Potassium Decay Noise Modeling for the Pacific Ocean Neutrino Explorer (P-ONE)

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WNPPC

P-ONE

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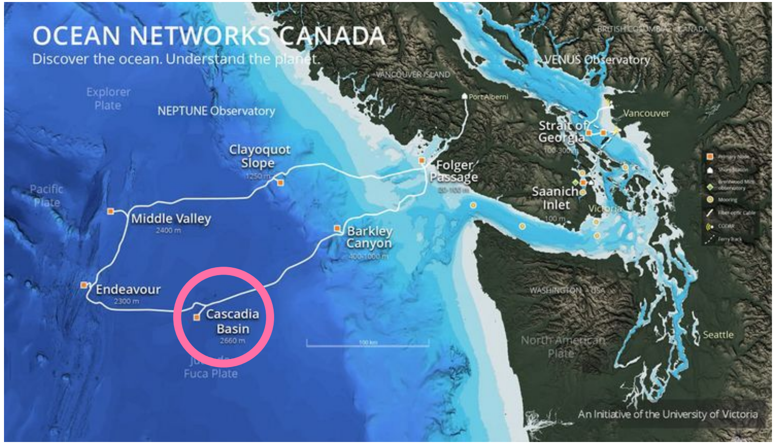
Studying Astrophysical Neutrinos

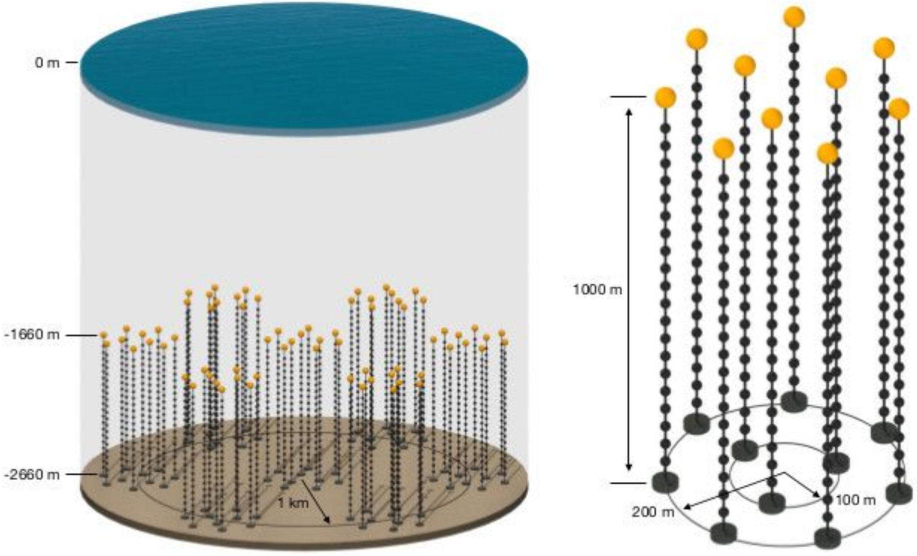
- The weakly interacting nature of neutrinos makes them great candidates for studying the physics behind violent astrophysical phenomena
- Recent observations using neutrino telescopes such as IceCube have thoroughly cemented the physics potential of neutrino astronomy
- Neutrino cross section with Earth increases with neutrino energy. The Earth ends up shielding observatories from high energy neutrinos
- Development of more observatories leads to increased sky coverage and an increased rate of event observations

What is P-ONE?

- Proposed cubic-kilometer scale neutrino telescope in the Pacific Ocean
- Make use of existing Ocean Networks Canada (ONC) infrastructure



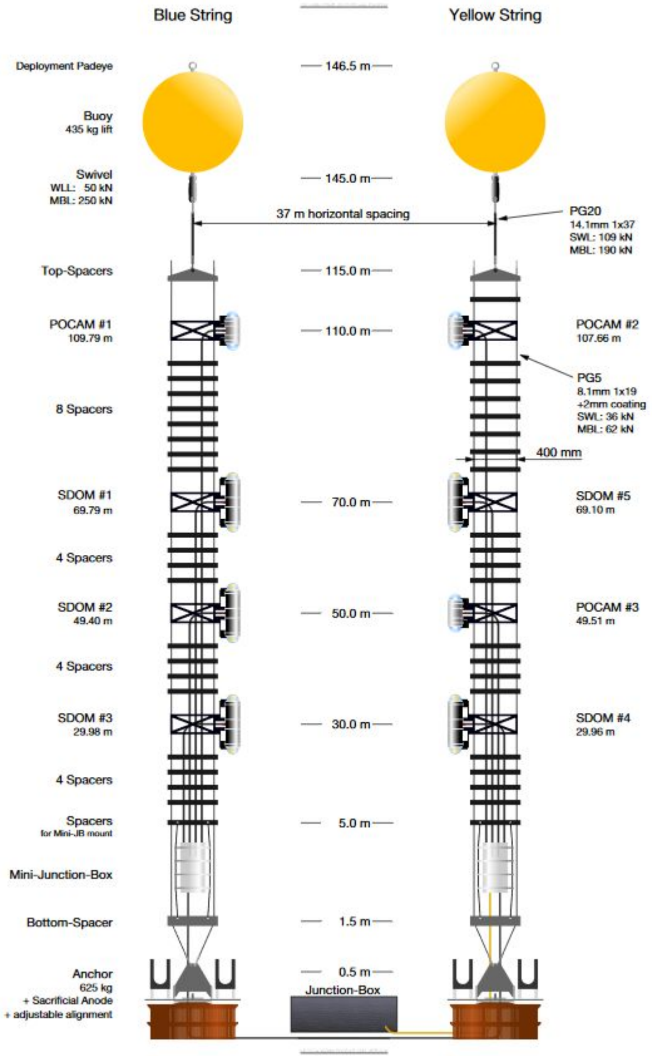
Map of the ONC NEPTUNE observatory. Credit to ONC [1]



Layout of P-ONE [1]

The STRAW Pathfinder

- Deployed in the Cascadia Basin to study site characteristics
  - **Scattering length**
  - **Absorption length**
  - **Ambient undersea background**
- System of two mooring lines equipped with
  - **Light flashing modules (POCAM)**
  - **Light sensing modules (SDOM)**
- Understanding background is important for future event trigger development



STRAW schematic [2]

Potassium Decay Noise Study

Radioactive Potassium Background

- Radioactive isotopes in saltwater undergo β^- decay producing electrons which can emit Cherenkov radiation. Potassium is a significant contributor to this decay noise

