ICRR Inter-University Research Program 2021

Neutrino and Astroparticle Research Division

New Photogrammetry Calibration for Super-Kamiokande and Hyper-Kamiokande

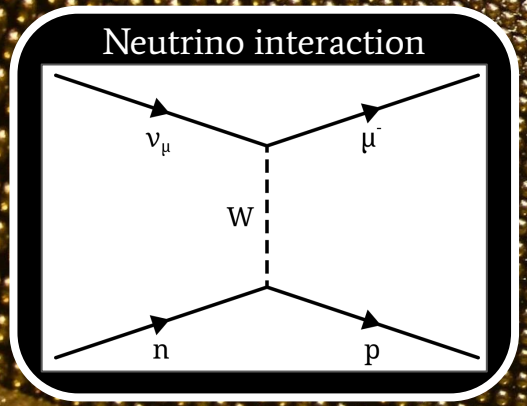
TRIUMF

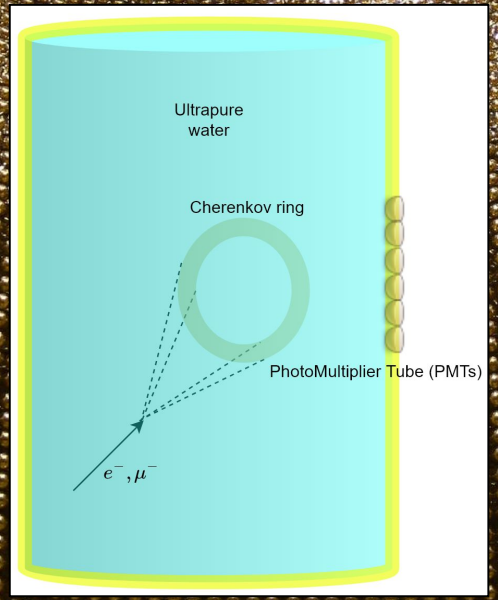
KAVLI IPMU

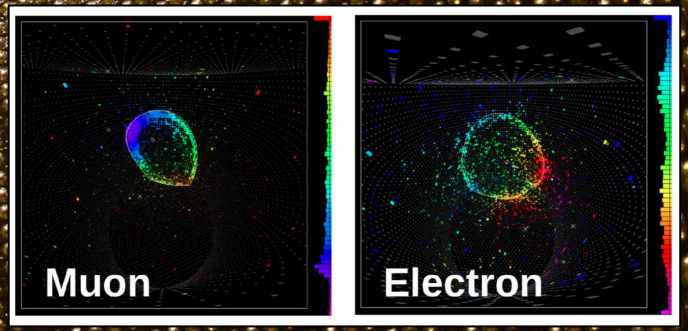
Patrick de Perio

January 25, 2022

Super-Kamiokande

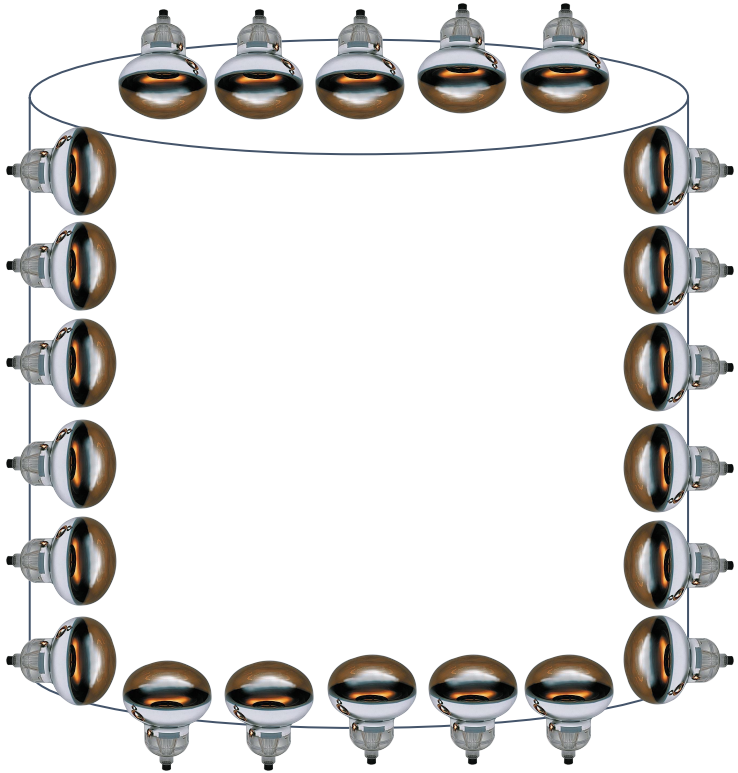






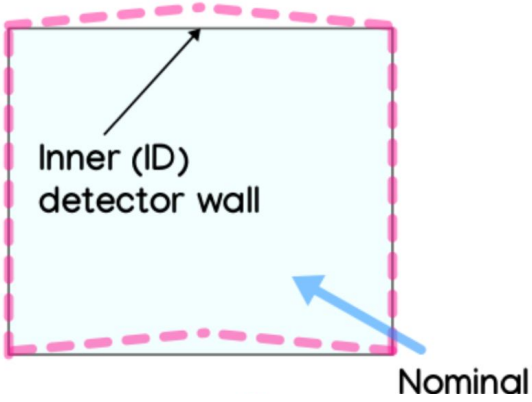
