CAP Congress 2022
New Directions in Accelerator Based Experiments

Photogrammetry Calibration of the Super-K and Hyper-K Detectors

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TRIUMF: Patrick de Perio, **Rhea Gaur**, Xiaoyue Li, Nick Prouse, Michael Sekatchev

University of Winnipeg: Tapendra B. C., Blair Jamieson

Imperial College London: Dan Martin, Mark Scott

Presentation Outline

Introduction to the Current and Future Kamiokande Water Cherenkov Detectors

Reducing Systematic Uncertainty: The Photogrammetry Pipeline

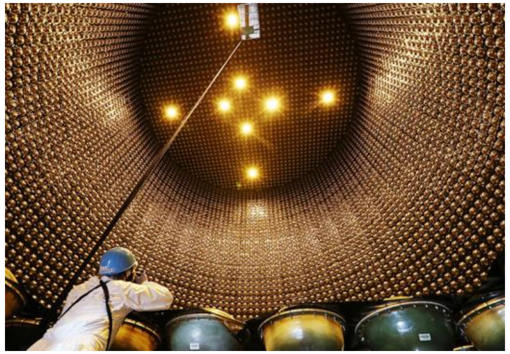
Novel Underwater Survey of Super-K

Preliminary Results with Super-K

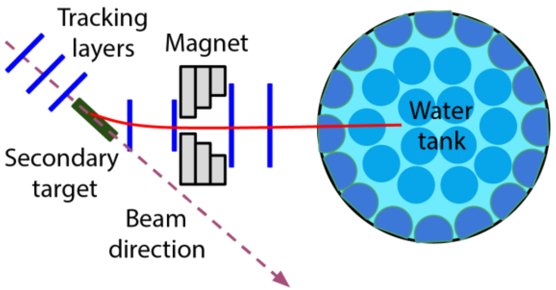
Research and Development for Hyper-K

Present and Future Water Cherenkov Detectors

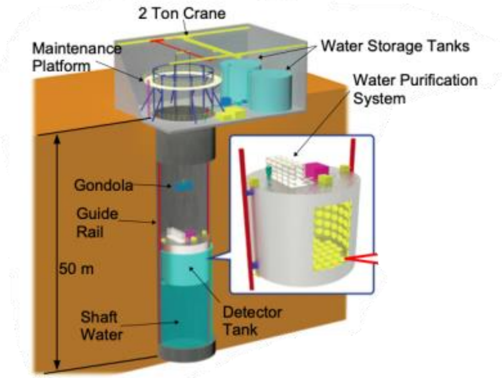
1996 – Present	*2024 – TBD*	*2027 – ∞ ??*	
Super-Kamiokande	**Water Cherenkov Test Experiment (WCTE)**	**Intermediate Water Cherenkov Detector (IWCD)**	**Hyper-Kamiokande**
• 41.4m x 39.3m • 50 000 tonnes • **~11 000 PMTs** • 2015 shared Nobel prize for neutrino oscillation discovery • T2K (Tokai to Kamioka) neutrino beam	• 3.5m x 4m • 50 tonnes • **100 PMTs** • IWCD prototype • Charged particle test beam experiment at CERN	• 8m x 10m • 600 tonnes • **480 PMTs** • In J-PARC neutrino beam • Study neutrino-nucleus interactions	• 71m x 68m • 187 000 tonnes (8x Super-K) • **>20 000 PMTs** • Precision ν oscillation (295km from JPARC) • Neutrino astronomy



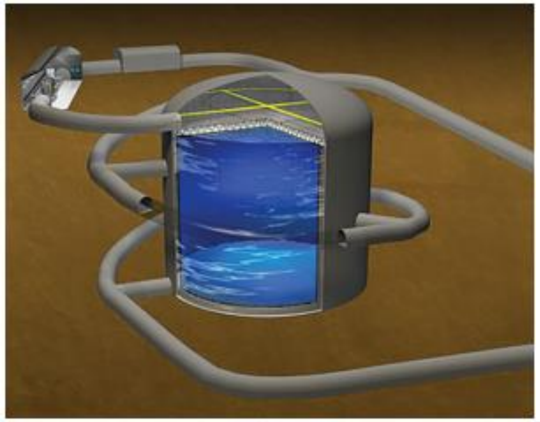
Inside of Super-K detector.



WCTE concept in well understood CERN beam.



IWCD concept scanning various angles relative to the neutrino beam direction.



Hyper-K detector concept.

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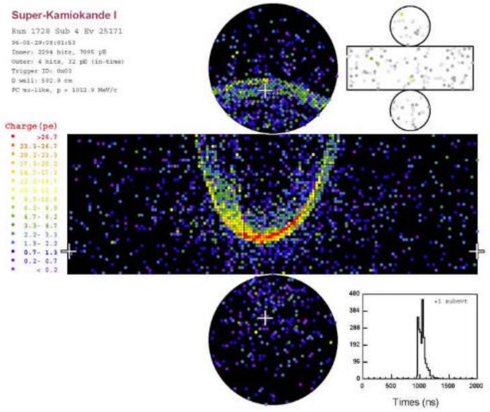
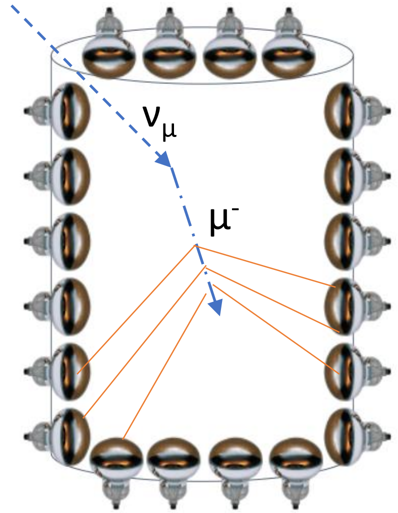
Problem: Systematic Uncertainty

- Current physics simulations and event reconstructions use “ideal”, design geometry
  - Assuming perfect array of pixels

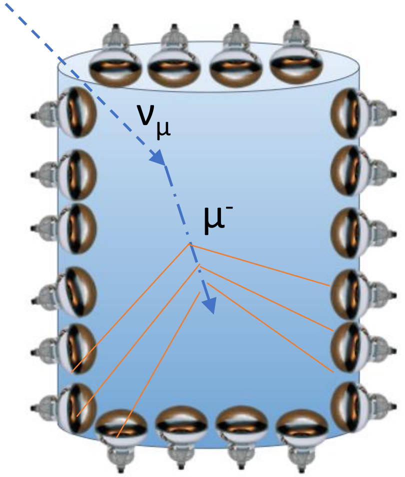


Super-K event display showing Cherenkov ring from muon neutrino event.



“Ideal” orientations of PMTs around detector.

- Require precise vertex reconstruction (start of particle track)
  - Fiducial error ~1%
- Uncertainty in PMT positions
  - Buoyancy effects can change the positions of PMTs after water filling, potentially introducing geometric distortions.

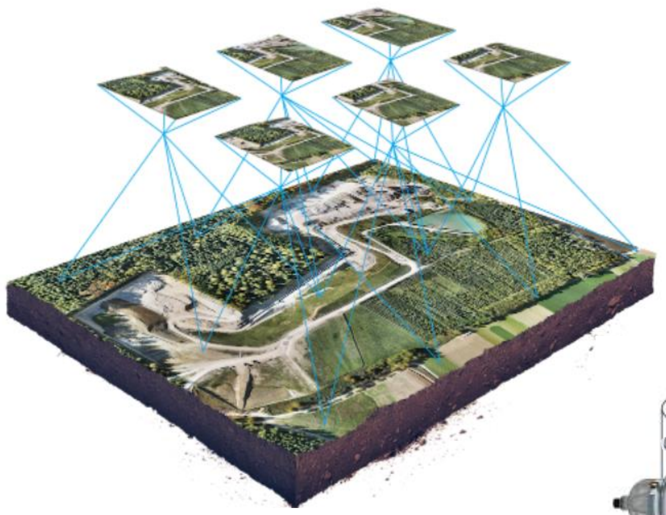


Water-filled detector induces buoyancy effects, changing PMT orientations and positions.

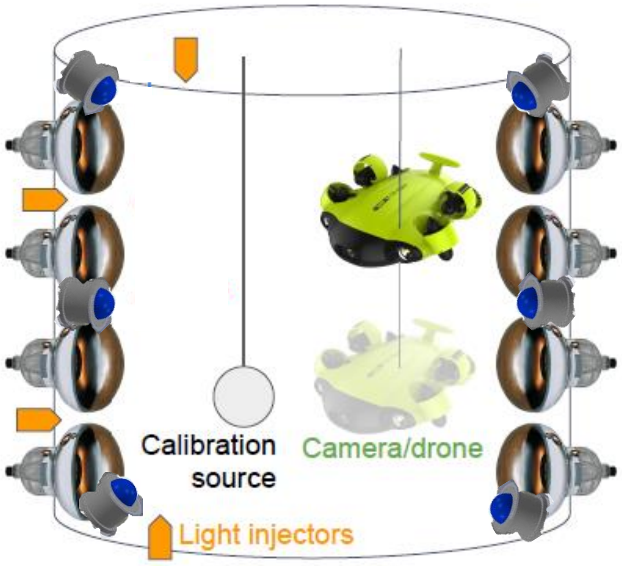
Solution: In-situ Calibration via Photogrammetry

Solution: Photogrammetry

- Uses 2D images of the detector to reconstruct the geometry in 3D world coordinates
- Addressing uncertainties in photosensor (pixel) positioning that limit measurement precision
- Aiming to achieve sub-cm precision

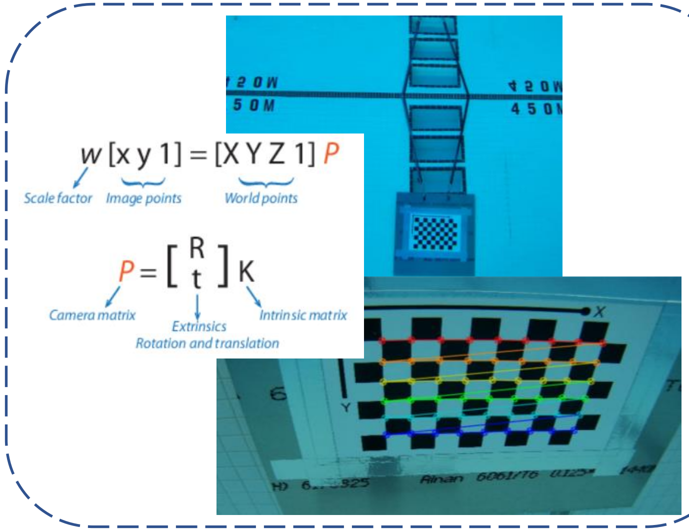


2D images are used to extract information about the features and geometry of 3D objects.



Photogrammetry concept for a water Cherenkov detector with fixed cameras and a remote operated vehicle (ROV drone).