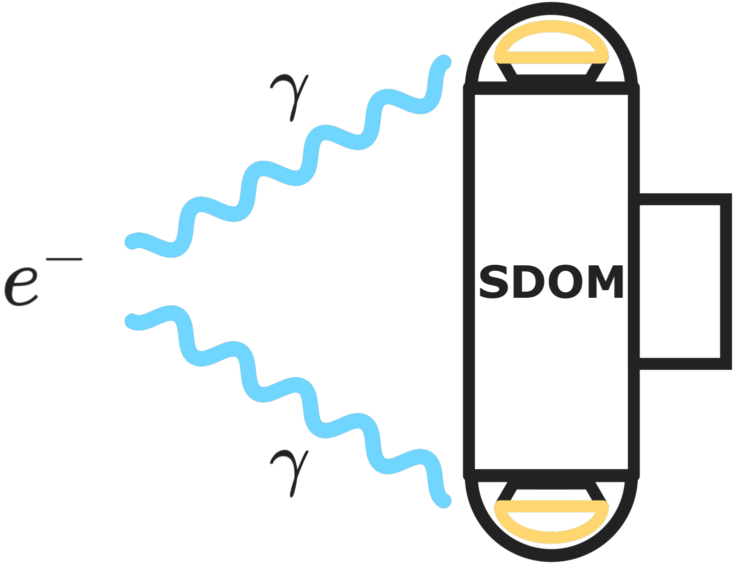
$$^{40}\mathrm{K} \rightarrow ^{40}\mathrm{Ca} + e^- + \bar{\nu}_e$$

- Unlike other stochastic noise sources, the potassium background is constant

- Simulate potassium activity around STRAW and compare to measured data

Coincident Detections

- Look for signals on adjacent PMTS that arrive at roughly the same time
- Plotting the coincidence rate per time differential should give a gaussian peaked at 0
- Compare STRAW coincidence analysis with simulation to verify simulation input parameters

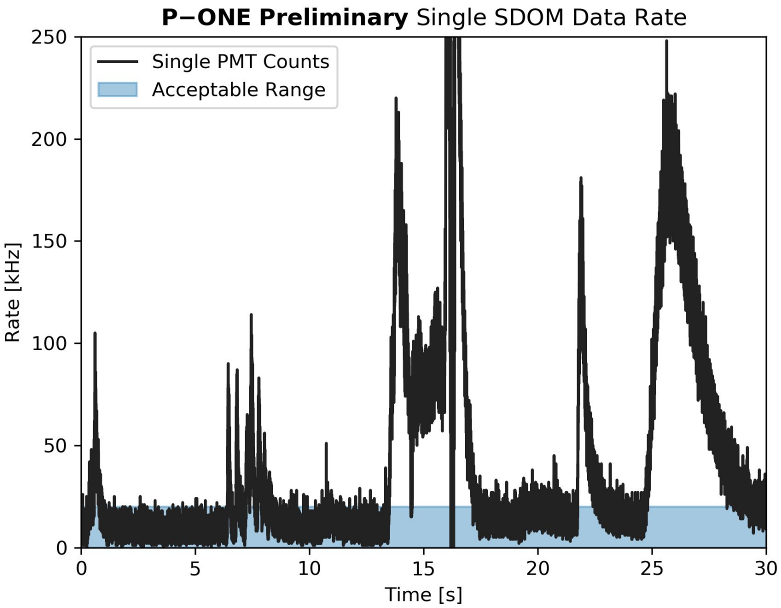


Example coincidence event

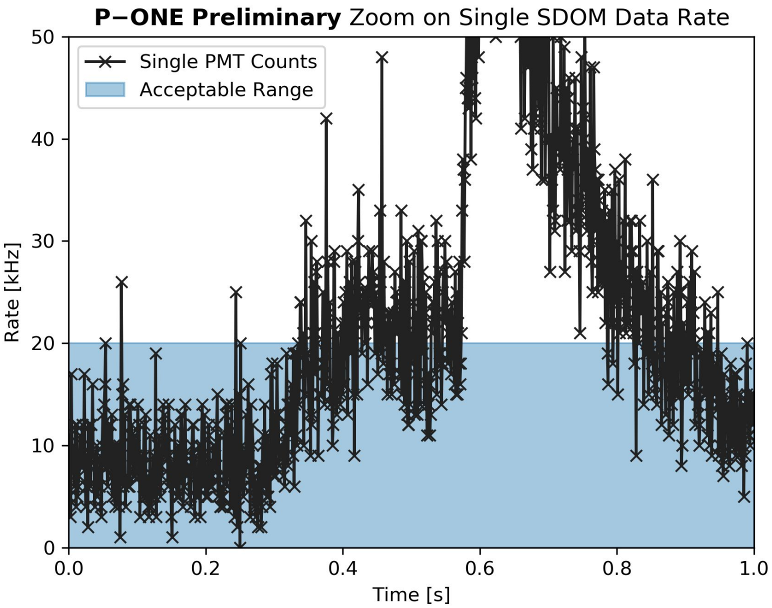
Finding Coincidences in STRAW Data

STRAW SDOM Measurements

- Potassium noise contributes to the low noise baseline in STRAW data
- For potassium coincidences, consider data from times of low hit rate (1-20 counts/ms)



SDOM data showing single PMT counts over 30 s



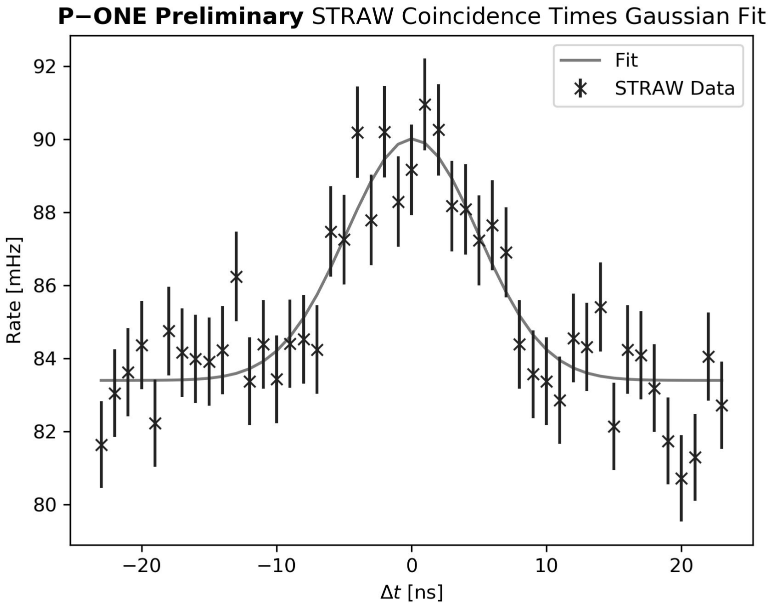
Single PMT counts over over the first second of data

