Improving Radar Performance

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Abstract:

RADAR, IFF, DME, TACAN, and even UWB receivers, can obtain a signal to noise ratio improvement due to bandwidth reduction by using a recently developed Ultra Narrow Band (UNB) filter that has zero group delay to pulsed signals. By using this filter to remove the sidebands, which are separable, and detect the carrier alone, a **(processing gain)/(signal to noise)** improvement greater than 30 dB can be obtained. Removing the sidebands causes a power loss of 6 dB in the AM pulse, but the filter bandwidth required using the carrier alone is reduced to 500 Hz. This narrow bandwidth, compared to the many MHz required for conventional matched filtering, greatly reduces the noise bandwidth in the IF so that the SNR is improved by the noise bandwidth reduction ratio. Frequency and Doppler drift can be compensated for by using a known circuit. (Refs. (2)(5

According to Nyquist's work, a pulse 1 microsecond wide requires a filter bandwidth 'B' of 1 MHz. The optimum, or matched, filter for this use, is described as "the filter that passes the most signal power with the least noise power". "A nearly matched filter receiver for a RADAR transmitting a Rectangular pulse is usually characterized by a bandwidth equal to the reciprocal of the pulse width τ,-- or BT = 1. It does not preserve the shape of the the input waveform.". (Ref. (1)). The matched filter normally used is an integrating filter with a group delay time (rise time) T_g as close to the pulse period as possible.

The following tests were made using a pulse 500 nanoseconds wide with a repetition rate of 100 kHz, using a 48 MHz carrier. The Nyquist bandwidth is 2 MHz at baseband and 4 MHz DSB at RF. Typically, RADAR and other pulse IF filters are slightly wider. The filter used for these tests has a bandwidth of 500 Hz instead of the 2 - 4 MHz minimum required for a Nyquist filter. The noise power bandwidth ratio (processing gain) is 2,000,000/500 = 36 dB. Since only the carrier is detected, there is a power loss of 6 dB, so the SNR improvement is 30 dB - or more - depending on the actual Nyquist filter bandwidth used in practice.

The Fourier envelop spectrum of the test signal is determined from Eq. 1.

$$y(t) = A_{peak}\,(t/T_p)\,[\,\tfrac{1}{2} + (2/\pi)\cos\pi(nt/2T_p) - (2/2\pi)\cos 2\pi(nt/2T_p) + (2/3\pi)\cos 3\pi(nt/2T_p) - (2/4\pi)\cos 4\pi(nt/2T_p) + (2/5\,\pi)\cos 5\pi(nt/2T_p)\,]$$

- which nulls when $n(t/2T_p) = 1.0$
- t = pulse width, T_p is repetition period.

This spectrum is displayed on the spectrum analyzer in Figure 1. Although there are many sidebands, they alternately +- cancel part of the power of the adjoining sideband frequency spike and the total power contributed by all of the sidebands is only 6 dB**. *This can be measured by notching out the carrier and comparing the detected signal with and without the carrier. With the very low repetition rates of Radar pulses, there are hundred of these sidebands instead of the relatively small number shown in Figure 1. The number of these sidebands has no power contributing effect.***

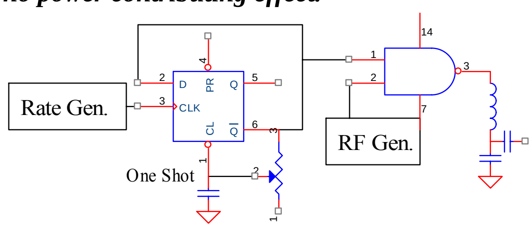

Figure 1. Pulse generator to generate pulse bursts of variable width.

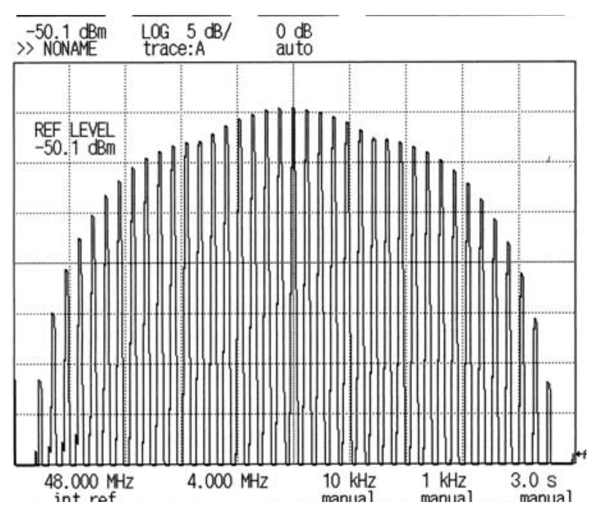

Figure 2. The Fourier sinx/x spectrum of the test apparatus showing the Sinx/x envelop and the 2π/T sideband frequency spikes.

