Digital Pulse Processors, Theory of Operation

Digital Pulse Processors (DPP) are now widely used in high performance nuclear instrumentation and are at the heart of most of the systems sold by Amptek, Inc. A DPP performs the same functions as an analog shaping amplifier but has intrinsic performance advantages which have led to its widespread adoption where both the lowest noise and the highest count rates are needed. Although the function of the DPP is the same as an analog shaper, the implementation is different and some of the concepts and terminology are different. The purpose of this application note is to compare analog and digital shapers, to aid users in understanding digital processors, and to explain their advantages and disadvantages.

Simplified Schematics

Figure 1 and Figure 2 show simplified schematics of analog and digital shaping amplifiers, respectively. Both have the same detector and charge sensitive preamplifier circuits. In both cases, the preamplifier produces an output which consists of small steps, millivolts in height. In both cases, the preamp pulses are differentiated so that the step voltage can be measured. An integrator (a.k.a. low pass filter) improves the signal-to-noise ratio. In both cases, the output pulses are digitized and a histogram of the pulse heights is stored in memory. These key elements are the same in both systems.

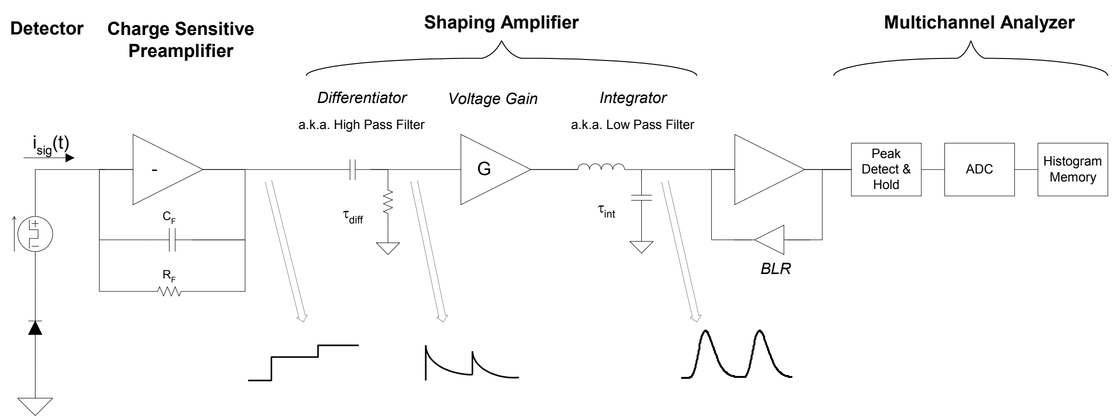

Figure 1. Schematic of a simple analog pulse shaper (with CR-RC^2 shaping)

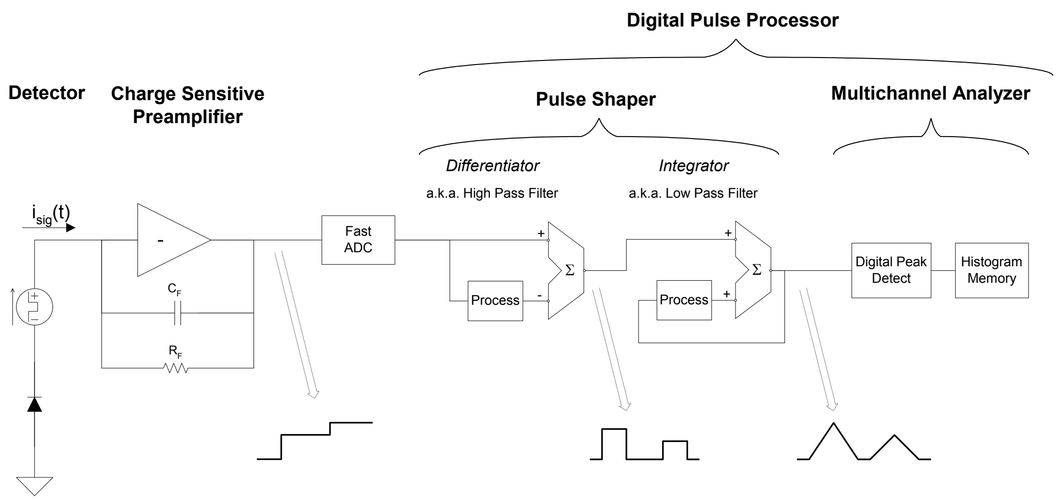

Figure 2. Simplified schematic of an "ideal" digital pulse processor.