STRAW Coincidence Fit

- Data collected from multiple SDOMs over 5 months in the summer of 2020
- About 16 hours of data collection analyzed for coincidences
- Considering only coincident hits with $\Delta t \leq$±25 ns

$$f = b + ae^{-\frac{\left(\Delta t - \bar{\Delta t}\right)^2}{2\sigma^2}}$$

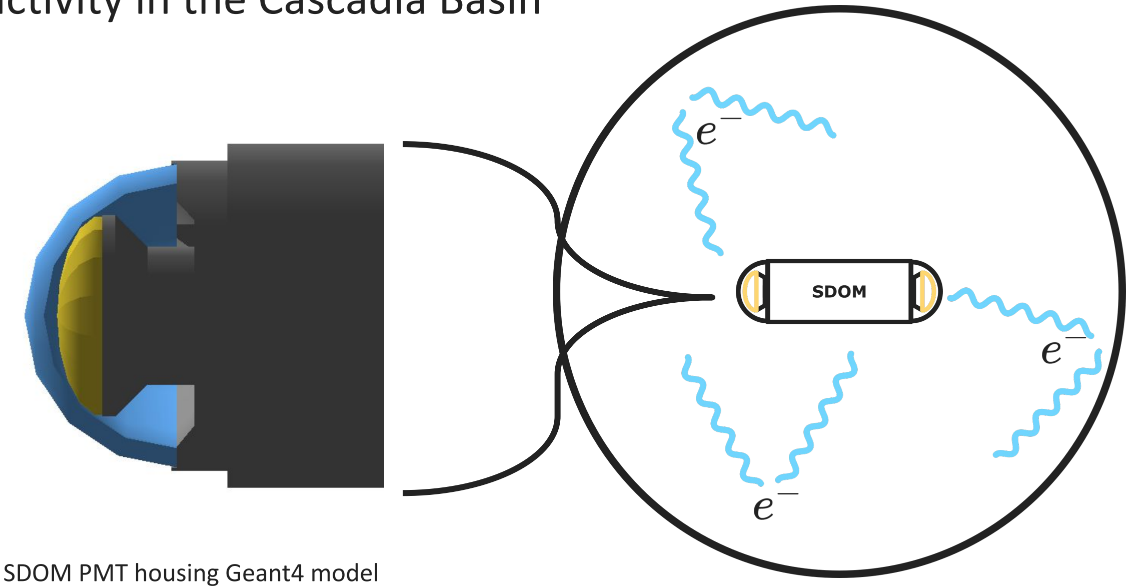
$b =$ 83.3 ± 0.3 mHz
$a =$ 6.6 ± 0.3 mHz
$\sigma =$ 4.9 ± 0.2 ns
$\bar{\Delta t} =$ 0.06 ± 0.2 ns



Simulating Potassium Activity

Simulation - Modeling

- Model an SDOM in Geant4 inside a spherical world of sea water
- Generate electrons throughout the 25 m radius spherical volume based on the rate of potassium activity in the Cascadia Basin

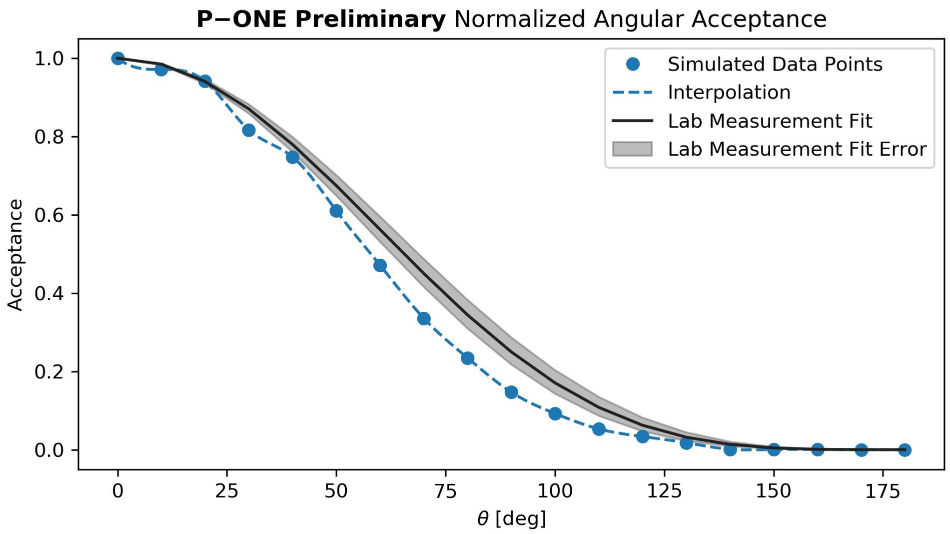


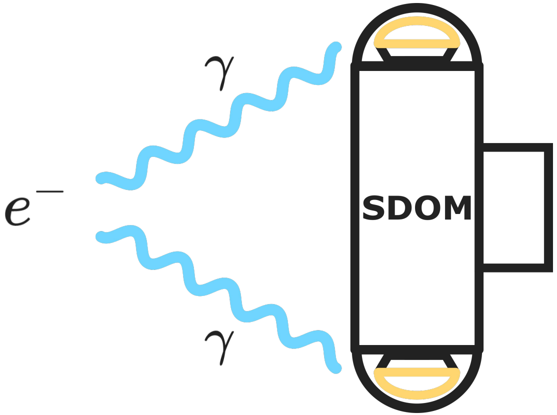
SDOM PMT housing Geant4 model

Geant 4 simulation world model

Simulation - Angular Acceptance

- The SDOM geometry is not ideal for making coincident measurements because most coincident photons are going to be arriving at large angles

