NTIA Technical Memorandum 07-446

BANDWIDTH CORRECTION FACTOR EQUATIONS USED TO ASSESS THE INTERFERENCE IMPACT OF IMPULSE AND PULSED SIGNALS ON RADIO RECEIVERS

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EXECUTIVE SUMMARY

In assessing the compatibility between unlicensed ultrawideband (UWB) devices and selected Federal systems operating above 960 MHz, the National Telecommunications and Information Administration (NTIA) Office of Spectrum Management (OSM) performed analyses to determine the maximum allowable equivalent isotropically radiated power (EIRP) of UWB devices. As part of its analyses, OSM developed bandwidth correction factor (BWCF) equations. The BWCF provides a means of converting the power (peak or average) of impulse and pulse waveforms as measured in one bandwidth to what would be expected in another bandwidth. The BWCF also includes a conversion between peak and average power levels. In the analyses, OSM used the BWCF to correct for the average and peak power level of the UWB signal at the victim receiver intermediate frequency output. To develop the BWCF, NTIA's Institute for Telecommunication Sciences (ITS) performed a limited number of computer simulations and measurements.

As part of the President's Spectrum Policy Initiative, NTIA will promote selected best practices in spectrum management for use by regulators, technology developers, manufacturers, and service providers. This effort will include the development of a Best Practices Handbook that will bring together a common set of approaches for conducting engineering analyses and will develop a common set of criteria for performing technical studies to evaluate emerging technologies. NTIA will prepare a series of technical memorandums on various topics related to performing engineering analyses and will use the results of the individual technical memorandums to develop the Best Practices Handbook. This technical memorandum is one in a series addressing the topics related to spectrum engineering.

The objective of the measurements and analysis documented in this technical memorandum is to develop BWCF equations for impulse and pulsed signals to be used in interference assessments. In order to accomplish this objective, ITS measured power levels of impulse and pulsed signals with various pulse repetition frequency (PRF) values received in various measurement bandwidths.

The analysis in this technical memorandum shows that the measured BWCF data is consistent across the different types of impulse and pulsed signals and PRFs considered.

For impulse trains with a constant PRF (non-dithered impulse) the data shows a BWCF of 0 dB for a bandwidth (BW) less than 0.6 times the PRF. This 0 dB factor applies to both peak and average signals and is the result of only a single spectral line occurring in the measurement filter.

For dithered impulse trains and for both impulse and pulse trains with constant PRFs when the BW is at least 2 times the PRF of the pulse train, the BWCF for converting average power levels at one BW to average power levels at another BW follows a 10 Log (ratio of BWs) trend. When the BWs are at least 2 times the PRF of the impulse or pulse trains, or when the signals are dithered, the BWCFs for converting peak signal levels at one BW to peak signal levels at another BW follows a 20 Log (ratio of BWs) trend.

For dithered impulse signals when the bandwidth is less than two times the PRF, the signal should be treated as noise-like, and as such, only the average power level would be of concern in performing an interference analysis.

NTIA developed four sets of equations to compute the BWCF for peak and average power levels and for pulsed and dithered and non-dithered impulse signals. NTIA also portrays an explanation of how to apply these sets of equations to convert peak and/or average power levels to the levels expected in a different bandwidth.

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GLOSSARY OF ACRONYMS AND ABBREVIATIONS

AWG	Arbitrary Waveform Generator
BW	Bandwidth
BW_R	Bandwidth of the Reference Receiver
BW_V	Bandwidth of the Victim Receiver
BWCF	Bandwidth Correction Factor
$BWCF_A$	Average Power Bandwidth Correction Factor
$BWCF_P$	Peak Power Bandwidth Correction Factor
EIRP	Equivalent Isotropically Radiated Power
ITS	Institute for Telecommunication Sciences
IF	Intermediate Frequency
NTIA	National Telecommunications and Information Administration
OSM	Office of Spectrum Management
PRF	Pulse Repetition Frequency
RBW	Resolution Bandwidth
RMS	Root Mean Square
SA	Spectrum Analyzer
UWB	Ultrawideband
VSA	Vector Signal Analyzer

SECTION 1.0
INTRODUCTION

1.1 BACKGROUND

In assessing the compatibility between unlicensed ultrawideband (UWB) devices and selected Federal systems operating above 960 MHz, the National Telecommunications and Information Administration (NTIA) Office of Spectrum Management (OSM) performed analyses to determine the maximum allowable equivalent isotropically radiated power (EIRP) of UWB devices.[1] As part of its analyses, OSM developed Bandwidth Correction Factor (BWCF) equations. The BWCF provides a means of converting the power (peak or average) of impulse and pulse waveforms as measured in one bandwidth to what would be expected in another bandwidth. The BWCF also includes a conversion between peak and average power levels. In the analyses, OSM used the BWCF to correct for the average and peak power level of the UWB signal at the victim receiver intermediate frequency (IF) output. To develop the BWCF, NTIA's Institute for Telecommunication Sciences (ITS) performed a limited number of computer simulations and measurements.

As part of the President's Spectrum Policy Initiative, NTIA will promote selected best practices in spectrum management for use by regulators, technology developers, manufacturers, and service providers.[2] This effort will include the development of Best Practices Handbook that will bring together a common set of approaches for conducting engineering analyses and will develop a common set of criteria for performing technical studies to evaluate emerging technologies. NTIA will prepare a series of technical memorandums on various topics related to performing engineering analyses and will use the results of the individual technical memorandums to develop the Best Practices Handbook. This technical memorandum is one in a series addressing topics related to spectrum engineering.

1.2 OBJECTIVE

The objective of these measurements and analyses is to develop equations for the BWCF for impulse and pulsed signals to be used in interference assessments.

1.3 APPROACH

As determined in the initial work performed by ITS, the measured emission amplitudes from impulsive UWB signals varies as a function of the measurement bandwidth and pulse repetition frequency (PRF). This variation represents the relative

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1. National Telecommunications and Information Administration, NTIA Special Publication 01-43, *Assessment of Compatibility Between Ultrawideband Devices and Selected Federal Systems* (January 2001).

2. United States Department of Commerce, *Spectrum Management for the 21st Century, Plan to Implement Recommendations of the President's Spectrum Policy Initiative* (May 2005).

levels that are coupled into receivers that are bandwidth limited. In order to extrapolate from one bandwidth to another when performing compatibility analysis, it is necessary to understand this relationship.

In order to accomplish the objective, NTIA took a two step approach. The first step involved collecting and analyzing an initial set of measured data. NTIA documented the results of this first step in NTIA Technical Memorandum 04-408.[3] Based on an examination of the initial data, NTIA identified a requirement for further measured data. This additional data extended the range of parameters considered. This technical memorandum is based on the analysis of the complete set of measured data and thus supersedes NTIA Technical Memorandum 04-408.

The following approach was used to carry out the measurements:

- An arbitrary waveform generator (AWG) and several impulse signal generators were used to generate the following test waveforms: 1) 50 kHz, 200 kHz, and 800 kHz PRF non-dithered signals with pulsewidths of 250 and 500 picoseconds; 2) 50 kHz and 800 kHz PRF 50% absolute referenced dithered impulse signals with a 500 picosecond pulsewidth; and 3) 200 kHz PRF 10% absolute referenced dithered signal with a pulsewidth of 250 picoseconds.

- A pulsed signal generator and an AWG were used to generate pulsed waveforms with a 1 microsecond width pulse and PRFs of 250 Hz, 500 Hz, 1000 Hz, and 2000 Hz. A reference carrier frequency in the 10 to 50 MHz range was used. For the 500 Hz PRF reference signal, two additional pulsed signals were generated and interposed in time between the reference signals. One of these interposed signals was operated with a carrier frequency 500 kHz below the reference carrier, the other at 500 kHz above. For the 250 Hz PRF reference signal, four additional pulsed signals with 250 Hz PRF were generated at carrier frequencies of -500, -250, +250, and +500 kHz relative to the reference. These additional signals were interposed in the reference signal in the time domain.

- A pulse signal generator and an AWG were used to generate pulsed waveforms with a 1 microsecond pulsewidth width a PRF of 1 kHz and a 100 nanosecond pulsewidth with PRFs of 50 kHz and 500 kHz.

- A spectrum analyzer (SA) and vector signal analyzer (VSA) in combination were used to measure the power level of the impulse and pulsed signals with peak and root-mean-square (RMS) detectors in a filter bandwidth (BW) that varies between 1.8 kHz and 30 MHz. Two types of filters were studied. The

3. National Telecommunications and Information Administration, NTIA Technical Memorandum 04-408, *Examination of the Bandwidth Correction Factors Used To Assess The Interference Impact Of Impulse and Pulsed Signals On Radio Receivers* (January 2004).

first type had a Gaussian shaped selectivity function that represented the typical filter employed in a spectrum analyzer. The second type of filter had a much sharper fall-off compared to the Gaussian filter.

The measurement results were then analyzed to empirically develop BWCF curves for the conditions studied.

SECTION 2.0
BWCF MEASUREMENT PROCEDURES

2.1 MEASUREMENT SETUP

The measurement setup shown in Figure 2-1 was used to generate the data used to create the BWCF curves.

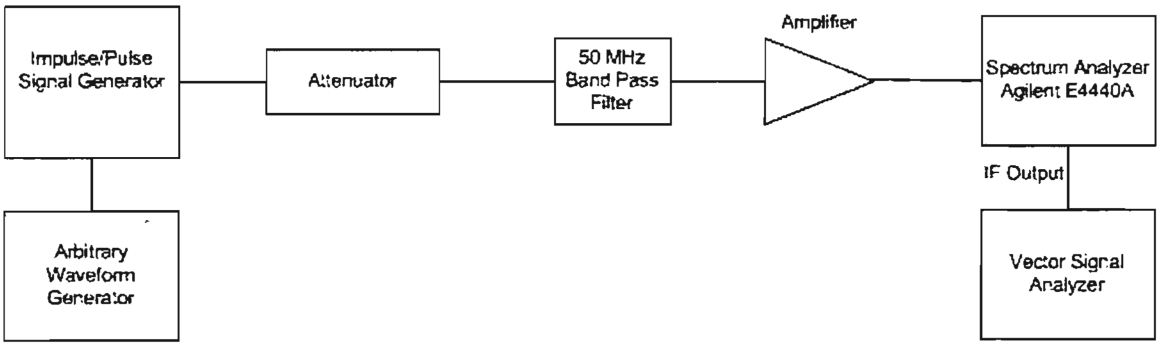

Figure 2-1. Measurement Setup

2.2 MEASUREMENT PROCEDURES FOR IMPULSE SIGNALS

The measurement procedures described below were used to generate the data used to create the BWCF curves for impulse signals. The AWG was programmed to generate an un-modulated non-dithered (i.e., constant PRF) impulse signal. The output of the AWG was used to trigger the impulse generator (pulsewidth of approximately 500 and 250 picoseconds) to create a test waveform with a PRF of 800 kHz.

A. The VSA filter BW was tuned such that it was centered on one dominant spectral line as defined by the PRF.

B. The 36 MHz wide intermediate frequency (IF) output of the SA was input to the VSA. The VSA digitized the IF signal, which was then applied to digital filters generated using MatLab[4] with BWs varying from 1.8 kHz to 30 MHz. Filters having both Gaussian and non-Gaussian (sharp fall-off) selectivity characteristics were employed. The peak power was measured using the peak detector in each of the filter BWs. The measurement time was long enough to include 100 or more pulses.