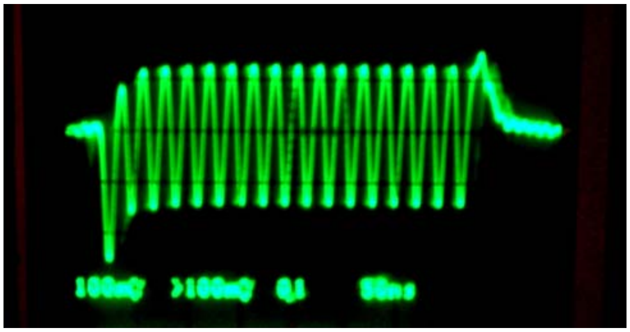

Figure 3. The waveform of the pulse associated with the spectrum of Figure 1. This is at the filter input from the pulse modulator of Fig. 1. A pulse width of 350 ns is shown.

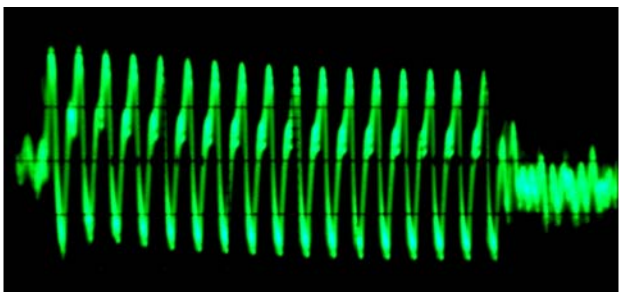

Figure 4. The preserved waveform after 1 stage of near zero group delay filter.

Note: While the spectrum analyzer shows the spectral component level rising and falling with a change in pulse width, the voltage peak as seen at the filter output (Fig. 4) does not change as pulse width is varied.

$y(t) = A_{peak}(t/2T_p)$ changes with $t/2T_p$, but this has no effect on carrier voltage levels, or detected output level.

The group delay (rise time) T_g for conventional Nyquist filters is traditionally calculated to be:

$$T_g = [\Delta\Phi / (2\pi \Delta f)]$$ **Derived from $\omega t = \Phi$. Eq. 2.**

T_g can be measured from the rise/fall time, or from the phase shift after the filter.. It can be positive, negative , or zero. Any resonant circuit affects group delay. It can be seen from Figure 4 that the rise time, hence the group delay T_g of this filter is less than the period of one IF cycle, hence is essentially zero. There has been no signal integration as would be the case with a conventional Nyquist filter. The frequency for the above waveforms is 48 MHz. One IF cycle is 20 nanoseconds.

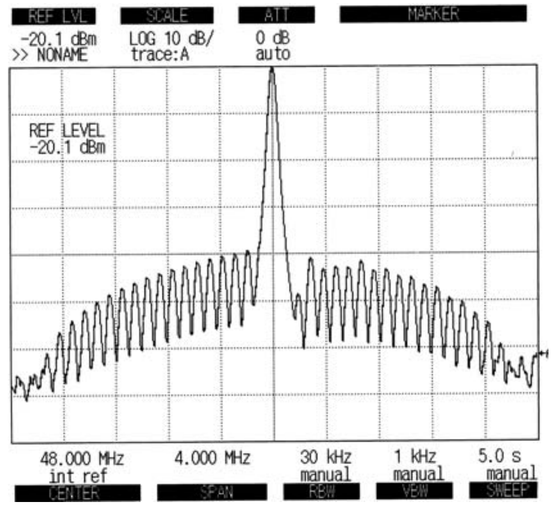

Figure 5. Post filter spectrum. The filter is 3 stages cascaded of the zero group delay filter of Fig. 7. The sidebands in Fig. 2 are reduced 40 dB.

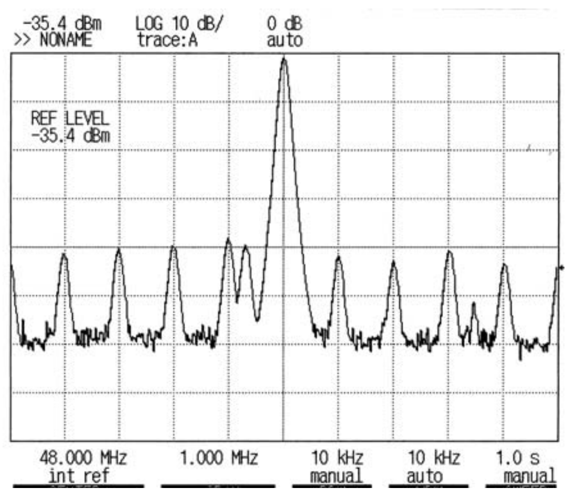

Figure 6. Post filter spectrum -- close in detail of part of sinx/x sideband distribution, when the sideband frequency spikes are reduced 40 dB.