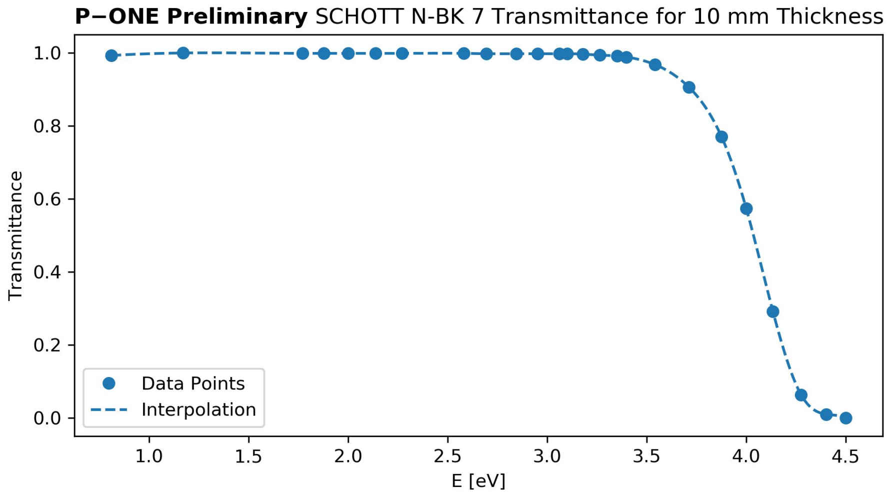


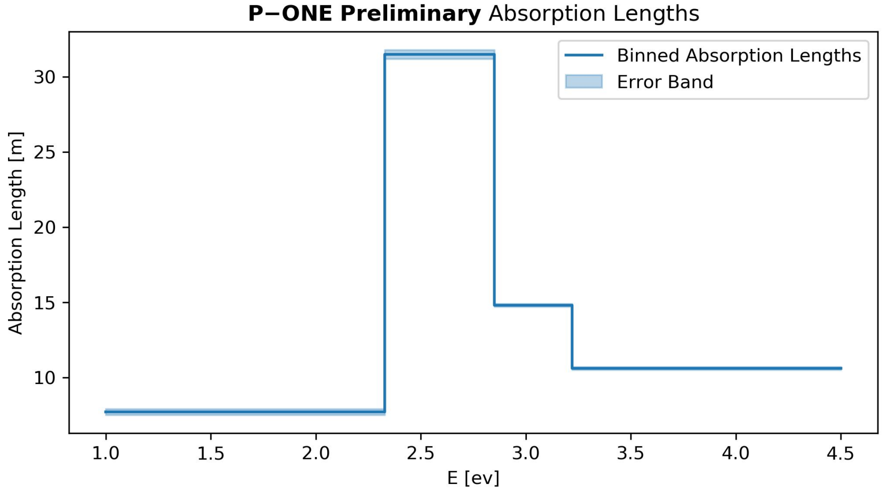


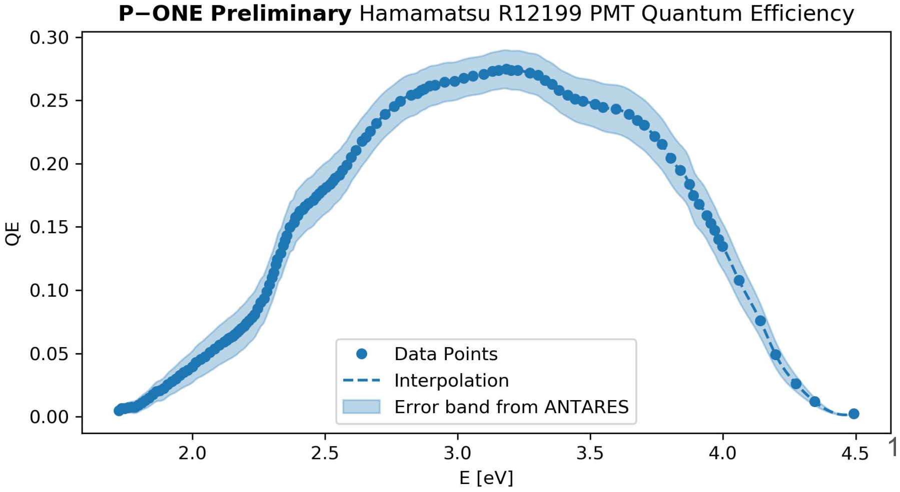
Simulated angular acceptance (blue) plotted against fit to measured angular acceptance data [2]

Simulation - Inputs

- Inputs into simulation and analysis include
  - **Absorption length in water**
  - **Glass and gel transmittance**
  - **PMT geometry**
  - **PMT quantum efficiency**
  - **PMT transit time ~ 6.5 ns**
  - **DAQ trigger efficiency ~ 85%**





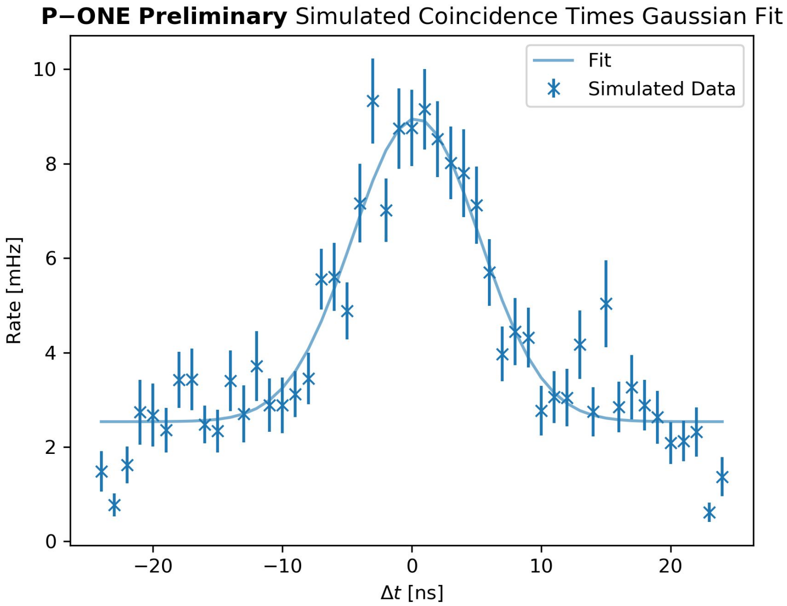


Simulated Coincidence Fit

- Ran electron generation simulation using a single SDOM at the centre of the water volume
- Total of about 2.7 minutes of data simulated in Geant 4

$$f = b + ae^{-\frac{\left(\Delta t - \bar{\Delta t}\right)^2}{2\sigma^2}}$$

$b =$ 2.5 ± 0.2 mHz
$a =$ 6.42 ± 0.02 mHz
$\sigma =$ 4.92 ± 0.02 ns
$\bar{\Delta t} =$ 0.33 ± 0.02 ns