Systematic Error: Geometry

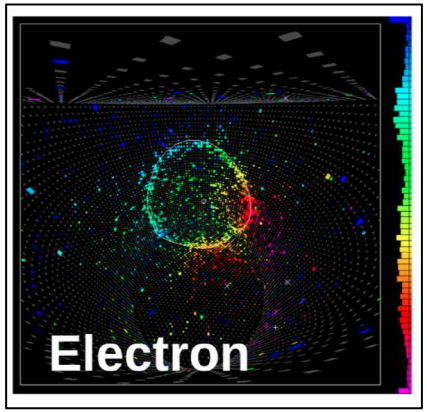
PMTs assembled in air



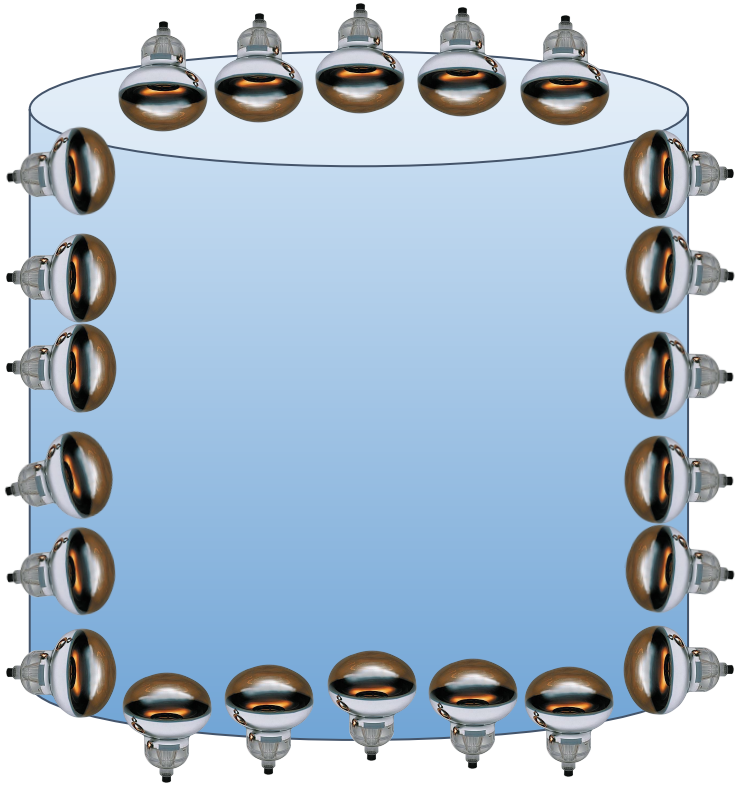
Systematic Error: Geometry

- Example systematic deviation of ID PMT geometry
- Nominal assumption in analysis can produce incorrect results
  - Critical for precision measurements



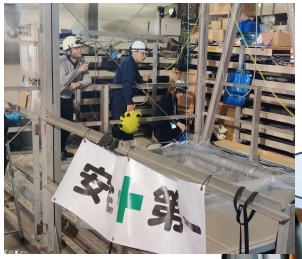


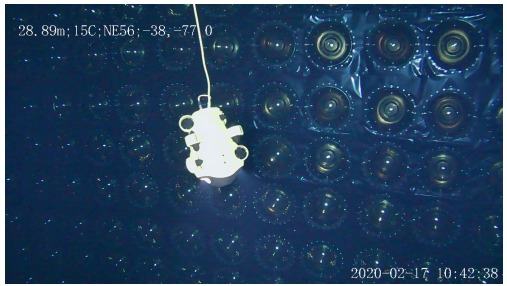
Potential PMT shifting due to buoyancy after water filling