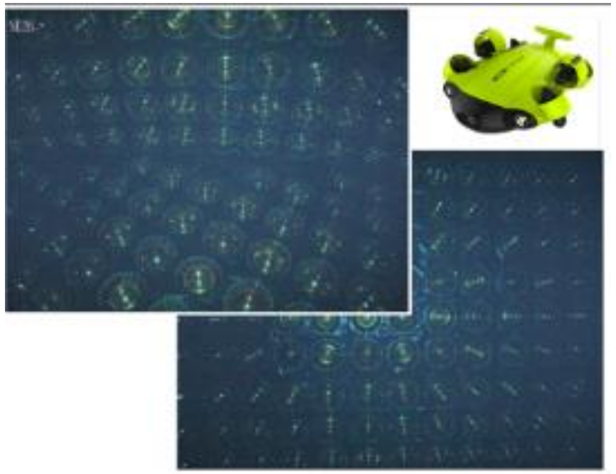
The Photogrammetry Pipeline



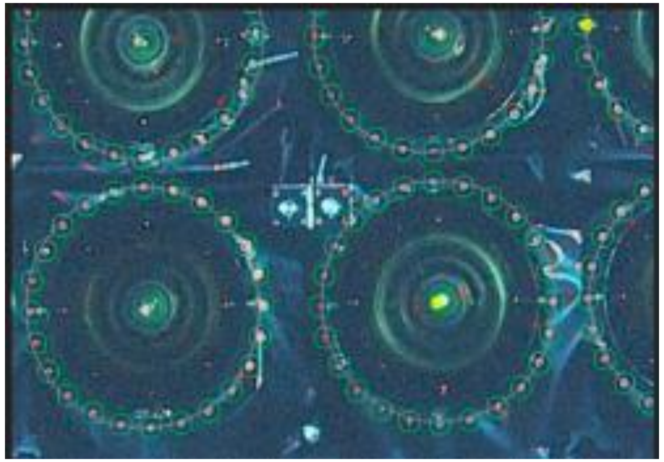
Camera Calibration

Calibration Photos → Optics Calibration

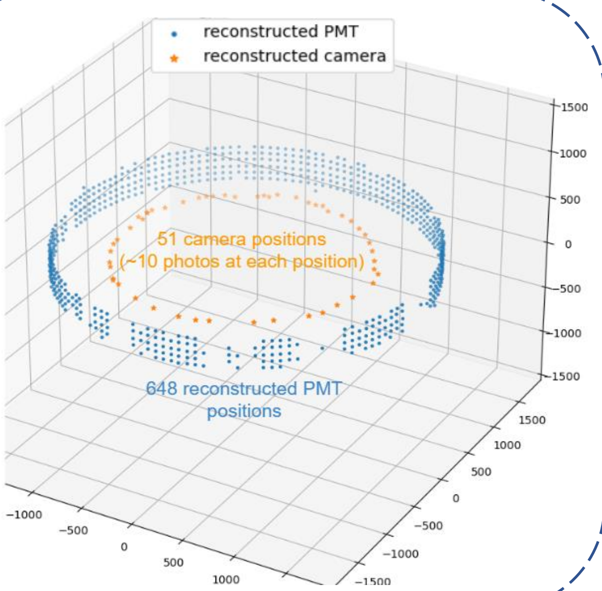
Photos of detector



Feature Detection



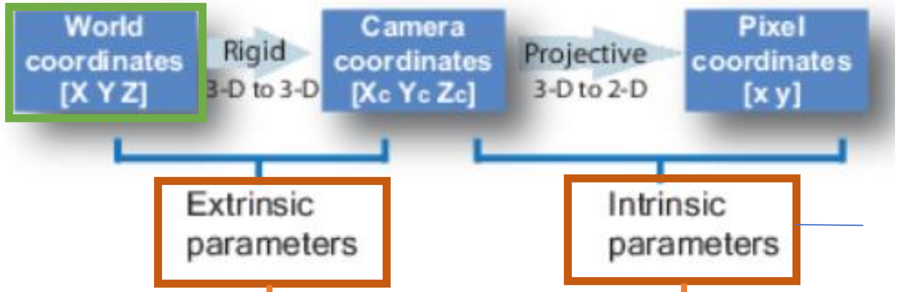
Stereoscopic Reconstruction



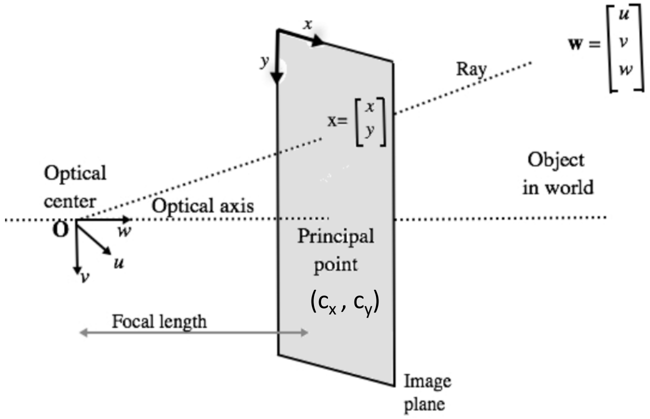
Underwater Camera Calibration

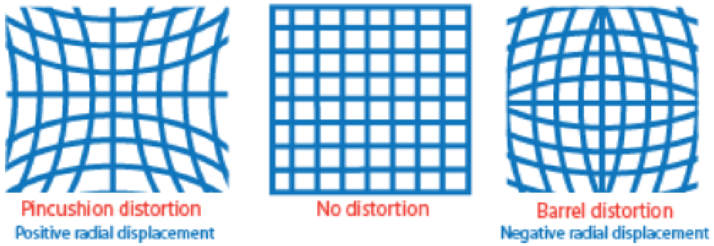
Unknown
Known

Reprojected/
image point



Camera model (intrinsic parameters and lens distortion) can be constrained using chessboard pattern with features of known size.





$$x_{distorted} = x(1 + k_1{*}r^2 + k_2{*}r^4 + k_3{*}r^6)$$

$$y_{distorted} = y(1 + k_1{*}r^2 + k_2{*}r^4 + k_3{*}r^6)$$

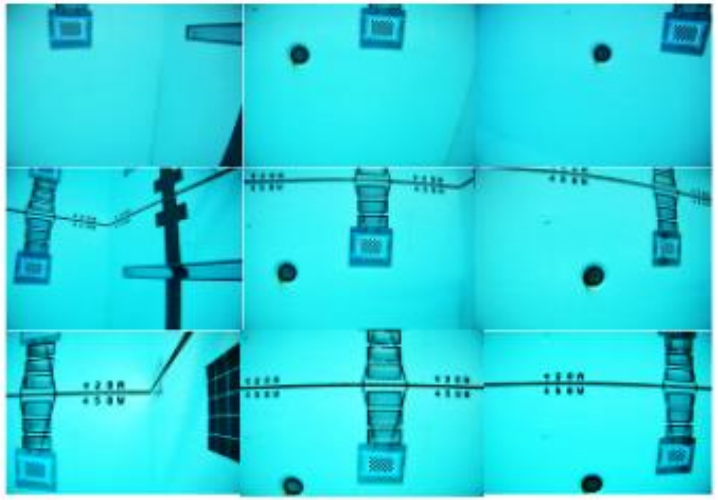
Lens distortion model used to correct for radial distortion.

$$w\,[x\ y\ 1] = [X\ Y\ Z\ 1]\,P$$

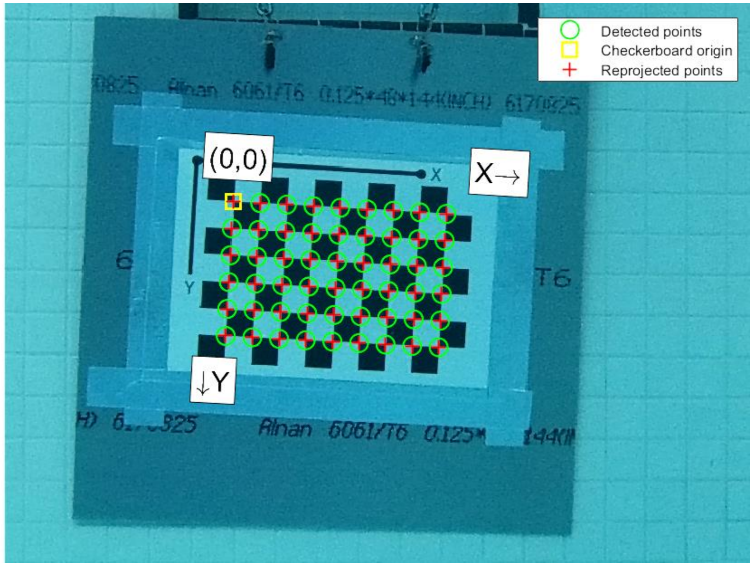
Scale factor | Image points | World points

$$P = \begin{bmatrix} R \\ t \end{bmatrix} K \qquad K = \begin{bmatrix} f_x & 0 & 0 \\ s & f_y & 0 \\ c_x & c_y & 1 \end{bmatrix}$$

Camera matrix | Extrinsics, Rotation and translation | Intrinsic matrix



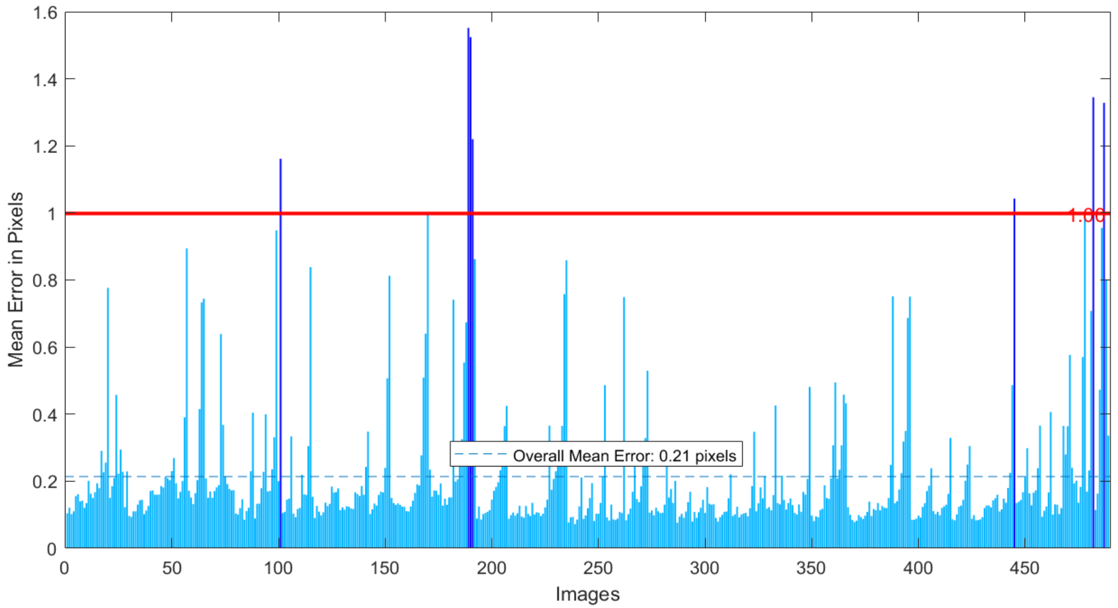
Calibration pattern imaged with Fifish V6 drone in different parts of the FOV.