Systematic Error Analysis

Potential Sources of Error

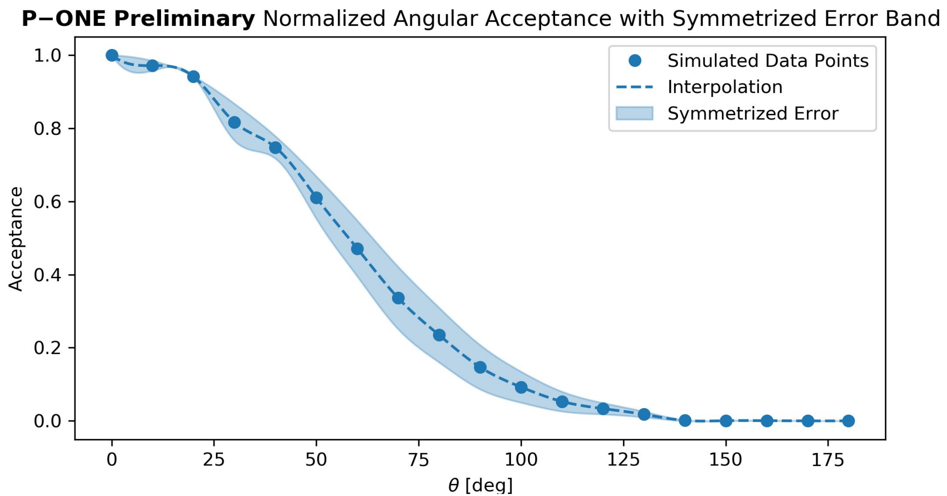
- Sources of systematic error considered
  - **Angular acceptance**
  - **Quantum efficiency**
  - **Absorption length**
  - **Transit time**
- First three factors come in as a multiplicative scaling term for counts on each PMT
- Total error is obtained from summing the relative errors in quadrature

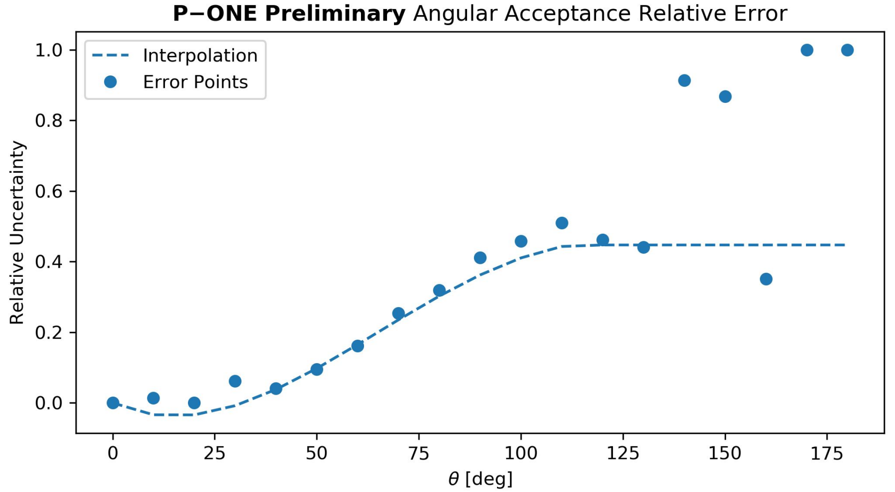
Angular Acceptance Error

- Dominant simulation error
- Assumed symmetrized error band based on the ratio of the simulated fit to the measured fit

$$\text{Error} = 1 - \frac{\text{Simulated Fit}}{\text{Measured Fit}}$$

- Fit a polynomial to relative error points and assumed constant error beyond measured data

