TEK PULSED SIGNAL SPECTRUM ANALYSIS

APPLICATION NOTE
26W-7044

PULSED SIGNAL SPECTRUM ANALYSIS

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Chief Engineer

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PULSED SIGNAL SPECTRUM ANALYSIS

Introduction

Pulsed signals are always around us. Some are undesired interference, such as stray computer clocks or automotive ignition noise. Other pulses are intended to perform a useful function, such as in radar. In either case, the amplitude/frequency distribution is an important parameter which is easily determined with the spectrum analyzer. A spectrum analyzer is a very versatile instrument for this application because:

- It covers a very wide frequency range from hundreds of hertz to hundreds of GHz.
- The spectrum analyzer can detect small, nanovolt-level signals, and display large, over 80dB, amplitude dynamic range.
- Modern spectrum analyzers contain high accuracy frequency counters with better than 1×10^{-9} frequency accuracy.
- A wide range of resolution bandwidth, from a few hertz to multi megahertz, permits characterization of several millisecond pulse widths down to sub-nanosecond widths.
- Occupied spectrum width or signal bandwidth, spectrum amplitude (also known as spectral intensity), carrier frequency, pulse shape/width via inverse transform observation, carrier on/off ratio, pulse repetition frequency, pulse rise/fall time, signal-to-noise ratio, carrier stability/phase-noise characteristics, presence of carrier fm, peak power level — all can be determined directly or computed from direct spectrum analyzer measurements.

All signals are pulses because nothing lasts forever — there are just long pulses and short pulses. A continuous wave (CW) signal is a long pulse and a zero time width impulse is a short pulse. Neither CW signals nor impulses are physically attainable functions. However, signals can be made of sufficiently long or short time duration to behave as CW or impulse signals with respect to measuring equipment. It should, therefore, come as no surprise that the same signal can appear to be different depending on the type, or setting, of the measurement apparatus.

The theoretical spectrum (or frequency domain description) of pulsed signals is provided by Fourier Mathematics. We use the Fourier series to compute the peak amplitude level of sinewave harmonics of which the pulse train consists (C_n amplitude for n harmonic number). We use the Fourier transform to compute the spectrum amplitude [$S(\omega)$ in volts per hertz of impulse bandwidth], when the pulsed signal appears as a continuous spectral intensity distribution. The crossover between these two aspects of pulsed signals occurs when the pulse repetition frequency (PRF) equals the spectrum analyzer measurement bandwidth. A summary of relationships is provided in Appendix A.

A knowledge of spectrum analyzer impulse bandwidth (Bi) is essential for the accurate determination of spectral intensity amplitude level, as the measurement is in units of volts/hertz, or the dBm equivalent. Spectrum analyzers do not routinely specify impulse bandwidth, and the specified resolution bandwidth has a poor tolerance (usually $\pm 20\%$). Therefore, the impulse bandwidth needs to be measured, computed or otherwise determined as discussed in Appendix B.

With the previous as background, we can now proceed to practical measurements.

1. Accurate Spectrum Definition

The spectrum analyzer is a calibrated measurement instrument. Accurate analytical information will be obtained from a properly used spectrum analyzer. However, an improperly used instrument can mislead as to spectrum shape, let alone spectrum numeric values.

Figure 1 shows a portion of the spectrum of a rectangular pulse train. Lobe width between the markers is near 200kHz (199.9kHz readout), for $1/(2 \times 10^5) = 5\mu s$ pulse width. Figure 2 shows a distorted version of the same spectrum as the resolution bandwidth is switched from 10kHz to 100kHz (lower right readout). The pulse width — bandwidth products are 0.05 and 0.5 respectively. An accurate spectrum shape will be produced for a product $\alpha = t_0 B^* = 0.1$ or less. A fair representation will occur up to $\alpha = 0.3$ as noted in Appendix A. The product $\alpha = 0.5$ of Figure 2 is clearly too much for an accurate analysis of the spectrum.

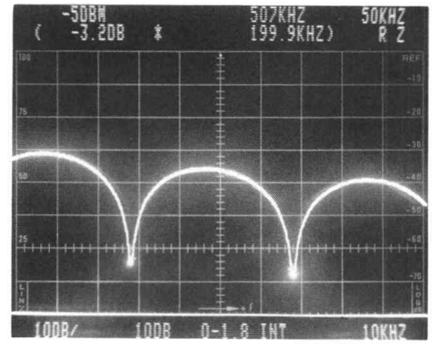

Figure 1. Part of rectangular pulse spectrum. Correct Spectrum analyzer control settings.

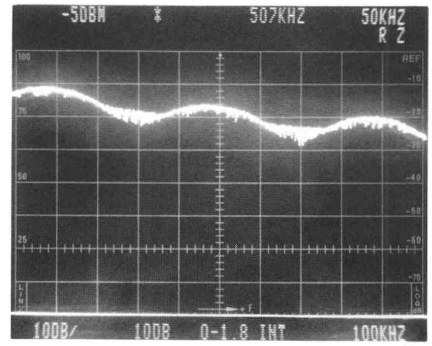

Figure 2. Same signal as for Figure 1, but improper spectrum analyzer control settings.

The $5\mu s$ wide pulse is repeated every 10ms for a 100Hz rate (as shown in the zero span display of Figure 3). This low repetition rate spectrum would usually be displayed on the spectrum analyzer as shown in Figure 4. Each incoming pulse yields a spectrum analyzer response, and the envelope of the lines is the spectrum shape. Changing detector time constants or slowing down the sweep time to increase display density yields the smooth spectrum shape of Figure 1. This is a dense spectrum display because B > PRF, as discussed in Appendix A. The individual lines of Figure 4 do not contain any spectrum information except for pulse repetition frequency (Figure 3). Computation of pulse level or other factors, with the idea that these lines are pulse harmonics, will be in error. Therefore, it is usually best to display the spectrum as a dense, continuous frequency distribution as shown in Figure 1. This eliminates possible confusion, and also makes it easier to identify spectrum features such as spectrum nulls, at which the markers are set in Figure 1.

* Strictly speaking, this should be B_i, the impulse bandwidth. However, the 6dB resolution bandwidth is also frequently used. Most of this paper refers to B, the bandwidth, without indicating which bandwidth.

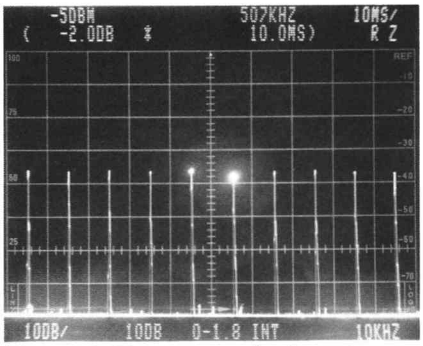

Figure 3. Zero span display of pulse repetition rate intercept lines.

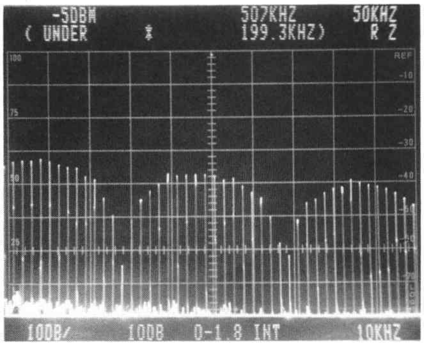

Figure 4. Pulse spectrum showing repetition rate lines.

Individual pulse harmonic lines are not displayed unless the pulse repetition frequency is greater than the measurement bandwidth. This condition is illustrated in Figure 5, where the spectrum analyzer's frequency counter shows a line spectrum spacing of 31.638kHz between the markers. The spectrum outline is unchanged and the nulls are still 200kHz apart, representative of a 5μs pulse. However, exact null spacing is very difficult to determine. A dense spectrum showing sharp nulls, as in Figure 1, makes this measurement much easier.

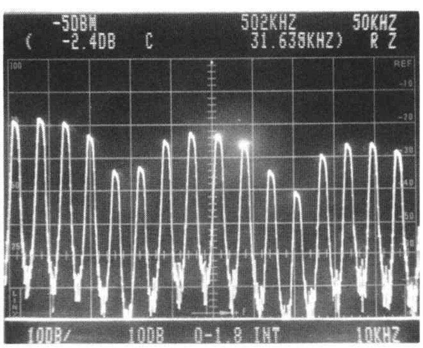

Figure 5. Individual pulse harmonics are observed at B < PRF.

