PDE Measurement for Digital SiPMs: Comparison Between Pulsed And Continuous Light Methods

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Terminology

Analog SiPM:
- each SPAD is coupled 1 to 1 to a passive quenching resistor
- SPAD signals are summed up to a common reading node before amplification, shaping and digitization

Digital SiPM:
- each SPAD is coupled 1 to 1 to a CMOS quenching circuit (QC)
- each QC output is read and digitalized (event counter, TDC, SPAD address, etc.)
Typical data outputs in a digital SiPM

Analog monitor (current sum)

Fully digital communication: 4 x 64-bit data frame

With control over:
- hold-off time
- pulse amplitude

Start frame
SiPM address
0000000000000000
0009073DF45802FF
AAAAAABAAAAAAB
Event counter
Timestamps
SPAD address
Stop frame

Fig. 11. Charge histogram for four different light intensities with clear steps of 0 to 90 SPADs triggered at the same time showing the single photon resolution capability of the digital SiPM. [Nolet 2016] doi: 10.1109/TNS.2016.2582686

Custom communication protocol for PET scanner
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Definition of PDE:

\[ \text{PDE} = \text{QE}(\lambda) \cdot \mathcal{P}_{BD}(E) \cdot FF \]

where
- QE : quantum efficiency
- \( \mathcal{P}_{BD} \) : breakdown initiation probability
- FF : filling factor

Very basics of the PDE measurement:

Ratio between detected photons \( N_{\text{ph}} \) and photons really impinging on the detector \( N_{\text{ref}} \).

\[ \text{PDE} = \frac{N_{\text{photon} + \text{dark noise}} - N_{\text{dark noise}}}{N_{\text{ref}}} \]
SiPM Photon Detection Efficiency

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Challenge: distinguishing correlated events (afterpulsing, optical crosstalk) from uncorrelated events (thermal noise, photons) otherwise → PDE overestimation
PDE measurement methods

Methods commonly used in the literature:

- Photocurrent method: IV characteristics [Zappalà 2016]
- Continuous-light counting method: Time delays distribution [Piemonte 2012]

PDE measurement methods

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Comparing their applicability to digital SiPM

Setup

Two steps measurement using continuous light

1. Measure light intensity with a calibrated photodiode

\[
N'_{\text{Ref.}} = \frac{\lambda}{h \cdot c} \cdot (P_{\text{ph+dn}} - P_{\text{dn}})
\]

2. Record SiPM event time stamps and calculate the rate of uncorrelated events using either methods
Setup

Two steps measurement using continuous light

1. Measure light intensity with a calibrated photodiode

\[ N_{\text{Ref.}} = N'_{\text{Ref.}} \cdot (1 - T_{\text{NDF}}(\lambda)) \]

2. Record SiPM event time stamps and calculate the rate of uncorrelated events using either methods

\[ N'_{\text{Ref.}} = \frac{\lambda}{h \cdot c} \cdot (P_{\text{ph}+dn} - P_{dn}) \]

1. Power meter
2. Event time stamps

Wideband Tungsten Halogen Lamp
Monochromator
Optical Fiber
Calibrated Neutral Density Filter
Positioning Camera
Calibrated Photodiode
Microscope Lens
DUT
XYZ stage

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Continuous-light counting method

- Measure time delays between consecutive events

- Build a $\Delta t$ histogram: according to Poisson statistic, time delays of uncorrelated events (thermal noise or photons) will follow an exponentially decreasing distribution

- Extract uncorrelated events from correlated events with the appropriate fit.
Continuous-light counting method

Log Y-axis and Linear X-axis

Log Y-axis and Log X-axis
Continuous-light counting method

Log Y-axis and Linear X-axis

Log Y-axis and Log X-axis

Afterpulsing
Continuous-light counting method

Log Y-axis and Linear X-axis

Log Y-axis and Log X-axis

Afterpulsing

Fit limits
Continuous-light counting method

Log Y-axis and Linear X-axis \( y = -CR \cdot t \)

Log Y-axis and Log X-axis \( y = A \cdot t \cdot \exp(-CR \cdot t) \)

Afterpulsing

Count Rate

Fit limits

SPAD address: M14-S02
Wavelength: 480 nm
\( t_0 \): 200 ns
- Count the number of times where no events were detected during a given interval

- Assuming that uncorrelated events (thermal noise and photons) follow a Poisson distribution, the probability of events is:

\[
\mathcal{P}(k \text{ events in interval}) = e^{-\mu} \frac{\mu^k}{k!}
\]

where

- \( \mu \) is the average number of events per interval
- \( k \) is the number of events during an interval
Pulsed-light counting method

