PROCEEDINGS OF SCIENCE

Calibration-based waveform reconstruction in JUNO

Junting Huang [a,*] **for the JUNO collaboration**

[a] *School of Physics and Astronomy, Shanghai Jiao Tong University, 800 Dongchuan Road, Shanghai, China*

E-mail: junting@sjtu.edu.cn

Jiangmen Underground Neutrino Observatory (JUNO) is a multi-purpose 20 kton liquid scintillator detector being constructed in southern China. It aims to measure the neutrino mass ordering using reactor neutrinos. The key to this measurement is the superior energy resolution of JUNO, which is directly affected by the waveform reconstruction of the 17 612 20-inch PMTs to be installed on the detector. This poster presents a data-driven approach for the waveform reconstruction based on calibration, motivated by the characteristic long-tail of the single photoelectron charge spectrum of the MCP-PMTs used in JUNO and their effect in the energy resolution.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

*Speaker

PoS(ICRC2023)1121

1. JUNO Experiment

Jiangmen Underground Neutrino Observatory (JUNO) is a reactor neutrino experiment under construction near the city of Kaiping, Guangdong province in southern China. With a baseline of 52.5 km to two nuclear power plants, it aims to measure the neutrino mass ordering (NMO) through reactor antineutrino disappearance ($\overline{\nu}_e \rightarrow \overline{\nu}_e$) [1].

As shown in Figure 1 (top), the JUNO central detector is made of an acrylic sphere of 35.4 m diameter, containing 20 kton liquid scintillator. Neutrino signals are detected by a dense array of PMTs immersed in water surrounding the acrylic sphere.

2. JUNO PMTs

For the NMO measurement, the JUNO detector requires an energy resolution of $< 3\%$ at 1 MeV. To achieve this, 17612 20-inch PMTs will be deployed, two-thirds of which are micro-channel plate (MCP) PMTs from North Night Vision Technology (NNVT) and one-third are dynode PMTs from Hamamatsu. In addition, 25600 3-inch PMTs will be used for calibrating the non-linearity of the 20-inch PMTs. The layout of the PMTs are shown in Figure 1 (bottom). In total, the photocathode coverage is 78%. Improving the reconstruction of the waveforms from these PMTs could be a key to improve the energy resolution in the data analysis.

3. Charge Resolution of MCP PMTs

Due to the electrons spilled over from the top of one micro-channel to its neighboring micro-channels, a "long tail" is seen in MCP PMT single photoelectron (SPE) charge distribution, as shown in Figure 2 (left) [2]. This "long tail" gets passed on to the results of a deconvolution-based waveform reconstruction used in JUNO, as shown in Figure 2 (right), and poses a challenge to achieving a good energy resolution. The motivation of this study is to develop a new waveform reconstruction method to remove this "long tail" after the charge reconstruction and to improve the energy resolution.

4. Methodology

The main idea of this work is to assemble fake waveforms of any number of photoelectrons (NPE) using SPE pulses found in calibration data (see Figure 3a for an example). ^{137}Cs calibration data are good sources for SPE pulses due to its low gamma energy (662 keV). As shown in Figure 3b, with a ^{137}Cs calibration source at the center of the detector, SPE pulses are the most prevalent among the PMTs. Alternatively, one may also look for dark current pulses by triggering the detector at a random rate.

The waveform assembly is based on the SPE pulse shape, pulse height distribution and all possible hit timing PDFs, as described in the next section. Based on these fake waveforms, a machine-learning model can be trained to reconstruct the NPE of a waveform. With this data-driven method, any known or unknown PMT effects will be taken into account automatically.

