Technical Appendix C
to the Reply Comments of Time Domain Corporation

ET Docket 98-153

Prepared by the Technical staff members of

Time Domain Corporation

Appendix C
UWB Measurement Techniques and Issues

Overview

A critical component of the UWB rulemaking is the measurement technique and the associated limits that regulate the power or electric field strength. This is a challenge due to the diversity of UWB signal structures, and the time domain nature of the waveform. The goal is a measurement technique that is reliable and repeatable, not overly complicated, cost effective, and resembles the kind of interference that would be perceived by a common victim receiver. To that end, the FCC has recommended an average, bandlimited peak, and absolute peak measurement.

In reading the FCC's NPRM and other comments supplied, TDC chose to study the different possible techniques that had been outlined to determine their feasibility and limitations. TDC understand that there are a number of different approaches to measuring UWB signals, many of them just as valid as the ones we were researching. The following list of studies provided in this Appendix is by all means not exhaustive, but does represent some very interesting observations and recommendations on how to move forward with practical measurement techniques for UWB systems.

Study 1: Conducted Impulse Response

Study 2: Radiated Impulse Response

Study 3: Suggested UWB Measurement Techniques

Study 4: Magnitude versus RBW for Fixed PRF

Study 5: Radiated Emissions of Multiple UWB Transmitters

The following recommendations regarding measurement techniques emerged from TDC's research process.

- Both peak and average measurements should be performed at 1 meter rather than 3 meters (with an appropriate adjustment made to the limit to reflect the electric field strength at 1 meter) in order to get the necessary sensitivity.[1]

- Antenna heights for both transmit and receive antennas should be at least 2 meters above the floor. This is in order to separate the direct path pulse from the reflected path pulse for time domain peak measurements, since the overlap of those pulses may be either deconstructive or constructive, which would change the peak measurement.

- For average measurements, when the PRF is less than the specified 1 MHz RBW, then either a correction factor[2] needs to be used for the narrow VBW averaging technique or the use of a true average detector with a wide VBW.

- Peak measurements are best performed using a horn antenna, a digital sampling oscilloscope (DSO) with input from a tunable bandpass filter rather than the IF output of a wideband receiver.

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[1] This was discussed in detail in TDC's opening comments and is not covered in any more detail in these studies.

[2] This correction factor is shown in detail in Study 4.

- Since the peak measurements need to be made with fast DSOs, then UWB manufacturers could make the peak measurements and supply them to the certification lab for approval and submittal to the FCC. This would be much more cost-effective than requiring all certification labs to purchase DSOs.

We recognize that there are other experiments and studies to be performed and plan on continuing this research effort. As we complete these future tests, we will supply the Commission with the data and conclusions we have drawn.

Study 1: Conducted Impulse Response

Purpose:

The primary purpose of this study was to investigate the impulse response, both measured and predicted in a conducted setting. The individual objectives of the study were:

- To perform impulse response measurements in a very controlled setting to gain insight into mechanisms involved in determining the peak impulse response.
- To predict the impulse response of a known bandpass filter.
- To predict the impulse response of the IF output of a wideband receiver.
- To evaluate a bandpass filter technique versus a wideband IF receiver technique for repeatability, accuracy, and traceability.
- To develop mathematical relationships for predicting the impulse response peak voltage, verify the relationship by making measurements, and compute the correlation between prediction and measurement.

Conclusions:

The following conclusions were drawn from this study. The Detailed Technical Discussion below presents the data and arguments from which these conclusions have been formulated.

- The impulse response of a known bandpass filter can be predicted very accurately and these match the measurements very well.

- It is possible to predict the general trends of the bandlimited peak using the IF receiver technique. However, the values are not consistent and repeatable due to the large number of variables (e.g. receiver settings, LO leakage, etc) that change values for every different setting of the receiver (e.g. change in ref level, attn level, center freq, etc).

- In a wideband receiver (including spectrum analyzer), the calibration is from the input to the display. Using the IF to DSO technique breaks that chain and therefore the measurement is uncalibrated.

In conclusion, it is best to use a known tunable bandpass filter over an IF wideband receiver technique.

Detailed Technical Discussion:

Bandpass Filter Impulse Response

One of the most important aspects of any measurement technique is the accuracy of the measurement referenced to mathematical prediction and a calibration standard or method. The basis of the 50 MHz bandwidth peak measurements is the impulse response of a bandpass filter. In order to develop and verify mathematical predictions of bandpass filter impulse responses, TDC constructed a Bessel bandpass filter based on TDC's best estimate of a flat phase filter and conducted a series of impulse response tests. The predicted impulse response of a Bessel bandpass filter is shown in Figure 1.

The test setup used to perform impulse response verification measurements is simple and accurate and is shown in Figure 2. This testing is important because it paves the way for the development of a calibration setup for the peak electric field time domain measurement setup. Whatever test setup is used to measure the peak value of the electric fields, it must be predictable and repeatable in the presence of a known stimulus. The plots shown in Figure 2 show a series of impulse waveforms and the corresponding impulse response of the Bessel filter. TDC also calculated what the

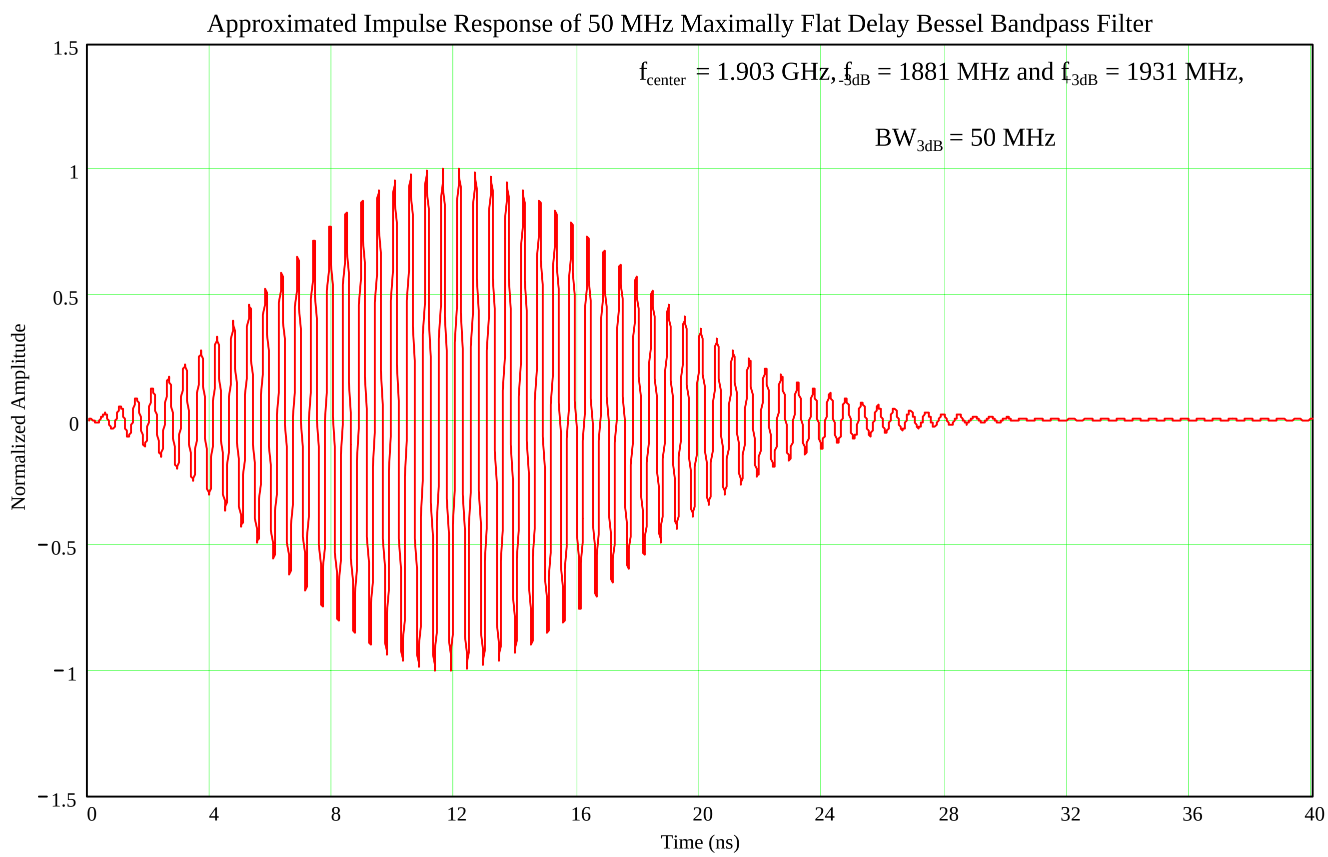
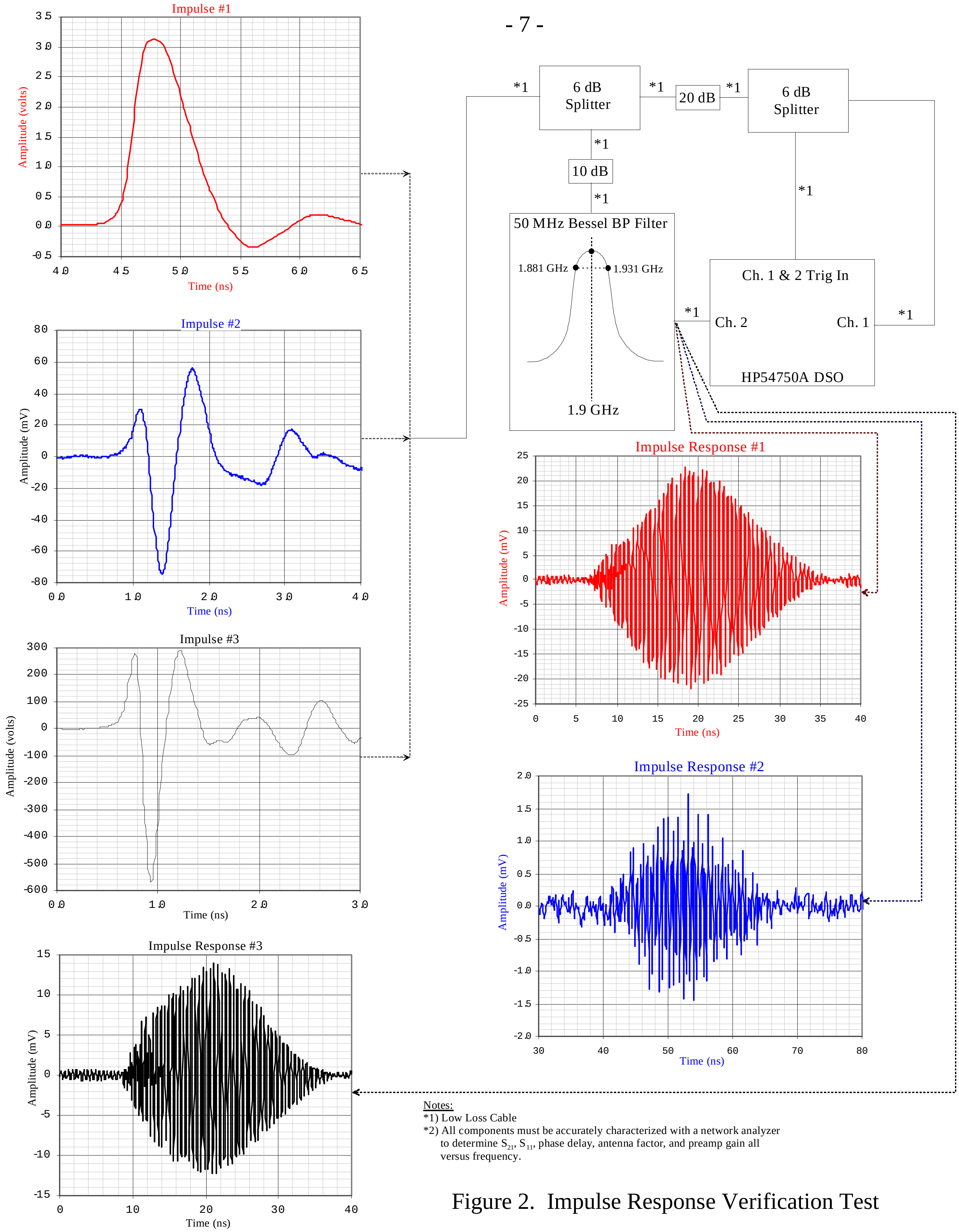


Figure 1. Bessel Bandpass Filter Impulse Response



Notes:
*1) Low Loss Cable
*2) All components must be accurately characterized with a network analyzer to determine S_{21}, S_{11}, phase delay, antenna factor, and preamp gain all versus frequency.