Chessboard pattern with detected and reprojected square corners.

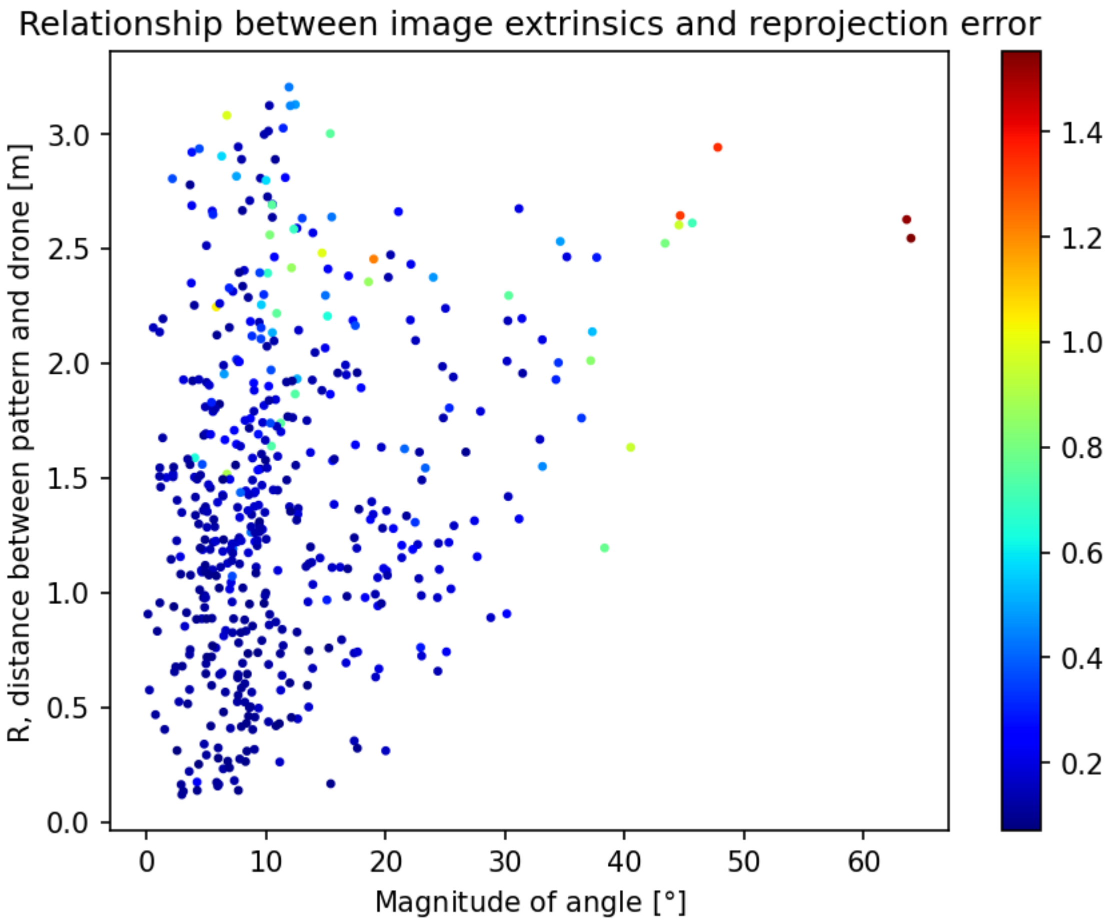
Super-K Underwater Drone Calibration

- Higher order description of distortions
- Systematic image acquisition procedure
- Large image sets
- Improved reprojection errors



New reprojection errors for SK drone image set. Mean error = 0.21 pixels.
Improved from previous mean error of 0.51 pixels.

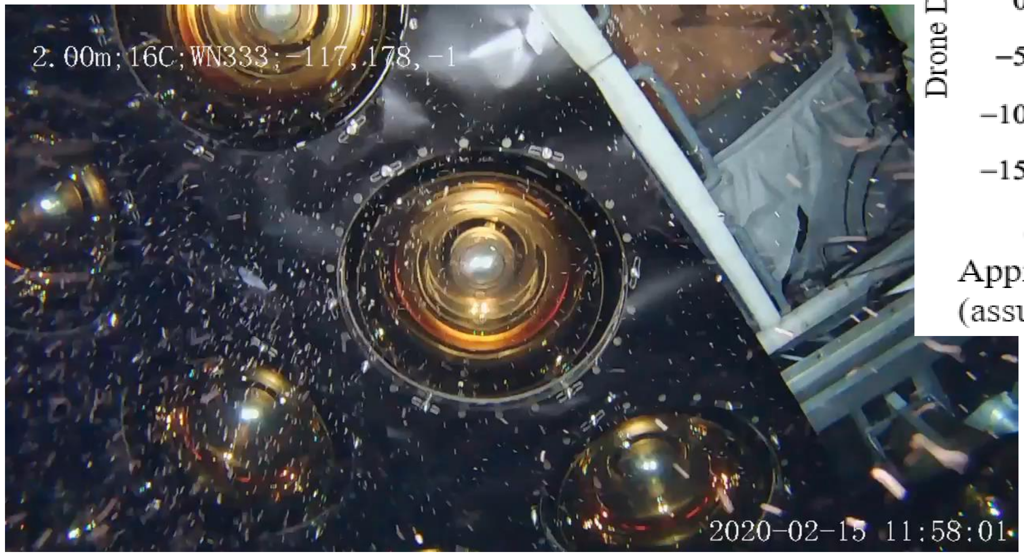
- Optimal camera positioning relative to calibration pattern to minimize reprojection error and build accurate models.



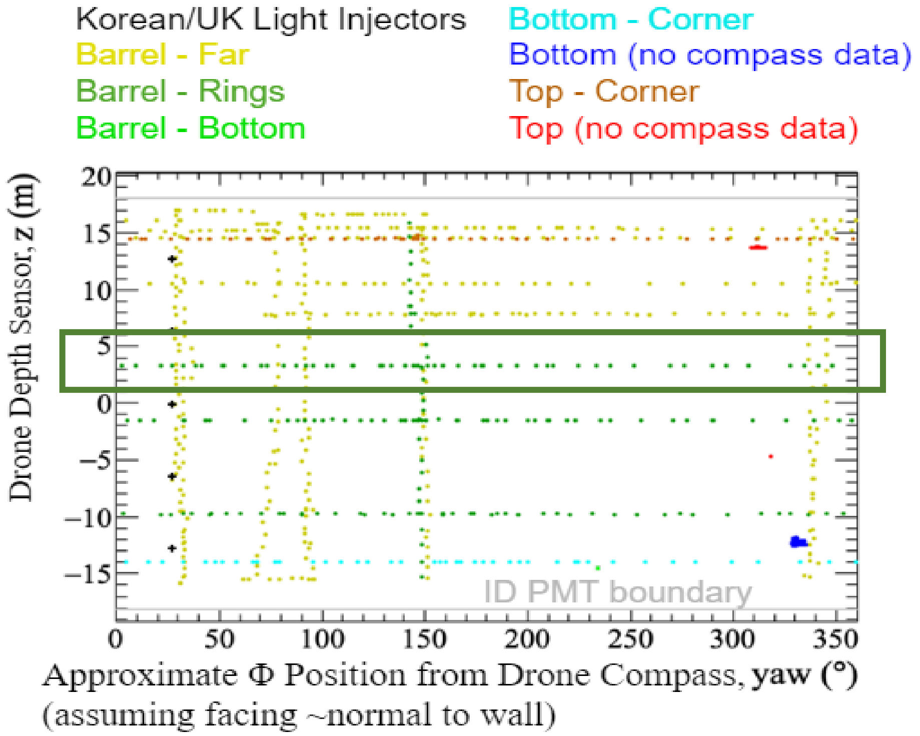
First Underwater Survey of Super-Kamiokande

- 2020: photos of Super-K collected using QYSEA Fifish V6 underwater drone
  - ~13 000 images taken of entire detector

Canadian Super-K group members operating ROV in the Super-K tank.

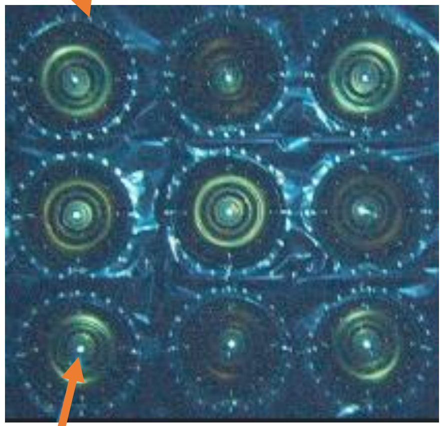


Drone deployment in Super-K.

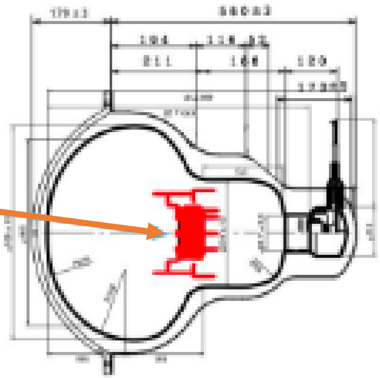


Feature Recognition

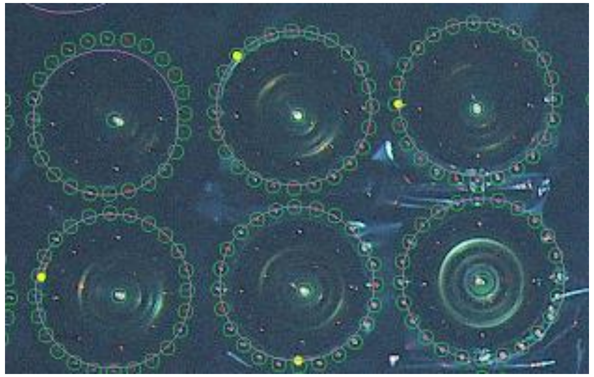
PMT surrounding bolts.



