

## Digital Signal Processing for SiPM Timing Resolution

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**Abstract.** Digital signal processing (DSP) is an emerging trend in experimental studies and applications of various detectors including SiPMs. In particular, the DSP is recognized as a promising approach to improve coincidence timing resolution (CTR) of fast SiPM-based scintillation detectors. Single photon timing resolution (SPTR) is one of the key parameters affecting CTR, especially important in a case when CTR is approaching to its ultimate limits as, for example, highly demanded in Time-of-Flight PET. To study SiPM timing resolution, we developed a special DSP software and applied it to both SPTR and CTR measurements. These measurements were carried out using 3x3 mm<sup>2</sup> KETEK SiPM samples of timing optimized and standard designs with 405 nm picosecond laser for SPTR and with 3x3x5 mm<sup>3</sup> LYSO crystals and 511 keV Na-22 source for CRT. Results of the study are useful for further improvements of DSP algorithms and SiPM designs for fast timing.

### Introduction

A variety of applications related to a detection of high energy particles and light pulses in coincidence or Time-of-Flight (ToF) modalities demands for high timing resolution [1]. SiPMs are widely recognized now as a detector of choice for a number of such applications substituting conventional PMT and APD based photodetectors [2, 3]. In the same time, digital signal processing (DSP) gradually becomes more and more convenient technique for extraction of more detailed and more precise quantitative information from detector responses with respect to conventional analogue detection. “Go digital as soon as possible” approach is claimed as a new era and inevitable trend in signal processing and development of sensors and systems on a chip [4].

Positron-emission tomography (PET) is one of the most powerful medical imaging techniques for diagnostics of metabolic processes with high efficiency and spatial resolution. ToF modality improves a quality of the image reconstruction in comparison with conventional PET systems due to increased signal-to-noise ratio (SNR) resulting in higher sensitivity with lower dose [1, 3, 5]. However, the ToF modality becomes practically feasible at CTR of PET detectors below 500 ps FWHM, and this level is now achieved in commercial SiPM-based ToF PET scanners. Moreover, a new goal of 10 ps timing resolution for ToF PET system is recognized as a revolution in time-resolved detection which allows direct image reconstruction by timing information from two annihilated gammas [1, 6].

Another example of ToF applications with challenging demands for fast timing and high SNR is a laser distance ranging (3D mapping, guidance, surveillance, profiling) by various so-called LIDAR systems. Considerations of SiPMs as promising photodetectors for LIDAR applications have been started a few years ago [7, 8] and now SiPM applicability is under experimental evaluation [9]. The

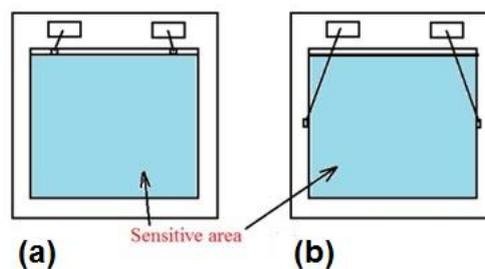


LIDAR ToF technique of 3D object reconstruction would benefit from a good timing resolution of SiPM and its expected improvements with an appropriate DSP.

Therefore, we started to study SiPM performance in CTR accounting for its dependence on SPTR and utilizing DSP. For this initial stage of the studies, we developed a special DSP software based on the linear fitting algorithm [10] as the most affordable in terms of low computational requirements and fast operations.

### Materials and Methods

Two types of setups – one for SPTR and another for CTR measurements – were used to acquire digitized data. The setup for SPTR includes picosecond laser (405nm), digital oscilloscope LeCroy WaveRunner 620Zi (4ch, 2 GHz bandwidth, 20GS/s sampling rate) and KETEK SiPM evaluation kit [11]. Two different kinds of 3x3 mm<sup>2</sup> KETEK SiPM were used (figure 1). SiPM #1 is of standard packaging where wire bonding connections are on the upper surface and both contact pads are located on one side of the sensitive area [12]. Timing optimized SiPM #2 is of special packaging where contact pads are at the centre of the opposite sides of sensitivity area [13]. The light intensity of laser emission was set as low as required to achieve very small probability (a few percentage) of two and more mean number of photoelectrons per pulse.