Figure 2. Impulse Response Verification Test

impulse response should be based on the driving function. It is clear from the measurements and analysis that predicting the impulse response of a bandpass filter is fairly easy once the normalized response curve for the filter topology is known.

The equation used to predict the bandpass filter impulse response peak voltage of the test setup shown in Figure 2 is a modification of the more general equation that would be utilized during an actual measurement. The general equation is developed in many texts such as Engelson's, "Modern Spectrum Analyzer Measurements," Blinchikoff's and Zverev's, "Filtering in the Time & Frequency Domains," and Zverev's, "Handbook of Filter Synthesis." The equation developed for use during the Bessel bandpass filter impulse response testing had to account for the fact that the spectrum peak of the pulse frequency spectrum was different than the center frequency of the Bessel bandpass filter. During an actual calibration or measurement the receiving system will be tuned to the peak frequency to eliminate the need to compensate for the different frequencies of the pulse spectrum peak and the filter center. The general equation for predicting a filter's impulse response peak voltage can be calculated using the relationship listed in Equation 1. Equation 1 can be used to determine measurement system bandwidth and gain correction factors used to calculate the peak value of the radiated electric fields. The use and modification of Equation 1 will be discussed later in this report.

$$V_{PkBW} \approx V_{PkNormalized} \cdot 2 \cdot \pi \cdot BW_{-3dB} \cdot Pulse_{Area} \qquad (1)$$

where:

$V_{PkNormalized}$ = peak value of the normalized low pass filter impulse response. The normalized curves are based on the filter type such as Bessel, synchronously tuned, Elliptic, etc. This term is dimensionless.

BW_{-3dB} = Bandpass filter –3dB bandwidth in (Hz).

V_{PkBW} = Filter impulse response peak voltage in (volts)

$Pulse_{Area}$ = Leading edge impulse area, for each leading edge in (Volt-seconds). The single polarity impulse (see Figure 2, impulse 1) would be the simplest case of the variable $Pulse_{Area}$. Figure 3 demonstrates this definition.

Whatever dv/dt polarity occurs first at the filter input combined with the charging characteristics of the filter determines the response. For example the first waveform has a positive dv/dt which is seen first by the filter and as the dv/dt starts to change sign the filter inductance tries to maintain the direction of current flow until the dv/dt changes back to the same dv/dt polarity, which is when current is pumped back in to the inductance and stored in the magnetic field. This is valid for filter rise times that are long in comparison to the impulse dv/dt transitions.

Two of the three predicted impulse responses, from impulses 1 and 3 in Figure 2, were less than 0.6 dB different than the measurements with the third prediction about 1.9 dB different than the measurement (impulse response 2 in Figure 2). It is clear from the plot that the impulse response waveform is in the noise of the DSO and the measured peaks are noise spikes amidst the impulse waveform. The prediction was 1.37 mV_{pk} and the measured peak was 1.7 mV_{pk}, which are very small levels to be measured accurately in a noisy environment.

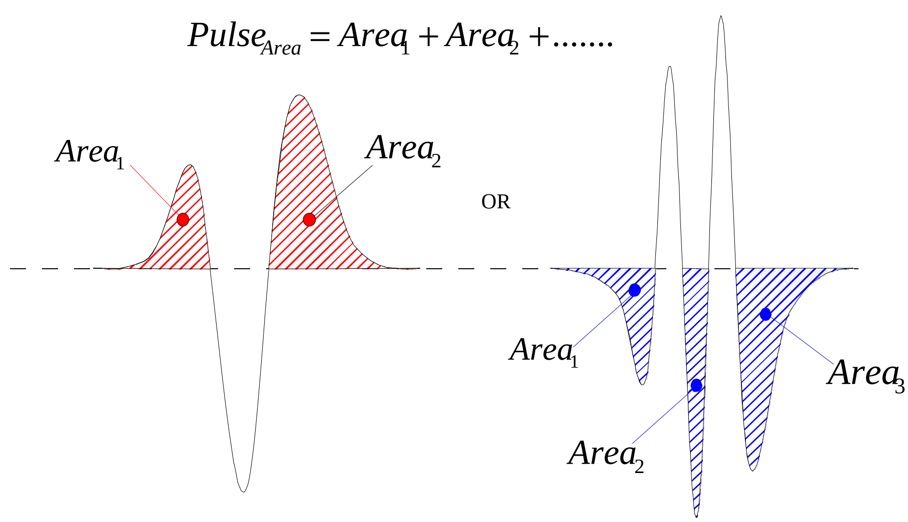


Figure 3. Leading Edge Impulse Area

Spectrum Analyzer IF Impulse Response

A series of tests were conducted on the IF and video output of a spectrum analyzer to assess the accuracy and repeatability of using the IF or video output of a wideband receiver as an indication of victim receiver impulse response. The RBW of the spectrum analyzer was set to 10, 5, and 3 MHz with the UWB signal PRF set to 1 MHz allowing the spectrum analyzer RBW to operate in the pulse spectrum mode. The spectrum analyzer peak detector was used as well as the VBW set to the highest setting, 10 MHz, to prevent any averaging of the randomly time modulated pulse. The amplitude is the same for a time modulated or non-modulated signal when the PRF is greater than the RBW. Both the IF and video output of the spectrum analyzer were monitored for the IF impulse response and the log envelope curve of the IF impulse response. The test setup is shown in Figure 4. Various attenuation levels, center frequencies, and RBW settings were used during the measurements so that enough data could be gathered to determine an impulse response correction factor for the IF and video output. The correction factor would allow accurate prediction of the IF output impulse response peak voltage given a known impulse at the spectrum analyzer input. The assumption was that the correction factor would be constant and repeatable. By modifying Equation 1 we get Equation 2, which can be used to determine the correction factor for the IF output peak voltage.

$$V_{Pk\_corr\_factor} = \frac{V_{IF\_Pk}}{2 \cdot \pi \cdot Pulse_{Area} \cdot RBW_{-3dB} \cdot Spectrum_{Pk\_PSD\_corr}} \qquad (2)$$

where:

$$V_{Pk\_corr\_factor} = K \cdot V_{PkNormalized}$$

$V_{PkNormalized}$ = peak value of the normalized low pass filter impulse response. The normalized curves are based on the filter type such as Bessel, synchronously tuned, Elliptic, etc. This term is dimensionless.

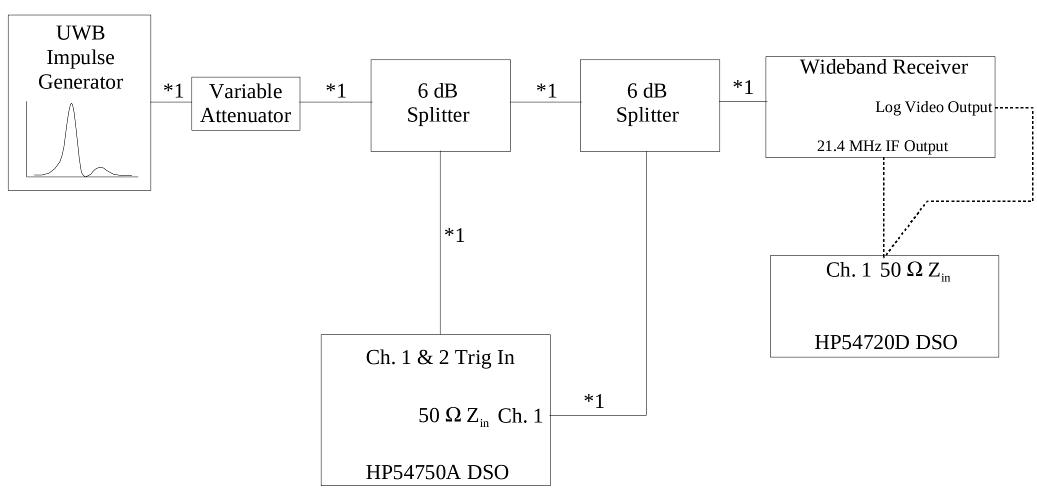
RBW_{-3dB} = Resolution Bandwidth filter 3dB bandwidth in (Hz).

$Pulse_{Area}$ = Leading edge impulse area, for each leading edge in (Volt-seconds).

K = IF RF chain gain and bandwidth correction factor. This term is dimensionless.

$Spectrum_{Pk\_PSD\_corr}$ = Ratio of the impulse spectrum peak amplitude to the frequency component amplitude, of the impulse, at the tuned center frequency of the spectrum analyzer.

V_{IF_Pk} = IF output impulse response peak voltage in (volts)



Notes:
*1) Low Loss Cable
*2) All components must be accurately characterized with a network analyzer to determine S_{21}, S_{11}, phase delay, antenna factor, and preamp gain all versus frequency.

Figure 4. Wideband Receiver IF Output Test Setup

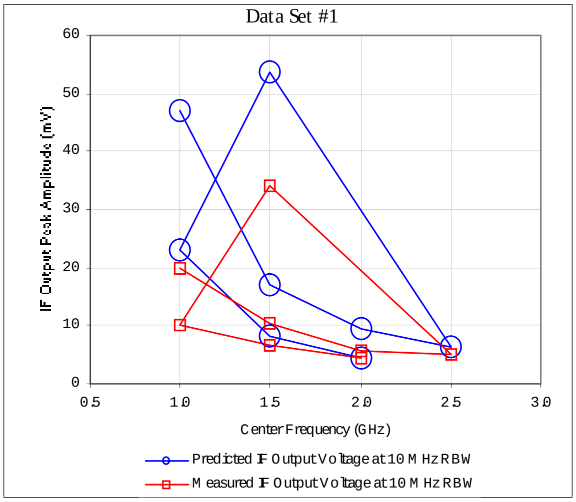
Equation 2 will allow the measurement receiver to be calibrated with an impulse of known impulse area and shape. A tabulated list of data and calculated correction factors are listed in Table I. A plot of IF output voltage variation is shown in Figure 5. As can be seen from Table I and Figure 5, the IF output voltage is not repeatable or constant. There are several reasons for the variation: (1) IF RF chain is different for each RBW; (2) RBW shape factor variations; (3) gain variations with internal attenuator and reference level changes; (4) spectrum analyzer calibration is only valid for end to end use, not in the middle of the IF RF chain; and (5) LO leakage and IF output noise. Since the video output is just a log envelope of the IF output, the same errors contribute to the video signal error as well.