4. MatLab is a commercially available interactive system and programming language for general scientific and technical computation. MatLab was used to model measurement filters with wider bandwidths and steeper selectivity fall-offs than are available with the spectrum analyzer.

C. Step B was repeated using an RMS detector. The RMS averaging time was long enough to include 100 or more pulses. The impulse signal power level and PRF remained the same as in Step B.

D. Steps A through C were repeated with the AWG programmed to generate a non-dithered impulse signal with a PRF of 200 kHz. The impulse signal power level and SA settings remained the same for the peak and average power measurements.

E. Steps A through C were repeated with the AWG programmed to generate a non-dithered impulse signal with a PRF of 50 kHz. The impulse signal power level and SA settings remained the same for the peak and average power measurements.

F. Steps A through C were repeated with the AWG programmed to generate a 50% absolute referenced dithered impulse signal with a pulsewidth of 500 picoseconds and PRFs of 800 kHz and 50 kHz. The impulse signal power level and SA settings remained the same for the peak and average power measurements.

G. Steps A through C were repeated with the AWG programmed to generate a 10% absolute referenced dithered impulse signal with a PRF of 200 kHz and a pulsewidth of 500 picoseconds. The impulse signal power level and SA settings remained the same for the peak and average power measurements.

2.3 MEASUREMENT PROCEDURES FOR INTERPOSED PULSED SIGNALS

The measurement procedures described below were used to generate the BWCFs for interposed pulsed signals.[5] The measurement setup was the same as shown in Figure 2-1, with the exception that the impulse signal generator was replaced with a pulsed signal generator. The pulsed signal generator operates with carrier frequencies in the 10 to 50 MHz range.

A. The AWG was programmed to generate a pulse waveform with a pulse width of 1 microsecond. The PRF of the test waveform was 2000 Hz and the carrier frequency was constant.

B. The peak power level of the pulsed signal was measured in each of the filter BWs. The filters were implemented in the VSA through digital filters generated using MatLab with the following BWs: 3 MHz, 1 MHz,

5. The tests for trains of pulsed signals with interposed signals were performed under a completely different investigation, not part of the BWCF study. However, in the interest of including as much experimental data as possible, the data was corrected for the impact of the extra signals and used in this study.

300 kHz, 100 kHz, and 30 kHz. The measurement time was long enough to include 100 or more pulses.

C. Step B was repeated using an RMS detector. The RMS averaging time was long enough to include at least 100 pulses. The pulsed signal power level and PRF remained the same as in Step B.

D. Steps A through C were repeated with a PRF of 1000 Hz.

E. The AWG and pulse signal generator were programmed to generate a reference pulse waveform with a pulse width of 1 microsecond and a PRF of 500 Hz. In addition, two additional pulse trains were generated with carrier frequencies of -500 and + 500 kHz relative to the carrier of the reference signal. These additional pulse trains were made up of 1 microsecond pulses and each had a PRF of 500 Hz. The timing of these additional signals was such that they both were interposed in time between the pulses of the reference signal with no overlap in the time domain.

F. For the signal in Step E, Steps B and C were repeated.

G. The AWG and pulse generator were programmed to generate a reference pulse waveform with a pulse width of 1 microsecond and a PRF of 250 Hz. In addition, four additional pulse trains were generated with carrier frequencies of -500, -250, +250, and + 500 kHz relative to the carrier of the reference (center) frequency. These additional pulse trains were made up of 1 microsecond pulses, each with a PRF of 250 Hz. The timing of these additional pulses was such that they were interposed in time between the pulses of the reference signal with no overlap in the time domain.

H. For the signal in Step G, Steps B and C were repeated.

2.4 MEASUREMENT PROCEDURES FOR PULSED SIGNALS

The measurement procedures described below were used to generate the data used to create the BWCF curves for pulsed signals (no interposed pulses). The measurement setup was the same as shown in Figure 2-1, with the impulse signal generator replaced by a pulsed signal generator.

A. The AWG was programmed to generate a pulse train with a 1 microsecond pulsewidth and a PRF of 1 kHz.

B. The peak power level of the pulsed signal was measured in each of the digital filter BWs generated using MatLab. The BWs varied from 30 kHz to 3 MHz. Both filters with a Gaussian and non-Gaussian (sharp) fall-off were used. The measurement time was long enough to include 100 or more pulses.

C. Step B was repeated using an RMS detector. The RMS averaging time was long enough to include at least 100 pulses. The pulsed signal power level and PRF remained the same.

D. Steps B and C were repeated with a PRF of 50 kHz, a pulsewidth of 100 nanoseconds and BWs varied from 27 kHz to 8 MHz.

E. Step D was repeated with a PRF of 500 kHz.

SECTION 3.0
ANALYSIS OF BWCF MEASUREMENTS

3.1 BWCF Measured Data

The objective of the BWCF was to provide a means of converting the power (peak or average) of impulse and pulsed waveforms as measured in one bandwidth to what would be expected in another bandwidth. The BWCF also includes a conversion between peak and average power levels. This section of the technical memorandum provides a presentation of the analysis of measured data resulting in the derivation of the BWCFs over a fairly extensive range of impulse and pulsed waveform characteristics.

The signals measured to derive the BWCFs consisted of:

a) train of impulses with PRFs of 50, 200, and 800 kHz;

b) series of impulses with PRFs of 50, 200, and 800 kHz and the time between pulses varied in a random fashion (i.e., dithered);

c) reference train of pulses with additional pulses interposed in the time domain. (The interposed pulses have the same pulse width as the reference pulse train but have different carrier frequencies. This results in various degrees of pulse overlap in the frequency domain but not in the time domain.); and

d) train of pulses with PRFs of 1, 50, and 500 kHz.

The impulses involved in the first of the above cases had pulsewidths of 250 and 500 picoseconds. In the dithered case, the pulsewidth was 500 picoseconds and the time spacing between impulses was varied in relation to a clock reference. The time placement of the dithered pulses varied in a pseudo-random fashion over the range from occurring at the clock reference point to one half (50% dithered) the time between adjacent clock reference points and an additional signal was dithered to one tenth (10% dithered) the time between adjacent clock reference points. For the dithered pulses, clock reference rates of 50 kHz, 200 kHz, and 800 kHz were used in the measurements. The third set of signals consisted of four different pulse trains all with pulses having a pulsewidth of 1 microsecond with a nominal carrier frequency in the 10 to 50 MHz range. Two pulse trains were generated with no interposed pulses. The PRFs of these two pulse trains were 2 kHz and 1 kHz. In addition, two pulse trains with interposed pulses were generated. In the first interposed case there were two pulses placed between each pulse of the reference signal. One of the interposed signals operated with a carrier frequency that was 500 kHz below the carrier frequency of the referenced signal. The other interposed signal operated with a carrier frequency 500 kHz above the reference signal. With these conditions, the two off-tuned signals were each 4 dB less in amplitude at the center frequency of the reference signal. The three signals each operated at a PRF of 500 Hz. These three signals were generated so that there was no overlap in the time domain.

This results in a pulse repetition time of 2 milliseconds. Thus, every 2 milliseconds, a narrowband filter tuned to the center frequency of the reference signal would see one pulse at full power and two at 4 dB less power. The non-overlap in the time domain results in the peak power of the complete signal being the peak power of the reference signal. However, the overlap in the frequency domain results in the average power of the complete signal being approximately 3 dB higher than the average power of the reference signal. The second interposed pulse train consisted of four pulses between the reference pulses. Two of these pulse trains were tuned below the reference/carrier frequency by 250 kHz and 500 kHz respectively. The two other interposed pulse trains were 250 kHz and 500 kHz above the carrier frequency. Again these signal overlapped in frequency but not in time. The PRF of each of these 5 pulse trains was 250 Hz. The result was to not increase the peak power level but to increase the average power level of the reference signal by 5 dB when the resultant ensemble pulse train is measured with a relatively narrow filter.

The last set of measurements involved trains of pulses, some made up of the pulses with 1 microsecond pulsewidths and some with 100 nanosecond pulsewidths. The PRFs covered a range of 1 kHz, 50 kHz, and 500 kHz.

Most of the measurements summarized above were carried out using filters having a Gaussian-shaped fall-off selectivity. However, in several cases the measurements were repeated using a non-Gaussian (sharp) fall-off selectivity to examine the effect, if any, of filter shape upon the measured BWCF.

The peak and average power levels of the periodic impulse signals for each PRF were measured using peak and RMS detectors. These measurements were carried out over a range of RBWs varying in discrete steps. For the range of PRFs and RBWs employed, measurements were made with a spectral line centered in the RBW. For each PRF, the measured ratio of peak to average values for each RBW and the ratio of peak-to-peak and average-to-average for differing RBWs are meaningful on a relative basis, but not on an absolute basis. To accommodate the measured data and for the purpose of developing the BWCFs, the data was plotted with the power in a single line for each PRF as the BWCF level of 0 dB. In addition, the individual RBWs used in each measurement were normalized to a multiple of the PRF of the impulse waveform. Figures 3-1 through 3-3 show the resulting BWCF data plot for a non-dithered impulse signal. The BWCF allows one to correct a measured power level (peak or average) to a different bandwidth and/or to convert between peak and average power. The absolute power is determined by a calibrated measurement in a reference bandwidth; whereas the BWCF is a relative factor. The data shown in Figures 3-2 and 3-3 were taken with a set of RBWs that provided further definition in the vicinity of the BW/PRF ratio of 1, which represents a transition region in the BWCF measurements.

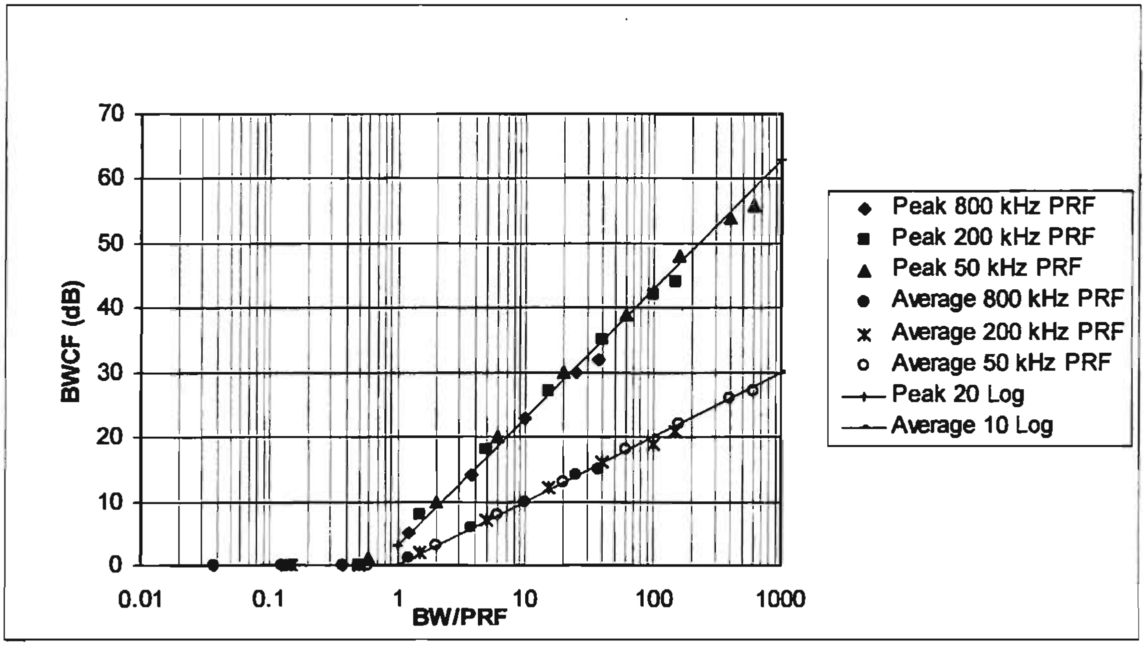

Figure 3-1. BWCF Plot for Non-Dithered Impulse Signals (500 picosecond pulsewidth)