The analog system shown in Figure 1 yields the pulse shapes shown in Figure 3 (left). The differentiator is an RC high pass filter. It passes the rising edge from the preamp, and then the voltage decays exponentially back to baseline with time constant τ_{diff}. The integrator is a low pass filter with response time τ_{int}. There are many types of shaping amplifiers (semi-Gaussian, pseudo-Gaussian, quasi-triangular, etc) which use different low pass filters. The more sophisticated using complex pole-pairs have a rapid return to baseline with a more symmetric shape. Generally, the shape is approximated by a Gaussian with a characteristic shaping time τ. The time to peak is approximately 2.2τ, with a comparable duration at half the peak voltage, but the tail persists for a longer time. The baseline restorer (BLR) keeps the baseline from which the peak is measured at a constant value. Without a BLR, the AC-coupled output of the differentiator will shift down at high count rates, since the DC output must be zero. An analog peak detect and hold circuit captures this peak height, which is then digitized. This single digital sample represents the pulse, so the ADC must be very linear but need not be very fast, since it digitizes only one sample per pulse.[1]

In the "ideal" digital system shown in Figure 2, the preamplifier signal is digitized directly, using a fast ADC. This is differentiated using a discrete differencing circuit. This is sent to a low pass filter which integrates the differentiator output. The two blocks labeled "process" represent algorithms which are applied to the inputs and which differ from one digital processor to the next. With the most common low pass filter, the result is a triangular output. Trapezoidal pulses are also easily synthesized, along with more complex shapes such as the cusp. The values are already digitized, so a digital peak detect is used and this value sent to the histogram memory. The output of the integrator may also be sent to a DAC, so the user can view the pulses on an oscilloscope, but the system need not generate an analog shaped pulse. The pulse shapes are shown in Figure 3 (right).

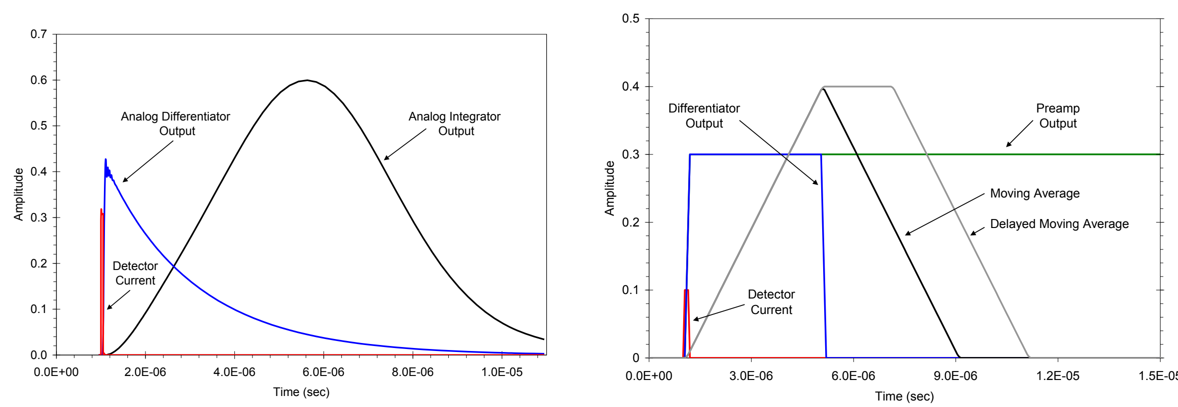

Figure 3. Left: Pulse shapes in an analog pulse shaper. These are for a quasi-triangular shaper using complex poles, which most closely approximates a triangle. Right: Pulse shapes in a digital pulse processor with triangular and trapezoidal shapes.