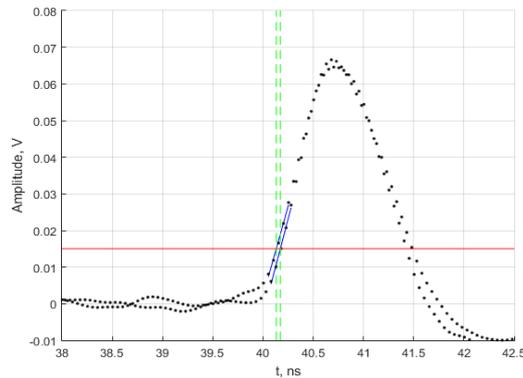


**Figure 1.** (a) Standard packaging SiPM #1, (b) timing optimized SiPM #2

The coincidence timing resolution (CTR) was measured with two identical detectors positioned about 5 cm apart and a Na-22 source placed between them. Each detector consisted of the LYSO crystal wrapped in a Teflon tape coupled with the SiPM on the KETEK evaluation board. The size of the LYSO crystal was 3x3x5 mm<sup>3</sup> to minimize effects of scintillation light distribution and collection. Both outputs of the evaluation kit were used, namely the monitor output for charge measurements and the high-gain output for time measurements. All measurements were done using digital oscilloscope LeCroy WaveSurfer 64MXs-B (4ch, 600 MHz bandwidth, 5GS/s sampling rate). Temperature correction for SPTR and CTR measurements has not been applied due to more or less stabilized room temperature condition. All pulses were shaped with RC-filter ( $C = 62$  pF,  $R = 100$  Ohm) to cut-off SiPM's pulse long tail. As before, measurements were conducted for the both types of SiPM mentioned above.

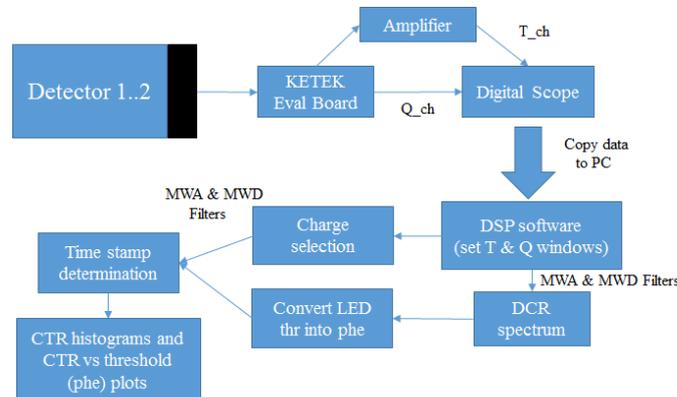
### Digital Data Processing Algorithms

For SPTR measurements we used external synchronization from laser trigger. The SiPM signals were measuring from amplified channel of the KETEK evaluation board. All waveforms were digitized by digital oscilloscope LeCroy WaveRunner 620Zi. The data set was converted from single binary waveforms to MATLAB [14] binary data file. After baseline correction for each waveform, only waveforms with single photoelectron pulses were selected for further processing. The timestamps were defined as the moments where the pre-set leading edge threshold crossed the linear fit function of the rising edge of the signal pulse (figure 2). The SPTR was obtained as FWHM of the time stamps' histogram.