The pulse shape is rectangular, which produces a sin x/x spectrum as discussed in Appendix A. The first sidelobe peak should theoretically be 13.26dB below mainlobe peak for this display. Figure 6 shows a marker measurement of 13.2dB indicating that the pulse train is indeed rectangular, resulting in a sin x/x spectrum shape. A different pulse shape will result in a different spectrum shape as illustrated in Figure 7. The measured 26.8dB main to first side lobe ratio is appropriate for a triangular pulse of sin ^{2}x/x^2 shape.

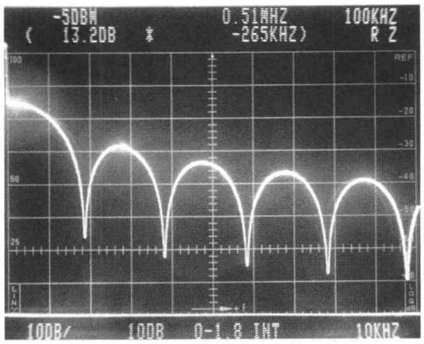

Figure 6. Rectangular pulse shape results in 13.2dB mainlobe to first sidelobe ratio.

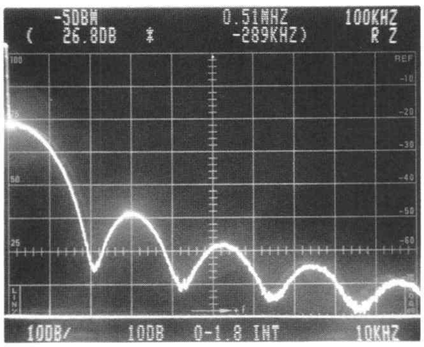

Figure 7. 26.8dB mainlobe to first sidelobe ratio is representative of a triangular pulse shape.

2. Amplitude Measurement

Dense Spectrum

The spectrum amplitude for narrow, impulse-like pulses is measured as a voltage spectral intensity in units of volt/hertz of measurement impulse bandwidth. Impulse bandwidth can be approximated as the 6dB bandwidth, or computed, or measured for greatest accuracy as discussed in Appendix B. For Figure 8, showing a marker amplitude level of −11.2dBm at the peak of a 500MHz pulsed carrier, the absolute spectral intensity level is −11.2dBm −20Log 110.8 = −52.1dBm/kHz, for an impulse bandwidth of 110.8kHz (see Appendix B). The amplitude level per hertz, or kHz, or any other reference unit can be similarly computed. The spectral intensity at other frequencies or in units of volts/hertz is also easily established.

Determination of absolute pulse amplitude, rather than spectral intensity, calls for a knowledge of pulse widths as well as impulse bandwidth (per Appendix A). Pulse width is the inverse of sidelobe width. From Figure 9: t_0 = 1/614kHz = 1.63μs. The display level is −11.2dBm (Figure 8), and the impulse bandwidth is 110.8kHz (Appendix B). From Appendix A, $S(\omega) = B i t_0 A/\sqrt{2}$. Hence: A(dB) + $20\text{Log}\,(110.8 \times 10^3 \times 1.63 \times 10^{-6})/\sqrt{2} = -11.2$. Therefore the peak pulse level is A = +6.68dBm, or 482.5mV in a 50Ω system.*

* The level can be computed from $V^2/R = P$, etc. A simple shortcut is to remember that 1mw (i.e., 0dBm) represents 223.6mV in a 50Ω system.

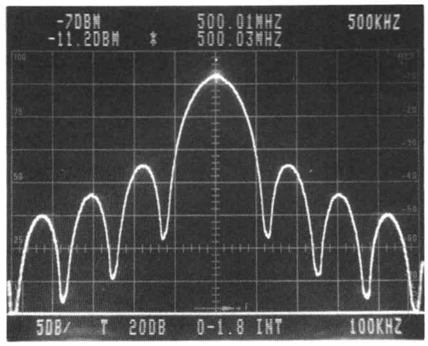

Figure 8. Pulsed carrier, absolute amplitude measurement.

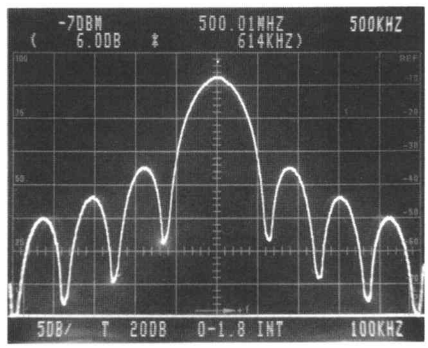

Figure 9. Null to null width determination needed to determine pulse width.

Line Spectrum

A different way of looking at the signal is to display a line spectrum where the pulse repetition rate is greater than the measurement bandwidth. The pulse measurement (resolution) bandwidth has been reduced from 100kHz to 10kHz and pulse rate increased to 75.568kHz as shown by the delta frequency counter measurement of Figure 10. This level of accuracy and frequency resolution is only possible with spectrum analyzers that contain a frequency counter. The carrier, or C_0, line amplitude is −14dBm per Figure 11. Since

$$\frac{\text{Sin}\,(n\pi t_0/T)}{(n\pi t_0/T)} = 1, \text{ as } n \rightarrow 0,$$

then $C_0 = At_0/\sqrt{2}\ T$ per Appendix A. Hence, −14dBm =

$$20\text{Log}\left(\frac{A 1.63 \times 10^{-6} \times 75.568 \times 10^3}{\sqrt{2}}\right);$$

A = +7.2dBm.

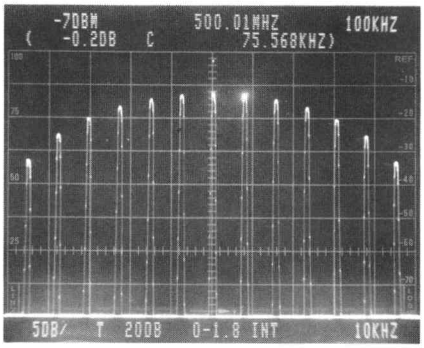

Figure 10. Pulse repetition rate measurement using frequency counter.

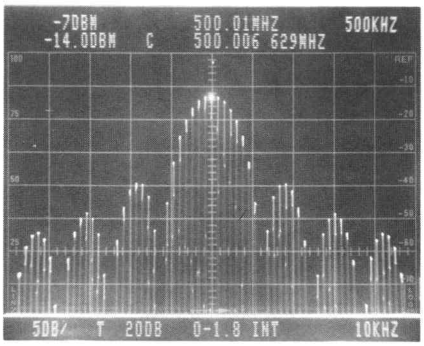

Figure 11. Carrier, C_0, line amplitude measurement.

Errors

This is a difference of 7.2 −6.7 = 0.5dB compared to the previous measurement. Why the difference? Could it be a pulse width error, or a pulse rate error, or an impulse bandwidth error, or an amplitude level error or what? Frequency measurement error is not a good suspect, given counter reference accuracy of 1 part in 10^{-9}. Amplitude accuracy is also an unlikely cause since the two levels are almost identical (−11.2dBm and −14dBm). The difference is traced to resolution bandwidth amplitude switching error between the 100kHz and 10kHz settings. This affects both impulse bandwidth determination accuracy and hence $S(\omega)$ computation, and the −11.2dBm and −14dBm measurements. Subtle errors of this type can have an important impact on accuracy.

Carrier Line

The carrier, or C_0, Fourier line appears in several amplitude considerations. A knowledge of the C_0 level permits computation of the peak pulse level per the previous discussion. It should be clear that the C_0 line indicates the average amplitude, taking into account the pulse train duty factor. Therefore, the average rms level of the pulse train whose peak level was calculated at +7.2dBm, is −14dBm from Figure 11. With a 1.63μs wide pulse repeating at a 75.6kHz rate, the duty factor is 0.12 (1.63 × 0.0756). The C_0 carrier line is also used in carrier on/off determination as discussed next.

On/Off Ratio

Figure 12 shows carrier leakage from incomplete carrier turnoff as the signal is pulsed on and off. The spectrum shape is impossible to observe because the pulse repetition rate is very low and not enough pulses are intercepted during the sweep to display a discernible shape. The only thing we can tell is that carrier leakage shows at −49.6dBm as indicated by the marker readout. Figure 13 shows the spectrum shape built up over time as pulse intercepts are held in memory with the Max Hold function activated. The original display (Figure 12) is also shown recalled from storage in another memory. Tektronix intelligent markers that can measure between memories show an amplitude difference of 29.6dB between the spectrum peak and carrier leakage. From Appendix A, α = to B = $1.63 \times 10^{-6} \times 1.108 \times 10^5$ or, −14.9dB combined with the measured 29.6dB, yields an on/off ratio of 44.5dB.