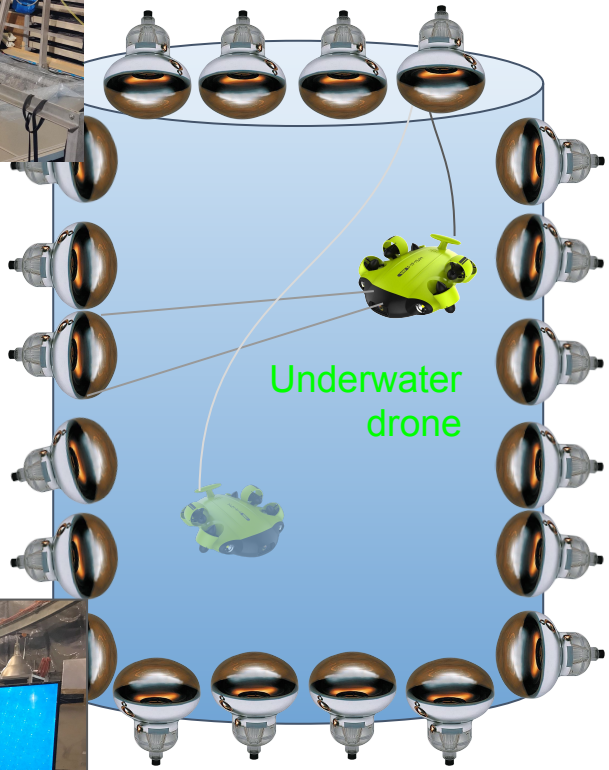


Photogrammetry Review

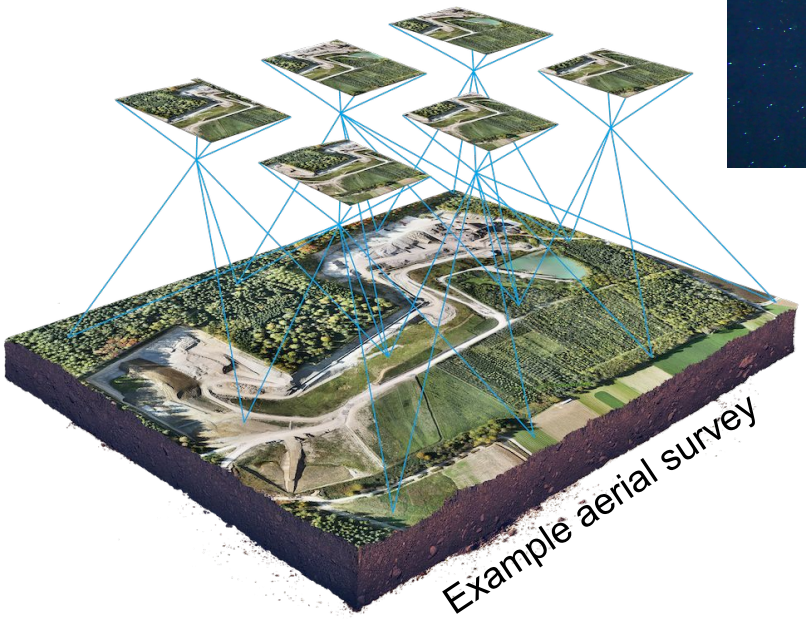
Reconstruct the 3D structure from multiple 2D photographs to mitigate systematic error





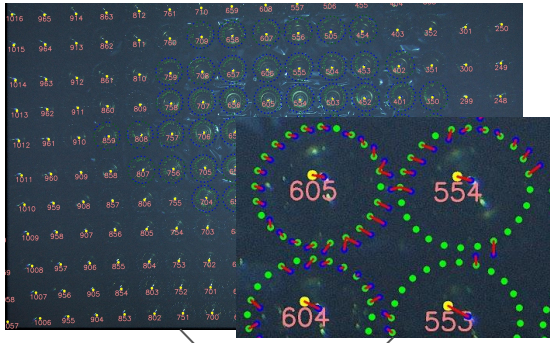


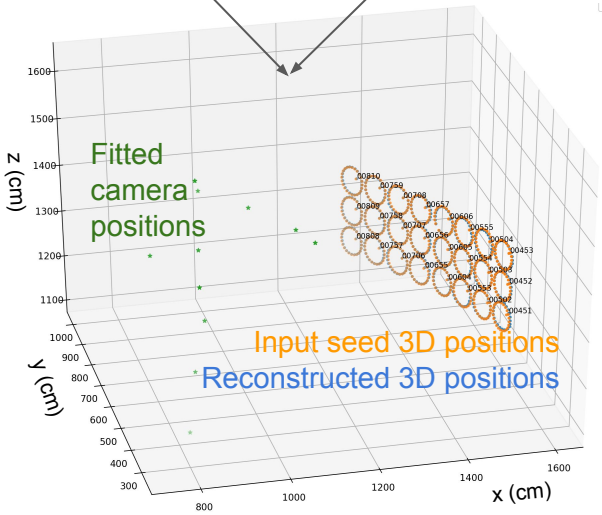
<u>Feb. 2020</u>
Took ~13000 photos
(~1800 positions)

