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Parameterize PMT Single Photoelectron Response Shape Variance with Linear Models

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PMT is widely used in high energy physics experiments to detect single photons. The PMT single photoelectron (PE) response (SER) is a template function describing the pulse shape of single PE. In PMT waveform simulation and analysis, the shape of SER are usually fixed for the one PMT. This work proposes a linear model using multiple Gaussian parameters and multiple basis, which allows SER to adjust its shape without introducing much complexity such as non-linear and empirical SER formula. This model provides an easy extension to PMT electronics simulation and waveform analysis. The corresponding calibration algorithm is developed and applied to dark noise data of JNE 1ton experiment, which demonstrates the shape variance of PMT PE pulses.

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1. Introduction

Single photon detectors including PMT and Si-PM are widely used in high energy physics experiments involving Cerenkov or scintillation processes. With the advancement of electronic readout system, the voltage output, waveform, can be recorded at a sample rate of 1Gs/s for offline analysis.

Xu et al. [1] summaries and compares various waveform analysis methods for neutrino and dark matter experiments in scope of event time and energy resolution. Well performed methods also require precise knowledge of single photoelectron waveform response (SER). This makes SER modeling and calibration vitally important.

Traditionally, a fixed and normalized template SER(t) × varying amplitude (charge) q is used:

$$q \cdot \mathrm{SER}(t),\ q \sim N(\mu_q, \sigma_q^2);\ w(t) = \sum_{i=1}^{\mathrm{nPE}} q_i \cdot \mathrm{SER}(t - t_i) \tag{1}$$

Gain calibration is responsible to retrieve Gaussian parameter μ_q and σ_q^2 from SER charge spectrum. And the model of waveform $w(t)$ is summing up all pulses induced by PEs, each with amplitude q_i, as Eq. (1) shows. SER(t) is fixed for one PMT, which fails capture shape variance across pulses.

2. Multi-base linear parameterization and calibration

By introducing more variables, each pulse can change its shape. To model the shape variance and keep simplicity, Eq. (1) is extended to Eq. (2) with multiple SER template SER$_j$.

$$q \cdot \mathrm{SER}(t) \longrightarrow \sum_{j=0}^{n-1} q_j \cdot \mathrm{SER}_j(t),\ q_j \sim N(\mu_{q\,j}, \sigma_{q\,j}^{\,2});\ w(t) = \sum_{i=1}^{\mathrm{nPE}} \sum_{j=0}^{n-1} q_{ij} \cdot \mathrm{SER}_j(t - t_i) \tag{2}$$

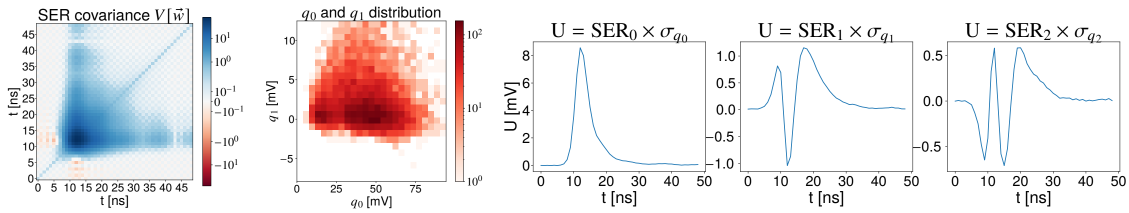
Considering the output waveform is discretized, $w(t)$ and SER$_j(t)$ becomes row vectors $\vec{w}$ $\overrightarrow{\mathrm{SER}}_j$. To calibrate $\overrightarrow{\mathrm{SER}}_j$ and distribution of q_j (governed by $\mu_{q\,j}, \sigma_{q\,j}^{\,2}$), principal component analysis (PCA) is applied. Denote S as a matrix whose rows are $\overrightarrow{\mathrm{SER}}_j$. The mean value of waveform is $E[\vec{w}] = E[\vec{q}]S$, and $V[\vec{w}] = S^\intercal V[\vec{q}]S$. By diagonalizing $V[\vec{w}]$ and sorting the eigenvalue σ_q^2 in descending order, several largest σ_q^2 and their corresponding $\overrightarrow{\mathrm{SER}}_j$ are extracted from S as calibration result.

