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A pure probabilistic approach to event reconstruction at JUNO

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We propose a novel probabilistic model for the reconstruction of point-source events, with the dependence of scintillation light time response curve on the number of photoelectrons deduced from first principles. It follows naturally from the time response curve and is unbiased.

The Jiangmen Underground Neutrino Observatory (JUNO) detector is 20 kton underground liquid scintillator detector, with the primary physics goal of determining the neutrino mass hierarchy. At JUNO, the model is applicable to small photomultipliers with first photoelectron time and charge integration readouts, but can also be used for fast reconstruction using large photomultipliers with waveform readouts. We evaluate the performance based on JUNO Monte Carlo simulations.

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1. Introduction

JUNO (Jiangmen Underground Neutrino Observatory) detector is a 20 kton multi-purpose underground spherical liquid scintillator detector. It has two main physical goals: determining neutrino mass hierarchy at 3-4σ and measuring neutrino oscillation parameters $\sin^2\theta_{12}$, Δm^2_{21} and $\left|\Delta m^2_{\mathrm{ee}}\right|$ better than 1%. For JUNO 3-inch photomultiplier (PMT) with first photoelectron (PE) time and charge readouts, the reconstruction approach considers dependence of scintillation light time response curve on PE number, which follows naturally from the time response curve and is unbiased.

2. Method

2.1 Problem Model

According to the actual JUNO detector, we extract the problem model with some assumptions. The detector is rotationally symmetrical about the O-$\vec{r}_j$ axis, where $\vec{r}_j$ is the position of PMT j. Considering $\vec{r}_k$, the position of event k, we find that only the length r of $\vec{r}_k$ and the angle θ between $\vec{r}_k$ and $\vec{r}_j$ are important. PE number on PMT j follows nonhomogeneous Poisson process, where the average function of Poisson process is $R(t)$. Besides, all PMTs are identical, in order to simplify the problem.

2.2 PMT Expected Response Function

The response function is defined as average function of Poisson process $R_j(t;r,\theta,E)$ for point source event $\delta(\vec{r},E)$. As the result of energy linearity, we can extract the energy E from intensity function

$$R_j(t;r,\theta,E) = ER_j(t;r,\theta), \tag{1}$$

then we use polynomials to express $R_j(t;r,\theta)$

$$R_j(t;r,\theta_j) = \frac{1}{l_j^2(r,\theta_j)}\left[\sum_{m,n} a^{mn} P_m\left(t - s_j(r,\theta_j)\right) Z_n(r,\theta_j)\right]^2, \tag{2}$$

where t is PE time, which is mapped to $(-1,1)$; r and θ are position of initial vertex relative to PMT j; $P_m(t)$ is m order Legendre polynomial; $Z_n(r,\theta)$ is n order Zernike polynomial; $l_j(r,\theta_j)$ is distance between initial vertex and image of PMT j; $s_j(r,\theta_j)$ is flight time from initial vertex to image of PMT j; a^{mn} is fitting coefficient. The square in (2) is used to ensure the non-negativity of intensity. $l_j(r,\theta_j)$ and $s_j(r,\theta_j)$ are added to (2) in order to reduce the difficulty of fitting and improve fitting accuracy.

The likelihood for calibrating a^{mn} in (2) is:

$$\begin{aligned}\log\mathcal{L} &= \log\left\{\prod_i R_{j_i}\left(t_i;r_i,\theta_{j_i}\right)\prod_{k,j}\exp\left[-\int R_j\left(t;r^k,\theta_j^k\right)\mathrm{d}t\right]\right\}\\ &= \sum_i \log R_{j_i}\left(t_i;r_i,\theta_{j_i}\right) - \sum_{k,j}\int R_j\left(t;r^k,\theta_j^k\right)\mathrm{d}t\end{aligned} \tag{3}$$

where i, j and k are the index of PE, PMT and event, respectively.

2.3 Reconstruction Methodology

For JUNO 3-inch PMT readouts, the joint distribution of first PE time T_j and PE number N_j need to be considered. We can write down the probability in three parts of time windows $(-\infty, +\infty)$.

