A Primitive Water Fitter for Single Vertex Position in SNO+

K.W. Ho[1]

[1]Department of Physics
The Chinese University of Hong Kong

SURE, 2017

Outline

Outline

- SNO+ is a large-scale liquid scintillator experiment located underground at the depth of 5890 ± 94 meter water equivalent (m.w.e.) with the main goal to search for the rare neutrinoless double-beta decay $(0\nu\beta\beta)$ of $^{130}\mathrm{Te}$.
- It also allows the opportunities for other physics investigation including the measurements of geo-neutrinos, low energy solar neutrinos and supernova neutrino watch as well as the search for exotic physics.

Outline

- The detector centers with a spherical acrylic vessel (AV) of 6 m radius with 5.5 cm of thickness. Concentric to the AV is the geodesic stainless steel structure (PSUP) of around 8.9 m radius supporting $\sim$ 9300 PMTs.
- Cavity outside the PSUP and volume between the PSUP and the AV are filled ultra-pure water to shield the AV from radioactivity of the rock and the PMTs themselves. The AV will be filled with different liquid during different phases.

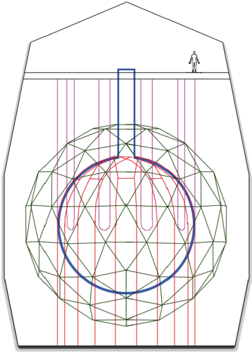


Figure 1: SNO+ detector consists of three major components including the spherical acrylic vessel (blue), the geodesic stainless steel structure (green) as well as the rope system (red) suspending the acrylic vessel.[1]

Outline

- Events in SNO+ is defined by crossing of the analogue trigger threshold, which is adjustable and dependent on purpose of the run. It refers a minimum number of PMTs get hit within a certain time interval. Once the crossing is achieved, information of the PMT hits, including charge and hit time, will be recorded from 180ns before the trigger latches and 220ns after the trigger latches.

The Water Phase

- During the water phase of SNO+, the AV will be filled with $\sim$ 905 tonnes of ultra-pure water and different calibration processes will be ran to test the PMT's performance and characteristics of the data acquisition system, the background radioactive noises and optical properties of water.

- It also provides opportunities to test accuracy of the Geant4-based software package RAT developed to simulate the physics events in the SNO+ detector.

Outline

- Based on the recorded hit time and previously measured positions of the PMTs with the origin set at the center of the AV, the Waterfitter within RAT can be employed to reconstruct a single most likely vertex for the water phase.
- Detailed account of light scattering, refraction and reflection as well as the detector's geometry to determine the best fitted vertex position that matches with the PMT info recorded. A typical physics run that lasts for around 1 hour would take up to a day for the the fitting.

Outline

- One is motivated to look into depreciation of the Waterfitter if all lights are assumed to be travelling in a straight line instead from the vertex to the PMTs.
- To achieve this, one could try to minimize the following function:

$$\chi^2 = \sum_i [c(t_i - t) - |\mathbf{x_i} - \mathbf{x}|]^2 \tag{1}$$

, where c is the speed of light in water assumed to be a constant, t and $\mathbf{r}$ are the time and position of the vertex respectively and t_i and $\mathbf{r_i}$ are the time and position of the PMT hits respectively whereas the number of hits is different for each event.

- Refer to Eq.(2), the speed of light in water corresponding to different wavelength should be determined for the iteration method. In particular, the refractive index for wavelength of 400 mm is 1.31481002573999062 and for wavelength of 700 mm is 1.31481001470856707 which account to a difference of around 6×10^{-9} % difference in c.
- Define

$$r_i(t, \mathbf{x}) = c(t_i - t) - |\mathbf{x_i} - \mathbf{x}| \tag{2}$$

,

$$\mathbf{v} = (t, \mathbf{x}) \tag{3}$$

and the Jacobean

$$J_{ij} = \frac{\partial r_i}{\partial v_j} \tag{4}$$

, the Gauss-Newton algorithm solves for $\mathbf{v}$ by iterations that minimizes χ^2:

$$\mathbf{v_{n+1}} = \mathbf{v_n} - (\mathbf{J^T J})^{-1} \mathbf{J^T r(v)} \tag{5}$$

. Computationally, the inverse is handled by turning Eq. (5) into the following linear equation:

$$(\mathbf{J^T J})(\mathbf{v_n} - \mathbf{v_{n+1}}) = \mathbf{J^T r(v)} \tag{6}$$

in the standard form of $\mathbf{Ax} = \mathbf{b}$, where $\mathbf{x}$ can be solved by Gaussian elimination.