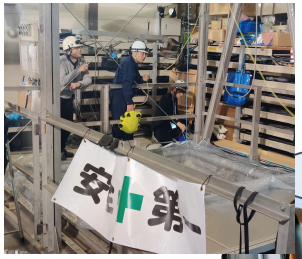


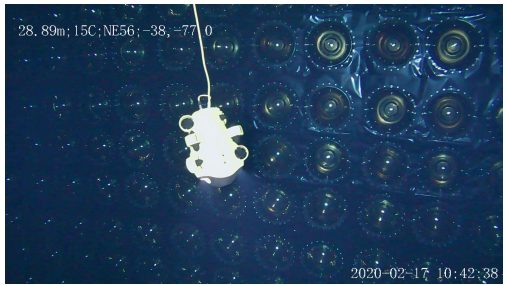
Previous Results

Manual feature labeling of 24 PMTs in ~12 photos









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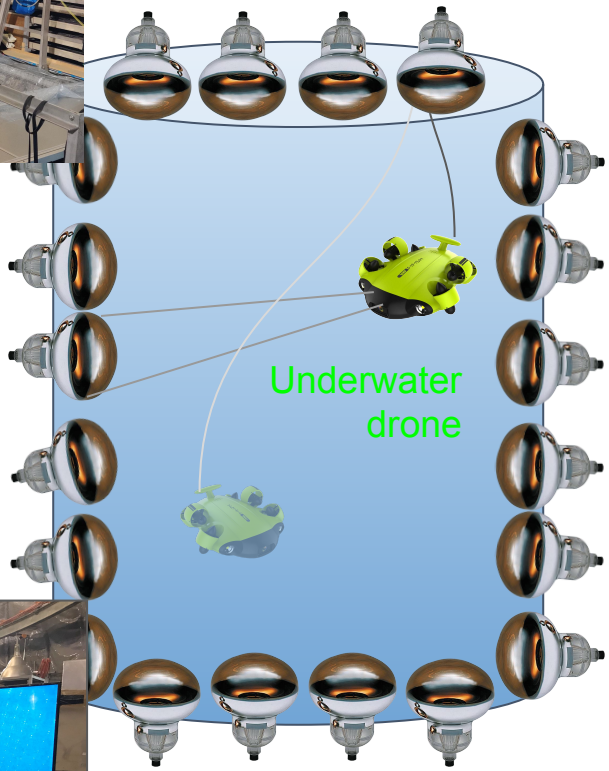
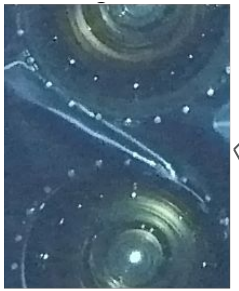


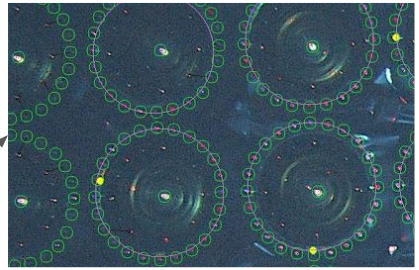
New Automated Feature Detection

Developed 2 feature detection methods to identify PMT bolts and centers:

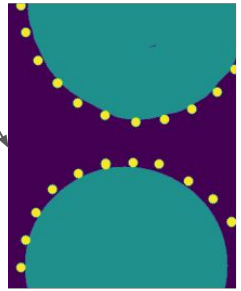
Original image



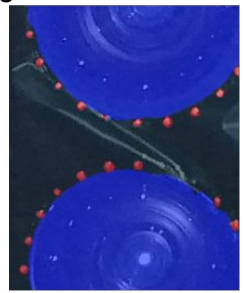
1) Blob detection & Hough transform ellipse finding



2) Machine learning semantic segmentation



Segmented by eye for training



Segmented by CNN

More systematic and reproducible than previous manual labeling

Software Details

Traditional image processing using OpenCV software

UNet with Image Segmentation Keras package

Pros/Cons

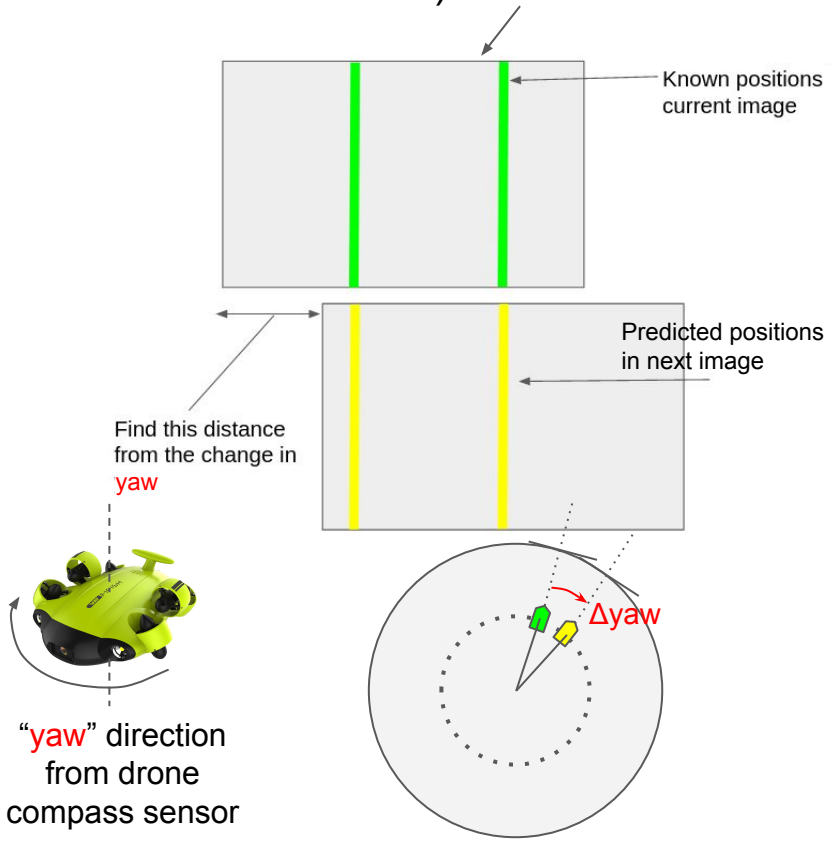
Easier to understand, but many finely tuned parameters depending on properties of each photo.

