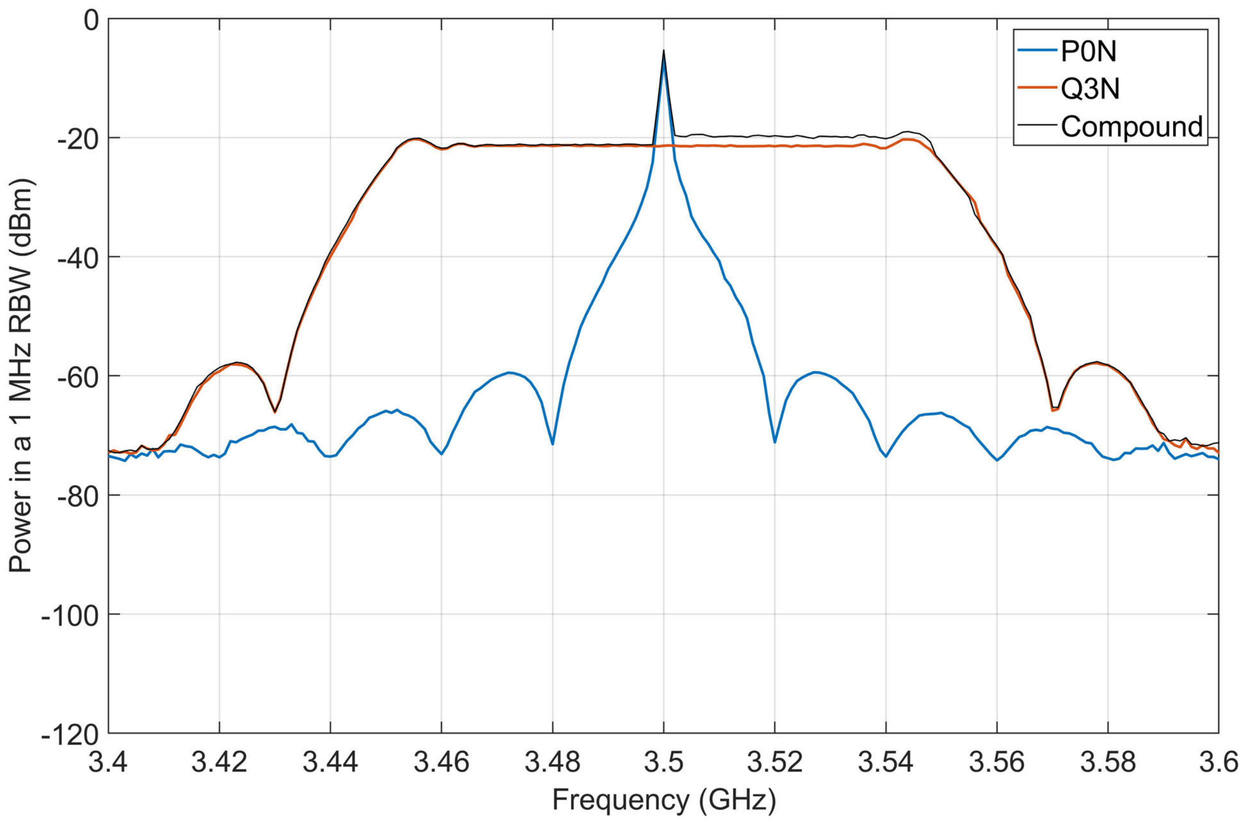

Figure 43. Spectrum measurement of waveform 24 (equal peak power) with its P0N and Q3N components at RBW = 1 MHz.

Figure 44 shows waveform 27 with its P0N and Q3N components measured with a RBW setting of 100 kHz. In this case, the compound spectrum is the same as the Q3N spectrum because the P0N spectrum is well below that of the Q3N spectrum.

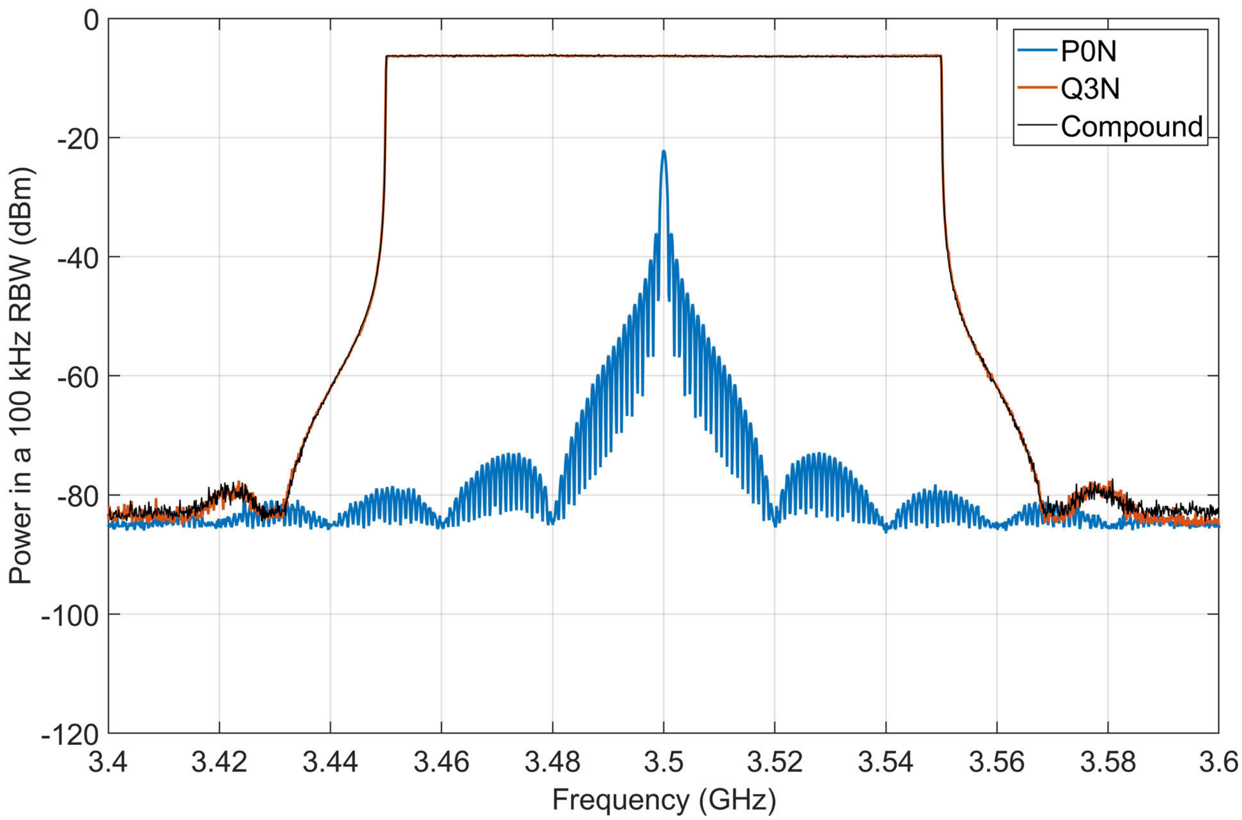

Figure 44. Spectrum measurement of waveform 27 (equal peak power) with its P0N and Q3N components at RBW = 100 kHz.

Next, Figure 45 shows waveform 31 with its P0N and Q3N components measured with a RBW setting of 10 kHz. In this case, the compound spectrum follows the maximum of its components. At the fundamental frequency, the P0N component dominates the spectrum and then drops down to where the Q3N component begins to dominate the compound waveform. At about ±10 MHz from the fundamental, all the spectra appear to be about the same. An enhanced view of the fundamental is provided in Figure 46 to clearly demonstrate this phenomenon.

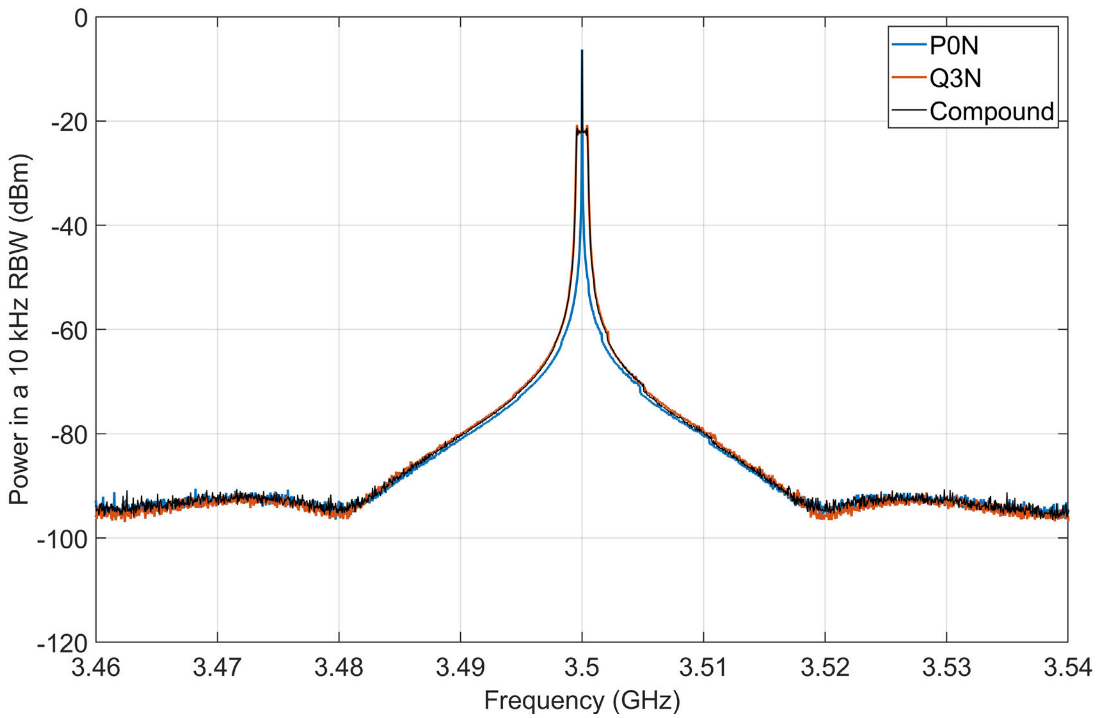

Figure 45. Spectrum measurement of waveform 31 (equal peak power) with its P0N and Q3N components at RBW = 10 kHz.

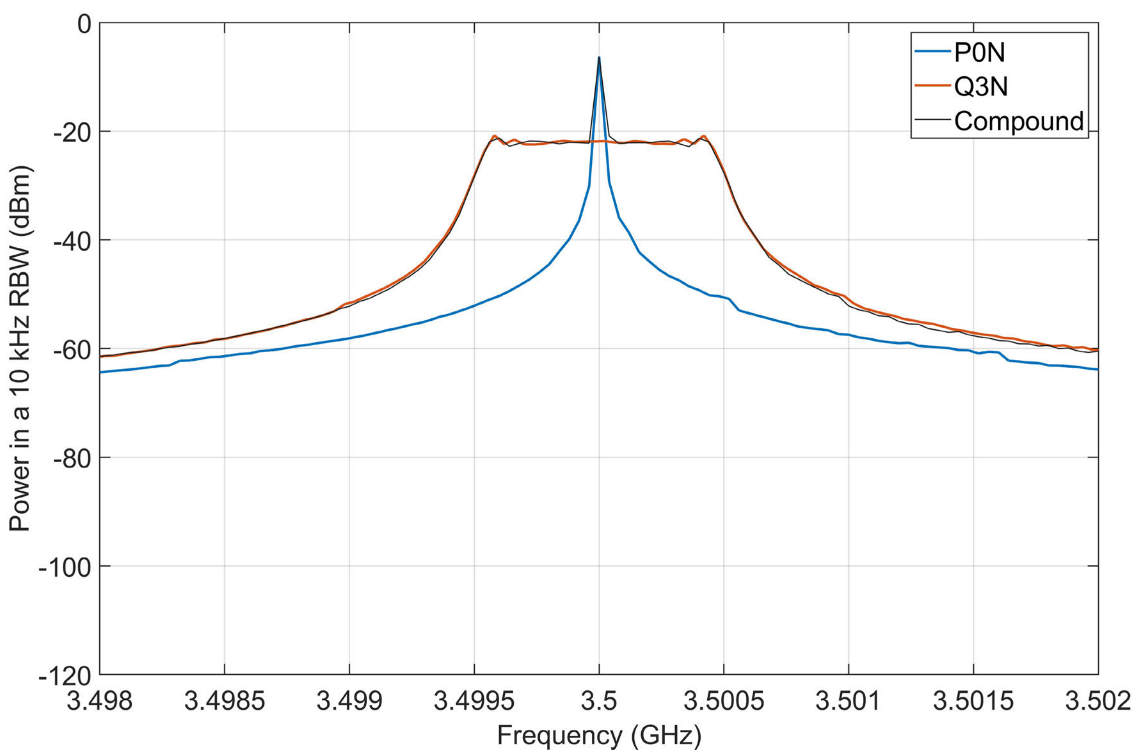

Figure 46. Close-up of the fundamental from Figure 45 showing the P0N spectrum component dominating near the fundamental frequency and the Q3N spectrum dominant elsewhere.

Figure 47 shows waveform 32 with its P0N and Q3N components measured with a RBW setting of 10 kHz. For this waveform, the peak power of the component pulses is the same. In the next example (waveform 33), a compound waveform with the same components is presented, but the peak power of each of the components is not the same.

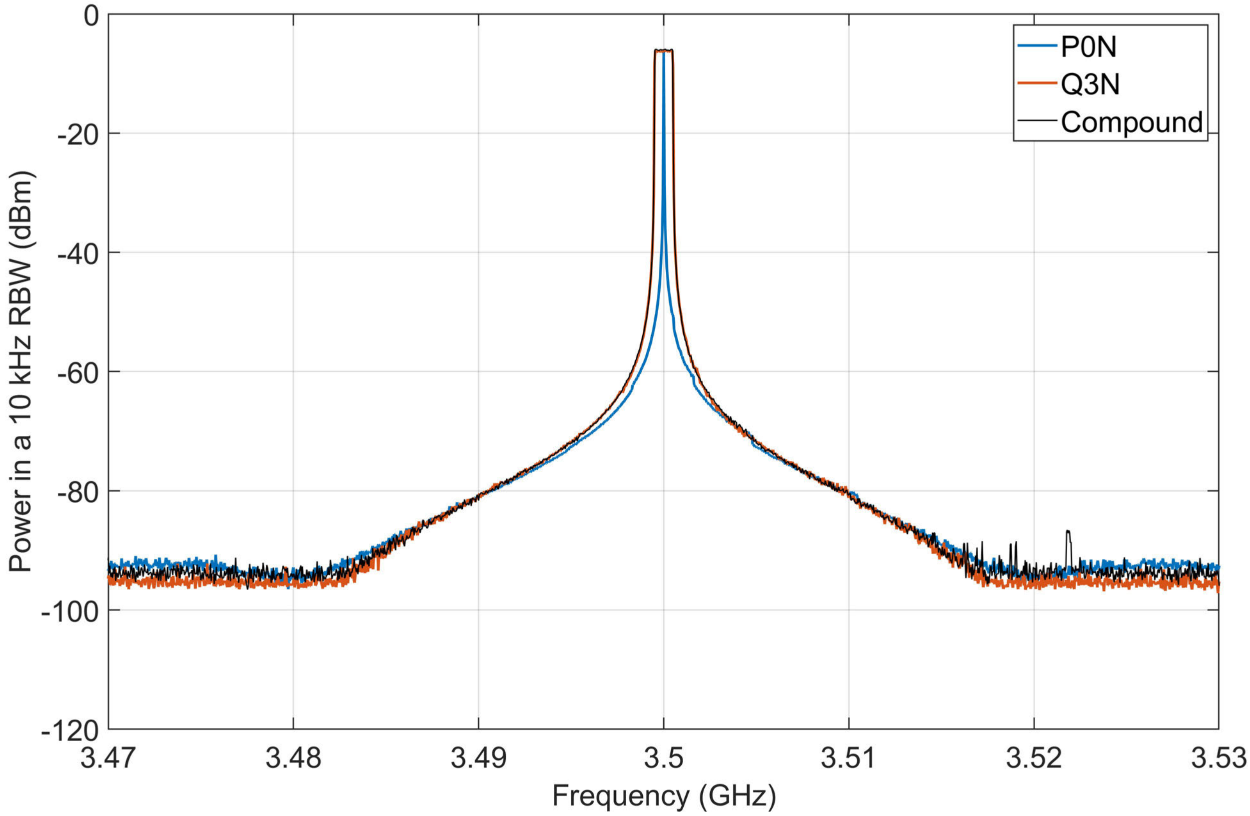

Figure 47. Spectrum measurement of waveform 32 (equal peak power) with its P0N and Q3N components at RBW = 10 kHz.

Next, Figure 48 shows waveform 33 with its P0N and Q3N components measured with a RBW setting of 10 kHz. For this waveform, the peak power of each component pulse is not the same. In this case, the Q3N spectrum completely dominates the compound spectrum because the P0N pulse has 20 dB less peak power, so it is even further below the Q3N spectrum than in the previous example with waveform 32.

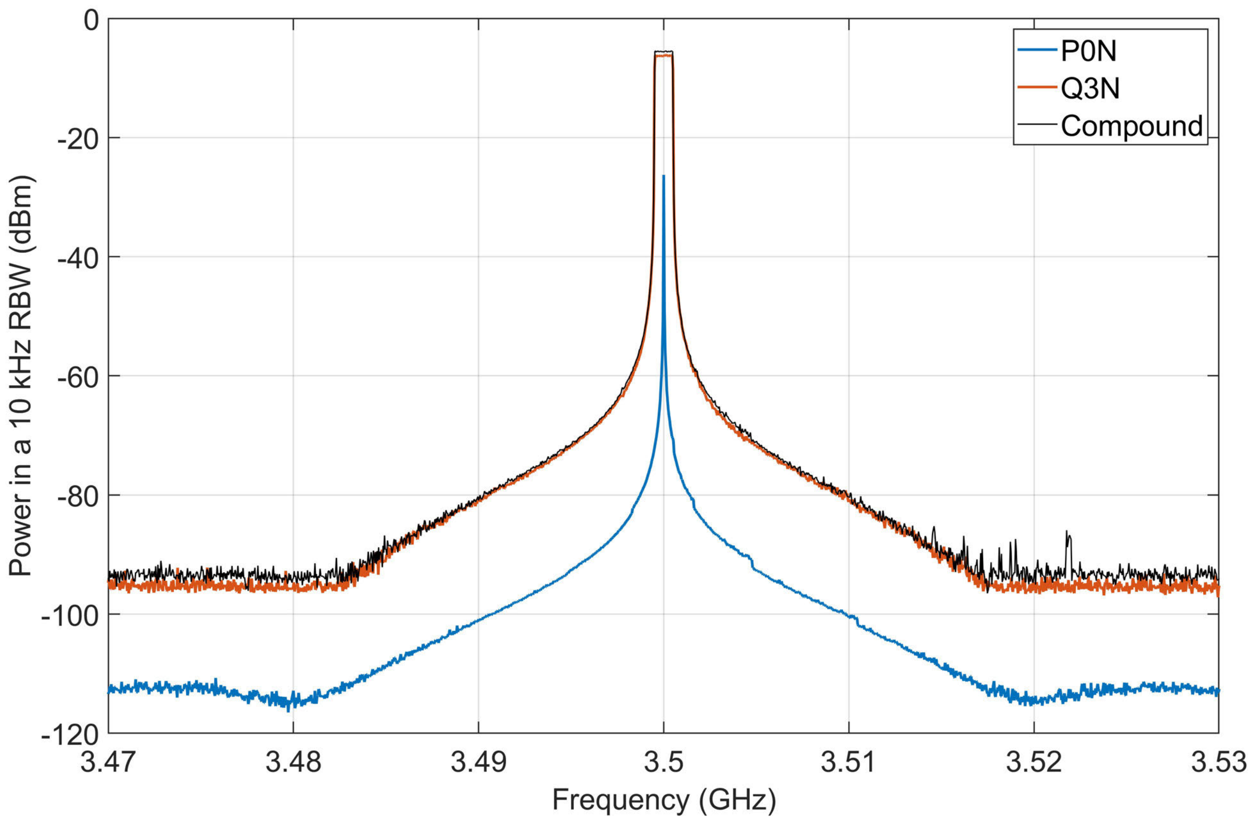

Figure 48. Spectrum measurement of waveform 33 (unequal peak power) with its P0N and Q3N components at RBW = 10 kHz.

Next, Figure 49 shows waveform 42 with its P0N and Q3N components measured with a RBW setting of 1 kHz. In this case, the compound spectrum follows the maximum of the component spectra. The compound spectrum is mostly formed by the P0N spectrum except near the fundamental where the influence of the Q3N spectrum widens out the compound spectrum to 1 MHz, at about 45 dB below the peak of the P0N component at 3.5 GHz.

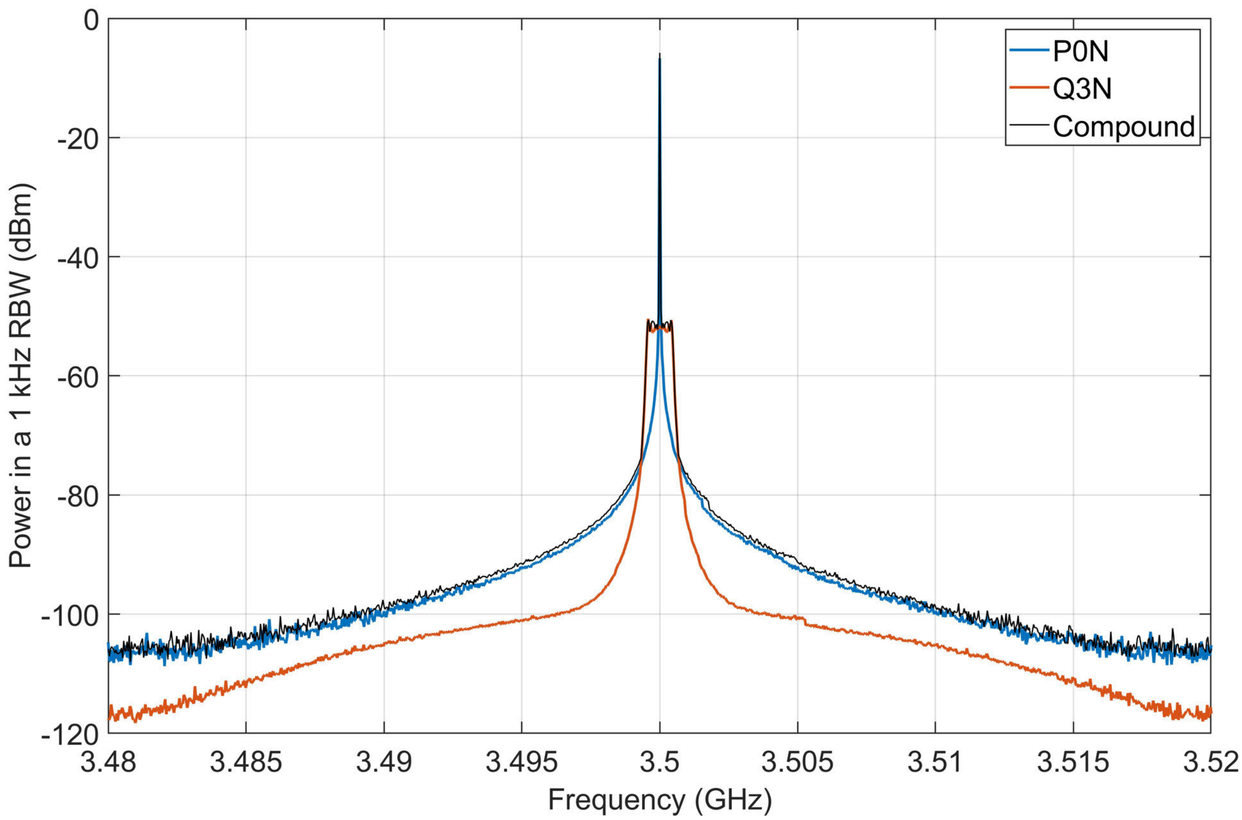

Figure 49. Spectrum measurement of waveform 42 (unequal peak power) with its P0N and Q3N components at RBW = 1 kHz.

Figure 50 shows waveform 46 with its P0N and Q3N components measured with a RBW setting of 1 kHz. For this waveform, each pulse's peak power is the same. In the next example, a compound waveform consisting of the same components is presented, but the peak power of the pulses is adjusted to simulate the components having the same amplitude. In this case, as with previous examples, the compound spectrum follows the maximum of the component P0N and Q3N components at each point in the spectrum.

Figure 51 shows waveform 47 with its P0N and Q3N components measured with a RBW setting of 1 kHz. For this waveform, each component pulse's peak power is not equal. Compared to waveform 46, the P0N component has more influence on the compound spectrum, protruding about 10 dB further out of the Q3N spectrum. This makes sense, since the peak power of the Q3N pulse is reduced by 10 dB.

The remaining figures showing the compound radar spectra with their component parts are provided in Section B.2.

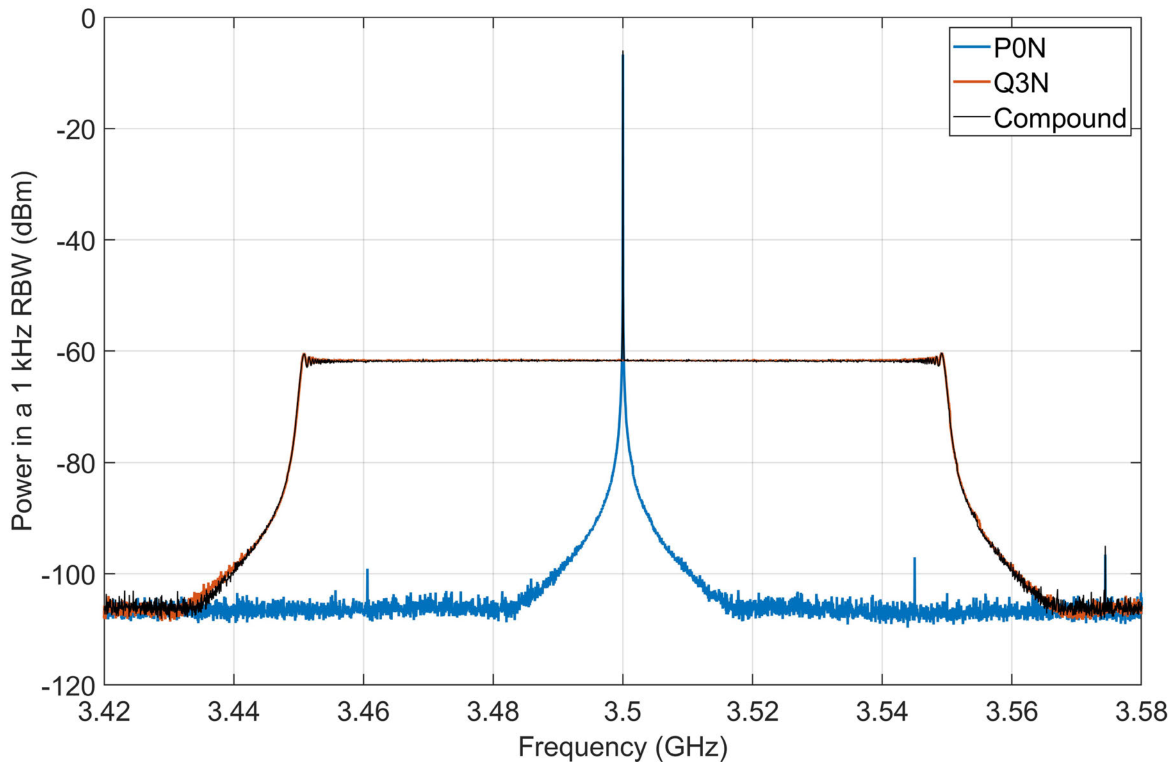

Figure 50. Spectrum measurement of waveform 46 (equal peak power) with its P0N and Q3N components at RBW = 1 kHz.

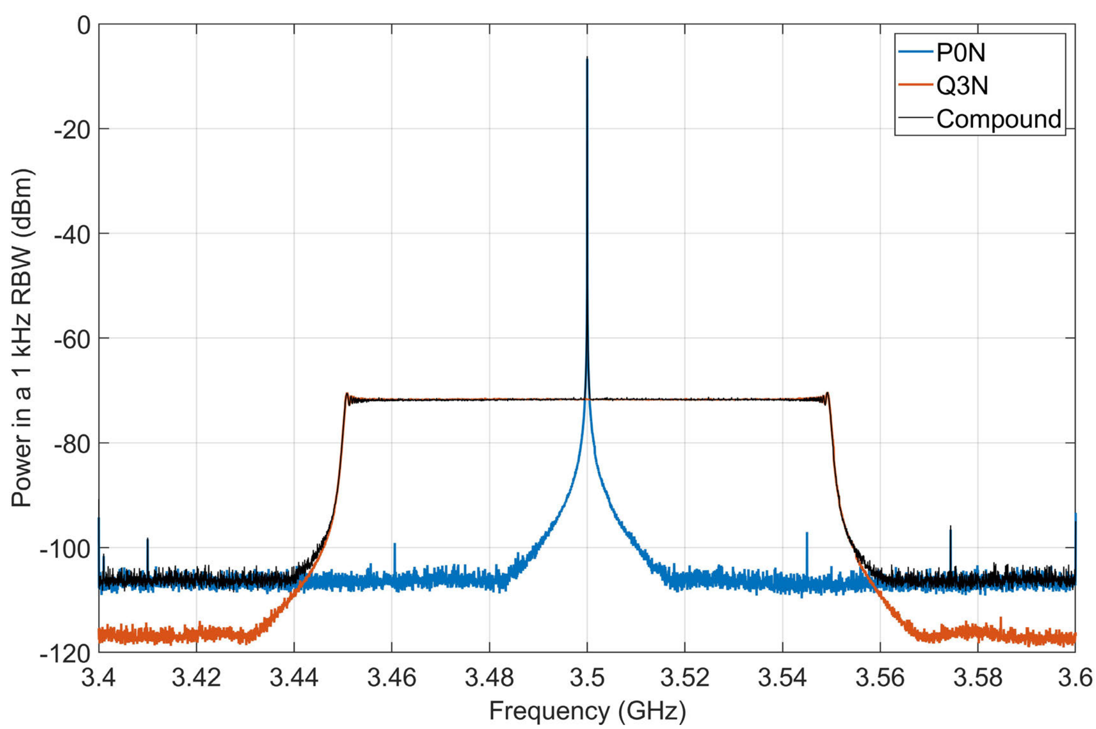

Figure 51. Spectrum measurement of waveform 47 (unequal peak power) with its P0N and Q3N components at RBW = 1 kHz.

3.3.3 Comparison of Compound Waveforms with Different Q3N to P0N Ratios

As shown in Table 5, waveforms 20, 24, 39, and 40 were measured at three different Q3N to P0N ratios: 1:1, 100:1, and 1000:1. Figure 52 provides a comparison of all the ratios measured of waveform 24. In this case the optimum RBW is 1 MHz and the spectra of the three ratios are nearly identical. The higher level of the spectrum at frequencies above 3.5 GHz is because the automated measurement algorithm did not reduce the attenuation enough at these frequencies.

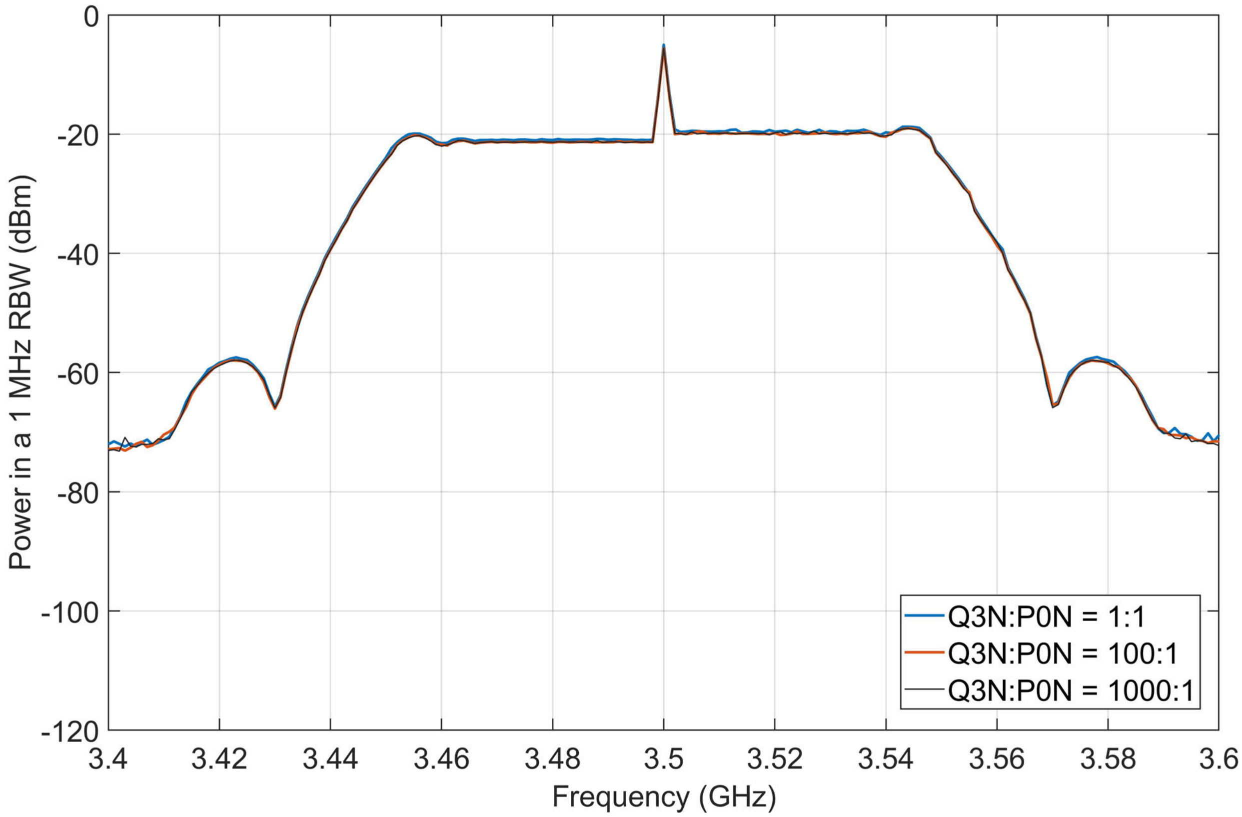

Figure 52. Comparison of waveform 24 with 3 Q3N:P0N ratios (1:1, 100:1, 1000:1) all measured with a 1 MHz RBW.

It is not always the case that the ratio of P0N to Q3N does not create a difference in the emission spectra. If the optimum RBW for the compound waveform is less than the PRR of one of the components than the ratio can affect the spectral lines differently (see [5] for more information on spectral lines). Figure 53 provides an example of this from waveform 39. The spectral lines of 1:1 test case are much lower than those of the 100:1 and 1000:1 test cases. The 100:1 and 1000:1 test cases are nearly identical. All three ratios are nearly identical at the fundamental frequency, 3.5 GHz.