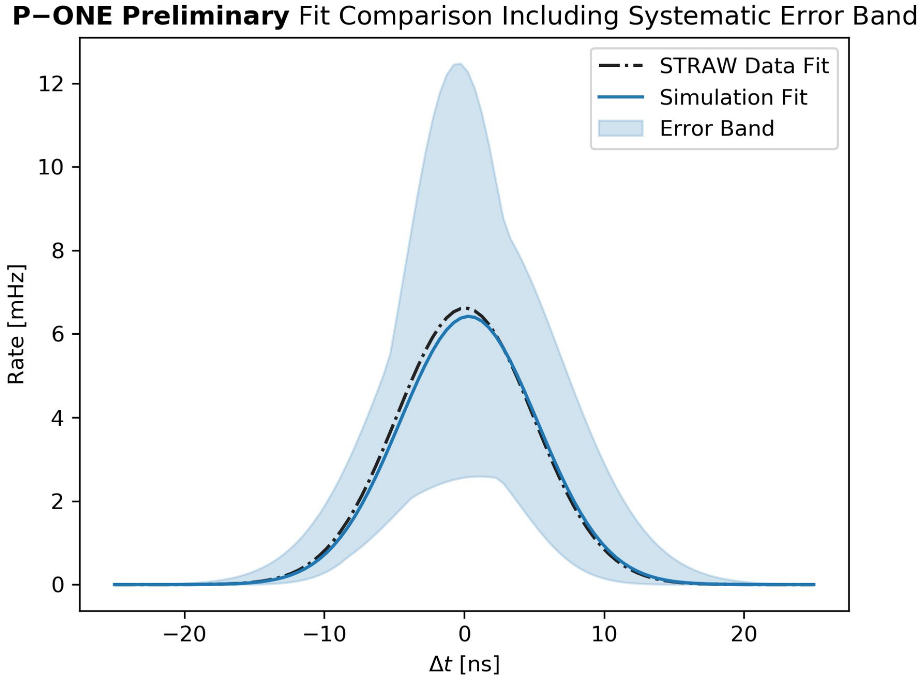


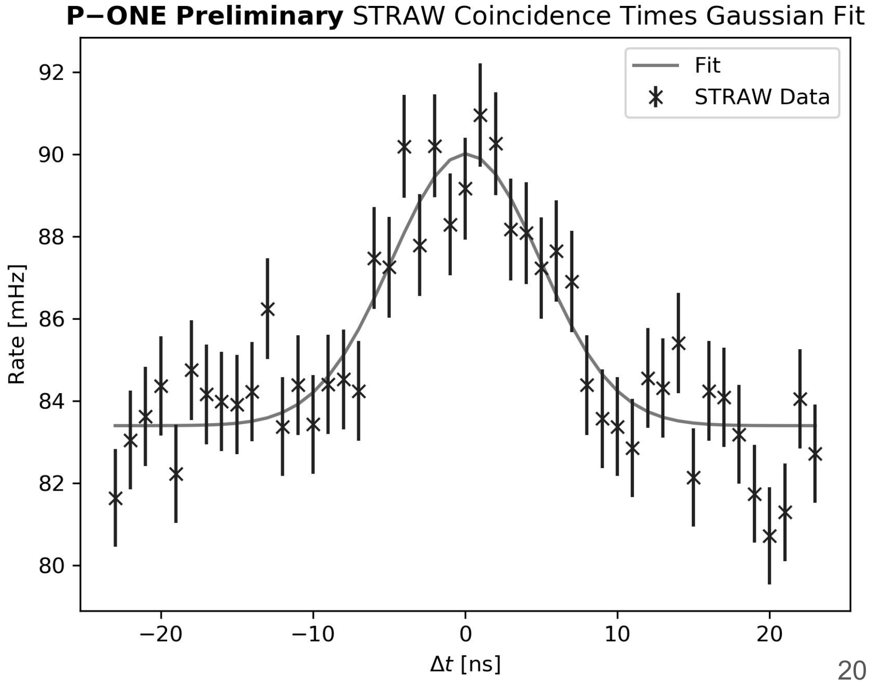


Analysis Results

Comparing Gaussian Fits Including Error

- Removing the baseline so that only true coincidences are considered, we can compare the fits including a final systematic error band





Detector Effective Volume and Ocean Salinity

- Calculate effective volume

$$V_{\text{eff}} = \frac{n_d}{n_{gen}} V_{gen} = 8.7 \pm 4.7 \text{ cm}^3$$

- Calculate potassium activity rate

$$B_q = \frac{1}{V_{\text{eff}}} \frac{a\sigma\sqrt{2\pi}}{\Delta\tau} = 9.3^{+10.8}_{-3.3} \times 10^3 \, \frac{\text{Decays}}{\text{sm}^3}$$

- Calculate salinity

$$r_s = \frac{r_K r_I \rho}{B_q} \frac{\ln 2}{\tau_{1/2}} \frac{N_A}{A} = 2.7^{+3.1}_{-0.9} \, \%$$

- From Ocean Networks Canada (ONC) the Pacific Ocean salinity should be roughly constant at 3.482 % [7]

Conclusions

- Simulation based on measured in situ inputs confirms validity of model undersea environment
- Successful closure check showing that simulations using measured parameters and natural potassium match directly observed site characteristics
- Direct confirmation that the water properties found using POCAM flashes are correct
- Understanding the water properties in the Cascadia Basin is critical for future developments of P-ONE

References

[1] P-ONE, “Pacific Ocean Neutrino Explorer: Towards a new neutrino telescope in the pacific” 2019. https://www.pacific-neutrino.org/

[2] M. Boehmer et al., “Straw (strings for absorption length in water): pathfinder for a neutrino telescope in the deep pacific ocean,” Journal of Instrumentation, vol. 14, pp. P02013–P02013, 2 2019.

[3] M. Aartsen et al., “Multimessenger observations of a flaring blazar coincident with high-energy neutrino icecube-170922a,” Science, vol. 361, 7 2018.

[4] M. G. Aartsen et al., “Measurement of the multi-tev neutrino interaction cross-section with icecube using earth absorption,” Nature, vol. 551, 11 2017.

[5] A. Albert et al 2018 arXiv:1805.08675v2

[6] S. Aiello et al 2018 JINST13 P05035

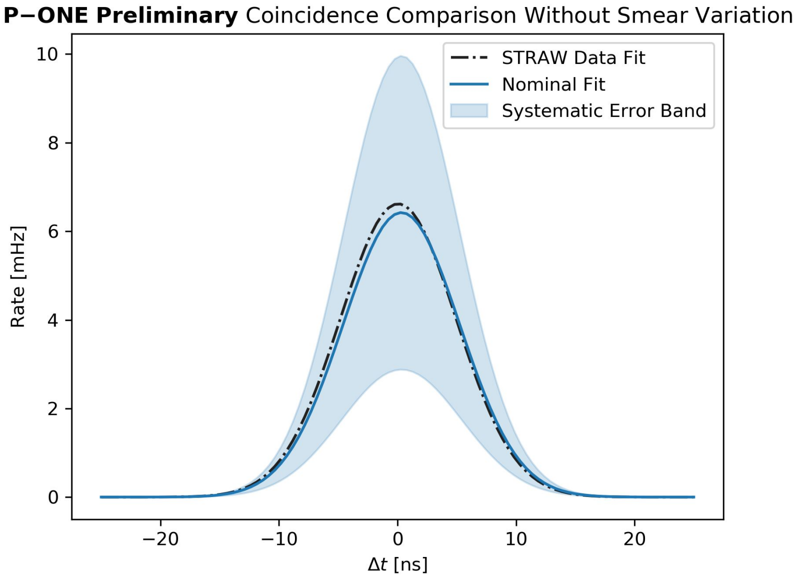
[7] Ocean Networks Canada, "Cascadia Basin," 10 Feb 2021. [Online]. Available: https://www.oceannetworks.ca/observatories/pacific/cascadia-basin#SOO-ODP1026.

Questions?

Backup Slides

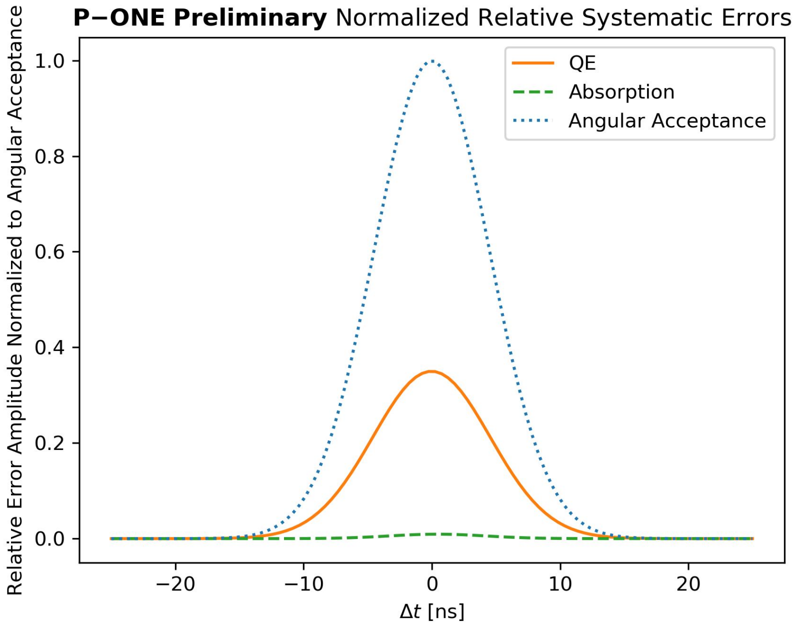
Coincidence Fit Without Smear Variation

- Gaussian fit without smear variation. These fits were used for integrating during effective volume calculations