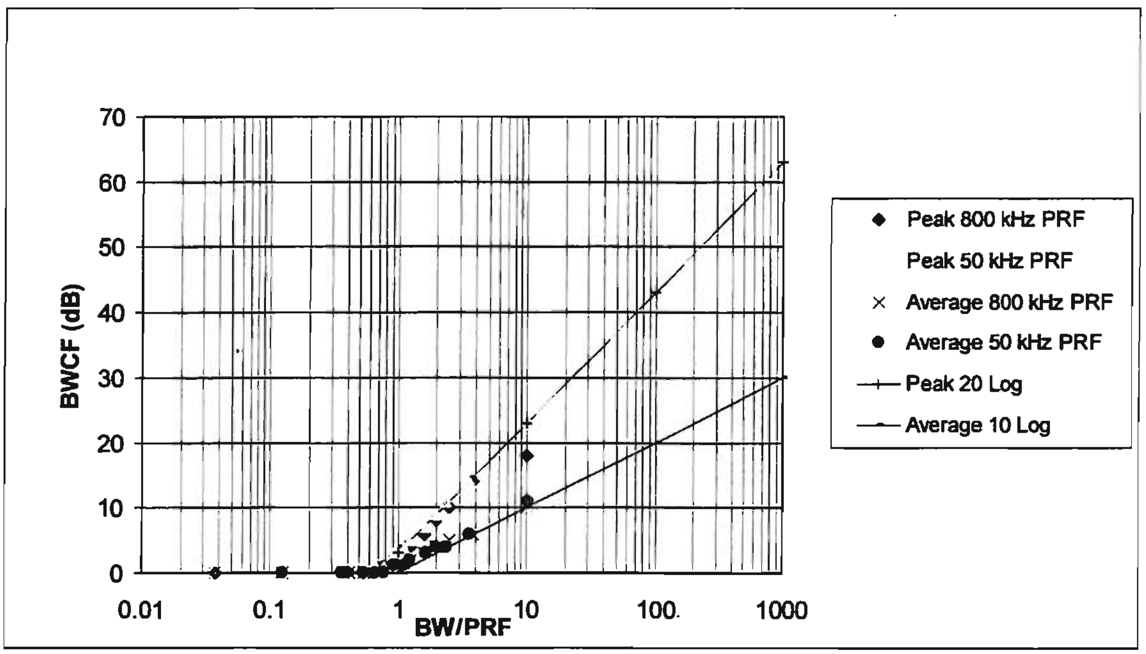

Figure 3-2. BWCF Plot for Non-Dithered Impulse Signals (500 picosecond pulsewidth)

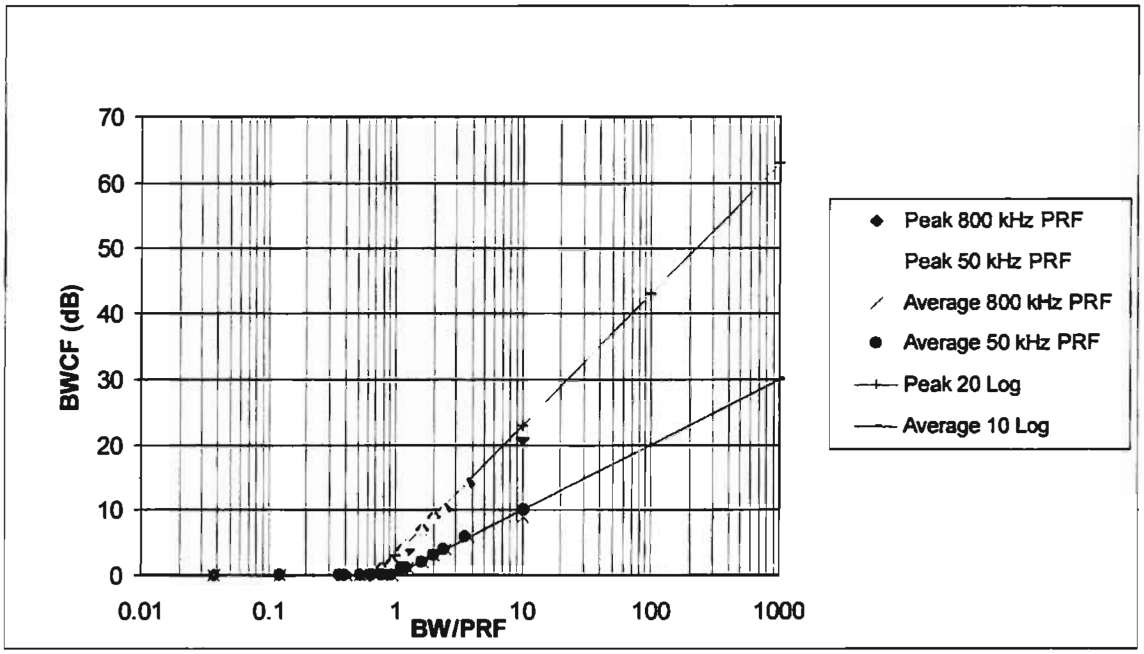

Figure 3-3. BWCF Plot for Non-Dithered Impulse Signals (250 picosecond pulsewidth)

The average and peak power levels for the dithered impulse signal PRFs of 50 kHz and 800 kHz were measured with RBWs varying in discrete steps. The average and peak levels measured, for each RBW, are correct on a relative basis, but there is no absolute measurement to relate the data to other PRFs or to the non-dithered data. The peak and average power level data were normalized (in amplitude) so that the average power data (extended, by a 10 Log (ratio of bandwidths) relation) were set at a BWCF of 0 dB at a point where the RBW equals the PRF. The actual measured data were then adjusted to this reference maintaining the relative basis of the data. This power level normalization is explained further in Appendix A. Figures 3-4 and 3-5 show the resulting BWCF data plots for dithered impulse signals. The data shown in Figure 3-5 were taken with a set of RBWs that provided further definition in the vicinity of BW/PRF ratio of 1, a transition region.

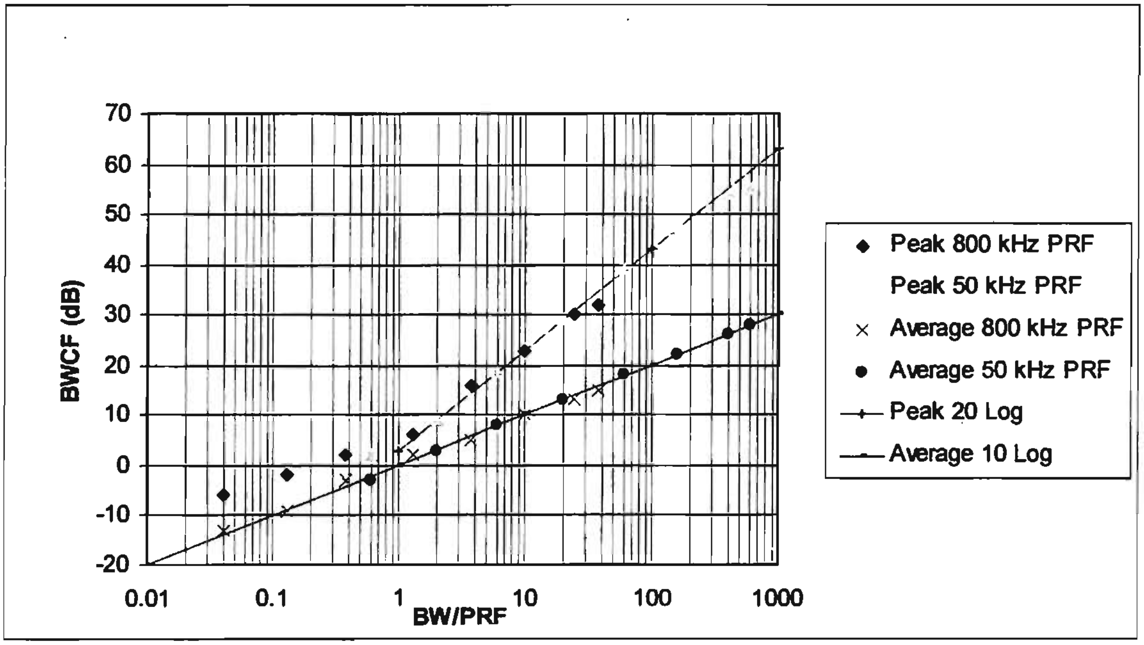

Figure 3-4. BWCF Plot for 50% Dithered Impulse Signals

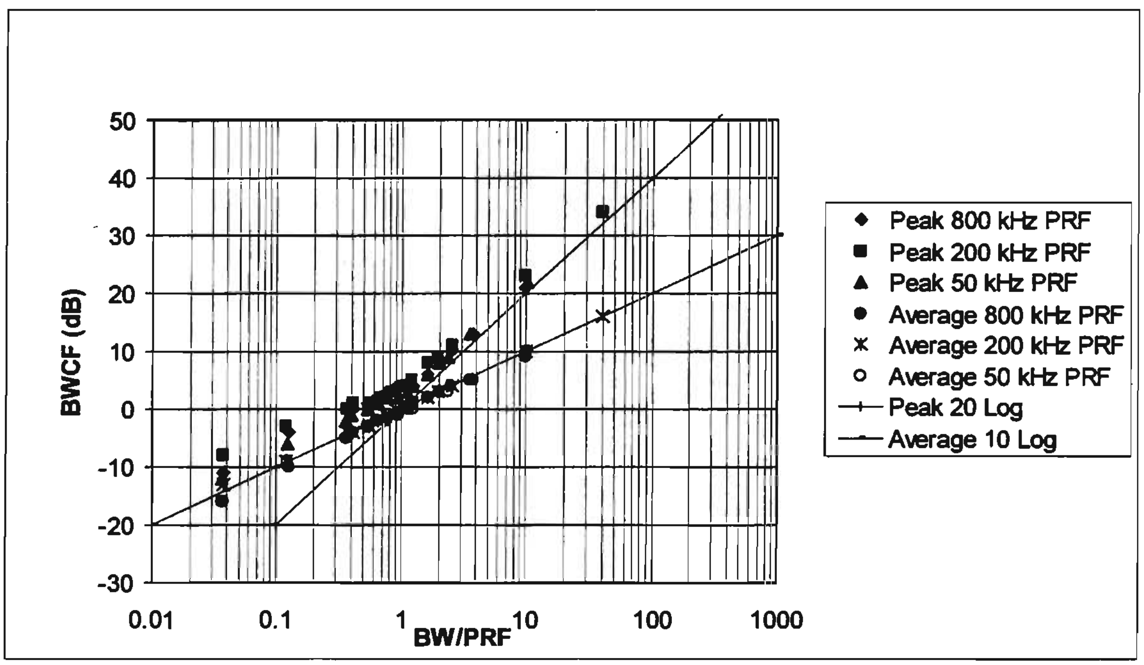

Figure 3-5. BWCF Plot for 50% and 10% Dithered Impulse Signals

For some pulse trains of 1 microsecond pulses, the average and peak power levels were measured with PRFs of 250, 500, 1000, and 2000 pulses per second. For the pulse train with 250 pulses per second, there were four additional pulses interposed between the reference pulses. For the pulse train with 500 pulses per second, there were two additional pulses interposed between each reference pulse. The 1000 and 2000 pulses per second signals had no interposed pulses in the pulse train. Again the average and peak power levels were measured on a relative basis which is acceptable for the BWCF. In addition, the average power level data for the 250 and 500 reference pulses per second signals were reduced by 5 dB and 3 dB, respectively, to account for the increased average power level caused by the interposed pulses. Again the reference was set to 0 dB for the average power where the RBW equals the PRF. Figure 3-6 shows the resulting BWCF data plot for these pulsed signals.