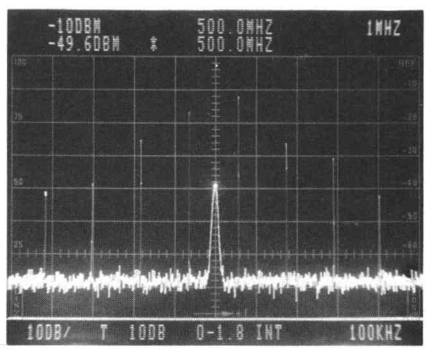

Figure 12. Carrier leakage amplitude measurement.

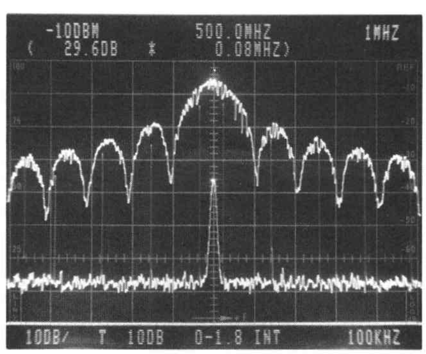

Figure 13. Spectrum peak to carrier leakage amplitude dB difference measurement.

Another variety of on/off measurement is illustrated in Figure 14. Here the carrier leakage is enhanced by video filter and digital averaging the spectrum (lower trace). Spectral intensity level is reduced by duty factor ratio while carrier leakage is not affected. The upper trace shows the undiminished spectrum shape from a 118ns pulsed carrier. We compute αdB = 20Log $118 \times 10^{-9} \times 110.8 \times 10^3$ = −37.7dB. The displayed amplitude difference measures −12.4dB, and the on/off ratio is 12.4 +37.7 = 50.1dB.

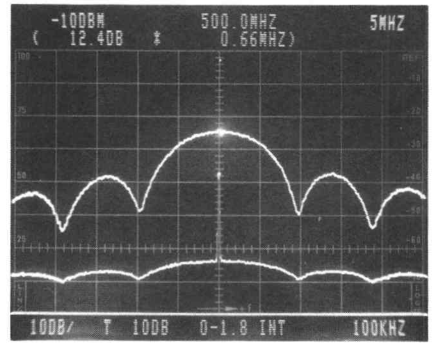

Figure 14. Carrier leakage enhanced by pulsed spectrum averaging.

Squarewave Symmetry

Pulsed spectrum amplitude measurement shows up in various relationships, not always for the need to determine signal level. Consider the squarewave, which on the basis of Appendix A, is characterized by:

$$C_n = \frac{At_0}{\sqrt{2}\,T} \; \frac{\sin(n\pi t_0/T)}{n\pi t_0/T};$$

with t_0/T=0.5,

$$C_n = \frac{A}{2\sqrt{2}} \; \frac{\sin(n\pi/2)}{(n\pi/2)}$$

Therefore, even order harmonics, where n = 2, 4, 6, should be zero since $\sin \pi = 0$ (or multiples of π). Figure 15 shows the spectrum of a 2μs (500kHz repetition rate) squarewave. Even harmonics are near 50dB below fundamental level. That would ordinarily be considered an excellent squarewave. However, symmetry can be adjusted for even better results with the aid of a spectrum analyzer as illustrated in Figure 16. Here, the even harmonics are down even further — specifically, 64.8dB down as measured in Figure 17. The ratio of C_1 to C_2 for a pulsed signal is

$$\frac{2 \sin(\pi t_0/T)}{\sin 2\pi t_0/T}$$

(from Appendix A equations). A ratio of 64.8dB is 1738 times in volts. Consequently, $\sin 2\pi (t_0/T) = 1/869$, and t_0/T = .49982, or within 0.036% of a perfect 0.5 ratio. The spectrum analyzer delta marker not only measures amplitude difference, but also a frequency difference of 451kHz. This shows that the pulse generator setting of 2μs is not quite right — we have a 1/.451 = 2.2μs squarewave.

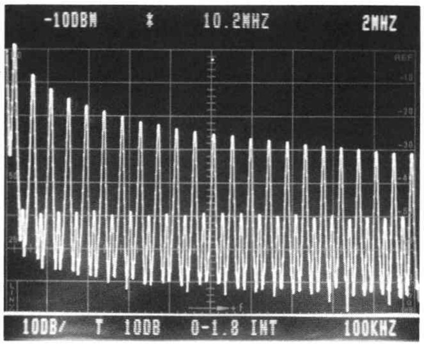

Figure 15. Spectrum of 500kHz squarewave.

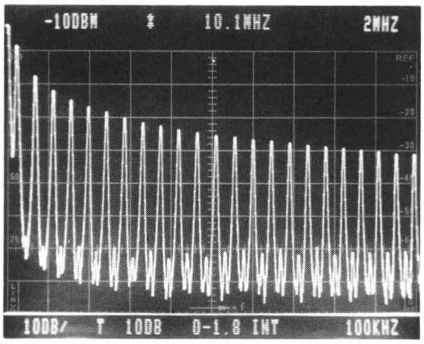

Figure 16. Same as Figure 15 but better symmetry adjustment reduces even harmonics.

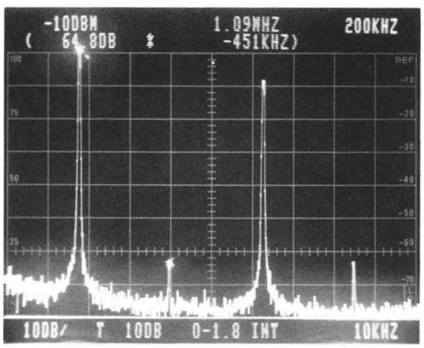

Figure 17. Same as Figure 16. Even harmonics measure 64.8dB down.

3. Frequency Measurements

Pulsed signal amplitude measurement is used for various purposes. Sometimes the need is to obtain amplitude level information, such as spectral intensity level. Amplitude measurement is also used as an indicator of something else, such as squarewave symmetry. The same variety of need applies to frequency information. Spectrum null to null frequency spacing provides information on pulse width. Spectrum line to line spacing provides information on pulse train repetition rate or interpulse time interval. And, of course, the spectrum analyzer is used to determine the frequency of various spectrum features and pulsed carrier frequency.

Frequency measurement technique and accuracy depends on instrument capability. A spectrum analyzer having several megahertz of frequency uncertainty is not a good candidate for precision carrier frequency determination. An instrument without frequency markers requires several measurements, combined with manual computation for frequency difference measurement, compared to a simple determination with delta (Δf) marker capability. Accuracy and technique with a frequency counter is different than without a counter. Most modern spectrum analyzers include markers — therefore, illustrative examples assume the use of markers. Many of the newest instruments also include frequency counters — hence the use of frequency counters for most of the examples.

Pulse Width

The previous sections of this note include many examples of frequency measurement. Figure 1 shows a null to null frequency difference measurement using difference markers; $\Delta f = 199.9$kHz. From this we can establish that the pulse width is $1/.1999 = 5.003\mu s$. This many decimal places is within marker readout accuracy. However, the markers cannot be positioned that precisely within the spectrum nulls. Therefore, all we can say is that we have a $5\mu s$ wide pulse. The frequency counter, assuming this spectrum analyzer had one, could not be used. There is no continuous signal to count because the display is a dense, volts/hertz, spectral intensity distribution. The same pulse repeating at a more frequent rate shows the individual line spectrum of Figure 5. The frequency counter is used to measure the individual harmonic line spacing at 31.638kHz. This is a cycle period of $1/.03164 = 31.6\mu s$. Therefore, for a $5\mu s$ pulse width the duty factor is 0.16.

The delta marker amplitude measurement of Figure 7 shows that this is the spectrum of a triangular pulse. The same marker setting also contains frequency information, showing 289kHz frequency difference between the mainlobe peak and first sidelobe peak. This represents the inverse of 1.5 pulse widths. Hence, $t_0 = 1.5/.289 = 5.2\mu s$. The spectrum width to pulse width relationship applies at the one half voltage width of the pulse. Therefore, the Figure 7 spectrum comes from a triangular pulse, $10.4\mu s$ wide at the base.