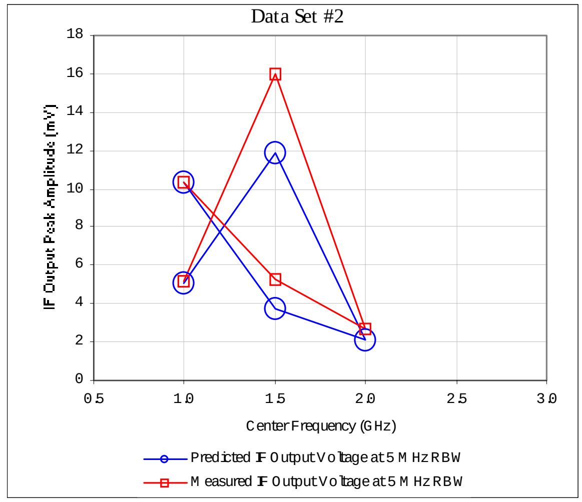
Table I. IF Output Correction Factors

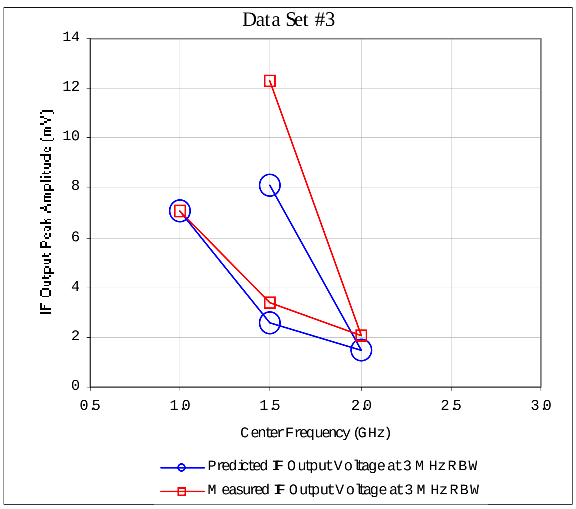
Data Set/Trial	$V_{Pk\_corr\_factor}$	V_{IF_Pk} *(mVpk)*	BW_{-3dB} *(MHz)*	$Pulse_{Area}$ *(V-s)*	$Spectrum_{Pk\_PSD\_corr}$	*Center Frequency (GHz)*	*1/Q*	*Reference Level (dBm)*	*Correct Voltage (mVpk)*
1/1	4.38	19.96	10	1.617E-10	0.449	1.0	2.193E+02	-20	46.91
1/2	2.28	10.39	10	1.617E-10	0.163	1.5	6.041E+02	-20	17.03
1/3	3.47	5.75	10	1.617E-10	0.092	2.0	1.070E+03	-20	9.61
1/4	5.32	4.97	10	1.617E-10	0.059	2.5	1.669E+03	-20	6.16
1/5	56.72	33.98	10	1.617E-10	0.163	1.5	6.041E+02	-30	53.81
1/6	6.04	10.00	10	8.213E-11	0.442	1.0	4.386E+02	-20	23.07
1/7	2.87	6.54	10	8.213E-11	0.155	1.5	1.251E+03	-20	8.09
1/8	5.68	4.54	10	8.213E-11	0.087	2.0	2.229E+03	-20	4.54
2/1	23.11	10.37	5	1.617E-10	0.449	1.0	4.386E+02	-20	10.37
2/2	2.32	5.28	5	1.617E-10	0.163	1.5	1.208E+03	-20	3.76
2/3	3.24	2.68	5	1.617E-10	0.092	2.0	2.141E+03	-20	2.12
2/4	34.21	15.98	5	1.617E-10	0.163	1.5	1.208E+03	-30	11.89
2/5	6.23	5.16	5	8.213E-11	0.442	1.0	8.773E+02	-20	5.10
3/1	6.22	7.09	3	1.617E-10	0.449	1.0	7.311E+02	-20	7.09
3/2	2.47	3.38	3	1.617E-10	0.163	1.5	2.014E+03	-20	2.57
3/3	4.17	2.07	3	1.617E-10	0.092	2.0	3.568E+03	-20	1.45
3/4	43.89	12.30	3	1.617E-10	0.163	1.5	2.014E+03	-30	8.13
4/1	6.22	3.09	10	5.252E-11	0.431	1.0	7.035E+02	-10	3.09
4/2	5.60	7.97	10	5.252E-11	0.431	1.0	7.035E+02	-20	9.77
4/3	17.09	24.30	10	5.252E-11	0.431	1.0	7.035E+02	-30	30.90
4/4	56.98	81.00	10	5.252E-11	0.431	1.0	7.035E+02	-40	97.71

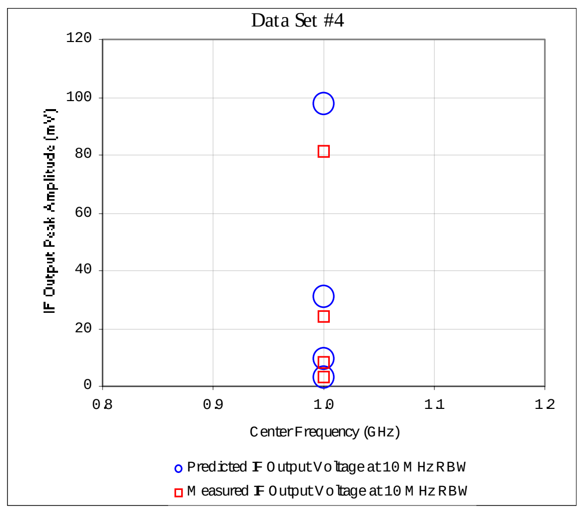
$$Q = 2 \cdot \pi \cdot Pulse_{Area} \cdot RBW_{-3dB} \cdot Spectrum_{Pk\_PSD\_corr}$$

Figure 5. IF Output Variation versus Predicted









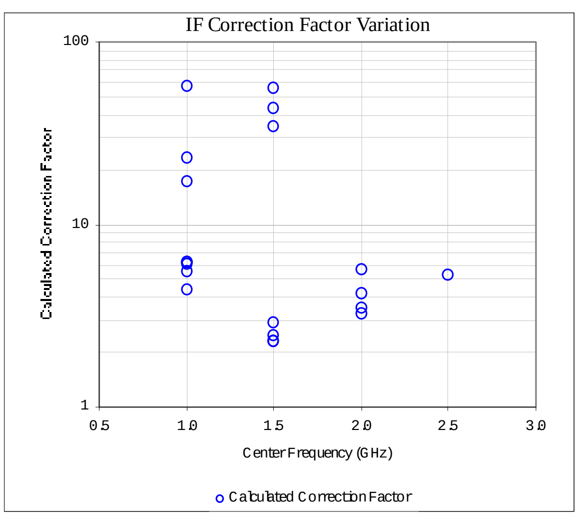


Figure 5 shows four plots of IF peak voltage variations versus center frequency and one plot of correction factor variations versus center frequency. Each data set is based on a RBW setting and calculated versus measured peak IF output voltage. All of the plotted data and spectrum analyzer settings are listed in Table I. Since the absolute correction factor for each spectrum analyzer setting is not known, the calculated trend was based on using one of the measured values as a reference and basing all subsequent calculation on the reference value. The line with squares is the calculated trend and the line with larger circles is the measured trend. The reference value is located where the circle and square are exactly on top of each other. The plots indicate that the general trend of the predicted and measured curves is similar but with large deviations in predicted and measured voltage. If the deviations were constant then the offset could be lumped in with the correction factor, but they are not, so determining a correction factor to be used as a traceable link to a known stimulus is difficult and tedious. Without a detailed analysis of the spectrum analyzer system TDC is unable to quantify the exact contribution of each source to the total error, but can illustrate the contribution of error of the LO leakage and IF output noise to the impulse response measurement. A plot, shown in Figure 6, of the IF output with no signal present at the spectrum analyzer input is superimposed with one of the measured impulse responses at the IF output.

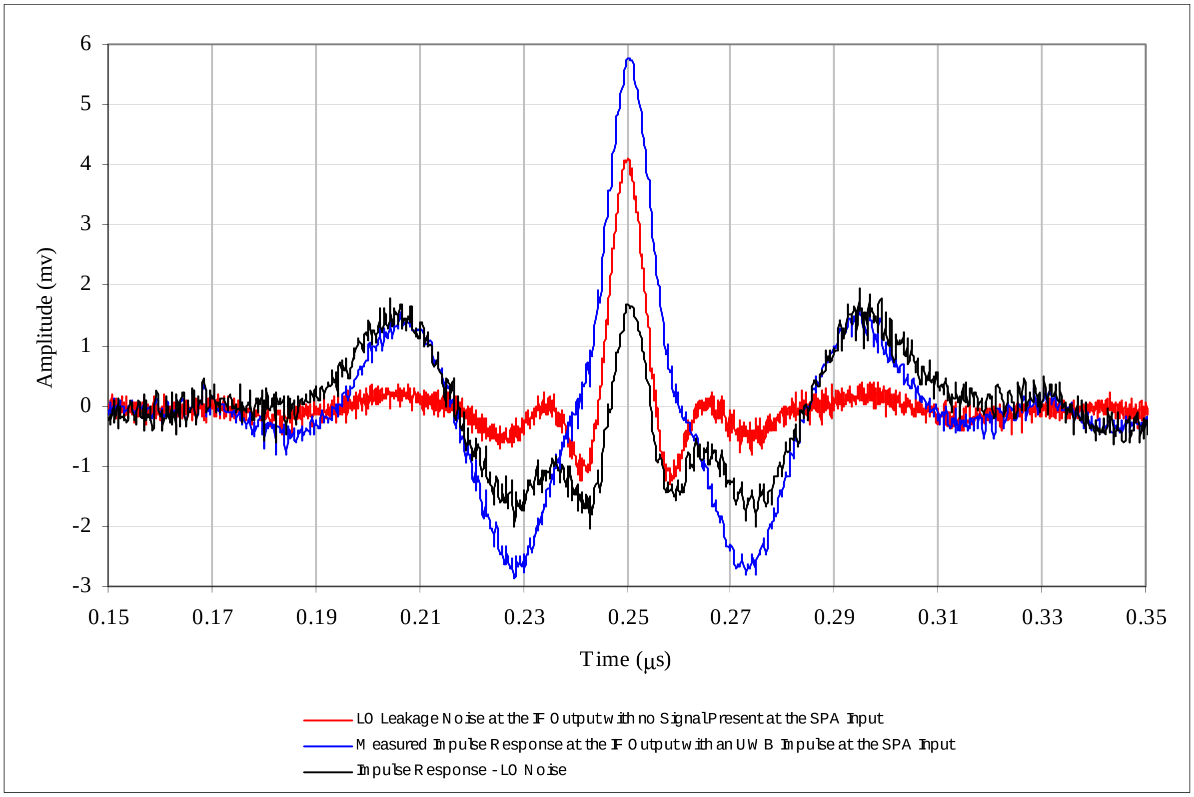


Fig. 6. Spectrum Analyzer IF Output Impulse Response Error Due to Noise

The noise signal at the IF output composes a significant portion of the measured impulse response, adding a lot of error bias to the measurement. A true impulse response would be reasonably symmetric about the x-axis as shown in Figures 1 and 2. Many of the measured impulse responses were not symmetric, and as the input impulse amplitude decreased so did the symmetry of the impulse response waveform. By subtracting the IF noise from the measured waveform a certain amount of symmetry is restored, but the true impulse response peak value is still unknown. The IF output noise signal varies with attenuator settings, RBW settings, reference level settings, and even center frequency (to a lesser degree due to noise floor changes). For the reasons discussed above, measuring the IF output of a spectrum analyzer and/or wideband receiver is not recommended for determining compliance to a band limited peak limit of an impulsive signal. An alternate measurement setup shall be presented reporting Study 3 of this report that will yield a repeatable and traceable impulse response measurement.

Study 2: Radiated Impulse Response

Purpose:

The primary purpose of this study was to investigate the impulse response, both measured and predicted in a radiated setting. The individual objectives were:

- To perform impulse response measurements in a real world environment since the transmit antenna is a key factor in pulse shaping.
- To predict and validate by measurement the peak output voltage of a characterized filter stimulated by a known input function.
- To predict and validate by measurement the peak output voltage of a spectrum analyzer and/or wideband receiver IF output stimulated by a known input function.
- To evaluate a bandpass filter technique versus a wideband IF receiver technique for radiated measurements for repeatability, accuracy, and traceability.
- To predict the absolute peak electric field.
- To develop mathematical relationships for predicting the bandlimited peak electric field, verify the relationship by making measurements, and compute the correlation between prediction and measurement.

Conclusions:

The following conclusions were drawn from this study. The "Detailed Technical Discussion below presents the data and arguments from which these conclusions have been formulated.