Figures 5 and 6 show the spectrum after 3 stages of the zero group delay filter, showing the sidebands reduced to insignificance and the carrier raised 40 dB above the strongest sinx/x sideband.

$$I_t = I_m(\cos \omega_c t) + 0.5K(\cos\omega_c + F)t + 0.5K(\cos \omega_c - F)t \qquad \text{Eq. 3}$$

Equation 3 is the general equation for all AM modulation methods, including pulse modulation. Each sideband contributes 0.5K to the signal, where K is the modulation index. When the sidebands are reduced 40 dB as shown in Figs. 5 and 6, it is the equivalent of reducing K to 0.005.

The upper trace in Fig. 9 is the signal waveform at the filter input, the lower trace is the detected signal. As noted above, the matched Nyquist filters do not preseve the waveform**. *The zero group delay filter does preserve the pulse waveform shape as seen in Figs. 9 and 14 with a synchronous detector.*** This can improve range resolution for distance measuring devices.

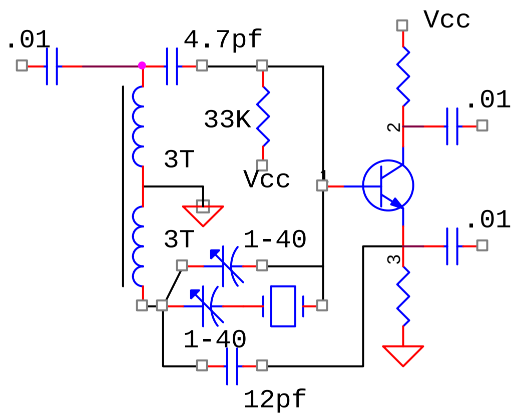

Figure 7. Schematic of the near zero group delay filter. The gain is determined by the load resistor. The output can be taken from either point.

The lower variable at approximately 27 pf has little effect on the crystal resonant frequency. A fixed capacitor cann be substituted. The crystal tuning capacitor C tunes the carrier frequency.

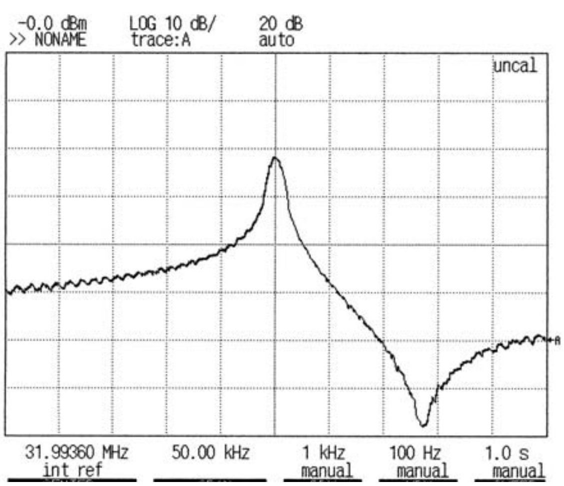

Fig. 8. Swept bandpass of one stage of bridge filter as adjusted for pulses. When optimally tuned the shoulders may not be as low.

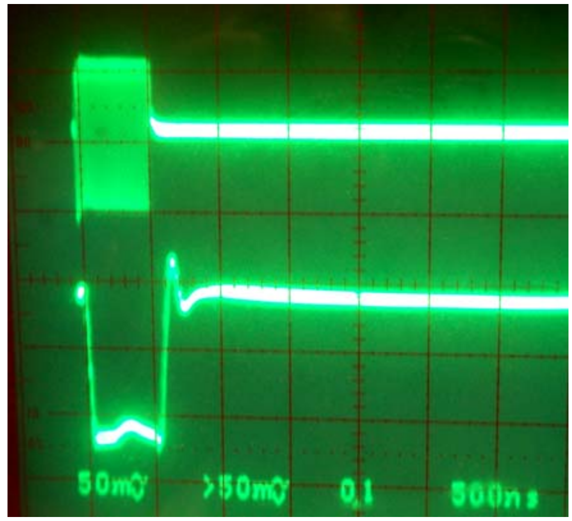

Figure 9. The detected waveform of the test signal using a synchronous detector after 2 cascaded stages of filtering. (Fig. 7).