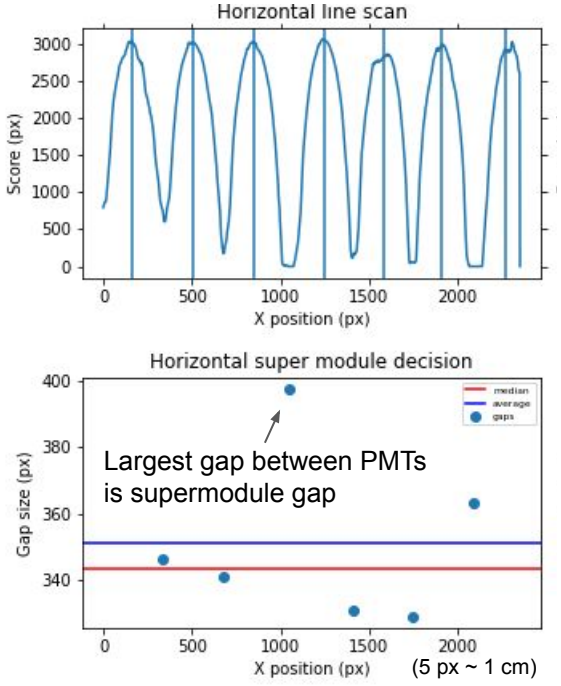
Still requires some manual labeling for training sample, but potentially more robust to variations in photos (e.g. angled or detector corners)

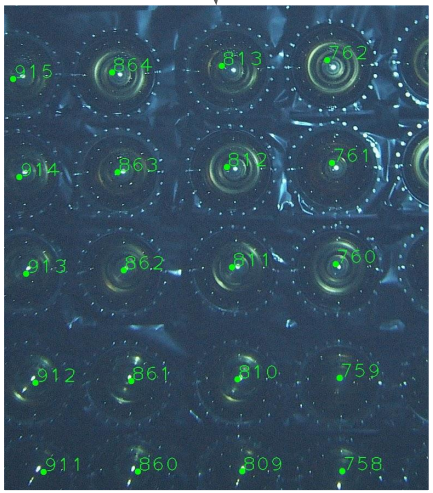
New Automated Feature Labeling

Identifying PMTs across images with almost identical repeating pattern is very challenging

Combine info from: 1) drone direction & 2) known spacing between PMT modules to get initial guess of PMT labels in all images



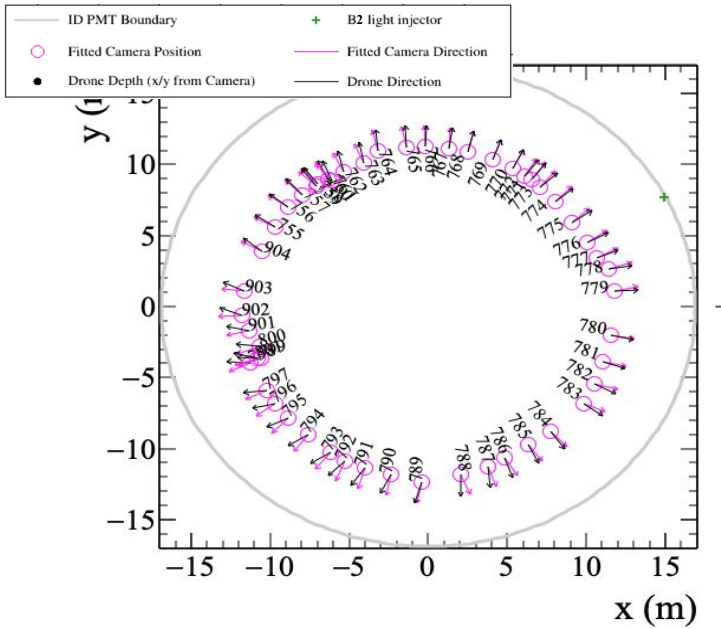


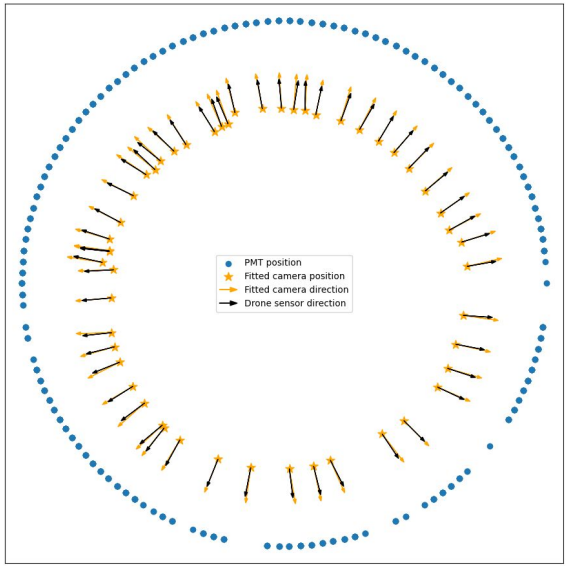


New ***Semi-***Automated Feature Labeling

Unfortunately, initial guess was not perfect when applied to a set of images at the same depth going around the barrel…