- We can predict the output voltage of a known bandpass filter in a bandlimited peak electric field measurement.

- It is possible to predict the general trends of the bandlimited peak electric field using the IF receiver technique. However, the values are not consistent and repeatable due to the large number of variables (*e.g.*, receiver settings, LO leakage, etc.) that change values for every different setting of the receiver (*e.g.*, change in ref level, attn level, center freq, etc.).

In conclusion, it is best to use a known tunable bandpass filter over an IF wideband receiver technique.

Detailed Technical Discussion:

This particular study in many ways is a follow-on to the previous study that was in a conducted environment. To calculate the real electric field strength at a given frequency for a radiated experiment requires a mathematical development of how to correlate the measured voltage at the DSO to the electric field sensed by the receiving antenna. The following section describes that in detail.

Band Limited Time Domain Electric Field Calculations

To calculate the peak electric field of a bandlimited impulse at a receiving antenna we need to apply one half of the Fourier transform pair shown in Equation 3.

$$PulseElectricField(PEF)_{50MHz}(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} PEF_{50MHz}(j\omega)e^{j\omega t}\,d\omega \qquad (3)$$

where: $PEF_{50MHz}(j\omega)$ is the corrected frequency domain pulse spectrum.

The corrected spectrum consists of removing the magnitude and phase characteristics of any cables, receiving antenna, preamps, filters insertion loss, and any other components in the test setup as shown in Equation 4.

$$PEF_{50MHz} = \left(\frac{Pulse(j\omega)\cdot AF(j\omega)\cdot CBL(j\omega)\cdot Fil(j\omega)}{Gain(j\omega)}\right) \qquad (4)$$

where:

$Pulse(j\omega) =$ the measured pulse magnitude and phase voltage spectrum

$AF(j\omega) =$ the antenna factor magnitude and phase spectrum

$CBL(j\omega) =$ cables loss magnitude and phase spectrum

$Gain(j\omega) =$ preamp gain magnitude and phase spectrum

$Fil(j\omega) =$ filter insertion loss magnitude. Only the filter insertion loss magnitude that is constant throughout the passband will be removed.

Another way to write Equation 4 is to separate the magnitude and phase terms in polar notation as shown in Equation 4.

$$PEF_{50MHz} = \left(\frac{r_{pulse}(\omega) \cdot r_{AF}(\omega) \cdot r_{CBL}(\omega) \cdot r_{Fil}(\omega)}{r_{gain}(\omega)} \right)$$

$$\angle\left(\theta_{pulse}(\omega) - \theta_{AF}(\omega) - \theta_{CBL}(\omega) - \theta_{Gain}(\omega)\right) \qquad (5)$$

If we make the assumption that all test setup component variations across a 50 MHz bandwidth are constant then Equations 4 and 5 can be written as:

$$PEF_{50MHz} = \left(\frac{Pulse(j\omega) \cdot K_{AF} \cdot K_{CBL} \cdot K_{Fil}}{K_{Gain}} \right) = \left(\frac{r_{pulse}(\omega) \cdot K_{AF} \cdot K_{CBL} \cdot K_{Fil}}{K_{Gain}} \right)$$

$$\angle\left(\theta_{Pulse}(\omega) - \left(\theta_{AF@50MHz} + \theta_{CBL50MHz} + \theta_{Gain50MHz}\right)\right) \qquad (6)$$

Substituting Equation 6 into Equation 3 we obtain:

$$PEF_{50MHz}(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \left(\frac{Pulse(j(\omega - \theta_{comp50MHz})) \cdot K_{AF} \cdot K_{CBL} \cdot K_{Fil}}{K_{Gain}} \right) e^{j\omega t} d\omega \qquad (7)$$

where: $$\theta_{comp50MHz} = \theta_{AF@50MHz} + \theta_{CBL50MHz} + \theta_{Gain50MHz} \qquad (8)$$

We can move the constants outside of the integral to obtain Equation 9.

$$PEF_{50MHz}(t) = \left(\frac{K_{AF} \cdot K_{CBL} \cdot K_{Fil}}{K_{Gain}} \right) \left(\frac{1}{2\pi} \int_{-\infty}^{\infty} Pulse(j(\omega - \theta_{comp50MHz})) e^{j\omega t} d\omega \right) \qquad (9)$$

The integral part of Equation 9 is the pulse measured by the DSO and by multiplying the peak voltage by the constants in the parentheses we obtain the peak electric field strength of the band limited case as shown in Equation 10.

$$PEF_{Peak\,50MHz} = \left(\frac{K_{AF} \cdot K_{CBL} \cdot K_{Fil}}{K_{Gain}} \right) DSO_{PeakVoltage} \qquad (10)$$

K_{AF} = magnitude of the antenna factor

K_{CBL} = magnitude of the cable loss

K_{FIL} = magnitude of the filter loss at the filter center frequency

K_{Gain} = magnitude of the amplifier gain

Each of the constants in Equation 10 are assumed to be only constant over the 50 MHz bandwidth centered at a frequency measured to be the peak value of the frequency spectrum. The numerical values of these constants will change as the filter center frequency is changed, so care must be taken to determine the insertion loss value of the test setup components, at the filter center frequency.

Total Bandwidth Time Domain Electric Field Calculations

Equations 2, 3 and 4 are the same equations used to calculate the pulse electric field for the broadband case. The main difference between the narrowband and broadband case is that the magnitude and phase, of each test setup component, varies with frequency and has to be accounted for in the Fourier transform. This is a very intensive math and data process and is generally something that compliance labs do not perform. However, it has been found from testing that the narrowband technique yields a rough approximation (about 6 dB) at the peak frequency, with knowledge of the non-bandlimited impulse at the antenna terminals.

Bandpass Filter Impulse Response

As a follow-on to the testing performed using the 50 MHz Bessel bandpass filter, a set of radiated emission tests were performed to compare predicted results with measured results. An UWB source with power density of –41.25 dBm/MHz was placed in an anechoic chamber at 1 and 3 meter distances as shown in Figure 7. The predicted peak voltages were about 5 dB lower than the measured voltages. Differences between the predicted and measured results can mainly be attributed to the waveform shape driving the bandpass filter. In this set of tests, the antenna terminal voltage is assumed to be the same wave shape as measured at channel one of the DSO, shown in Figure 7. The amplitude of the measured waveshape is adjusted according to the gains and losses from the antenna terminals to the measurement channel input. The adjusted waveshape is then used in the prediction calculations. The problem with using the measured waveshape in the calculations is that the measured waveshape is not the waveshape at the filter input. Since the filter is reflective outside of the pass band, any out-of-band energy is reflected back to the input causing distortion to the driving impulse and subsequently to the waveshape measured by the DSO at channel one. Both the prediction and measurement followed the voltage amplitude relationship of 20Log(Distance). At 1 meter the prediction was 90 dBμV/m and the measured was 95 dBμV/m (as shown in Figure 8), and at 3 meters the prediction was 81 dBμV/m and the measured was 86 dBμV/m (as shown in Figure 9). The prediction assumed a constant phase and amplitude variation within the filter pass band. A calibration of the test setup can take into account all of the amplitude and phase variations of the test setup by disconnecting the antenna and injecting a single polarity impulse of known shape. The difference between the measured peak impulse response voltage and the predicted is the correction factor to be added or subtracted, depending on sign, from the measured value during the radiated emission testing.

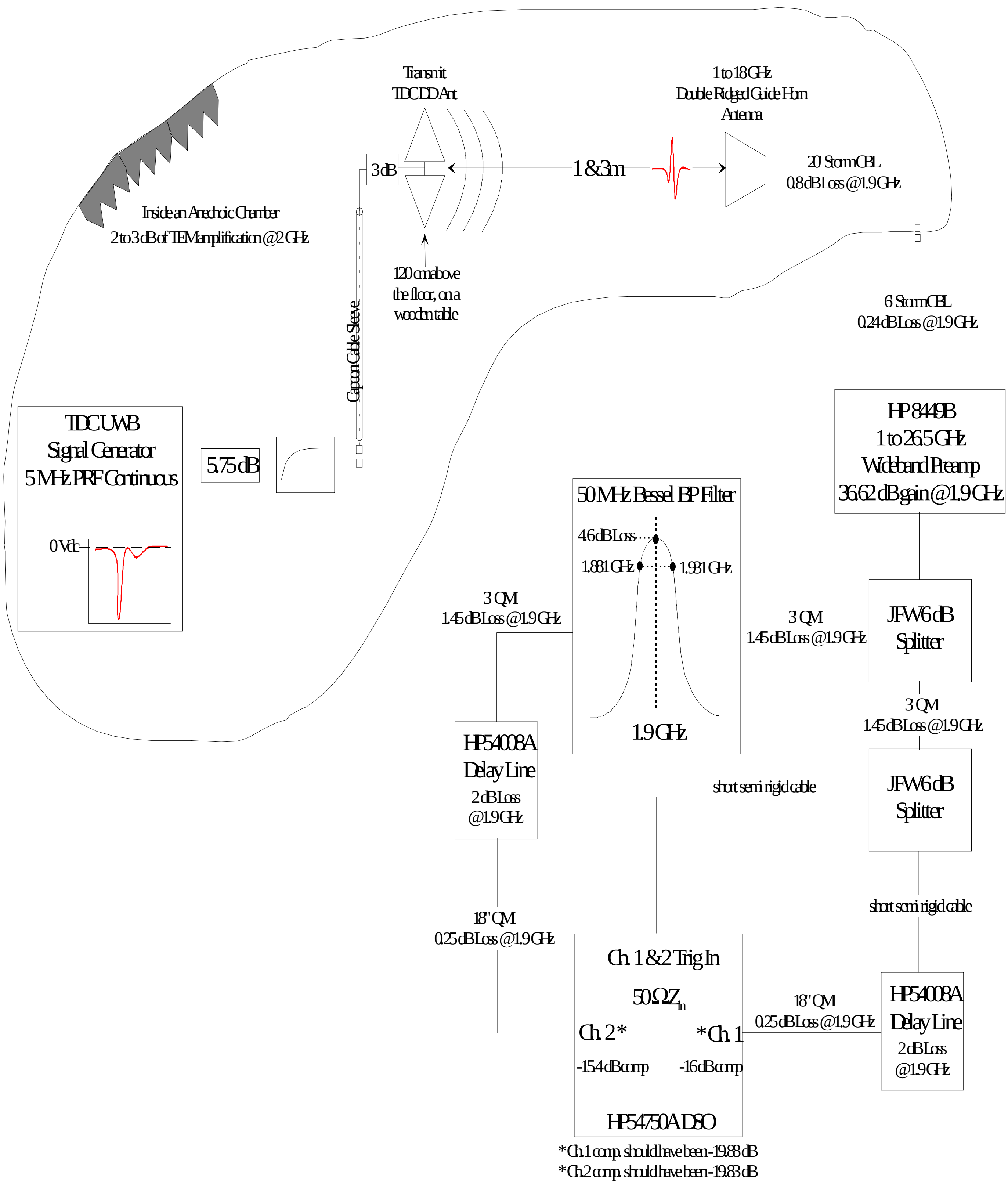
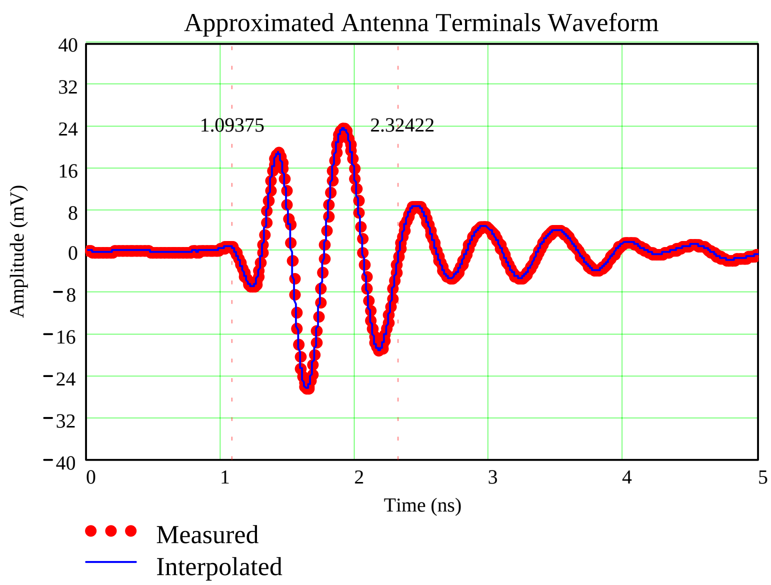
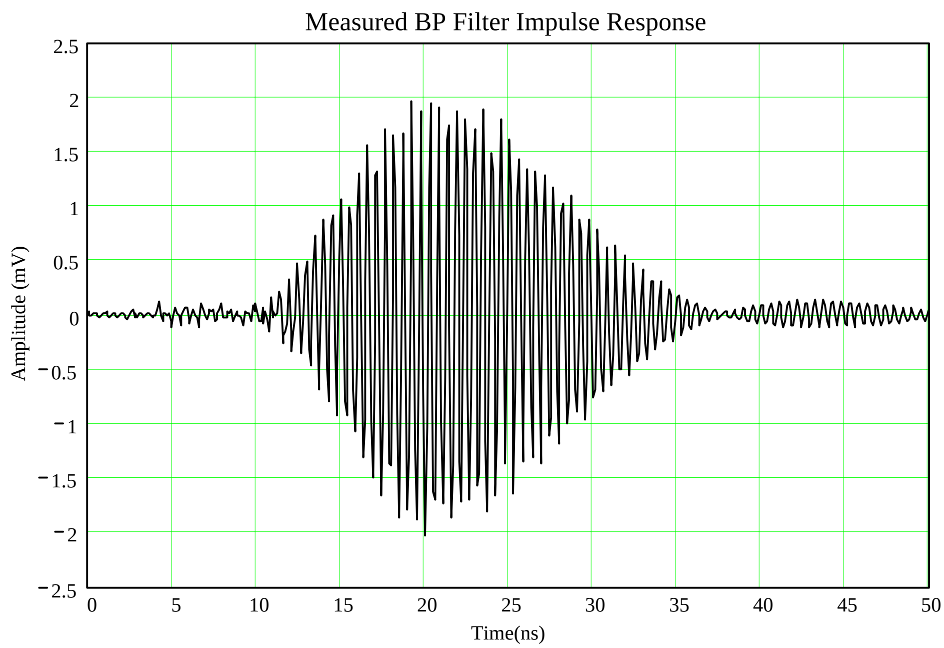