In Figure 9 it can be seen the incoming waveform swing is balanced about a steady state DC potential. One method of detection consists of introducing a non-linearity that will cause a DC offset of the RF cycles. (See Fig. 12). There are several circuits that can accomplish this, but using the filter itself as combination narrow band filter and non-linear circuit to introduce DC offset is the simplest, if not the most effective means of detection. It can also offer a mininum of waveform distortion and good pulse edge resolution, or with RC integration added at the output, it can be compared to an integrating Nyquist filter, which has a rise time equal to the pulse width where BT=1. (See Fig. 11).

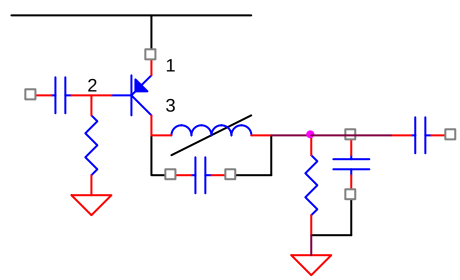

Figure 10. DC Offset Detector for matched filter use, but which can also respond to cycle by cycle detection.

Fig. 10 shows a detector similar to a square law diode detector with amplification. This detector integrates the wavform to have a rise time peak at the end of the pulse period as is required for a matched filter. The response is BT = 1, where T is the pulse period. Figure 11 shows the pulse and the integrated detector output.

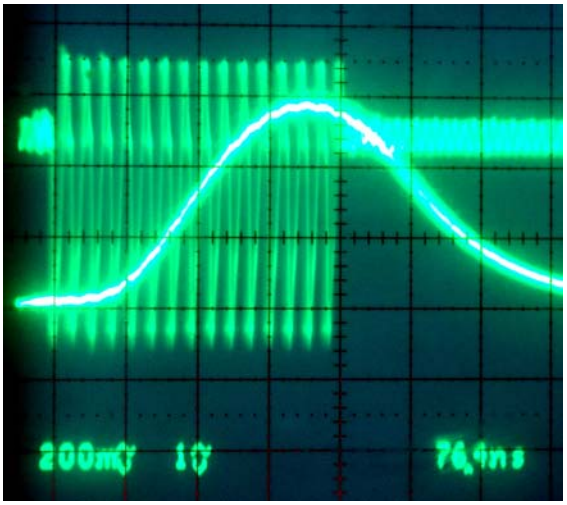

Figure 11. Pulse at filter output when L has been omitted from last filter stage collector. The detector response is equivalent to an integrating matched filter where BT=1, using Fig. 10 with RC load as a detector...

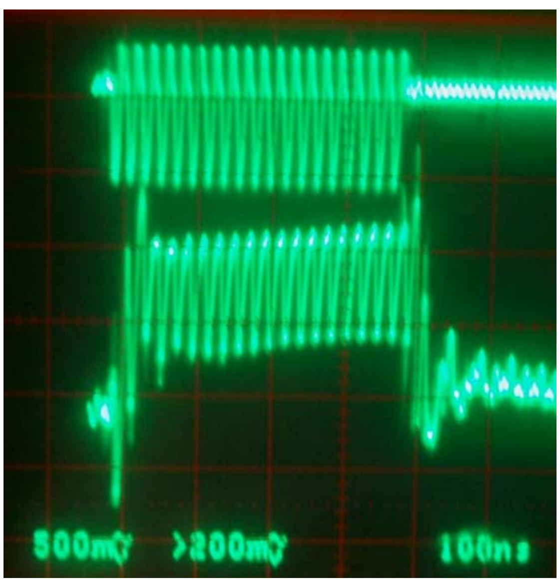

Figure 12. Output of the square law detector of Figure 10 with no RC load and RF removing LC. The last stage of the filter (Figure 7) has .47 uH Z omitted. Without the integrating RC, the original pulse waveform is retained as seen in Fig. 13.

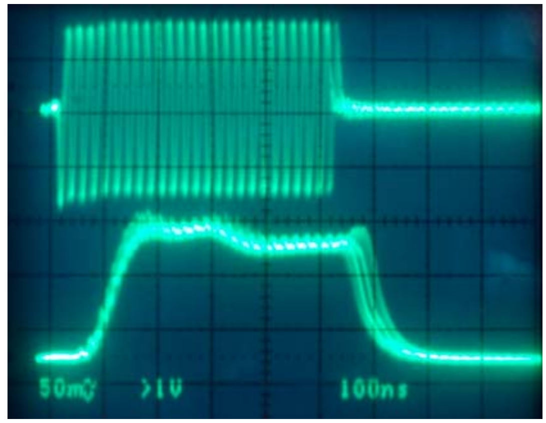

Figure 13. 500 ns pulse with 2N2907 square law detector at detector output with RF suppressed. Note uncertainty of leading edge cycles (+- 1cycle at input). The detected output has +- 1 cycle uncertainty.