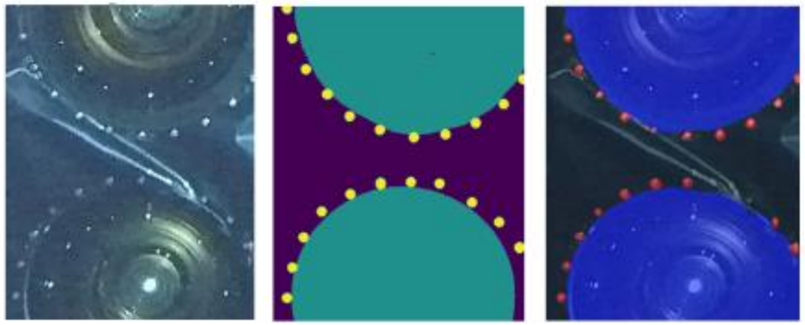
PMT dynode



- Detection and matching of PMTs across almost identical images.
- Image processing methods target outlines of PMTs and surrounding bolts.
  - Traditional blob detection and Hough transforms using OpenCV software.
  - Machine learning CNN using UNet with Image Segmentation Keras package
- Output is PMT centres in each 2D image.
- PMT numbers labelled with reference to light injectors.
- Current feature detection precision ~2-4 pixels
  - Work for improvements underway.
  - Incorporating PMT bolts into feature recognition output.



Blob detection and Hough transform ellipse finding algorithm.



Original Image

Segmented by eye for network training

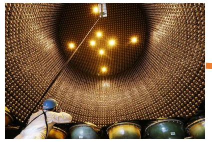
Segmentation by CNN

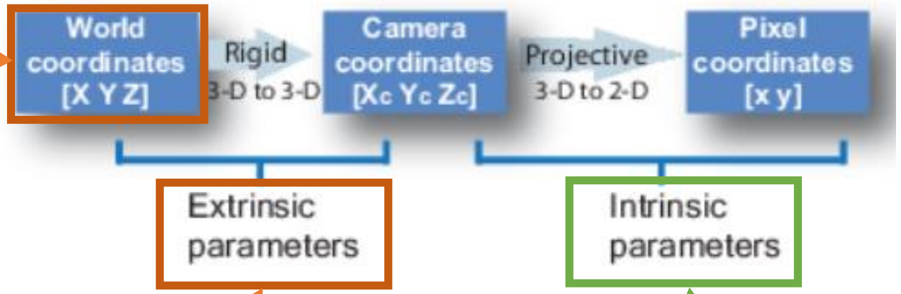
Stereoscopic Detector Reconstruction

Unknown
Known

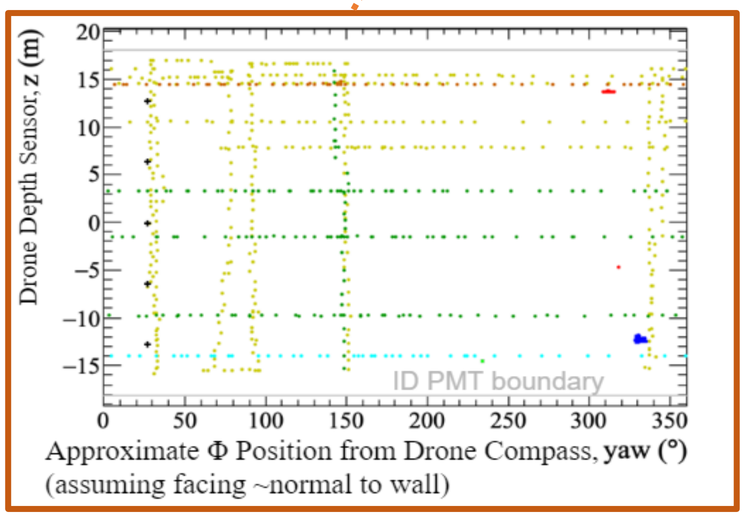
- Photogrammetric reconstruction of detector using detected feature positions:

1. First fit for approximate camera poses (extrinsics) performed assuming fixed design geometry and intrinsics from calibration.
2. Minimize reprojection error by simultaneously varying camera poses and 3D feature positions (world coordinates).





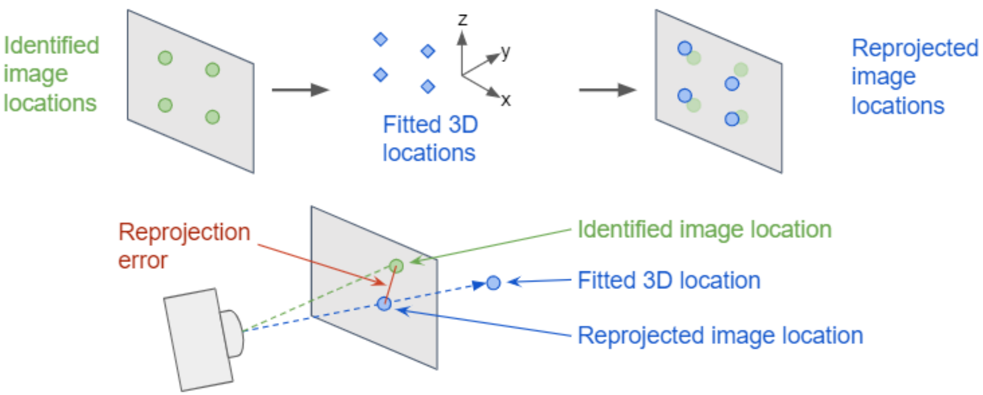
(Sensor data not yet used to constrain)



$$\begin{bmatrix} f_x & 0 & 0 \\ s & f_y & 0 \\ c_x & c_y & 1 \end{bmatrix}$$

$$x(1 + k_1{*}r^2 + k_2{*}r^4 + k_3{*}r^6)$$

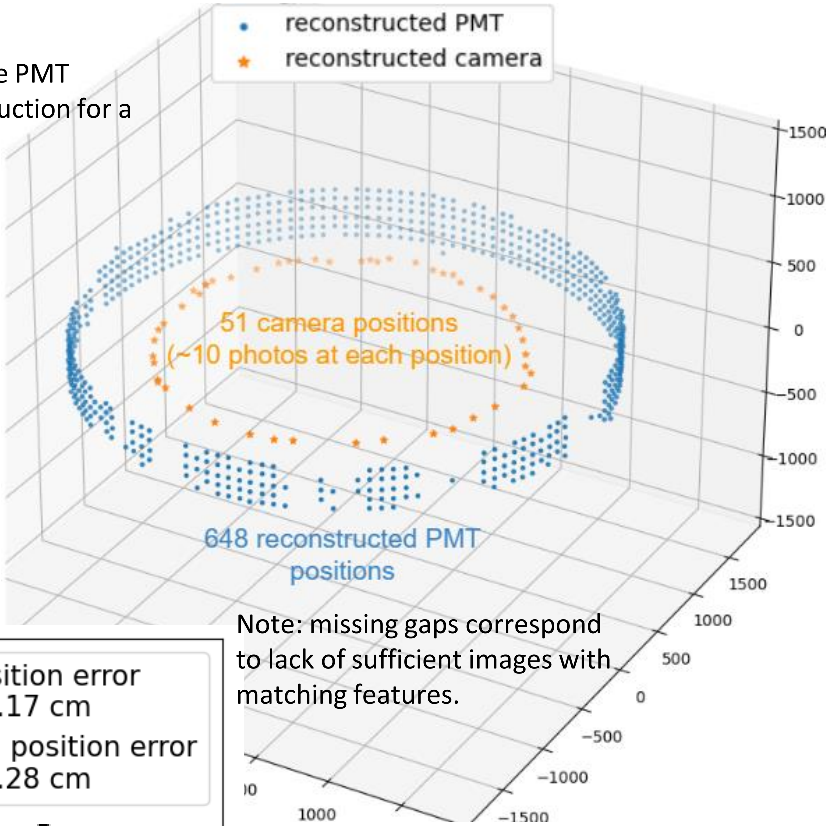
$$y(1 + k_1{*}r^2 + k_2{*}r^4 + k_3{*}r^6)$$



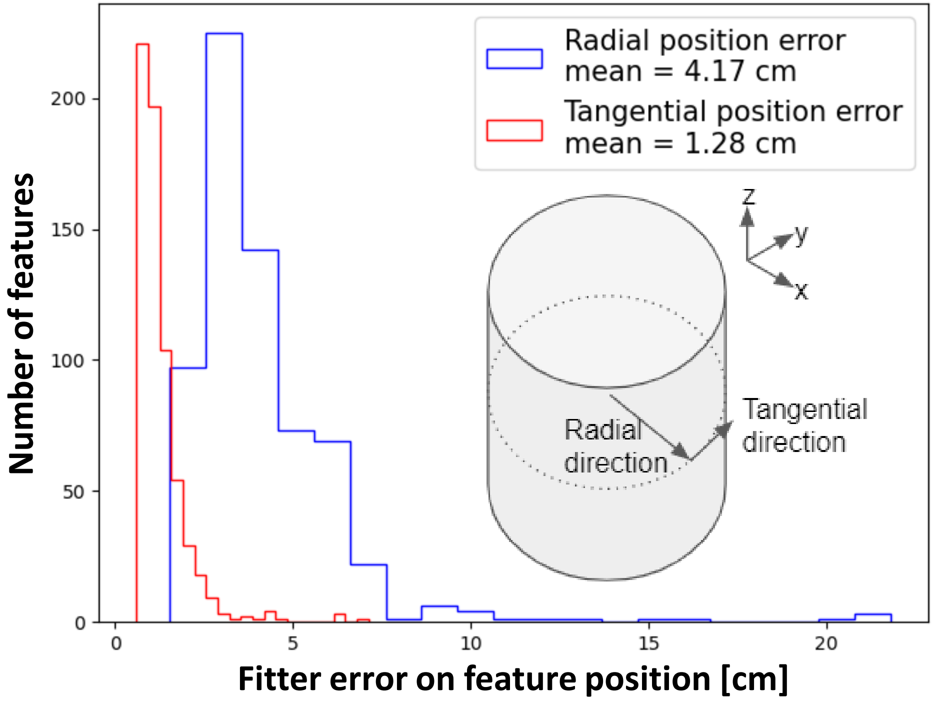
Super-K Results

- First reconstruction of ring of PMTs in Super-K.
- Reprojection error indicates quality of fit
  - Mean error: 3 pixels
  - Mean 3D position error: ~3-4 cm
  - Aim to reduce error to 1-2 cm
- Sources of error to address:
  - Feature position detection and labeling
  - Camera calibration
  - Fit convergence

Super-Kamiokande PMT positions reconstruction for a barrel ring using photogrammetry.