PoS(ICRC2023)1121

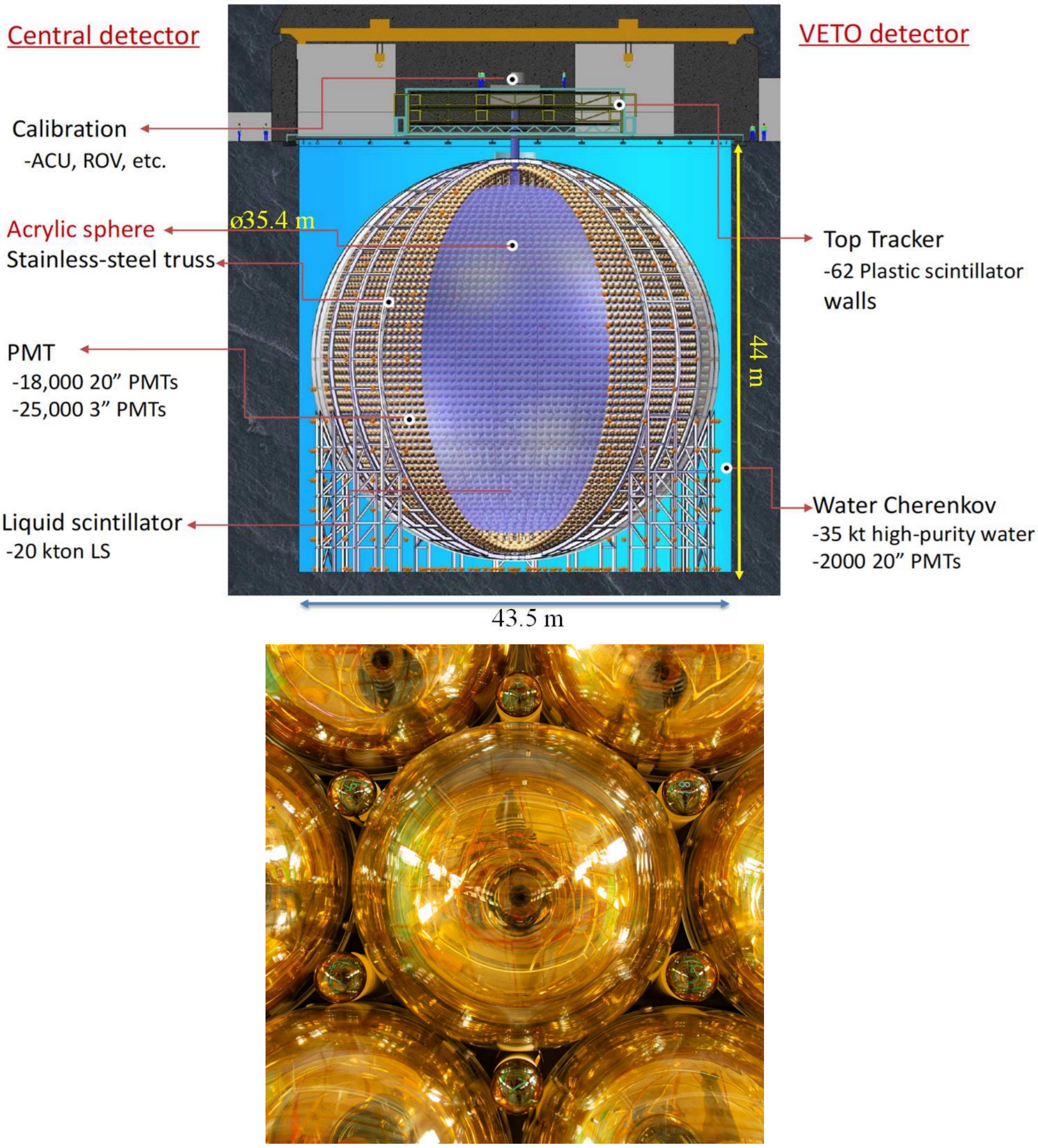


Figure 1: Top: The design of the JUNO detector. Bottom: The layout of the 20-inch and 3-inch PMTs in the JUNO detector.

5. Building Fake Waveforms

Similar to traditional waveform reconstruction methods, such as simple charge integration and deconvolution, the approach of building fake waveforms of any NPEs from SPE pulses relies on that the response of a PMT to multi-photoelectrons is the simple sum of the responses of individual photoelectrons.

The procedure involves acquiring SPE waveforms in calibration data, and assemble them according to the timing PDFs we expect to see in the JUNO detector.