Real Digital Processor

Real digital processors have a few key differences from this "ideal". Most importantly, it is not practical to directly digitize the preamplifier output due to the dynamic range. Each preamp output step, usually millivolts in amplitude, is riding on a baseline which can be several volts in magnitude, varying with time. The step needs to be digitized to 10 to 14 bits, and there simply do not exist ADCs which combine that precision with the dynamic range of the preamp output and the necessary speed. Therefore, the preamp output is passed to an analog prefilter circuit which permits the step to be accurately digitized. Several different approaches are used to eliminate the baseline and amplify the step prior to digitization. In addition, there are different implementations of the differentiator, of the low pass filter or integrator, and of the peak detect logic.

Summary: Advantages and Disadvantages of Digital Pulse Processing

A digital processor has a few key advantages, summarized here then explained more below. A DPP has better performance (both lower noise and higher count rate capability), greater flexibility for tailoring to a specific application, and greater stability and reproducibility.

1. Researchers derived long ago the ideal filters for use in nuclear electronics, to give the best signal-to-noise ratio at a given count rate. The ideal transfer function cannot easily be produced in practical op-amp circuits but digital processors more closely approximate the ideal.
2. There is no dead time associated with the peak detect and digitization, so a digital processor has considerably higher throughput than an analog system. Further, since it has a finite impulse response, pile-up and other pulse overlap effects are reduced. The digital processor's performance advantage is particularly good at high count rates.
3. In an analog pulse processor, most parameters are determined by resistors and capacitors. It is impractical to have many different configuration options in an analog system. In a digital system, one can have far more shaping time constants, BLR options, etc, so the user can readily tailor a system to the needs of an application, resulting in better performance.
4. Because the analog system relies on resistors and capacitors, its stability is limited to the stability of these components and its reproducibility to their tolerances. In a digital system, the stability and the reproducibility are much better, because they derive from a few very accurate references, e.g. the crystal oscillator to set timing.

There are disadvantages to a digital processor. First, it tends to dissipate more power: an ADC which suitable speed and precision dissipates more power than many analog designs. Second, the design is more complicated than that of an analog shaping amplifier.

Advantages of Digital Pulse Processing

Finite Impulse Response:

In the analog shaper, an impulse input leads to an exponential tail from the differentiator, which takes an infinite length of time to return to zero. This is termed an "infinite impulse response", or IIR. The output is negligible after a finite time, of course, but it is measurably nonzero for a long time, typically many times the nominal "width" of the pulse. Subsequent pulses "ride up" on the tail of earlier pulses. Since the DC output of the high pass filter is obviously ground, the baseline shifts with count rate: the long term average of the pulses is very important and is affected by this long duration but small amplitude tail. So both peak pile-up and baseline shifts result from the IIR of the analog differentiator.

In the digital shaper, an impulse response leads to the rectangular response from the differentiator: the response goes to zero after k samples. It has a "finite impulse response" (FIR), meaning that any input has zero effect after a finite time. This is fundamentally different from the analog shaper. Whatever happens at the input to the DPP, the consequence on the output is zero after some time period. This significantly improves the performance of the DPP at high count rates, reducing pile-up, baseline shifts, etc.

Elimination of Ballistic Deficit

In the analog shaper, the preamp is nominally a step: a fast rise and then a flat top. The differentiator passes the step but then immediately begins to decay. If the rising edge is slow, then its time constant is convolved with the falling exponential and the pulse does not reach full amplitude, as shown in Figure 4 (left). These plots are from a PSPICE model of a sophisticated analog pulse shaper. The loss of pulse height with risetime is termed *ballistic deficit* and affects resolution when the risetime varies from one pulse to the next. In this example, with a 4.8 μsec peaking time, a 500 nsec risetime leads to a 0.5% pulse height deficit. The problem arises because the analog "differentiator" does not pass the actual derivative and so does not pass the flat top. The advantage of the digital differentiator is that is actually implements a differencing operation, the digital true derivative, so it passes the actual flat top, as seen in Figure 4 (right). The rising edge and flat top have the same shape as the preamp pulse. The digital processor is therefore immune to ballistic deficit, for risetimes shorter than the flat top duration.