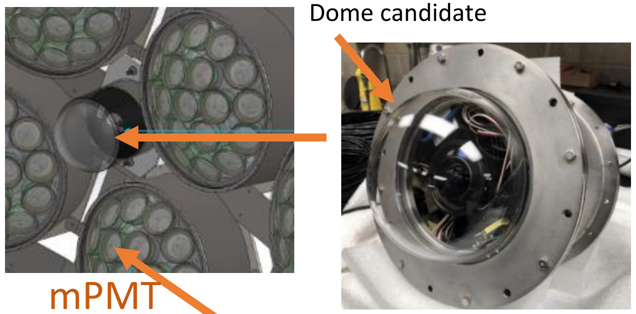


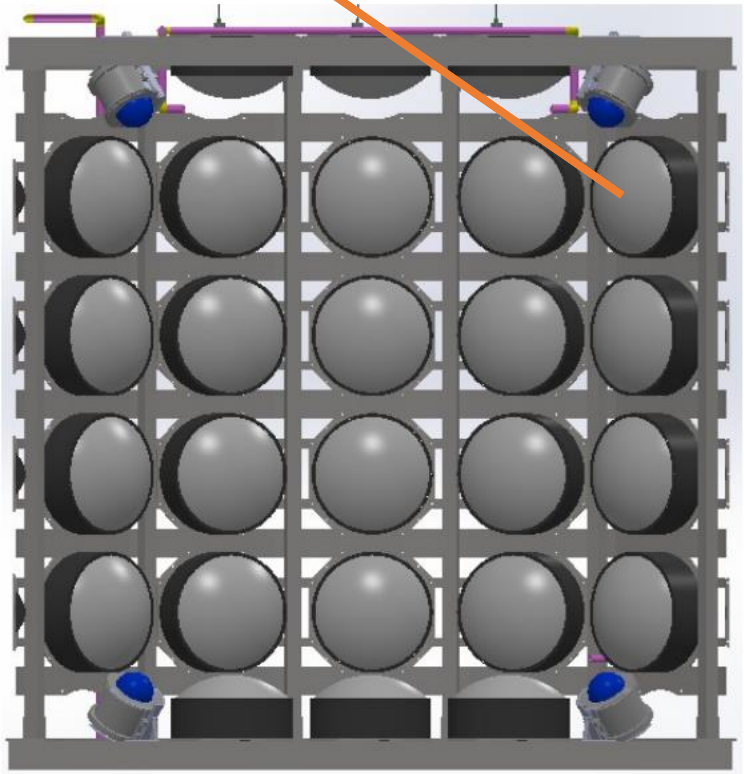
Note: missing gaps correspond to lack of sufficient images with matching features.



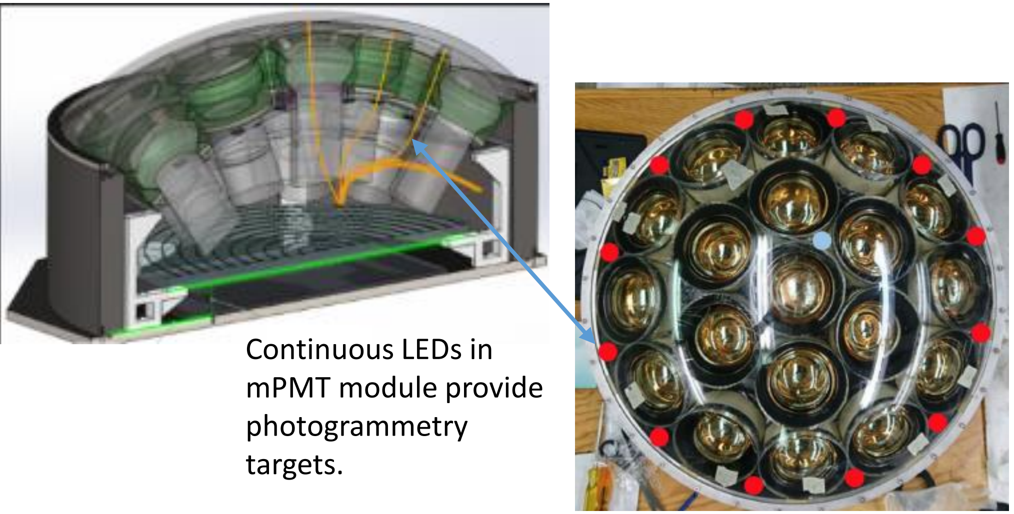
Hardware Development

- WCTE, IWCD and Hyper-K to have fixed and movable cameras.
- Design, testing and upgrade work being done for camera housing and the mPMTs.





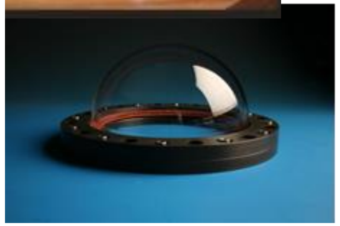
WCTE photogrammetry design schematic.



Continuous LEDs in mPMT module provide photogrammetry targets.

Optical dome port candidates under testing:

[EZTops]



[Rayotek]

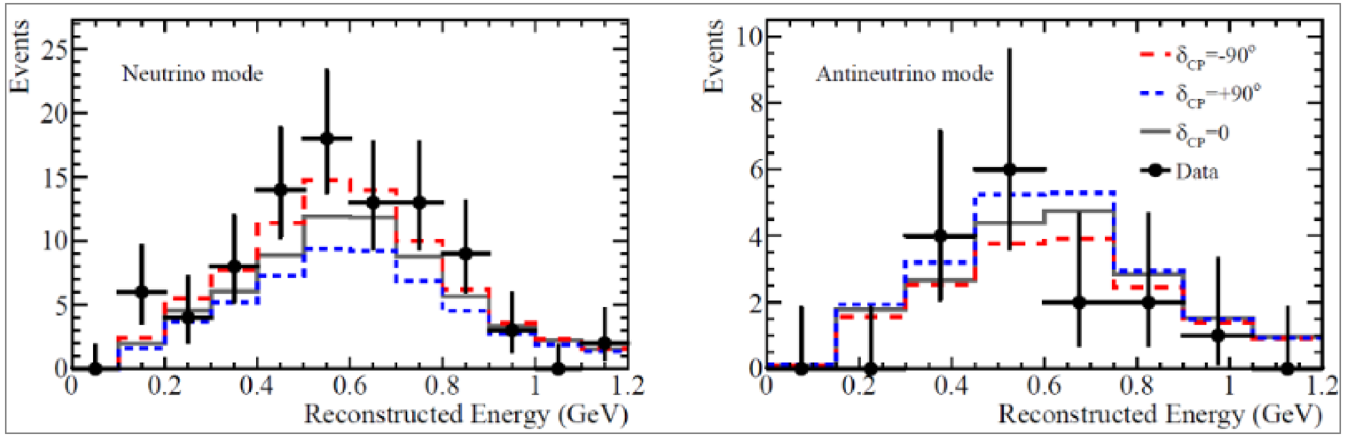
Summary and Continued Work

- Need precise detector calibration for future water Cherenkov detectors.
  - In-situ measurements of detector geometry will reduce systematic uncertainty propagated through to physics measurements
- Photogrammetry pipeline demonstrated through ring geometry reconstruction of Super-K
  - Underwater camera calibration (for Super-K drones and camera candidates for future detectors)
  - Feature detection and labeling
    - Employs machine learning segmentation
    - Requires refined automation and new detection techniques to avoid mislabeling
  - Stereoscopic reconstruction for full 3D geometry (Super-K and WCTE in near future)
- Hardware and simulation studies to finalize plans for future water Cherenkov detectors

Appendix

Motivating Large Physics Goal: Symmetry Breaking

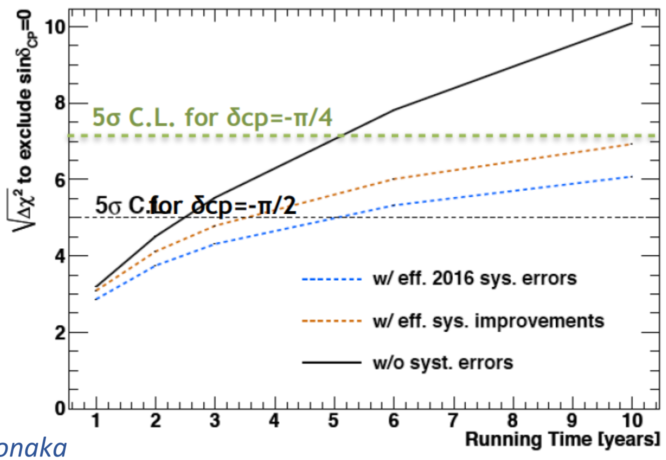
- δ_{cp} phase governs matter/antimatter symmetry breaking in neutrino oscillations
  - Constraints show strong enhancement of neutrino oscillations but confidence is too low to claim CP violation
- Super-Kamiokande oscillation measurements hit floor at 5% systematic uncertainty
  - Non-Gaussian systematics for Hyper-K
- Must increase Super-K and Hyper-K CP sensitivity
  - **Improvement of systematics is essential.**



From: T2K Collaboration.

Observed electron neutrino (left) and electron antineutrino (right) event candidates with predictions for maximal neutrino and antineutrino enhancement.

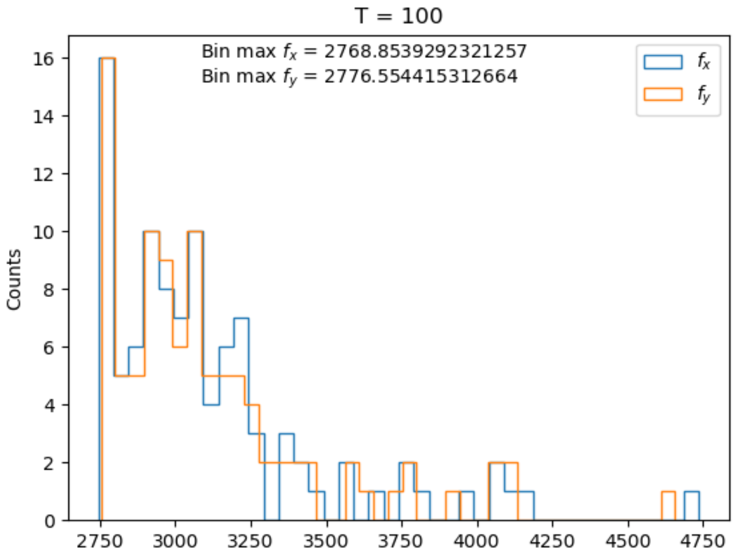
HK Sensitivity for δcp=-π/2 (maximal CP viol.)