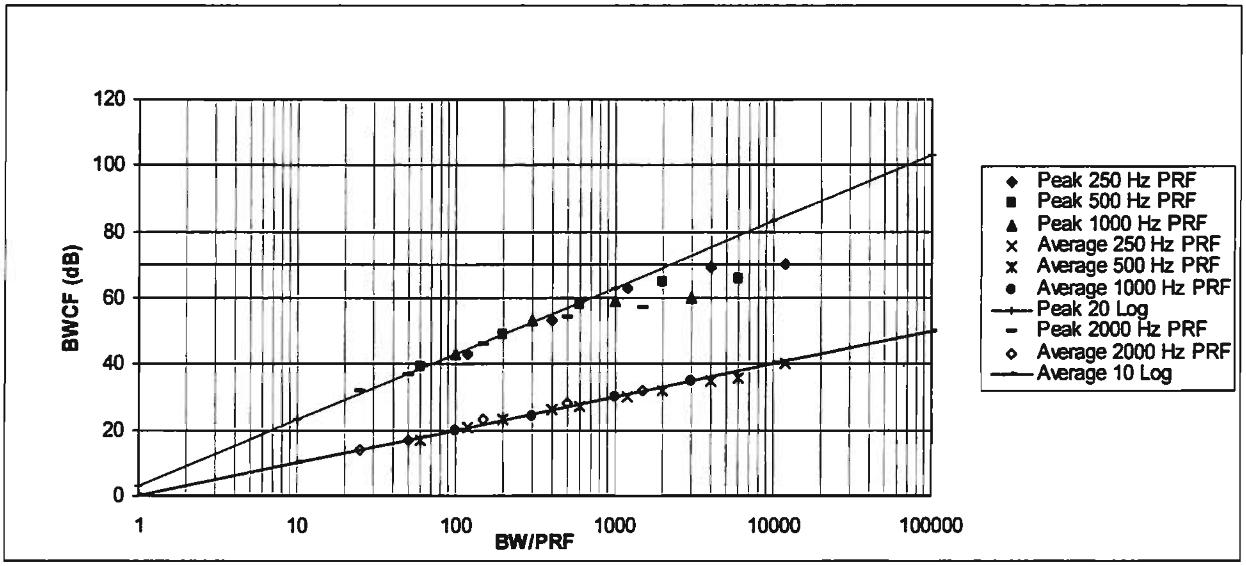

Figure 3-6. BWCF Plot for Pulsed Signals

Another set of measurements was taken for pulse widths of 1 microsecond and 100 nanoseconds. The pulse trains were for a constant PRF of 1, 50, and 500 kHz. The data also included measurements with filters having a Gaussian-shaped fall-off selectivity (the filter shape that is usually available in a spectrum analyzer) and another set of non-Gaussian filters having a sharp roll-off selectivity. These tests were carried out to determine whether filter selectivity has a significant impact on the BWCF. Figure 3-7 shows the BWCF for a 100 nanosecond pulsewidth, a 50 and 500 kHz PRF, and the Gaussian filter roll-off. Figure 3-8 shows the BWCF for a 100 nanosecond pulsewidth, a 50 and 500 KHz PRF, and a non-Gaussian filter roll-off. Figure 3-9 provides the BWCF for a 1 microsecond pulsewidth, a 1 kHz PRF and both Gaussian and non-Gaussian filter roll-offs.

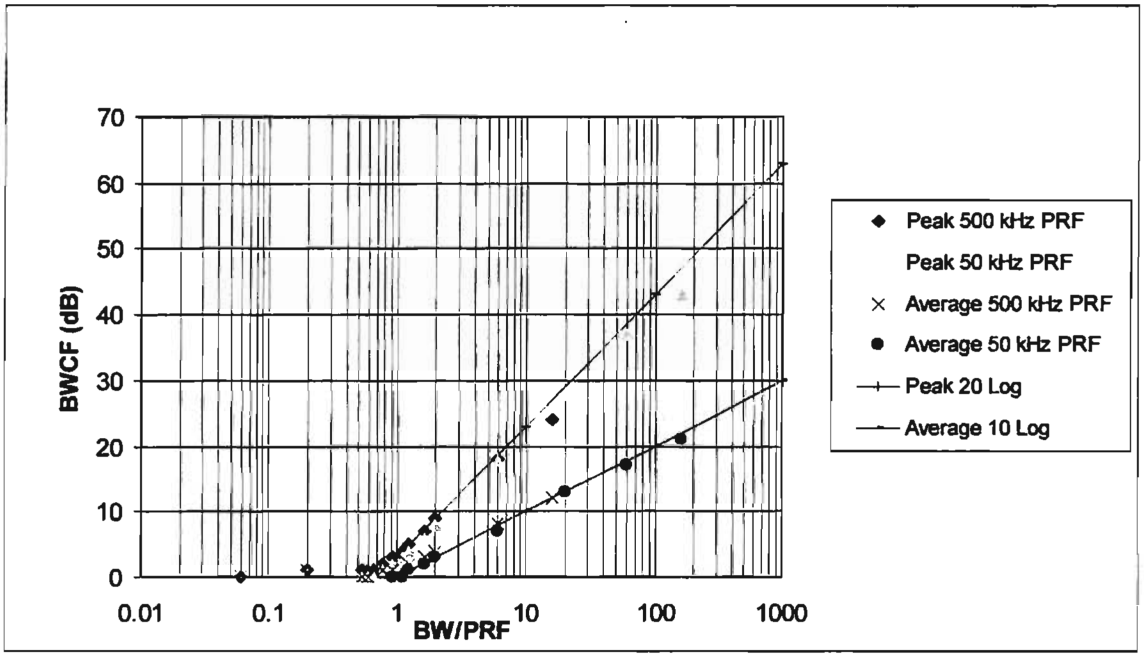

Figure 3-7. BWCF Plot for Pulsed Signals (Gaussian Filter 100 nanosecond pulsewidth)

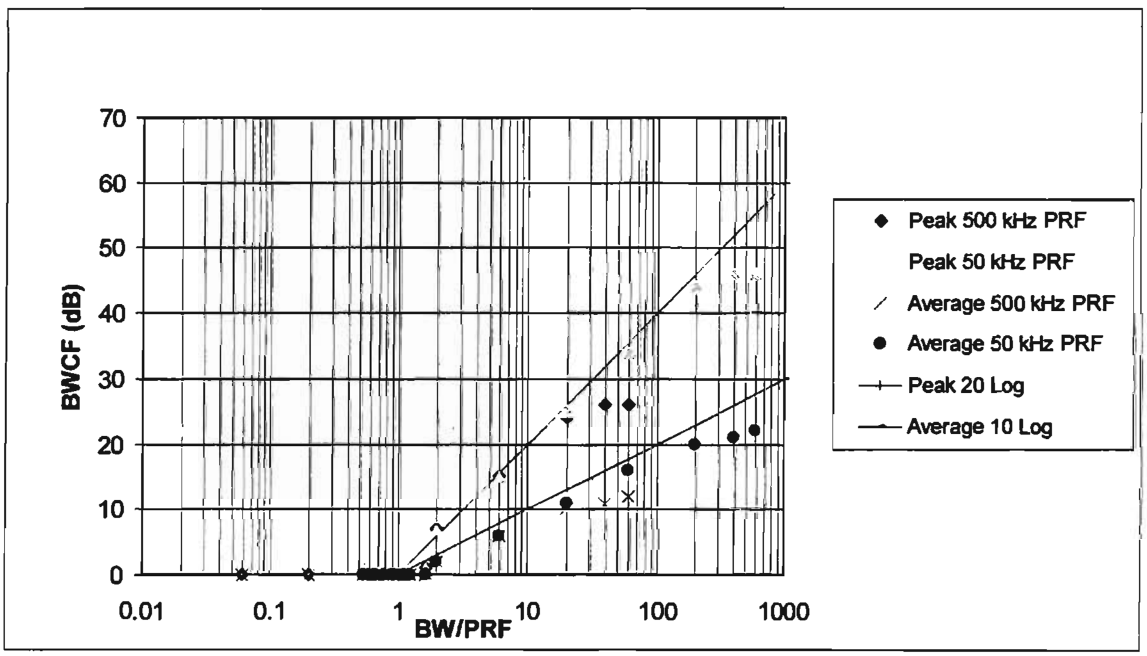

Figure 3-8. BWCF Plot for Pulsed Signals (Non-Gaussian Filter 100 nanosecond pulsewidth)

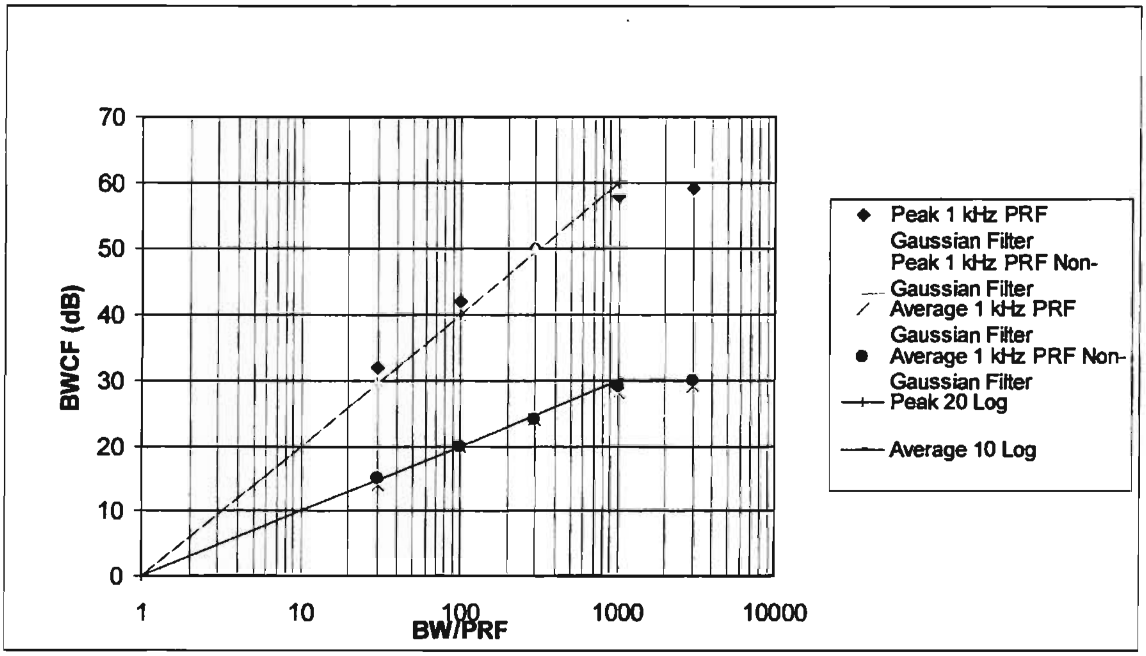

Figure 3-9. BWCF Plot for Pulsed Signal (1 microsecond pulsewidth)

3.2 Observations from BWCF Data Plots

3.2.1 Non-Dithered Impulse Signals and Pulsed Signals

The BWCF data for the periodic impulse signals, Figure 3-1 through 3-3, shows that when the RBWs are below 0.6 times the PRF, the peak and average power levels are equal and independent of filter bandwidth. This is as expected since there is only a single spectral line within the measurement bandwidth for these conditions and the measurements were made such that the line was centered in the filter bandwidth.

