Snowmass2021 - Letter of Interest

ANALOG PHOTON PROCESSOR ASIC

IF Topical Groups: (check all that apply ☐/■)

☐ (IF7) ASIC Design
☐ (IF2) Photon Detection
☐ (NF10) Neutrino Detectors

Contact Information:

Joshua R. Klein [jrk@hep.upenn.edu]
Amanda Bacon
Bill Heintzelman
David Rivera
Christopher Mauger
Mitch Newcomer
Rick Van Berg

Abstract: As detectors get larger, digitizing every waveform of every channel becomes very expensive in terms of ADC costs, storage requirements, and time and effort for offline analysis. Photon-based detectors, in particular large-scale neutrino or dark matter detectors, typically see only 1 to 1000 photons/sensor, and each photon produces a pulseshape with only small variations. Thus all information in the waveforms reduces to just the number of photons detected, and their individual arrival times. These observables can be determined by using metrics derived by analog processes at far lower cost and power than digitizing waveforms and extracting the same features. We describe the motivations and conceptual design of an "Analog Photon Processor" (APP) ASIC here. An analog approach also will allow greater dynamic range and higher precision for timing, both of which are important for hybrid Cherenkov/scintillation detectors.

It has become increasingly common that waveforms from many particle detectors are digitized at or near their front-ends. The resulting digitized signals may or may not be zero-suppressed, and often simple signal processing is applied, such as extracting integrals of any pulses that cross a pre-determined or even a dynamically-determined threshold. That the approach is so nearly universal is due to the fact that it is so remarkably flexible—decisions about exactly what to extract from the digitized data can be postponed until final data analysis is done, as long as the data does not exceed an experiment's storage limits. And there is obviously the fact that sampling at the relevant Nyquist frequency ensures that no information from the waveform is lost, and that there will be no aliasing as long as the filter bandpass is sharply defined and no out-of-band noise is added between front-end shaping and digitzers. For detectors with complex waveforms—ionization chambers, time projection chambers, calorimeters—the ability to apply complex pulse-shape analyses to individual pulses is critical, and thus Nyquist sampling is generally a requirement.

Photon detectors—in particular, large-scale photon detectors like those used in neutrino or dark matter experiments—are different, however. The individual photon sensors in these detectors—such as silicon photomultiplieres (SiPMs) or photomultiplier tubes (PMTs)—operate in a regime that typically runs from single photon detection to perhaps several hundred photons. By contrast, low-noise ionization detectors often have noise levels that run at many hundreds of electrons, and signals far bigger than that. In a photon detector, we are interested *only* in the number of photons the sensor detected, and their times of arrival—there is no additional useful information. Signals from photon sensors in large-scale detectors can thus be entirely characterized by far less information than Nyquist sampling provides.

Using simple metrics derived from an analog waveform from a photon sensor, rather than digitizing the whole waveform, is at least as old as the photomultiplier tube. What requires new thinking is that future photon-based detectors will have more aggressive goals, and operate in regimes that previous detectors either were not interested in, or unable to access. These goals fall into just two classes: a desire for timing with greater precision and higher resolution, and a need for large dynamic range in both signal size and duration.

The physics drivers of the first goal are many: improved position resolution, PID, and discrimination of Cherenkov and scintillation light in liquid scintillator or liquid noble gas detectors. The second goal—increased dynamic range—is driven also by an interest in hybrid Cherenkov/scintillation detectors. The Cherenkov light yield in scintillating materials is at least 100 times smaller than the scintillation light. Precisely recording both single-pe and many-thousand-pe events in a single detector, including cases where there is large pileup in a single sensor, will be crucial for those experiments to achieve the full breadth of their physics programs.