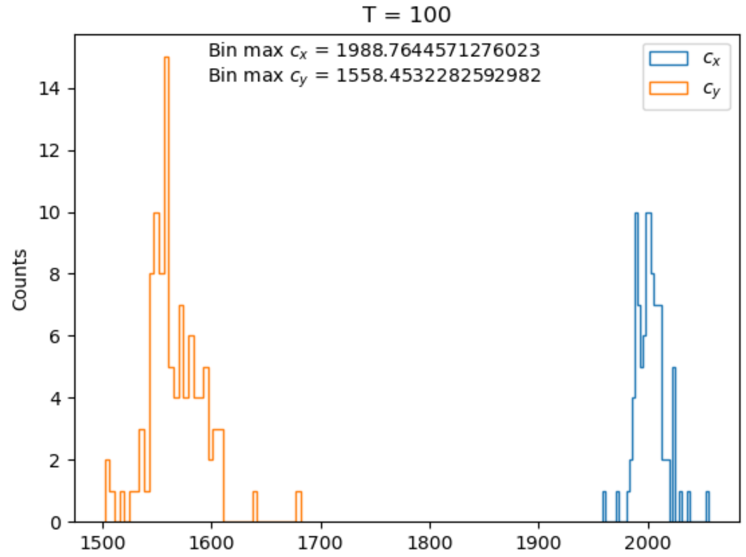


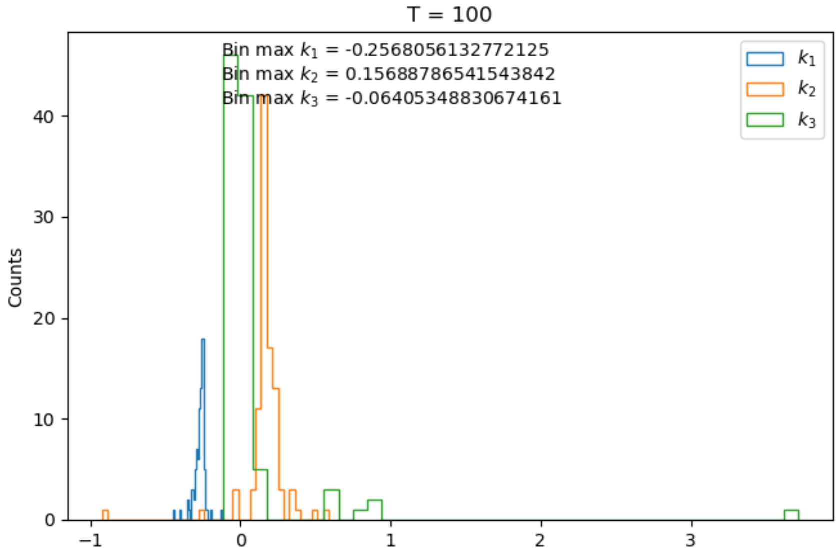
A. Konaka

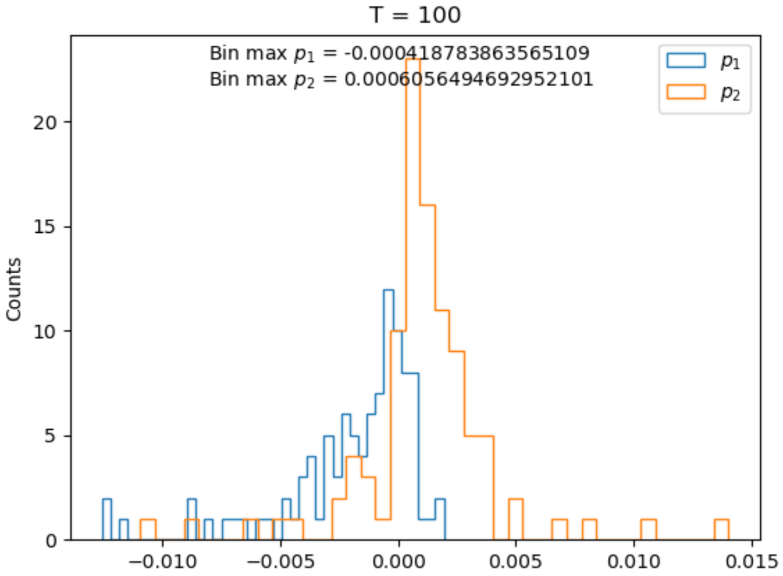
Camera Intrinsic Matrix Parameter Studies

- 100 randomly sampled subsets of 100 images analyzed from original 880 image set for Super-K drone









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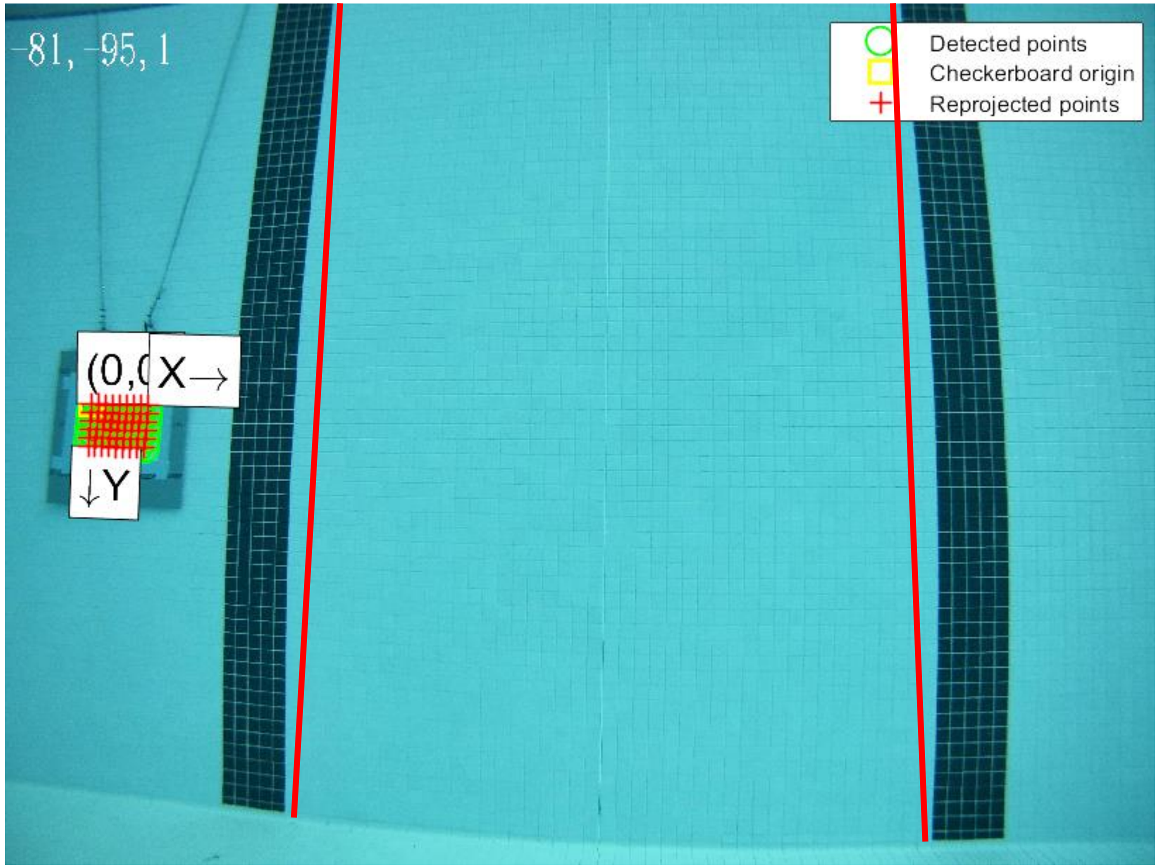
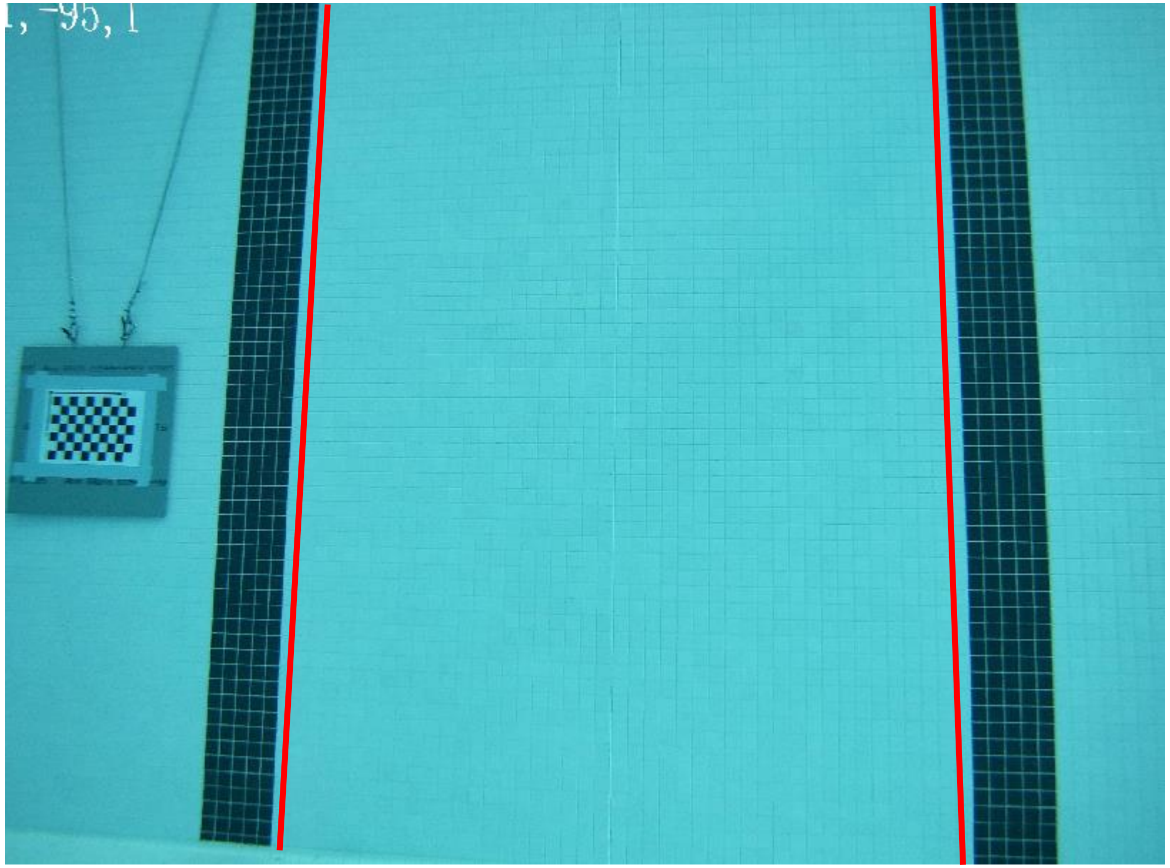
Undistortion Performance

Raw, distorted image with detected checkerboard.

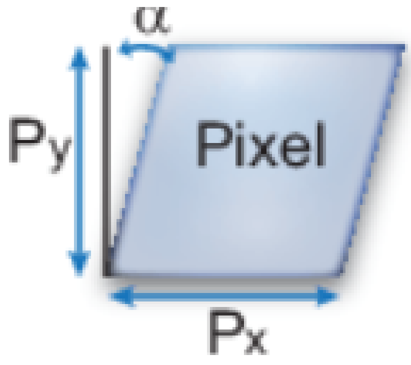


Application of camera model to undistorted image.



