Characterization and optimization of an optical and electronic architecture for photon counting

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Abstract. This work shows a time-domain method for the discrimination and digitization of pulses coming from optical detectors, considering the presence of electronic noise and afterpulsing. The developed signal processing scheme is based on a time-to-digital converter (TDC) and a voltage discriminator. After setting appropriate parameters for taking spectra, acquisition data was corrected by wavelength, intensity response function, and noise suppression. The performance of this scheme is discussed by its characterization as well as the comparison of its spectra to those obtained by an Ocean Optics HR4000 commercial reference.

1. Introduction
There are experiments in which the acquisition of very low luminous intensity is done through optical detectors which have a pulsed current response, such as photomultiplier tubes (PMT), avalanche diodes (APD) or charge-coupled devices (CCD). For PMTs, a pulse often has a nanosecond-order duration and an amplitude of hundreds of millivolts.

The earliest and most used method for signal processing is a dual voltage threshold discriminator and a digital counter [1]. However, this method could not make a distinction between signal and noises that have similar amplitudes and weights, like what happens with afterpulsing and cosmic rays. To make it possible, several schemes have been developed, such as time-to-amplitude converters [2], constant-fraction discriminators [3], simplified schemes of lock-in amplifiers [4], and time-over-threshold discrimination [5]. This last scheme allows a flexible development of a TDC and usage of device built-in LVDS buffers intentionally used as comparators [6]. Moreover, this scheme can use a ramp generator to make a single-slope ADC.

Our aim is to show an alternative to the most used photon counting technique, in order to alleviate the effects of electronic noise and afterpulsing. This work shows a cost-sensitive readout system that offers estimation of pulse parameters, as well as discrimination of amplitude and width. This scheme is targeted at frequency-domain spectroscopy techniques, and it was designed for further demonstration of its usability in time-domain spectroscopy techniques.

2. Discrimination and digitizing scheme set-up
A light source hits a sample. The scattered light is focused by a lens and directed through a slit. An Oriel Cornerstone 130 monochromator filters the passing light by wavelength, which is received by a Hamamatsu R2295 photomultiplier. The output current pulse was preamplified with a Mini-circuits ZX60-P103LN+ module. Then, a LVDS buffer, used intentionally as a comparator, makes a digital representation of the pulse [6-7]. The noninverting output receives the measure signal, whereas the inverting output receives a voltage threshold adjusted by a digital-to-analogue converter (MAX5825,
1mV\) resolution). A designed and implemented FPGA-based TDC (Xilinx XC6SLX45T, SP-605 board) measures its duration. Its output samples are extracted to characterize the TDC. Also, all samples can be compared with time upper and lower limits in spectra acquisition. If a sample is within these limits, it is considered as a valid count. Finally, the valid counts per second are transferred to the computer in order to plot spectra.

3. Design and implementation of the TDC

The TDC was designed as a set of interpolators receiving multiple clock phases [8-10]. Figure 1 shows a schematic of the developed digital architecture. It is divided in four interpolation phases shifted in quadrature. Each interpolator consists of two fine synchronizers for start and stop signals, a coarse synchronizer, a coarse counter, and two delay lines with their own pre-encoder. The results given by each interpolation phase are pre-processed and coded in a finite state machine. Next, the result goes to a FIFO-memory, which transmits data to RAM memory through AXI-4 DMA core in burst mode. The stream is retrieved by a Microblaze processor and then transmitted to a PC via USB-UART interface. Results follow two paths: one, pulse validation by width and voltage threshold levels in the acquisition of spectra; two, characterization procedures based on the statistical code density test [10]. For this test, 128 × 103 samples of an uncorrelated 27MHz oscillator signal was collected. The results are shown in Figure 2 and Table 1. The test done indicates that DNL (differential non-linearity) varies between 1LSB and 2.74LSB, and INL (integral non-linearity) varies between −2.75LSB and 3.39LSB. Also, it indicates that the TDC resolution (TLSB) varies between 19.7ps and 23.6ps.

**Figure 1.** Schematic of the developed digital architecture.

**Figure 2.** Results of the statistical code density test, showing DNL and INL of start and stop delay lines at (a) 0°, (b) 90°, (c) 180° and (d) 270°, respectively.

\[\text{Figure 1.} \text{ Schematic of the developed digital architecture.}\]

\[\text{Figure 2.} \text{ Results of the statistical code density test, showing DNL and INL of start and stop delay lines at (a) 0°, (b) 90°, (c) 180° and (d) 270°, respectively.}\]
### Table 1. Results of the statistical density code test for all delay lines.