The average power BWCF data follows a 10 Log (ratio of the bandwidths) slope when the RBW is at least twice the PRF.

For RBWs greater than two times the PRF, the peak power curve for the signals measured follows a trend of 20 Log (ratio of bandwidths). The BWCF for converting peak power at one bandwidth to peak power in another bandwidth (both bandwidths at least two times the PRF) is characterized by the slope of the line (i.e., 20 Log (ratio of the bandwidths)). All of the data shown in Figures 3-1 through 3-3 was measured with RBWs having a Gaussian filter roll-off. Furthermore, two different impulse widths are represented in the data and the width does not seem to be a factor.

The BWCF data for the periodic pulsed signals, Figures 3-6 through 3-9, is in agreement with the impulse data shown in Figures 3-1 through 3-3. Thus the pulsed and impulse data can be treated as one case. The data in Figure 3-7 through 3-9 shows the 20 Log trend for peak power BWCF and a 10 Log trend for average power BWCF for

BW/PRF ratios greater than one. This data also shows more detail for the BWCF in the vicinity of BW/PRF ratio of 1, which represents a transition region. This data was measured over a range of pulsewidths and PRFs. In addition, the measurements were made with Gaussian and non-Gaussian filter fall-offs. The transition region data showed that the peak power BWCF was 0 dB for BW/PRF ratios less than 0.6 and the peak power BWCF was 3 dB at a BW/PRF ratio equal to 1. This transition region was modeled as a straight line for BWCF (in dB) as a function of Log (BW/PRF).

3.2.2 Dithered Impulse Signals

The BWCF data in Figures 3-4 and 3-5 for the average power shows a 10 Log (ratio of bandwidth) trend over the full range of the measured data. It is likely that dithered impulse signals would appear noise-like at least up to the point where the RBW is wide enough to resolve the individual pulses.[6] For the data shown, the RBWs where the pulses are resolved appear to occur when the RBW is greater than 2 to 3 times the PRF. At this point, the peak power of the individual pulses is being measured. As previously discussed, this train of impulses was generated with the dithering of 10% and 50% of the reference pulse rate. The measured results show that for RBWs less than 2 to 3 times the PRF the peak-to-average ratio is 5 to 8 dB. If the measured signal was truly noise-like, the expected peak-to-average ratio would be on the order of 10 dB.

The equation (Equation 3-4a) to determine the peak power for dithered signals for RBWs less than 2 times the PRF is included in this report primarily for completeness. For these PRF/RBW conditions, the average power should be determined and treated in the interference analysis as a noise signal. The dithered signal will appear as a continuum in the time domain with a noise-like, variable amplitude. When the signal is combined with receiver system noise of higher or comparable signal level the result is certainly noise-like.

As with the non-dithered data, the dithered signal BWCF for peak power levels follows a 20 Log (ratio of the bandwidths) trend for RBWs greater than 2 to 3 times the PRF.

3.2.3 BWCF Model

The data contained in this report was analyzed to develop a BWCF model. The resultant model with a methodology to apply the model is presented in the following subsections. Before the BWCF model is discussed, the following terms must be defined:

> BW_R is the reference signal bandwidth in which the reference power is determined through measurements, specifications or emission limits. For example, BW_R = 1 MHz for the Part 15 average power limit of -41.3 dBm/MHz. The reference power can be a peak or average power value.

6. National Telecommunications and Information Administration, Institute for Telecommunication Sciences, NTIA Report 01-383, *The Temporal and Spectral Characteristics of Ultrawideband Signals* (January 2001) at 8-36, Figure 8.63.

BW_V is the bandwidth (same units as BW_R) in which the average or peak power is to be determined, for example, the bandwidth of the receiver being examined for possible interference (e.g., victim receiver).

BW is the general term for bandwidth.

PRF is the pulse repetition frequency of the reference signal. For non-dithered signals the PRF is the signal repetition frequency. For dithered signals, PRF is the average or reference clock repetition frequency. PRF has the same units as BW_R.

$BWCF_A$ is the average power bandwidth correction factor (dB).

$BWCF_P$ is the peak power bandwidth correction factor (dB).

There are also several considerations/limitations to the BWCF model equations that must be discussed:

- BW_R and BW_V must be less than or equal to the 3 dB bandwidth of the reference signal to apply the BWCF model directly. If the BW_R is greater than the 3 dB bandwidth of the reference signal, BW_R should be set equal to the bandwidth of the reference signal. The reference power level should remain at the level measured. If BW_V is greater than the 3 dB bandwidth of the reference signal, the BWCF (peak or average) for BW_V should be determined for a bandwidth equal to the bandwidth of the reference signal. After these adjustments are made the BWCF model can be applied directly.

- The BWCF model is applicable to pulsed and impulse non-dithered (constant PRF) signals and to dithered impulse signals. The dithered signals are absolute reference dithered signals with dithering in the range of 10% to 50%. For non-dithered signals, both BW_R and BW_V are centered on a spectral line when the BW/PRF ratio is less than 1.

3.2.3.1 BWCF Equations

The BWCF equations for average power ($BWCF_A$) of a non-dithered signal are:

$$BWCF_A = 0 \qquad \text{for } BW/PRF < 1 \qquad (3\text{-}1a)$$

$$BWCF_A = 10 \text{ Log } (BW/PRF) \qquad \text{for } BW/PRF > 1 \qquad (3\text{-}1b)$$

The BWCF equations for peak power ($BWCF_P$) of a non-dithered signal are:

$$BWCF_P = 0 \qquad \text{for } BW/PRF < 0.6 \qquad (3\text{-}2a)$$

$$BWCF_P = 3 + 13.6 \text{ Log } (BW/PRF) \qquad \text{for } 0.6 < BW/PRF < 1 \qquad (3\text{-}2b)$$

$$BWCF_P = 3 + 20 \text{ Log } (BW/PRF) \quad \text{for } BW/PRF > 1 \qquad (3\text{-}2c)$$

The BWCF equation for average power ($BWCF_A$) of a dithered signal are:

$$BWCF_A = 10 \text{ Log } (BW/PRF) \qquad (3\text{-}3)$$

In the case of modeling the peak power BWCF ($BWCF_P$) of a dithered signal, the measured data shows a degree of variability (± 3 dB) for BW/PRF ratios of less than two. The BWCF model yields an "expected value" for BW/PRF ratios less than two. The "expected value" passes approximately through the mid-point of the measured BWCF data. The "expected value" equations for the peak power ($BWCF_P$) of a dithered signal are:

$$BWCF_P = 5 + 10 \text{ Log } (BW/PRF) \quad \text{for } BW/PRF < 2 \qquad (3\text{-}4a)$$

$$BWCF_P = 2 + 20 \text{ Log } (BW/PRF) \quad \text{for } BW/PRF > 2 \qquad (3\text{-}4b)$$

3.2.3.2 Application of BWCF Equations

This subsection contains a tabulation of applications of the BWCF equations to determine the power (peak and average) in a specific receiver bandwidth.

3.2.3.2.1 Non-dithered signals

The following conversion methodologies are for a non-dithered signal where the average and peak power (not BWCFs) levels are in dB relative to a reference power (e.g., dBm or dBW).

For conversion of average power in BW_R to average power in BW_V for a non-dithered signal the following procedure should be used.

- determine the values for $BWCF_A$ for BW_R and BW_V using Equations 3-1a and 3-1b.

- Determine the average power in BW_V using, average power in BW_V = (average power in BW_R) + ($BWCF_A$ at BW_V/PRF - $BWCF_A$ at BW_R/PRF).

For conversion of peak power in BW_R to peak power in BW_V for a non-dithered signal the following procedure should be used.

- Determine the values for $BWCF_P$ for BW_R and BW_V using Equations 3-2a, 3-2b, and 3-2c.

- Determine the peak power in BW_V using, peak power in BW_V = (peak power in BW_R) + ($BWCF_P$ at BW_V/PRF - $BWCF_P$ at BW_R/PRF).

For conversion of average power in BW_R to peak power in BW_V for a non-dithered signal the following procedure should be used.

- Determine the value for $BWCF_A$ for BW_R using Equations 3-1a, and 3-1b.

- Determine the value for $BWCF_P$ for BW_V using Equations 3-2a, 3-2b, and 3-2c.

- Determine the peak power in BW_V using, peak power in BW_V = (average power in BW_R) + ($BWCF_P$ at BW_V/PRF - $BWCF_A$ at BW_R/PRF).

For conversion of peak power in BW_R to average power in BW_V for a non-dithered signal the following procedure should be used.

- Determine the value for $BWCF_P$ for BW_R using Equations 3-2a, 3-2b, and 3-2c.

- Determine the value for $BWCF_A$ for BW_V using Equations 3-1a, and 3-1b.

- Determine the average power in BW_V using, average power in BW_V = (peak power in BW_R) + ($BWCF_A$ at BW_V/PRF – $BWCF_P$ at BW_R/PRF).

3.2.3.2.2 Dithered signals

The following conversion methodologies apply to dithered signals. When determining the peak power BWCF, there is some variability (± 3 dB) for BW/PRF ratios of less than two. The "expected value" is used in the following conversions. The average and peak power (not BWCFs) are in dB relative to a reference power level (e.g., dBm or dBW).

For conversion of average power in BW_R to average power in BW_V for a dithered signal the following procedure should be used.

- Determine the values for $BWCF_A$ for BW_R and BW_V using Equations 3-3.

- Determine the average power in BW_V using, average power in BW_V = (average power in BW_R) + ($BWCF_A$ at BW_V/PRF - $BWCF_A$ at BW_R/PRF).

For conversion of peak power in BW_R to peak power in BW_V for a dithered signal the following procedure should be used.

- Determine the values for $BWCF_P$ for BW_R and BW_V using Equations 3-4a and 3-4b.

- Determine the peak power in BW_V using, peak power in BW_V = (peak power in BW_R) + ($BWCF_P$ at BW_V/PRF - $BWCF_P$ at BW_R/PRF).

For conversion of average power in BW_R to peak power in BW_V for a dithered signal the following procedure should be used.

- Determine the value for $BWCF_A$ for BW_R using Equations 3-3.

- Determine the value for $BWCF_P$ for BW_V using Equations 3-4a and 3-4b.

- Determine the peak power in BW_V using, peak power in BW_V = (average power in BW_R) + ($BWCF_P$ at BW_V/PRF - $BWCF_A$ at BW_R/PRF).

For conversion of peak power in BW_R to average power in BW_V for a dithered signal the following procedure should be used.

- Determine the value for $BWCF_P$ for BW_R using Equations 3-4a and 3-4b.

- Determine the value for $BWCF_A$ for BW_V using Equations 3-3.