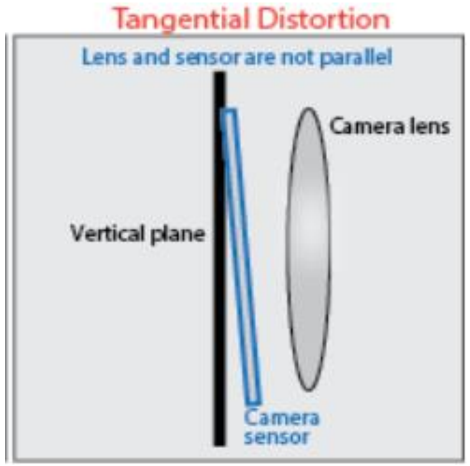
Additional Camera Model Parameters

- Skew: non-zero if axes of image are not parallel
  - Parameter in intrinsic camera matrix



Skew

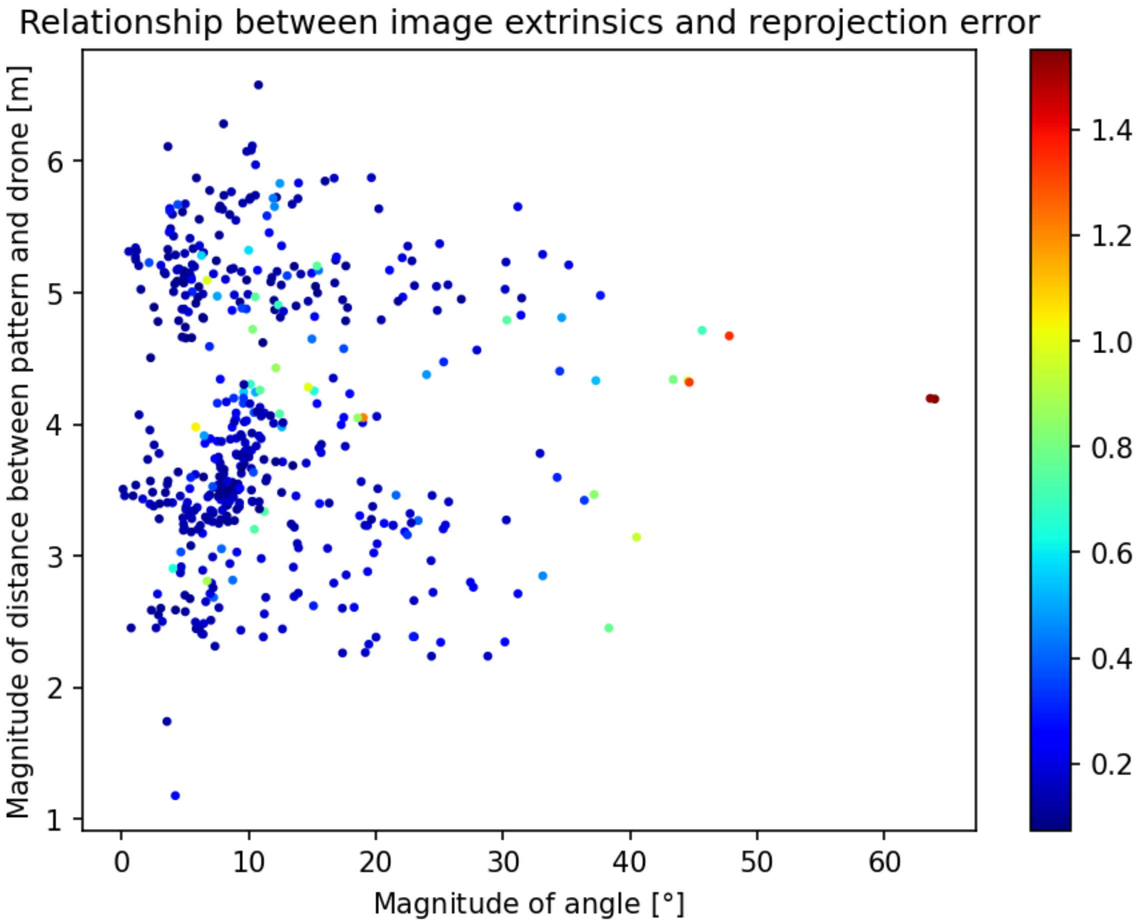
- Tangential distortion: lens and image plane are not parallel
  - 2 tangential distortion coefficients (p_1 and p_2)

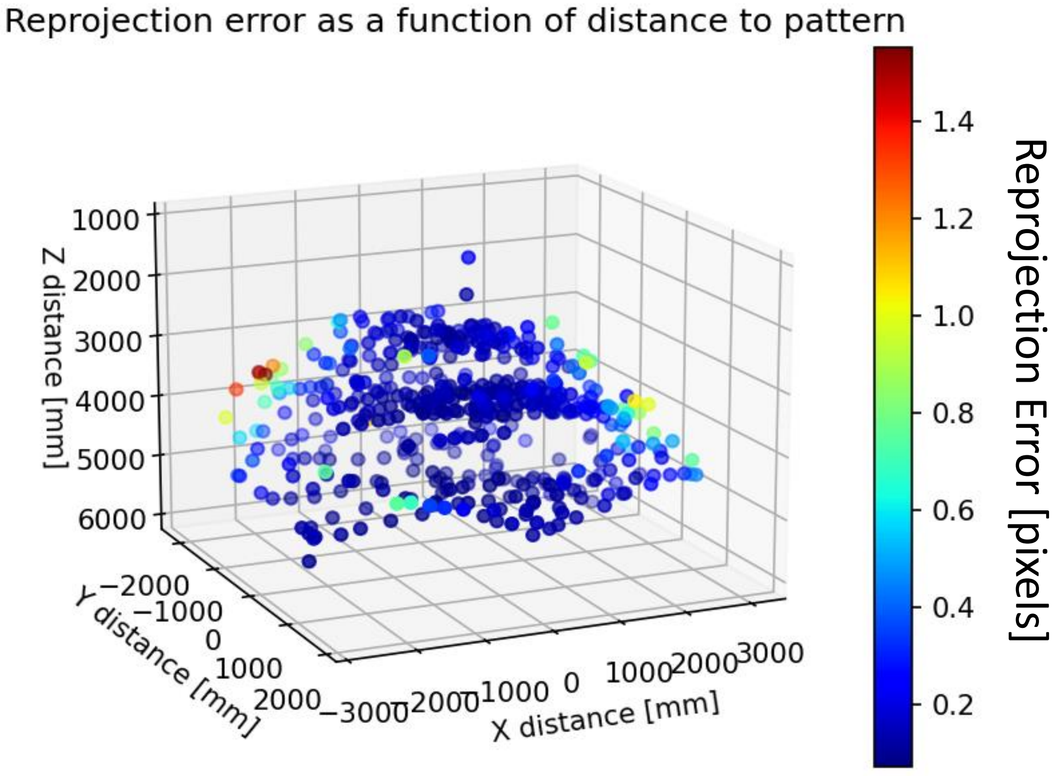


$$x_{\text{distorted}} = x + [2 * p_1 * x * y + p_2 * (r^2 + 2 * x^2)]$$

$$y_{\text{distorted}} = y + [p_1 * (r^2 + 2 * y^2) + 2 * p_2 * x * y]$$

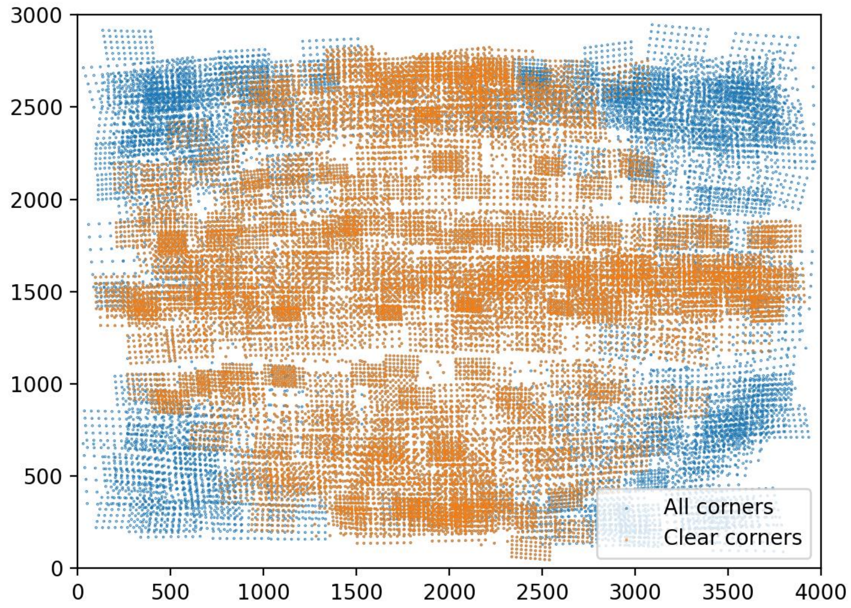
Reprojection Error and Extrinsics





Correlating Camera Calibration Errors

- Impacts on image sharpness and feature detection by place in FOV?
  - Corners of FOV exhibit higher blur values (do not meet cutoff)
  - Most “clear” images exhibit RE < 0.5 pixels
  - Random scattering of higher RE > 1 pixel points
- Investigation of errors associated with corner finding algorithm and propagation through to intrinsics and reprojection.



Images measured against fixed blur threshold as a function of image coordinates (in pixels).

X. Li

- Previously just assigned discrete values for the errors without correlation

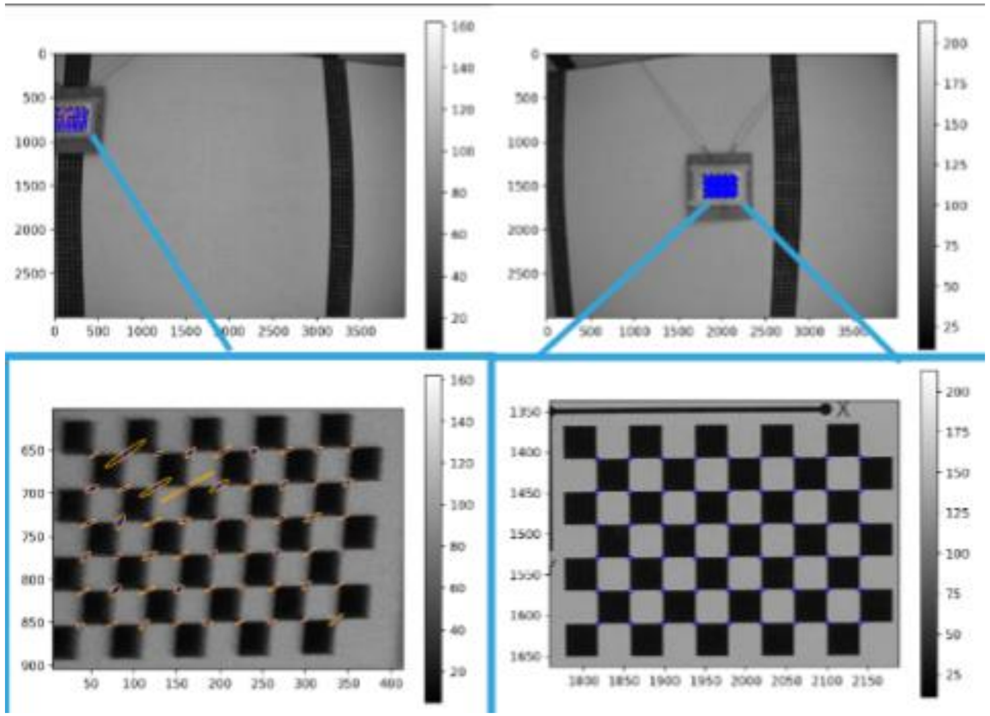
Minimization of “reprojection error”

$$\epsilon^2_{\text{res}} = \sum_{i\in\mathcal{F}}\sum_{j\in\mathcal{C}} \left|\mathbf{u}_{ij} - \mathbf{p}(\mathbf{x}_{ij}, \theta, \mathbf{\Pi}_i)\right|^2$$