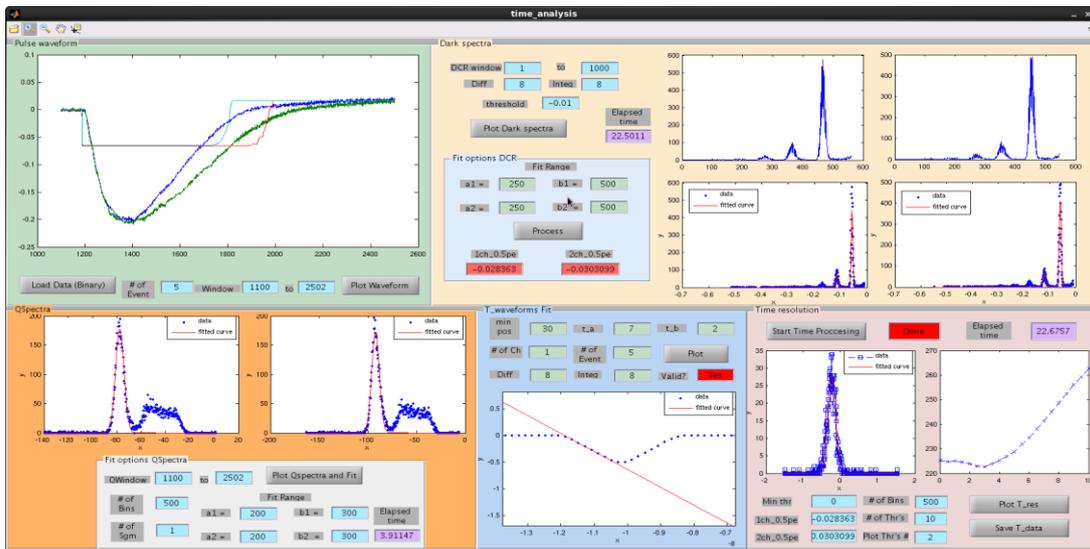


**Figure 2.** Example of time stamps processing.

For CTR measurements all four signals (two per detector: one for the time measuring and another for the charge) were digitized and recorded as waveforms for each event. Moreover, the channels with amplified time signals were set in saturated mode on the scope to get only small part of a leading edge for a time stamp, about 1-20 photoelectrons. The special digital signal processing (DSP) software was developed to analysed the data obtained from CTR measurements (in MATLAB). The main steps of this algorithm are the following. Initially, the charge spectra were plotted for both charge (energy) channels and then only the events with both signals in the range of respective photopeak ( $\text{mean} \pm \sigma$ ) were selected for further analysis. For timing stamp determination, the waveforms from saturated channels were processed with moving window average (MWA, this method relates every data point to the average of itself and the last ( $N_a-1$ ) data points) and moving window differentiation (MWD, in this method every  $i^{\text{th}}$  sample is related to the difference of its value and the value of the  $(i-N_d)^{\text{th}}$  sample) filters [15] and the rising edge of each pulse was fitted with a linear function. The fit procedure searches for the minimum of the negative polarity pulses and auto-selects the range for the linear fit. The timestamps again were the moment where the leading edge threshold crossed with the linear fit function of the rising edge. The difference in timestamps from two detectors for all selected events was plotted as the histogram and fitted with Gaussian function to get CTR FWHM of Gaussian fit. To define the threshold in photoelectrons the dark counts spectra was obtained from the first  $\sim 500$  points of each waveform and then each filtered amplitude was converted to a number of photoelectrons by using the distance between the pedestal and the first photoelectron peak from dark counts spectra. The block scheme of DSP software is presented in figure 3. Thus the output data of DSP was the CTR values versus the threshold in photoelectrons scale. The screenshot of DSP graphical user interface (GUI) is presented in figure 4.



**Figure 3.** DSP algorithm block-scheme.



**Figure 4.** GUI of DSP software. Top-left: setting up the processing window; top-right: the dark count spectra histograms; bottom-left: charge selection; bottom-middle: time stamp determination tuning; bottom-right: CTR histogram and CTR vs threshold plot.

**Results**

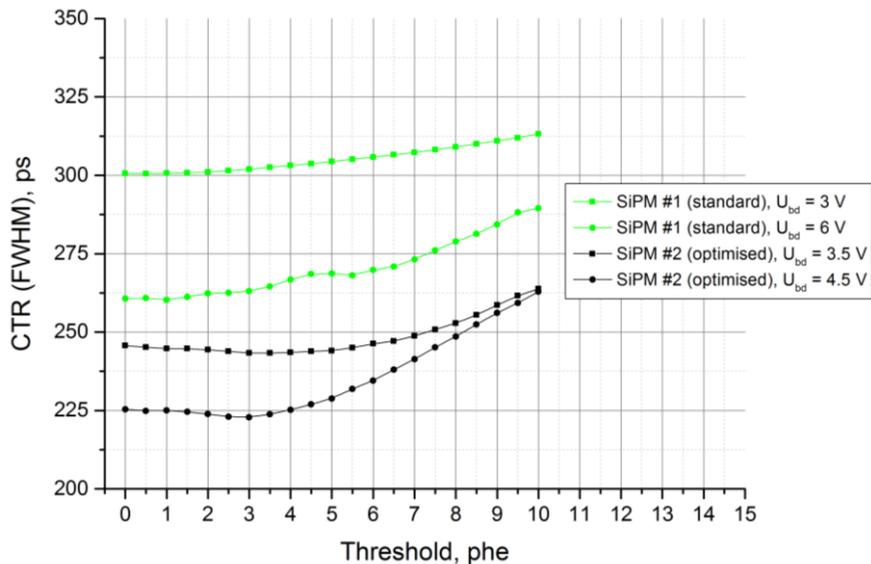
The results of SPTR and CTR measurements with studied SiPMs are presented in table 1.

**Table 1.** Results of measurements of 3x3 mm<sup>2</sup> SiPM SPTR and CTR with 3x3x5 mm<sup>3</sup> LYSO.

Sample	SPTR, ps	CTR, ps
SiPM #1	800	260
SiPM #2	225	223

Since all tested SiPMs have the same 3x3 mm<sup>2</sup> area and the same microcell sizes of 50um, their photon detection efficiencies are approximately the same. One can see that the timing optimized KETEK SiPM #2 has the best SPTR of 225 ps.

The results of CTR measurements with KETEK evaluation kits and LYSO crystals are plotted as a function of the threshold for different overvoltages (figure 5). The data was processed with DSP software. The parameters of filtering were set as N<sub>a</sub> = 8 and N<sub>i</sub> = 8 (as optimal parameters for output results). The timing optimized SiPM #2 has the best CTR of 223 ps at 4.5 V overvoltage.



**Figure 5.** Coincidence timing resolution as function of threshold for different overvoltages.

### Discussion

Our measurements show that SiPM #2, where the contact pads is located in the centres of opposite sides of the SiPM, has significantly improved SPTR value. This improvement can be explained by a reduction of differences in transit time between microcells from different parts of the SiPM.

It seems that the results of CTR measurements depend on SPTR of studied SiPM samples. The best CRT result was obtained with timing optimized SiPM #2.

### Summary

The digital signal processing (DSP) software was developed to analyse the data from measurements of SiPM SPTR and CTR with scintillators. The SPTR and CTR measurements with different samples of 3x3 mm<sup>2</sup> KETEK SiPMs were carried out. The best results achieved with timing optimized SiPM #2. The SPTR for that variety of SiPM was measured to be 225 ps and CTR with 3x3x5mm<sup>3</sup> LYSO crystals was 223 ps. More detailed studies of SPTR and CTR are in progress to understand the relations between that characteristics. DSP approach seems to be suitable and provides potential ability to extract all information from measurements. DSP of SiPM responses looks as a promising way towards ultimate timing performance in ToF applications.

### Acknowledgments

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