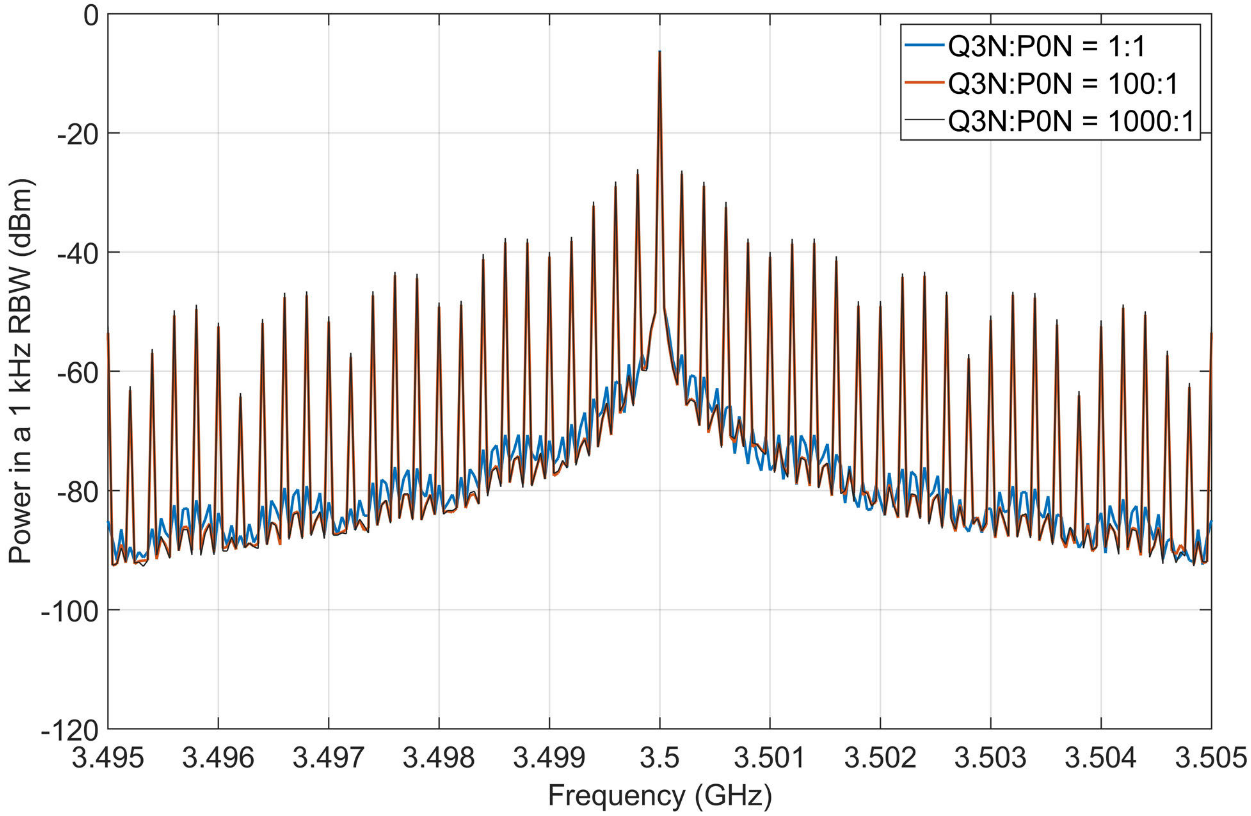

Figure 53. Close-up of the fundamental of waveform 39 with three different Q3N:P0N ratios (1:1, 100:1, 1000:1) measured with the optimum RBW of 1 kHz.

The PRRs of each of the components in waveform 39 are different, so in the 1:1 test case the PRR is not consistent from pulse to pulse. To investigate this further, the ratios of waveform 24 are compared again those measured in a 1 kHz RBW. Waveform 24 was selected because both components have a PW of 1 µs and a PRR of 100 kHz, so even for the 1:1 test case the PRR is consistent from pulse to pulse. The results of this comparison are shown in Figure 54.

In this case, the higher ratios do have spectral lines at higher power levels most of the time, but the difference is not as great. The spectral lines of the 1:1 test case are much more prominent than they are in Figure 53 for waveform 39. The spectral lines of the 1:1 test case actually exceed those of the other test cases near 3.5 GHz. Note that RBW = 1 kHz is not the optimum RBW for compound waveform 24 and this case was only examined because of the PRR characteristics of the waveform.

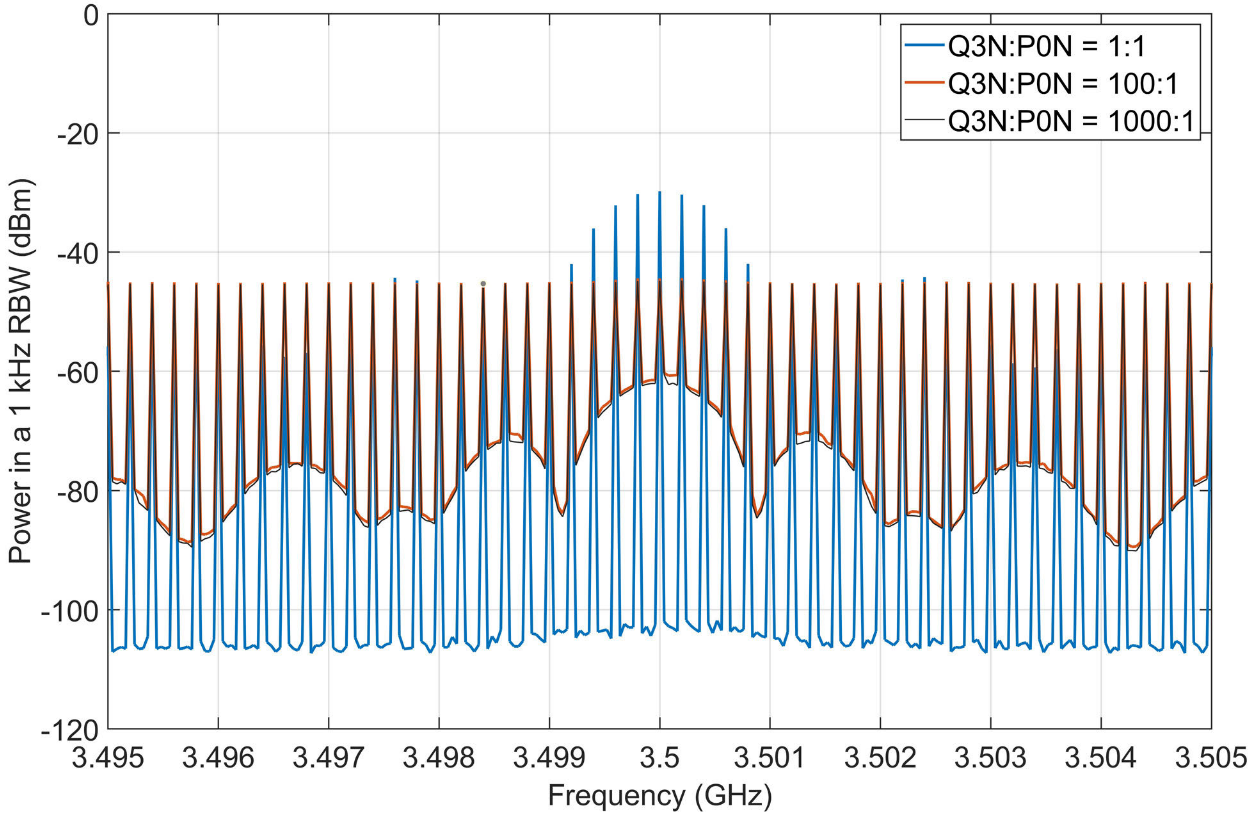

Figure 54. Close-up near the fundamental frequency, 3.5 GHz, of waveform 24 with three different Q3N:P0N ratios (1:1, 100:1, 1000:1) measured with a RBW of 1 kHz.

4. CONCLUSIONS AND RECOMMENDATIONS

Based on the results of this study the following conclusions can be drawn:

1) As seen in Table 8, the recommendation in [4] that the minimum calculated RBW from the component waveforms of a compound radar waveform be used to measure the spectrum is sufficient for conducting radar emission measurements for RSEC certification.

2) Generally, the compound spectrum is the maximum of the component waveform spectra (e.g., Figure 49, among others). This appears to always be true through the fundamental but may not be true in the OOB region.

3) However, if the optimum RBW used to measure the compound radar waveform is less than the PRR of one of the components, then line spectrum can influence the overall compound spectrum and 2) will not be true in the OOB region. This is seen in Figures 11 and 12.

4) The calculated optimum RBW does not always agree with the empirically observed one. This is especially true with Q3N waveforms because (2) is only an approximation.

5) If the calculated optimum RBW for a compound radar waveform does not agree with the empirical one, then this will likely be the case for the component that is determining the optimum RBW as well.

6) The relative peak power of the component pulses of a compound radar waveform has a significant impact on the measured spectrum of the compound radar waveform.

7) It is important to use the correct RBW when measuring compound radar spectra because using an RBW setting that is too high may mask the effects of one or more of the component waveforms.

8) The ratio of P0N to Q3N pulses only appears to create a difference in the spectrum if the appropriate RBW is less than the PRR of one of the components, as seen in Figure 52.

The objective of this study was narrow in scope, investigating only how to choose an appropriate RBW when measuring compound radar emissions following the stepped measurement method described in [4]. The main conclusion is that the recommendation for how to choose an RBW when measuring compound radar emissions provided in [4] is sufficient; however, a bandwidth progression measurement should be performed at the fundamental to determine the empirical optimum RBW. The data used in this study is freely available and publicly accessible at DOI:10.5281/zenodo.7871632 [6].

In addition, there have been many advancements in spectrum analysis and measurement equipment since the stepped measurement method was developed that could allow for the development of more accurate and efficient radar emission measurement methods. ITS and NTIA are continuing this research by investigating other measurement methods that include the collection of in-phase and quadrature (I/Q) data to measure and analyze compound radar emissions. The findings of this research will be released in a future report.

One possible way to update the RSEC to accommodate modern radars would be to construct the RSEC mask for the compound mask from the masks defined by the individual P0N and Q3N components. This would require accurately measuring the relative peak powers of the component waveforms at their fundamentals. With this information, the RSEC masks of the individual components could be offset by these same relative peak power levels and combined to form a single RSEC mask to apply to the compound radar waveform.

Another option is to analyze the component pulses within a compound radar individually. This would not require an update to the RSEC since mask requirements already exist for single-pulse-parameter radar waveforms. However, this would require measurement techniques different than those defined in [4] because this method does not allow for analyzing the pulses individually. New techniques using I/Q data (time-domain) could be developed to analyze component pulses individually.

5. REFERENCES

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[2] International Telecommunications Union Radiocommunication Sector (ITU-R), "Unwanted Emissions in the Out-of-band Domain," Report ITU-R SM.1541-6, Geneva, August 2015. https://www.itu.int/rec/R-REC-SM.1541-6-201508-I/en

[3] Sanders, F.H. and R. A. Dalke, "Relationships Between Measured Power and Measurement Bandwidth for Frequency-Modulated (Chirped) Pulses", NTIA Report TR-12-488, U.S. Department of Commerce, August 2012. https://www.its.ntia.gov/publications/2680.aspx

[4] Sanders, F. H., R. L. Hinkle, and B. J. Ramsey, "Measurement Procedures for the Radar Spectrum Engineering Criteria (RSEC)", NTIA Report TR-05-420, U.S. Department of Commerce, March 2005. https://www.its.ntia.gov/publications/2450.aspx

[5] Keysight Technologies, "Spectrum and Signal Analysis Pulsed RF", Application Note, August 2, 2014. https://www.keysight.com/us/en/assets/7018-06767/application-notes/5952-1039.pdf

[6] Data for NTIA Technical Memorandum TM-23-566: Examining the Effects of Resolution Bandwidth when Measuring Compound Radar Waveforms. DOI:10.5281/zenodo.7871632

APPENDIX A

A.1 P0N Emission Measurements at Several RBW Settings

This section provides the results of the emission measurements performed on the P0N waveforms at multiple RBW settings that are not presented in Section 3.1.1. In some cases, a close up view of the fundamental is also provided when it is hard to make out the individual spectra in the plot.

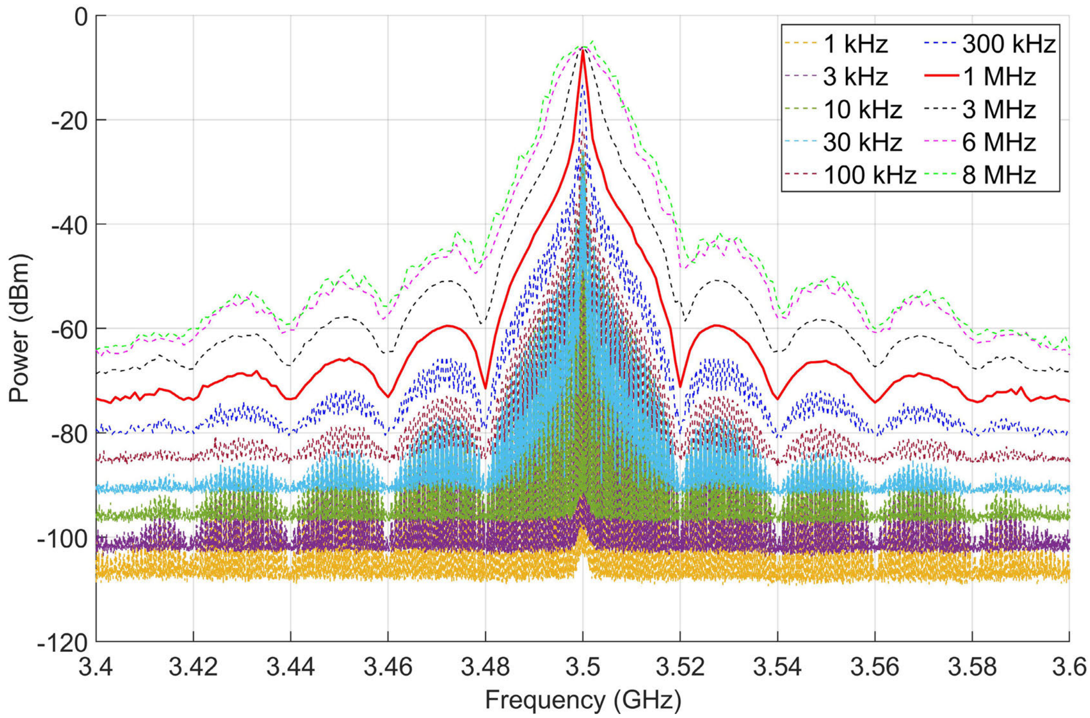

Figure A-1. Spectrum emission measurements at multiple RBW settings for waveform 1 (PW = 1 µs, PRI = 10 µs, and $T_r = T_f = 50$ ns). RBW = 1 MHz is the optimum RBW from calculation and empirically for this measurement.

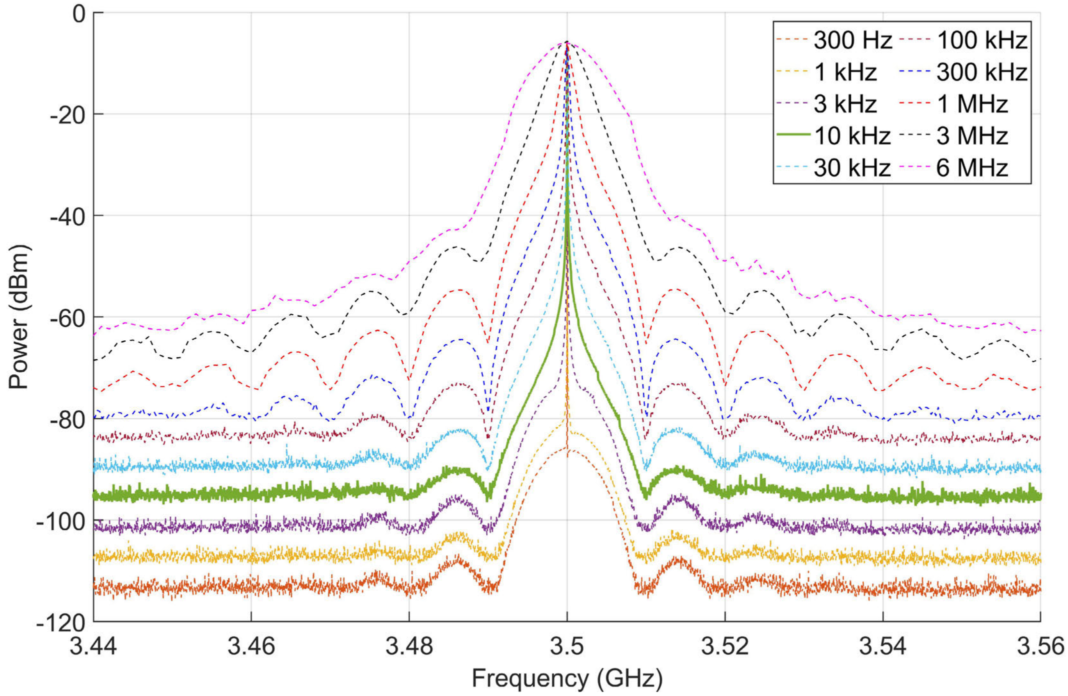

Figure A-2. Spectrum emission measurements at multiple RBW settings for waveform 2 (PW = 100 μs, PRI = 1 ms, and $T_r = T_f = 100$ ns). RBW = 10 kHz is the optimum RBW from calculation and empirically for this measurement.

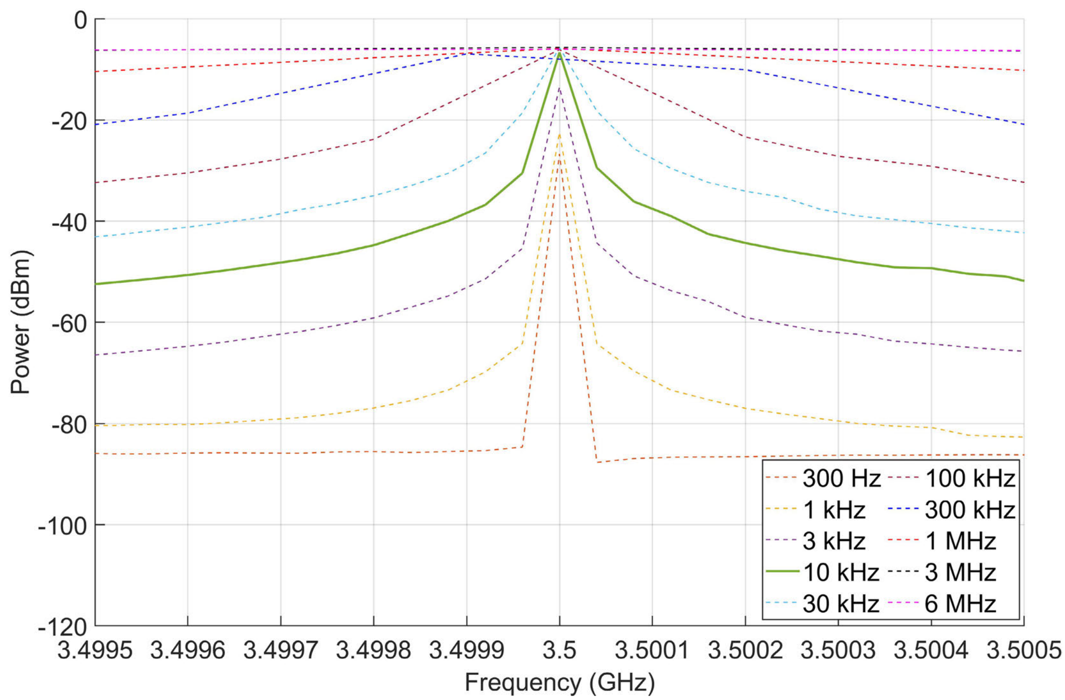

Figure A-3. Close-up view of the fundamental from Figure A-2 showing that RBW = 10 kHz is the optimum RBW for this measurement.

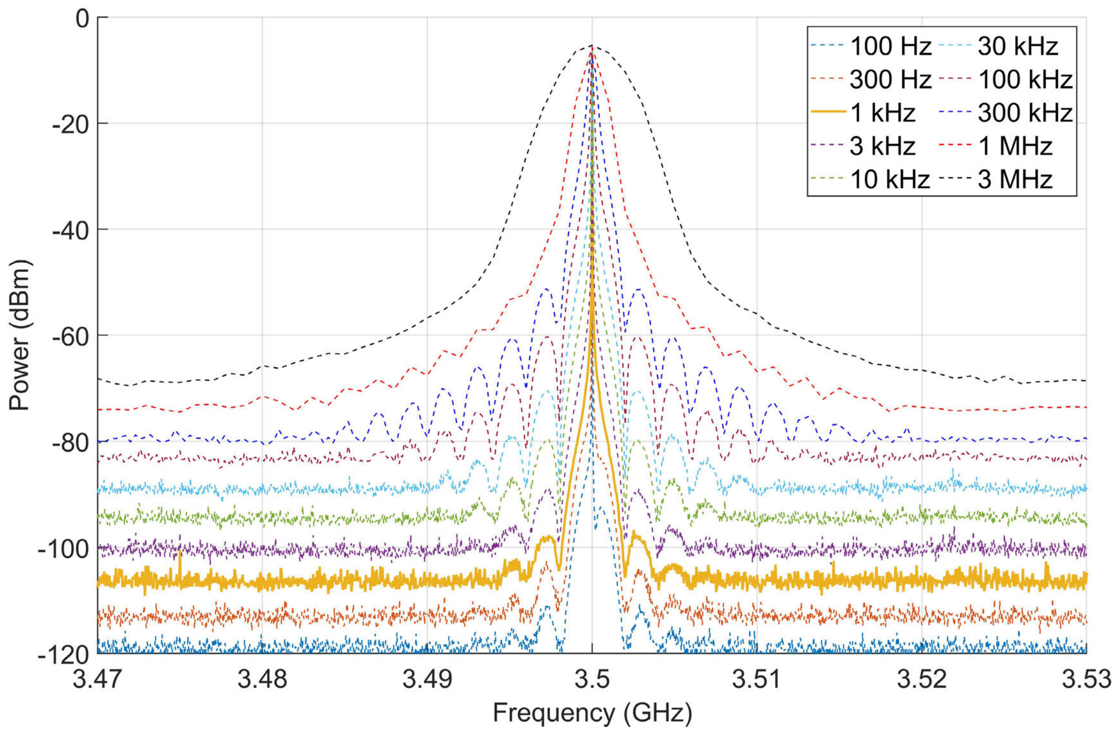

Figure A-4. Spectrum emission measurements at multiple RBW settings for waveform 3 (PW = 1 ms, PRI = 10 ms, and $T_r = T_f = 500$ ns). RBW = 1 kHz is the optimum RBW from calculation and empirically for this measurement.

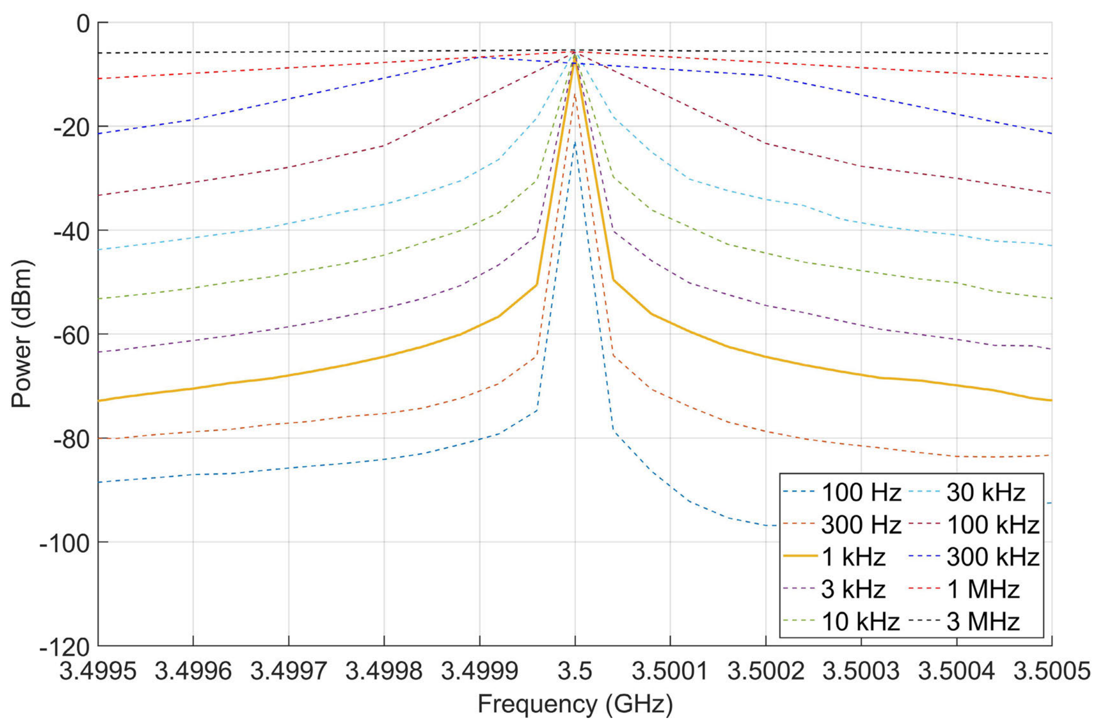

Figure A-5. Close-up view of the fundamental from Figure A-4 showing that RBW = 1 kHz is the optimum RBW for this measurement.

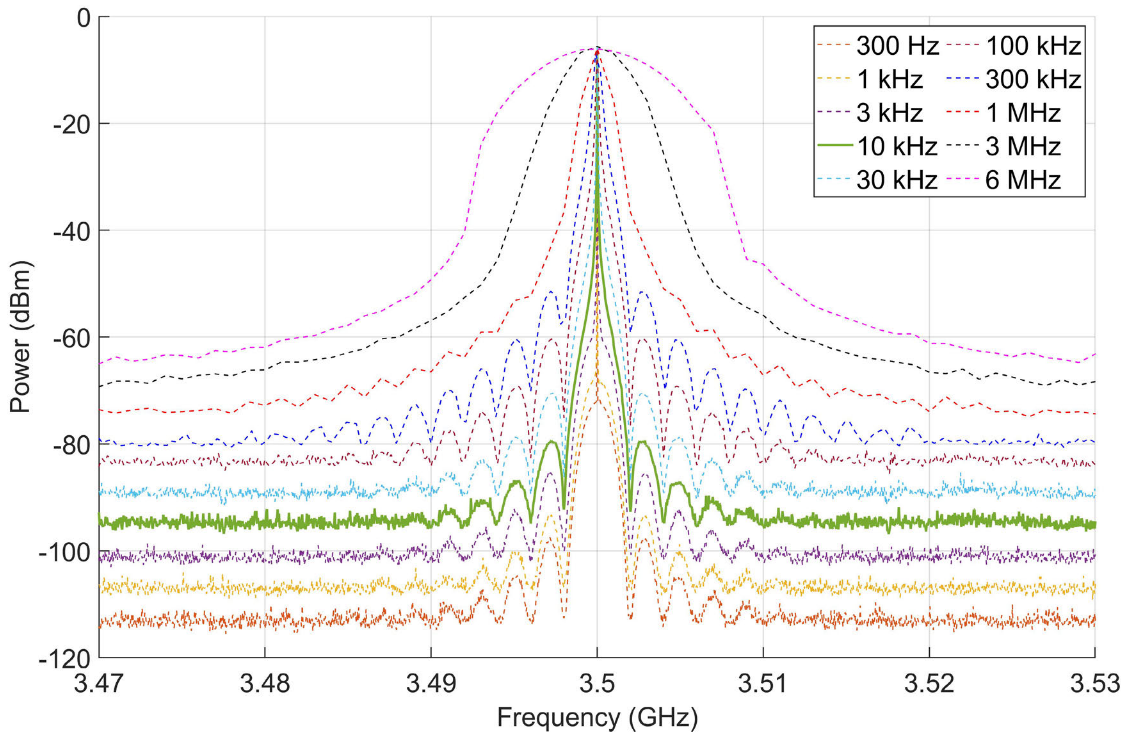

Figure A-6. Spectrum emission measurements at multiple RBW settings for waveform 5 (PW = 100 µs, PRI = 1 ms, and $T_r = T_f = 500$ ns). RBW = 10 kHz is the optimum RBW from calculation and empirically for this measurement.

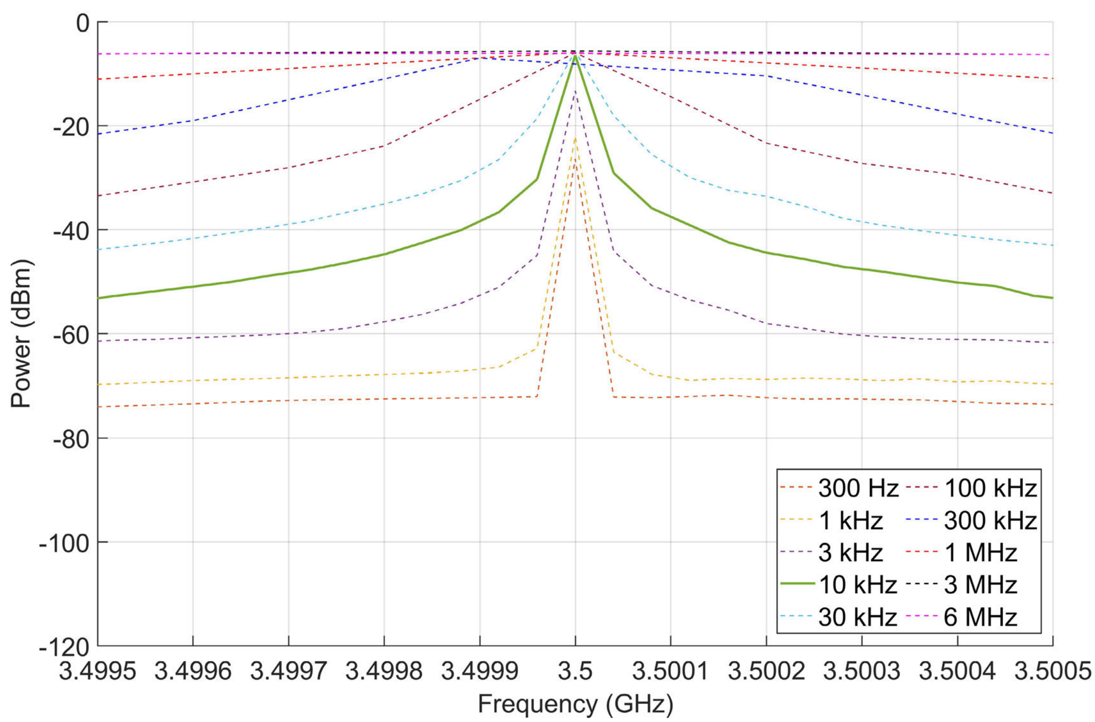

Figure A-7. Close-up view of the fundamental from Figure A-6 showing that RBW = 10 kHz is the optimum RBW for this measurement.

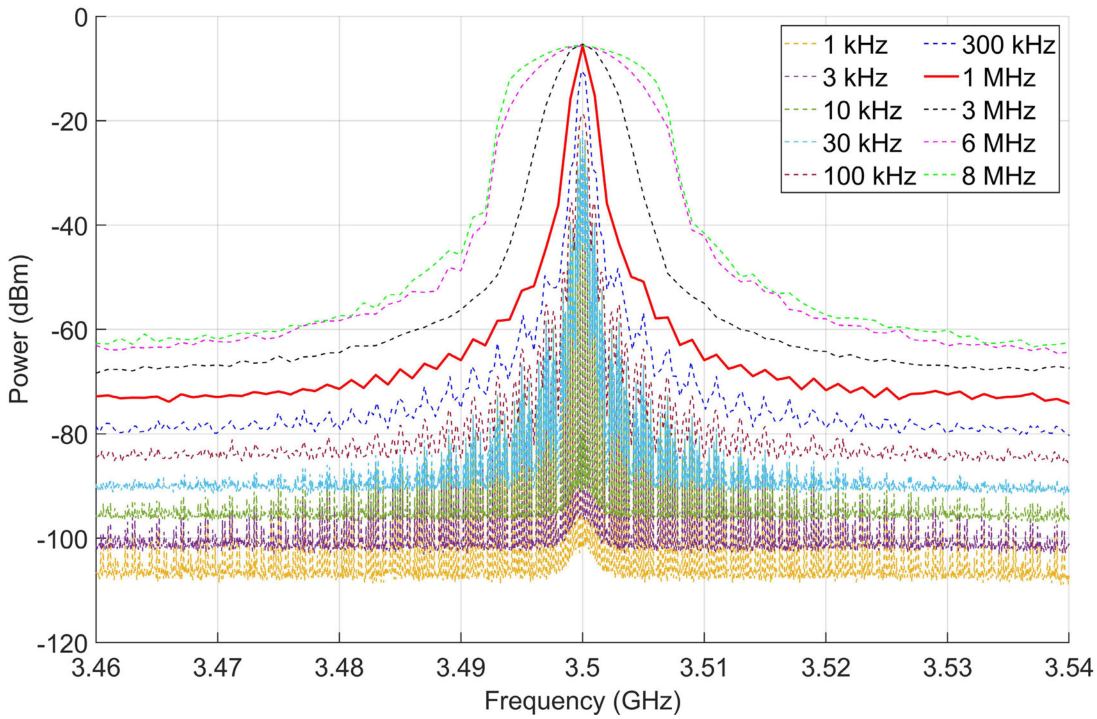

Figure A-8. Spectrum emission measurements at multiple RBW settings for waveform 7 (PW = 1 μs, PRI = 10 μs, and $T_r = T_f = 500$ ns). RBW = 1 MHz is the optimum RBW from calculation and empirically for this measurement.

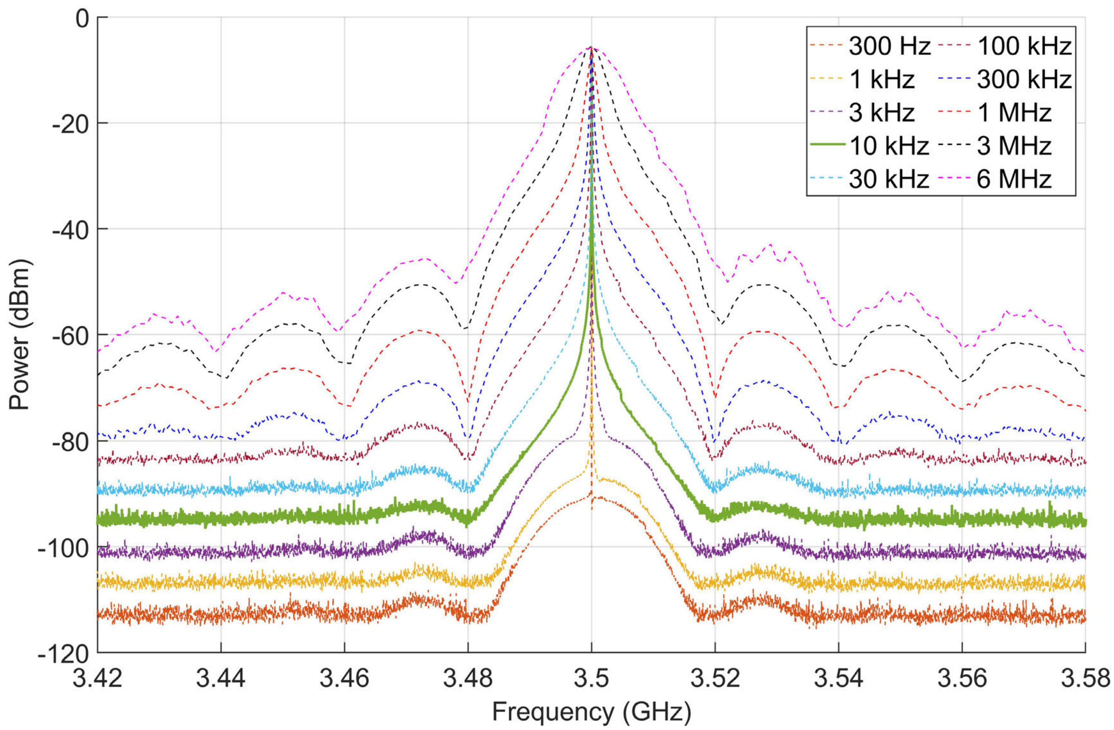

Figure A-9. Spectrum emission measurements at multiple RBW settings for waveform 8 (PW = 100 µs, PRI = 1 ms, and $T_r = T_f = 50$ ns). RBW = 10 kHz is the optimum RBW from calculation and empirically for this measurement.