… Needed to manually shift PMT labels to “fit” the camera positions & directions

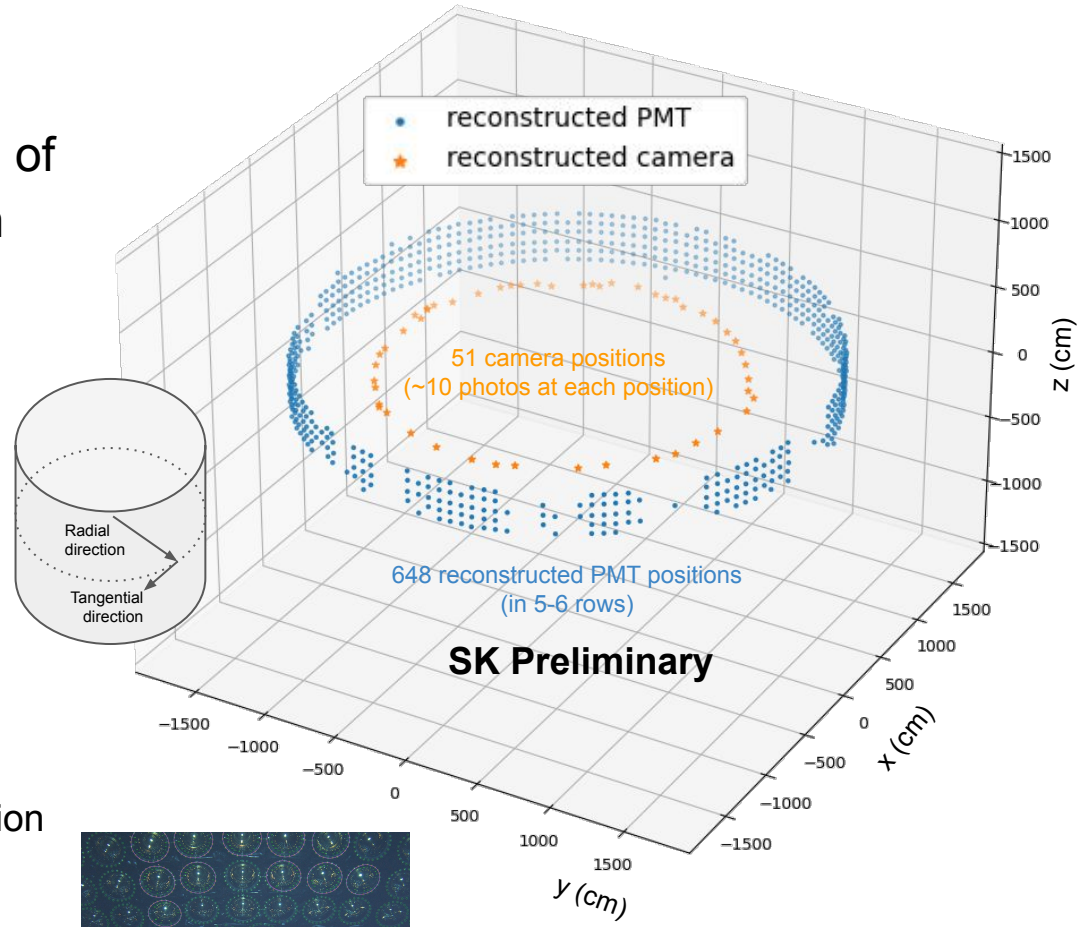


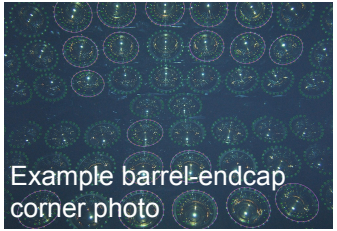


Ongoing work: Trying to automate this “manual shift” by using more geometrical info from photos

New Results

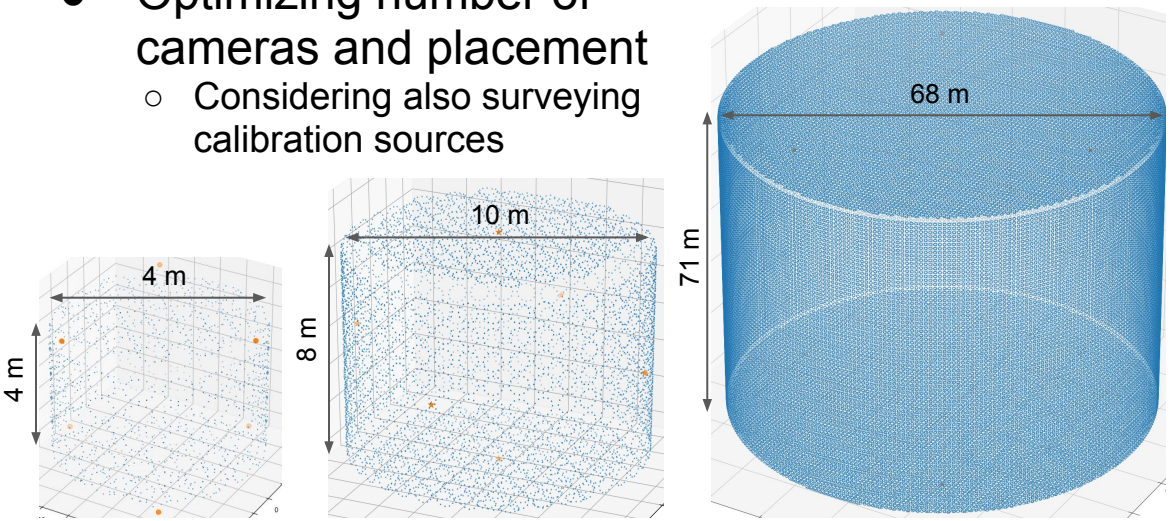
- First underwater survey of a ring of PMTs in Super-K since inception
- No indication of deviation from (circular) design geometry
  - Within preliminary measurement uncertainty of 1.3 (4.2) cm in the tangential (radial) direction
- Ongoing work to reduce uncertainties by e.g. improving feature detection
  - And proper estimates and propagation of systematic errors
- Ultimately, extending the analysis to entire detector