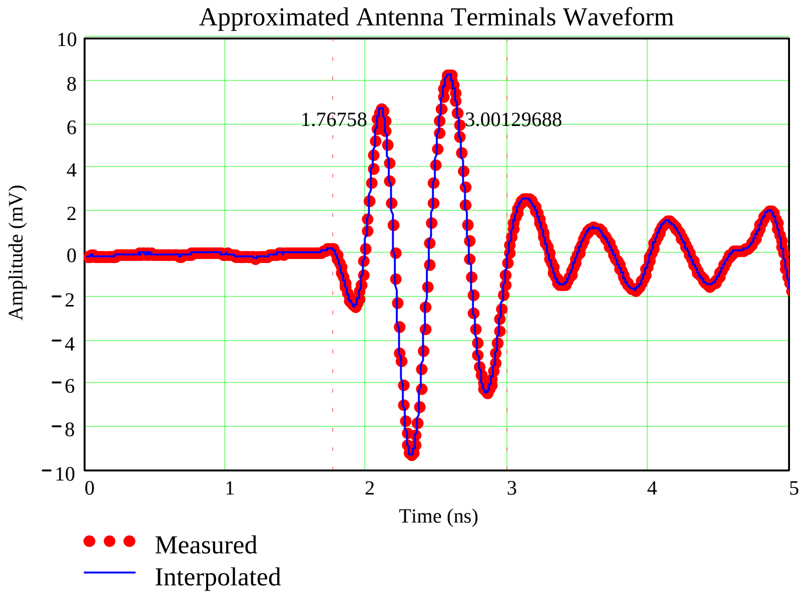
Figure 7. Radiated Electric Field Emission Measurement Setup of a Bessel Filter Band Limited Impulse

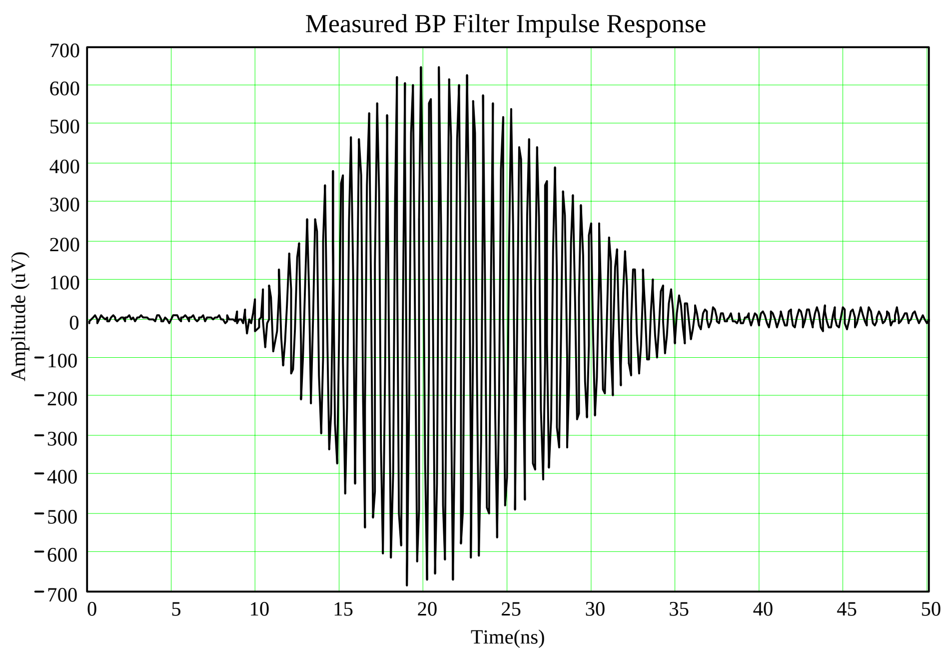




- NPRM 50 MHz Peak 1 meter Limit 84 dBµV/m @ 1m
- NPRM Absolute Peak 1 meter Limit 116 dBµV/m @ 1m
- 95 dBµV/m @ 1m = Measured 50 MHz Peak Electric Field Strength @ 1m
- 90 dBµV/m @ 1m = Predicted 50 MHz Peak Electric Field Strength @1m
- 117 dBµV/m @ 1m = Measured Absolute Peak Electric Field Strength @1m

Figure 8. One Meter Radiated Emission Bandpass Filter Peak Impulse





- NPRM 50 MHz Peak 3 meter Limit 74 dBμV/m @ 3m
- NPRM Absolute Peak 1 meter Limit 116 dBμV/m @ 1m
- 95 dBμV/m @ 1m = Measured 50 MHz Peak Electric Field Strength @ 1m
- 90 dBμV/m @ 1m = Predicted 50 MHz Peak Electric Field Strength @1m
- 117 dBμV/m @ 1m = Measured Absolute Peak Electric Field Strength @1m

Figure 9. Three Meter Radiated Emission Bandpass Filter Peak Impulse

IF Output Impulse Response

Preliminary testing and results suggest that using the IF output of a spectrum analyzer or wideband receiver is not an accurate method for measuring the band limited peak of a radiated impulse. A radiated emission test was performed in order to compare the measurements of an IF output with those using a bandpass filter. An UWB source, PRF of 1 MHz, was placed in a semi anechoic chamber, as shown in Figure 10, 3 meters from the measurement antenna. The spectrum analyzer RBW and VBW were set to 10 MHz to simulate a victim receiver bandwidth larger than the PRF and to detect the peak signal with no averaging. In order to predict the peak output voltage at the IF output an average of three correction factors, determined at 2.0 GHz as listed in Table I, was applied to Equation 2. The delta between the measured, 88 dBμV/m, and the predicted, 79 dBμV/m, is 9 dB, as shown in Figure 11. Due to the correction factor uncertainty, shown in Figure 5, there is a large variance between the prediction and the measurement. In order to determine an accurate correction factor it would have to be determined with the <u>exact</u> same spectrum analyzer or wideband receiver instrument settings and setup that was used during the measurement.