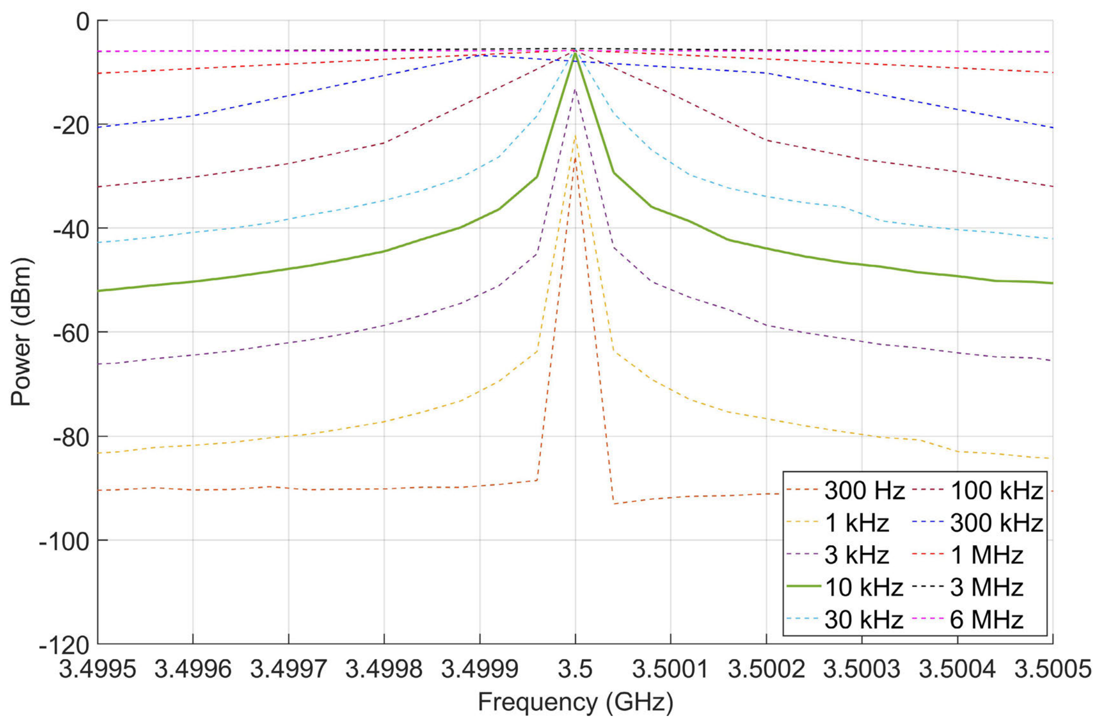

Figure A-10. Close-up view of the fundamental from Figure A-9 showing that RBW = 10 kHz is the optimum RBW for this measurement.

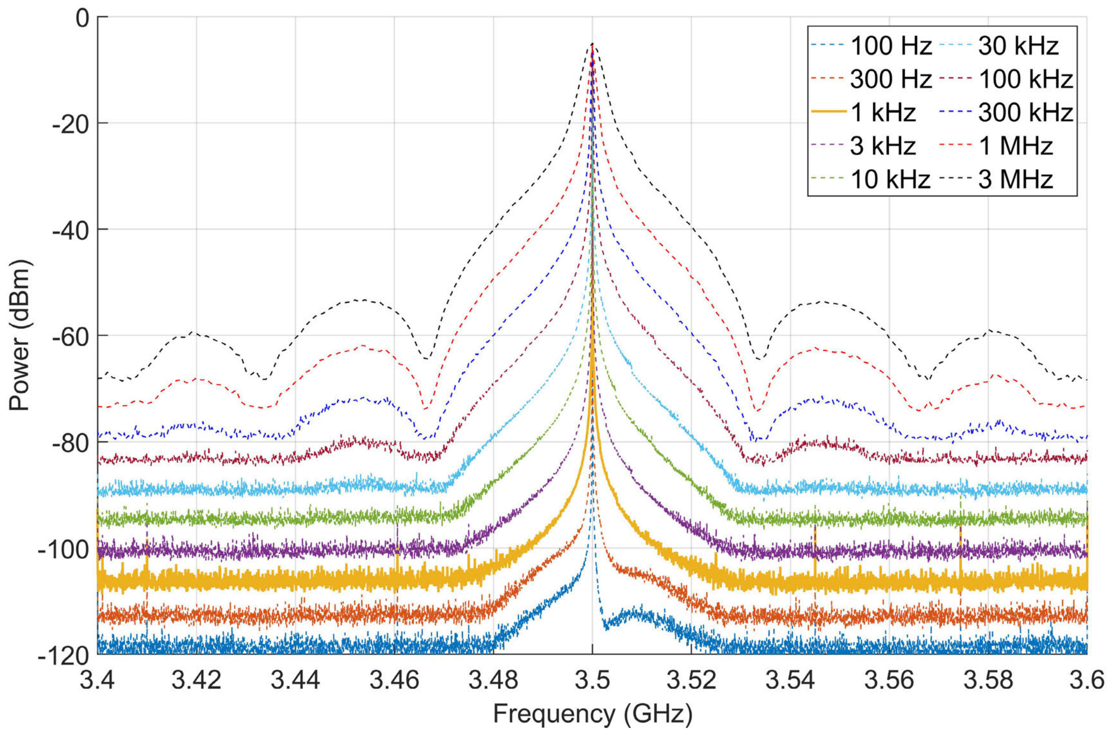

Figure A-11. Spectrum emission measurements at multiple RBW settings for waveform 9 (PW = 1 ms, PRI = 10 ms, and $T_r = T_f = 100$ ns). RBW = 1 kHz is the calculated optimum RBW from calculation and empirically for this measurement.

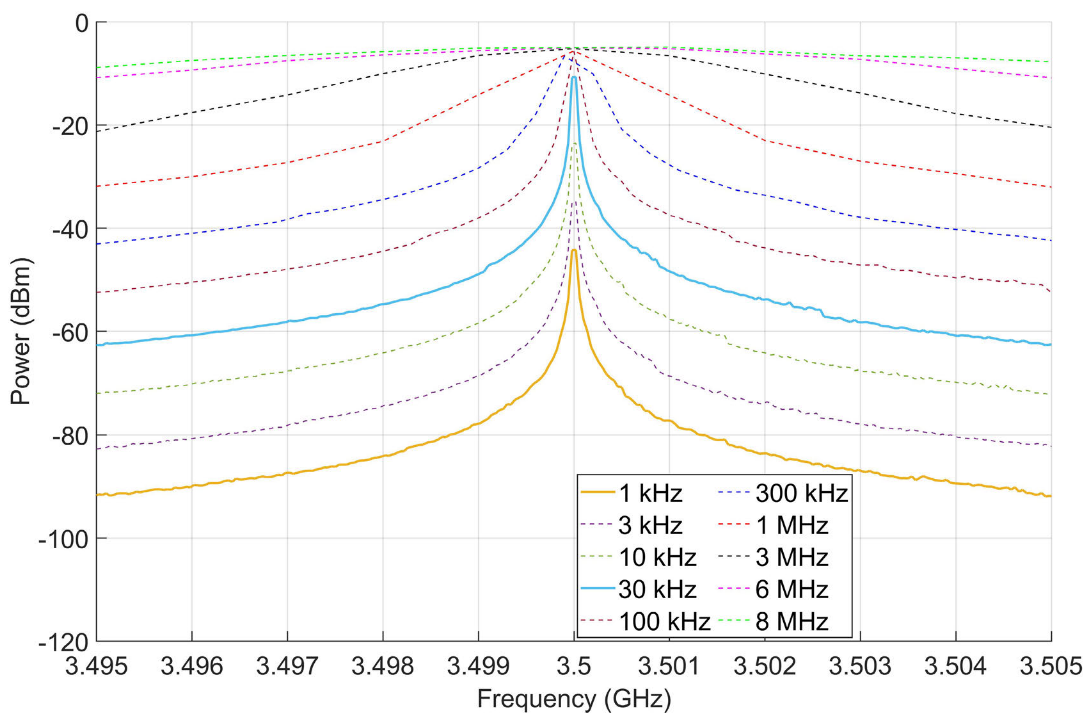

Figure A-12. Close-up view of the fundamental from Figure A-11 showing that RBW = 1 kHz is the optimum RBW for this measurement.

A.2 Q3N Emission Measurements at Several RBW Settings

This section provides the remainder of the results of the emission measurements performed on the Q3N waveforms at multiple RBW settings that are not presented in Section 3.2.1. In some cases, a close up view of the fundamental is also provided when it is hard to make out the individual spectra in the plot. For all of the test case presented, $T_r = T_f = 50$ ns.

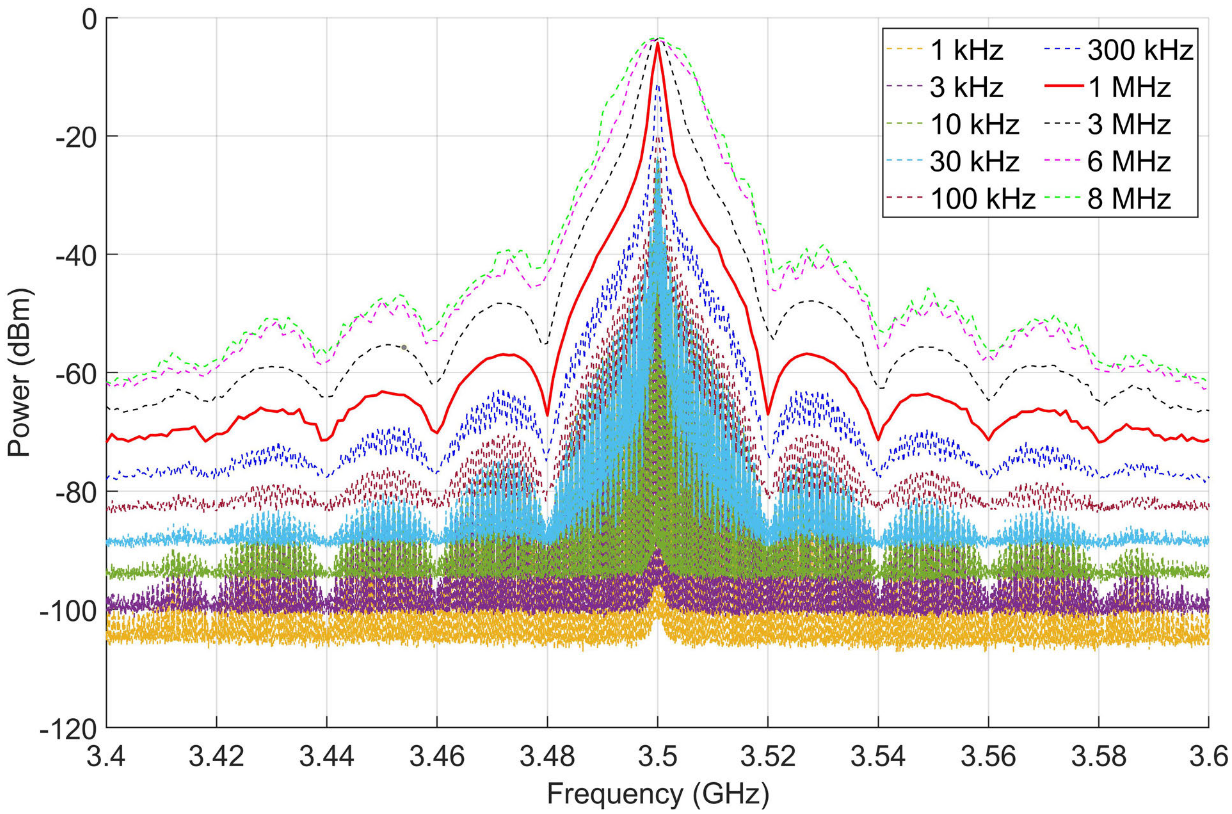

Figure A-13. Spectrum emission measurements at multiple RBW settings for waveform 10 (PW = 1 μs, PRI = 10 μs, and B_c = 1 MHz). RBW = 1 MHz is the calculated and empirical optimum RBW setting to use for this measurement.

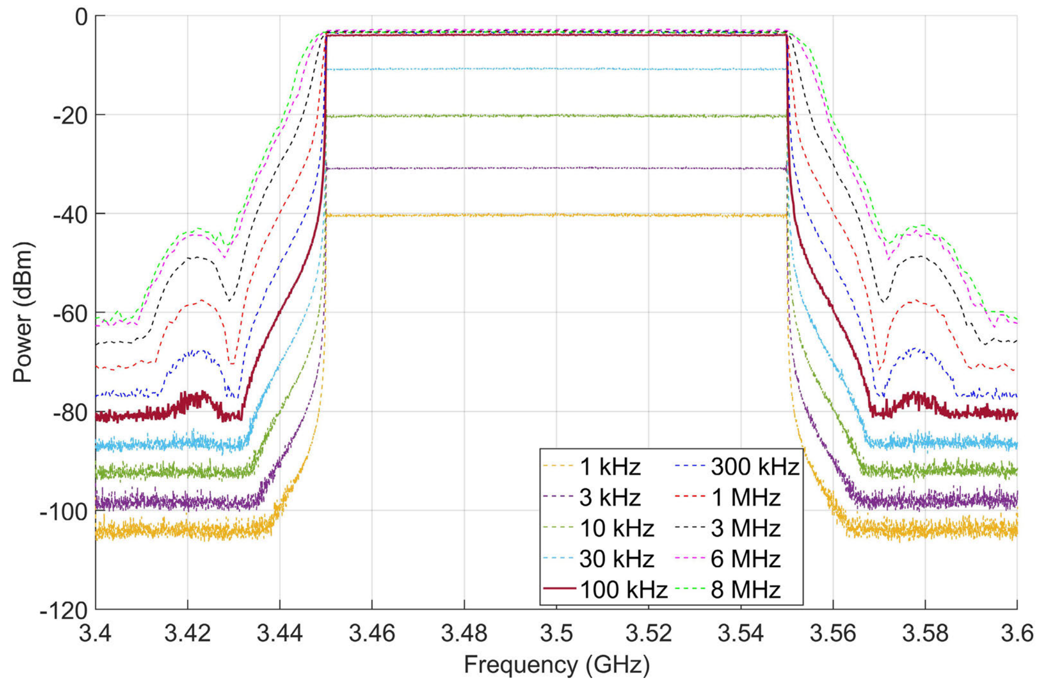

Figure A-14. Spectrum emission measurements at multiple RBW settings for waveform 12 (PW = 10 ms, PRI = 100 ms, and B_c = 100 MHz). RBW = 100 kHz is the calculated and empirical optimum RBW setting to use for this measurement.

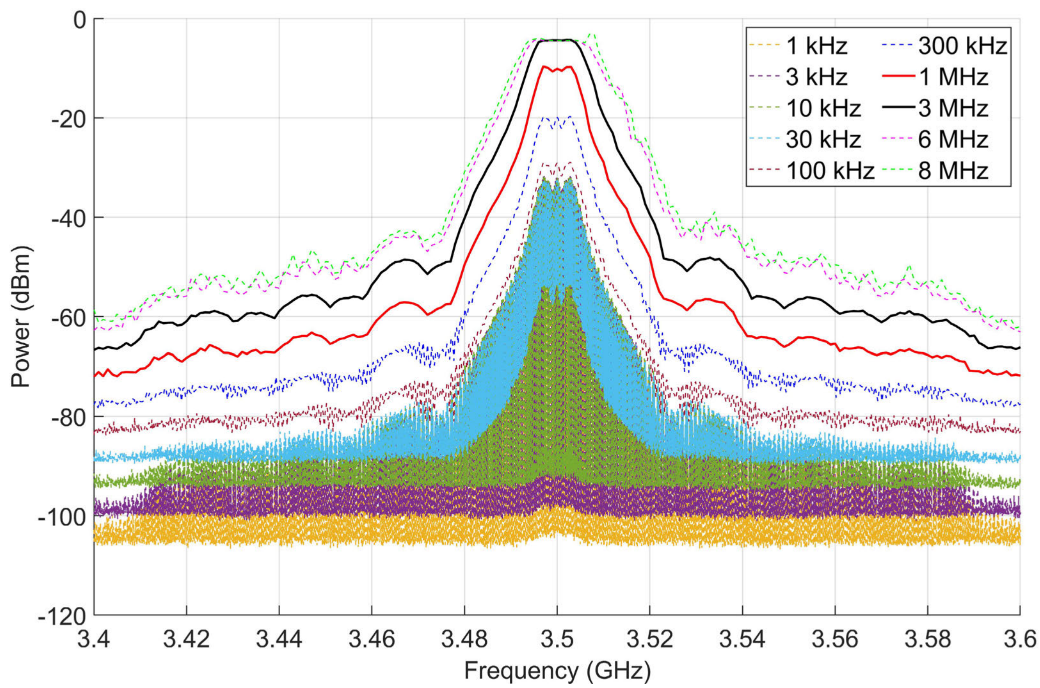

Figure A-15. Spectrum emission measurements at multiple RBW settings for waveform 13 (PW = 1 µs, PRI = 10 µs, and B_c = 10 MHz). RBW = 3 MHz is the calculated optimum RBW setting to use for this measurement. Empirically, RBW = 1 MHz is the optimum RBW but the improvement is minimal.

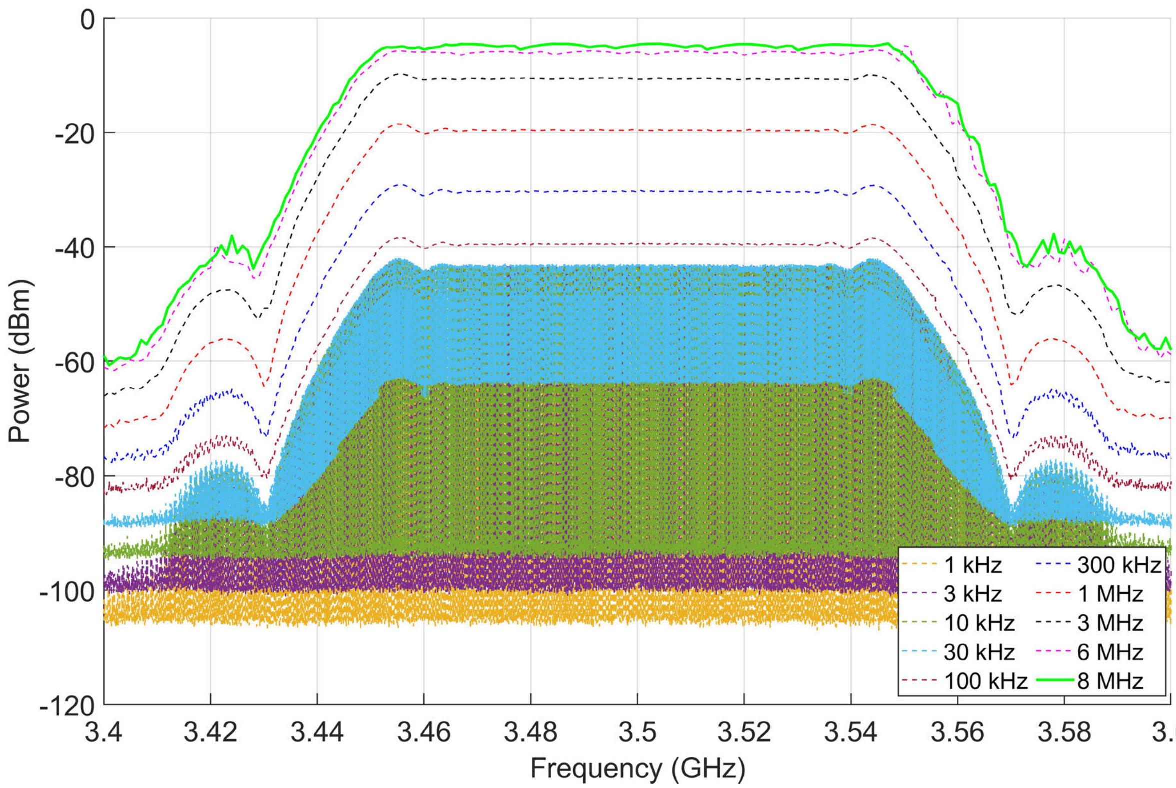

Figure A-16. Spectrum emission measurements at multiple RBW settings for waveform 16 (PW = 1 μs, PRI = 10 μs, and B_c = 100 MHz). RBW = 10 MHz is the calculated optimum RBW setting to use for this measurement. This study only examines RBW settings up to 8 MHz.

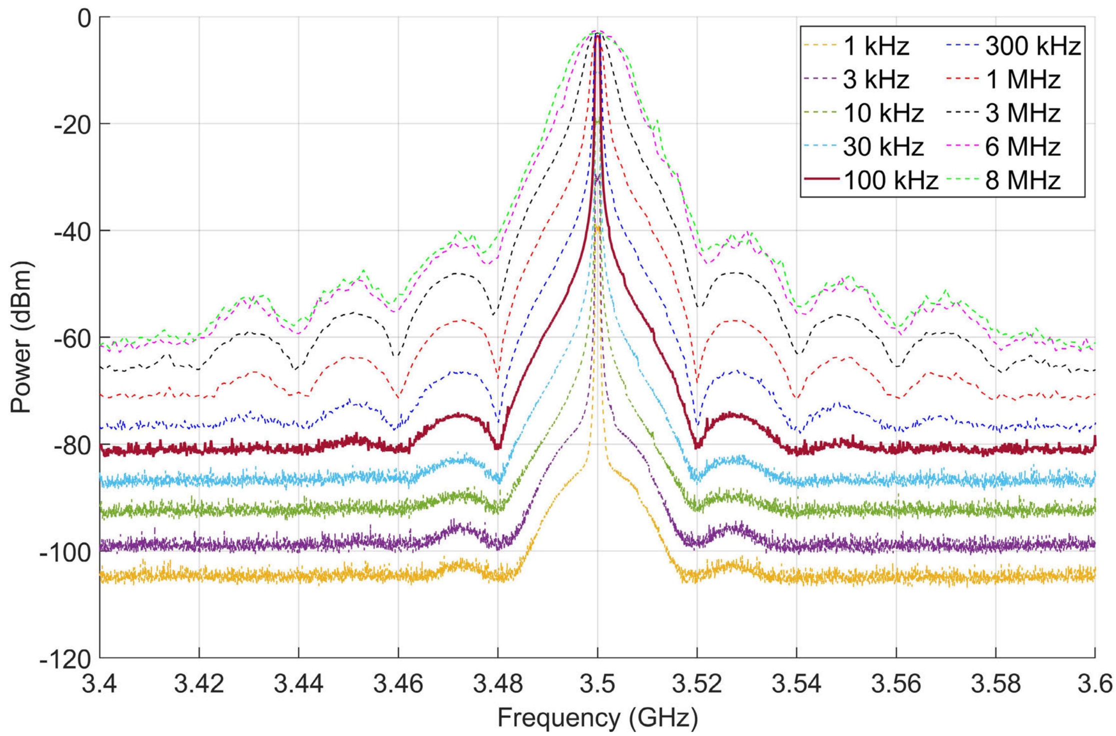

Figure A-17. Spectrum emission measurements at multiple RBW settings for waveform 17 (PW = 100 µs, PRI = 1 ms, and B_c = 1 MHz). RBW = 100 kHz is the calculated and empirical optimum RBW setting to use for this measurement.

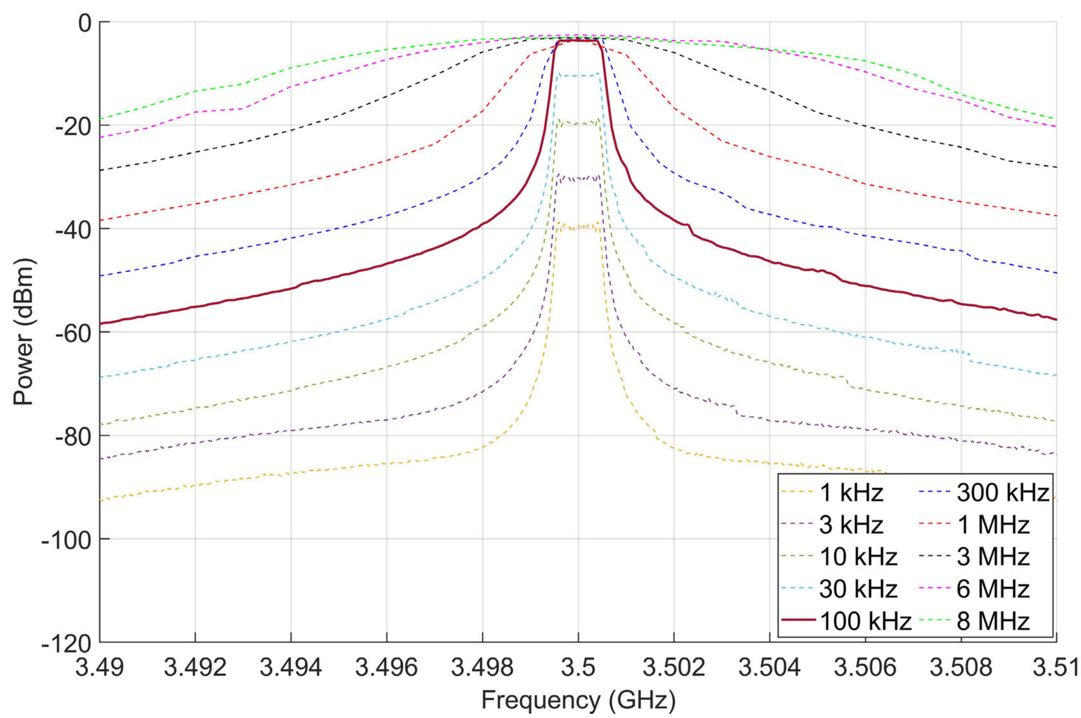

Figure A-18. Close-up view of the fundamental from Figure A-17 showing that RBW = 100 kHz is the optimum measurement bandwidth.

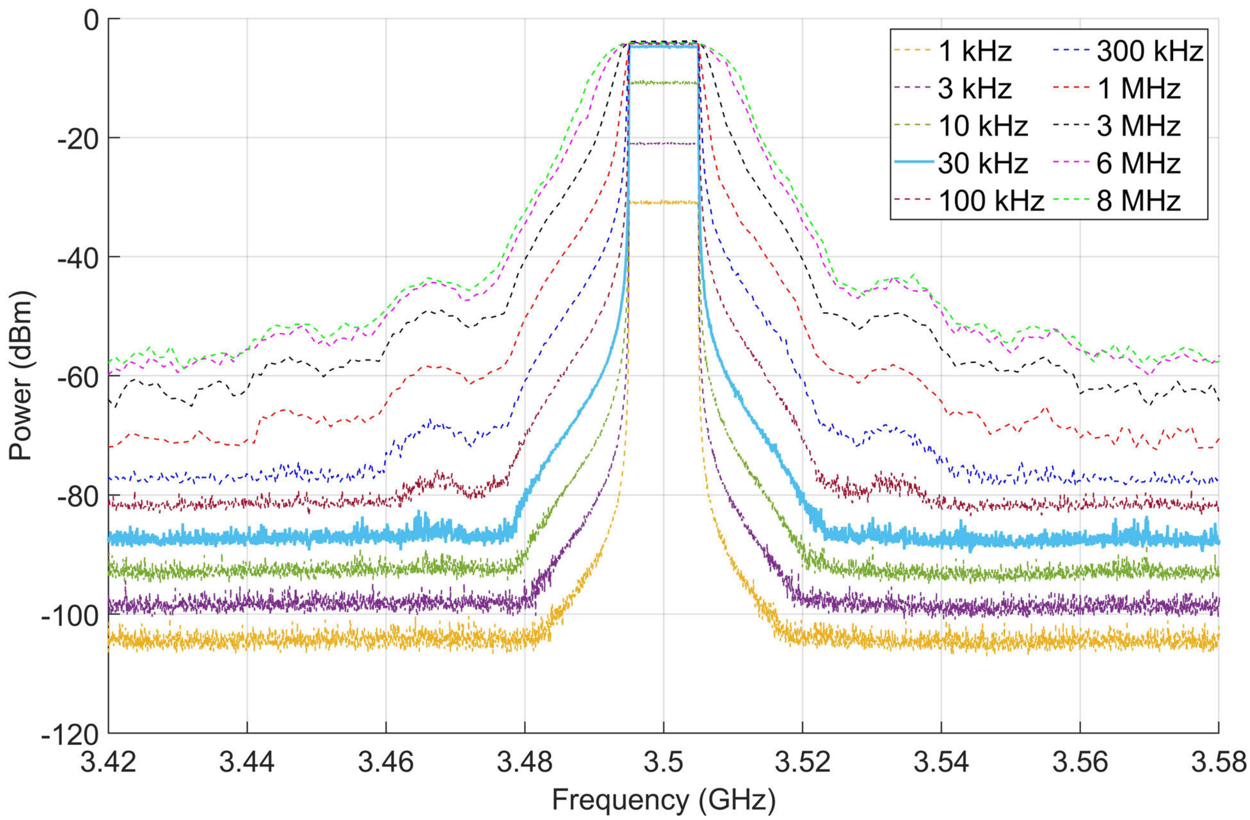

Figure A-19. Spectrum emission measurements at multiple RBW settings for waveform 18 (PW = 10 ms, PRI = 100 ms, and B_c = 10 MHz). RBW = 30 kHz is the calculated and empirical optimum RBW setting to use for this measurement.

APPENDIX B

B.1 Compound Radar Emission Measurements at Several RBW Settings

This section provides the remainder of the results of the emission measurements performed on the compound waveforms at multiple RBW settings that are not presented in Section 3.3.1. In some cases, a close-up view of the fundamental is also provided when it is hard to make out the individual spectra in the plot. For all of the test cases presented, $T_r = T_f = 50$ ns and the ratio Q3N:P0N is 1:1. The peak power of the component pulses is equal, unless noted otherwise in the figure caption.

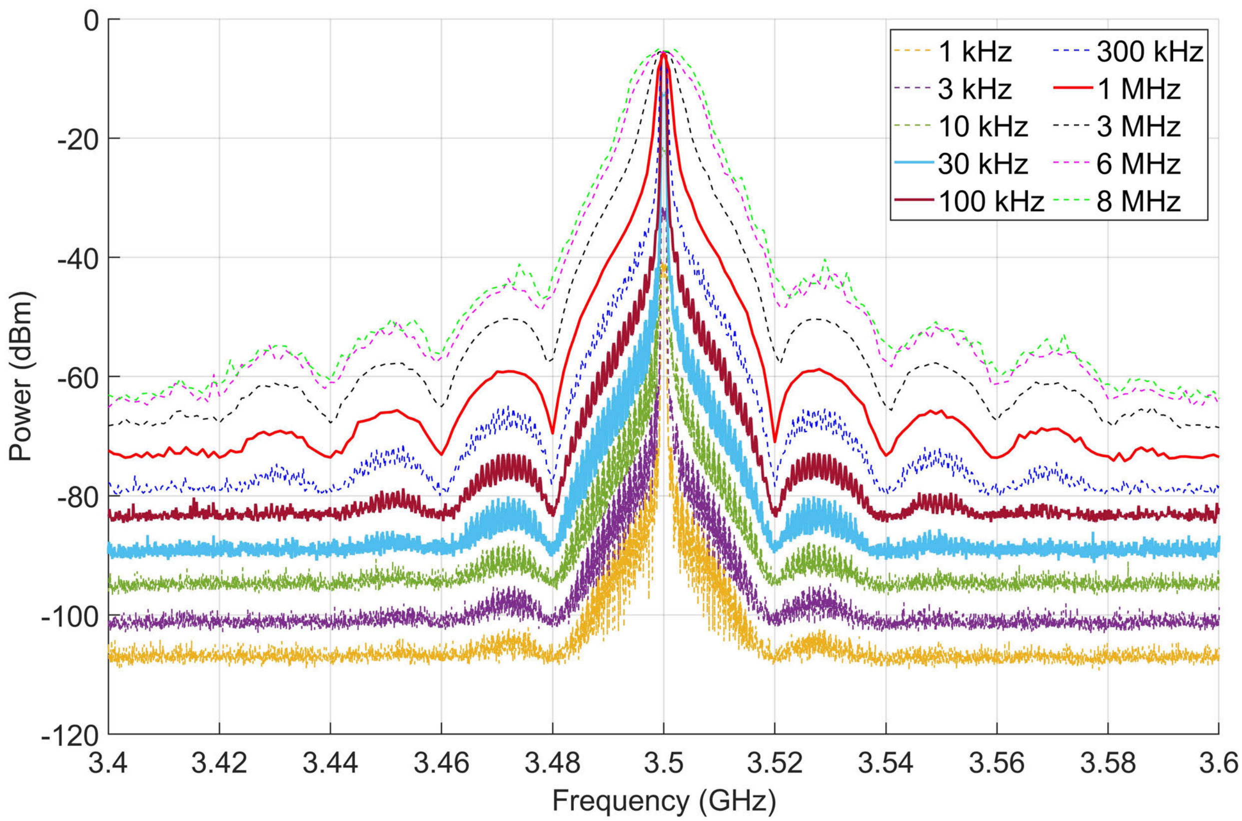

Figure B-1. Spectrum emission measurements at multiple RBW settings for compound waveform 20 (P0N waveform 1 and Q3N waveform 17). The calculated RBW setting for the P0N component is 1 MHz and it is 100 kHz for the Q3N component. The empirical optimum RBW setting to use for this measurement is 30 kHz.

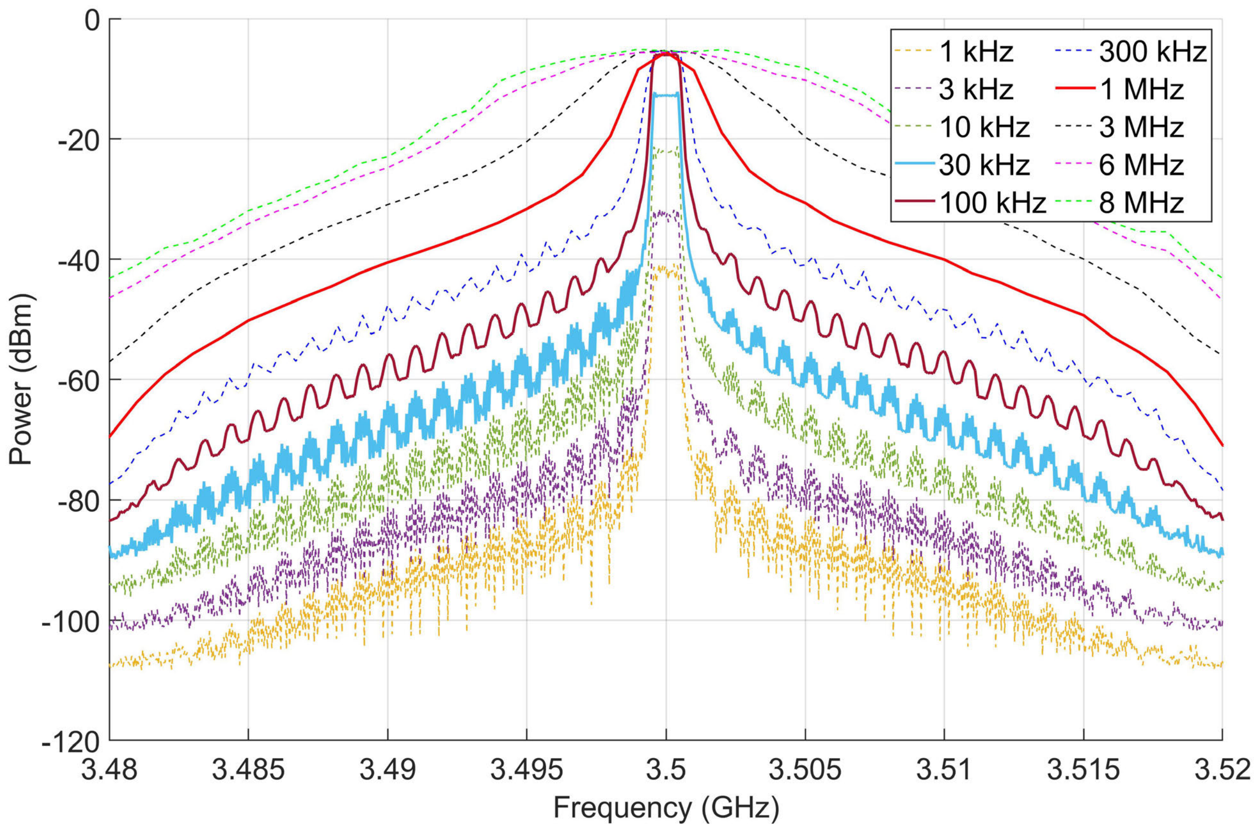

Figure B-2. Close-up view of the fundamental from Figure B-1 showing that RBW = 30 kHz is the optimum measurement bandwidth but the improvement is minimal.