A more elaborate analysis involving frequency measurements was discussed in respect to Figures 9, 10 and 11 involving signal level determination. A different but equally subtle aspect of frequency measurement is illustrated below for pulse carrier frequency determination. This technique has many versions depending on type of signal and on whether the measurement is done manually or automated in software (see patent 4,761,604).

Carrier Frequency

Most modern spectrum analyzers, equipped with markers, include various marker shift functions such as "find peak". The marker, originally to the right of center on Figure 18, moves to the largest (middle) line on "peak find" command. The middle line shows as a fraction of a dB larger than adjacent ones at 1dB/div vertical display setting. That, however, is enough for the marker processing routine to find it. The central carrier, or C_0, line could also easily be identified from spectrum symmetry observation. This is important because a small amount of carrier leakage, due to less than perfect on/off ratio, may add out of phase and cause the carrier line to be smaller than adjacent components. The carrier frequency can now be determined to whatever degree of accuracy the spectrum analyzer can measure a CW signal. The accuracy would be especially good if a frequency counter mode is available.

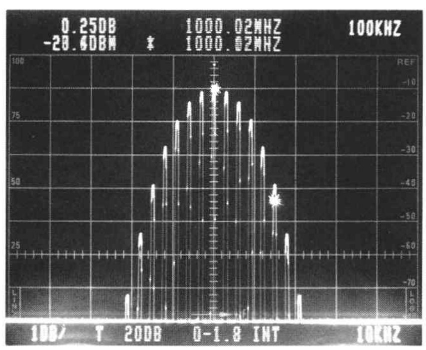

Figure 18. Double exposure showing marker shift to largest (center) line on "peak find" command.

The "find peak" technique only works at relatively large on/off duty factors, even if carrier leakage does not get in the way. The sin x/x function is unity at x = o for the carrier line, and sin x/x is down by 0.1dB at x = 0.26 radians. This is a duty factor of $0.26/\pi = 0.08$. A duty factor of 0.05, representing 20 lines within each side of the mainlobe, gives a C_0/C_1 amplitude ratio of 0.04dB. This indicates that the simple technique of finding the largest line, or easily picking the middle line, will not work much below a duty factor ratio of about 10:1. Such a situation is illustrated in Figure 19. The "find peak" command places the marker somewhere in the center. But we do not really know if this is the C_0 line or one near it. In fact, we could tell which is the C_0 line by observing that the line just to the right of the marker is somewhat lower in amplitude. This is due to out of phase addition of carrier leakage. But you cannot count on this kind of luck in every case. The key to finding the carrier line here is to determine the mean frequency between pulse nulls.

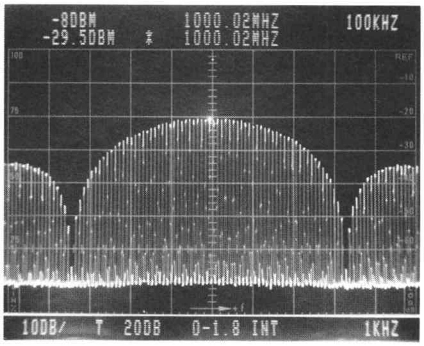

Figure 19. Marker set to find peak for large duty factor.

Figure 20 shows a frequency count of 999.671061MHz for the line closest to one of the nulls. There is no reason why the line should fall precisely on the exact interlobe null. Such a condition would require that the pulse rate and width have an exact integer relationship. However, by picking the lowest amplitude line, we are within at least one-half line spacing from the null. If the two lowest amplitude lines are pretty much equal in amplitude then the null can be assumed to be about midway between these. A similar measurement using the counter is made at the other null. We can now determine the frequency of the middle line to better than half a line spacing. The carrier line is then marked and counted. This is shown in Figure 21 where the exact carrier frequency is counted as 1000.012836MHz. Carrier pickoff prior to pulse modulation falls on top of the counted line, thus showing that the appropriate line was counted. An alternate procedure, taking advantage of a Tektronix intelligent marker algorithm, is illustrated in Figure 22. Intelligent marker manipulation permits marking a signal and then reading a second delta marker at a different frequency location even when the first marker moves off screen. Figure 22 shows a counted frequency difference of 680.103kHz even though the first marker, placed on the lower null, is off screen. The center of the mainlobe should be halfway between markers or 680/2 = 340kHz from the null. This is 1000.354 −0.340 = 1000.14 based on the upper null, or 999.671 + 0.340 = 1000.011 based on the lower null. The measured carrier line at 1000.012836MHz is in the middle. Procedures for automating this process and how to make measurements on more difficult signals is discussed in the reference.

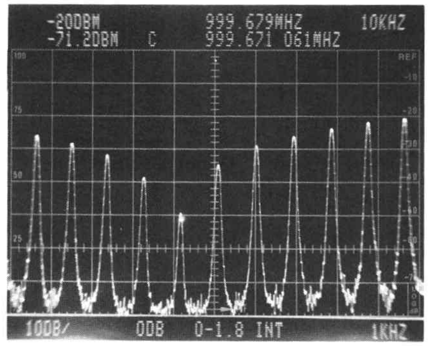

Figure 20. Line frequency measurement at pulse null.

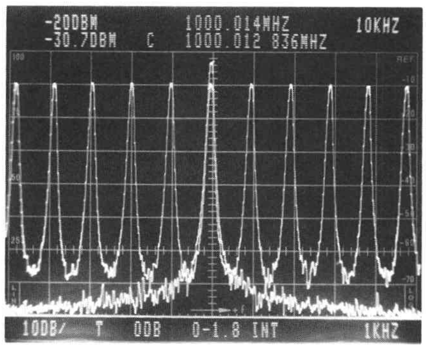

Figure 21. Counting the carrier frequency.

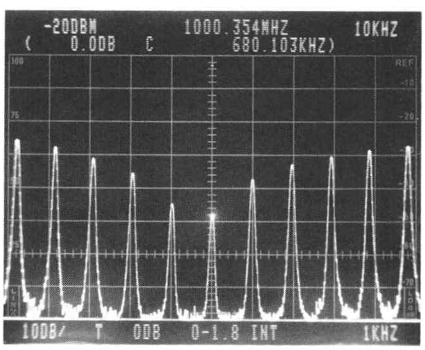

Figure 22. Null-to-null frequency counter measurement.

4. Additional Factors

Spectrum Recognition

The essential pulse signal relationships are provided in Appendix A. Everything else is an elaboration on the basic relationships or description of measurement procedures. Measurement technique or procedure depends on many factors such as available spectrum analyzer features and specifications and personal experience or comfort level. For example, pulse repetition rate frequency can be measured to a high degree of accuracy by setting the resolution bandwidth below the PRF and counting line spectrum spacing, provided the spectrum analyzer includes a frequency counter (see Figure 5). An alternate procedure is to measure pulses per unit time as illustrated in Figure 3. If there is no frequency counter, then one can use the delta markers. If there are no delta markers, then one can read the frequency difference off the frequency span, etc. Additional varieties of measurement technique and signal analysis are provided below.

Tektronix' more advanced spectrum analyzers include a signal recognition algorithm, accessible via the menu shown in Figure 23. The CW mode considers that a CW, or line spectrum signal, will show an outline of the resolution filter. The width of the response on the display is just the ratio of resolution bandwidth and span settings. Hence various prestored signal and marker manipulation programs, such as "find signal peak" or "next lowest" or "next right peak" can choose line spectrum signals and ignore all others. By contrast, the pulse mode does not look for resolution-shaped responses. Here the intent is to find broad spectrum envelope distributions of the sin x/x variety. A "find peak" command will place the marker on the center of the mainlobe. A find next peak to the right command will place the marker on the center of the right sidelobe and not on the next line to the right. The spurious, or spurs, command will respond to any spectrum whether noise or pulse or line, as long as the amplitude is above the chosen threshold. Choice of appropriate signal type will enhance the ease with which desired measurements can be made.

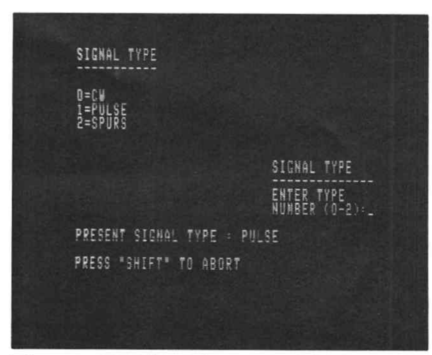

Figure 23. Signal recognition menu.