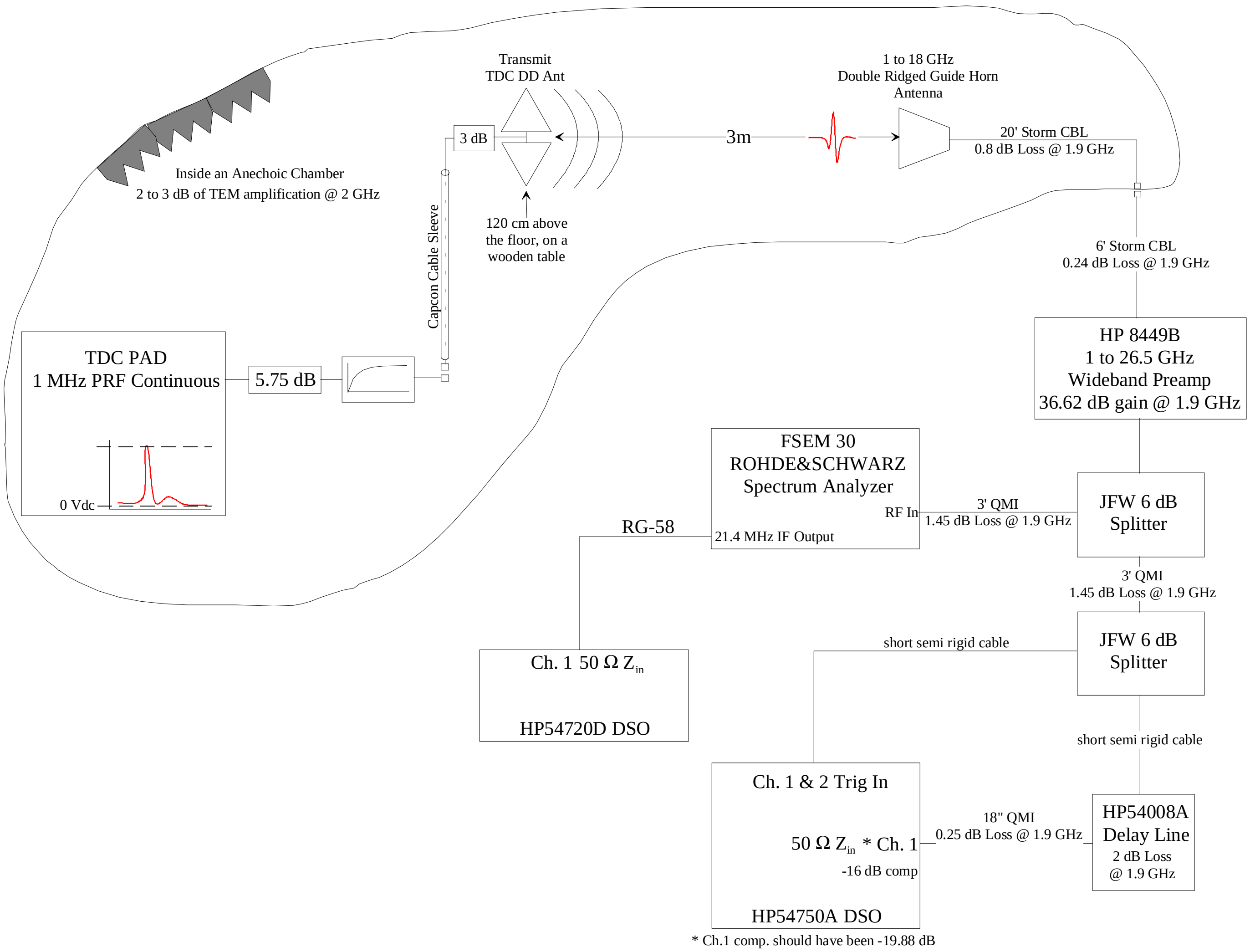
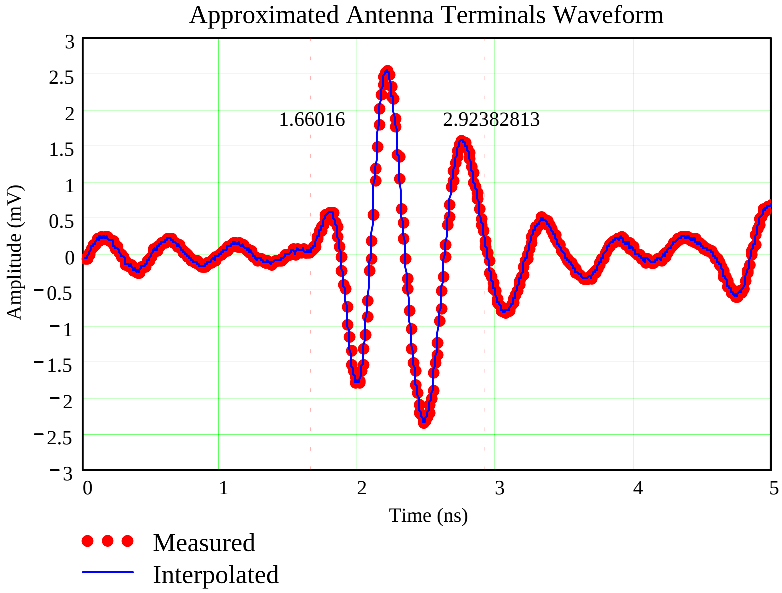
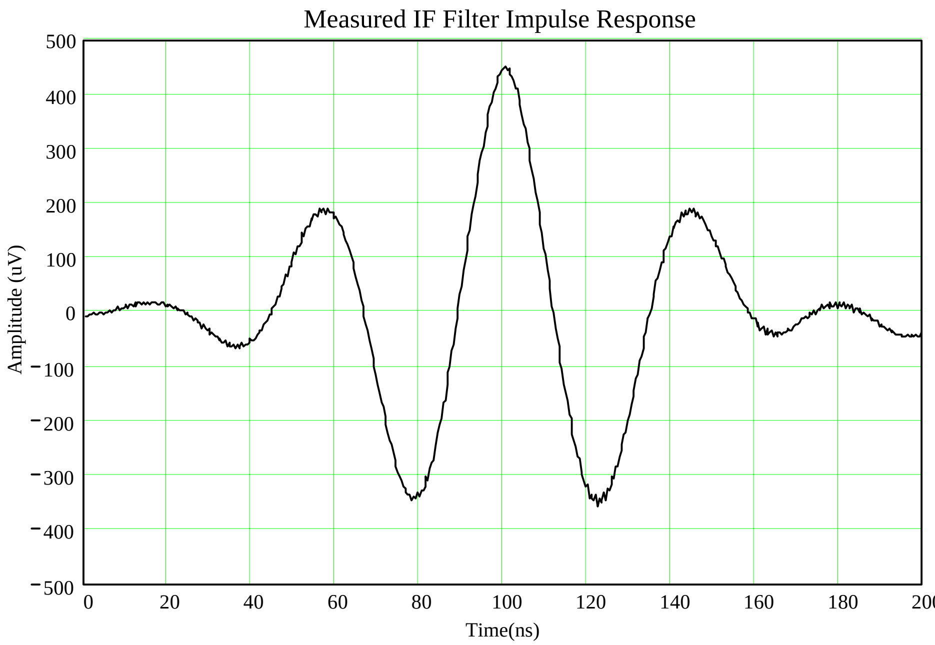


Figure 10. Radiated Electric Field Emission Measurement Setup of a Spectrum Analyzer RBW and IF Processing Chain Band Limited Impulse





- NPRM 50 MHz Peak 3 meter Limit 74 dBμV/m @ 3m
- NPRM Absolute Peak 3 meter Limit 106 dBμV/m @ 3m
- 88 dBμV/m @ 3m = Measured 50 MHz Peak Electric Field Strength @ 3m
- 79 dBμV/m @ 3m = Predicted 50 MHz Peak Electric Field Strength @3m
- 102 dBμV/m @ 3m = Measured Absolute Peak Electric Field Strength @3m

Figure 11. Three meter Radiated Emission IF Output Peak Impulse

Study 3: Suggested UWB Measurement Techniques

Purpose:

The primary purpose of this study was to develop the average and peak measurement techniques for ultra-wideband systems. The individual objectives were:

- To outline the average measurement technique for UWB devices.
- To create and outline the bandlimited peak measurement technique for UWB devices.
- To create and outline the absolute peak measurement technique for UWB devices.

Conclusions:

The following are the conclusions were drawn from this study. The Detailed Technical Discussion below presents the data and arguments from which these conclusions have been formulated.

- One meter separation distances should be used for both average and peak measurements.[3]
- For peak or time domain measurements, antenna heights should be 2 meters above the ground.
- Data from an anechoic chamber is much better than an OATS simply due to reduction in ambient.

[3] This was covered in detail in TDC's opening comments.

- The techniques outlined in this study are reliable, repeatable and also include calibration procedures.

The UWB manufacturer may be best suited for the time domain measurements simply due to on-site equipment (*e.g.*, DSO). Regardless if the manufacturer or a lab performs the peak measurements the tunable bandpass technique is much more cost effective and reliable compared to the wideband receiver.

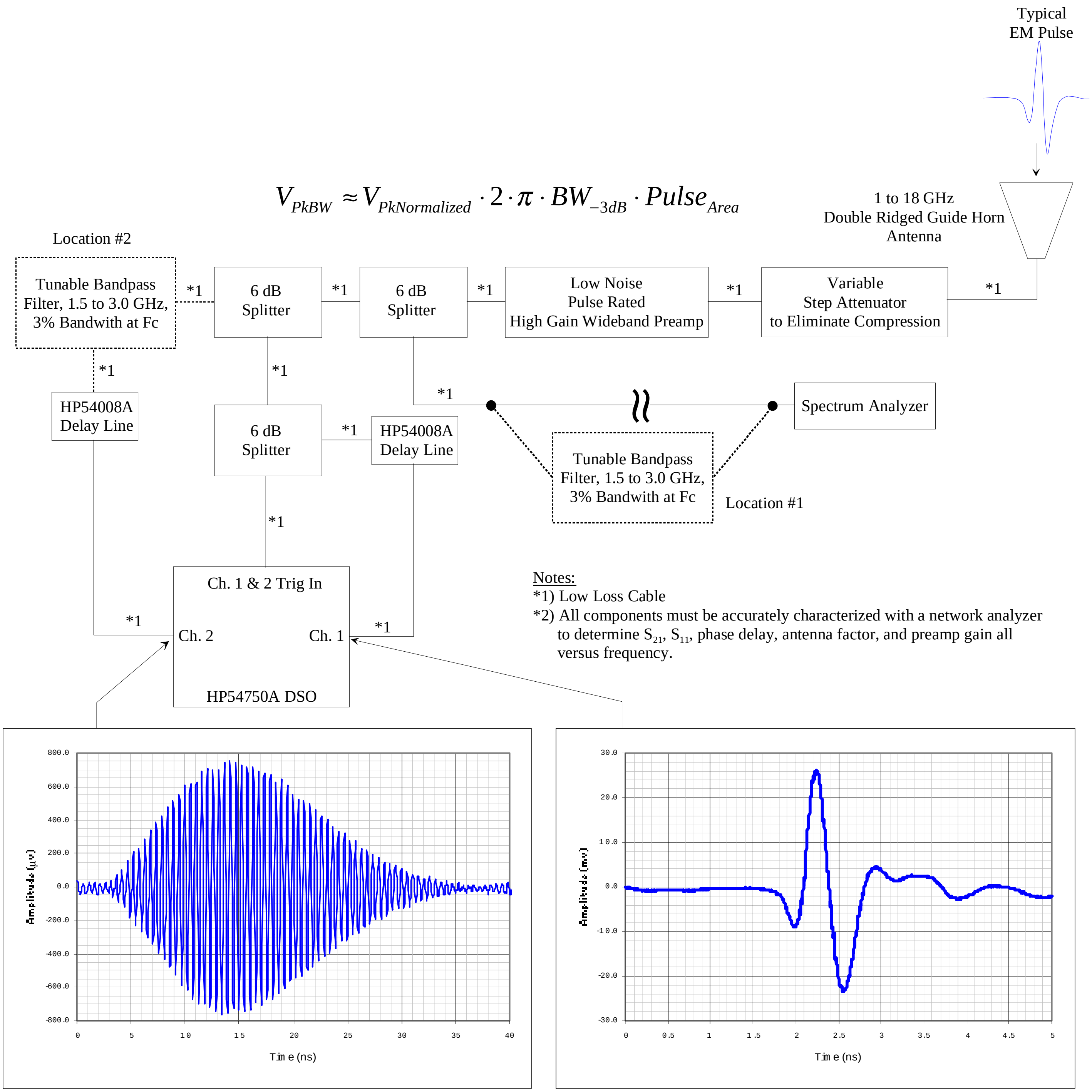
Detailed Technical Discussion:

Recommended Radiated Impulse Peak Measurement Test Setup

Based on the previous test results TDC recommends a modification to the suggested absolute and 50 MHz band limited peak measurement technique. There are three compliance measurements that the NPRM is suggesting for an UWB device: (1) Average electric field strength; (2) peak electric strength measured in a 50 MHz BW; (3) absolute peak electric field strength. Instead of using the IF output of a wideband receiver or spectrum analyzer as the measurement port for a DSO, TDC believes a more accurate, repeatable, and less costly measurement setup, shown in Figure 12, can be achieved by replacing the wideband receiver, at a cost of > $150K, with a $2500 tunable (K&L) bandpass filter. The bandpass filter would have a mechanically adjustable center frequency using a synchronously tuned multi-section filter. The bandwidth about the center frequency is approximately 2.5% of the tuned center frequency, so the bandwidth does change, but a simple correction factor can normalize the filter peak voltage to 50 MHz. With a 1500 to 3000 MHz filter the bandwidth would vary from 37.5 to

75 MHz, which is a –2.5 to +3.5 dB variation in peak voltage with PRFs less than 50 MHz. If a different center frequency range is needed, simply use a different octave bandpass filter. With PRFs less than the measurement bandwidth the correction factor equation is $20Log_{10}$(BW/50 MHz). With PRFs greater than the measurement bandwidth the coded signal appears as noise for both a wideband receiver or bandpass filter and the bandwidth dependence of the measured level follows a $10Log_{10}$(BW/50 MHz) relationship, which is power not voltage. For an uncoded system with a PRF greater than 50 MHz the voltage values do not change versus intercepting bandwidth so again it is the same for the tunable bandpass filter or IF output of a wideband receiver. The setup in Figure 12 can be used to measure the average, 50 MHz BW voltage and absolute peak electric field strength. In previous comments TDC has suggested that the measurement distance be 1 meter due to sensitivity issues. For the time domain measurements it is important to also use a test distance of 1 meter in addition to an antenna height of 2 meters to completely separate the incident and reflected waveforms at the receiving antenna.

$$V_{PkBW} \approx V_{PkNormalized} \cdot 2 \cdot \pi \cdot BW_{-3dB} \cdot Pulse_{Area}$$



$$EField_{PkBW}(dB\mu V/m) \approx AF_{dB} + 20 \cdot Log_{10}\left(\frac{V_{PkBW}}{1 \cdot 10^{-6} \dfrac{v}{\mu v}} \right)$$

$$EField_{Pk}(dB\mu V/m) \approx AF_{dB} + 20 \cdot Log_{10}\left(\frac{V_{Pk}}{1 \cdot 10^{-6} \dfrac{v}{\mu v}} \right)$$

Figure 12. Recommended UWB Peak Radiated Measurement Test Setup

Impulse Calibration

Due to the gain/loss and phase variations versus frequency in a typical emission test setup it is necessary to perform an impulse calibration when making band limited impulse response measurements. A single polarity impulse with short pulse width, with respect to the filter rise time, of known area can be used to stimulate the setup in order to determine a correction factor that accounts for the magnitude and phase variations upstream of the DSO measurement channel. The correction factor is only used for the band limited peak measurement not for the absolute peak measurement. The correction factor can be determined by rewriting Equation 2 as shown in Equation 11.

$$V_{Pk\_corr\_factor} = \frac{V_{50MHz\_Pk}}{2 \cdot \pi \cdot Pulse_{Area} \cdot BW_{-3dB} \cdot Spectrum_{Pk\_PSD\_corr}} \qquad (11)$$

where:

$V_{50MHz\_Pk} =$ Filter impulse response peak voltage measured with the DSO in (volts)

$V_{Pk\_corr\_factor} = K \cdot V_{PkNormalized}$

$V_{PkNormalized} =$ peak value of the normalized low pass filter impulse response. The normalized curves are based on the filter type such as Bessel, synchronously tuned, Elliptic, etc. This term is dimensionless.