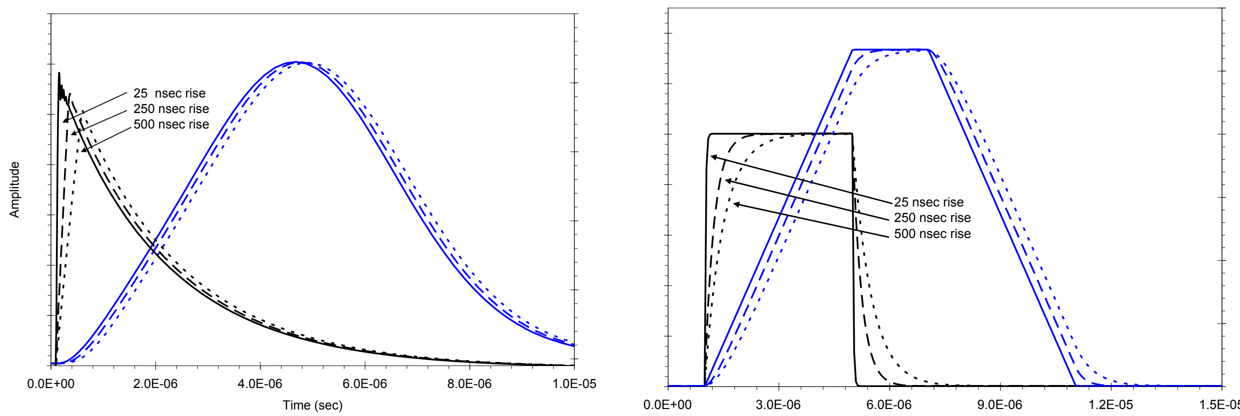

Figure 4. Plots of differentiator output for analog (left) and digital (right) shaping.

Reduced Pileup and Higher Throughput

Figure 5 shows the output pulse shapes from three different pulse shapers, all adjusted to give the same pulse duration when measured as full width at half maximum. The red curve shows the output of the simplest shaper, an analog RC-CR. The blue shows the shape from a high end analog shaper, a quasi-triangular shaping amplifier using 6 poles of low pass filtering (three complex pole pairs). The black curve is from a digital trapezoidal shaper. The most important thing to notice is that, although they have the same FWHM pulse duration, the digital shaper will exhibit no pile-up at all if two pulses are separate by more than (τ_{peak}+τ_{flat}). The two analog shapers have exponential tails extending to many times the FWHM duration. Pulses overlapping during this time will pile-up.