- Determine the average power in BW_V using, average power in BW_V = (peak power in BW_R) + ($BWCF_A$ at BW_V/PRF – $BWCF_P$ at BW_R/PRF).

SECTION 4.0
CONCLUSIONS

4.1 CONCLUSIONS

The measured BWCF data, after normalization of the RBW to a multiple of signal PRF and the adjustment of the measured average power to a BWCF of 0 dB at a point where the RBW equals the PRF, is consistent across the different types of impulse and pulsed signals and PRFs considered in this study.

For impulse trains with a constant PRF, the data shows a BWCF of 0 dB for RBWs less than 0.6 times the PRF. This 0 dB factor applies to both peak and average signals and is the result of only a single spectral line occurring in the measurement filter.

For pulse trains, in general, the BWCF for average power levels follows a 10 Log (ratio of bandwidths) trend for dithered pulse trains and for pulse trains with constant PRFs when the RBW is at least 2 times the PRF of the pulse train. The BWCFs for converting peak signal levels at one bandwidth to peak levels at another bandwidth follows a 20 Log (ratio of bandwidths) trend. This 20 Log trend is applicable for bandwidths greater than 2 times the PRF for pulse trains with a constant PRF and for dithered signals.

For dithered impulse signals when the bandwidth is less than 2 times the PRF, the signal should be treated as noise-like and as such only the average power level would be of concern when performing an interference analysis.

In Section 3.2.3, equations to compute the BWCF for peak and average power levels and for dithered and non-dithered signals were developed. An explanation of how these sets of equations can be applied to convert peak and/or average power levels to the levels expected in a different bandwidth is provided in Section 3.2.3.2.

APPENDIX A
MEASURED BWCF DATA

NORMALIZATION OF MEASURED DATA

This appendix contains a tabulation of the measured Bandwidth Correction Factor (BWCF) data. The basic measured data is in the form of relative power level (peak or average) as a function of measurement bandwidth for specific impulse or pulsed signals. Because of differences between specific impulse and pulsed signals, particularly in the power out of the signal source for each signal, the absolute power level, if measured, would have varied for each impulse and pulsed signal. During the measurement of a specific impulse or pulsed signal, only the bandwidth of the measurement filter and detector functions were changed. Thus, the measured power levels are consistent on a relative basis within a data set for a specific impulse or pulsed signal, but the measured power levels cannot be compared directly across differing impulse and pulsed signals. This is not a significant problem as the BWCF is a relative correction. That is, if the average or peak power of an impulse or pulsed signal is measured in a certain bandwidth, the BWCF is the correction to convert from peak to average or average to peak and/or to the power level in a different bandwidth. In order to organize the measured BWCF in a more meaningful form, the measured data was normalized as explained in the following examples.

The first data set explained covers a non-dithered (constant pulse repetition frequency (PRF)) impulse signal. The impulse signals measured had PRFs of 50, 200, and 800 kHz. Table A-1 provides the measured data for the non-dithered impulse signal for an 800 kHz PRF. The impulse signals had a 500 picosecond pulsewidth.

Table A-1. 800 kHz PRF Measured BWCF Data

Bandwidth	Relative Measured Peak BWCF	Relative Measured Average BWCF
30 kHz	-32.5 dB	-32.5 dB
100 kHz	-32.5 dB	-32.5 dB
300 kHz	-32.5 dB	-32.5 dB
1 MHz	-27.5 dB	-31.5 dB
3 MHz	-18.5 dB	-26.5 dB
8 MHz	-9.5 dB	-22.5 dB
20 MHz	-2.5 dB	-18.5 dB
30 MHz	-0.5 dB	-17.5 dB

As stated in Section 3 of this technical memorandum, the normalization in all cases involved expressing the measurement bandwidth as a multiple of the PRF. For the constant PRF case, the power was normalized so that the power in a single spectral line resulted in a BWCF of 0 dB. For the 800 kHz PRF data, the measurements for bandwidths of 300 kHz or less represented the power in a single spectral line. Thus, the normalized 800 kHz PRF BWCF data, which was used in Figure 3-1, involved dividing the PRF (800 kHz for this example) by the measurement bandwidth and adding 32.5 dB to all of the power levels. Table A-2 lists the normalized data for the 800 kHz PRF.

Table A-2. 800 kHz PRF Normalized BWCF Data

Bandwidth/PRF	Relative Measured Peak BWCF	Relative Measured Average BWCF
0.0375	0 dB	0 dB
0.125	0 dB	0 dB
0.375	0 dB	0 dB
1.25	5 dB	1 dB
3.75	14 dB	6 dB
10	23 dB	10 dB
25	30 dB	14 dB
37.5	32 dB	15 dB

The average power BWCF curve for the non-dithered PRF impulse data shows a slope of 10 Log (ratio of the bandwidths) for BW/PRF ratios greater than 1. If this slope is extended, the line passes through the point where the BWCF equals 0 dB and the point where the measurement bandwidth equals the PRF.

Table A-3 lists the measured data for the 50 kHz PRF, dithered impulse signal. This data was for a 50% absolute dithered impulse signal with a pulsewidth of 500 picoseconds.

Table A-3. 50 kHz PRF Measured BWCF Data

Bandwidth	Relative Measured Peak BWCF	Relative Measured Average BWCF
30 kHz	-53 dB	-58 dB
100 kHz	-46 dB	-52 dB
300 kHz	-36 dB	-47 dB
1 MHz	-26 dB	-42 dB
3 MHz	-16 dB	-37 dB
8 MHz	-8 dB	-33 dB
20 MHz	-1 dB	-29 dB
30 MHz	0 dB	-27 dB

The data was normalized by dividing the PRF (50 kHz) by the measurement bandwidth and adding 55 dB to all of the measured power levels. The 55 dB was determined by interpolating (using logarithmic scale) between the 30 kHz and 100 kHz PRF data points to determine the average value at 50 kHz. This interpolated value was approximately -55 dB. The 50 kHz PRF represented the point where the measurement bandwidth equals the PRF. Thus, 55 dB is added to all of the power levels, as a result the average power BWCF passes through the normalized bandwidth of 1 and the BWCF equals 0 dB point. The normalized data for this case is listed in Table A-4.

Table A-4. 50 kHz PRF Normalized BWCF Data

Bandwidth/PRF	Relative Measured Peak BWCF	Relative Measured Average BWCF
0.6	2 dB	-3 dB
2	9 dB	3 dB
6	19 dB	8 dB
20	29 dB	13 dB
60	39 dB	18 dB
160	47 dB	22 dB
400	54 dB	26 dB
600	55 dB	28 dB

The establishment of the power normalization factor could not always be determined through interpolating between measurement points. In cases where the measurements were carried out with bandwidths that were high multiples of the PRF (e.g., the pulsed data discussed in the technical memorandum) the average power BWCF curves were extended using 10 Log (ratio of bandwidths) to determine the correction that results in a 0 dB BWCF at a bandwidth/PRF ratio of 1. The extension of the average power data can be shown in the case of the pulsed emission data with a PRF of 2 kHz and a pulsewidth of one microsecond. The measured BWCF data for this case is listed in Table A-5.

Table A-5. 2 kHz PRF BWCF Data

Bandwidth	Relative Measured Peak BWCF	Relative Measured Average BWCF
100 kHz	-21 dB	-41 dB
300 kHz	-12 dB	-35 dB
1 MHz	-4 dB	-30 dB
3 MHz	-1 dB	-26 dB

For this case, the bandwidth for the reference level would be 2 kHz. Extension of the 100 kHz data point using a 10 Log (ratio of the bandwidths) would yield:

$$-41 + 10 \text{ Log } (2 \text{ kHz}/100 \text{ kHz}) = -58 \text{ dB}$$

The measured power data was normalized by adding 58 dB to each value. This results in the average BWCF having a value of 0 dB when the RBW equals the PRF of 2 kHz. The resulting normalized data is listed in Table A-6.

Table A-6. 2 kHz PRF Normalized BWCF Data

Bandwidth/PRF	Relative Measured Peak BWCF	Relative Measured Average BWCF
50	37 dB	17 dB
150	46 dB	23 dB
500	54 dB	28 dB
1500	57 dB	32 dB

SUMMARY OF BWCF DATA

The following tables summarize the measured BWCF data along with the normalized data.

Non-Dithered Impulse Signals

The following tables list the measured BWCF data along with the normalized data for the 50 kHz, 200 kHz, and 800 kHz PRF non-dithered impulse signals.

Table A-7. Non-Dithered Impulse BWCF Data (50 kHz PRF and 500 picosecond pulsewidth)

Bandwidth	Bandwidth/PRF	Peak BWCF		Average BWCF	
		Measured	Normalized	Measured	Normalized
30 kHz	0.6	-56 dB	-1 dB	-56 dB	-1 dB
100 kHz	2	-46 dB	9 dB	-53 dB	2 dB
300 kHz	6	-36 dB	19 dB	-48 dB	7 dB
1 MHz	20	-26 dB	29 dB	-43 dB	12 dB
3 MHz	60	-17 dB	38 dB	-38 dB	17 dB
8 MHz	160	-8 dB	47 dB	-34 dB	21 dB
20 MHz	400	-2 dB	53 dB	-30 dB	25 dB
30 MHz	600	0 dB	55 dB	-29 dB	26 dB

Table A-8. Non-Dithered Impulse BWCF Data (200 kHz PRF and 500 picosecond pulsewidth)

Bandwidth	Bandwidth/PRF	Peak BWCF		Average BWCF	
		Measured	Normalized	Measured	Normalized
30 kHz	0.15	-44 dB	0 dB	-44 dB	0 dB
100 kHz	0.5	-44 dB	0 dB	-44 dB	0 dB
300 kHz	1.5	-36 dB	8 dB	-42 dB	2 dB
1 MHz	5	-26 dB	18 dB	-37 dB	7 dB
3 MHz	15	-17 dB	27 dB	-32 dB	12 dB
8 MHz	40	-9 dB	35 dB	-28 dB	16 dB
20 MHz	100	-2 dB	42 dB	-25 dB	19 dB
30 MHz	150	0 dB	44 dB	-23 dB	21 dB

Table A-9. Non-Dithered Impulse BWCF Data (800 kHz PRF and 500 picosecond pulsewidth)

Bandwidth	Bandwidth/PRF	Peak BWCF		Average BWCF	
		Measured	Normalized	Measured	Normalized
30 kHz	0.0375	-32.5 dB	0 dB	-32.5 dB	0 dB
100 kHz	0.125	-32.5 dB	0 dB	-32.5 dB	0 dB
300 kHz	0.375	-32.5 dB	0 dB	-32.5 dB	0 dB
1 MHz	1.25	-27.5 dB	5 dB	-31.5 dB	1 dB
3 MHz	3.75	-18.5 dB	14 dB	-26.5 dB	6 dB
8 MHz	10	-9.5 dB	23 dB	-22.5 dB	10 dB
20 MHz	25	-2.5 dB	30 dB	-18.5 dB	14 dB
30 MHz	37.5	-0.5 dB	32 dB	-17.5 dB	15 dB

The following tables list additional measured BWCF data along with normalized data for 50 kHz and 800 kHz PRF non-dithered impulse signals. This data set was measured for 500 and 250 picosecond pulsewidth impulse signals. These measurements were made using filter bandwidths that allowed more detail of the BWCFs in the vicinity of the bandwidth to PRF ratios of one. This ratio defines a transition region for the BWCF values.