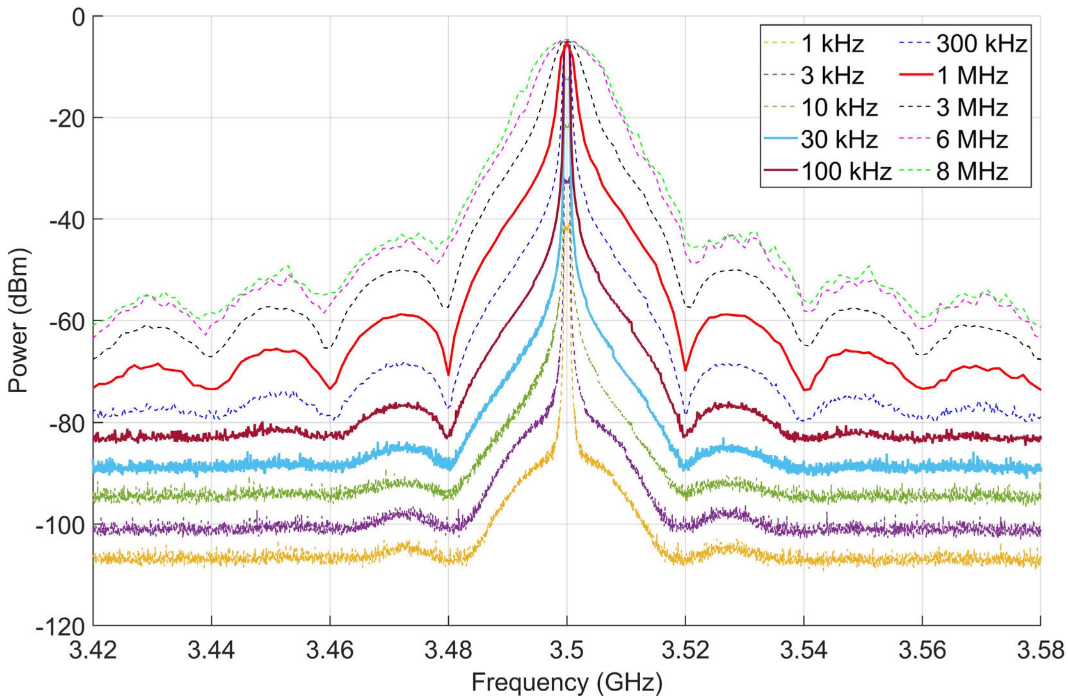

Figure B-3. Spectrum emission measurements at multiple RBW settings for compound waveform 21 (P0N waveform 1 and Q3N waveform 17, Q3N has 20 dB more peak power than P0N). The calculated RBW setting for the P0N component is 1 MHz and it is 100 kHz for the Q3N component. The empirical optimum RBW setting to use for this measurement is 30 kHz.

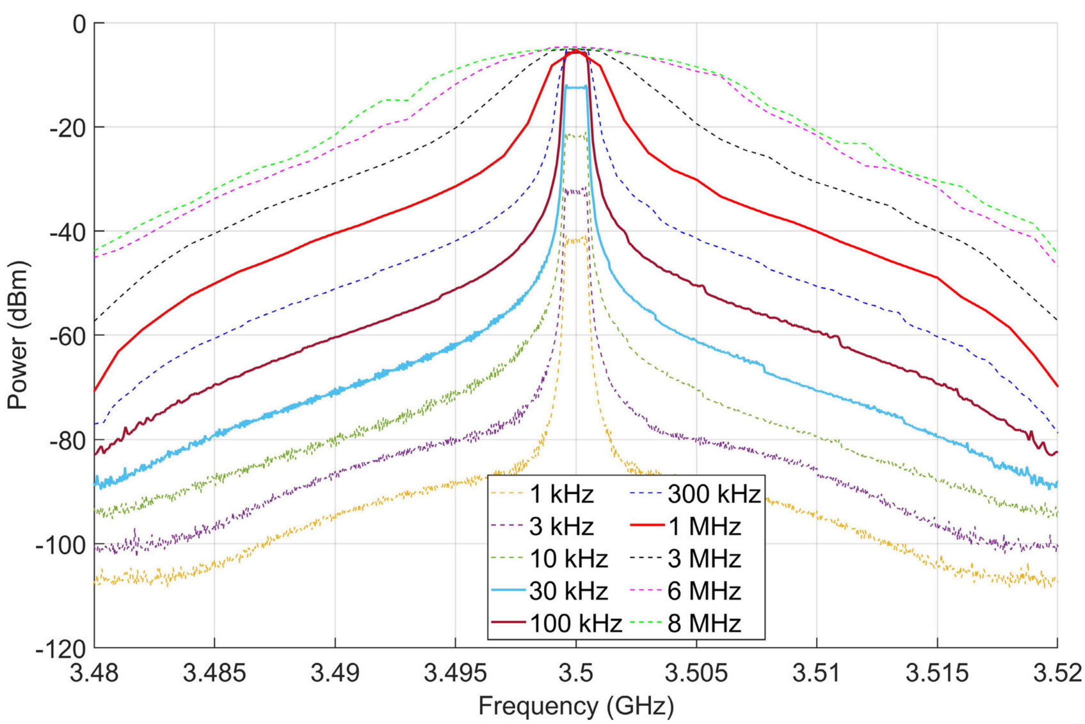

Figure B-4. Close-up view of the fundamental from Figure B-3 showing that RBW = 30 kHz is the optimum measurement bandwidth but the improvement is minimal.

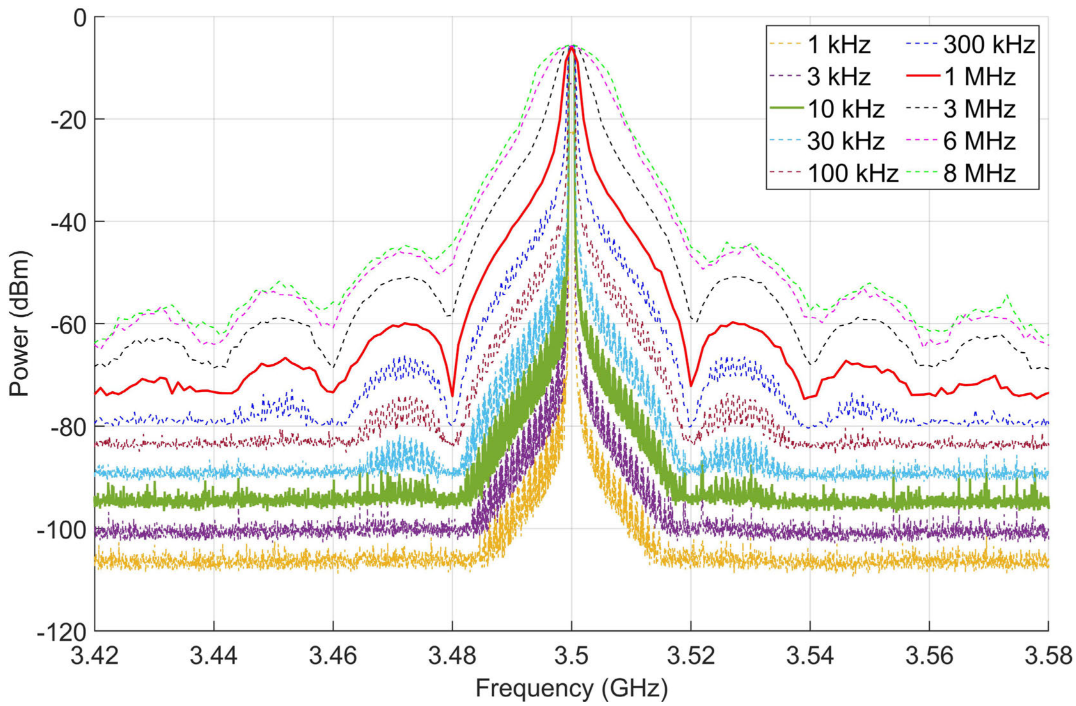

Figure B-5. Spectrum emission measurements at multiple RBW settings for compound waveform 22 (P0N waveform 1 and Q3N waveform 15). The calculated RBW setting for the P0N component is 1 MHz and it is 10 kHz for the Q3N component. The empirical optimum RBW setting to use for this measurement is 10 kHz.

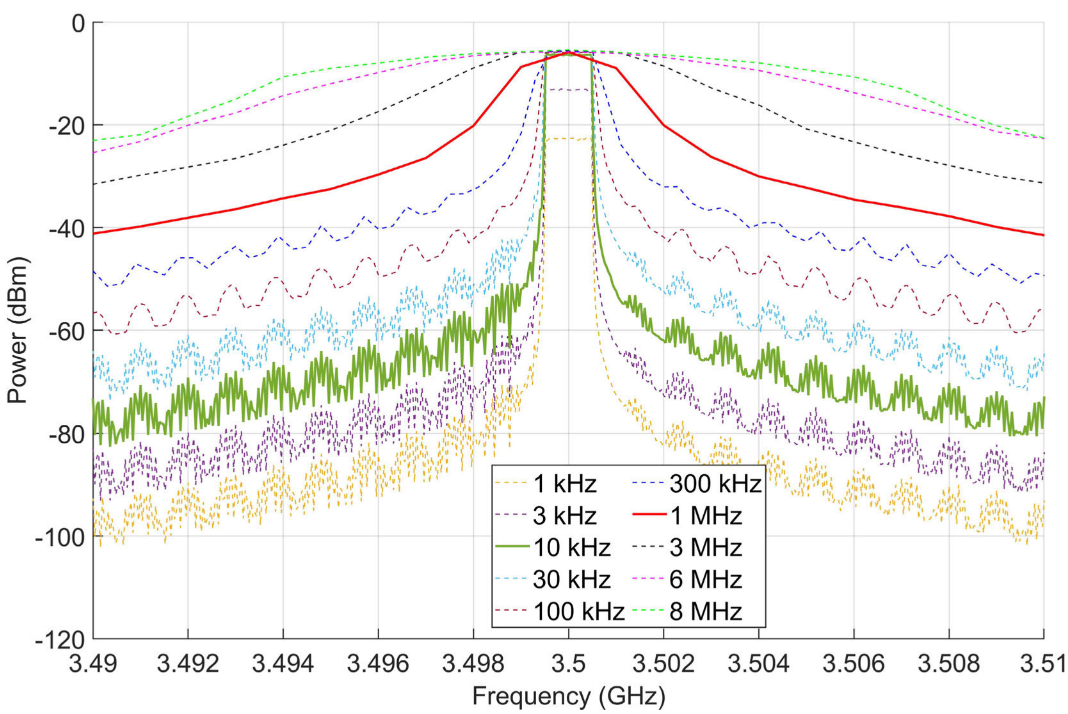

Figure B-6. Close-up view of the fundamental from Figure B-5 showing that RBW = 10 kHz is the optimum measurement bandwidth to use for this measurement.

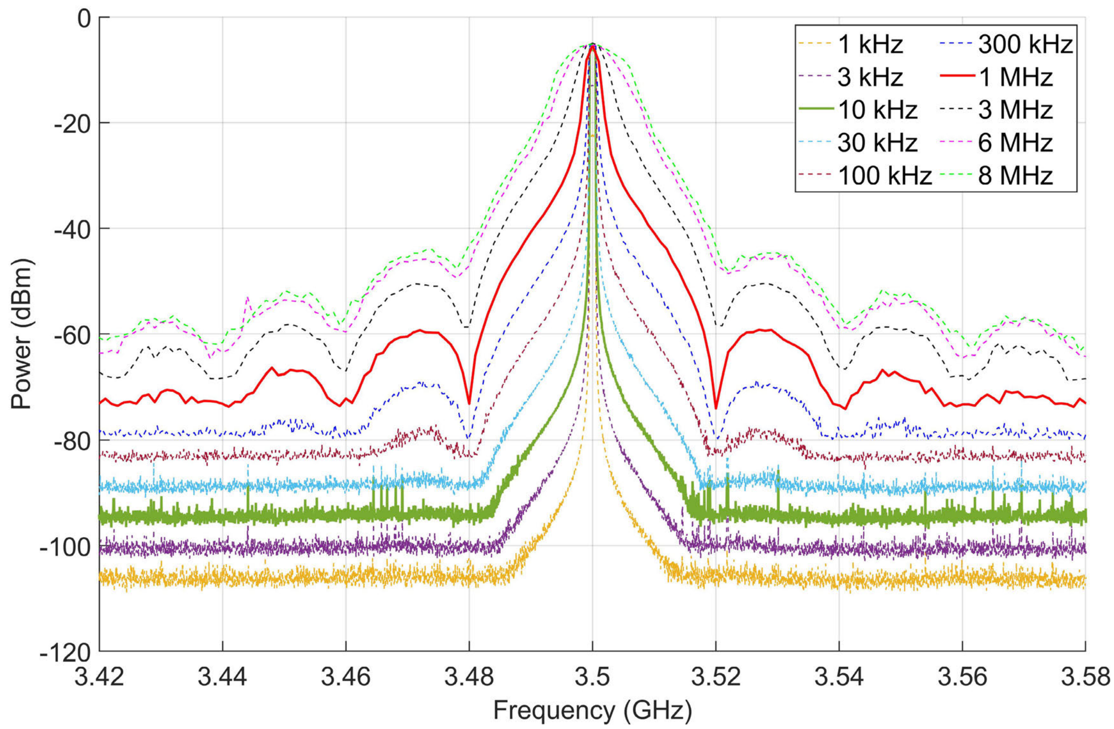

Figure B-7. Spectrum emission measurements at multiple RBW settings for compound waveform 23 (P0N waveform 1 and Q3N waveform 17, Q3N has 40 dB more peak power than P0N). The calculated RBW setting for the P0N component is 1 MHz and it is 10 kHz for the Q3N component. The empirical optimum RBW setting to use for this measurement is 10 kHz.

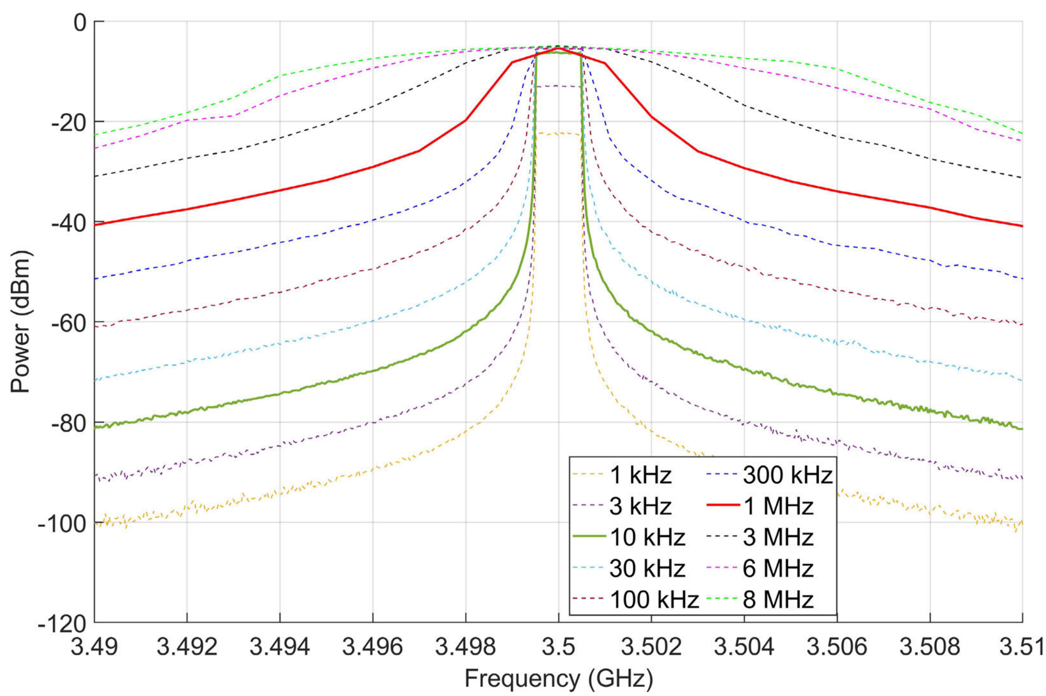

Figure B-8. Close-up view of the fundamental from Figure B-7 showing that RBW = 10 kHz is the optimum measurement bandwidth to use for this measurement.

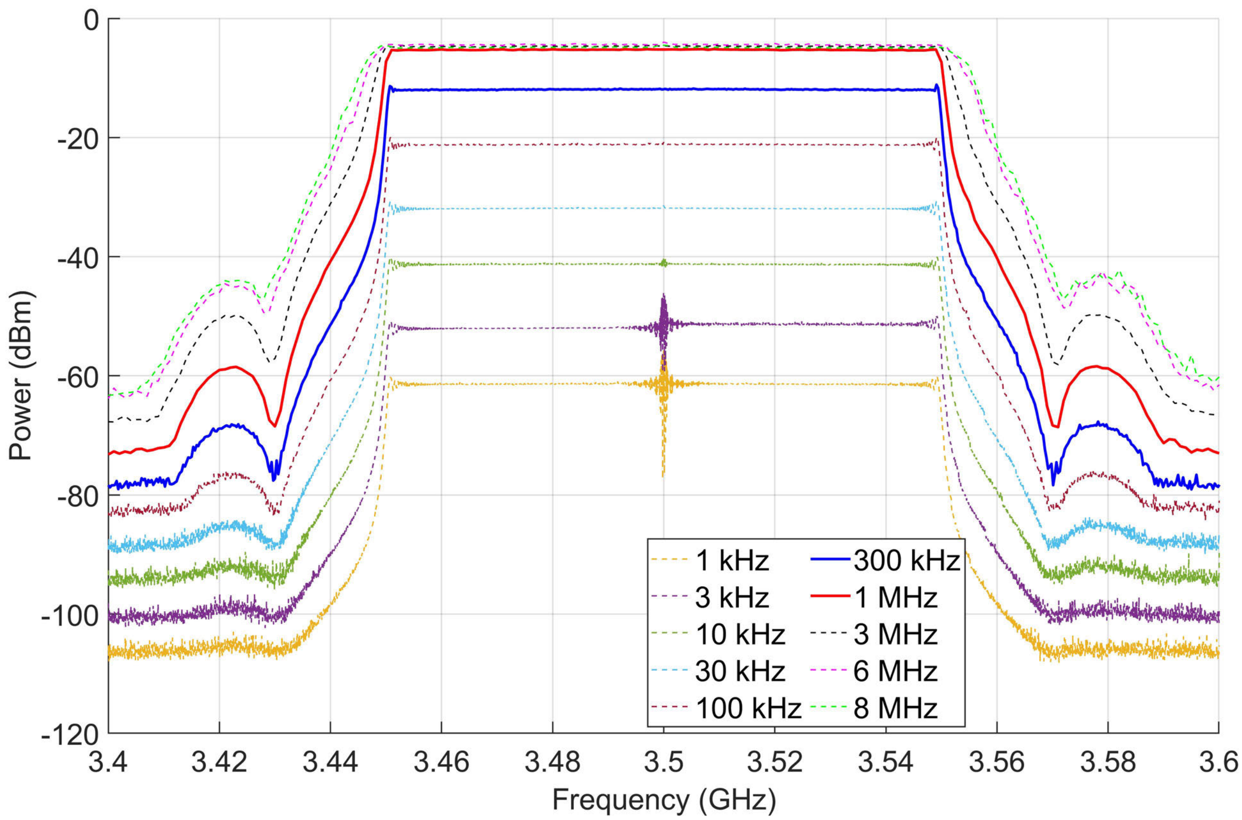

Figure B-9. Spectrum emission measurements at multiple RBW settings for compound waveform 25 (P0N waveform 1 and Q3N waveform 14). The calculated RBW setting for the P0N component is 1 MHz and for the Q3N component. The empirical optimum RBW setting to use for this measurement is 300 kHz but the improvement is minimal.

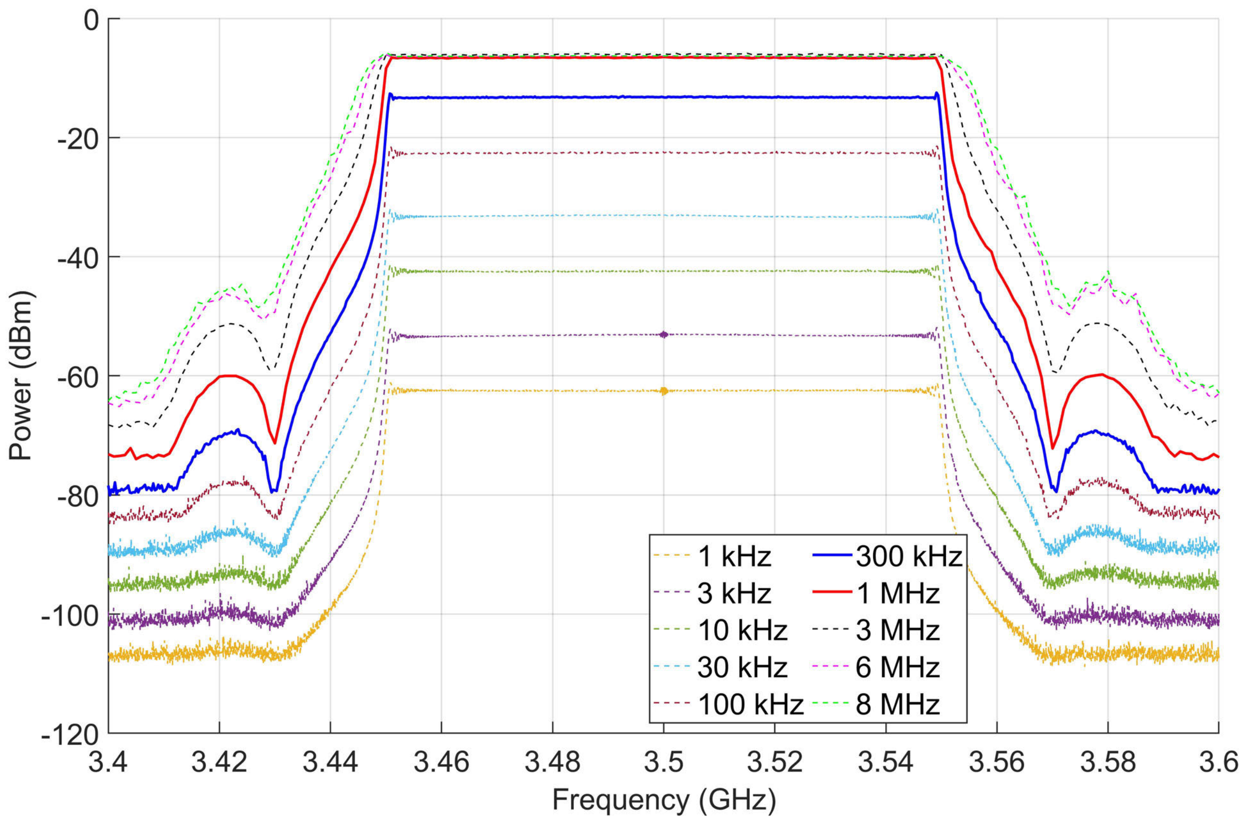

Figure B-10. Spectrum emission measurements at multiple RBW settings for compound waveform 26 (P0N waveform 1 and Q3N waveform 14, Q3N has 20 dB more peak power than P0N). The calculated RBW setting for the P0N and Q3N components is 1 MHz. The empirical optimum RBW setting to use for this measurement is 300 kHz, but the improvement is minimal.

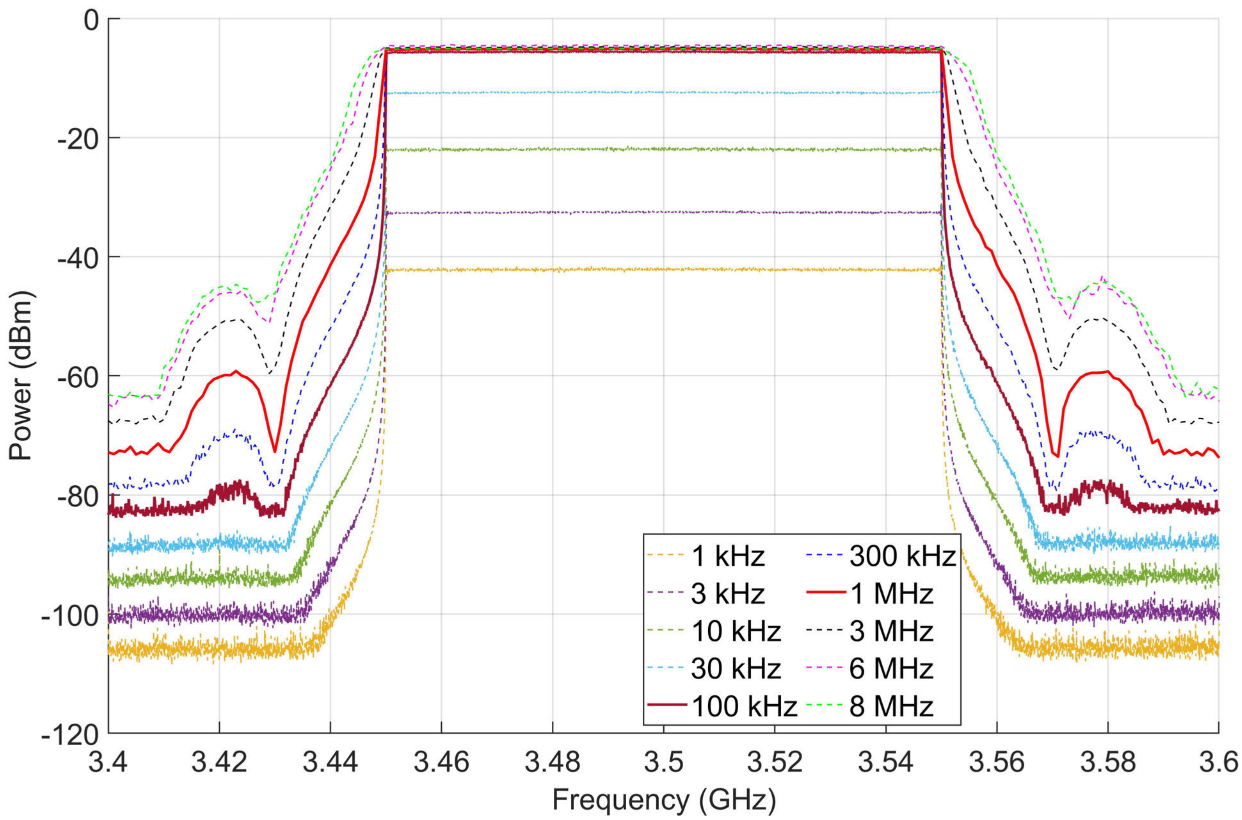

Figure B-11. Spectrum emission measurements at multiple RBW settings for compound waveform 28 (P0N waveform 1 and Q3N waveform 12, Q3N has 40 dB more peak power than P0N). The calculated RBW setting for the P0N component is 1 MHz and 100 kHz for the Q3N component. The empirical optimum RBW setting to use for this measurement is 100 kHz.

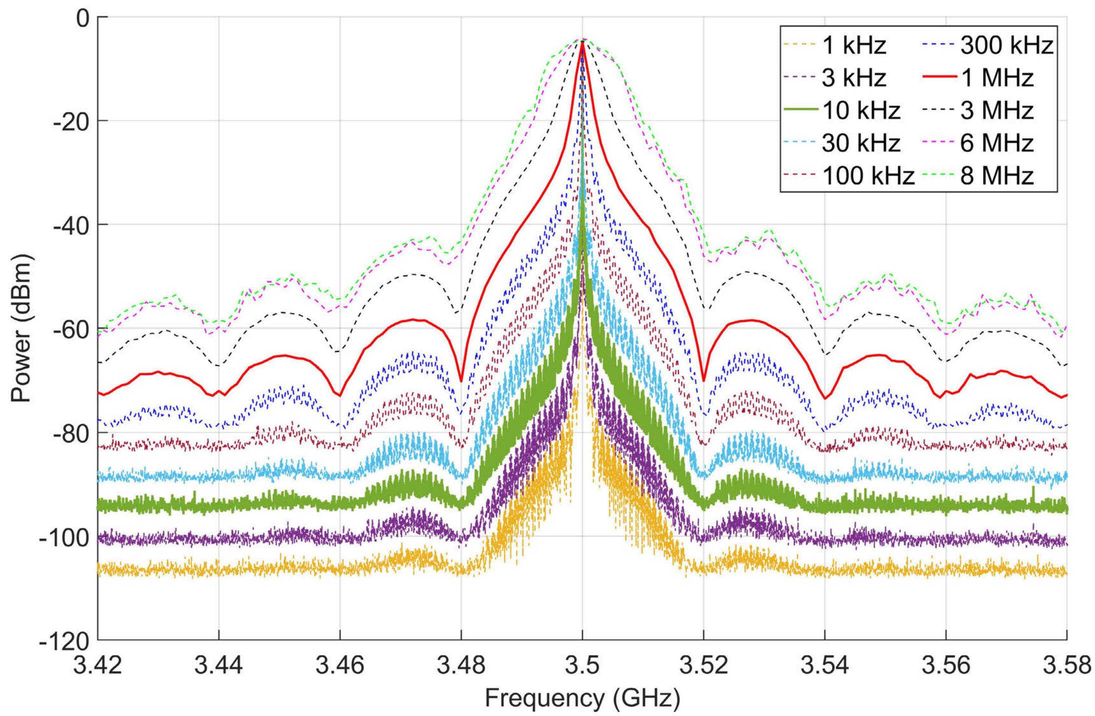

Figure B-12. Spectrum emission measurements at multiple RBW settings for compound waveform 29 (P0N waveform 8 and Q3N waveform 10). The calculated RBW setting for the P0N component is 10 kHz and 1 MHz for the Q3N component. The empirical optimum RBW setting to use for this measurement is 10 kHz.

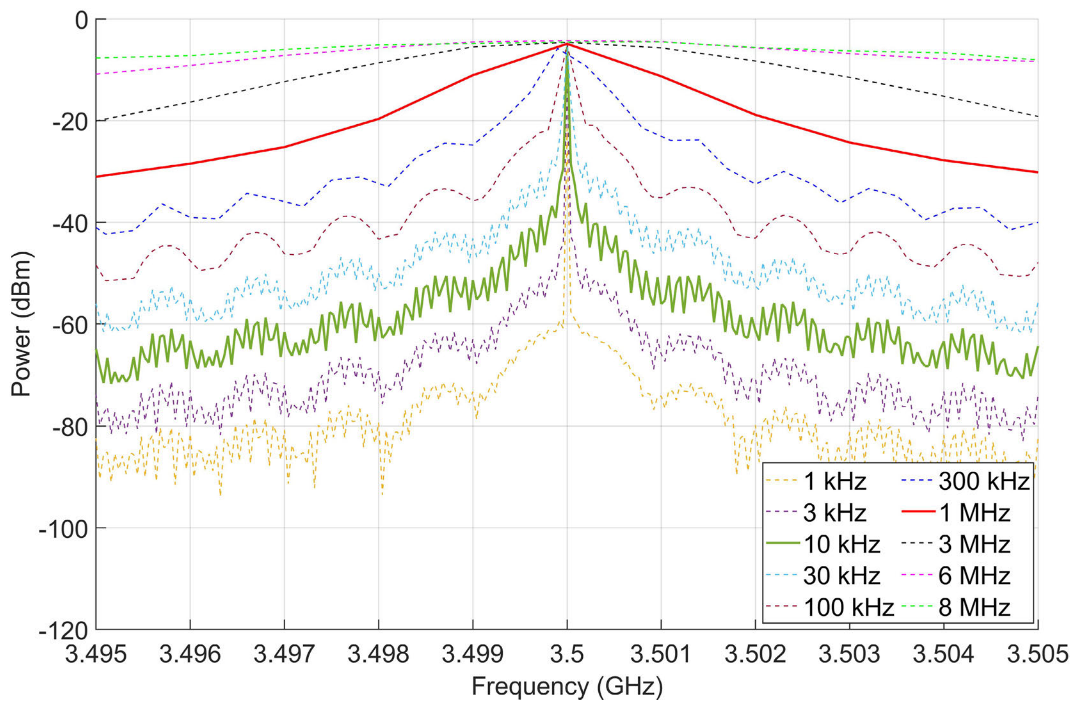

Figure B-13. Close-up view of the fundamental from Figure B-12 showing that RBW = 10 kHz is the optimum measurement bandwidth to use for this measurement.

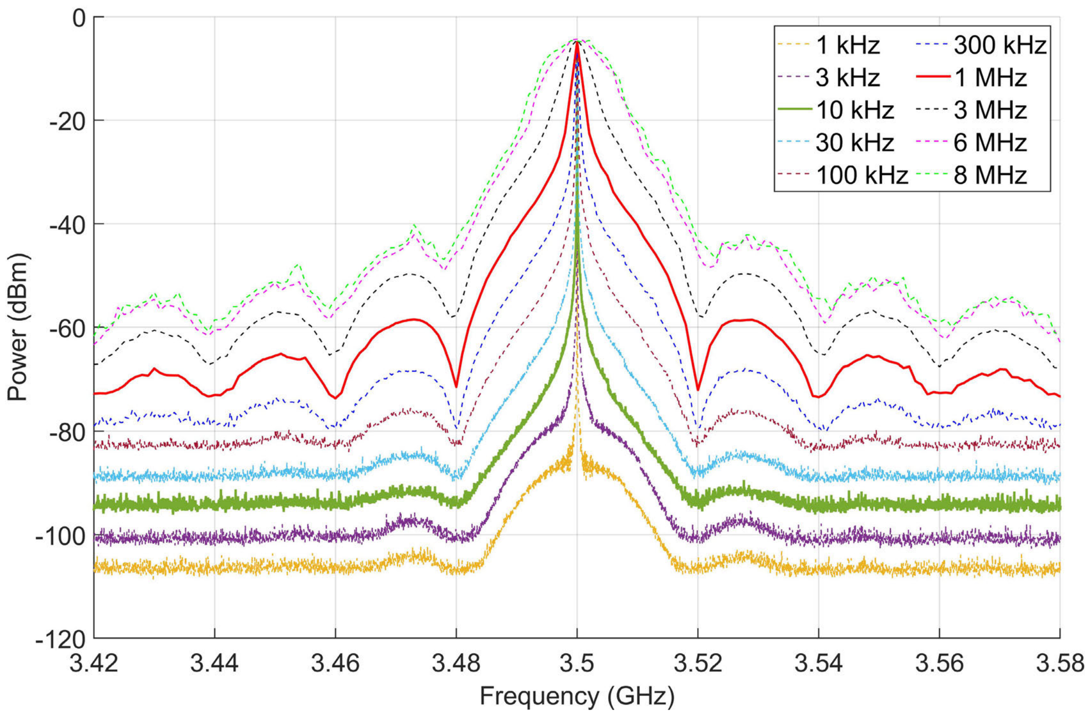

Figure B-14. Spectrum emission measurements at multiple RBW settings for compound waveform 30 (P0N waveform 8 and Q3N waveform 10, Q3N has 20 dB less peak power than P0N). The calculated RBW setting for the P0N component is 10 kHz and 1 MHz for the Q3N component. The empirical optimum RBW setting to use for this measurement is 10 kHz.

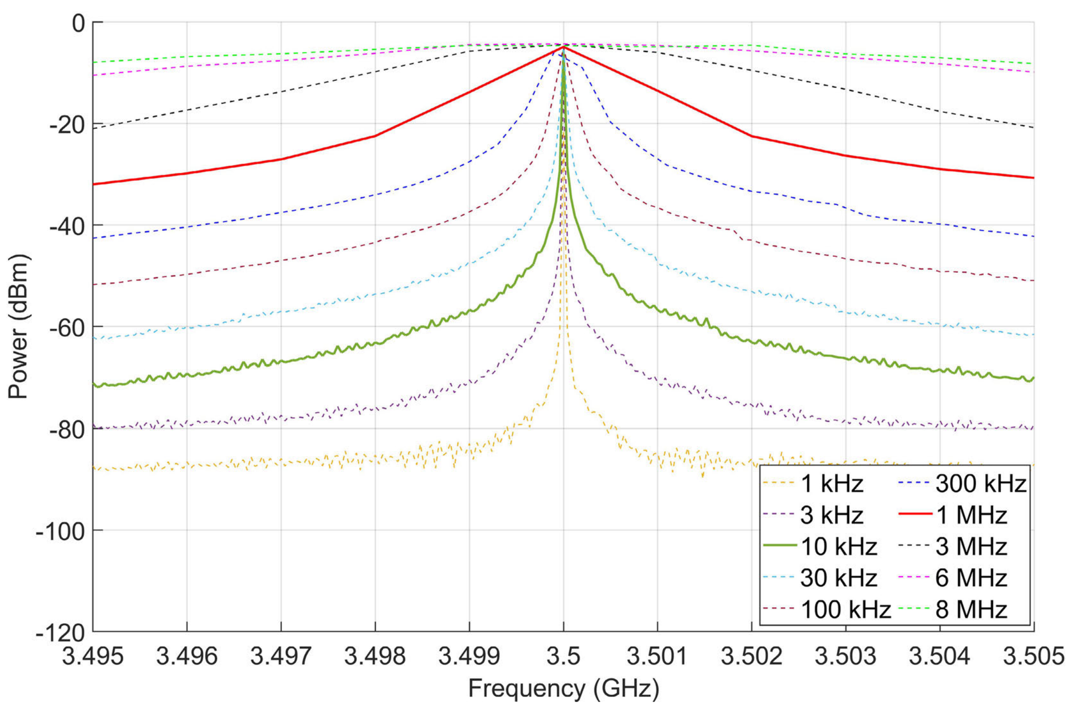

Figure B-15. Close-up view of the fundamental from Figure B-14 showing that RBW = 10 kHz is the optimum measurement bandwidth to use for this measurement.