Systematic Error Comparison

- Plot of all relative systematic errors normalized to the dominant error
- Error dominated by uncertainty in angular acceptance

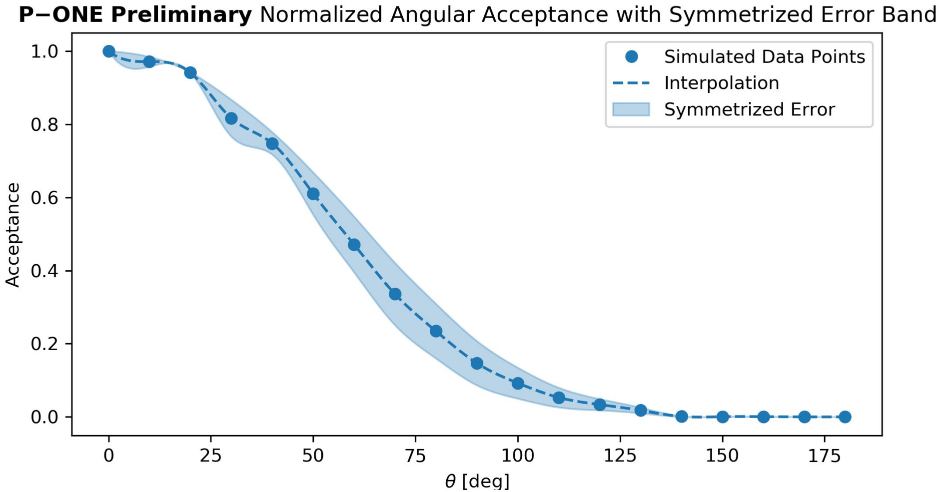


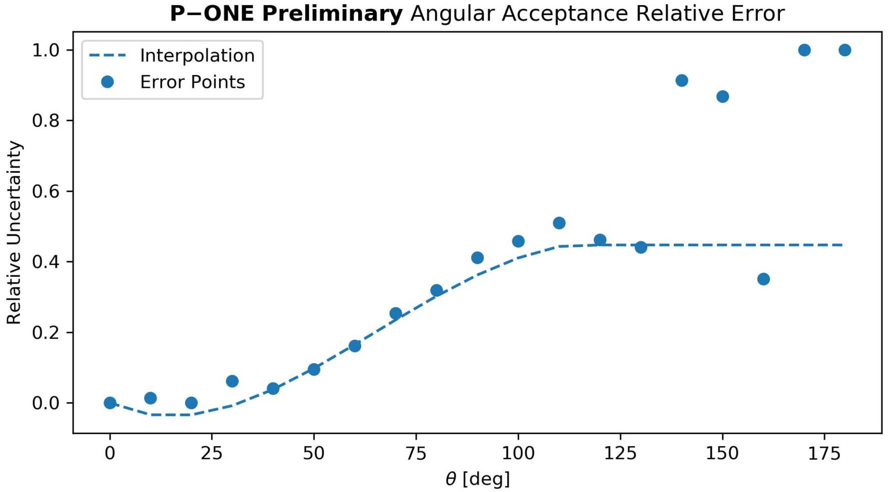
Angular Acceptance Error

- Added a symmetrized error band based on the ratio of the simulated fit to the measured fit

$$\text{Error} = 1 - \frac{\text{Simulated Fit}}{\text{Measured Fit}}$$

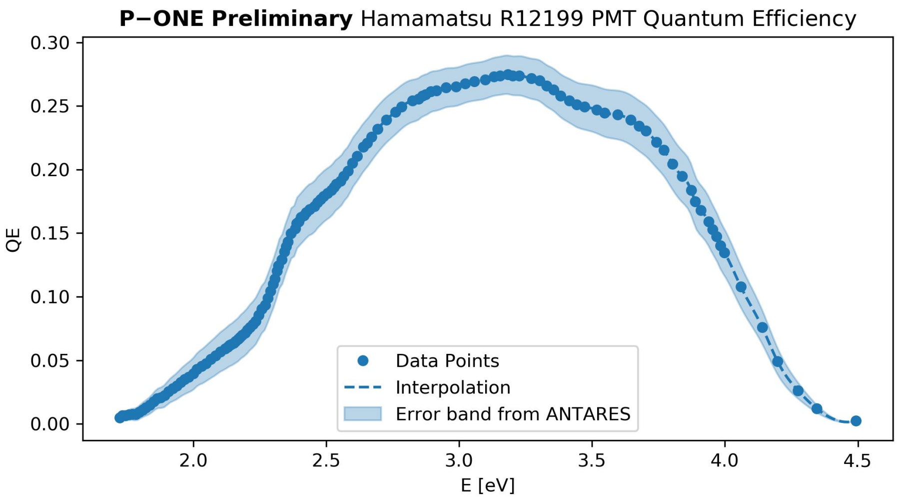
- Fit a 4th order polynomial to the relative error points and assumed constant error beyond measured data points

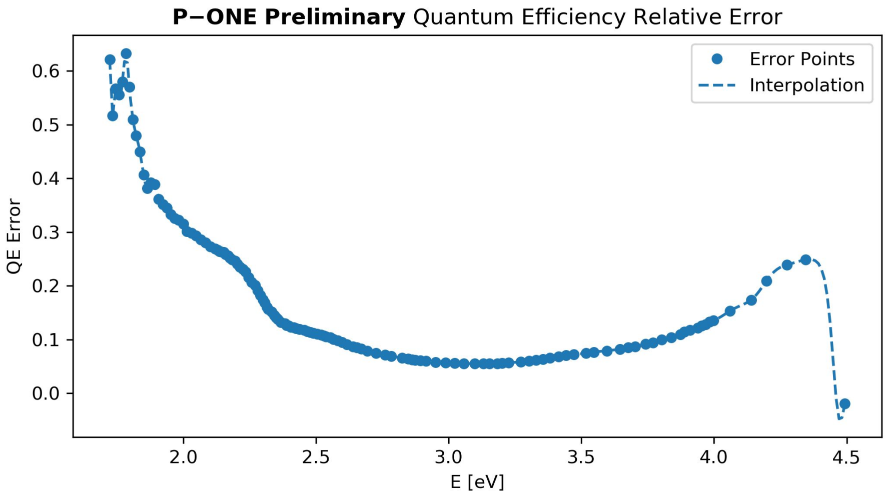




Quantum Efficiency Error

- Error band based off of KM3NeT PMT characterization [6]
- Relative error found by ratio of absolute QE error and QE