Table A-10. Non-Dithered Impulse BWCF Data (800 kHz PRF and 500 picosecond pulsewidth)

Bandwidth	Bandwidth/PRF	Peak BWCF		Average BWCF	
		Measured	Normalized	Measured	Normalized
30 kHz	0.0375	-29 dB	0 dB	-29 dB	0 dB
100 kHz	0.125	-29 dB	0 dB	-29 dB	0 dB
300 kHz	0.375	-29 dB	0 dB	-29 dB	0 dB
330 kHz	0.41	-29 dB	0 dB	-29 dB	0 dB
430 kHz	0.54	-29 dB	0 dB	-29 dB	0 dB
510 kHz	0.64	-29 dB	0 dB	-29 dB	0 dB
620 kHz	0.78	-28 dB	1 dB	-28 dB	1 dB
750 kHz	0.94	-27 dB	2 dB	-28 dB	1 dB
910 kHz	1.14	-25 dB	4 dB	-28 dB	1 dB
1 MHz	1.25	-25 dB	4 dB	-27 dB	2 dB
1.3 MHz	1.625	-23 dB	6 dB	-26 dB	3 dB
1.6 MHz	2	-21 dB	8 dB	-25 dB	4 dB
2 MHz	2.5	-19 dB	10 dB	-24 dB	5 dB
3 MHz	3.75	-15 dB	14 dB	-23 dB	6 dB
8 MHz	10	-11 dB	18 dB	-19 dB	10 dB

Table A-11. Non-Dithered Impulse BWCF Data (50 kHz PRF and 500 picosecond pulsewidth)

Bandwidth	Bandwidth/PRF	Peak BWCF		Average BWCF	
		Measured	Normalized	Measured	Normalized
1.8 kHz	0.036	-57 dB	0 dB	-57 dB	0 dB
6.2 kHz	0.124	-57 dB	0 dB	-57 dB	0 dB
18 kHz	0.36	-57 dB	0 dB	-57 dB	0 dB
20 kHz	0.4	-57 dB	0 dB	-57 dB	0 dB
27 kHz	0.54	-56 dB	1 dB	-57 dB	0 dB
33 kHz	0.66	-56 dB	1 dB	-57 dB	0 dB
39 kHz	0.78	-56 dB	1 dB	-57 dB	0 dB
47 kHz	0.94	-54 dB	3 dB	-56 dB	1 dB
56 kHz	1.12	-53 dB	4 dB	-56 dB	1 dB
62 kHz	1.24	-52 dB	5 dB	-55 dB	2 dB
82 kHz	1.64	-50 dB	7 dB	-54 dB	3 dB
100 kHz	2	-48 dB	9 dB	-53 dB	4 dB
120 kHz	2.4	-46 dB	11 dB	-53 dB	4 dB
180 kHz	3.6	-43 dB	14 dB	-51 dB	6 dB
510 kHz	10.2	-34 dB	23 dB	-46 dB	11 dB

Table A-12. Non-Dithered Impulse BWCF Data (50 kHz PRF and 250 picosecond pulsewidth)

Bandwidth	Bandwidth/PRF	Peak BWCF		Average BWCF	
		Measured	Normalized	Measured	Normalized
1.8 kHz	0.036	-62 dB	0 dB	-63 dB	-1 dB
6.2 kHz	0.124	-62 dB	0 dB	-62 dB	0 dB
18 kHz	0.36	-62 dB	0 dB	-62 dB	0 dB
20 kHz	0.4	-62 dB	0 dB	-62 dB	0 dB
27 kHz	0.54	-62 dB	0 dB	-62 dB	0 dB
33 kHz	0.66	-61 dB	1 dB	-62 dB	0 dB
39 kHz	0.78	-61 dB	1 dB	-62 dB	0 dB
47 kHz	0.94	-60 dB	2 dB	-62 dB	0 dB
56 kHz	1.12	-58 dB	4 dB	-61 dB	1 dB
62 kHz	1.24	-57 dB	5 dB	-61 dB	1 dB
82 kHz	1.64	-55 dB	7 dB	-60 dB	2 dB
100 kHz	2	-53 dB	9 dB	-59 dB	3 dB
120 kHz	2.4	-52 dB	10 dB	-58 dB	4 dB
180 kHz	3.6	-48 dB	14 dB	-56 dB	6 dB
510 kHz	10.2	-40 dB	22 dB	-52 dB	10 dB

Table A-13. Non-Dithered Impulse BWCF Data
(800 kHz PRF and 250 picosecond pulsewidth)

Bandwidth	Bandwidth/PRF	Peak BWCF		Average BWCF	
		Measured	Normalized	Measured	Normalized
30 kHz	0.0375	-38 dB	0 dB	-38 dB	0 dB
100 kHz	0.125	-38 dB	0 dB	-38 dB	0 dB
300 kHz	0.375	-38 dB	0 dB	-38 dB	0 dB
330 kHz	0.41	-38 dB	0 dB	-38 dB	0 dB
430 kHz	0.54	-38 dB	0 dB	-38 dB	0 dB
510 kHz	0.64	-38 dB	0 dB	-38 dB	0 dB
620 kHz	0.78	-37 dB	1 dB	-38 dB	0 dB
750 kHz	0.94	-36 dB	2 dB	-38 dB	0 dB
910 kHz	1.14	-34 dB	4 dB	-37 dB	1 dB
1 MHz	1.25	-34 dB	4 dB	-37 dB	1 dB
1.3 MHz	1.625	-31 dB	7 dB	-36 dB	2 dB
1.6 MHz	2	-29 dB	9 dB	-35 dB	3 dB
2 MHz	2.5	-28 dB	10 dB	-34 dB	4 dB
3 MHz	3.75	-24 dB	14 dB	-32 dB	6 dB
8 MHz	10	-17 dB	21 dB	-29 dB	9 dB

Dithered Impulse Signals

The following tables list the measured BWCF data along with the normalized data for the 50 kHz and 800 kHz PRF dithered impulse signals.

Table A-14. Dithered Impulse BWCF Data
(50 kHz PRF, 500 picosecond pulsewidth and 50% dithering)

Bandwidth	Bandwidth/PRF	Peak BWCF		Average BWCF	
		Measured	Normalized	Measured	Normalized
30 kHz	0.6	-53 dB	2 dB	-58 dB	-3 dB
100 kHz	2	-46 dB	9 dB	-52 dB	3 dB
300 kHz	6	-36 dB	19 dB	-47 dB	8 dB
1 MHz	20	-26 dB	29 dB	-42 dB	13 dB
3 MHz	60	-16 dB	39 dB	-37 dB	18 dB
8 MHz	160	-8 dB	47 dB	-33 dB	22 dB
20 MHz	400	-1 dB	54 dB	-29 dB	26 dB
30 MHz	600	0 dB	55 dB	-27 dB	28 dB

Table A-15. Dithered Impulse BWCF Data (800 kHz PRF, 500 picosecond pulsewidth and 50% dithering)

Bandwidth	Bandwidth/PRF	Peak BWCF		Average BWCF	
		Measured	Normalized	Measured	Normalized
30 kHz	0.0375	-38 dB	-7 dB	-45 dB	-14 dB
100 kHz	0.125	-34 dB	-3 dB	-41 dB	-9 dB
300 kHz	0.375	-30 dB	1 dB	-35 dB	-4 dB
1 MHz	1.25	-26 dB	5 dB	-30 dB	1 dB
3 MHz	3.75	-16 dB	15 dB	-27 dB	4 dB
8 MHz	10	-9 dB	22 dB	-22 dB	9 dB
20 MHz	25	-2 dB	29 dB	-19 dB	12 dB
30 MHz	37.5	0 dB	31 dB	-17 dB	14 dB

The following tables list additional measured BWCF data along with normalized data for 10% and 50% absolute referenced dithered signals. This data set was measured for 500 picosecond pulsewidth impulse signals. These measurements were made using filter bandwidths that allowed more detail of the BWCFs in the vicinity of the bandwidth to pulse repetition frequency ratios of one.

Table A-16. Dithered Impulse BWCF Data (50 kHz PRF, 500 picosecond pulsewidth, and 50% dithering)

Bandwidth	Bandwidth/PRF	Peak BWCF		Average BWCF	
		Measured	Normalized	Measured	Normalized
1.8 kHz	0.036	-64 dB	-12 dB	-68 dB	-16 dB
6.2 kHz	0.124	-58 dB	-6 dB	-61 dB	-9 dB
18 kHz	0.36	-54 dB	-2 dB	-57 dB	-5 dB
20 kHz	0.4	-53 dB	-1 dB	-56 dB	-4 dB
27 kHz	0.54	-52 dB	0 dB	-55 dB	-3 dB
33 kHz	0.66	-51 dB	1 dB	-54 dB	-2 dB
39 kHz	0.78	-50 dB	2 dB	-53 dB	-1 dB
47 kHz	0.94	-50 dB	2 dB	-53 dB	-1 dB
56 kHz	1.12	-49 dB	3 dB	-52 dB	0 dB
62 kHz	1.24	-48 dB	4 dB	-52 dB	0 dB
82 kHz	1.64	-46 dB	6 dB	-50 dB	2 dB
100 kHz	2	-44 dB	8 dB	-49 dB	3 dB
120 kHz	2.4	-43 dB	9 dB	-49 dB	3 dB
180 kHz	3.6	-39 dB	13 dB	-47 dB	5 dB
510 kHz	10.2	-30 dB	22 dB	-42 dB	10 dB

Table A-17. Dithered Impulse BWCF Data
(200 kHz PRF, 500 picosecond pulsewidth and 10% dithering)

Bandwidth	Bandwidth/PRF	Peak BWCF		Average BWCF	
		Measured	Normalized	Measured	Normalized
7.5 kHz	0.0375	-49 dB	-8 dB	-54 dB	-13 dB
24 kHz	0.12	-44 dB	-3 dB	-50 dB	-9 dB
75 kHz	0.375	-41 dB	0 dB	-45 dB	-4 dB
82 kHz	0.41	-40 dB	1 dB	-45 dB	-4 dB
110 kHz	0.55	-40 dB	1 dB	-44 dB	-3 dB
130 kHz	0.65	-40 dB	1 dB	-43 dB	-2 dB
150 kHz	0.75	-39 dB	2 dB	-42 dB	-1 dB
180 kHz	0.9	-38 dB	3 dB	-41 dB	0 dB
220 kHz	1.1	-37 dB	4 dB	-40 dB	1 dB
240 kHz	1.2	-36 dB	5 dB	-40 dB	1 dB
330 kHz	1.65	-33 dB	8 dB	-39 dB	2 dB
390 kHz	1.95	-32 dB	9 dB	-38 dB	3 dB
510 kHz	2.55	-30 dB	11 dB	-37 dB	4 dB
2000 kHz	10	-18 dB	23 dB	-31 dB	10 dB
8000 kHz	40	-7 dB	34 dB	-25 dB	16 dB

Table A-18. Dithered Impulse BWCF Data
(800 kHz PRF, 500 picosecond pulsewidth and 50% dithering)

Bandwidth	Bandwidth/PRF	Peak BWCF		Average BWCF	
		Measured	Normalized	Measured	Normalized
30 kHz	0.0375	-39 dB	-11 dB	-44 dB	-16 dB
100 kHz	0.125	-32 dB	-4 dB	-38 dB	-10 dB
300 kHz	0.375	-28 dB	0 dB	-33 dB	-5 dB
330 kHz	0.4125	-28 dB	0 dB	-32 dB	-4 dB
430 kHz	0.5375	-27 dB	1 dB	-31 dB	-3 dB
510 kHz	0.6375	-26 dB	2 dB	-30 dB	-2 dB
620 kHz	0.775	-25 dB	3 dB	-30 dB	-2 dB
750 kHz	0.9375	-24 dB	4 dB	-29 dB	-1 dB
910 kHz	1.1375	-24 dB	4 dB	-28 dB	0 dB
1 MHz	1.25	-24 dB	4 dB	-27 dB	1 dB
1.3 MHz	1.625	-22 dB	6 dB	-26 dB	2 dB
1.6 MHz	2	-20 dB	8 dB	-25 dB	3 dB
2 MHz	2.5	-18 dB	10 dB	-24 dB	4 dB
3 MHz	3.75	-15 dB	13 dB	-23 dB	5 dB
8 MHz	10	-7 dB	21 dB	-19 dB	9 dB

Pulsed Signals

The following tables list the measured BWCF data along with the normalized data for the 250 Hz, 500 Hz, 1000 Hz, and 2000 Hz PRF pulsed signals.