Outline

- RAT is able to simulate a sudden burst of isotropic photons with user-defined wavelength from a user-defined positions which, for convenience, is referred to as a photonbomb.
- 1000 photonbombs are simulated at random and isotropic positions within the AV. Each bomb emitted 1000 photons with the wavelength of 400 mm from each position. PMTs noises are turned off for all simulations as no noise handler is implemented within the primitive straight line fitter.

- In the N16 calibration runs, radioactive $^{16}\mathrm{N}$ gas are pumped into a decay chamber with a radius of around 5 cm where the end of it is connected to a PMT to help signify if an event recorded is triggered by a N16 event. The whole setup can be hanged into the AV at a specified position.
- Seven runs of N16 data are available for the analysis where each run lasted for around 40 mins.

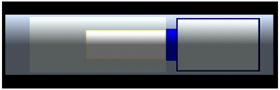
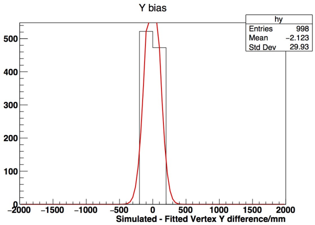
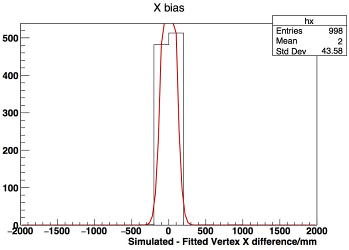


Figure 2: Side view of the N16 source geometry. The decay chamber is shown as the rectangle on the right while the small rectangle on the left represents the PMT. [2]

Outline

- Results of the Waterfitter give all three means of the biases to be close to zero from -2.694 mm to 2 mm with standard deviations from 29.93 mm to 48.36 mm.





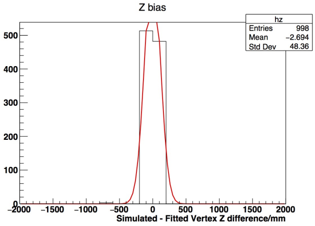
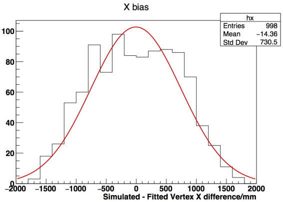
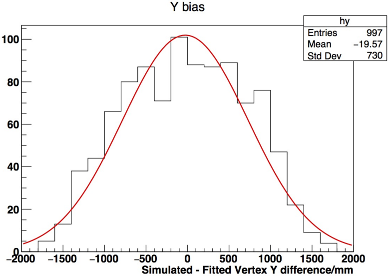


Figure 3: Difference between the coordinate positions of the fitted vertices and simulated vertices in simulations of photobombs with no PMTs noise with the Waterfitter.

- For the straight line fitter, means of the biases range from -19.57 mm to 11.2 mm with all standard deviations close to 730 mm. The biases' standard deviations are over 2000% higher which indicated that applying the straight line fitter directly without taking account of major physical processes depreciates quality of the fitter significantly.





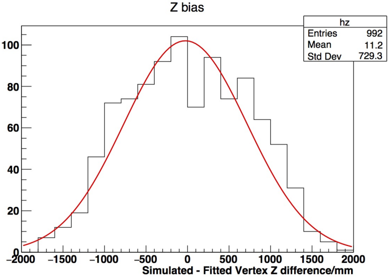


Figure 4: Difference between the coordinate positions of the fitted vertices and simulated vertices in simulations of photobombs with no PMTs noise with the straight line fitter.

Comparison of fitters

Results for the photonbomb

- When reflections of the PMTs concentrator are turned off, the standard deviations decrease significantly to around 275 mm which lowers the percentage difference to the Waterfitter from over 2000% to 818.8%.

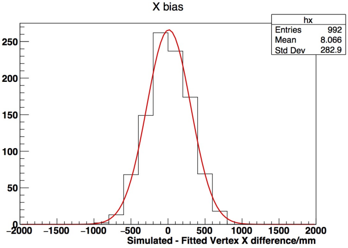
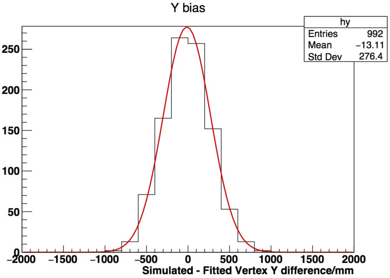
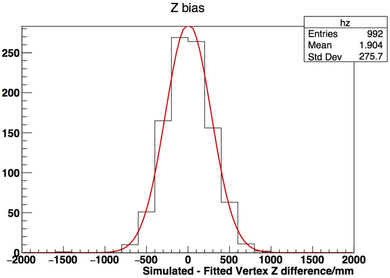


Figure 5: Difference between the coordinate positions of the fitted vertices and simulated vertices in simulations of photobombs with no PMTs noise and reflections of the PMTs concentrator with the straight line fitter.



