Introduction

IceCube is the high-energy cosmic neutrino detector with 4800 PMTs (Photomultiplier Tube) using the ice on the surface of the South Pole. The huge glacial ice on the South Pole is the clearest and the most transparent naturally occurring substance. And the stronger scattering and weaker absorption make it a better calibrator than water. Therefore, the IceCube detector can be an ideal high-energy neutrino telescope on earth with PMTs which detect the Cherenkov light from neutrino-induced charged leptons. Each PMTs are enclosed in a transparent pressure sphere to comprise an Optical Module (OM). IceCube detector design, 80 strings are regularly spaced by 125 m over an area of approximately one square kilometer, with OM at depth of 1.4 to 2.4 km below the surface.

PMT Calibration

IceCube detector uses the HAMAMATSU 10 inch R7081-02 photomultiplier tube with 10 dynodes inside. It has a spherical surface of the photocathode to enlarge its collection area. IceCube detector uses the HAMAMATSU 10 inch R7081-02 photomultiplier tube with 10 dynodes inside. It has a spherical surface of the photocathode to enlarge its collection area. We must learn at least about these three parameters of the PMT below in the event reconstruction.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Yield (aperture)</td>
<td>4 %</td>
</tr>
<tr>
<td>Photon energy fluctuation</td>
<td>4 %</td>
</tr>
<tr>
<td>Pressure</td>
<td>~ 1 %</td>
</tr>
<tr>
<td>Photon energy probe</td>
<td>~ 5 %</td>
</tr>
</tbody>
</table>

Total Error Budget: 12.7 %

Results

Horizontal axis is the length on cathode. 0 corresponds to the center of the photocathode, while the edge does about 15 cm off from the center. You can use the efficiency doesn’t change so much around center and the asymmetry of efficiency distribution. There’s almost no efficiency outside area at more than 15 cm from the center.

Verification

Check air condition/leakage/temperature

Noise and light induced noise (POLY) at 4K and ambient noise (PMT)

Time-dependent (stability check)

Process dependence analysis

Error budget

- Light Yield (aperture) : 4 %
- Photon energy fluctuation : 4 %
- Pressure : ~ 1 %
- Photon energy probe : ~ 5 %

Total Error Budget : 12.7 %

2D uniformity and 2D Gain scanning measurement

2D uniformity scanning

Two figures in the upper panel show the relative efficiency in two azimuthal angle slices (135° and 225°) for 4 tubes, SF0004, SF0016, SF0050 and SF0030. The efficiencies plotted here are normalized so that the average efficiency over entire photocathode is 100%. You can see the efficiency varies photon by photon. The plots shows the gain variance along the three slices with different rotation angles on the photo-cathode. The vertical axis represents the relative gain with respect to the overall average. The actual (absolute) gain in this data taking is approximately 4.0 (at room temperature). The spikes in the center is caused by an interpolation of the data points and should not neglect it.

although there are slight pmt-by-pmt variances, but the data of these three PMTs look like similar distribution, but trend of individual tubes starts to appear.

Absolute Efficiency (CE× QE)

1. Estimate the photoelectrons per laser shot. Supposing Poisson distribution of the charge response, photoelectron number can be described by the number of pedestal events and the all the event as follow:

\[ \text{photoelectron} = e^{-\text{mean}} \times \text{mean} \]

2. Photoelectron # = cathode hit photon # = initial photon # x aperture x Cross Section

Typically,

\[ 2 \times 10^9 \times 4.8 \times 10^{-11} = 1 \]

\[ \text{QE} (\text{absolute efficiency}) = \frac{\text{photoelectron} #}{\text{cathode hit photon} #} \]

Data Analysis

- Charge response of the PMT

The most simplistic formula to represent the signal part of ADC spectrum (single p.e.) can be easily supposed to be a gaussian function. However, our data shows the existence of another component: exponential-like component appears together with the main gaussian feature and dominates especially at lower ADC range. This behavior probably arises from the instability of first dynode gain.

We thus sum up both components and assumed it to be a model function of our data. Reduced fitting chi-square between our data and model were below 1.0, which justify our model assumption.

Measurement Setup

We use N2 laser (Laser Science VSL-532-SD), the wavelength of the shot is 537.1 nm. Each parameters are monitored as below:

- Absolute energy of the laser shot : Si energy probe (Laser Probe Inc. RJP-405)
- Pressure of inside the chamber : Pressure meter
- Temperature of inside the chamber : Platinum resistance thermometer

For more accuracy...

- Noise rate < ~1.5 kHz
- SN monitoring within ~130m

We must learn at least about these three parameters of the PMT below in the event reconstruction.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Yield (aperture)</td>
<td>4 %</td>
</tr>
<tr>
<td>Photon energy fluctuation</td>
<td>4 %</td>
</tr>
<tr>
<td>Pressure</td>
<td>~ 1 %</td>
</tr>
<tr>
<td>Photon energy probe</td>
<td>~ 5 %</td>
</tr>
</tbody>
</table>

Total Error Budget : 12.7 %

Charge histogram + signal subtraction

Gaussian

Non-Gaussian tail

Projection of the right panel

Charge histogram

Signal Subtraction

Energy meter

Numerical calculation

Distribution of Initial Photon #

Distribution of Initial Photon #

Signal Subtraction

Energy meter

Numerical calculation

Distribution of Initial Photon #

For more accuracy...

- Noise rate < ~1.5 kHz
- SN monitoring within ~130m

Conclusion

- Remove first 6,000 events.
- Remove events out of the one sigma.