$BW_{-3dB} =$ Bandpass filter 3dB bandwidth in (Hz).

$Pulse_{Area}$ = Leading edge impulse area, for each leading edge in (Volt-seconds).

K = IF RF chain gain and bandwidth correction factor. This term is dimensionless.

$Spectrum_{Pk\_PSD\_corr}$ = Ratio of the impulse spectrum peak amplitude to the frequency component amplitude, of the impulse, at the tuned center

The correction factor would be added or subtracted, depending on sign, to the voltage measured during the radiated emission test.

Measurement Overview

The test setup shown in Figure 12 can be utilized to measure the average, 50 MHz peak, and absolute peak electric field strength of an UWB source. Prior to any measurements each individual component of the test setup should be characterized (S_{21}, S_{11}, antenna factor, etc. all versus frequency) across the approximate 20 dB bandwidth of the UWB source. The bandwidth details can be obtained from the UWB manufacturer or conductively measured with a spectrum analyzer at the UWB device antenna output. If the UWB antenna bandwidth is significantly narrower than the measured spectrum then characterization only needs to be performed at the antenna 20 dB bandwidth points. The antenna data can be obtained from the UWB manufacturer. At this point it is a good idea to conductively measure the impulse wave shape and approximate PRF at the UWB antenna output with a high frequency DSO. By measuring the impulse waveform and determining the PRF an insight into the peak and average electric field strength can be obtained.

Now that all losses and gains versus frequency have been obtained, an accurate average electric field strength measurement can be obtained. The test distance should be 1 meter and the antenna height should be approximately 2 meters. Even though ANSI C63.4 requires that the receiving antenna be raised and lowered to maximize the amplitude, the highest field strength will be measured with the receiving antenna aligned on bore sight with the transmitting antenna. The preferable test site is an anechoic chamber with a 20 dB return loss quiet zone around the transmitter and receiving antenna, with the second choice being a qualified OATS.

The average electric field strength measurement uses a 1 MHz RBW and a VBW equal to or less than 0.01RBW or an average detector. Knowledge of the PRF of the signal is critical to understanding the accuracy of the spectrum analyzer measurement and its relationship to the true average in a given RBW bandwidth. If the PRF is lower than the 1 MHz RBW that means that the VBW is going to be a maximum of 1 kHz, which means that the average measurement will read much lower than the average as shown in Figures 13 and 14 for the narrow VBW case. A more accurate way is to use an average detector or screen averaging where the VBW is set to its widest value so as to not limit the RBW impulse bandwidth. The narrow VBW technique can be used to perform averaging when the PRF is larger than the 1 MHz RBW but when the PRF is below the 1 MHz RBW an averaging detector or correction factor must be used to determine the correct average reading. Precautions must be taken to eliminate the possibility of compressing the high gain wideband preamp, hence the need for a variable attenuator between the antenna and preamp, as shown in Figure 12. Additionally all high gain, low noise amplifiers do not possess good impulse response characteristics. If not specifically designed and characterized ("pulse rated") for such service the gain under impulse conditions may be significantly less than the measured CW gain. Worse, other distortions due to internal reflections may also be present. Both of these conditions can provide erroneous results. Using the test setup in Figure 12 and using the information previously discussed will yield repeatable and accurate average electric field strength and $BW_{10\ dB}$ measurements of an UWB radiating spectrum.

The 50 MHz BW and absolute peak measurements can also be performed with the test setup shown in Figure 12. The spectrum analyzer is used to find the peak frequency of the UWB spectrum, as was already done in the average measurement. With the spectrum analyzer at the peak frequency and narrow or zero span the tunable bandpass filter is connected, at location #1, in line with the spectrum analyzer and the filter tuned until a maximum reading is obtained on the spectrum analyzer. The bandpass filter is now tuned to the same peak frequency as the spectrum analyzer. The bandpass filter is disconnected from the spectrum analyzer and placed at location #2, while reconnecting the spectrum analyzer. The DSO is then triggered to capture both the Ch. 1 and 2 waveforms. The data should be saved on disk for future calculations. The correction factor, obtained from performing the impulse calibration, and antenna factor is applied to the measured peak voltage of the bandpass filter output, DSO Ch. 2. The result is the 50 MHz peak electric field strength in dBμV/m at 1 m.

A rough approximation of the absolute peak electric field strength can be calculated by applying the antenna factor to the peak voltage measured at Ch. 1 of the DSO. A more accurate calculation of the absolute peak will require all magnitude and phase variations to be taken account. For a detail explanation of the 50 MHz BW and absolute peak electric field calculations refer to Study 2, paragraphs ”Band Limited Time Domain Electric Field Calculations” and ”Total Bandwidth with Time Domain Electric Field Calculators” of this document, as well as Figure 12.

Study 4: Magnitude versus RBW for Fixed PRF

Purpose:

The primary purpose of this study was to investigate the magnitude values read off the spectrum analyzer for changing resolution bandwidths (RBW) for a constant pulse repetition frequency (PRF) and constant ratio between RBW and VBW. The individual objectives were:

- To understand the difference between the spectrum measurements of coded and uncoded UWB signals.
- To understand the inter-relationship between RBW, VBW and PRF.
- To compare the measured values with established predicted equations.

Conclusions:

The following conclusions were drawn from this study. The Detailed Technical Discussion below presents the data and arguments from which these conclusions have been formulated.

- For a coded system when the PRF<RBW (VBW=0.01RBW), then the displayed magnitude follow a 10 log trend, a noise like signal, which matches the theoretical.
- For an uncoded system when the PRF<RBW (VBW=0.01RBW), then the displayed magnitude is constant, which matches the theoretical.

- For a coded or uncoded system when the PRF>RBW (VBW>=RBW), then the displayed magnitude follows a 20 log trend, which matches the theoretical.

- For a coded or uncoded system when the PRF>RBW (VBW=0.01RBW), then the displayed magnitude does NOT follow either the 10 log or 20 log trend.

Detailed Technical Discussion:

It is important to understand the affect of a spectrum analyzer's RBW and VBW on the measurement results of a UWB impulse signal. Literature such as Hewlett Packard application notes 150-2, 150-4, and Engelson's books, "Modern Spectrum Analyzer Measurements," and "Modern Spectrum Analyzer Theory and Applications," reveal subtleties when using a spectrum analyzer to measure noise and pulsed signals. A pulse that is periodic in nature has a well defined harmonic spectrum relating to its PRF while an impulse that is randomly dithered in time has frequency characteristics that are both noise and pulse like depending on the measuring bandwidth. When measured with a spectrum analyzer, the periodic pulse is displayed in the line spectrum (Fourier Series) mode when the RBW is less than the PRF, and in the pulse spectrum (Fourier Transform of a single pulse) mode when the RBW is greater than the PRF. Two different spectrum analyzer measurements, results shown in Figures 13 and 14, were performed on an uncoded (1 MHz PRF) and coded UWB signal at various RBW and VBW settings.

Uncoded Signal

When the RBW is lower than the PRF for an uncoded system, the display amplitude should not change, regardless of the VBW setting, because the RBW is intercepting individual pulse harmonics, which are periodic. When the RBW is above the PRF, the

RBW intercepts multiple pulse harmonics and the display amplitude varies as $20\text{Log}_{10}(\text{RBW})$. The measured data agrees with the predicted except for the transition region, which is the region close to where the RBW equals the PRF, and when the VBW is equal to 0.01 RBW and the RBW is greater than the PRF. In the transition region, the spectrum analyzer is changing from the line spectrum to the pulse spectrum or vice versa, and the change in display amplitude versus RBW is difficult to predict. The VBW is a low pass filter and performs an averaging function. With a periodic function there is no variation in amplitude over time, so the average equals the amplitude of a single harmonic. However since the VBW is a low pass filter, in series with the RBW, the effective impulse bandwidth of the RBW and VBW combination are much lower than the RBW impulse bandwidth, as revealed in Engleson's book, "Modern Spectrum Analyzer Measurements." Equation 13 shows that the impulse response of a filter is directly proportional to it's bandwidth, and as the bandwidth decreases so does the peak amplitude of the impulse response, as shown in Figure 13.

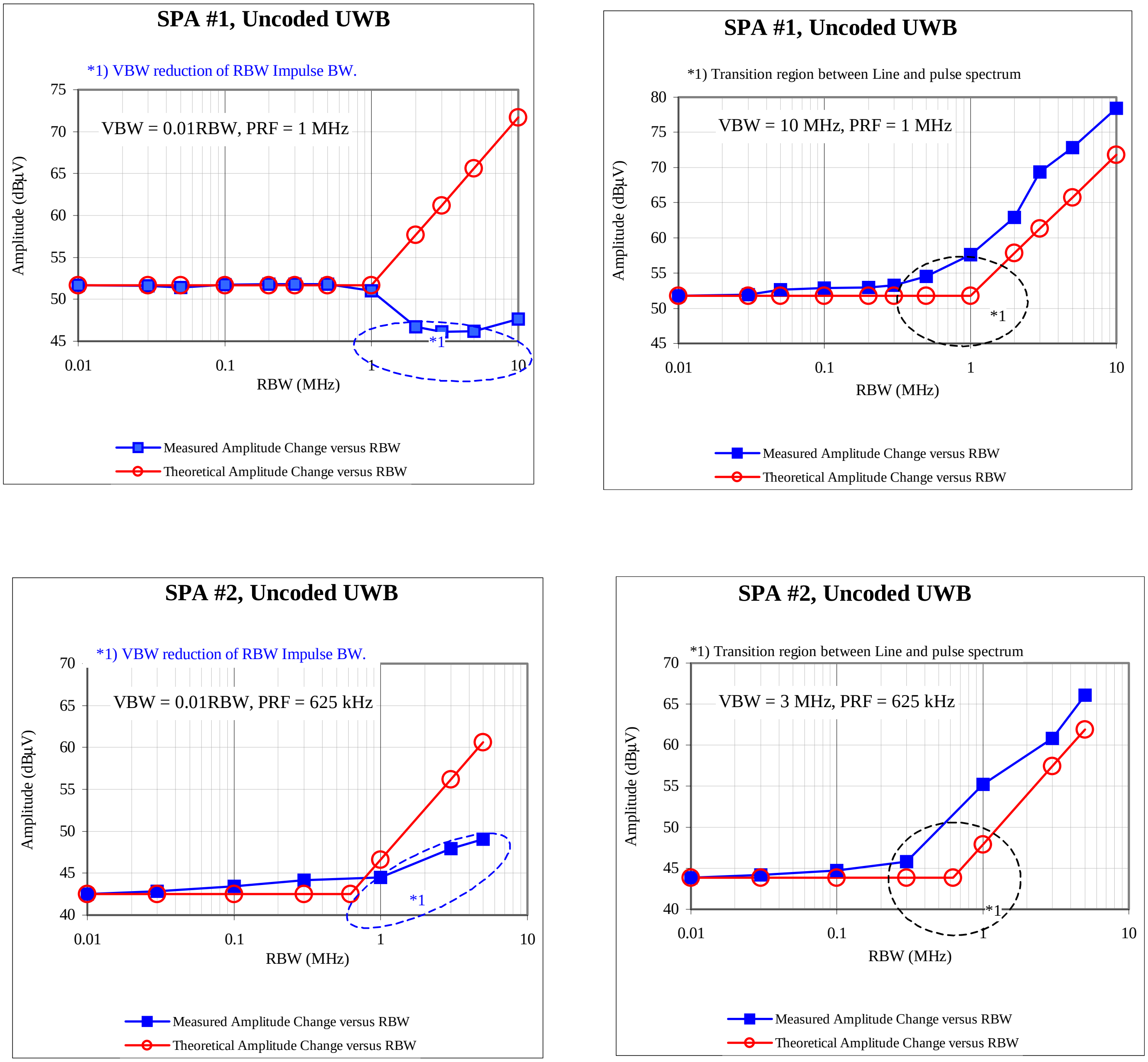


Figure 13. Spectrum Analyzer RBW and VBW Affects on the Displayed Amplitude of an Uncoded UWB Signal