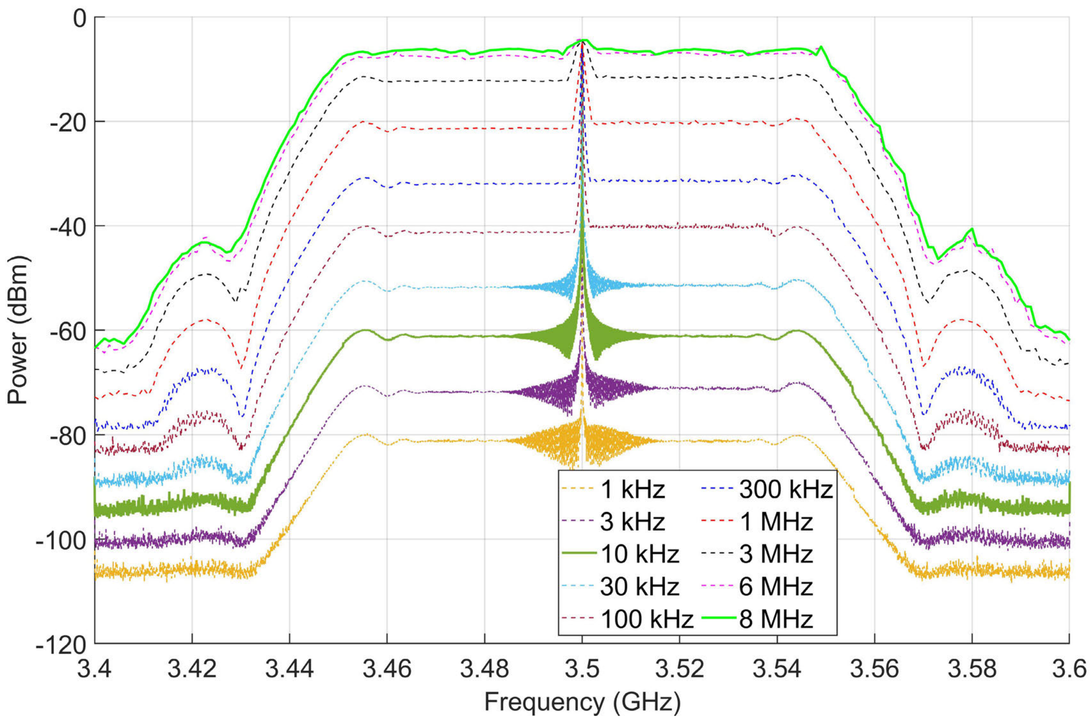

Figure B-16. Spectrum emission measurements at multiple RBW settings for compound waveform 34 (P0N waveform 8 and Q3N waveform 16). The calculated RBW setting for the P0N component is 10 kHz and 10 MHz for the Q3N component. The empirical optimum RBW setting to use for this measurement is 10 kHz.

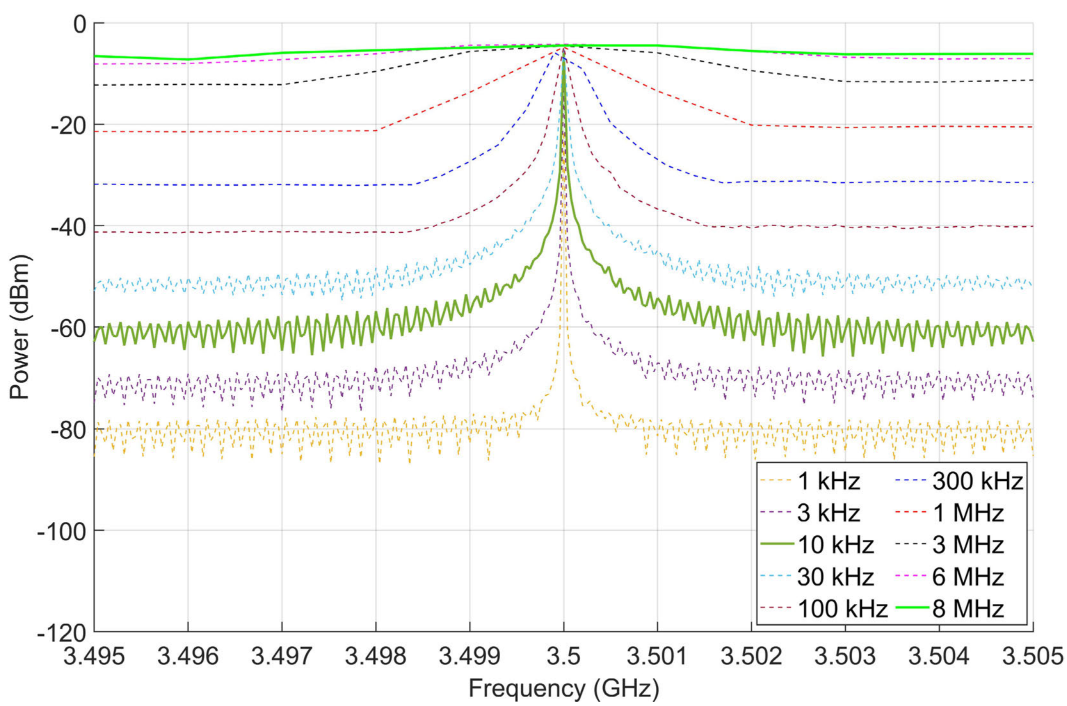

Figure B-17. Close-up view of the fundamental from Figure B-16 showing that RBW = 10 kHz is the optimum measurement bandwidth to use for this measurement.

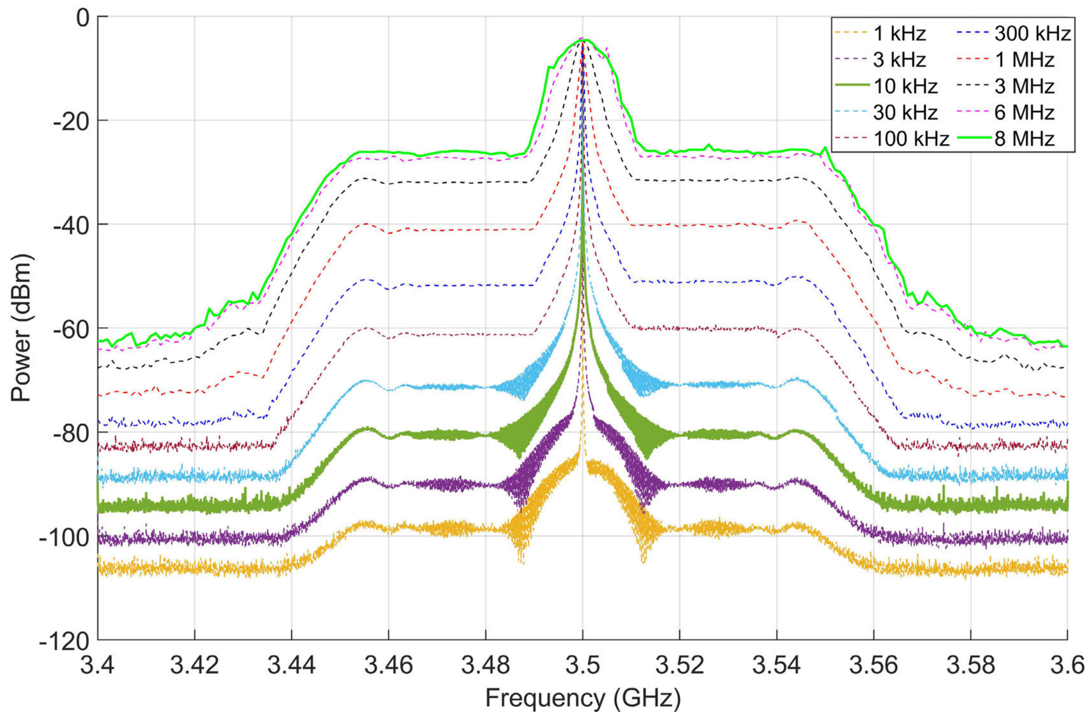

Figure B-18. Spectrum emission measurements at multiple RBW settings for compound waveform 35 (P0N waveform 8 and Q3N waveform 16, Q3N has 20 dB less peak power than P0N). The calculated RBW setting for the P0N component is 10 kHz and 10 MHz for the Q3N component. The empirical optimum RBW setting to use for this measurement is 10 kHz.

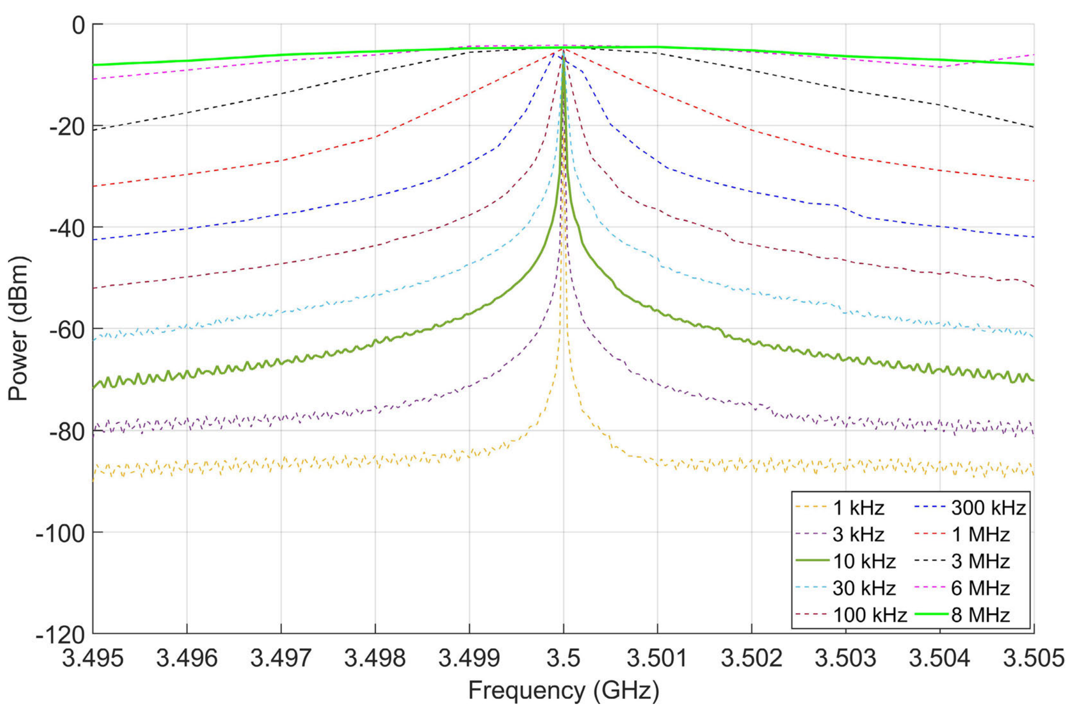

Figure B-19. Close-up view of the fundamental from Figure B-18 showing that RBW = 10 kHz is the optimum measurement bandwidth to use for this measurement.

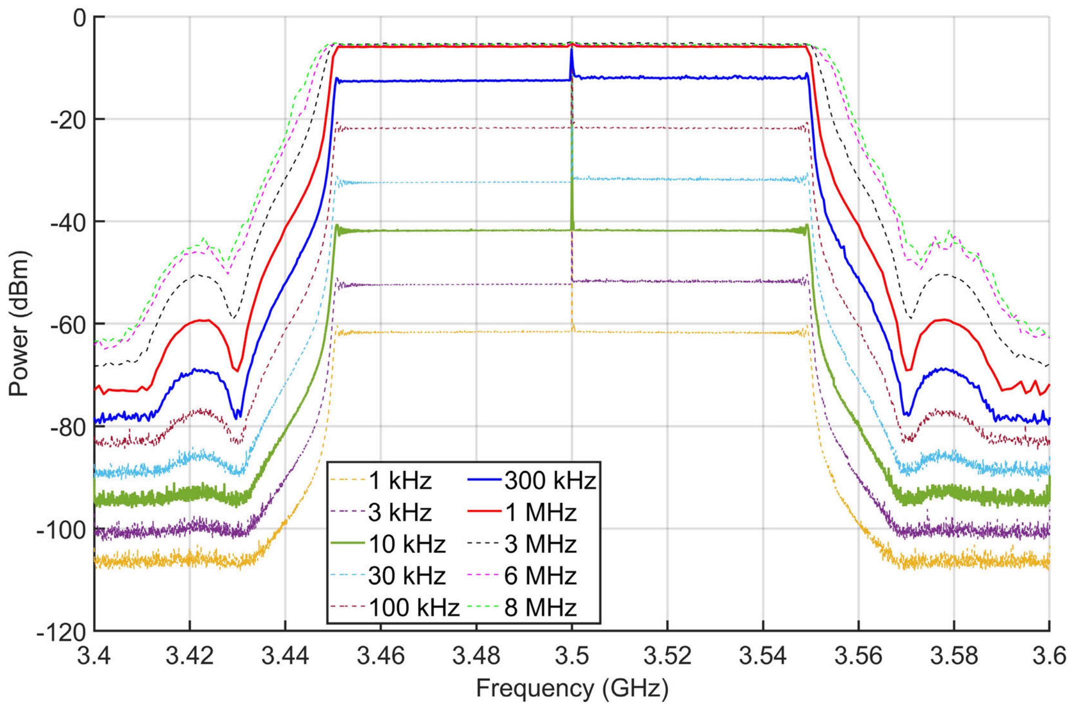

Figure B-20. Spectrum emission measurements at multiple RBW settings for compound waveform 36 (P0N waveform 8 and Q3N waveform 14). The calculated RBW setting for the P0N component is 10 kHz and 1 MHz for the Q3N component. The empirical optimum RBW setting to use for this measurement is 10 kHz.

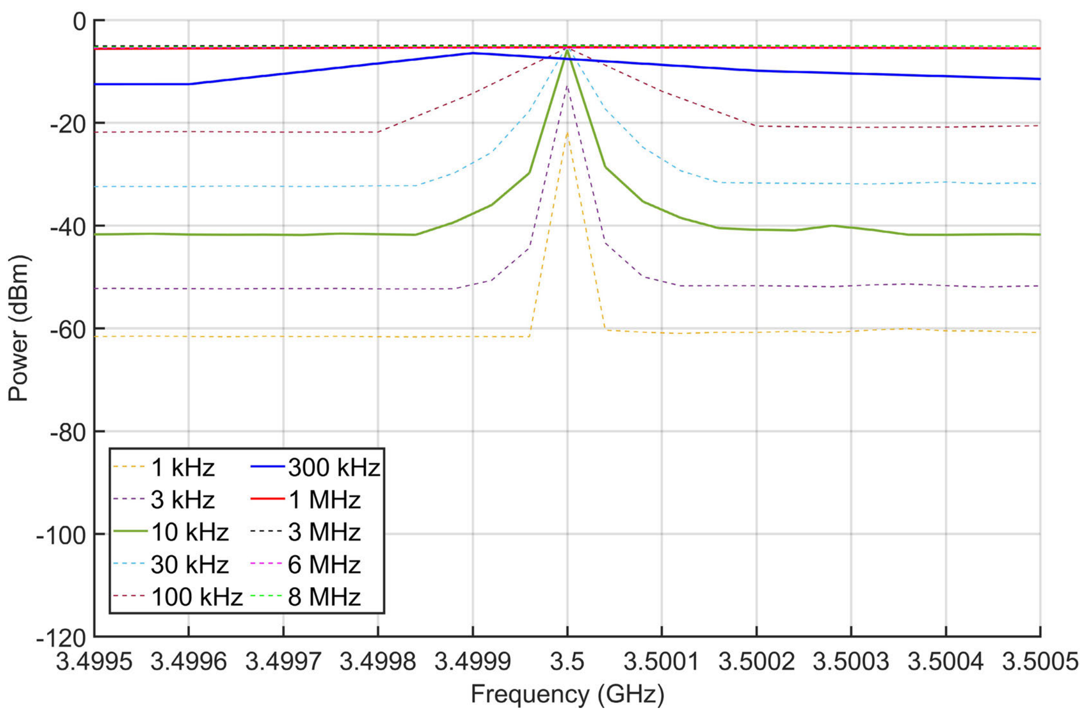

Figure B-21. Close-up view of the fundamental from Figure B-22 showing that RBW = 10 kHz is the optimum measurement bandwidth to use for this measurement.

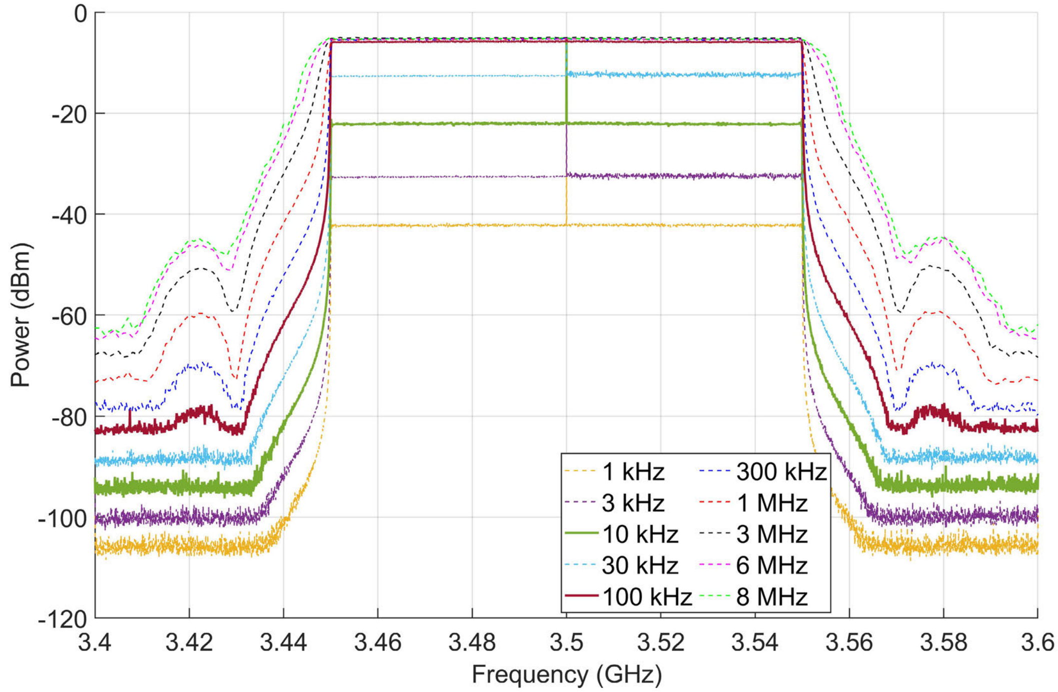

Figure B-22. Spectrum emission measurements at multiple RBW settings for compound waveform 37 (P0N waveform 8 and Q3N waveform 12). The calculated RBW setting for the P0N component is 10 kHz and 100 kHz for the Q3N component. The empirical optimum RBW setting to use for this measurement is 10 kHz.

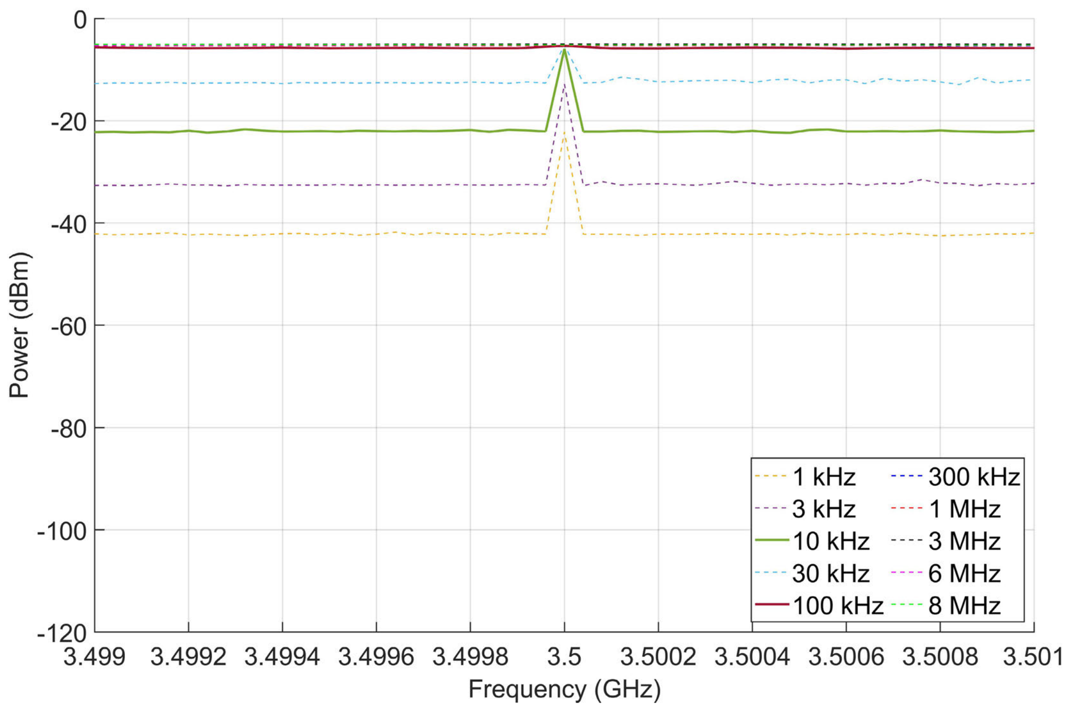

Figure B-23. Close-up view of the fundamental from Figure B-22 showing that RBW = 10 kHz is the optimum measurement bandwidth to use for this measurement.

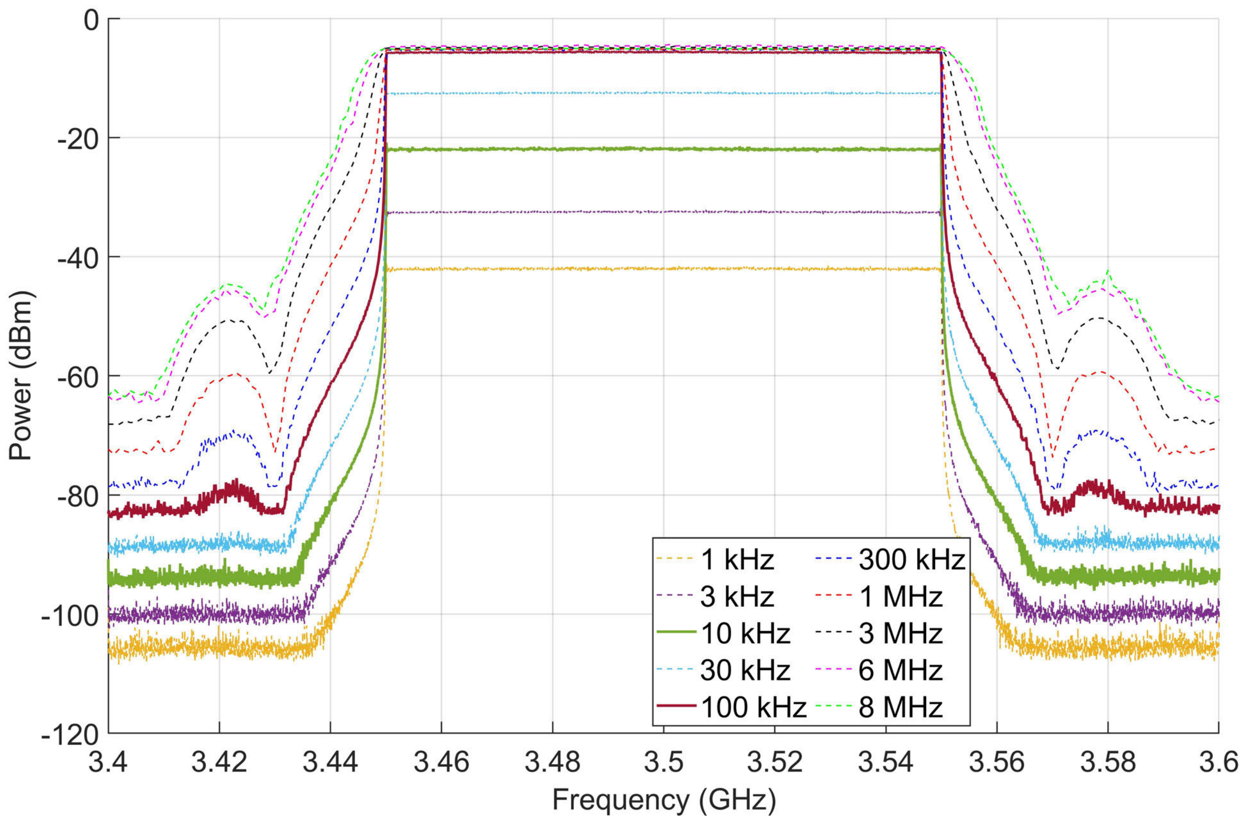

Figure B-24. Spectrum emission measurements at multiple RBW settings for compound waveform 38 (P0N waveform 6 and Q3N waveform 10, Q3N has 20 dB more peak power than P0N). The calculated RBW setting for the P0N component is 10 kHz and 100 kHz for the Q3N component. The empirical optimum RBW setting to use for this measurement is 100 kHz because the Q3N component dominates the spectrum. The P0N component is not visible at all at any RBW setting.

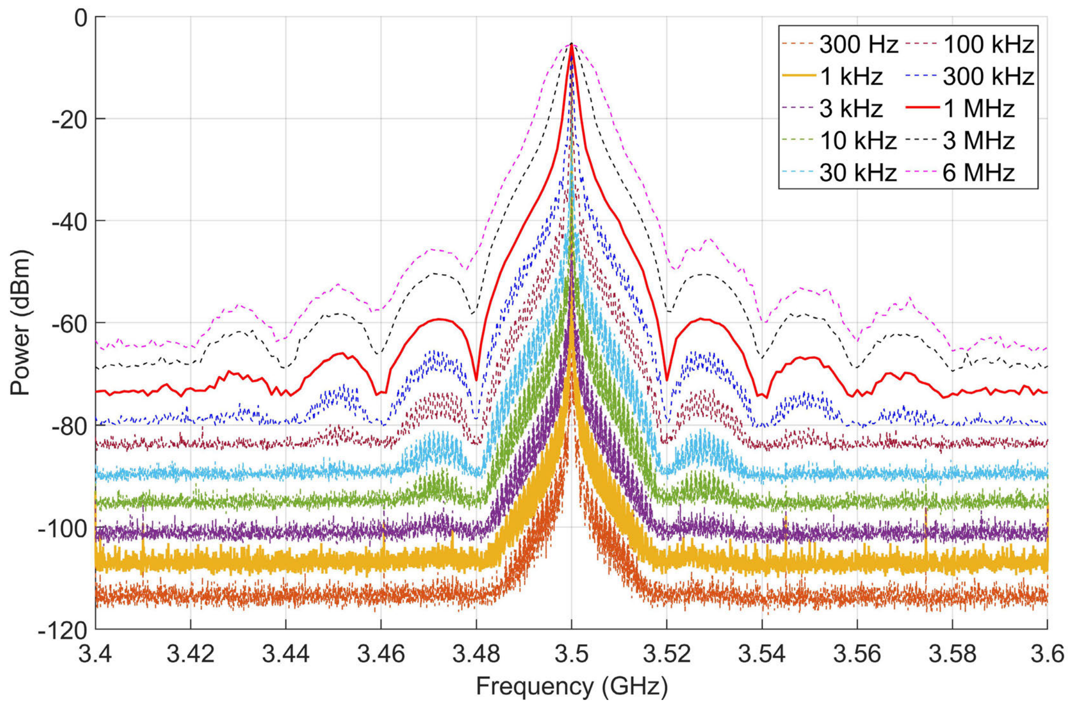

Figure B-25. Spectrum emission measurements at multiple RBW settings for compound waveform 39 (P0N waveform 6 and Q3N waveform 10). The calculated RBW setting for the P0N component is 1 kHz and 1 MHz for the Q3N component. The empirical optimum RBW setting to use for this measurement is 1 kHz.

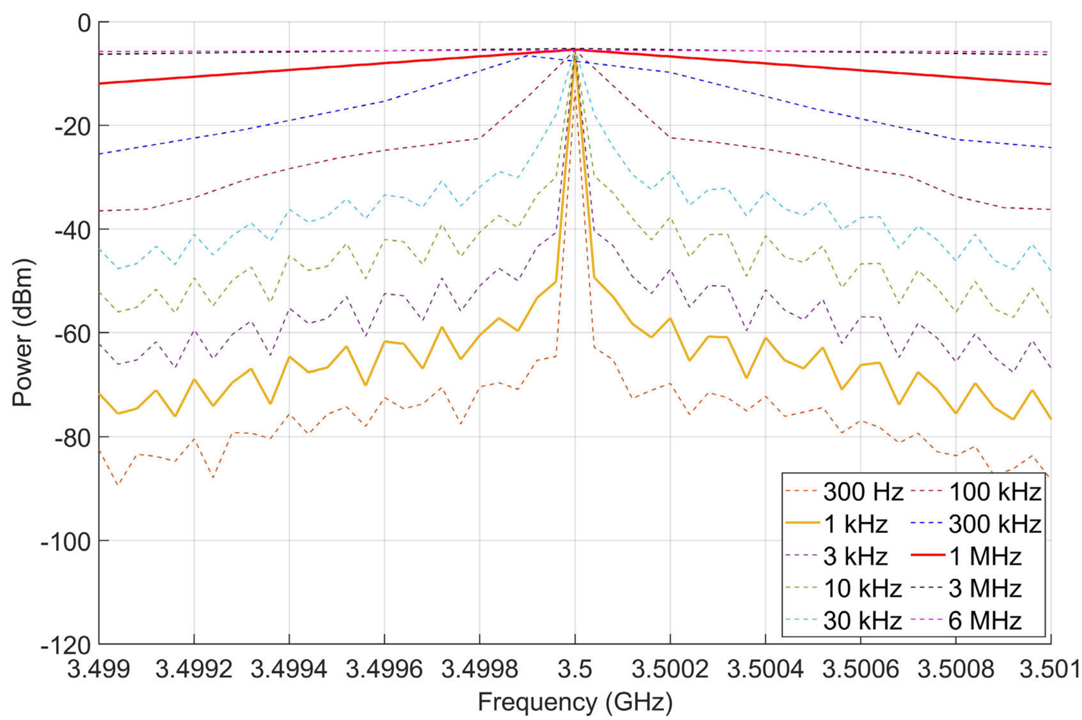

Figure B-26. Close-up view of the fundamental from Figure B-25 showing that RBW = 1 kHz is the optimum measurement bandwidth to use for this measurement.

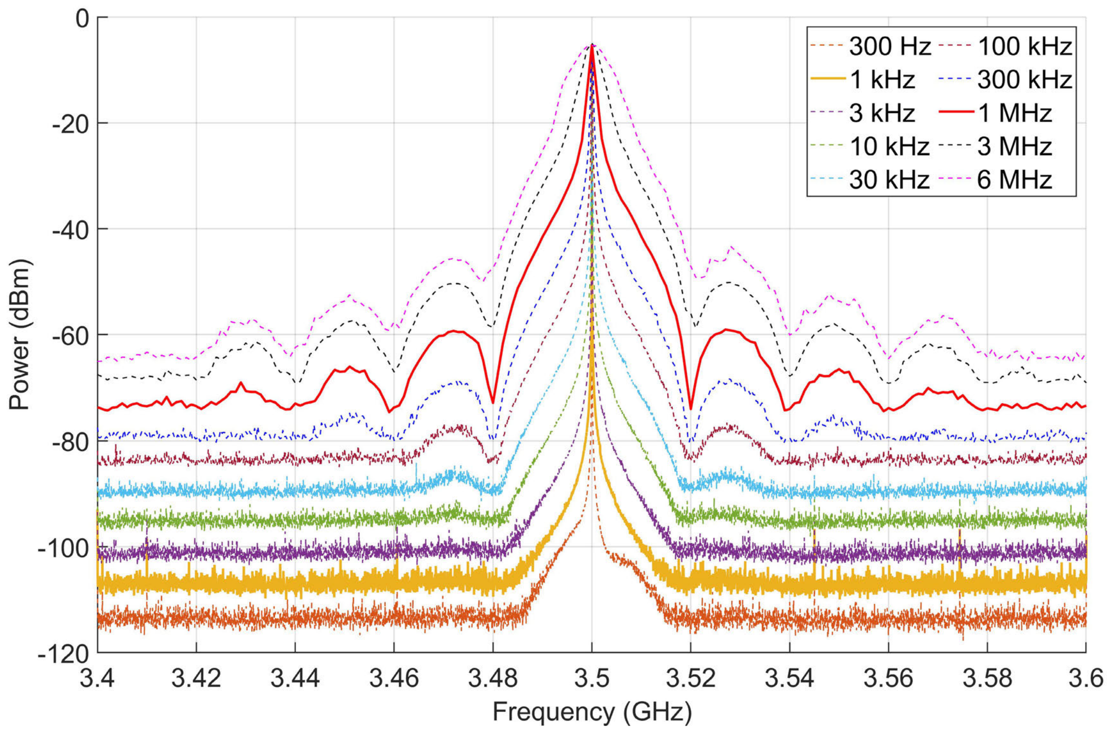

Figure B-27. Spectrum emission measurements at multiple RBW settings for compound waveform 40 (P0N waveform 6 and Q3N waveform 10, Q3N has 40 dB less peak power than P0N). The calculated RBW setting for the P0N component is 1 kHz and 1 MHz for the Q3N component. The empirical optimum RBW setting to use for this measurement is 1 kHz.

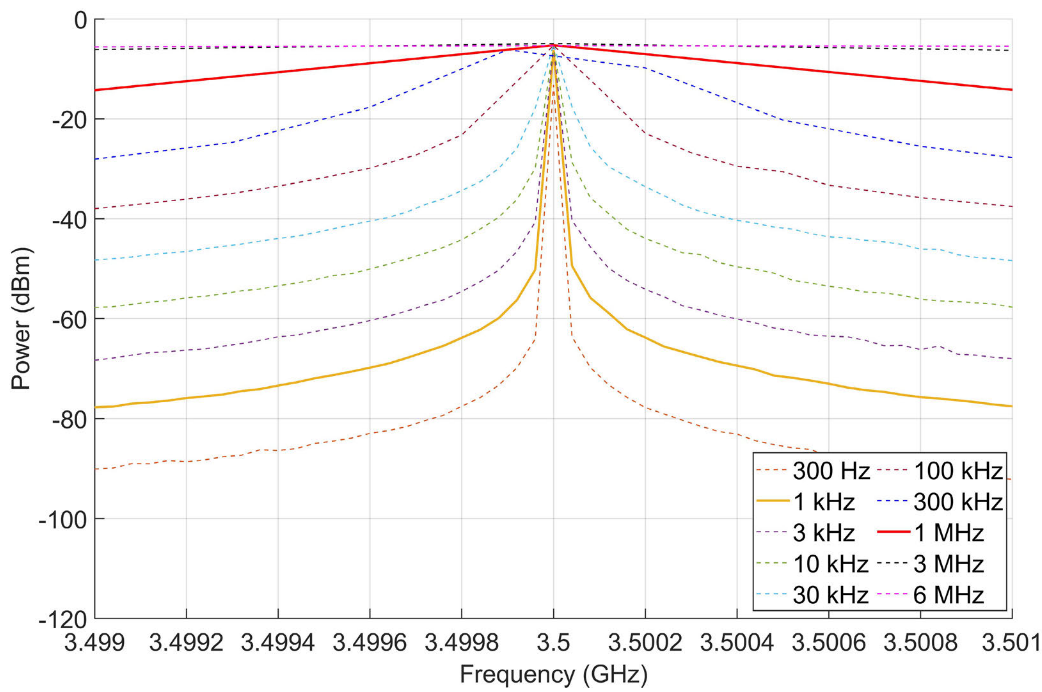

Figure B-28. Close-up view of the fundamental from Figure B-27 showing that RBW = 1 kHz is the optimum measurement bandwidth to use for this measurement.