Table A-19. Pulsed BWCF Data
(250 Hz PRF and 1 microsecond pulsewidth)

Bandwidth	Bandwidth /PRF	Measured Peak BWCF	Measured Average BWCF	Corrected Average[A]	Normalized Peak BWCF	Normalized Average BWCF
30 kHz	120	-27 dB	-46 dB	-51 dB	45 dB	21 dB
100 kHz	400	-17 dB	-41 dB	-46 dB	55 dB	26 dB
300 kHz	1200	-8 dB	-36 dB	-41 dB	64 dB	31 dB
1 MHz	4000	-2 dB	-32 dB	-37 dB	70 dB	35 dB
3 MHz	12000	-1 dB	-26 dB	-31 dB	71 dB	41 dB
Note A: The measured average BWCF was corrected by -5 dB to take into account the overlap in the frequency domain due to pulses at -500, -250, +250, and + 500 kHz relative to the reference carrier. The correction was appropriate as the BWCF is for a single pulse train. The additional signals did not overlap in the time domain so the peak power data did not require a correction.						

Table A-20. Pulsed BWCF Data
(500 Hz PRF and 1 microsecond pulsewidth)

Bandwidth	Bandwidth /PRF	Measured Peak BWCF	Measured Average BWCF	Corrected Average[A]	Normalized Peak BWCF	Normalized Average BWCF
30 kHz	60	-27 dB	-45 dB	-48 dB	39 dB	18 dB
100 kHz	200	-17 dB	-40 dB	-43 dB	49 dB	23 dB
300 kHz	600	-7 dB	-35 dB	-38 dB	59 dB	28 dB
1 MHz	2000	-2 dB	-30 dB	-33 dB	64 dB	33 dB
3 MHz	6000	-1 dB	-26 dB	-29 dB	65 dB	37 dB
Note A: The measured average BWCF was corrected by -3 dB to take into account the overlap in the frequency domain due to pulses at -500 and + 500 kHz relative to the reference carrier. The correction was appropriate as the BWCF is for a single pulse train. The additional signals did not overlap in the time domain so the peak power data did not require a correction.						

Table A-21. Pulsed BWCF Data
(1000 Hz PRF and 1 microsecond pulsewidth)

Bandwidth	Bandwidth/PRF	Peak BWCF		Average BWCF	
		Measured	Normalized	Measured	Normalized
100 kHz	100	-18 dB	43 dB	-41 dB	20 dB
300 kHz	300	-8 dB	53 dB	-36 dB	25 dB
1 MHz	1000	-2 dB	59 dB	-31 dB	30 dB
3 MHz	3000	-1 dB	60 dB	-26 dB	35 dB

Table A-22. Pulsed BWCF Data
(2000 Hz PRF and 1 microsecond pulsewidth)

Bandwidth	Bandwidth/PRF	Peak BWCF		Average BWCF	
		Measured	Normalized	Measured	Normalized
50 kHz	25	-26 dB	32 dB	-44 dB	14 dB
100 kHz	50	-21 dB	37 dB	-41 dB	17 dB
300 kHz	150	-12 dB	46 dB	-35 dB	23 dB
1 MHz	500	-4 dB	54 dB	-30 dB	28 dB
3 MHz	1500	-1 dB	57 dB	-26 dB	32 dB

The following tables list additional measured BWCF data along with normalized data for pulsed non-dithered signals. The data sets include PRFs of 1 kHz, 50 kHz, and 500 kHz and pulsewidths of 1 microsecond and 100 nanoseconds. This data was measured for both a set of filters with a Gaussian shaped selectivity and a set of filters with non-Gaussian shaped selectivity. Some of these measurements were made to show greater detail of the BWCFs in the vicinity of one for the ratio of BW/PRF.

Table A-23. Non-Dithered Pulse BWCF Data
(1 kHz PRF, 1 microsecond pulsewidth)

Bandwidth	Bandwidth/PRF	Peak BWCF		Average BWCF	
		Measured	Normalized	Measured	Normalized
30 kHz	30	-58 dB	32 dB	-76 dB	14 dB
100 kHz	100	-48 dB	42 dB	-70 dB	20 dB
300 kHz	300	-40 dB	50 dB	-66 dB	24 dB
1 MHz	1000	-32 dB	58 dB	-62 dB	28 dB
3 MHz	3000	-31 dB	59 dB	-61 dB	29 dB

Table A-24. Non-Dithered Pulse BWCF Data
(1 kHz PRF, 1 microsecond pulsewidth and non-Gaussian filter roll-off)

Bandwidth	Bandwidth/PRF	Peak BWCF		Average BWCF	
		Measured	Normalized	Measured	Normalized
30 kHz	30	-31 dB	30 dB	-46 dB	15 dB
100 kHz	100	-21 dB	40 dB	-41 dB	20 dB
300 kHz	300	-11 dB	50 dB	-37 dB	24 dB
1 MHz	1000	-2 dB	59 dB	-32 dB	29 dB
3 MHz	3000	0 dB	61 dB	-31 dB	30 dB

Table A-25. Non-Dithered Pulse BWCF Data (50 kHz PRF, 100 nanosecond pulsewidth and non-Gaussian filter roll-off)

Bandwidth	Bandwidth/PRF	Peak BWCF		Average BWCF	
		Measured	Normalized	Measured	Normalized
27 kHz	0.54	-46 dB	0 dB	-46 dB	0 dB
30 kHz	0.6	-46 dB	0 dB	-46 dB	0 dB
33 kHz	0.66	-46 dB	0 dB	-46 dB	0 dB
39 kHz	0.78	-46 dB	0 dB	-46 dB	0 dB
47 kHz	0.94	-46 dB	0 dB	-46 dB	0 dB
56 kHz	1.12	-46 dB	0 dB	-46 dB	0 dB
62 kHz	1.24	-46 dB	0 dB	-46 dB	0 dB
82 kHz	1.64	-45 dB	1 dB	-46 dB	0 dB
100 kHz	2	-39 dB	7 dB	-44 dB	2 dB
300 kHz	6	-31 dB	15 dB	-40 dB	6 dB
1 MHz	20	-21 dB	25 dB	-35 dB	11 dB
3 MHz	60	-12 dB	34 dB	-30 dB	16 dB
10 MHz	200	-2 dB	44 dB	-26 dB	20 dB
20 MHz	400	0 dB	46 dB	-25 dB	21 dB
30 MHz	600	0 dB	46 dB	-24 dB	22 dB

Table A-26. Non-Dithered Pulse BWCF Data (50 kHz, 100 nanosecond pulsewidth)

Bandwidth	Bandwidth/PRF	Peak BWCF		Average BWCF	
		Measured	Normalized	Measured	Normalized
27 kHz	0.54	-67 dB	0 dB	-68 dB	-1 dB
30 kHz	0.6	-67 dB	0 dB	-68 dB	-1 dB
33 kHz	0.66	-67 dB	0 dB	-68 dB	-1 dB
39 kHz	0.78	-66 dB	1 dB	-68 dB	-1 dB
47 kHz	0.94	-65 dB	2 dB	-67 dB	0 dB
56 kHz	1.12	-64 dB	3 dB	-67 dB	0 dB
62 kHz	1.24	-63 dB	4 dB	-66 dB	1 dB
82 kHz	1.64	-61 dB	6 dB	-65 dB	2 dB
100 kHz	2	-59 dB	8 dB	-64 dB	3 dB
300 kHz	6	-49 dB	18 dB	-60 dB	7 dB
1 MHz	20	-39 dB	28 dB	-54 dB	13 dB
3 MHz	60	-30 dB	37 dB	-50 dB	17 dB
8 MHz	160	-24 dB	43 dB	-46 dB	21 dB

Table A-27. Non-Dithered Pusle BWCF Data
(500 kHz PRF and 100 nanosecond pulsewidth)

Bandwidth	Bandwidth/PRF	Peak BWCF		Average BWCF	
		Measured	Normalized	Measured	Normalized
30 kHz	0.06	-48 dB	0 dB	-48 dB	0 dB
100 kHz	0.2	-47 dB	1 dB	-47 dB	1 dB
270 kHz	0.54	-47 dB	1 dB	-48 dB	0 dB
300 kHz	0.6	-47 dB	1 dB	-48 dB	0 dB
330 kHz	0.66	-47 dB	1 dB	-47 dB	1 dB
390 kHz	0.78	-46 dB	2 dB	-47 dB	1 dB
470 kHz	0.94	-45 dB	3 dB	-47 dB	1 dB
560 kHz	1.12	-44 dB	4 dB	-47 dB	1 dB
620 kHz	1.24	-43 dB	5 dB	-46 dB	2 dB
820 kHz	1.64	-41 dB	7 dB	-45 dB	3 dB
1 MHz	2	-39 dB	9 dB	-44 dB	4 dB
3 MHz	6	-30 dB	18 dB	-40 dB	8 dB
8 MHz	16	-24 dB	24 dB	-36 dB	12 dB

Table A-28. Non-Dithered Pulse BWCF Data
(500 kHz PRF, 100 nanosecond pulsewidth and non-Gaussian filter roll-off)

Bandwidth	Bandwidth/PRF	Peak BWCF		Average BWCF	
		Measured	Normalized	Measured	Normalized
30 kHz	0.06	-26 dB	0 dB	-26 dB	0 dB
100 kHz	0.2	-26 dB	0 dB	-26 dB	0 dB
270 kHz	0.54	-26 dB	0 dB	-26 dB	0 dB
300 kHz	0.6	-26 dB	0 dB	-26 dB	0 dB
330 kHz	0.66	-26 dB	0 dB	-26 dB	0 dB
390 kHz	0.78	-26 dB	0 dB	-26 dB	0 dB
470 kHz	0.94	-26 dB	0 dB	-26 dB	0 dB
560 kHz	1.12	-26 dB	0 dB	-26 dB	0 dB
620 kHz	1.24	-26 dB	0 dB	-26 dB	0 dB
820 kHz	1.64	-25 dB	1 dB	-26 dB	0 dB
1 MHz	2	-19 dB	7 dB	-24 dB	2 dB
3 MHz	6	-11 dB	15 dB	-20 dB	6 dB
10 MHz	20	-2 dB	24 dB	-16 dB	10 dB
20 MHz	40	0 dB	26 dB	-15 dB	11 dB
30 MHz	60	0 dB	28 dB	-14 dB	12 dB