What drives the need for a new approach is to satisfy these goals at reasonable cost and with reasonable stored data volumes. With plans for very high channel counts in bigger detectors, full waveform digitization will either compromise performance or be very expensive. Digitizer costs range from \$12/channel for restricted waveforms to \$200/channel for 16-bits at 500 MS/s, to \$10,000 for a fully instrumented 16-channel device. For detectors with 50,000 channels or more, these are high costs for large volumes of data that will ultimately be used to extract just a few parameters.

We have investigated the precision for extracting the number of photoelectrons in PMT waveforms and their arrival times, using simple analog-derivable metrics, in the case where all the photons pile up within the width of a single PMT pulse (the case where they are separated by more is trivially determined). We have used PMT waveforms from high-resolution single pe digitizations of R5912 pulses, and added them with varying delays to mimic photons that pile up. Using just time-over-threshold, pulse integral and peak height—all easily determined with analog instrumentation—we are able to determine well the true pe count. The left panel of Figure 1 shows the distribution of the most likely number of photoelectrons for these pulses, for the case where the true pileup is three. More challenging is determining precisely the photon arrival times. Using the times of the peaks and valleys of the pulse shape in addition to the metrics above, the right side of Fig. 1 shows the cumulative probability densities of the uncertainties for the times of three photons in a single waveform, when two are so coincident that they do not have distinct peaks. We see that the time of the first photon (PE 1) is determined to a small fraction of a nanosecond; the second (indistinguishable from the first or third in the waveform) is known to about 2 ns; the third is known with similar precision as the first.

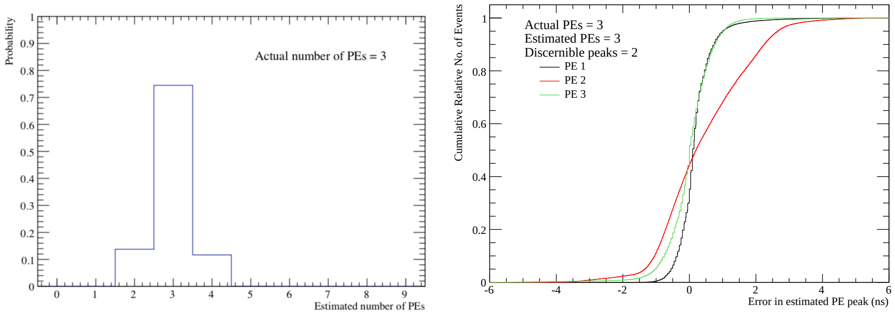

FIG. 1. Left: Distribution of most likely number of photons in a waveform of coincident photons, when the true number is three. Right: Cumulative probability densities for the uncertainties in arrival times for each of three photons in a single coincident pulse.

A real device—the Analog Photon Processor (APP)—will need to be retriggerable with small deadtimes to measure multiple photons even when they arrive at times separated by just a pulse-width; it will need analog memory cells that can be accessed at high rate (faster than 20μs per channel to accommodate up to 50 kHz singles rates) for digitization off-chip; and it should include as a “security blanket” an analog sum of all channels which can be used as a monitor. Off-chip digitization makes sense given the large resources already devoted by industry and others to development of ADCs. The analog parameters to be measured by the APP include pulse integral, time-over-threshold, pulse peak, the time of first threshold crossing, and the times of all major inflection points via differentiation. To ensure reasonable behavior, integral signal-to-noise levels need to be kept to roughly 100:1. Figure 2 shows a simplified block diagram of the APP, with the signal path for one waveform illustrated.

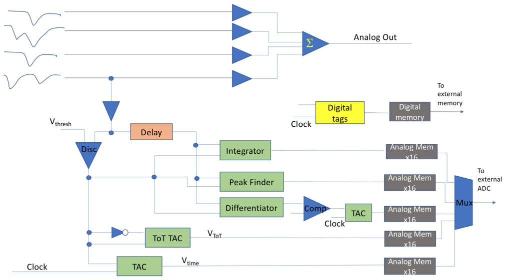

FIG. 2. Conceptual block diagram showing the signal path for one of four waveforms.