- New calibration to minimize “reprojection error”

$$\epsilon^2_{\text{res}} = \sum_{i\in\mathcal{F}}\sum_{j\in\mathcal{C}} \frac{\left|\mathbf{u}_{ij} - \mathbf{p}(\mathbf{x}_{ij}, \theta, \mathbf{\Pi}_i)\right|^2}{\sigma^2_{ij}}$$

- $\boldsymbol{\sigma}_{ij}$ is the corner finding error for each corner

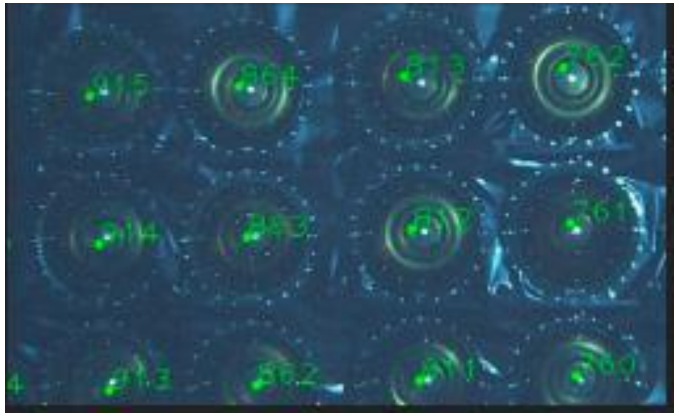


X. Li

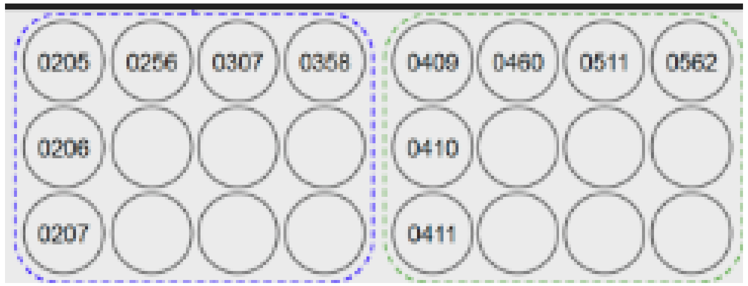
Reprojection errors for “clear” images as a function of image coordinates (in pixels).

Feature Labeling

- Known features, such as light injectors, used as reference point for labeling.
- PMT matching between images performed by using:
  - Drone depth and direction sensor data
  - 3 by 4 PMT “supermodule” gaps

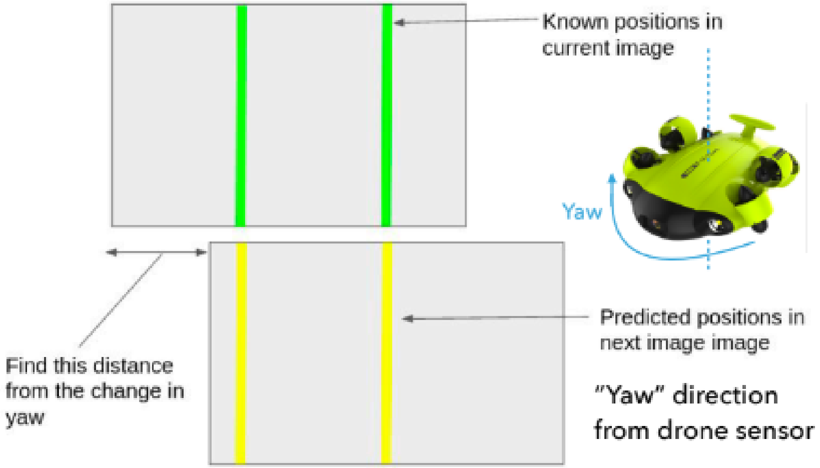


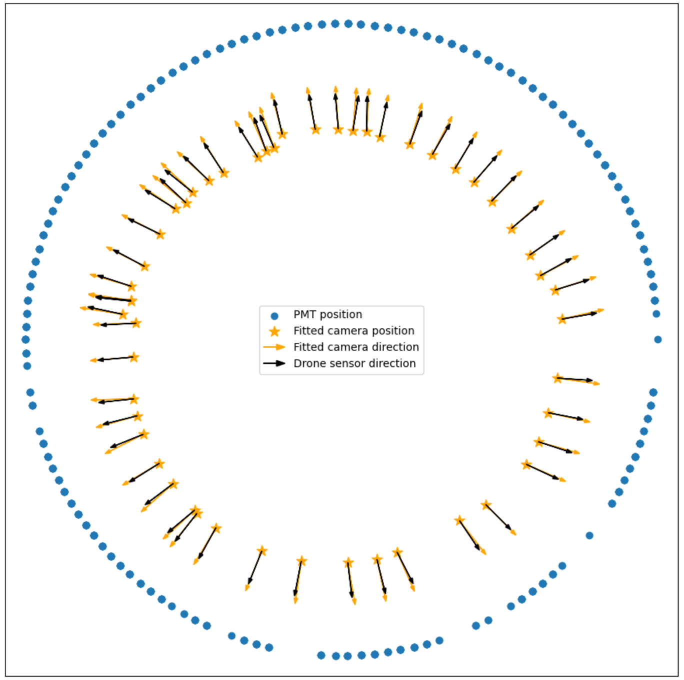
PMTs labeled using cable number.



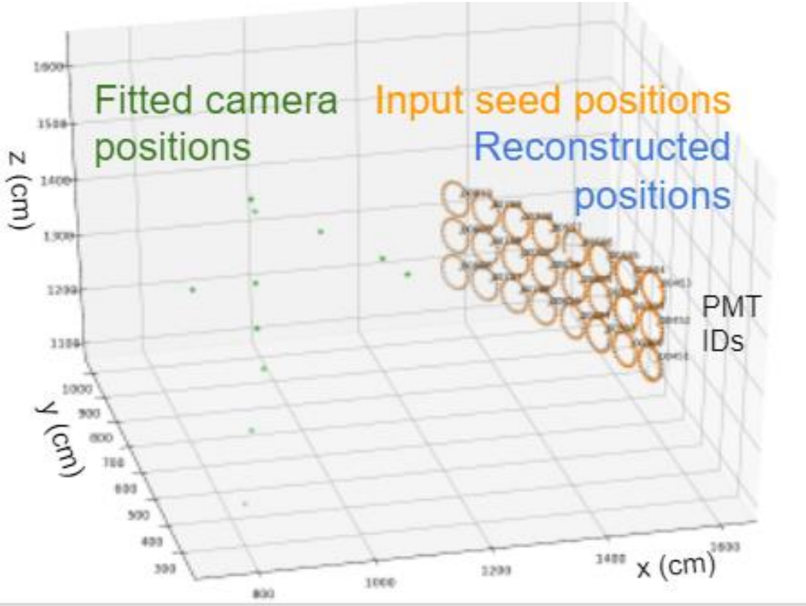
Mislabeling can occur when drone sensor information unknown

- Implement sequential corrections after initial labeling.





Photogrammetry Development



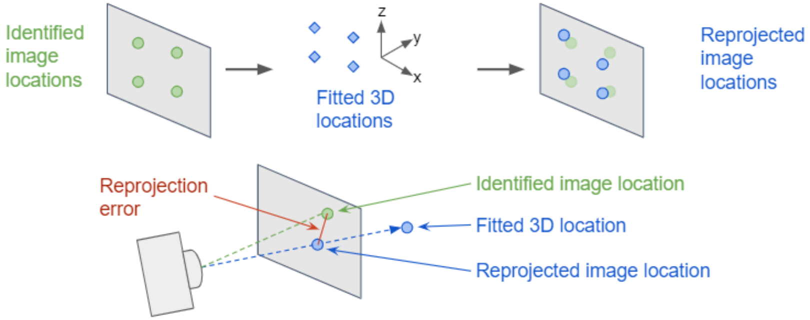
Super-Kamiokande PMT positions reconstruction for a barrel ring using photogrammetry.

Camera Calibration

- Usage of pattern with features of known distances (checkerboard pattern)
- Our programs can detect these features, compute the position of the camera in relation to the pattern, and build a model of camera parameters.
- Camera model allows the reprojection of these points with some reprojection error.

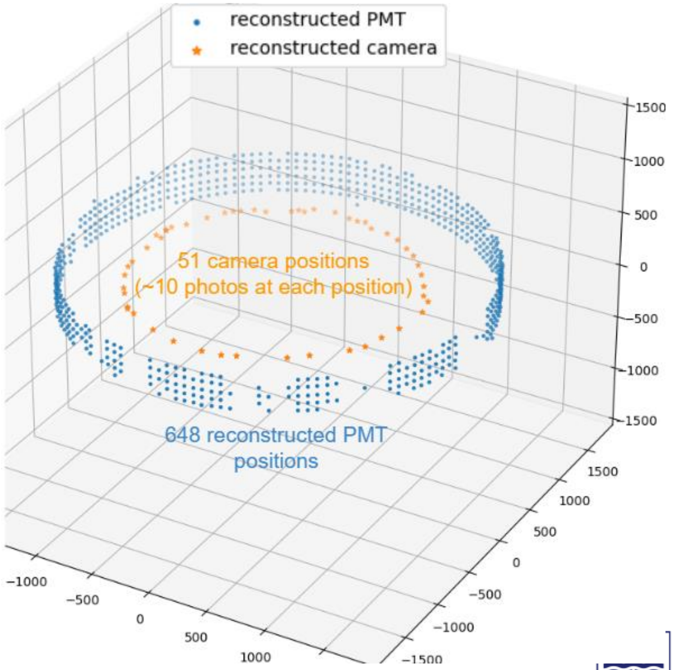
Feature Recognition

- Improving (machine learning) automated feature recognition and labeling of PMTs and surrounding features.
- Distances between camera and features can give a measure of deformation in the detector.



Detector Reconstruction

- Perform a fit relative to “ideal” feature coordinates in the world coordinate system.
- Can reconstruct both features and camera in question.
- Minimizing reprojection error.



Timeline for Activities