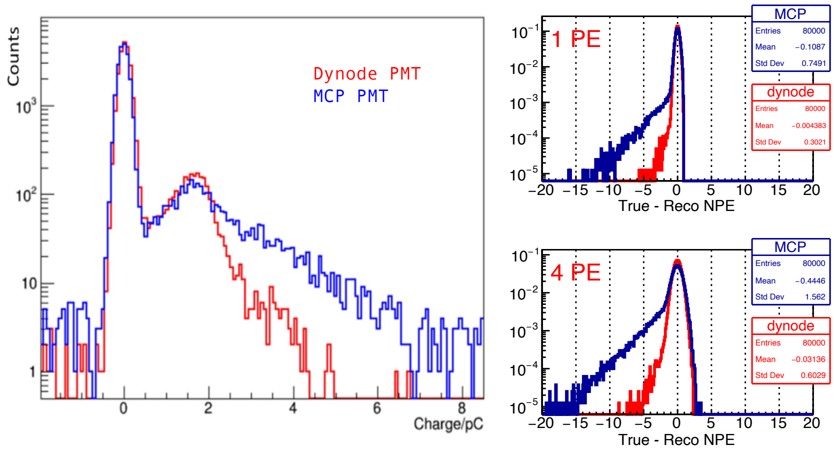
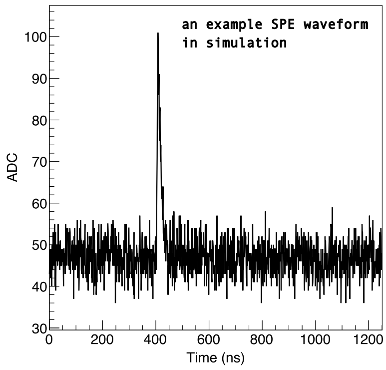
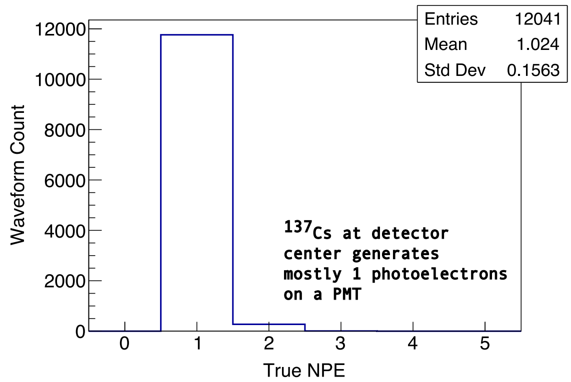


Figure 2: Left: "Long tail" observed in the single PE charge distribution of MCP PMTs. The figure is adapted from Reference [2]. Right: the "long tail" gets passed onto the output of a deconvolution-based waveform reconstruction.



(a) an example SPE pulse



(b) SPE dominates the ^{137}Cs sample

Figure 3: An example of SPE pulses from simulation (left), which dominate the PMTs in a ^{137}Cs calibration sample (right).

5.1 Acquiring SPE Waveforms

First, SPE pulses are identified with a peak finder. Though the probability is small, small pulses buried in the electronic noise may be missed by the pulse finder, and pulses induced by multi-photoelectrons may be misidentified as SPE pulses. These factors potentially contribute to a bias in the reconstruction result. However, this bias is correctable using the 3-inch PMTs and the laser calibration system [3]. The pulse height distribution, as shown in Figure 4, is saved for the random sampling of SPE pulses during the fake waveform building process.

In collecting SPE pulses, a wide enough time window around the SPE pulse is used in consideration of including any potential PMT effects, such as overshoot. Note that one cannot simply add these SPE pulses just yet due to the presence of electronic noise, which would accumulate in the summing process. To remove the noise, an averaging of pulses of similar heights is performed,

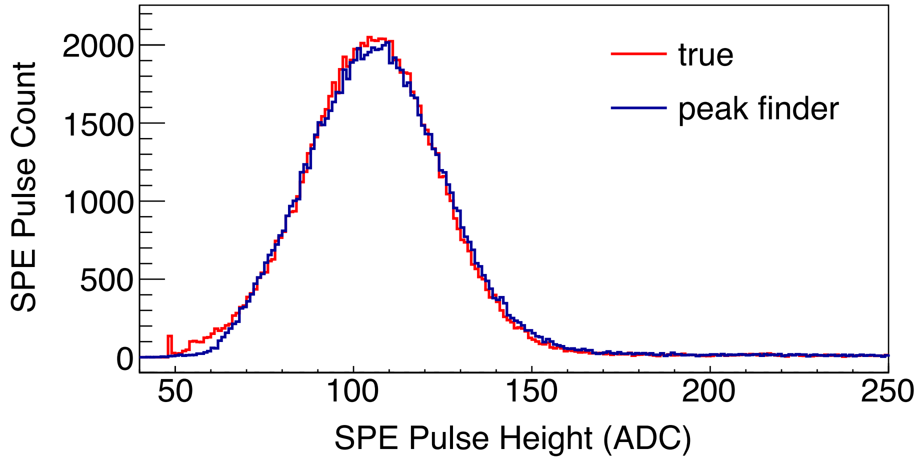


Figure 4: Distribution of the pulse height of the SPE found by a pulse finder. At the lower end one can see a deficit between the distribution of the true pulse height and that from the pulse finder. This is due to the small pulses missed by the pulse finder.