EMI

Most modern spectrum analyzers have a facility to plot or print the spectrum display. This provides large, page size prints suitable for formal reports. Alternate memory display storage of waveforms, annotation or numeric computation is easily combined with the original spectrum. All GPIB-controlled spectrum analyzers are suitable. Some manual spectrum analyzers have limited plot/print capabilities.

Figure 24 shows a plot of radiated electro-magnetic interference (EMI) compared to FCC specifications. This plot shows specification limits, EMI level, as well as compensation for antenna factor to provide results in units of dB above one microvolt per meter (dBmV/M). Clearly the limit is exceeded below 64MHz as well as a spike at 100MHz. The same spectrum, but without the annotation or spec limit, is shown in Figure 25. Figure 26 shows the result of signal averaging by application of a 3kHz video filter behind the 100kHz resolution bandwidth. The broadband, pulsed spectrum has been reduced with two narrow band (line) spectra remaining. One, at 100MHz, is large enough to have been previously observable. The other one was previously masked by the broadband noise.

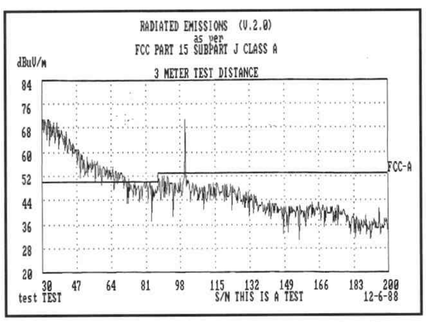

Figure 24. EMI spectrum including limit line and annotation.

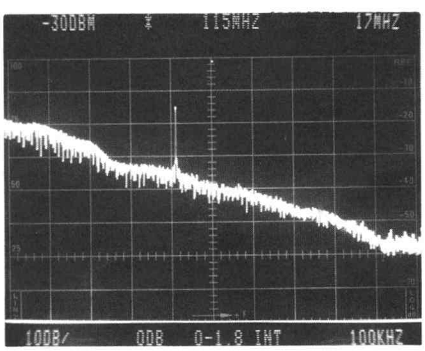

Figure 25. Same EMI spectrum as Figure 24, but without limit line or explanations.

Electromagnetic compatibility (EMC), electromagnetic interference (EMI) and radio frequency interference (RFI) are part of an extensive topic which is beyond the scope of this application note. It is, however, important to recognize that many EMI signals, such as illustrated in Figure 24, are of a broadband pulse signal nature. Measurement is in

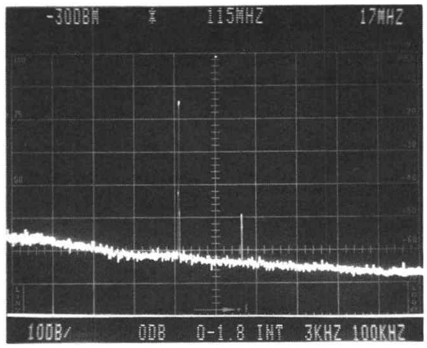

Figure 26. Same EMI signal as Figure 25, but with signal averaging added.

units of volts/hertz, or dB above a microvolt/hertz, or whatever other units may be specified. Strictly speaking, the measurement should be in units of impulse bandwidth, as for any pulsed signal. However, many EMI standards call out the 6dB bandwidth because it is easier to obtain. Also, some EMI standards require that the measurement be performed with a specific bandwidth, such as 9kHz or 120kHz for CISPR. Other specifications permit measurement with a wide range of bandwidths, but the result must be normalized to a specific bandwidth, such as 1MHz. Whatever the special requirements — broadband, impulsive EMI signals behave in accordance with the discussion of Appendix A.

Few Carrier Cycles

Appendix A has been cited several times as the primary reference for a theoretical description of the frequency domain aspects of pulsed signals. However, these equations are sometimes not easy to interpret. It is correct that the modulating pulse shape is the primary determining factor for the spectrum shape of a pulsed carrier. Thus, a rectangular modulating pulse will result in a sin x/x spectrum with the mainlobe centered at pulsed carrier frequency. A triangular pulse will result in a $\sin^{2}x/x^{2}$ spectrum shape, and so forth. However, there are a few factors that are exceptions to the rule. One factor is the number of carrier cycles within the pulse. Clearly, if the modulating pulse is one half of a carrier cycle wide, then the modulated output will be a half cycle sinewave and not the shape of the modulating pulse. Therefore, the resulting spectrum is the shape of the modulating pulse spectrum only when many carrier cycles are within the modulating pulse width. This factor is accounted for by the $\sin[\pi(2f_0 + \Delta f)t_0]/\pi$ ----- $/\pi(2f_0 + \Delta f)t_0$ term in the Appendix A equation. Without this term the result is an ordinary sin x/x. The impact of this additional carrier term is 1% for a pulse width 15 carrier cycles long. Most pulses are hundreds, or even many thousands of carrier cycles long. Therefore, the carrier correction term can be ignored in all but a few exceptional cases.

Carrier fm is another factor that will modify the spectrum shape. Frequency modulation will raise the nulls and sidelobes, and in extreme cases will significantly reduce mainlobe amplitude. Figure 27 illustrates the effect of fm. The lower trace is the usual sin x/x spectrum. The upper trace results from frequency modulation of the carrier. See Modern SA reference for details.

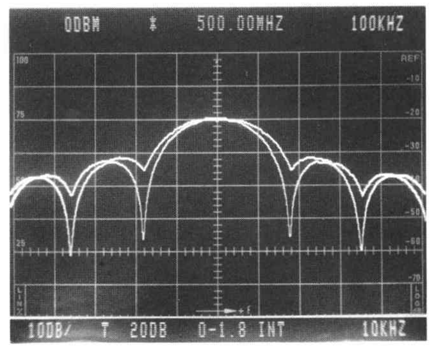

Figure 27. Rectangular pulse spectrum. Expected sin x/x, lower trace. With carrier fm, upper trace.

Digital Storage Bypass

All modern spectrum analyzers now provide digital storage display. This has many advantages, but there are some disadvantages as well. The primary disadvantage is the loss of complicated spectra detail discrimination or gray scale. That is why Tektronix spectrum analyzers permit by-passing digital storage at any span or sweep time setting. Figure 28 shows a digital storage spectrum display which is, at best, confusing. The analog (digital storage by-passed) display of Figure 29 clearly shows the sin x/x pulsed signal spectrum within the higher amplitude wideband spectrum previously masking it.

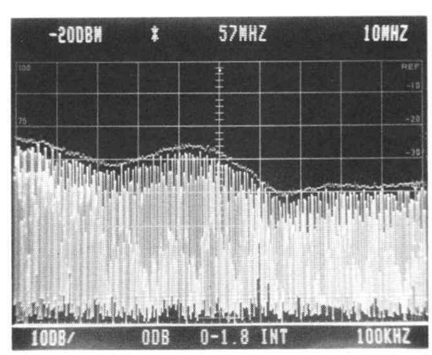

Figure 28. Multiple spectra in digital storage.

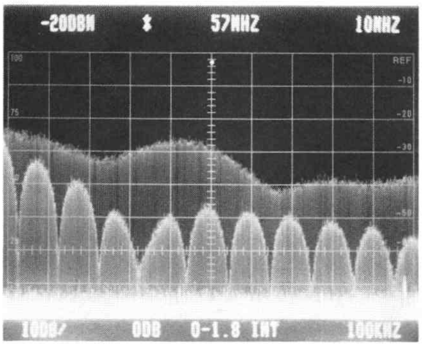

Figure 29. Multiple spectra showing gray scale with digital storage by-passed.

5. Sensitivity

Effect of Resolution Bandwidth

It is generally understood that the best spectrum analyzer sensitivity is obtained at the narrowest resolution bandwidth where the noise level is lowest. This applies to narrowband, line spectrum type, signals. Such is not the case for broadband, spectral intensity distribution measured in units of volts/hertz. A change in resolution bandwidth will change internal noise at the rate of 10LogB. However, the pulsed signal spectrum will change at 20LogB. Hence, best signal to noise ratio, or the sensitivity, will occur at the widest usable bandwidth. Spectrum shape and amplitude accuracy degrades significantly at t_0 B > 0.3 and no useful improvement results beyond t_0 B < 0.1. Therefore, the best setting is at $0.3 \geq t_0$ Bi ≥ 0.1. A 3MHz widest bandwidth will provide best sensitivity down to 30ns pulse widths. Better sensitivity could be obtained for narrower pulses if a wider bandwidth were available. An instrument with a 10MHz widest bandwidth will provide optimum results for pulses down to 10ns. The difference in sensitivity for a 10ns or narrower pulse, between a 3MHz and 10MHz bandwidth, is 10Log10/3 = 5dB.