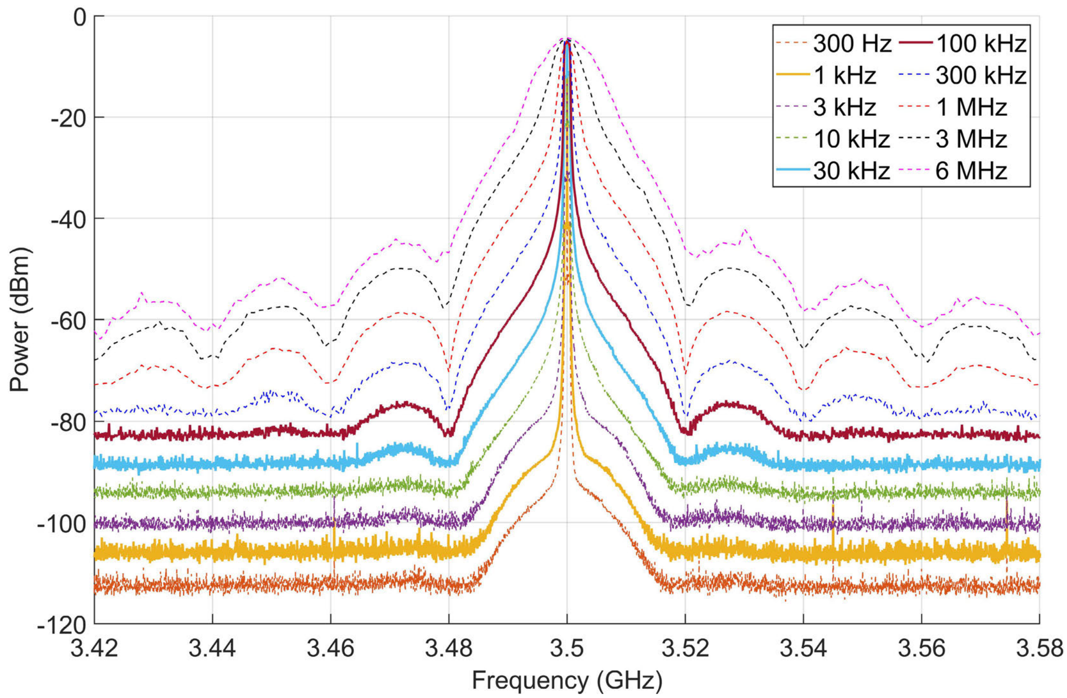

Figure B-29. Spectrum emission measurements at multiple RBW settings for compound waveform 41 (P0N waveform 6 and Q3N waveform 17). The calculated RBW setting for the P0N component is 1 kHz and 100 kHz for the Q3N component (30 kHz is the empirical RBW for Q3N). The empirical optimum RBW setting to use for this compound radar waveform is 1 kHz.

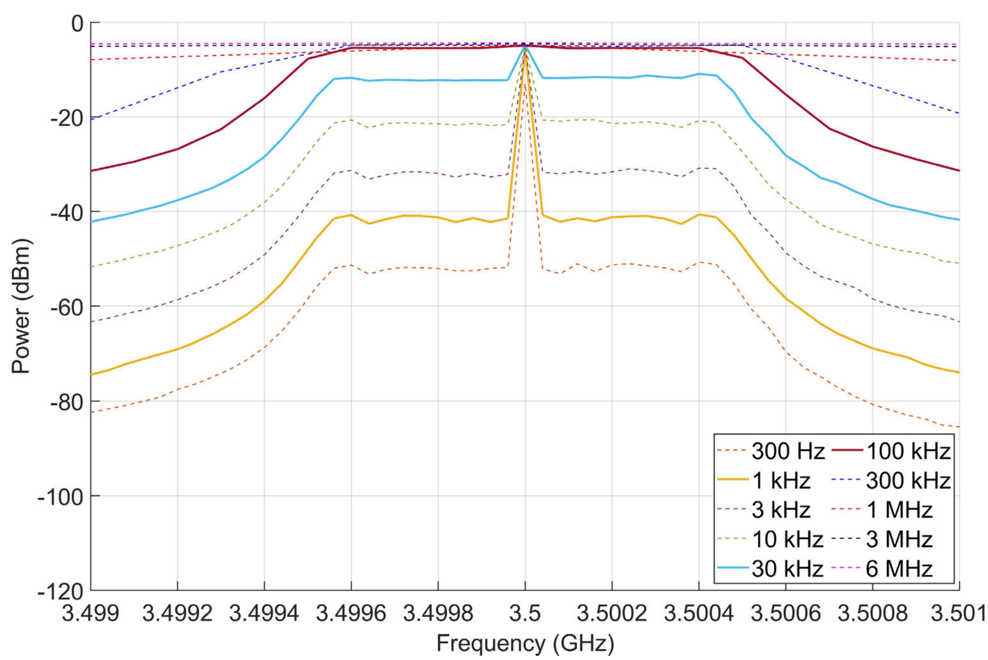

Figure B-30. Close-up view of the fundamental from Figure B-29 showing that RBW = 1 kHz is the optimum measurement bandwidth to use for this measurement.

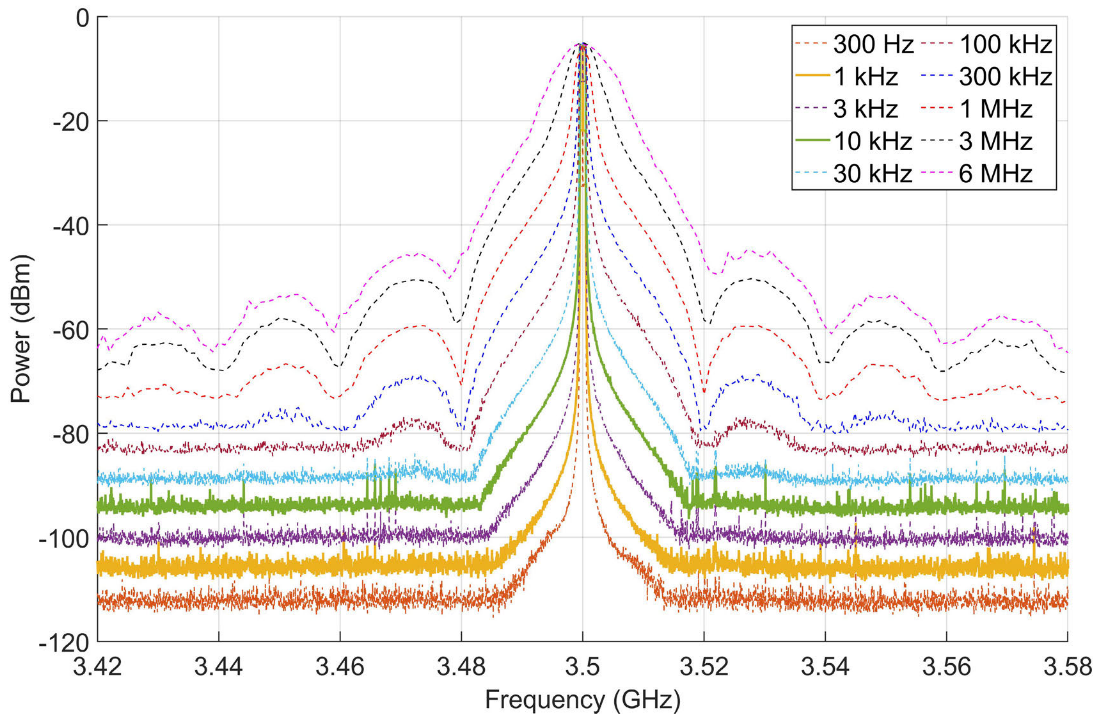

Figure B-31. Spectrum emission measurements at multiple RBW settings for compound waveform 43 (P0N waveform 6 and Q3N waveform 15). The calculated RBW setting for the P0N component is 1 kHz and 10 kHz for the Q3N component. The empirical optimum RBW setting to use for this compound radar waveform is 1 kHz.

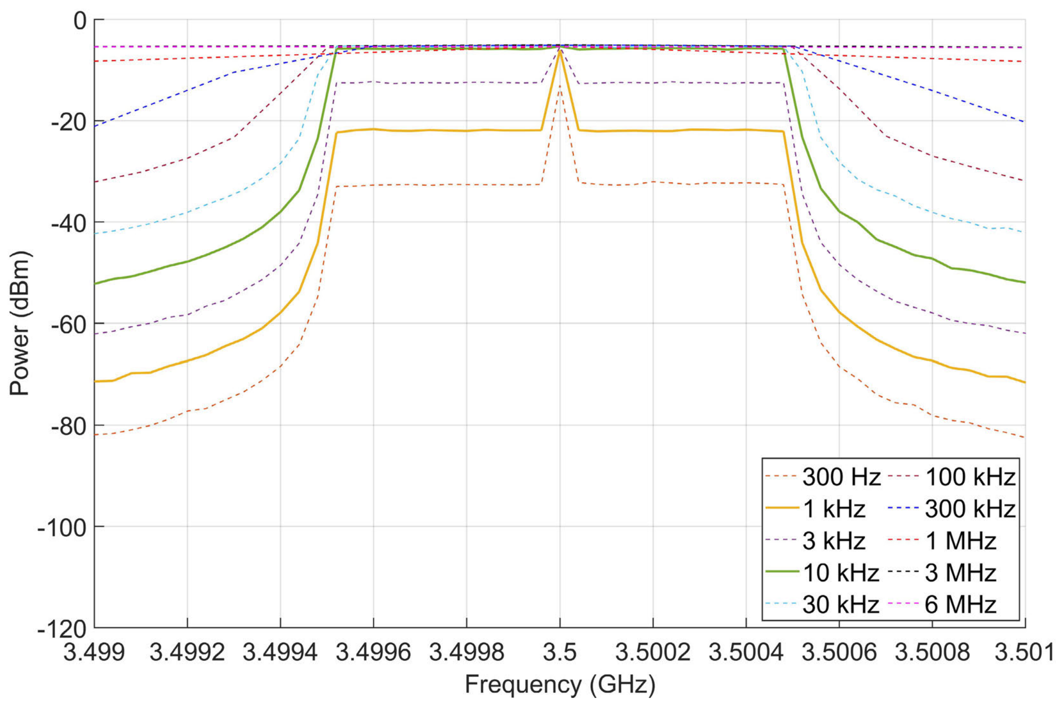

Figure B-32. Close-up view of the fundamental from Figure B-31 showing that RBW = 1 kHz is the optimum measurement bandwidth to use for this measurement.

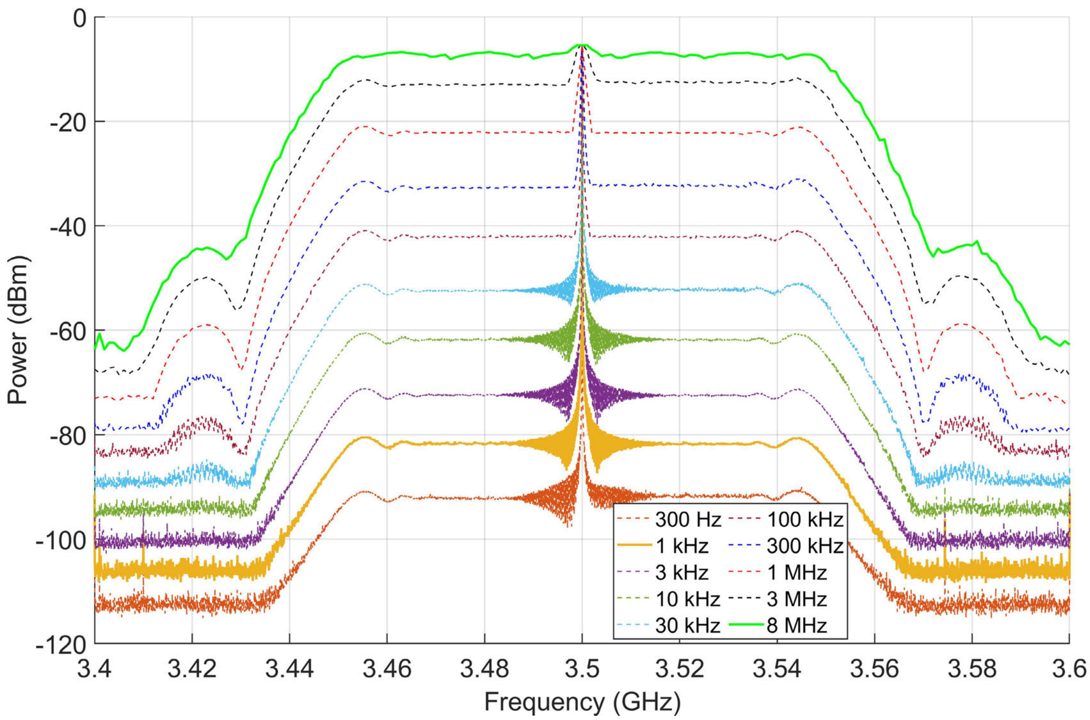

Figure B-33. Spectrum emission measurements at multiple RBW settings for compound waveform 44 (P0N waveform 6 and Q3N waveform 16). The calculated RBW setting for the P0N component is 1 kHz and 10 MHz for the Q3N component. The empirical optimum RBW setting to use for this compound radar waveform is 1 kHz.

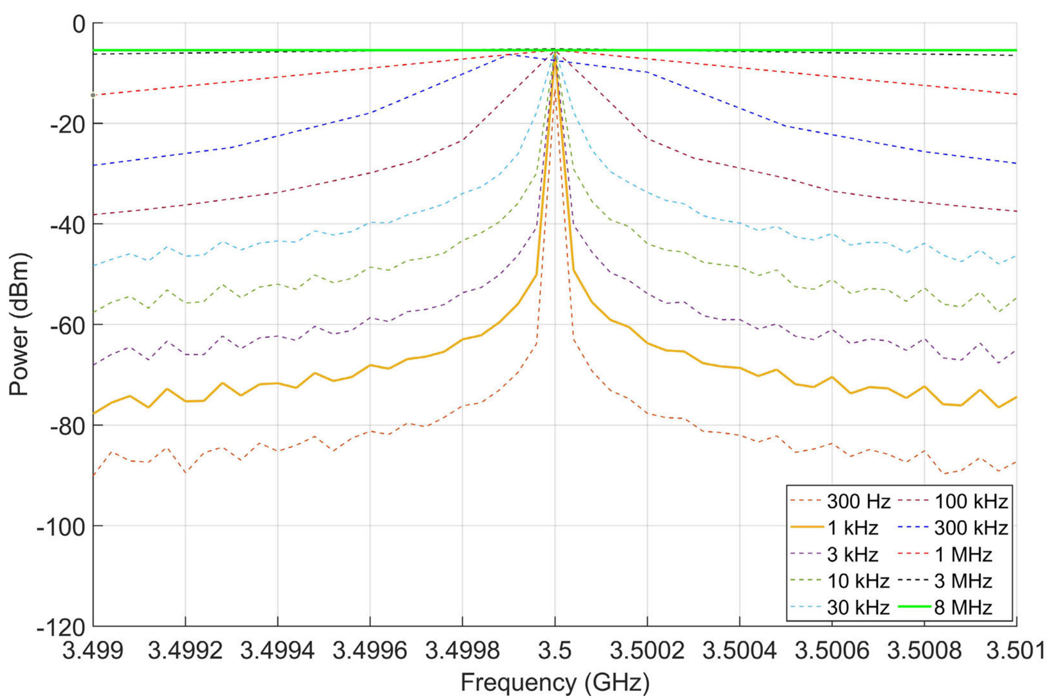

Figure B-34. Close-up view of the fundamental from Figure B-33Figure B-31 showing that RBW = 1 kHz is the optimum measurement bandwidth to use for this measurement.

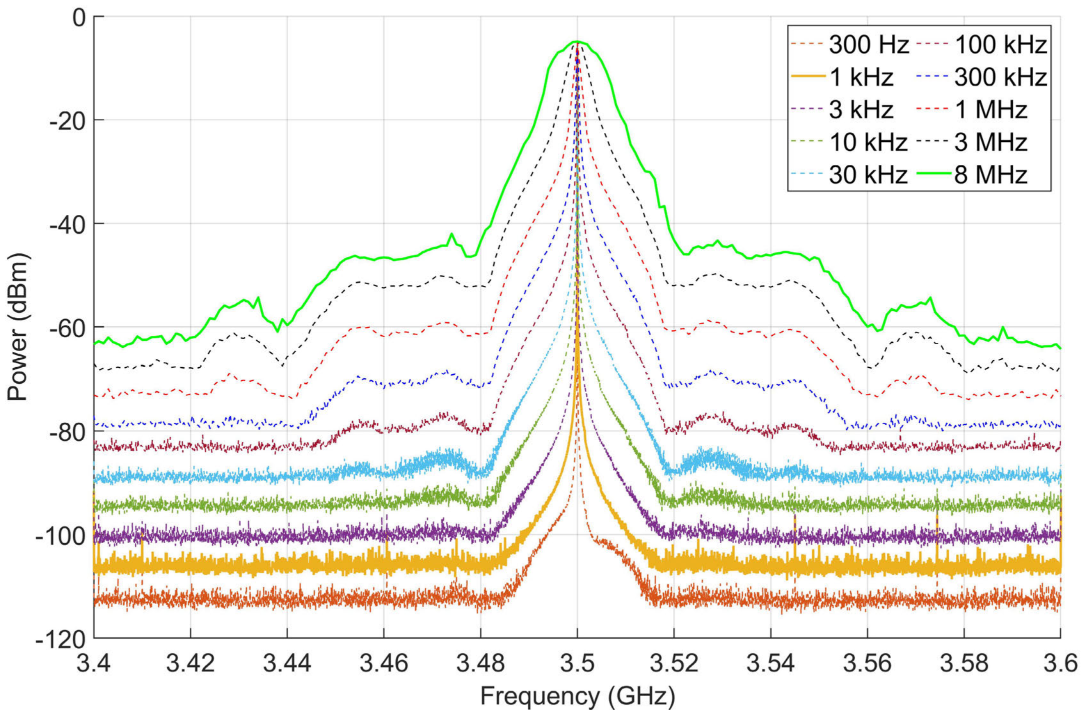

Figure B-35. Spectrum emission measurements at multiple RBW settings for compound waveform 45 (P0N waveform 6 and Q3N waveform 16, Q3N has 40 dB less peak power than P0N). The calculated RBW setting for the P0N component is 1 kHz and 10 MHz for the Q3N component. The empirical optimum RBW setting to use for this compound radar waveform is 1 kHz.

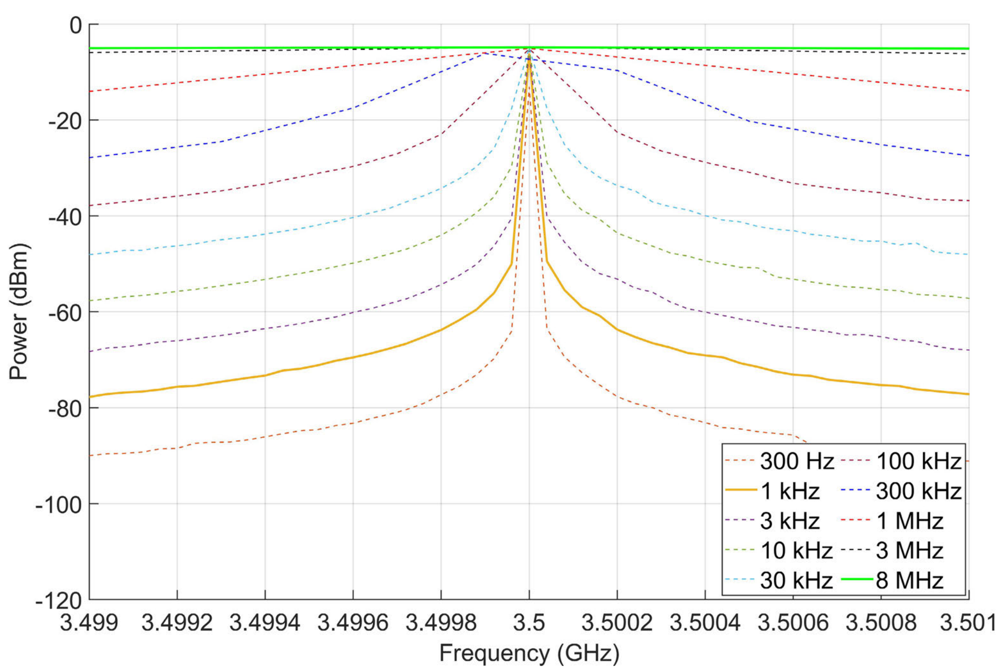

Figure B-36. Close-up view of the fundamental from Figure B-35Figure B-31 showing that RBW = 1 kHz is the optimum measurement bandwidth to use for this measurement.

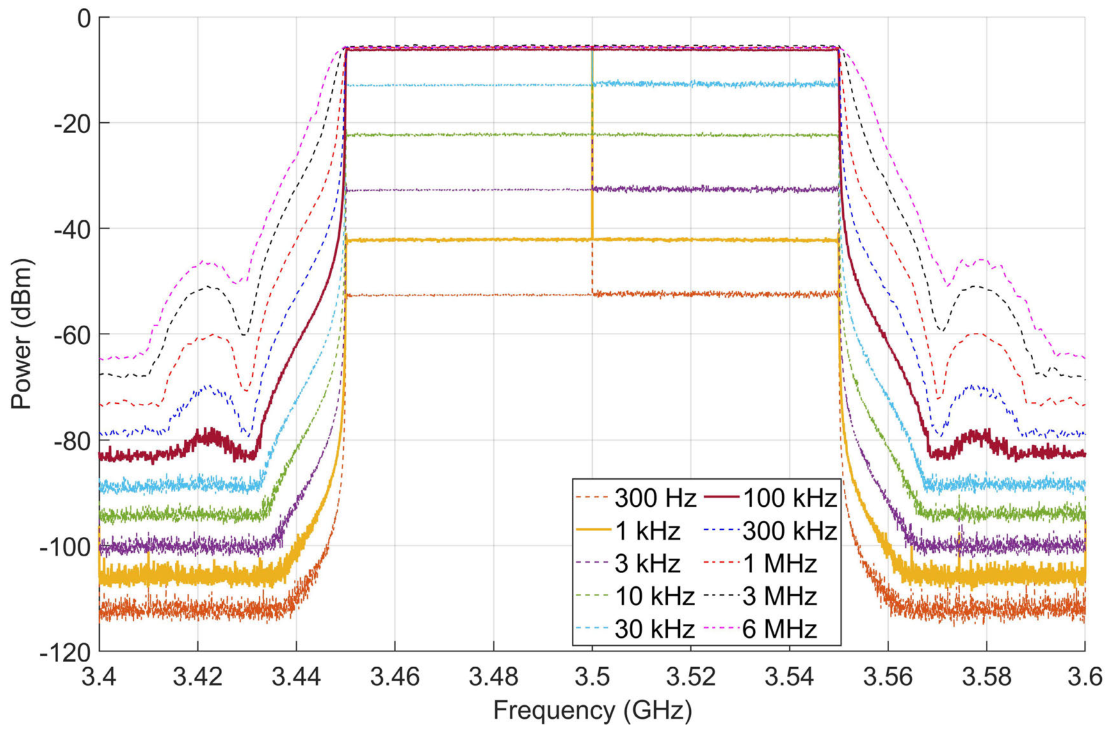

Figure B-37. Spectrum emission measurements at multiple RBW settings for compound waveform 48 (P0N waveform 6 and Q3N waveform 12). The calculated RBW setting for the P0N component is 1 kHz and 100 kHz for the Q3N component. The empirical optimum RBW setting to use for this compound radar waveform is 1 kHz.

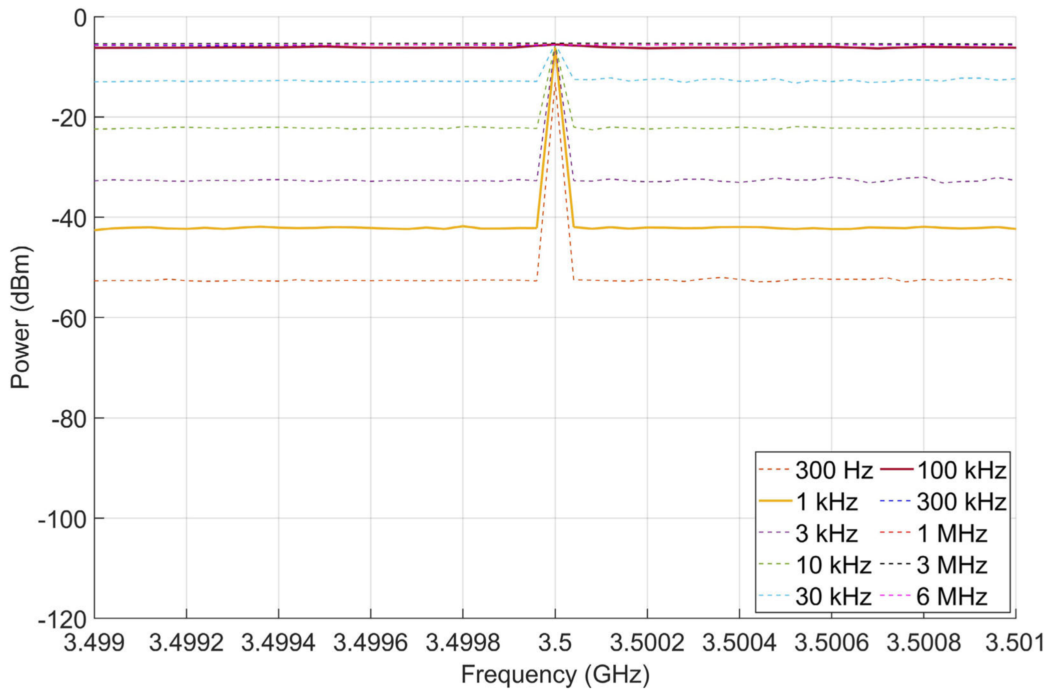

Figure B-38. Close-up view of the fundamental from Figure B-37Figure B-31 showing that RBW = 1 kHz is the optimum measurement bandwidth to use for this measurement.

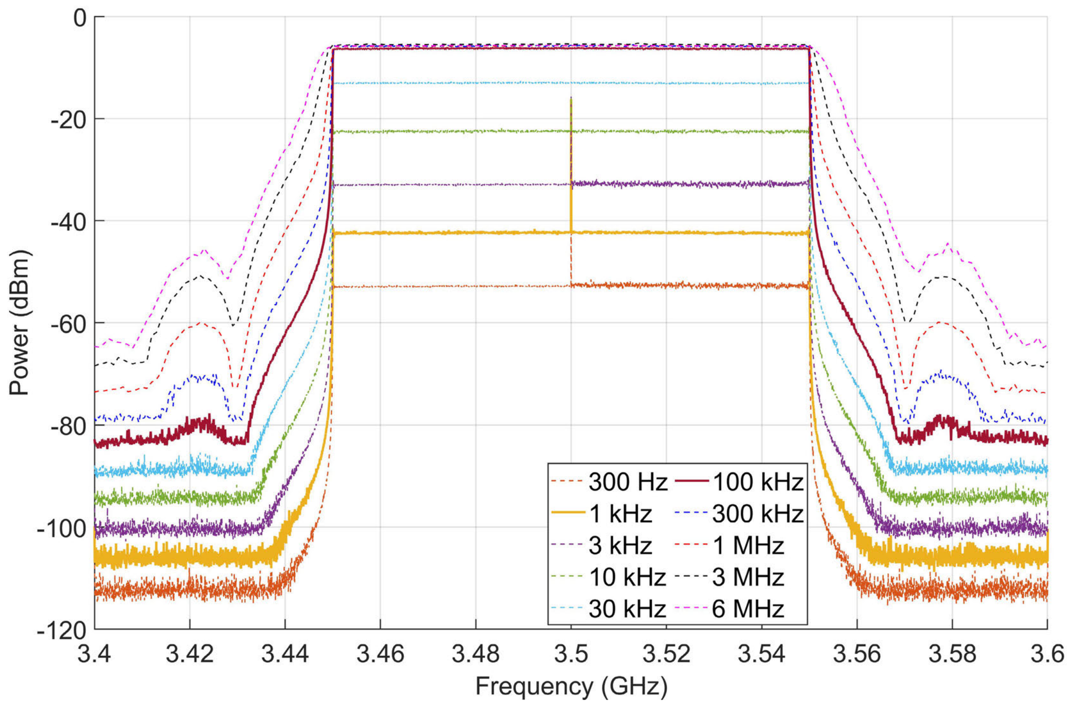

Figure B-39. Spectrum emission measurements at multiple RBW settings for compound waveform 49 (P0N waveform 6 and Q3N waveform 12, Q3N has 10 dB more peak power than P0N). The calculated RBW setting for the P0N component is 1 kHz and 100 kHz for the Q3N component. The empirical optimum RBW setting to use for this compound radar waveform is 1 kHz.

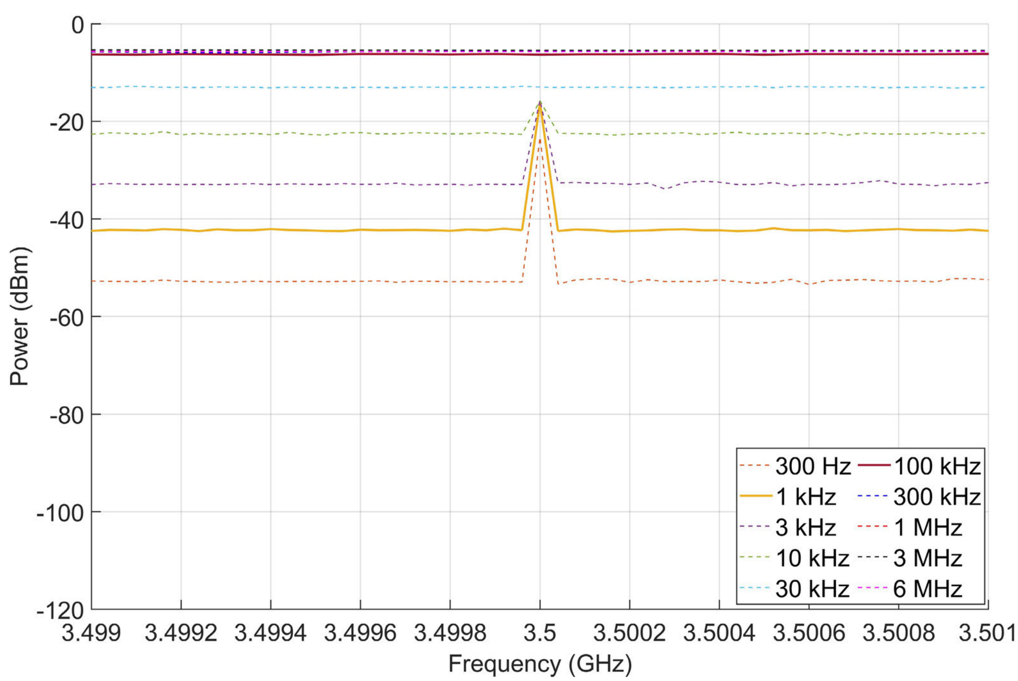

Figure B-40. Close-up view of the fundamental from Figure B-39Figure B-31 showing that RBW = 1 kHz is the optimum measurement bandwidth to use for this measurement.

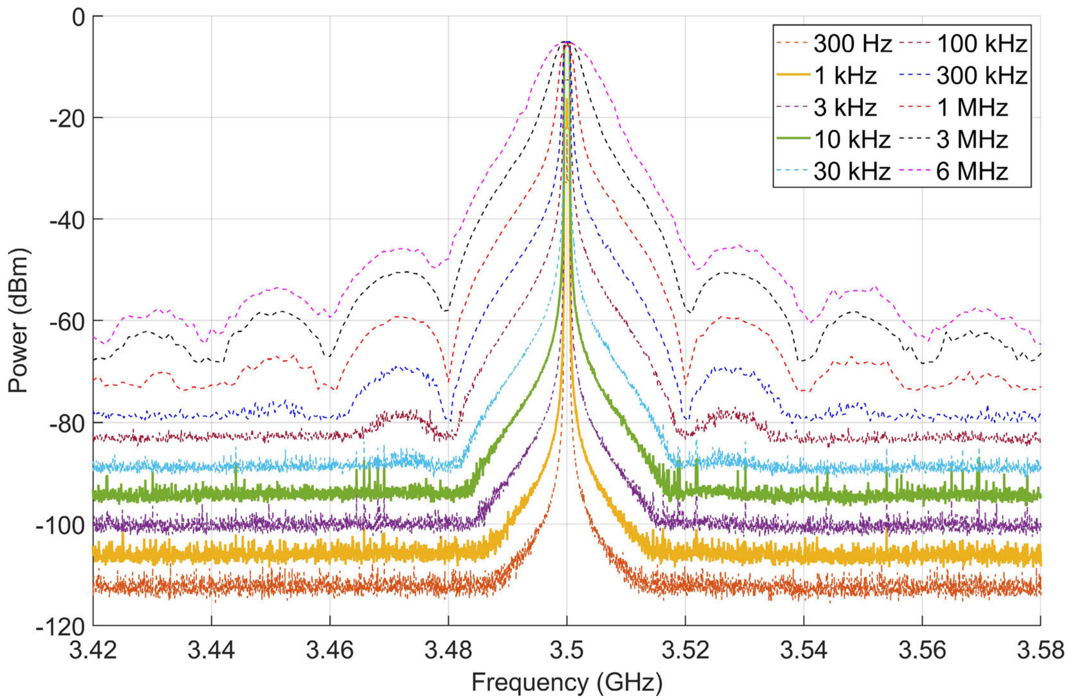

Figure B-41. Spectrum emission measurements at multiple RBW settings for compound waveform 50 (P0N waveform 6 and Q3N waveform 15, Q3N has 10 dB more peak power than P0N). The calculated RBW setting for the P0N component is 1 kHz and 10 kHz for the Q3N component. The empirical optimum RBW setting to use for this compound radar waveform is 1 kHz.

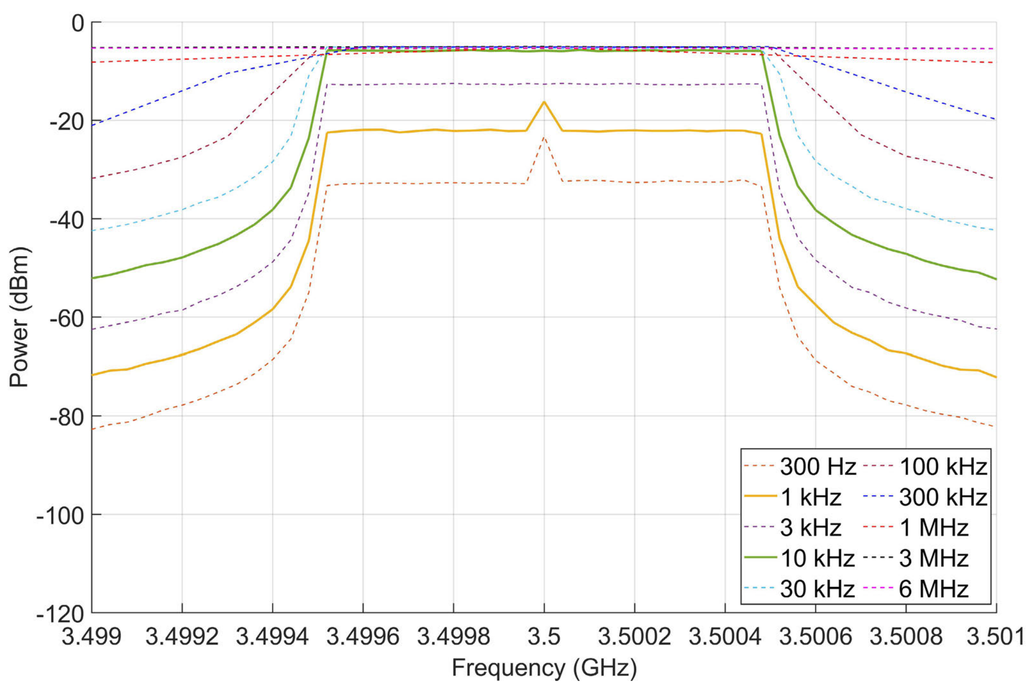

Figure B-42. Close-up view of the fundamental from Figure B-41Figure B-31 showing that RBW = 1 kHz is the optimum measurement bandwidth to use for this measurement.

B.2 Compound Radar Spectra with P0N and Q3N Components

This section provides the remainder of the results of the emission measurements performed on the compound waveforms at the optimum RBW with the component spectra that are not presented in Section 3.3.2. In some cases a close up view of the fundamental frequency is also provided when it is hard to make out the individual spectra in the plot. For all of the test case presented, $T_r = T_f = 50$ ns and the ratio Q3N:P0N is 1:1. The peak power of the component pulses are equal unless noted otherwise in the figure caption.