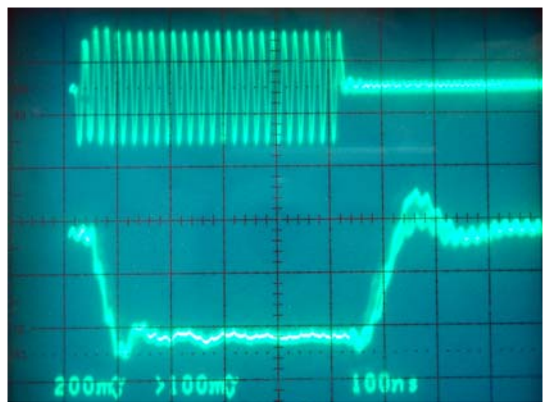

Figure 14. Detected waveform from a Gilbert cell synchronous detector. The leading edge for resolution is on the second RF cycle. The decay is unimportant. A group delay of +- 20 = 40 nanoseconds is implied. This delay is due to the detector characteristic and not to the filter. The full power of each RF cycle is available for nearly the entire pulse period. The leading edge uncertainty indicated is the equivalent of a range uncertainty of 3 to 6 meters.

UNB digital data modulation methods employ end to end switched AM pulses involving different phases on the carrier of the pulses representing ones and zeros. They are merely extensions of the method described here, but using broader pulses.

Nyquist:

Nyquist requires adherence to the BT = 1 rule.

A rise time of 1 IF cycle = T. The Nyquist bandwidth B of the zero group delay filters as calculated from this rule is equal to the intermediate frequency. (B = 1/T). Normally, with conventional filters that have a rise time equal to the bit, or pulse, period, the bandwidth equals the reciprocal of the rise time, or 1/period t. A 1 MHz data rate (in data systems) normally requires a filter BW = 1 MHz. The Nyquist bandwidth of **the zero group delay filters** does not match the noise bandwidth. Note also, that the separable carrier alone has no bandspread, but is a single frequency.

Shannon's Limit:

Shannon's Limit as expressed by Schwartz (6) is:

$$R = W \log_2(1 + \frac{C}{N}) = W \log_2(1 + SNR)$$

Eq. 4.

In this equation:
R = Maximum Data rate (Symbol Rate).
$W = B_w$ = Nyquist Bandwidth = Samples/Sec = $1/T_s$
C = Carrier Power
N = Total Noise Power
If R equals the present data rate and W equals the sampling rate, the equation balances when C/N and SNR = 1 = 0 dB. The Q statistical probability requires a larger SNR to obtain an acceptable bit error rate---
$\mathbf{P_e = ½ \; erfc \; [SNR]^{½}}$ ---so operation is generally with an SNR of 10 dB or higher.
SNR = (E_b/N_o). This is of no consequence in Radar.

"The data system channel capacity is obtained by multiplying the number of samples per second ($1/T_s$) by the information per sample.". (Schwartz, (6) pp 324 and equation 6-134). The present paper does not deviate from this statement.

As noted above BT_s = 1, or B = 1/T. Using the zero group delay filters, the sampling rate using a synchronous detector = IF.

Using the conventional Nyquist filters, the sampling rate is also the data rate.

Normal filters are integrating filters with a rise time according to bandwidth conforming to BT = 1. The zero group delay filters have a rise time of 1 IF cycle and a bandwidth and sampling rate = IF. The difference in filters results in a processing gain.

In no way does the present UNB pulse method violate either Nyquist's or Shannon's theories.

Summary: Using zero group delay filters to pass the carrier only can result in an improvement in pulse receiver sensitivity of 30 dB or more, while preserving the approximate pulse waveform to improve resolution. The bandwidth reduction of the method will also improve reception when subjected to jamming and enable the detection of targets with smaller cross sections.
The circuits described here may not be the best for the purpose intended.

Cdr. Walker, USN (ret,) holds BS, BSEE and MSEE degrees from the US Naval Academy and US Naval Postgraduate School. He has been involved in Electronics R&D for over 60 years, filing more than 40 patents. For the past 25 years he has been working with 'Ultra Narrow Band' modulation methods and holds most of the significant patents in that field.
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(6) Mischa Schwartz, " *Information Transmission, Modulation and Noise*".McGraw Hill, 1951.
(7) Google on "Negative Group Delay".