Display Loss vs CW

Of course, the spectrum display level for a pulsed signal is reduced from the equivalent CW level by $\alpha = t_0$ B. Hence, for a 10ns pulse and 10MHz bandwidth (strictly speaking it should be impulse BW), the loss is 20dB. For a 3MHz bandwidth the display level loss would be 30dB, but the noise level would drop by 5dB, for a sensitivity difference of 30 – 20 – 5 = 5dB. This sensitivity cannot be measured against the usual, averaged noise display level. Averaging a pulse signal drops the display level enormously (see Figure 14). Therefore, the appropriate factor to consider is the peak displayed noise level, about 10dB above the specified averaged noise sensitivity. For example, if the usual sensitivity is specified as −125dBm for the narrowest (100Hz) filter then for the widest (3MHz) filter the noise level is $-125 + 10\text{Log}3 \times 10^6/100 = -80$dBm; adding 10dB for peak noise level and a signal display loss for a 10ns pulse of $20\text{Log}3 \times 10^6 \cdot 10^{-8} = -30$dB, yields a sensitivity of −80 + 10 + 30 = −40dBm.

6. Narrow Pulse Considerations

Narrow or wide, a pulse is a pulse. The theory discussed in Appendix A is equally applicable. Nevertheless, measurement limitations and applicable procedures are affected. One example is the loss in display level, and consequent temptation to increase input amplitude to compensate, as discussed in the previous section. Costly repair bills for destroyed input circuits are a consequence of forgetting this factor.

Narrow pulse spectra are best measured with a spectrum analyzer that has a wide resolution bandwidth. The wider the bandwidth the better, as long as the tB product does not exceed 0.3, as discussed previously. The widest resolution spectrum analyzer currently (1989) available is the Tektronix 2782, with 10MHz. The following illustrates pulsed signal measurements using a wide bandwidth spectrum analyzer.

Figure 30 shows the gain in display amplitude from using a 10MHz bandwidth filter. The lower trace, using a 1MHz filter width specification, is 19.1dB below the upper trace using a 10MHz wide filter. An exact 10:1 impulse bandwidth ratio would show a 20dB difference. The pulse width is about 25ns based on 40MHz (2 divs at 20MHz/div) sidelobe width. This represents a 0.25 pulse/bandwidth product at the 10MHz setting, just within the 0.3 maximum for acceptable spectrum shape definition.

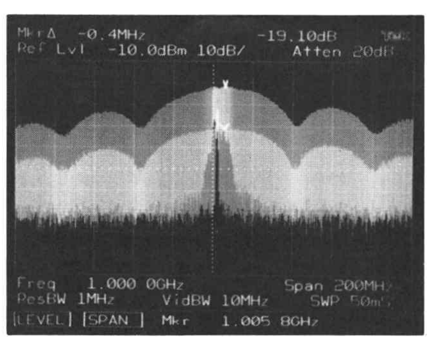

Figure 30. Display dynamic range improvement from use of 10MHz resolution bandwidth compared to 1MHz bandwidth.

Figure 31 shows that the 1GHz carrier is modulated with a rectangular pulse, based on a main/side lobe ratio of 13.2dB, as predicted by theory. Note that the marker has not been set precisely at the center, or highest point, of the mainlobe. This is because the rise in the center is due to carrier feedthrough due to poor on/off ratio. The narrower the modulating pulse, the more likely that the modulator will exhibit some carrier leakage. However, this need not affect the accuracy of the measurement. Change of amplitude in the vicinity of mainlobe peak is insignificant. Sin x/x = 1 at x = 0, while sin x/x = 0.998 at x = 0.1 radians. Measurement accuracy is not affected by moving the marker slightly off center.

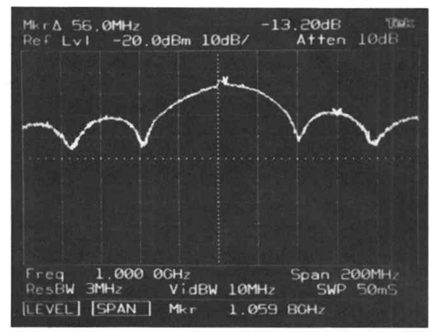

Figure 31. 13.2dBc main to sidelobe ratio indicates a rectangular modulating pulse.

Reading sidelobe width (and consequent pulse width determination) directly off the span is not very accurate. Using the markers, Figure 32 shows a sidelobe width of 37.4MHz, or a 1/37.4 = 27ns pulse width rather than the 25ns used before.

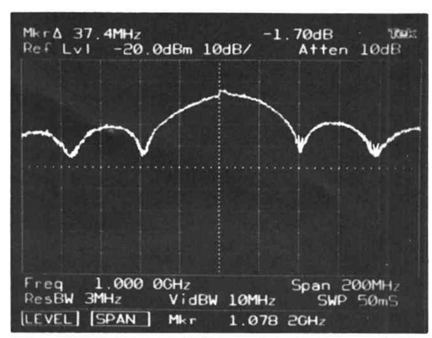

Figure 32. 37.4MHz sidelobe null to null spacing indicates a 1/37.4 = 26.7 ns pulse width.

Figure 33 shows the spectrum of an even narrower pulsed carrier. At 50MHz/div the sidelobe is 100MHz wide as measured with the markers, for a 10ns pulse width. The displayed amplitude changes by about 10dB for a bandwidth change from 10MHz to 3MHz, as it should (20Log10/3 = 10.5dB). Clearly the signal can be observed with both bandwidths, 3 and 10MHz. However, there is very little dynamic range to spare. Figure 34 shows a mainlobe peak to sensitivity noise level ratio of only 35.4dB using the 10MHz bandwidth. Dynamic range gets worse at narrower bandwidths because signal display level changes at 20LogB, while noise level changes at 10LogB.

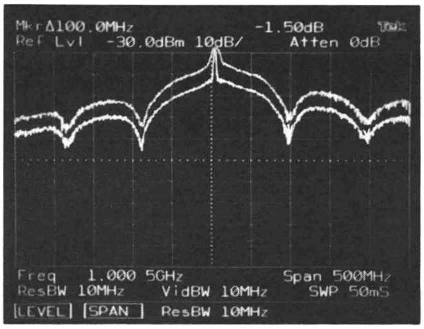

Figure 33. 100MHz delta marker measurement between sidelobe nulls indicates a 10ns pulse width.

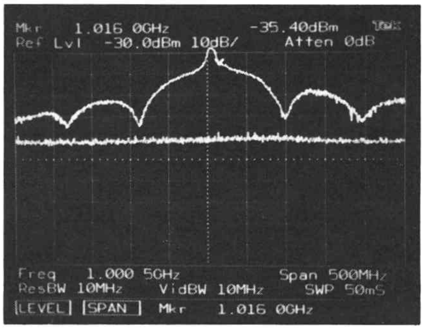

Figure 34. Internal noise level to mainlobe peak level is 35.4dB. This is the measurement dynamic range at 10MHz resolution bandwidth.

Figure 35 shows the ease with which basic measurements (such as on/off ratio) can be performed with the 2782. The pulse width is 20ns and the bandwidth is 10MHz, yielding a dB product of 14dB. Adding the display difference of 18.3dB, measured with the markers, shows an on/off ratio of 32.3dB. However, the impulse bandwith is not really 10MHz. A separate measurement shows it to be 5.7MHz, hence the on/off ratio is 20Log5.7/50 – 18.3 = –37.2dB.

One of the unique capabilities of the 2782 is to provide an analog display of detected/demodulated signals from the 10MHz resolution bandwidth. Figure 36 shows the spectrum from a 1/1.2 = 0.83μs pulsed carrier. Figure 37 shows the detected modulating pulse in linear vertical display mode. At 300ns/div, and 1.5 divisions at the mid point, the detected pulse is 7.5ns wide.

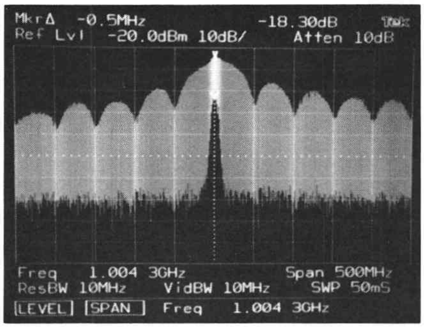

Figure 35. On/off ratio measurement.