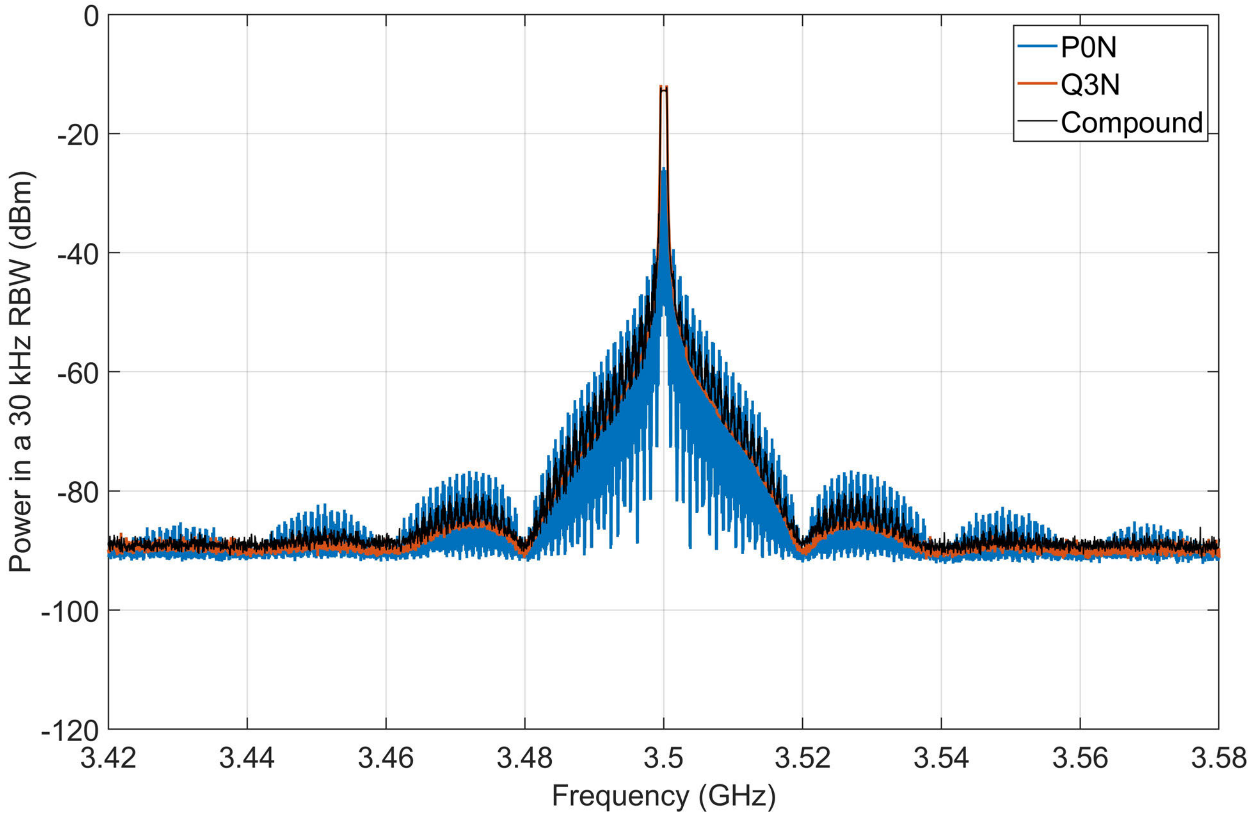

Figure B-43. Spectrum measurement of waveform 20 with its P0N and Q3N components at RBW = 30 kHz.

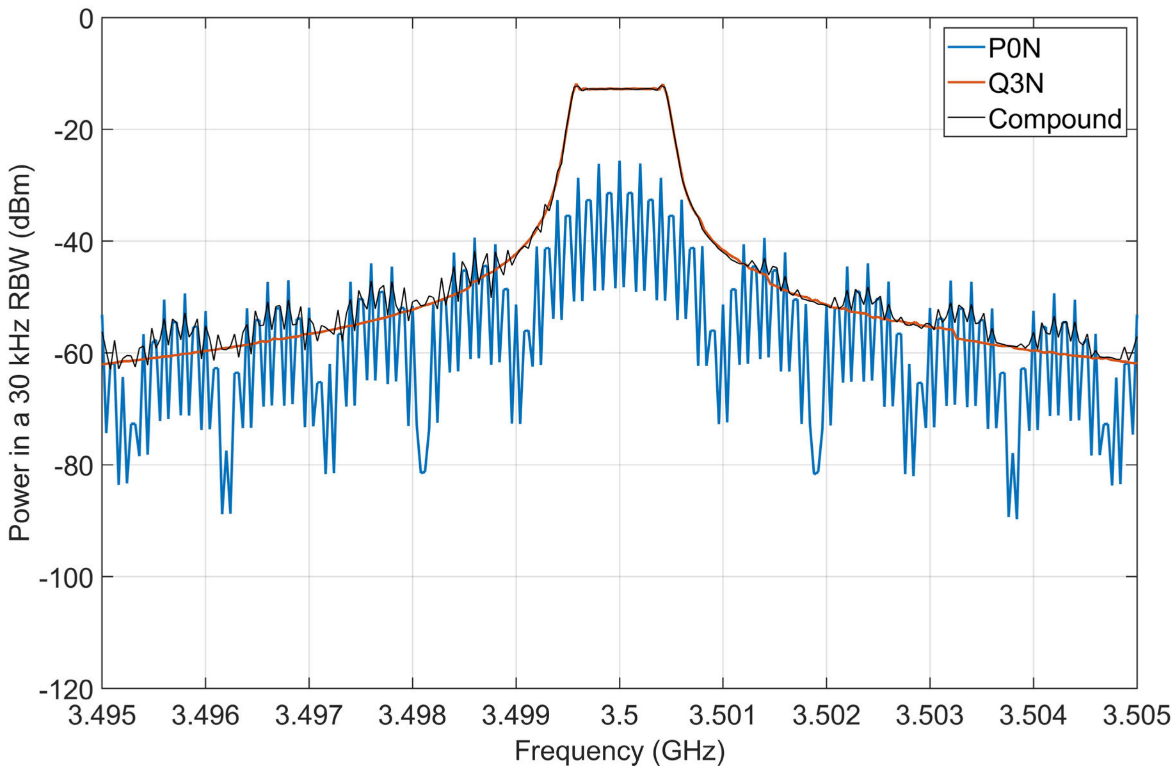

Figure B-44. Close-up view of the fundamental from Figure B-43.

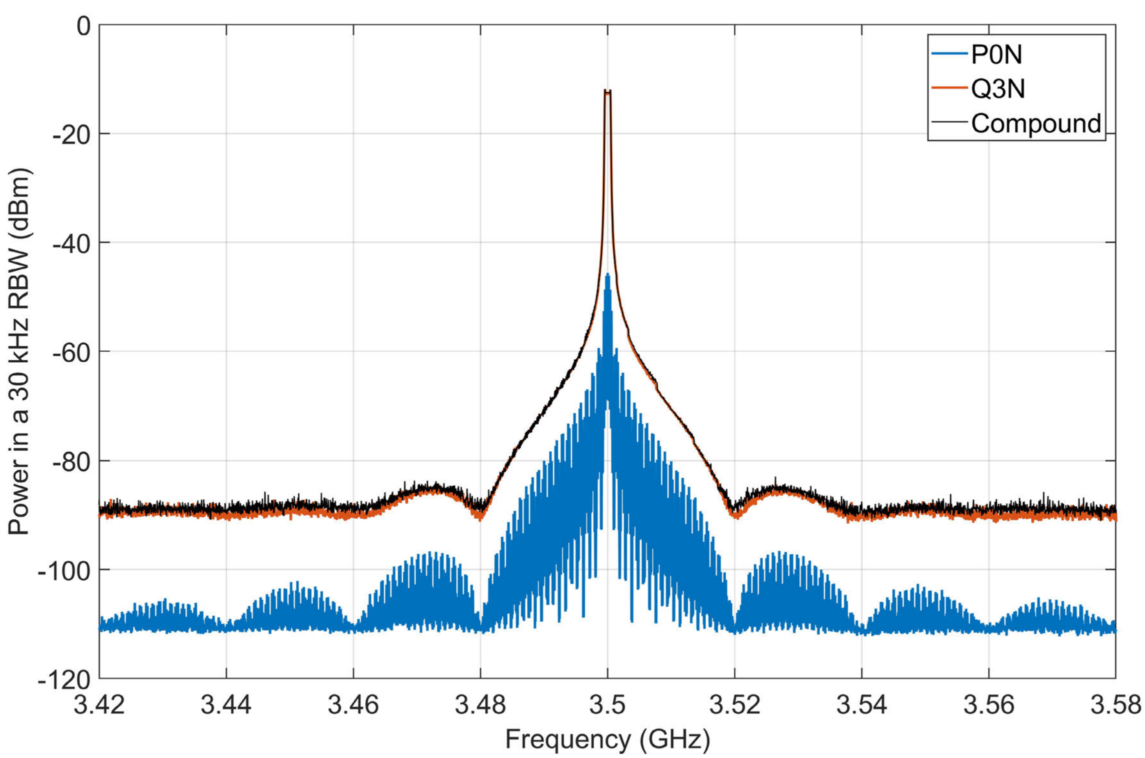

Figure B-45. Spectrum measurement of waveform 21 with its P0N and Q3N components at RBW = 30 kHz. Q3N has 20 dB more peak power than P0N.

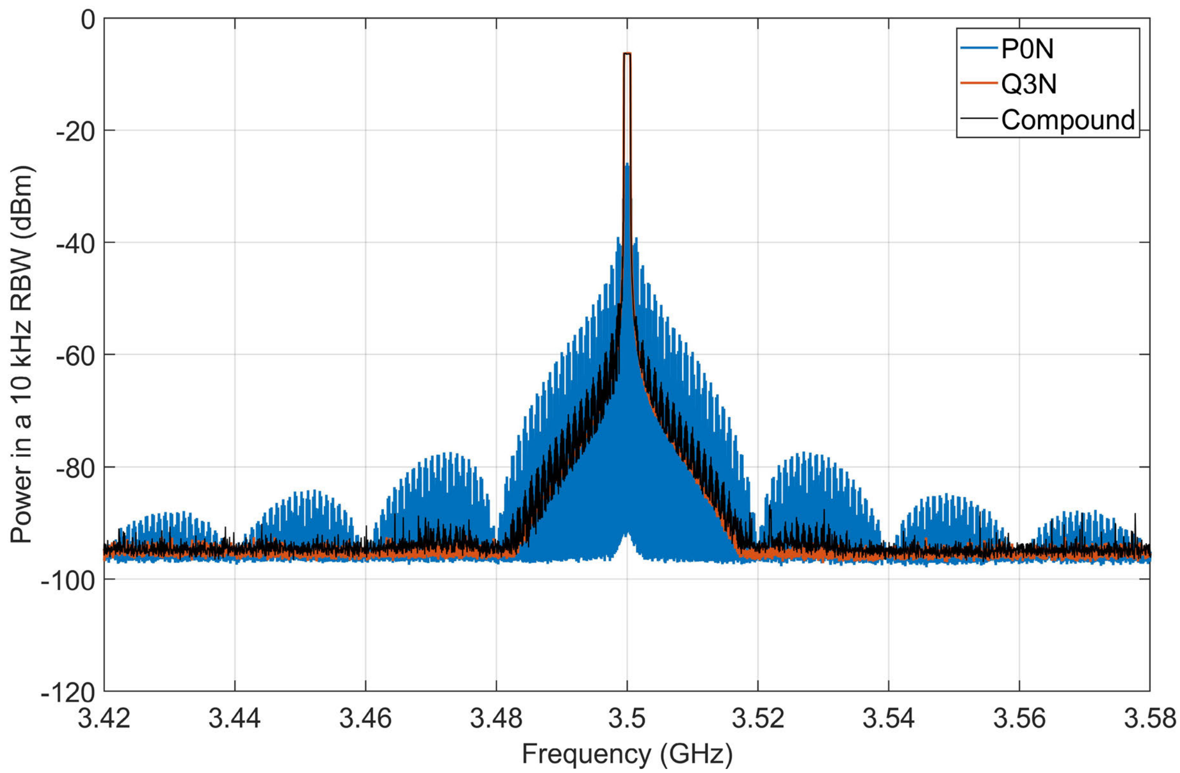

Figure B-46. Spectrum measurement of waveform 22 with its P0N and Q3N components at RBW = 10 kHz.

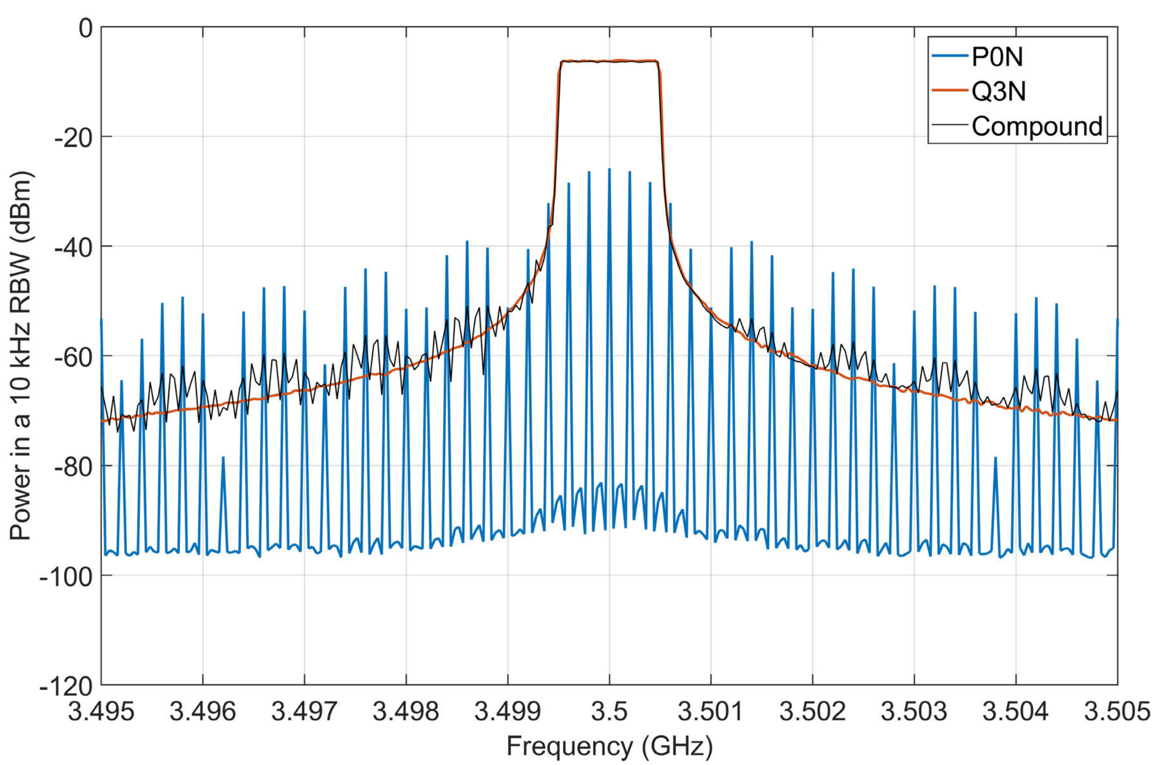

Figure B-47. Close-up view of the fundamental from Figure B-46.

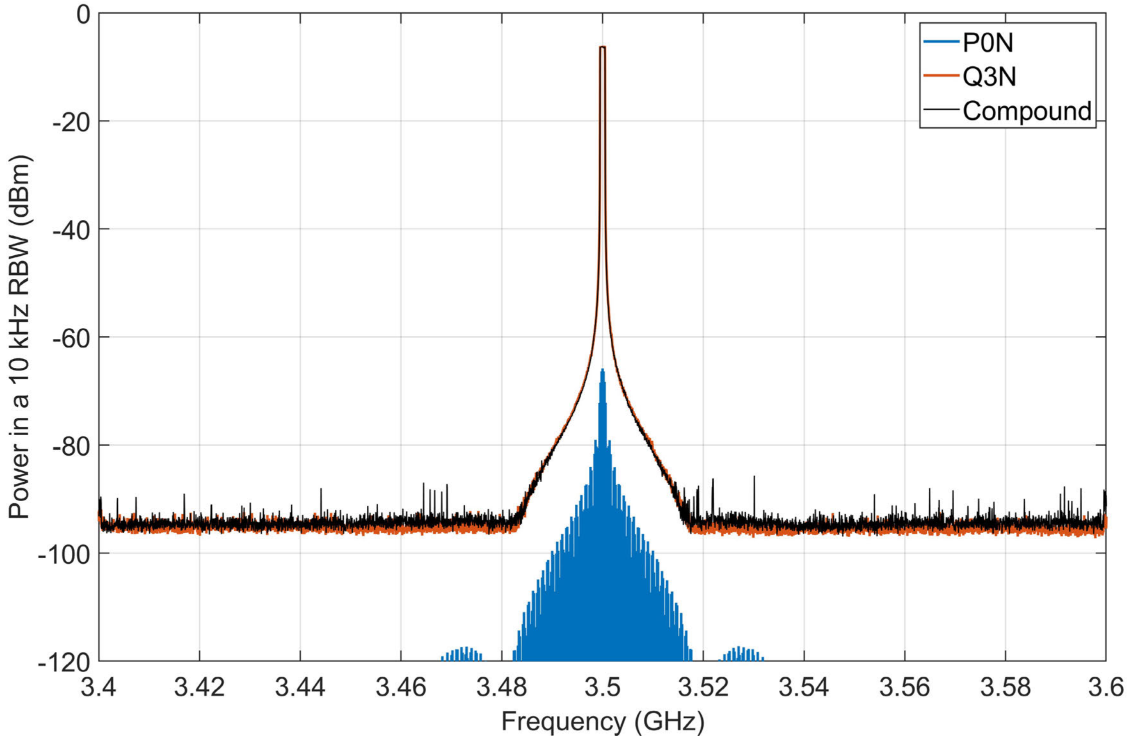

Figure B-48. Spectrum measurement of waveform 23 with its P0N and Q3N components at RBW = 10 kHz. Q3N has 40 dB more peak power than P0N.

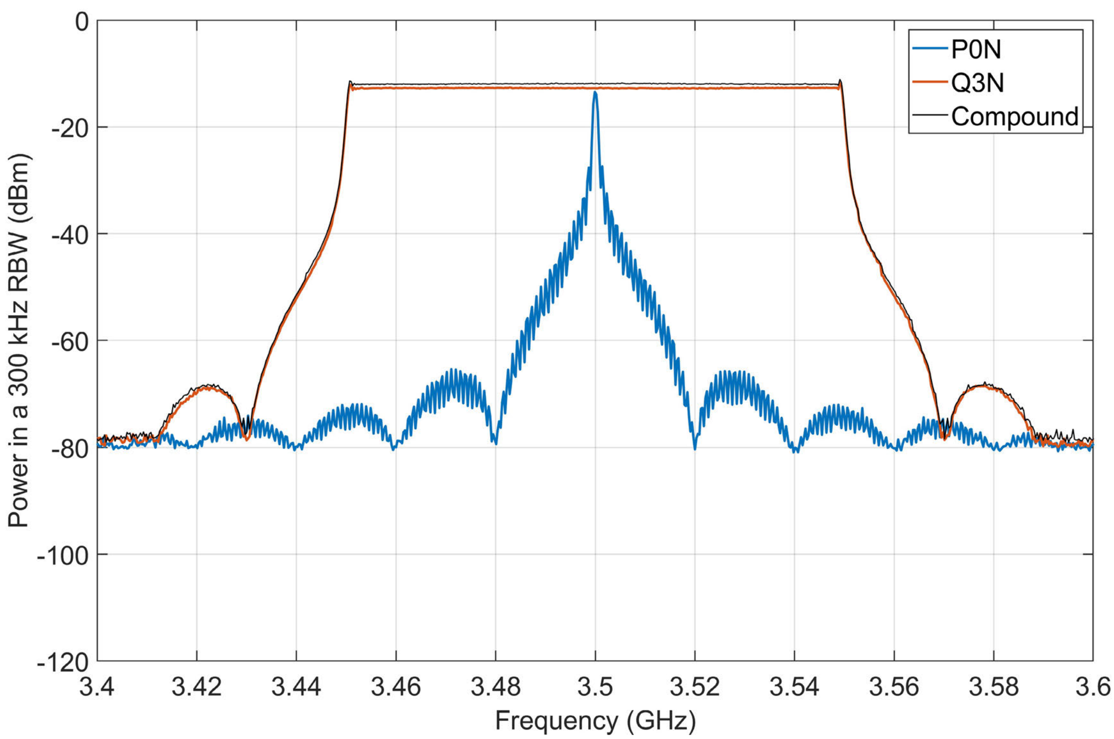

Figure B-49. Spectrum measurement of waveform 25 with its P0N and Q3N components at RBW = 300 kHz.

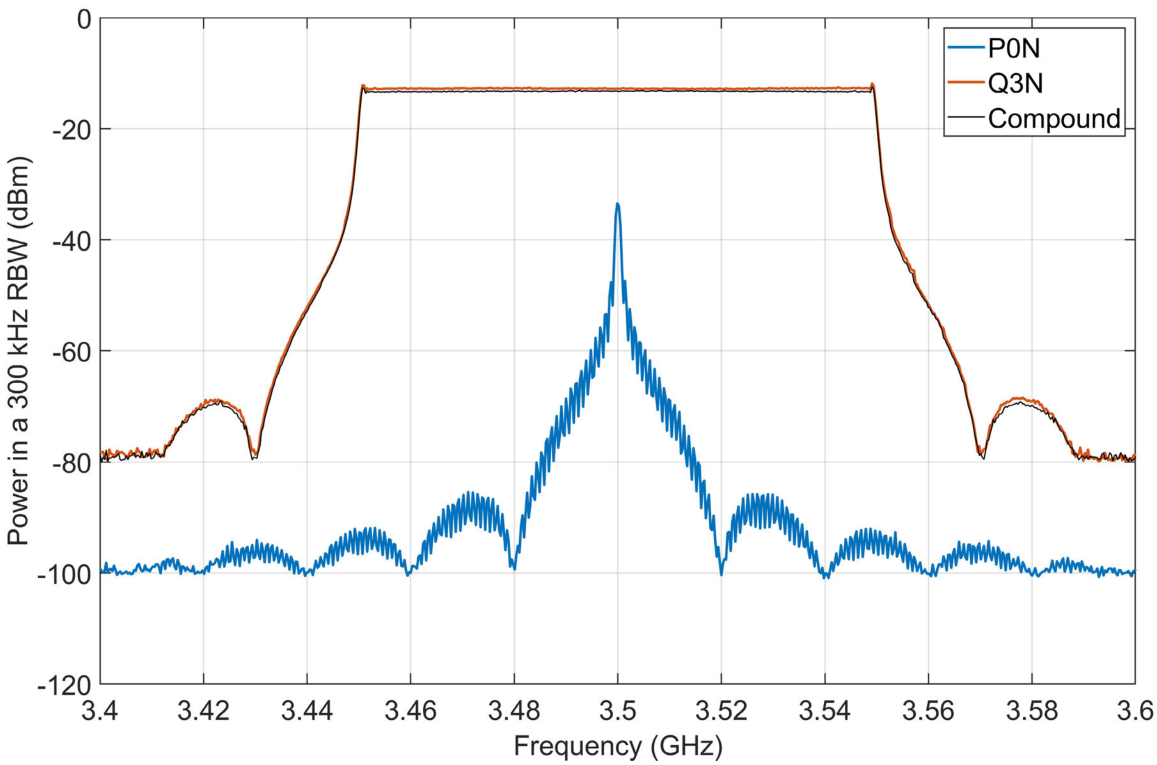

Figure B-50. Spectrum measurement of waveform 26 with its P0N and Q3N components at RBW = 300 kHz. Q3N has 20 dB more peak power than P0N.

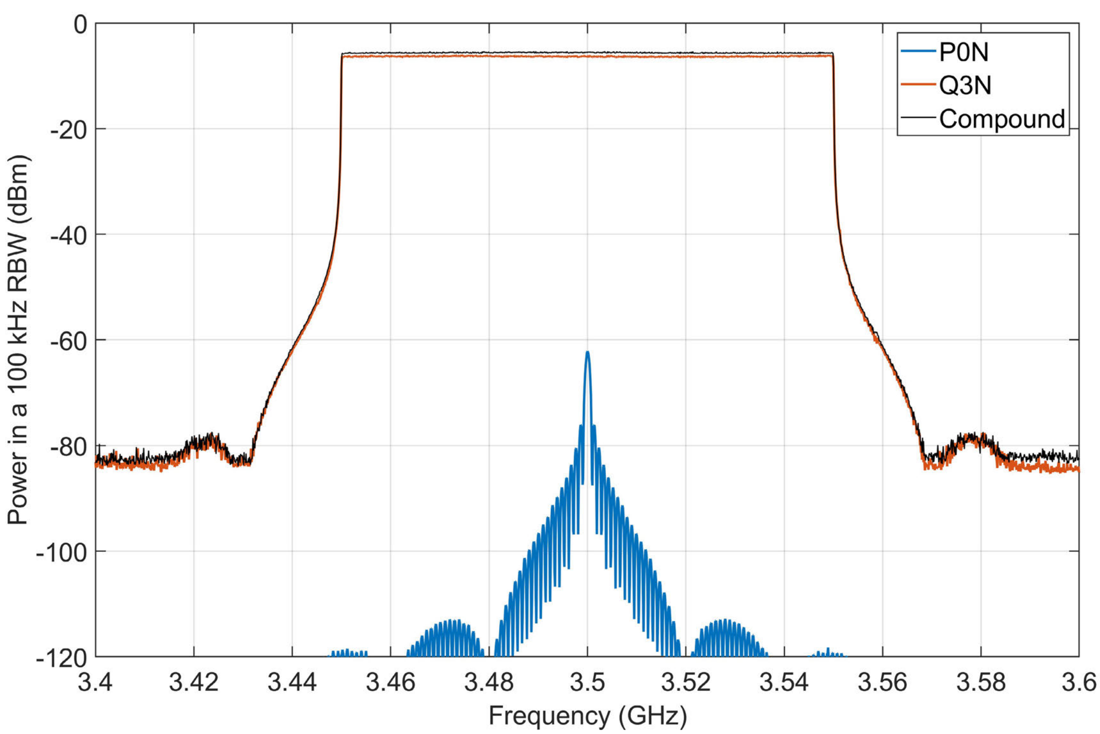

Figure B-51. Spectrum measurement of waveform 28 with its P0N and Q3N components at RBW = 100 kHz. Q3N has 40 dB more peak power than P0N.

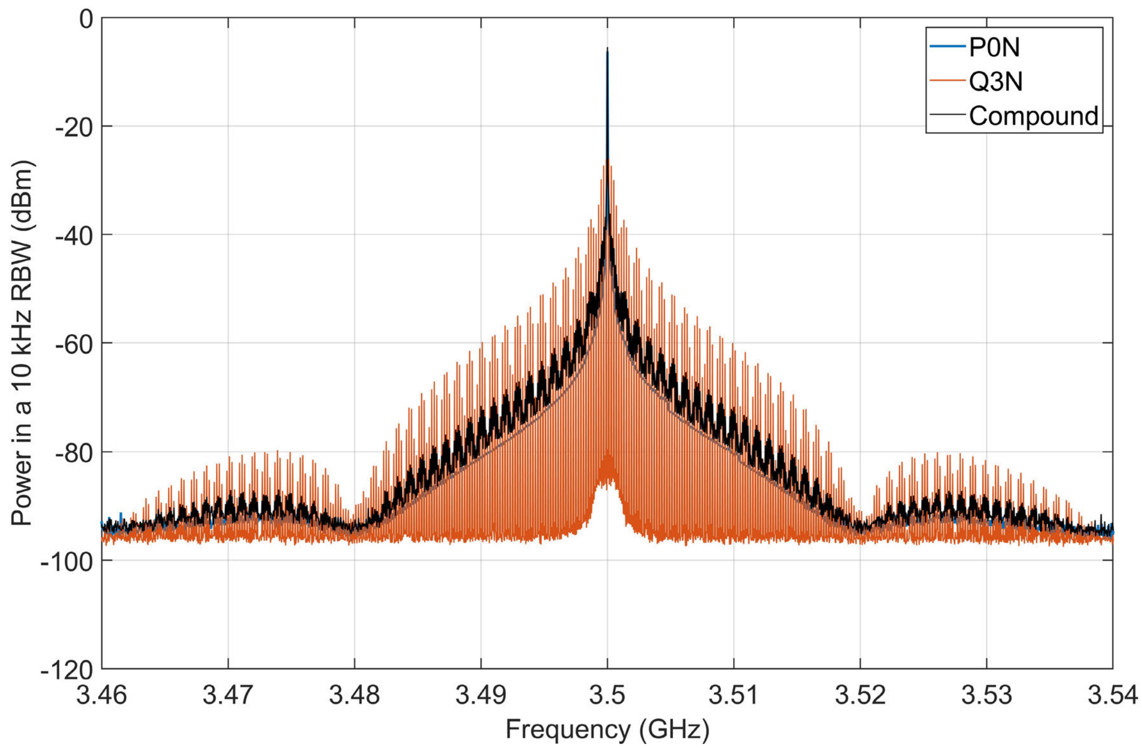

Figure B-52. Spectrum measurement of waveform 29 with its P0N and Q3N components at RBW = 10 kHz. 10 kHz is less than the PRR (100 kHz) of the Q3N component.

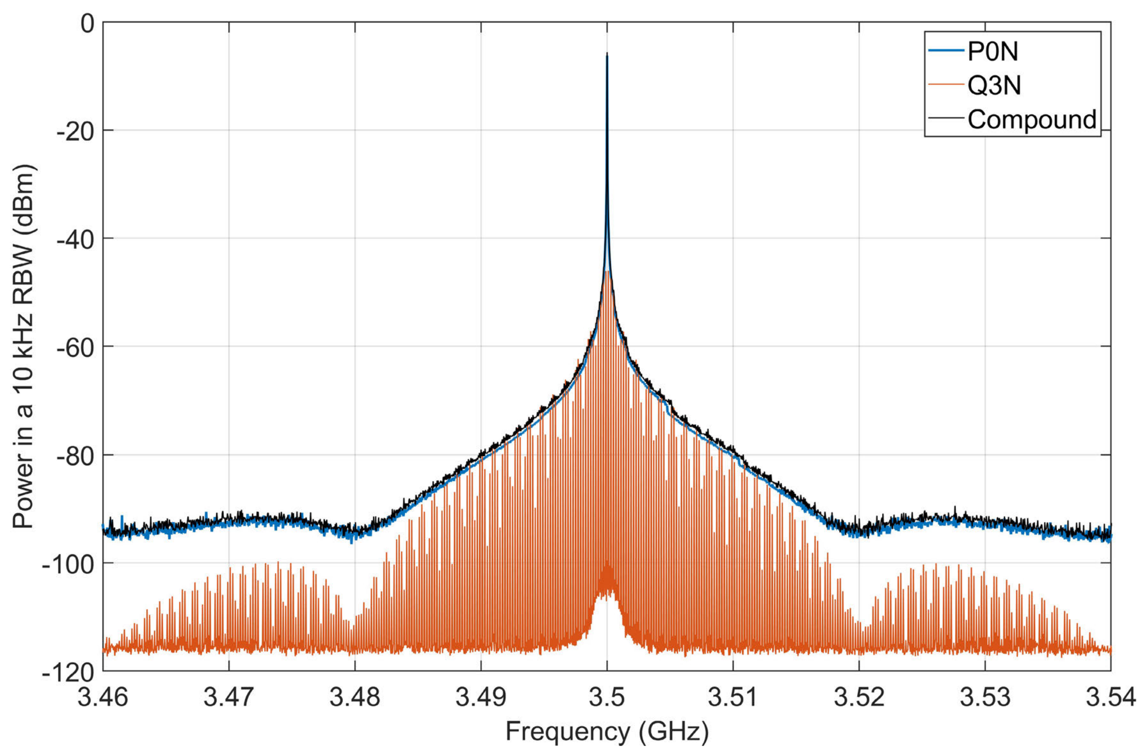

Figure B-53. Spectrum measurement of waveform 30 with its P0N and Q3N components at RBW = 10 kHz. Q3N has 20 dB less peak power than P0N.

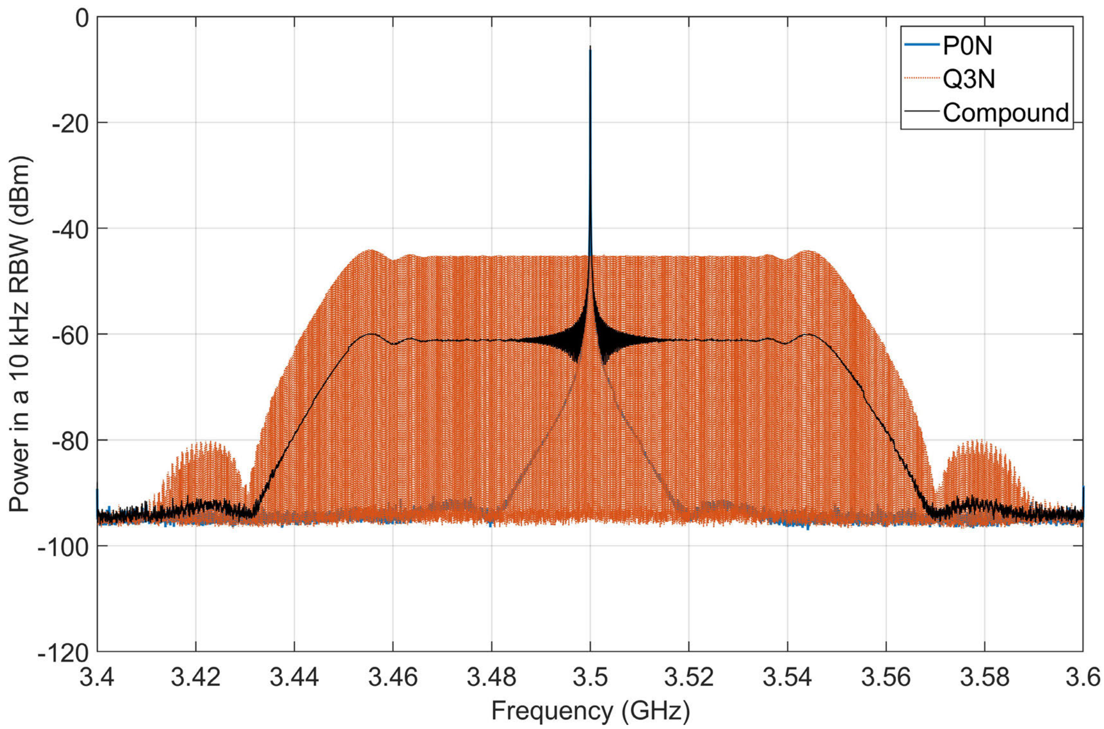

Figure B-54. Spectrum measurement of waveform 34 with its P0N and Q3N components at RBW = 10 kHz. 10 kHz is less than the PRR (100 kHz) of the Q3N component.

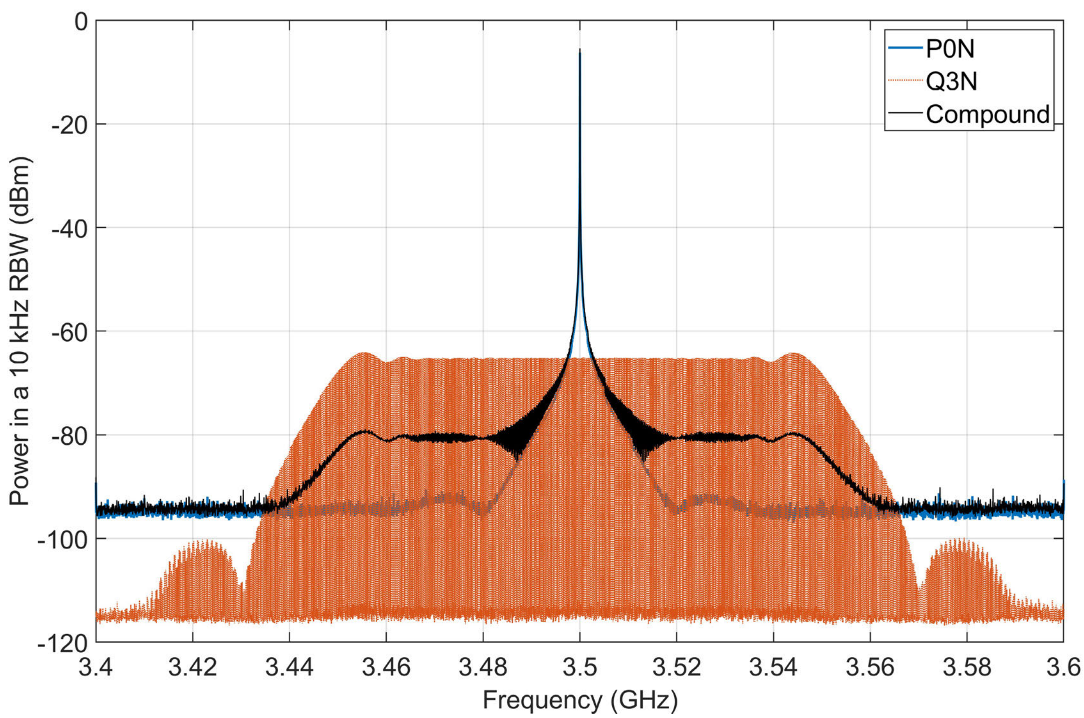

Figure B-55. Spectrum measurement of waveform 35 with its P0N and Q3N components at RBW = 10 kHz. Q3N has 20 dB less peak power than P0N. 10 kHz is less than the PRR (100 kHz) of the Q3N component.