- No PE in $(-\infty, T_j)$: $\exp\left(-\int_{-\infty}^{T_j} R_j(t)\mathrm{d}t\right)$,
- One PE in $(T_j, T_j + \Delta T)$: $\exp\left(-R_j(T_j)\Delta T\right) R_j(T_j)\Delta T$,
- $N_j - 1$ PEs in $(T_j + \Delta, +\infty)$: $\frac{\exp\left(-\int_{T_j+\Delta T}^{+\infty} R_j(t)\mathrm{d}t\right)\left[\int_{T_j+\Delta T}^{+\infty} R_j(t)\mathrm{d}t\right]^{N_j-1}}{(N_j-1)!}$,

then multiply the above probabilities and get the joint distribution

$$P(N_j, T_j) = \frac{\exp\left(-\int_{-\infty}^{+\infty} R_j(t)\mathrm{d}t\right) R_j(T_j)\left[\int_{T_j}^{+\infty} R_j(t)\mathrm{d}t\right]^{N_j-1}}{(N_j-1)!}. \tag{4}$$

The normalization of (4) is verified. The reconstruction likelihood is

$$\begin{aligned}\mathcal{L}_{T,N}(\vec{r}) &= \prod_j^{\text{hit}} P\left(N_j, T_j; \vec{r}\right) \times \prod_j^{\text{nonhit}} P\left(N_j = 0; \vec{r}\right) \\ &= \prod_j^{\text{hit}} \frac{\exp\left(-\int_{-\infty}^{+\infty} R_j(t;\vec{r})\mathrm{d}t\right) R_j(T_j;\vec{r})\left[\int_{T_j}^{+\infty} R_j(t;\vec{r})\mathrm{d}t\right]^{N_j-1}}{(N_j-1)!} . \times \prod_j^{\text{nonhit}} \exp\left(-\int_{-\infty}^{+\infty} R_j(t;\vec{r})\mathrm{d}t\right)\end{aligned} \tag{5}$$

3. Results

We evaluate the reconstruction approach by using 1 MeV electron from JUNO Monte Carlo simulation. The results (Figure 1 and 2) show that JUNO small PMT reconstruction is verified.

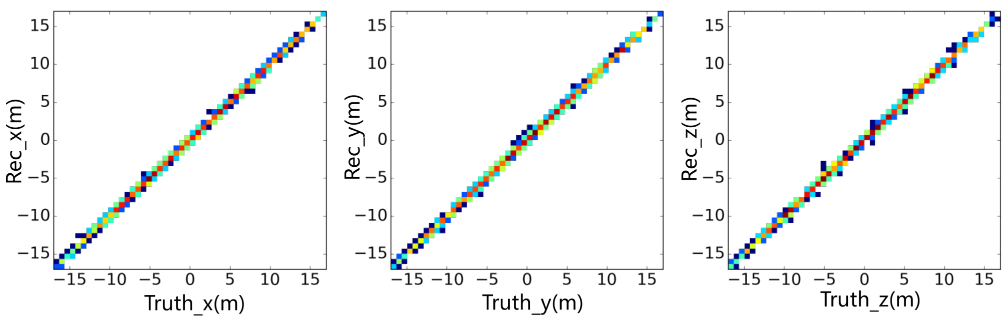

Figure 1: Reconstruction results on x, y and z axes.

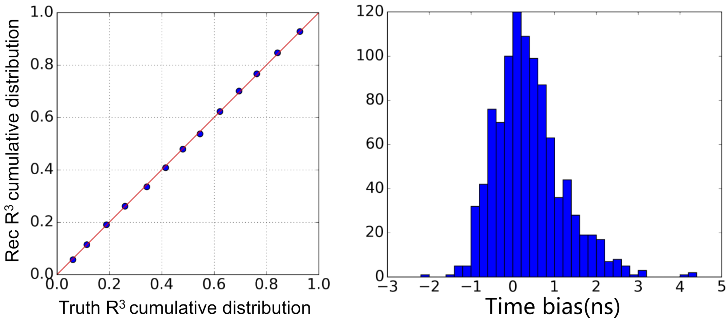

Figure 2: P-P plot of R^3(left) and time bias histogram(right).

4. Conclusion

With the assumption that PE number follows Poisson process, the PMT response function is effective to describe the response of point-source event. The reconstruction approach based on the response function is pure probabilistic and is verified to be unbiased on radius. In addition to JUNO 3-inch PMT, the approach can be applied to other system with time and charge readouts.

References

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