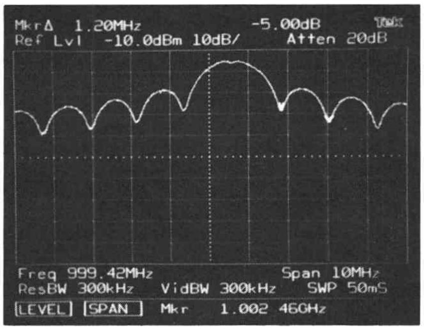

Figure 36. 1.2MHz sidelobe width indicates an 830ns pulse width.

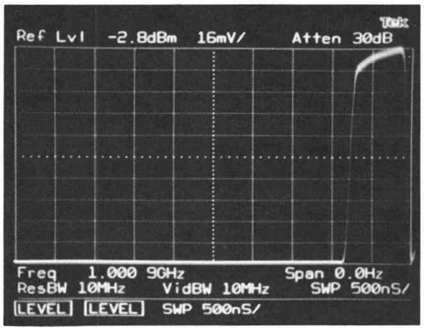

Figure 37. Spectrum detector at 10MHz resolution setting shows the modulating pulse in direct display analog mode at 500ns/div sweep time.

Dynamic Range

It is useless to increase the input level beyond the front-end gain compression point, because the measurements will be in error. Going significantly above this point may cause costly mixer damage. Never increase the input level in order to increase display level without some idea of $\alpha = t_0B$ loss. The best dynamic range will be obtained by optimizing the measurement within the following four factors.

– Basic sensitivity, specified as an averaged noise level.

– Loss in sensitivity due to inability to average the noise when viewing pulsed signals. This is approximately 10dB, the peak to average displayed noise level ratio.

– The ratio of input to display level for pulsed signals, $\alpha = t_0$ Bi. At best this loss is 10dB for $\alpha = 0.3$. For best spectrum shape definition α should be close to 0.1, yielding a 20dB loss. Note that this loss increases for very narrow pulses because the resolution/impulse bandwidth is not wide enough to provide an optimum α product of 0.1 to 0.3.

– The front-end compression input level, usually limited by a mixer capability of between 0dBm and –10dBm.

The procedure for determining pulsed signal dynamic range is illustrated for the coaxial input of the Tektronix 2782 spectrum analyzer. The needed specifications are:

Frequency To:	6.5GHz	21GHz	28GHz	33GHz
Sensitivity @ 10Hz BW	–132dBm	–125dBm	–120dBm	–107dBm
Input gain compression	0dBm	0dBm	–3dBm	–6dBm

The 6dB resolution bandwidth can be varied in 1, 3, 10 steps from 3Hz to 10MHz. Therefore, no matter what the pulse width, the product can always be set between 0.1 and 0.3, down to 30ns wide pulses. The α product is 0.3 for a 30ns pulse in combination with the widest, 10MHz filter. The product is reduced and display loss increases at narrower pulses. Accurate display loss calculations call for the use of the impulse bandwidth, rather than the resolution bandwidth. Usually the impulse bandwidth is close in value to the 6dB bandwidth, except for the widest filters. These can be significantly narrower due to display system, video bandwidth, and peak level sample and hold limitations. For the 2782 the impulse bandwidth for the 10MHz filter is only about 5MHz. This represents a 6dB additional loss for narrow pulses (20Log2 = 6dB).

Noise level changes at 10LogB, hence, the wider the bandwidth the worse the sensitivity. A sensitivity noise level of –125dBm at 21GHz for a 10Hz filter, is the same as –105dBm for 1kHz, or –75dBm for 1MHz bandwidth. However, the sensitivity for pulsed signals will be 10dB worse in every case because the video or display bandwidth can not be restricted for noise averaging. A low video bandwidth also cuts the impulse bandwidth. Thus, for a pulsed 21GHz signal the basic sensitivity is –95dBm using the 1kHz bandwidth, or –65dBm for the 1MHz bandwidth, and so forth.

It is clear from the foregoing that sensitivity noise level is worse for pulses than for CW signals. The opposite applies to gain compression. Many factors contribute to signal compression/limiting. Some of these factors are pulse rate and/or width dependent. Hence, gain compression is usually less severe by a few dB to over 10dB when measuring low duty cycle pulses. For approximate calculations, therefore, it is simplest to assume a constant gain compression level, in this case 0dBm, unless there is a significant variation with frequency.

We now have sufficient information to compute dynamic range expectations, as follows:

– A 0.1ms pulse width signal needs to use either the 3kHz or 1kHz filter for a 0.3, or 0.1 product. The display loss, at 20Log, is 10 to 20dB. The maximum input level is 0dBm (mixer compression), hence the display is between −10 and −20dBm. Pulse signal sensitivity is −95dBm for the 1kHz bandwidth, and 10Log3 = 5dB worse at a 3kHz bandwidth. The expected dynamic range is 95 – 20 = 75dB, and 90 – 10 = 80dB. At 33GHz the specified sensitivity is 120 – 107 = 13dB worse than at 21GHz, all else is unchanged. The dynamic range for the 100μs pulse is between 67 and 62dB, and most likely toward the low side because we've taken some liberties with the gain compression. A similar procedure can be used at all frequencies and pulse widths down to 30ns. The result is a straight line relationship on a logarithmic frequency scale.

– Conditions change at 30ns because the resolution filter bandwidth can no longer be increased to maintain an optimum pulsewidth-bandwidth product. At 21GHz the pulse sensitivity is −55dBm for the 10MHz bandwidth. The impulse bandwidth is about 5MHz and the display loss is 20Log (30ns × 5MHz) = −16.5dB. The dynamic range for a 0dBm compression point is 55 −16.5 = 38.5dB. Considering that compression drive level improves for pulses, especially very narrow pulses, we can state a round number estimate of 40dB dynamic range.

– For pulses less than 30ns wide the dynamic range degrades at 20Logα. Therefore, the value should be 20dB at 3ns, and 10dB at 1ns. However, another factor comes in to help. A 1ns pulse width represents a sin x/x spectrum with 1GHz sidielobes and a 2GHz wide mainlobe. All of this signal is applied to the mixer for frequencies up to 6.5GHz. Above 6.5GHz the signal goes through a preselector which is at most 300MHz wide. The mixer is then not subjected to the full signal level, the main part of which is 2GHz wide. This provides at least 3dB more of dynamic range.

– The dynamic range is unaffected for sub-nanosecond pulse widths as long as the preselector can handle the increased input levels. This limit is above +10dBm. Hence, the dynamic range at 0.3ns is as good as at 1ns.

– The pulsed signal dynamic range keeps decreasing at the rate of 20dB for every ten times pulse width reduction, for pulses narrower than 0.3ns.

Results of these dynamic range computations, for pulse widths from 1ns to 1ms, are illustrated in figure 38. Note that the dynamic range for a 33GHz carrier pulsed at a 1ns width is 0dB. In other words, the signal can not be displayed or measured. Pushing more signal level into the spectrum analyzer will not help with the measurement, and the instrument may be damaged. A wider resolution bandwidth would help. But at 10MHz, the 2782 provides the widest bandwidth currently available.

The simplest way to gain more dynamic range is to use a high efficiency external narrowband mixer. Tektronix waveguide mixers, for example, provide 20dB better sensitivity than the upper coaxial range. With a gain compression point of about 0dBm compared to +10dBm for the preselector, we have 10dB drive level loss and a 20dB sensitivity gain. This is a net gain of 10dB in pulsed signal dynamic range.

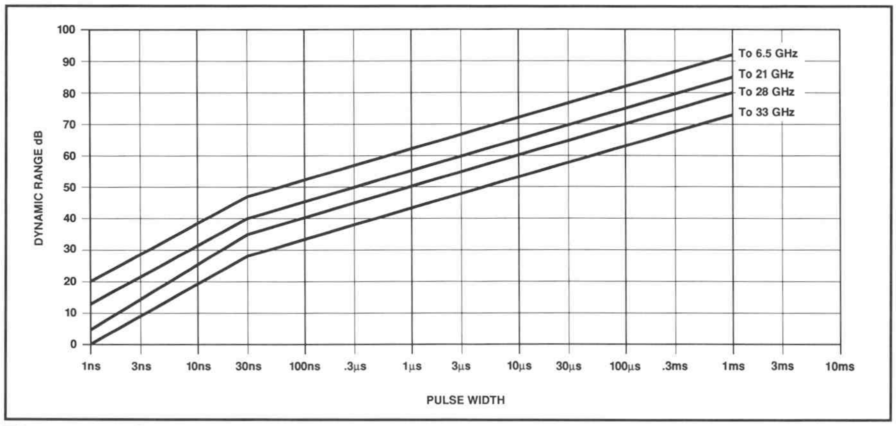

Figure 38. Computed pulsed signal dynamic range.