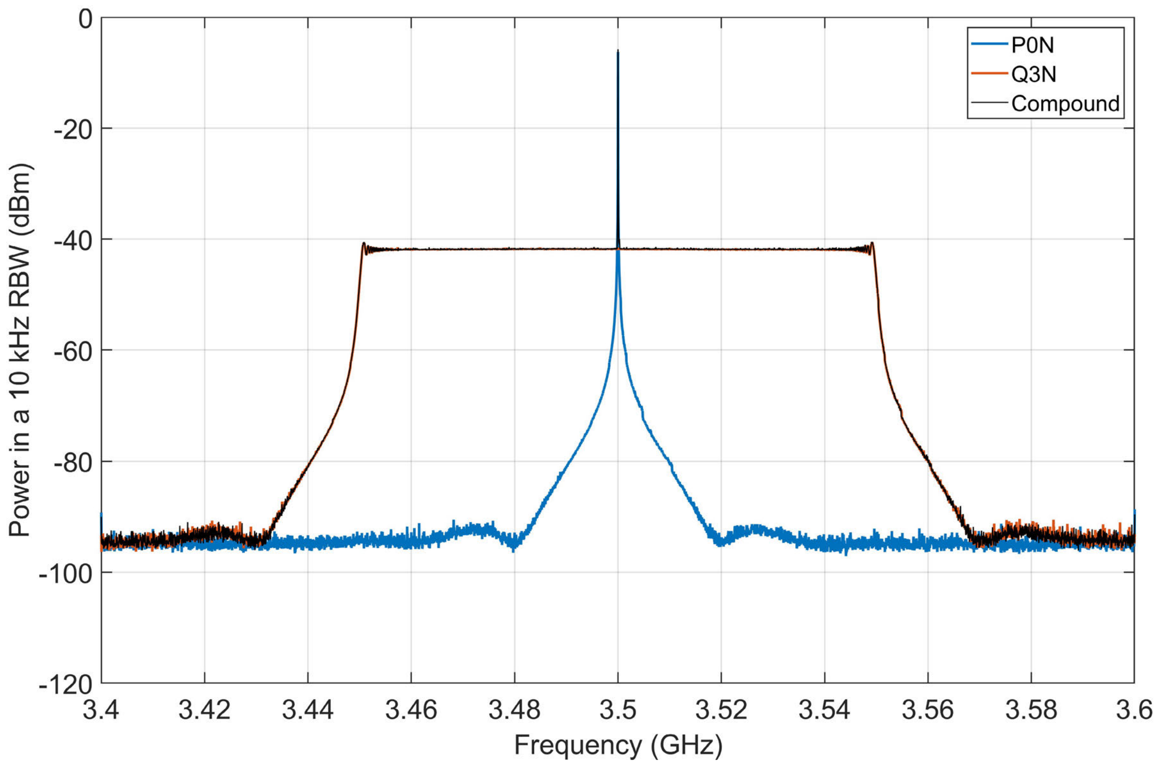

Figure B-56. Spectrum measurement of waveform 36 with its P0N and Q3N components at RBW = 10 kHz.

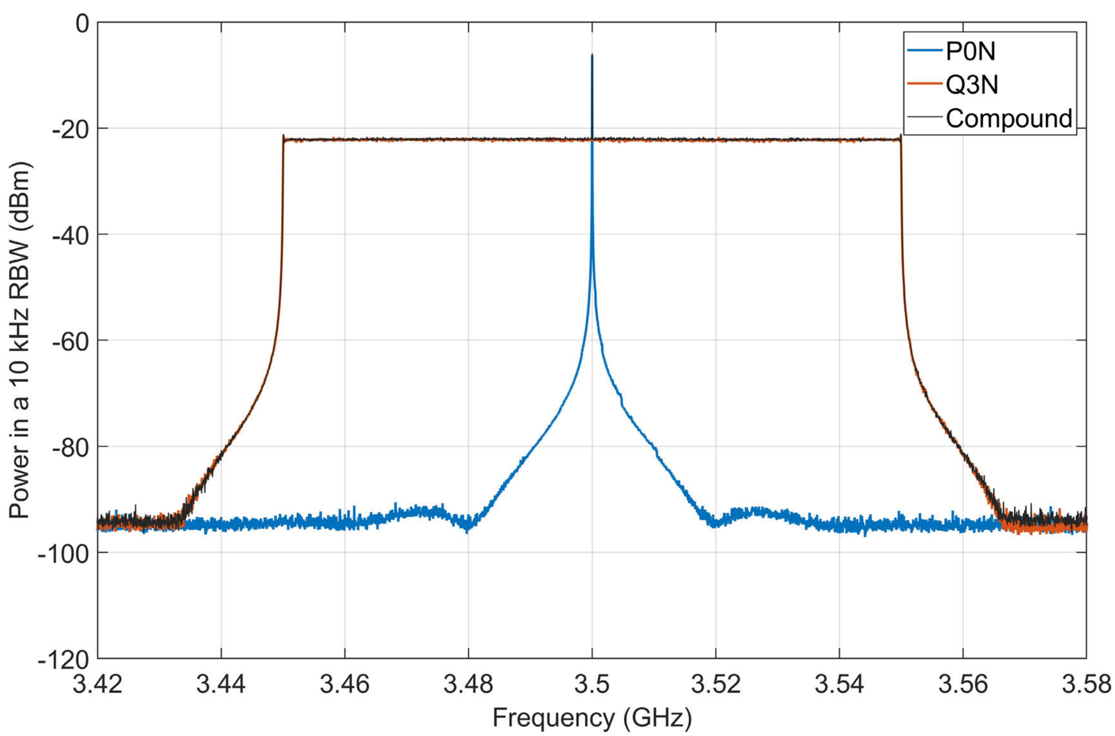

Figure B-57. Spectrum measurement of waveform 37 with its P0N and Q3N components at RBW = 10 kHz.

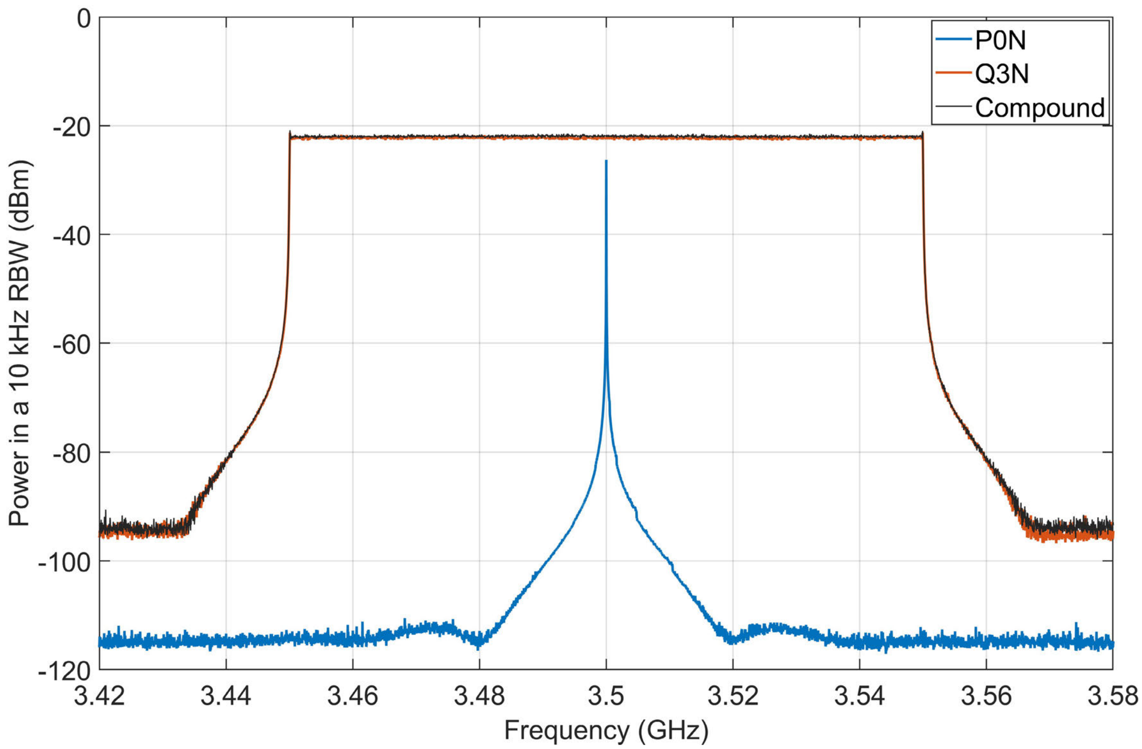

Figure B-58. Spectrum measurement of waveform 38 with its P0N and Q3N components at RBW = 10 kHz. Q3N has 20 dB more peak power than P0N.

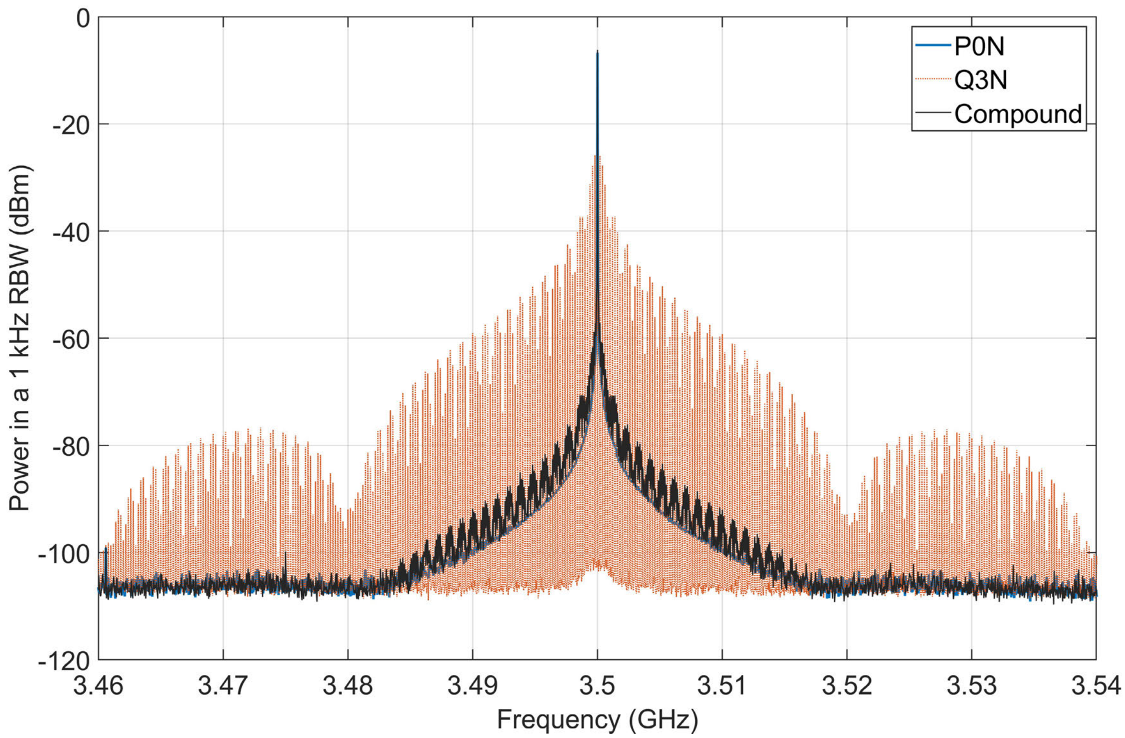

Figure B-59. Spectrum measurement of waveform 39 with its P0N and Q3N components at RBW = 1 kHz. 1 kHz is less than the PRR (100 kHz) of the Q3N component.

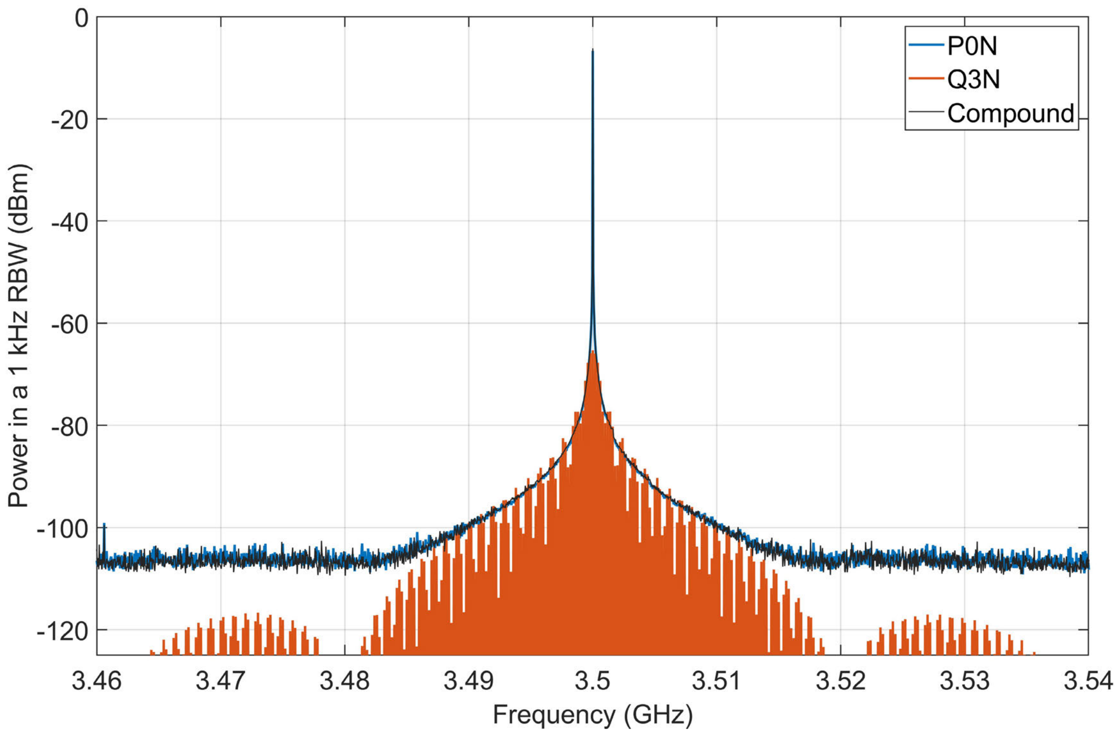

Figure B-60. Spectrum measurement of waveform 40 with its P0N and Q3N components at RBW = 1 kHz. Q3N has 40 dB less peak power than P0N. 1 kHz is less than the PRR (100 kHz) of the Q3N component.

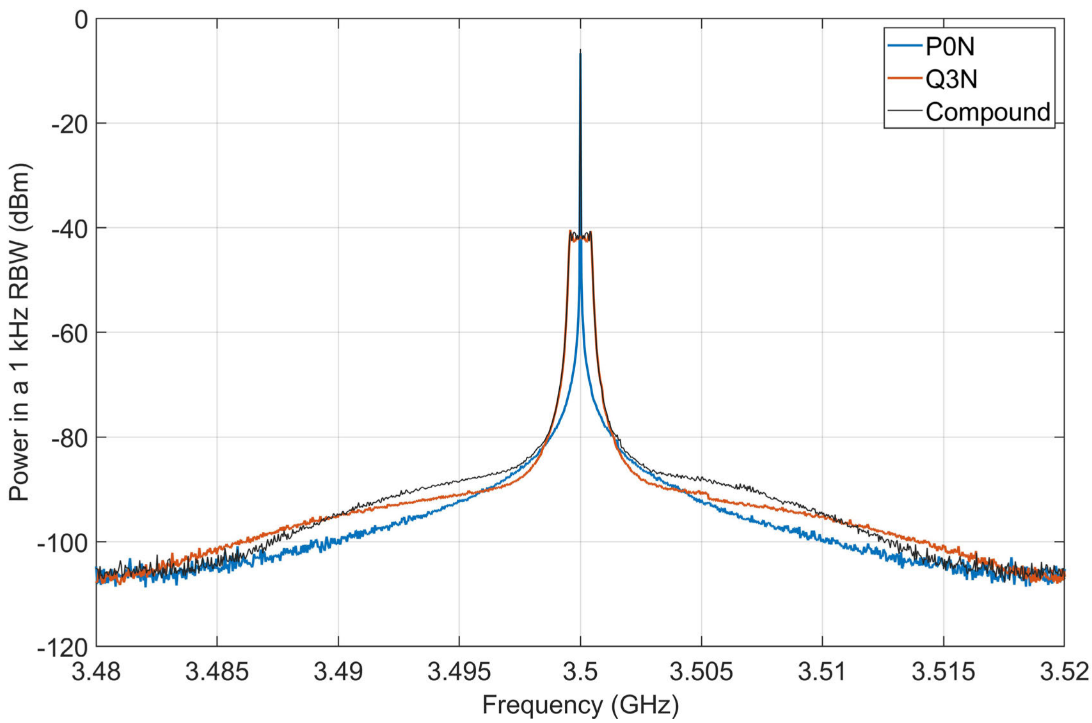

Figure B-61. Spectrum measurement of waveform 41 with its P0N and Q3N components at RBW = 1 kHz.

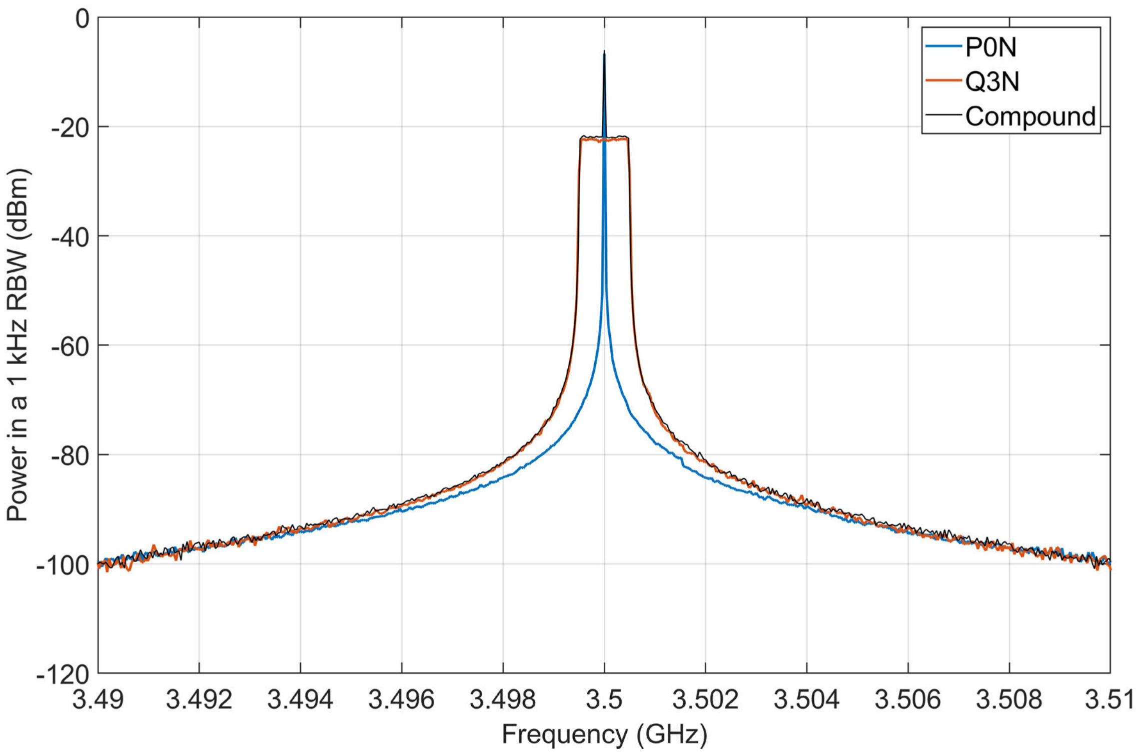

Figure B-62. Spectrum measurement of waveform 43 with its P0N and Q3N components at RBW = 1 kHz.

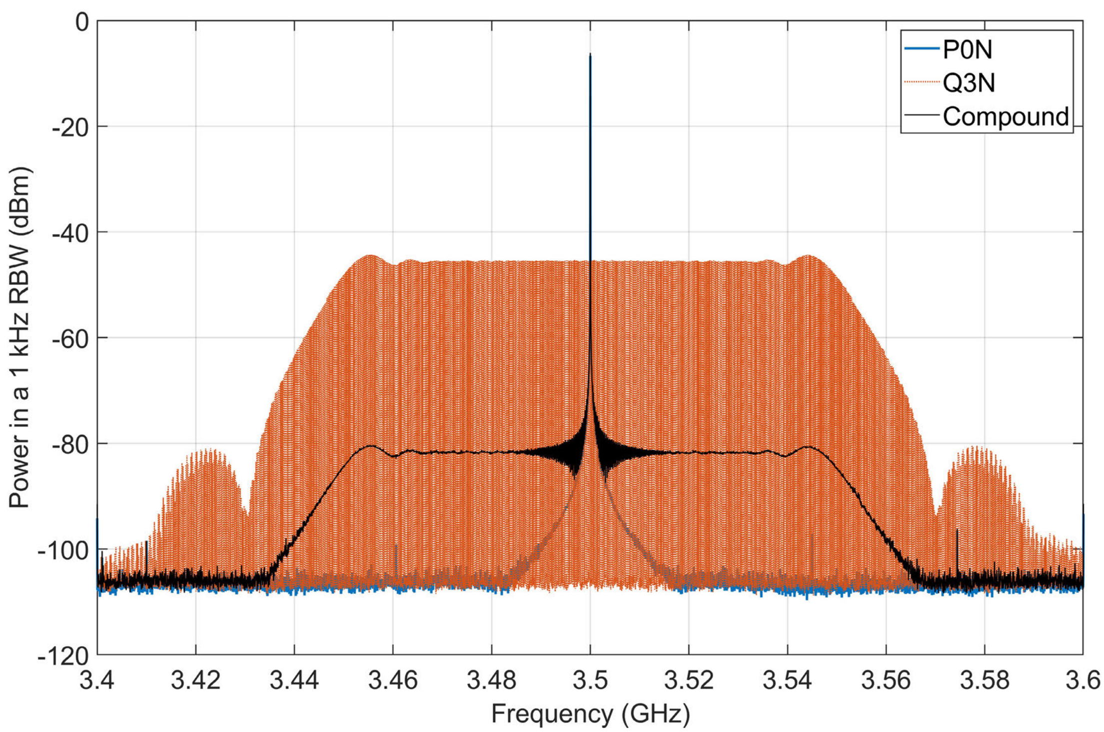

Figure B-63. Spectrum measurement of waveform 44 with its P0N and Q3N components at RBW = 1 kHz. 1 kHz is less than the PRR (100 kHz) of the Q3N component.

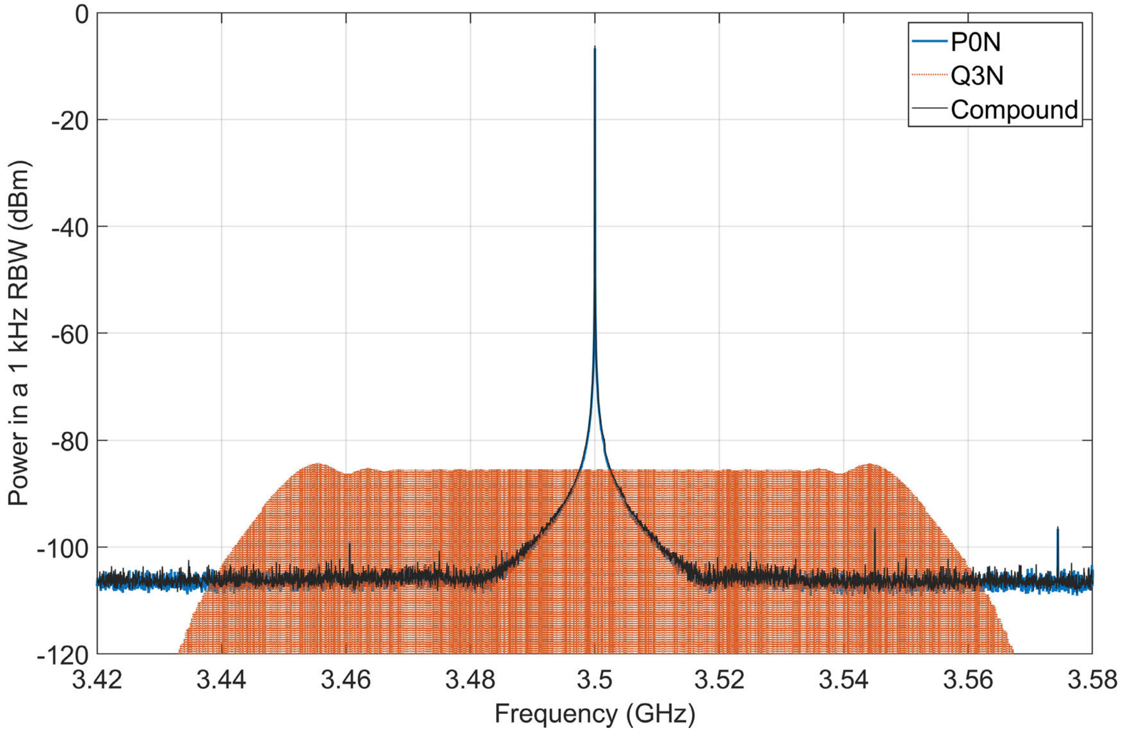

Figure B-64. Spectrum measurement of waveform 45 with its P0N and Q3N components at RBW = 1 kHz. Q3N has 40 dB less peak power than P0N. 1 kHz is less than the PRR (100 kHz) of the Q3N component.

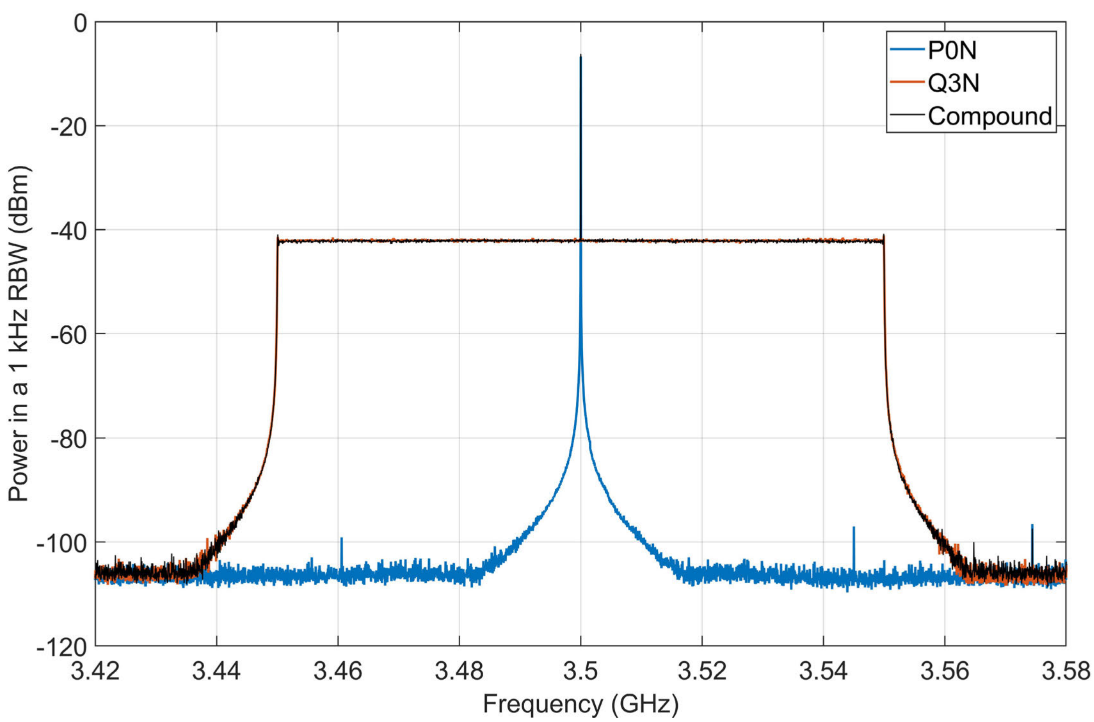

Figure B-65. Spectrum measurement of waveform 48 with its P0N and Q3N components at RBW = 1 kHz.

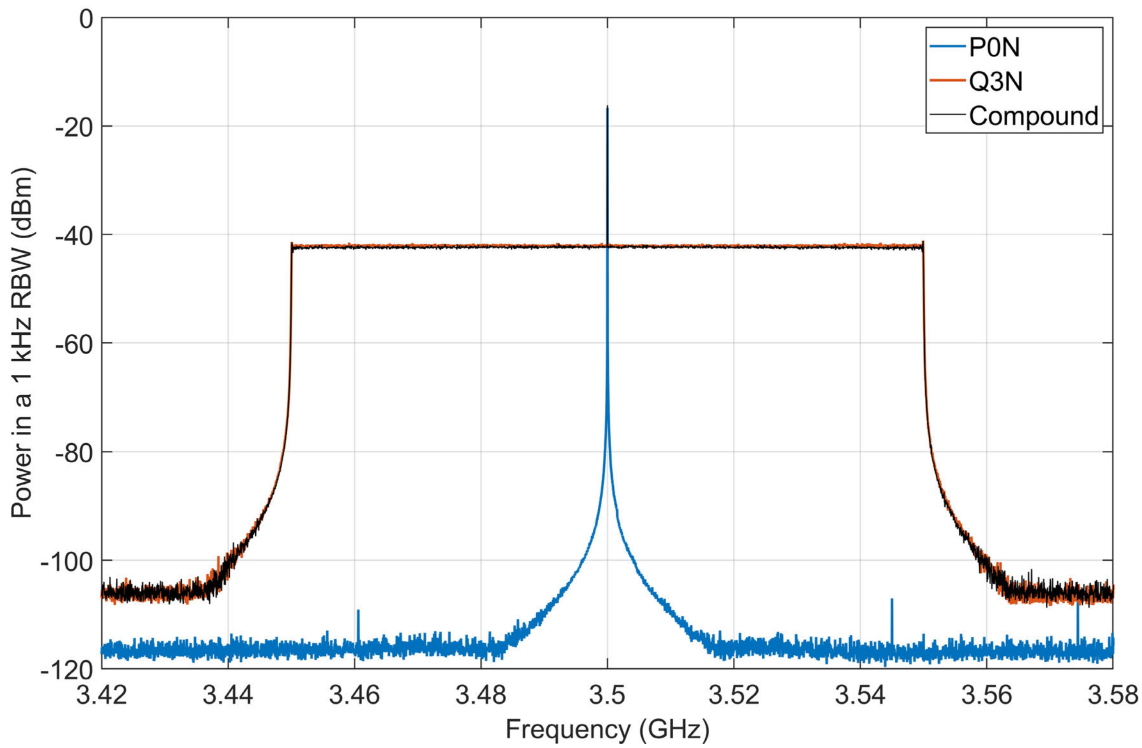

Figure B-66. Spectrum measurement of waveform 49 with its P0N and Q3N components at RBW = 1 kHz. Q3N has 10 dB more peak power than P0N.

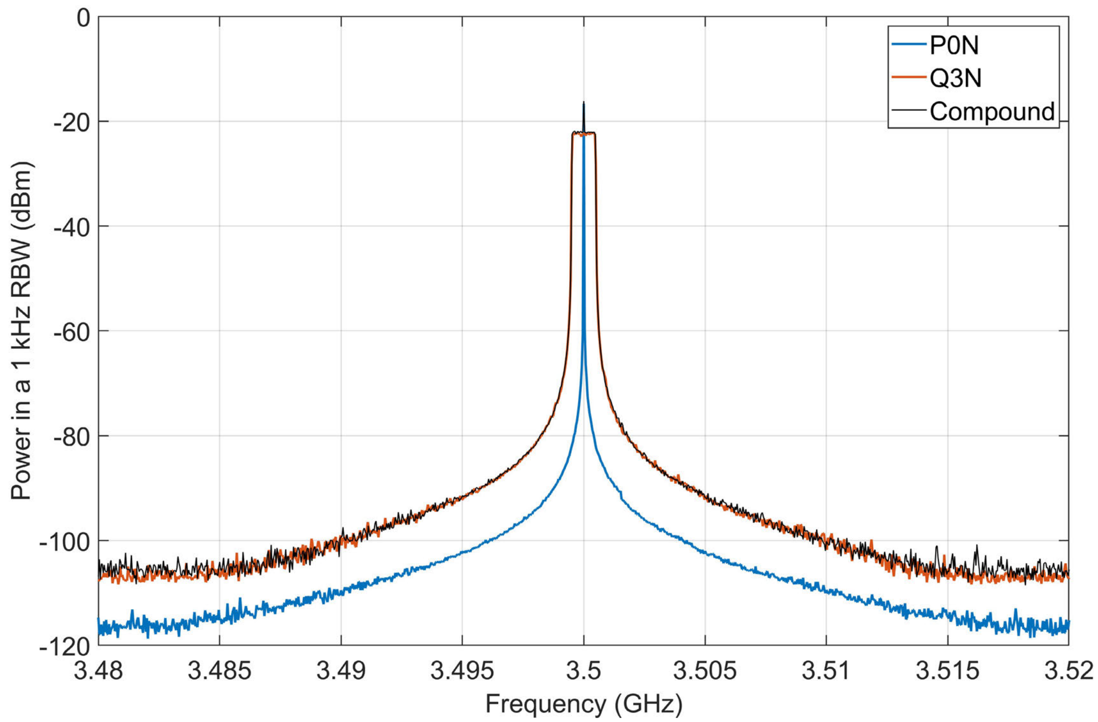

Figure B-67. Spectrum measurement of waveform 50 with its P0N and Q3N components at RBW = 1 kHz. Q3N has 10 dB more peak power than P0N.

NTIA FORM 29
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NATIONAL TELECOMMUNICATIONS AND INFORMATION

BIBLIOGRAPHIC DATA SHEET

1. PUBLICATION NO.	2. Government Accession No.	3. Recipient's Accession No.
TM-23-566		

4. TITLE AND SUBTITLE
Examining the Effects of Resolution Bandwidth when Measuring Compound Radar Waveforms

5. Publication Date
April 2023

6. Performing Organization Code
NTIA/ITS.M

7. AUTHOR(S)
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9. Project/Task/Work Unit No.

6505000-200

8. PERFORMING ORGANIZATION NAME AND ADDRESS
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10. Contract/Grant Number.

11. Sponsoring Organization Name and Address
National Telecommunications & Information Administration
Office of Spectrum Management
Herbert C. Hoover Building
14th & Constitution Ave., NW
Washington, DC 20230

12. Type of Report and Period Covered

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.)

This study examines the effects of resolution bandwidth (RBW) when using the measurement methods described in National Telecommunications and Information Administration (NTIA) Technical Report 05-420 to measure the emission spectra of compound radar waveforms. This study is being conducted in support of updating the Radar Spectrum Engineering Criteria (RSEC) described in Chapter 5.5 of the NTIA Manual of Regulations and Procedures for Federal Radio Frequency Management to better accommodate modern compound radars. Many different RBW settings were used to measure the spectra of single-pulse-parameter and multi-pulse-parameter radar waveforms of both P0N and Q3N pulse types. The results of these measurements are presented in this report along with the conclusions derived from the results. The main conclusion is that the NTIA TR-05-420 recommendation to use the minimum calculated RBW for each of the component pulse types of a compound radar waveform when measuring the compound spectrum is accurate.

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

ITU-R; Radar; Redbook; Resolution Bandwidth; RSEC; RSMS

17. AVAILABILITY STATEMENT	18. Security Class. (This report)	20. Number of pages
☒ UNLIMITED.	Unclassified	132
☐ FOR OFFICIAL DISTRIBUTION.	19. Security Class. (This page) Unclassified	21. Price: N/A

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