| Start Lines | Delay line cells | Measurement range (ps) | T\(_{\text{LSB}}\) (ps) | Stop Lines | Delay line cells | Measurement range (ps) | T\(_{\text{LSB}}\) (ps) |
|-------------|-----------------|------------------------|---------------------|------------|-----------------|------------------------|---------------------|
| 0º          | 47              | 923                    | 19.65               | 0º         | 48              | 972                    | 20.69               |
| 90º         | 44              | 937                    | 21.30               | 90º        | 40              | 895                    | 22.38               |
| 180º        | 41              | 889                    | 21.68               | 180º       | 36              | 821                    | 22.82               |
| 270º        | 48              | 999                    | 20.82               | 270º       | 45              | 1060                   | 23.55               |

### 4. Optimum time and amplitude parameters

The amplified PMT output signal was captured with a Tektronix TDS2014B oscilloscope in persistence mode, and its graphical plot is shown in Figure 3. The first and main pulse lasts within 2\(−\)7\(\text{ns}\), which should be consistent with time distributions obtained from the TDC. Also, there is afterpulsing. However, a set of valid time and amplitude limits should reject it. To estimate them, data were taken from time distributions under several voltage thresholds (in Figure 4(a)) and pulse height distributions under a selected time interval (in Figure 4(b)).

In time distributions taken from the TDC, lower voltage thresholds (up to 400\(\text{mV}\)) report similar curves, indicating that the pulses from the PMT are being picked up along with afterpulsing and other sources of noise. However, this does not happen for a 500\(\text{mV}\) threshold, in which the shape is scaled, indicating the presence of more counts due to light. For a 600\(\text{mV}\) threshold, the shape is distorted. This is due to the shortening of time intervals generated by the comparator under higher thresholds.

For pulse height distributions, a 2\(−\)7\(\text{ns}\) time interval was selected. These plots were taken under different light levels, searching for a noise-free level for voltage discrimination. Appropriate voltage levels were found from 525\(\text{mV}\) and beyond. Therefore, a 600\(\text{mV}\) threshold was selected.

![Figure 4. Examples of actual PMT output pulse waveforms.](image)

![Figure 4. Time (a) and height (b) distributions of pulses under different voltage thresholds.](image)
5. Acquisition of spectra

After setting the discrimination window, spectra from a mercury lamp and a rhodamine 6G sample in a polyvinyl matrix were taken [11]. In Figures 5 and 6, those spectra are shown, respectively. The raw mercury lamp spectrum was corrected by wavelength and relative intensity, based on the specifications of the optical setup. The fluorescence spectrum was corrected by wavelength only.

In detail, wavelength was corrected through a linear comparison between the mechanical steps from the monochromator and the wavelengths measured for a Nd:YAG and a HeNe laser. Relative intensity was corrected from an instrument response function estimated through a spectrum of a halogen tungsten lamp. Noise suppression and background elimination were done through an algorithm involving moving average filters [12].

The mercury lamp spectrum taken in this work and the respective spectrum taken with the Ocean Optics HR4000 spectrometer cover the main spectral lines. However, there are differences in their position, relative intensity, and background.

For relative intensity, the PMT sensitivity range is from 300 nm to 650 nm. However, an optimal quantum efficiency (> 10%) is found from 330 nm to 520 nm. The CCD sensor (Toshiba TCD1304AP) from the spectrometer has a sensitivity range from 200 nm to 1100 nm. This allows the detection of the spectral line around 312.6 nm in the CCD sensor.

For position, the most similar spectral lines are around 546 nm, and the 577 nm and 579 nm pair, respectively. This does not happen for spectral lines below 500 nm. In this work, it suggests that the wavelength correction algorithm should be refined through a polynomial function.

For background, the raw plot indicates a probability of PMT saturation around 400 nm and 500 nm, causing changes in heights of spectral lines.

![Figure 5. Spectra acquired from a mercury lamp.](image)

![Figure 6. Spectra acquired from a rhodamine 6G sample.](image)

In rhodamine 6G spectra, their shapes are similar. Maxima from this work and the HR4000 reference are 552.8 nm and 555 nm, respectively. From 620 nm and beyond, this work cannot retrieve the fluorescence shape, mainly due to sensitivity limitations in the PMT. This means that the choice of the optical detector is essential to ensure the acquisition of broad fluorescence shapes, unlike to what happens in the acquisition of narrow spectral lines.
6. Conclusions

The developed scheme can detect differences between pulses coming from optical detectors and the ones caused by sources of noise, such as after pulsing. This means that it can work under conditions of poor analog signal processing. Also, it can detect differences in levels of light. In conjunction with a TDC and a DAC, the range of pulse height and width of pulses for both optical detectors were found and successfully compared with data obtained from an oscilloscope. These data were used to define discrimination parameters in the acquisition of spectra.

This system will be further refined and used with an optical detector capable of detecting Raman scattering, in order to acquire spectra of low cross-section samples such as samples in powder. In particular, we intend to obtain spectra of samples of carbon nanostructures and iron oxides in the short term.

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