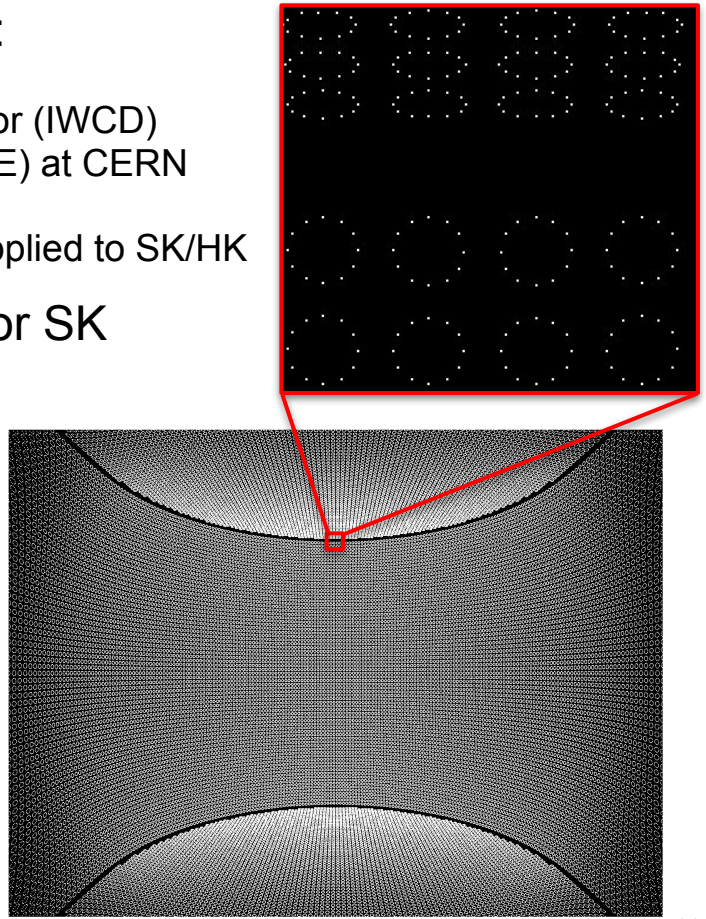




Software Development Towards Hyper-K

- Created rudimentary simulation of photographs in:
  1. Hyper-K far detector
  2. Hyper-K's moveable Intermediate Water Cherenkov Detector (IWCD)
  3. (IWCD prototype) Water Cherenkov Test Experiment (WCTE) at CERN particle beamline in 2023
     - Constraints on detector physics modeling aiming to be applied to SK/HK
- Applied reconstruction code that was developed for SK
- Optimizing number of cameras and placement
  - Considering also surveying calibration sources

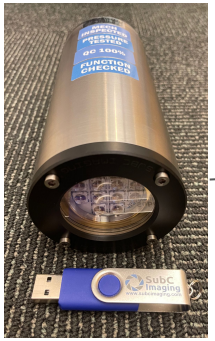


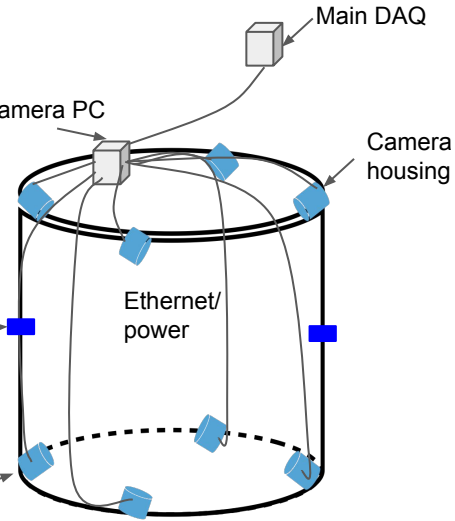


Hardware Development Towards Hyper-K

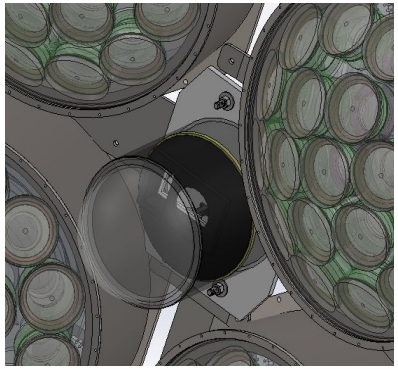
- Developing new fixed camera and lighting systems for Hyper-K, IWCD, and WCTE
- Prototypes being constructed and tested now