Appendix A. Mathematical Relationships

B> >PRF yields a dense, continuous spectral intensity, in units of volts per hertz of impulse bandwidth (B_i).

B< <PRF yields a discrete, line spectrum distribution, in units of volts.

For a rectangular pulse shape with peak amplitude A, pulse width t_0, and interpulse time period T, without a sinewave carrier (dc pulse), and with a carrier frequency f_0, we have:

	DC Pulse	Carrier Burst
Line Spectrum volts rms B< <PRF	$C_n = \frac{2}{\sqrt{2}}\frac{At_0}{T}\frac{\text{Sin}\left(\frac{n\pi t_0}{T}\right)}{\left(\frac{n\pi t_0}{T}\right)}$	$C_n = \frac{1}{\sqrt{2}}\frac{At_0}{T}\frac{\text{Sin}\left(\frac{n\pi t_0}{T}\right)}{\left(\frac{n\pi t_0}{T}\right)}$
Dense Spectrum Volts rms/Hz B> >PRF	$S(\omega) = \frac{2}{\sqrt{2}} At_0 Bi \frac{\text{Sin}(\pi f t_0)}{(\pi f t_0)}$	$S(\omega) = \frac{1}{\sqrt{2}} At_0 Bi \left[\frac{\text{Sin}(\pi t_0 \Delta f)}{(\pi t_0 \Delta f)} - \frac{\text{Sin}[\pi(2f_0 + \Delta f)t_0]}{\pi(2f_0 + \Delta f)t_0}\right]$

The general spectrum shape is of the sin x/x variety, e.g.

$$\frac{\sin(n\pi t_0)}{n\pi t_0} \rightarrow \sin x/x \text{ where } x = n\pi t_0.$$

Pulse shapes other than rectangular yield different spectrum shapes. A triangular pulse results in a sin $^2x/x^2$ spectrum shape. The pulse shape in the time domain and spectrum shape in the frequency domain are related through the Fourier transform pair:

$$F(\omega) = \int_{-\infty}^{+\infty} f(t)\epsilon^{-j\omega t} dt;$$

$$f(t) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} F(\omega)\epsilon^{+j\omega t} d\omega$$

For the rectangular pulse, the peak spectral intensity level at the carrier frequency is

$$S(\omega) = \frac{AtoBi}{\sqrt{2}} \text{ v rms/Hz.}$$

The rms amplitude for an unmodulated sinewave carrier is $A/\sqrt{2}$. The ratio of the two, $\alpha = t_0Bi$, is accurate for $t_0Bi < 0.3$.

Appendix B. Impulse Bandwidth

A narrow pulse, with time duration short in comparison to the reciprocals of frequencies of interest (e.g., input frequency or measurement bandwidth), is considered a practical impulse. The peak circuit output does not depend on the pulse shape but only on its spectrum amplitude, which is twice the pulse area (in units volts-seconds) and the circuit impulse bandwidth, Bi, in hertz. Thus, 2(V-S) (Hz) = output volts.

Many techniques for computing or measuring impulse bandwidth, based on the above basic definition or other relationships, will be found in the literature. There are many techniques, because no one method is accurate or easy to carry out in all cases.

Spectrum analyzer resolution filters usually consist of a cascade of single tuned filter circuits synchronously tuned to the same center frequency. Four and six filter sections are commonly used. Theoretical relationships for such circuits have been developed by Sabaroff.

Sabaroff has shown that the bandwidth relationships for the limiting case of a Gaussian shaped filter, consisting of an infinite number of such synchronously tuned filter sections, is:

$$\frac{B_i}{B_6} = \frac{1}{2}\sqrt{\frac{\pi}{\text{Log}_e 2}}, \quad B_6 = \sqrt{2}\, B_3$$

$$\frac{B_i}{B_3} = \frac{1}{\sqrt{2}}\sqrt{\frac{\pi}{\text{Log}_e 2}} = 1.505$$

Therefore, applications information frequently reference a 1.5 multiplier for determining approximate impulse bandwidth. Theoretical values for frequently used synchronous filters are:

Four sections: B6/B3 = 1.48, Bi/B6 = 1.09, Bi/B3 = 1.62

Six sections: B6/B3 = 1.46, Bi/B6 = 1.08, Bi/B3 = 1.58

Infinite sections: B6/B3 = 1.41, Bi/B6 = 1.06, Bi/B3 = 1.51

The theoretical bandwidth ratios for a filter consisting of a cascade of two stagger tuned sections, as mandated by CISPR EMI specifications, is: Bi/B6 = 1.05, Bi/B3 = 1.31.

Frequently the 6dB bandwidth is used as a convenient approximation to the impulse bandwidth.

Theoretical computation yields the upper bound of the impulse bandwidth because it is based on an assumption of filter linear phase response and no post-detection, video filter, bandwidth limitation. Real filters tend to be narrower. Therefore, it is useful to measure the impulse bandwidth for best accuracy. Among the measurement techniques is one that is fairly simple and very accurate, but is only applicable to multi-bandwidth receivers such as spectrum analyzers. The procedure cannot be used with a single bandwidth filter (see IB By Trimming reference).

It can be shown that when the pulse repetition frequency of a pulsed carrier signal is adjusted to provide the same display amplitude level for a line spectrum using a narrow bandwidth as the dense spectrum level using a wide bandwidth, that the impulse bandwidth of the wide filter equals the pulse repetition frequency*. Pulse shape and amplitude level are not a factor.

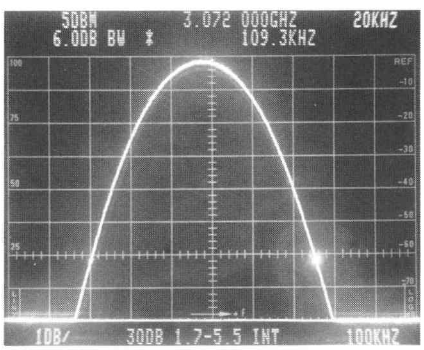

Figure B-1. 6dB resolution bandwidth measurement.

The procedure is illustrated in figures B-1 and B-2. Figure B-1 shows the 100 kHz resolution filter for a 494AP Spectrum Analyzer. The 6dB delta marker position shows a 109.3kHz bandwidth. Figure B-2 is a multi-trace display with the outer trace showing the dense spectrum at 100kHz resolution bandwidth, and the inner trace shows the line spectrum at 10kHz resolution bandwidth setting. The 3GHz pulsed carrier pulse repetition rate is increased from about 20kHz for the dense spectrum, until the inner line spectrum level is at the previously stored dense amplitude. Note that the vertical display is set at a sensitive 1dB/div for most accurate amplitude comparison. The 494AP frequency counter measures a line rate frequency difference of 110.759kHz. The impulse bandwidth at 110.8kHz is only slightly greater than the 109.3kHz 6dB bandwidth.

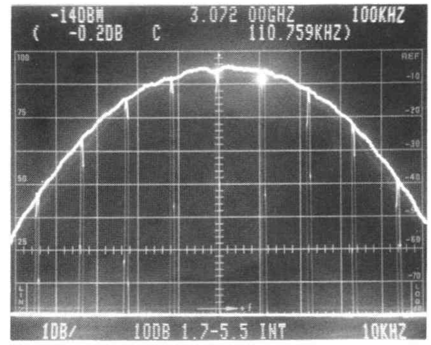

Figure B-2. Impulse bandwidth measurement.

*Many spectrum analyzers have a video bandwidth (B_V) default position equal to the resolution bandwidth (B_R). This will reduce the impulse bandwidth. Best (widest) impulse bandwith will be obtained at widest video bandwidth, though the impact is negligible beyond $B_V/B_R = 10$.

Some spectrum analyzers use a pulse stretcher to increase effective impulse bandwidth when video bandwidth is too narrow.

Set video bandwidth wider than the resolution bandwidth and activate the pulse stretcher, when there is one, to set widest impulse bandwidth and maximum pulse spectrum display.

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