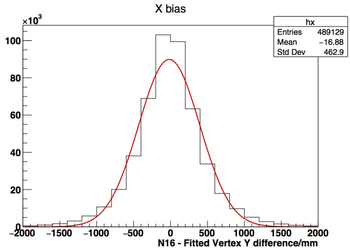


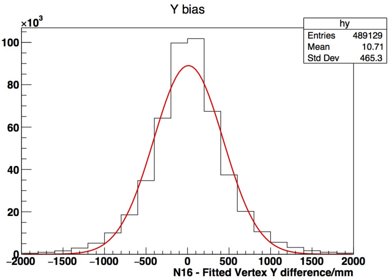
- As purpose of the concentrator is to increase the light yield of the PMTs by allowing photons that are not directed to align to the PMTs' front facing direction to be able to be reflected and collected by the PMTs. Radius of the concentrator used in SNO+ is around 30 cm which in turns refers that distance travelled by the photons reaching the PMTs is different to that predicted by the straight line fitter of the order of 100 cm.

Outline

- Precise position of the vertex for each run is not known but can be approximated as the center of the decay chamber which is measured in each run. Seven runs of N16 data are available for the analysis.

- Means of the biases for the Waterfitter range from -16.88 mm to 17.56 mm and standard deviations of the biases are from 438.6 mm to 465.3 mm.





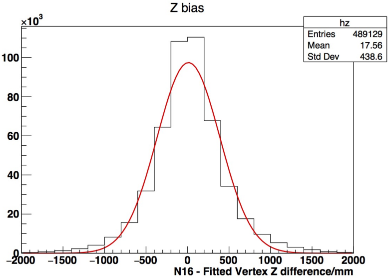


Figure 6: Difference between the fitted coordinate positions of vertices and center of the decay chamber using the Waterfitter.

- Means of the biases range from -24.68 mm to 86.36 mm.
- Standard deviations of the biases are from 2532 mm to 2739 mm for the straight line fitter. Maximum percentage difference of the standard deviations between the two fitters are around 524.4% which is in fact less than the simulated data.

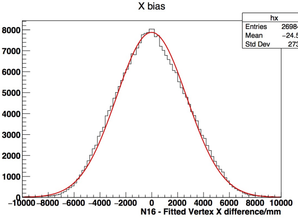
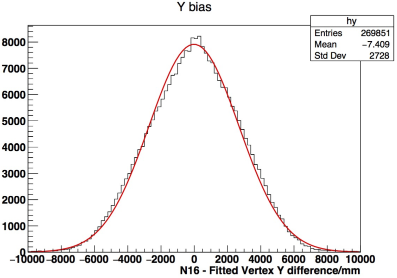
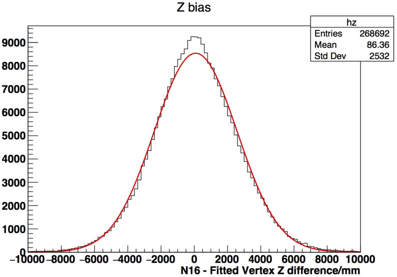


Figure 7: Difference between the fitted coordinate positions of vertices and center of the decay chamber using the straight line fitter.





Outline

- The straight fitter is a much simpler fitter for fitting the position of vertex which reduces the fitting time from around a day for a certain run to a few minutes.
- Although its performance is significantly depreciated compared to the sophisticated Waterfitter in terms of the standard deviations of the positions biases being over 500% larger for the N16 data, the straight fitter surprisingly returns vertices with a mean of the position biases close to zero.

Outline

- With the ability to eliminate the effect of noise and hits that undergo multiple reflections before entering the PMTs, the fitter performance can be significantly improved.
- Instead of following the traditional approach of carrying sophisticated accounting of each physical processes when fitting the vertex, methods for eliminating hits can be developed instead to feed the data to a less sophisticated fitter.
- Future investigations can also be carried out comparing efficiency of the Quad method, which is the current seeder of the Waterfitter, and the straight line fitter. If the extra time needed for the straight line fitter to carry out the fitting can compensate the run time of the Waterfitter due to its better accuracy of the fitted vertex position, the Quad method might be replaced for the overall efficiency of the Waterfitter.

Outline

Acknowledgements

Physics department of CUHK, Prof. Tseng and Prof. Chu:

Thank you!

Outline

Bibliography I

Sofia Andringa, Evelina Arushanova, Satoko Asahi, et al. "Current Status and Future Prospects of the SNO+ Experiment". In: *Advances in High Energy Physics* 2016 (2016), pp. 3–7. DOI: http://dx.doi.org/10.1155/2016/6194250.

Philip Jones. "Background Rejection for the Neutrinoless Double Beta Decay Experiment SNO+". PhD thesis. 2011, pp. 74–77.