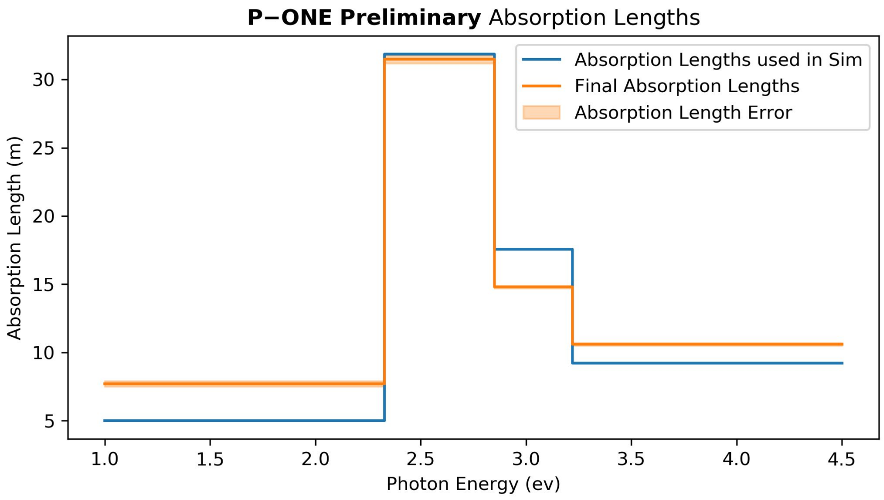
Absorption Length Error

- Scaled by ratio of exponential decays based on absorption length assuming negligible scattering

$$\text{Scaling} = \frac{e^{-r/\lambda_{\text{New}}}}{e^{-r/\lambda_{\text{Old}}}}$$

- Relative error found for each bin

$$\sigma = \sqrt{\left(\frac{\partial f}{\partial x}\right)^2 \Delta x^2}, \;\; f = \frac{e^{-r/\lambda_{\text{New}}}}{e^{-r/\lambda_{\text{Old}}}}, \;\; x = \lambda_{\text{New}}$$

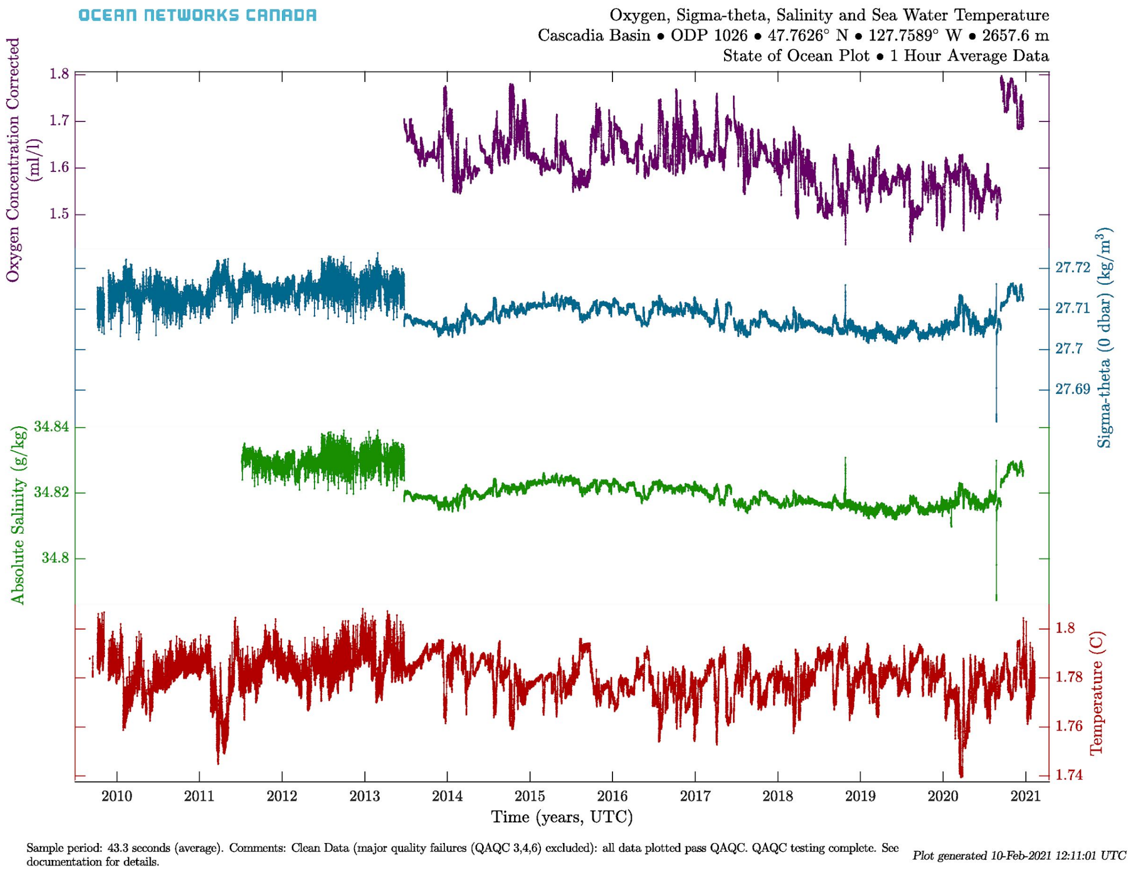


$$\sigma = \frac{r}{\lambda_{\text{New}}^2} \frac{e^{-r/\lambda_{\text{New}}}}{e^{-r/\lambda_{\text{Old}}}} \Delta\lambda_{\text{New}} \rightarrow \sigma_{\text{Relative}} = \frac{r}{\lambda_{\text{New}}^2} \Delta\lambda_{\text{New}}$$

Transit Time Error

- The time it takes for the PMT to output a signal from an incident photon is dependent on where the photon hits the PMT
- Need to add gaussian smearing to simulation data
- Appropriate smearing for large angles measured to be about 6.5 ns for the nominal case but we apply an error of ± 1 ns

ONC Cascadia Basin Water Properties



Cascadia Basin water properties. Plot by ONC [7]