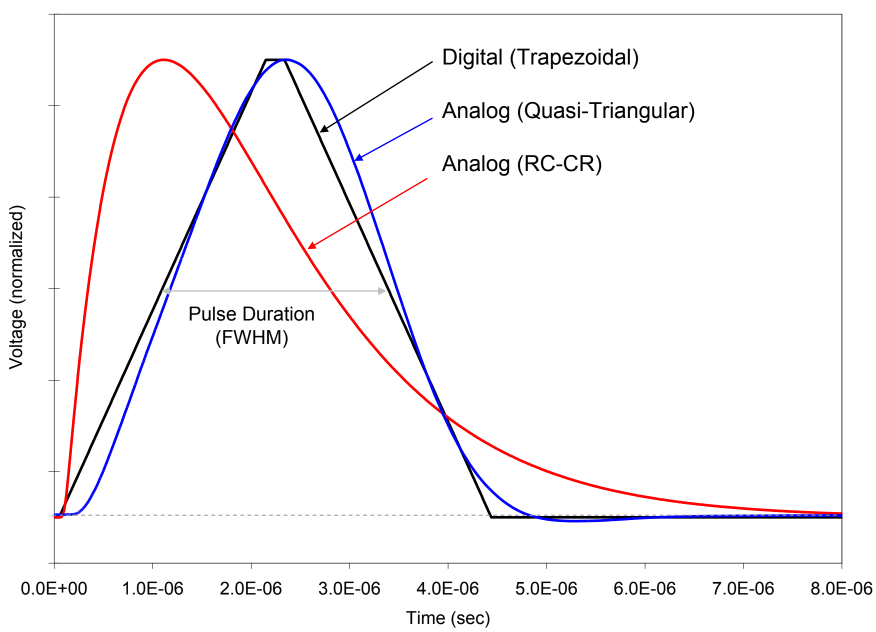

Figure 5. Plot showing pulse shapes from three different pulse shapers. All have essentially the same pulse duration, when specified as the full width at half maximum.

There are two advantages to the digital shaping. First, the digital shaper has less pile-up (even with the same FWHM duration). Second, the pile-up timing for the digital system is very clear: due to the pulse symmetry, there is no pile-up after a fixed time. The analog shapers must use a pile-up rejection interval much longer than the peaking time, reducing throughput, i.e. the dead time due to the pulse shaping is longer in the analog system. Therefore, the digital system has both less pile-up and higher throughput with pile-up rejection used than the analog shapers.

Signal to Noise Ratio

Researchers long ago concluded that, for a fixed pulse duration, the true triangle provides an optimum signal to noise ratio when series noise is dominant and the cusp when parallel noise is dominant[2]. Analog shapers approximate the triangle but the digital processor has a transfer function much closer to this ideal. The equivalent noise charge for a radiation detection system is characterized by noise indices for series and parallel noise generators, A_s and A_p, for a given peaking time τ_{peak}. The noise can be written

$$ENC^2 = \left(2qI_{leak} + R_P\right)\left(A_p \tau_{peak}\right) + \left(e_{pink}^2 C_{in}^2\right) + \left(\frac{4kT}{(2/3)\,g_m}\right)\left(C_{in}^2 \frac{A_s}{\tau_{peak}}\right)$$

where I_{leak} is the leakage current through the detector, R_P is the resistance in parallel with the detector, C_{in} is the total input capacitance, g_m is the transconductance of the FET, and e_{pink} is the pink or 1/f noise term. For this discussion, the key point is that the noise indices A_p and A_s depend on the details of the shaping amplifier.

The table below shows the noise indices and pulse duration (FWHM) for three common shaping amplifiers, similar to those illustrated in Figure 5. If one holds constant the peaking time, the trapezoidal and the Gaussian have the same parallel noise index, but the digital has lower series noise index and the Gaussian has a longer duration leading to degraded pile-up performance. One must be careful in this comparison, since the time to peak is not really the key parameter. In Figure 5, the pulses all have the same time to peak but quite different durations. The longer duration pulses will exhibit much worse pile-up even with the same time to peak. <u>The key point is that the digital pulse processor, with its true trapezoid, has lower noise indices and a narrower width in the time domain than comparable analog shapers. Therefore, it simultaneously reduces electronic noise and pile-up.</u>

	Step (parallel) noise index	**Delta (series) noise index**	**Duration (FWHM)**
	A_p	**A_s**	
Trapezoid (Digital)	$\frac{2}{3}\tau_{peak} + \tau_{flat}$	$\frac{2}{\tau_{peak}}$	$\tau_{peak} + \tau_{flat}$
7 real pole Gaussian	$\frac{2}{3}\tau_{peak}$	$\frac{2.53}{\tau_{peak}}$	$1.12\tau_{peak}$
CR-RC	$\frac{e^2}{4}\tau_{peak} = 1.87\tau_{peak}$	$\frac{e^2}{4}\tau_{peak} = 1.87\tau_{peak}$	$\frac{e^2}{3}\tau_{peak} = 2.46\tau_{peak}$

Table 1. Noise indices and pulse duration (FWHM) for three common shaping amplifiers. All are written in terms of the peaking time.