Coded Signal

All trends for the uncoded case are also applicable to the coded case, except for the case of the RBW less than the PRF. Coding refers to the random time dithering of the UWB impulse, which yields a spreading of spectral power in the frequency domain similar to noise. When the RBW is less than the PRF, the UWB signal varies as $10\text{Log}_{10}(\text{RBW})$, which is the same as the noise that would display if measured with a spectrum analyzer. Measurements of a coded UWB signal are shown in Figure 14. If the spectrum analyzer measurement is intended to be a peak measurement, then the VBW should always be set to the widest possible setting so as to not reduce the peak amplitude indicated on the spectrum analyzer. If the spectrum analyzer measurement is intended to be an average measurement, then the VBW should only be used to perform averaging when the RBW is lower than the PRF.

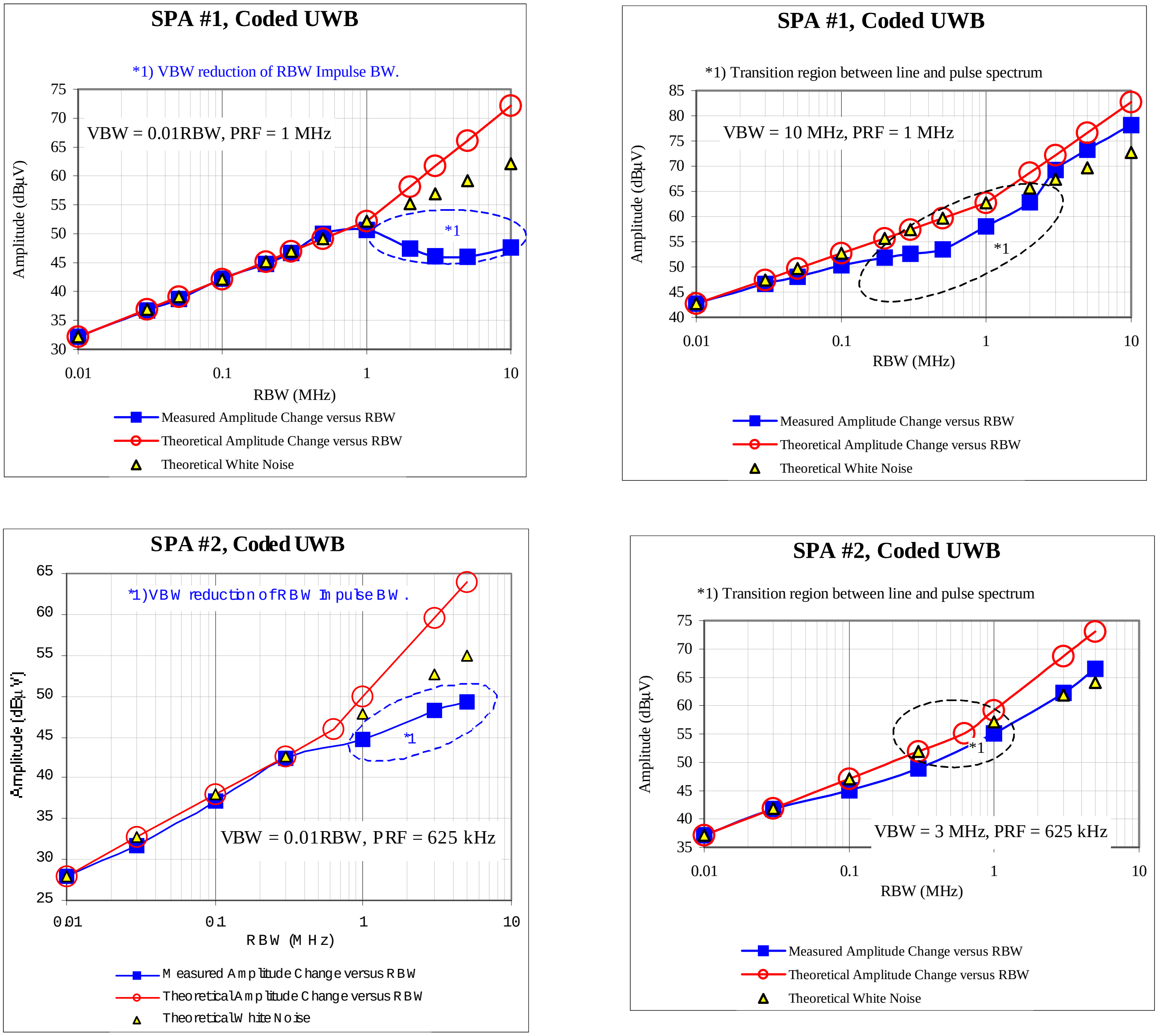


Figure 14. Spectrum Analyzer RBW and VBW Affects on the

Displayed Amplitude of a Coded and Uncoded UWB Signal

Study 5: Radiated Emissions of Multiple UWB Transmitters

Purpose:

The purpose of this study was to understand how a limited number of multiple UWB radiated sources combine for an average spectrum measurement.

Conclusions:

The following are the conclusions that were drawn from this study. The Detailed Technical Discussion below presents the data and arguments from which these conclusions have been formulated.

- The maximum measured combined level was 5 dB for 4 units, versus what would be 6 dB for a 4 white noise units.

- The addition of multiple UWB emitters appears to be like white noise.

Detailed Technical Discussion:

Testing was performed on multiple UWB transmitters to determine how they add in a radiated environment. The test was performed in a semi-anechoic chamber with the metal floor exposed. Testing was performed with 4 UWB signal generators at an approximate 5 MHz PRF. Measurements were made with a spectrum analyzer set to a RBW of 1 MHz and a VBW of 1 kHz, for averaging. The units were measured at 1 and 3 meter test distances with 10 inch separation between the units. The measurements were performed with a single unit, then 2 units, and so forth. A ll the units radiated approximately the same power over the same bandwidth. Each time a unit was added the spectrum analyzer was tuned to the highest emission level. All units were placed on a wooden table together at approximately the same distance from the receiving antenna. If the units were radiating noise, then the combined effect of uncorrelated noise would be approximately 3 dB for the first unit and a total of 6 dB for the 4 units. The maximum measured combined level was 5 dB above 1 unit, which occurred with the 1-meter emission distance. Even though there were a small number of aggregate units, the power seems to add as white noise. Testing is being performed at ARL to determine the aggregate radiated impact on GPS receivers from up to 16 simultaneous UWB transmitters, all radiating at the same approximate PRF and FCC class B level.

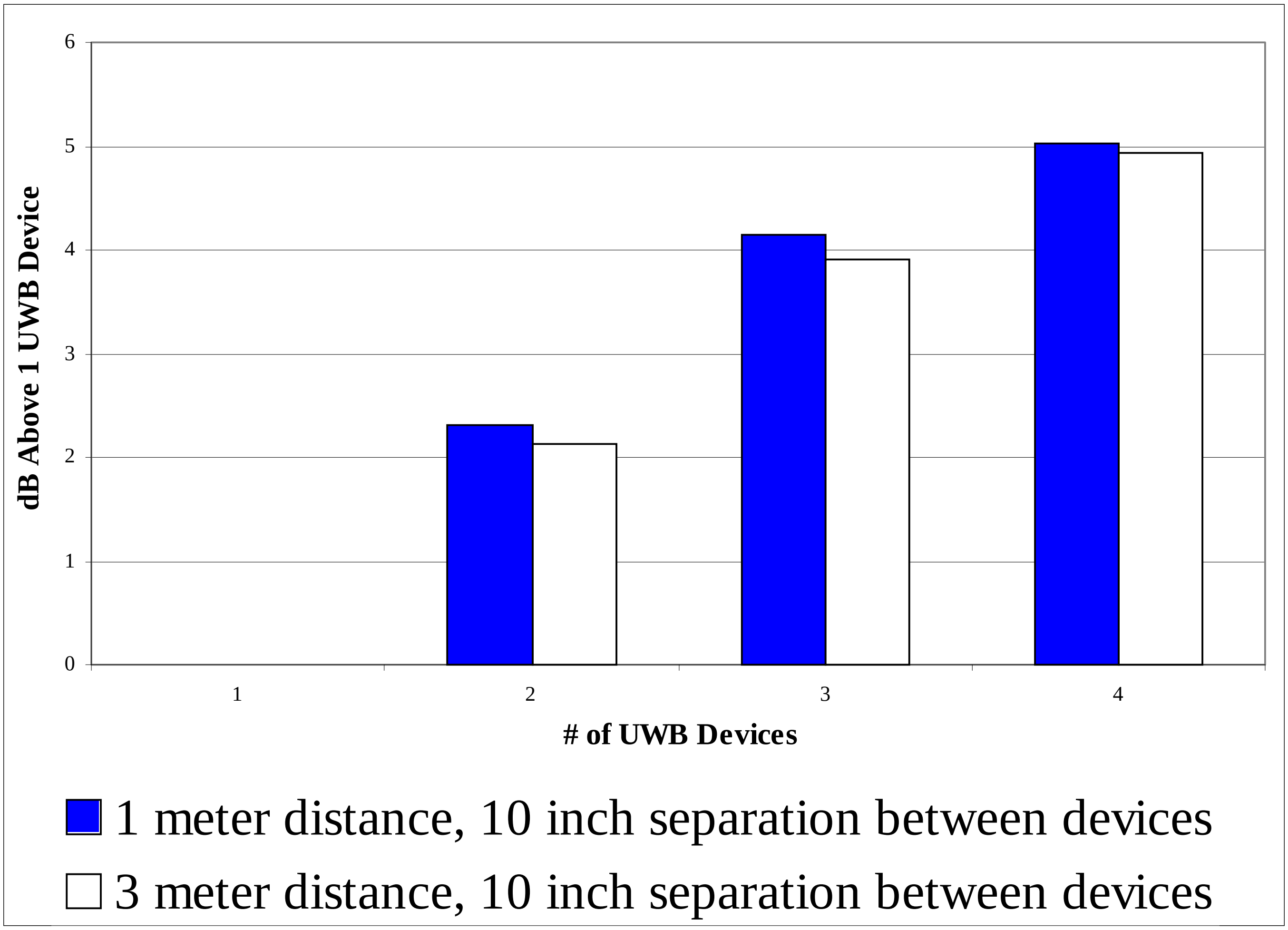


Figure 15. Combined Radiated Emissions of Multiple UWB Transmitters