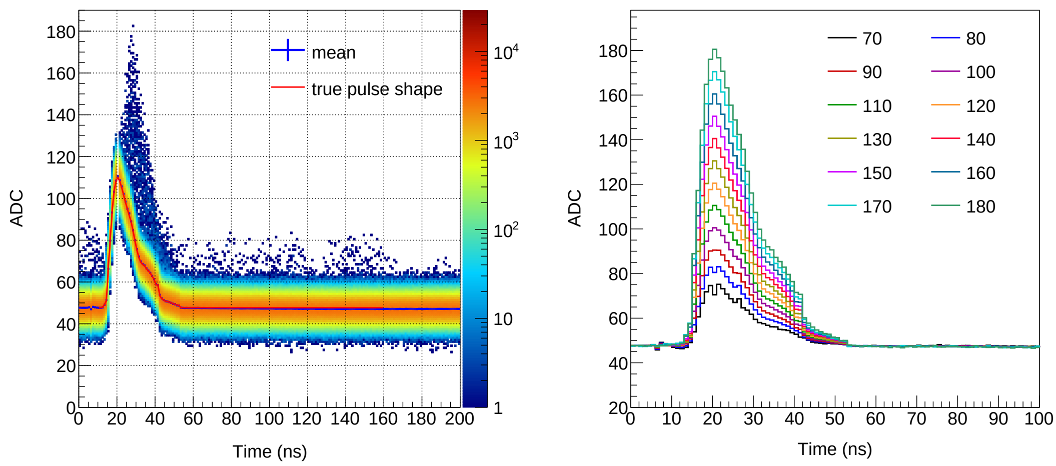


Figure 5: Left: An averaging of SPE pulses of similar heights is performed in order to remove the influence of electronic noise. Right: Examples of averaged SPE pulses for some selected pulse heights.

as shown in Figure 5. Noise will be added back in after summing the averaged SPE pulses to mock a real waveform.

5.2 Obtaining Hit Timing PDFs

To put SPE pulses together forming a fake waveform, one needs to consider the photon arrival time, i.e. timing PDFs which depend on relative positions between an event and a PMT. Due to the approximate spherical symmetry of the JUNO detector, it is possible roughly cover all possible timing PDFs by deploying the calibration source at different positions along the central axis and by dividing PMTs into different groups based on their zenith angle, as shown in Figure 6. A flat probability distribution is used to add pulses due to dark currents.

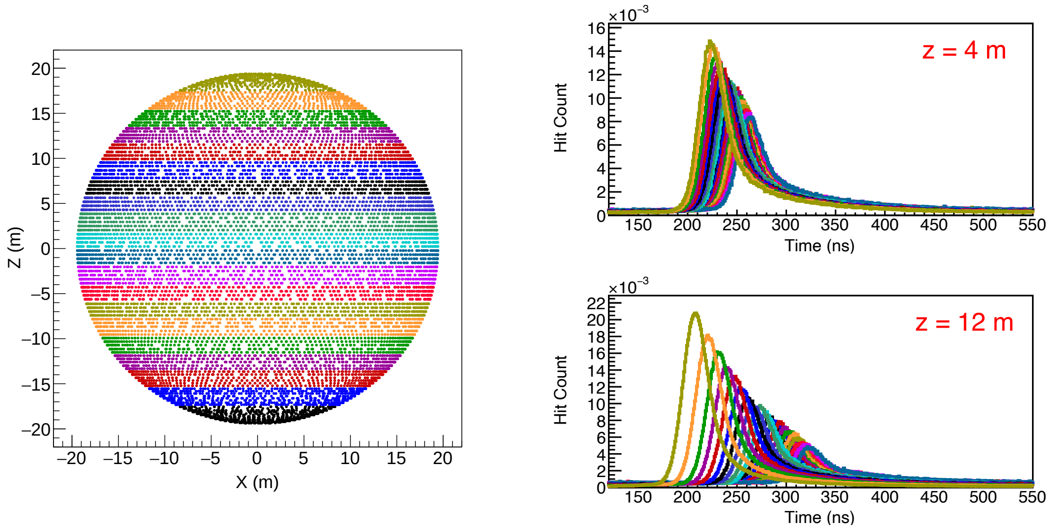


Figure 6: Left: PMTs are divided into different groups based on their zenith angle represented by different colors. Right: Example timing PDFs for different source z positions along the central axis of the detector and groups of PMTs.