3. Calibration result

The dataset of SER candidates are extracted from PMT dark noises in JNE 1ton prototype[2]. There has been an upgrade during 2024, where 30 dynode PMTs are replaced by 60 MCP PMTs with higher photon detection efficiency.

For dynode PMT, the covariance matrix $V[\vec{w}]$ is calculated, shown as Fig. 1a. After PCA calibration q_j distribution and $\overrightarrow{\mathrm{SER}}_j$ is obtained, as Fig. 1b and 1c shows.

As for MCP PMTs, the charge spectrum is no longer Gaussian [3]. Nevertheless, covariance matrix and PCA analysis can still retrieve principal $\overrightarrow{\mathrm{SER}}$, while $\mu_{q\,j}$ and $\sigma_{q\,j}^2$ are no longer sufficient to describe the joint q_j distribution. Compared to dynode PMTs, MCP PMTs have stronger correlation



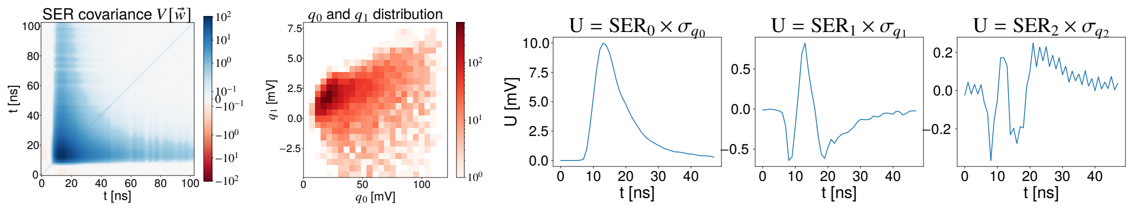
(a) The covariance matrix of SER candidates

(b) (q_0, q_1) distribution (first two components)

(c) The $\overrightarrow{\mathrm{SER}}_j$ of three principal components

Fig. 1: PCA multi-base calibration result on dynode PMT

between q_0 and q_1, implied by Fig. 2b. Fig. 2c are clipped in t axis for easier comparison with dynode $\overrightarrow{\mathrm{SER}}$. The length of MCP PMT SER is longer than dynode ones. The wiggles in $\overrightarrow{\mathrm{SER}}_2$ may come from periodic electronics noise, which is also observed in some Dynode PMT channels.



(a) MCP PMT covariance matrix

(b) MCP PMT (q_0, q_1) distribution

(c) Three major $\overrightarrow{\mathrm{SER}}_j$ of MCP PMT

Fig. 2: PCA multi-base calibration result on MCP PMT

4. Conclusion

Precise calibration of SER waveform is important for PMT waveform analysis in neutrino and dark matter experiments. A template with a varying amplitude, $q \cdot \mathrm{SER}(t)$, is the most common model, but it assumes no randomness in the SER shape and may not reflect reality. To address this, a set of SER-template basis is introduced as a minimal extension, allowing for variant shapes of each PE pulse. This model retains simplicity compared to non-linear SER formula, and can be adapted easily to PMT waveform simulation and reconstruction. Furthermore, the calibration method is proposed and applied on actual data, which favors the existence PMT SER shape variance in reality.

References

[1] D. C. Xu, B. D. Xu, E. J. Bao, Y. Y. Wu, A. Q. Zhang, Y. Y. Wang et al., *Towards the ultimate PMT waveform analysis for neutrino and dark matter experiments*, Journal of Instrumentation **17** (2022) P06040.

[2] Y. Wu, J. Li, S. Chen, W. Dou, L. Guo, Z. Guo et al., *Performance of the 1-ton prototype neutrino detector at CJPL-I*, NIMA **1054** (2023) 168400.

[3] J. Weng, A. Zhang, Q. Wu, L. Ma, B. Xu, S. Qian et al., *Single electron charge spectra of 8-inch high-collection-efficiency mcp-pmts*, NIMA **1066** (2024) 169626.