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- If \( k = 0 \) \( \rightarrow P(0) = e^{-\mu} \) &rightarrow; immune to correlated events
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- The number of intervals with 0 event is:

\[ N_0 = N_{\text{total}} \cdot P(0) \]

where
- \( N_{\text{total}} \) is the total number interval taken
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\[
N_0 = N_{\text{total}} \cdot P(0)
\]

where
- \( N_{\text{total}} \) is the total number interval taken

The average number of uncorrelated events in a given interval is then:

\[
\mu_{\text{ph}} = \mu_{\text{ph+dn}} - \mu_{\text{dn}} = -\ln\left(\frac{N_0^{\text{ph+dn}}}{N_{\text{total}}}\right) + \ln\left(\frac{N_0^{\text{dn}}}{N_{\text{total}}}\right) = \ln\left(\frac{N_0^{\text{dn}}}{N_0^{\text{ph+dn}}}\right)
\]
Pulsed-light counting method

- Common procedure for analog SiPM is by flashing a LED so that, in the same data set, some intervals at a known rate contain photon events ($\mu_{ph+dn}$) and some, dark noise events ($\mu_{dn}$).

![Amplitude vs. Time Graph]

- Maximum pulse height in interval:
  - Dark Noise interval (dn): 2
  - Flash interval (ph+dn): 0
  - Dark Noise interval (dn): 1
  - Flash interval (ph+dn): 1

Pulsed counting method using a continuous-light source

**Different procedure using a continuous-light source with digital SiPM time stamps**

1. Acquire 2 time stamps frame: with and without light

2. Sample frame to the event distribution
   a) Draw a random time between given boundaries
   b) Count number of events in a time interval of fixed width
   c) Acquire a large number of intervals
   d) Build a histogram of 0, 1, 2, ..., k events
   e) Extract $N_{0}^{dc}$, $N_{0}^{ph+dc}$ and $N_{total}$

\[ \mu_{ph} = \ln \left( \frac{N_{0}^{dc}}{N_{0}^{ph+dc}} \right) \]
Pulsed counting method using a continuous-light source

Extracting $N_0$ and $N_{\text{total}}$

from time stamps (Digital SiPM)

from pulse amplitudes (Analog SiPM)

Figure 5: Pulse-height distributions of Hamamatsu SiPM signals recorded in a PDE measurement. See text for details on the signal extraction. A total of 10,000 flashes contribute to each distribution.


Pulsed counting method using a continuous-light source

Dependence on interval width

- Interval width is chosen where the count rate plateaus
- Number of total intervals taken gives an upper limit

Expression of event

\[ t_{\text{hold-off}} \]

Interval width

Time of event

Absolute time of event (s)

1n 10n 100n 1µ 10µ 100µ 1m 10m 100m 1

Count Rate (s⁻¹)

0,0 1,5x10⁴ 3,0x10⁴ 4,5x10⁴ 6,0x10⁴

Interval width (s)

N_{total} = 10^5

SPAD address : M14-S02
Wavelength : 480 nm
\( t_{\text{hold-off}} \) : 200 ns
\( V_{\text{ov}} \) : 0.6 V

Dependence on interval width - Interval width is chosen where the count rate plateaus - Number of total intervals taken gives an upper limit

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- Interval width is chosen where the count rate plateaus
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Time of event

- Interval width

Count Rate (s⁻¹)

Interval width (s)

SPAD address : M14-S02
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\( t_{\text{hold-off}} \) : 200 ns
\( V_{\text{ov}} \) : 0.6 V

\( \ln(N_{\text{total}}) \) / Interval Width

\( N_{\text{total}} = 10^5 \)
Pulsed counting method using a continuous-light source

**Dependence on interval width**

- Interval width is chosen where the count rate plateaus.
- Number of total intervals taken gives an upper limit.

![Graph showing count rate vs. interval width](image)
Pulsed counting method using a continuous-light source

Dependence on interval width

- Interval width is chosen where the count rate plateaus
- Number of total intervals taken gives an upper limit

Time of event

Count Rate (s⁻¹)
Interval width (s)
SPAD address : M14-S02
Wavelength : 480 nm
\( t_{\text{hold}} \) : 200 ns
\( V_{\text{ov}} \) : 0,6 V

\( \sum \) : 10⁵

\( N_{\text{total}} = 10^5 \)
Comparison between methods

Time delays and pedestal peak using a continuous-light source

\[ PDE(\lambda) = \frac{N_{ph+dn} - N_{dn}}{N'_{Ref.} \cdot (1 - T_{NDF})} \]
Both methods do apply to digital SiPM time stamps: time delays and pedestal peak.

Both methods were done only using a continuous-light source (instead of flash LED).

- Gives access to any wavelengths.

Digital SiPM are built most of the time following an application-specific architecture.

- For characterization purposes having access to time stamps of event is sufficient.

- … or a time-driven event counter with a configurable interval width.
Acknowledgements

Thank you!