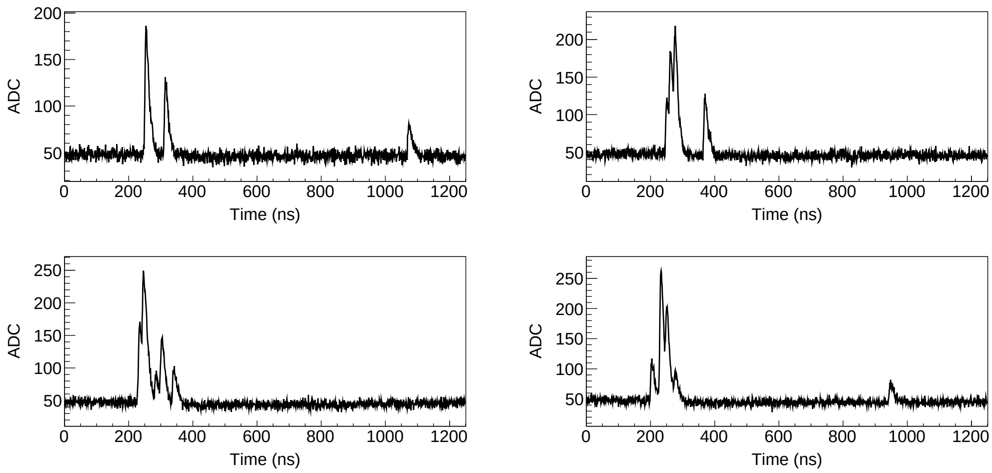


Figure 7: Examples of fake waveforms with 4 (top) and 8 (bottom) photoelectrons.

6. Example of Fake Waveforms

By picking SPE pulses of random heights and putting them together randomly in time based on the timing PDFs, one can build random fake waveforms of known NPEs. Some examples of fake waveforms are shown in Figure 7.

7. Training on Fake Waveforms and Reconstruction Performance

With the fake waveforms of different NPEs prepared, a simple two-layer neural network, with 32 and 64 nodes for each layer respectively, is trained. In this neural network, the full fake waveform

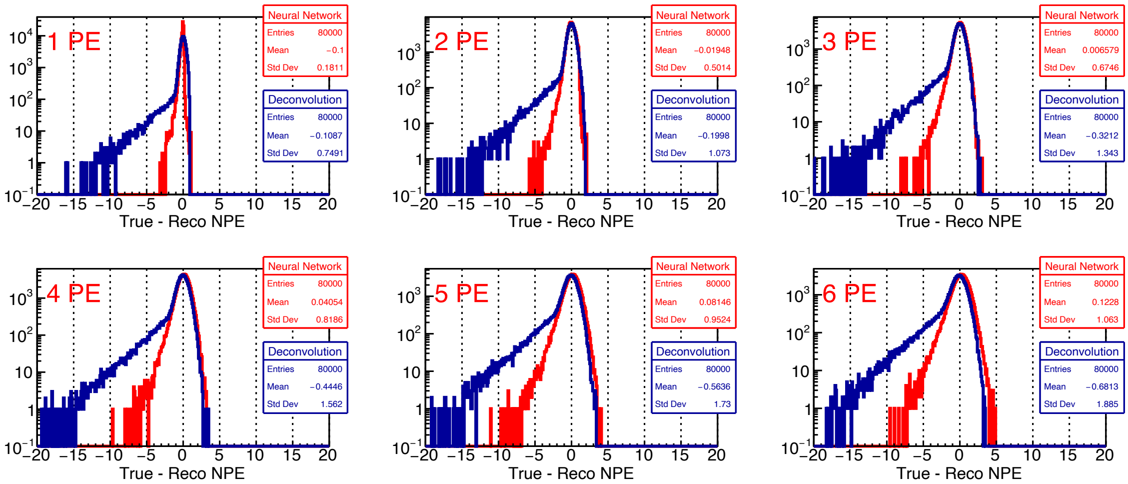


Figure 8: Waveform reconstruction results based on training fake waveforms.

represented by a one-dimensional array is used as the input, the true NPE is used as the label, and the regression output is the reconstructed NPE, which can be a non-integer number.

The training result is shown in Figure 8. One can see that the "long tail" is significantly reduced compared to the deconvolution results. This would eventually lead to a resolution improvement in energy reconstruction.

References

[1] F. An *et al.* [JUNO], J. Phys. G **43**, no.3, 030401 (2016) doi:10.1088/0954-3899/43/3/030401 [arXiv:1507.05613 [physics.ins-det]].

[2] H. Q. Zhang, Z. M. Wang, F. J. Luo, A. B. Yang, D. R. Wu, Y. C. Li, Z. H. Qin, C. G. Yang, Y. K. Heng and Y. F. Wang, *et al.* JINST **16**, no.08, T08009 (2021) doi:10.1088/1748-0221/16/08/T08009 [arXiv:2103.14822 [physics.ins-det]].

[3] Y. Han, "Dual Calorimetry for High Precision Neutrino Oscillation Measurement at JUNO Experiment," tel-03295420.