MCA Throughput

There are two sources of dead time in an analog system: some pulses may be lost (not detected) because (a) the pulses overlap in time or (b) the peak detect and digitizer circuits are busy. Most MCAs use ADCs which require microseconds, and even if the analog pulses do not overlap in time, counts will be lost due to the digitizer's dead time. In the digital processor, there is no dead time associated with the peak digitization. The entire pulse shape is already being digitized, at a fast rate, e.g. 20 MHz. There will be a few clock cycles required to update the histogram memory but this is negligible. So the digital system has no dead time associated with MCA peak acquisition. It does have a dead time associated with the pulse duration, as discussed above.

Linearity

In the analog system, the nonlinearity of the ADC has a major impact on system nonlinearity. Since the MCA makes a single measurement of the peak height, any nonlinearity in the size of the ADC steps will result in a nonlinear pulse height measurement. One common approach to ADC nonlinearities is dithering, where one adds random numbers to the pulse, digitizes, and then subtracts the random numbers. The result is that several ADC codes are used to measure the voltages of a single pulse height. In the digital system, each pulse amplitude is the sum of many different ADC measurements, inherently using many different ADC codes. This gives the digital system much improved linearity.

Configurability

In an analog pulse processor, most parameters are determined by resistors and capacitors. In a pseudo-Gaussian shaper, shaping time is determined by a set of fourteen resistors and capacitors, for example. An analog shaping amplifier with four shaping time constants will require four different sets of all of these components. It is impractical to have many different configuration options in an analog system.

In a digital system, shaping time is set by the number of clock cycles in the digital delay and in the accumulator. One can easily change between shaping times, and with a 20 MHz clock, the step size is 50 nsec giving a very fine adjustment. This permits processing options not possible in the analog domain. For example, some digital processors adjust the peaking time on a pulse-by-pulse basis: if the interval between two pulses is short, then a shorter peaking time is used, adding some noise but eliminating pile-up and count losses. In a digital system, one can easily have many more parameters and configuration options. These parameters include not only the shaping time but baseline restoration parameters, pile-up rejection parameters, etc. A digital system has far more configuration options so the user can readily tailor a system to the needs of an application, resulting in better performance.

Stability and Reliability

Because the analog system relies on resistors and capacitors, its stability is limited to the stability of these components and its reproducibility to their tolerances. The temperature coefficient of the resistors and capacitors will cause gain and shaping to drift with temperature. Tolerances among resistors and capacitors will cause the pulse shape to differ between nominally identical shapers or when changing from one setting to another. Fine gain is usually set by a potentiometer and it is difficult to return to a previous setting, difficult to precisely tune two systems to match.

In a digital system, the stability and reproducibility derive from a few very accurate references, e.g. the crystal oscillator to set timing. Temperature drifts are much lower. Reproducibility is much improved. In a digital system, where fine gain is set digitally, one can return exactly to previous parameters. Moreover, the failure rates of the gates in an FPGA are very low compared with the failure of many discrete components, with their soldered joints.

Conclusion

The digital processor has intrinsic performance advantages compared to analog shapers. It has a finite impulse response, reducing pile-up and baseline shifts; it provides better noise filtering (for the same pulse width); it reduces ballistic deficit and improves linearity; it has better configurability, stability, and reliability.

Its primary disadvantage is that the fast ADC consumes considerably more power than the op-amps and slow ADC used in an analog shaper. When the best performance is required, the lowest noise and operation at the highest count rates, the digital processor is clearly the best solution.

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[1] For additional information on typical pulse shapers, a good reference is G.F. Knoll, *Radiation detection and measurement*, 3rd edition, chapters 16 and 17, Wiley & Sons (2000) or H. Spieler, *Semiconductor detector systems*, chapter 4, Oxford University Press (2005). Many other references exist.

[2] F.S. Goulding, *Pulse-shaping in low-noise nuclear amplifiers: A physical approach to noise analysis*, Nucl. Instrum. Meth. 100 (1972), 493-504.