Underwater lamp purchased through ICRR IURP

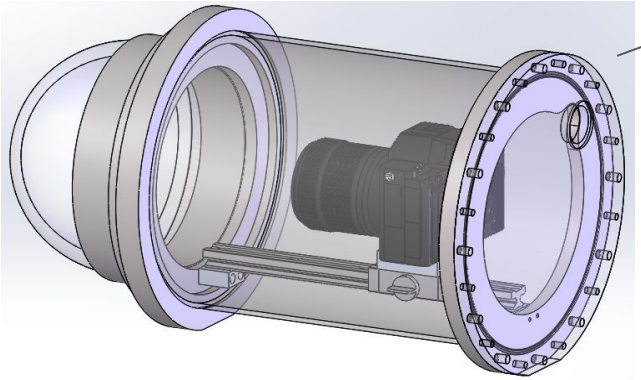




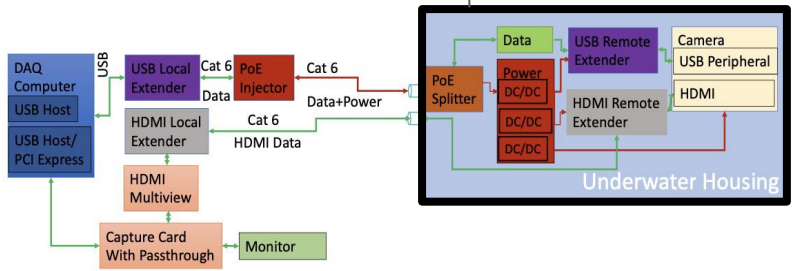
IWCD with mPMTs



Camera housing design



Camera readout electronics design



Funding Summary

Approved amounts:

Year	Goods	Travel	Top-up	Total
2019	700,000	300,000	500,000	1,500,000
2020	200,000	300,000		500,000
2021	300,000	200,000		500,000

Actual spending:

Year	Goods	Travel		Total	Remainder
2019	832,236	653,170		1,485,406	14,594
2020	0	127,739		127,339	372,261*
2021	872,234	0		872,234	27

*Carried over due to COVID-19

Funding Summary

- 2019 Goods: Drone, cameras and lamps, deployment hardware
- 2019 Travel: Detector survey and presenting work at collaboration meetings

- 2020 Travel: Temporarily shipped equipment to Canada to continue calibrations

- 2021 Goods: Underwater red LED lamp

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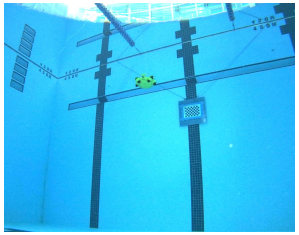
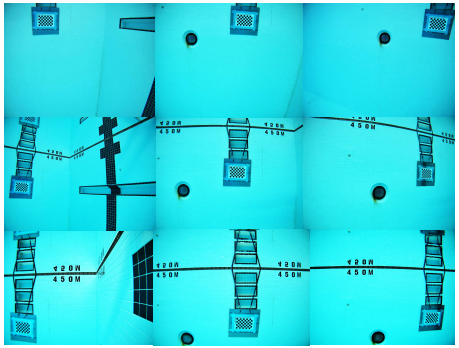
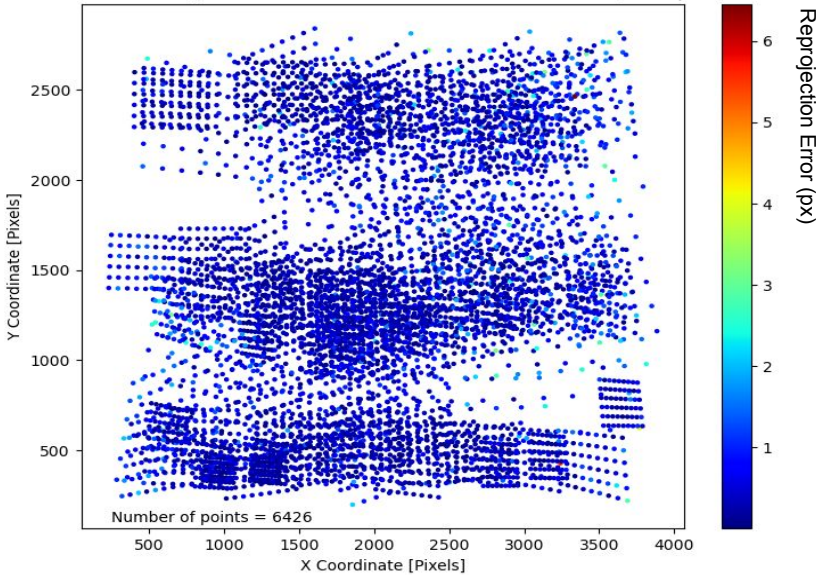
Improving Super-K Drone Calibration

- Collected new, more complete, calibration data for both drones used in the Super-K survey
- Analysis ongoing for better characterization and reduction of systematic errors

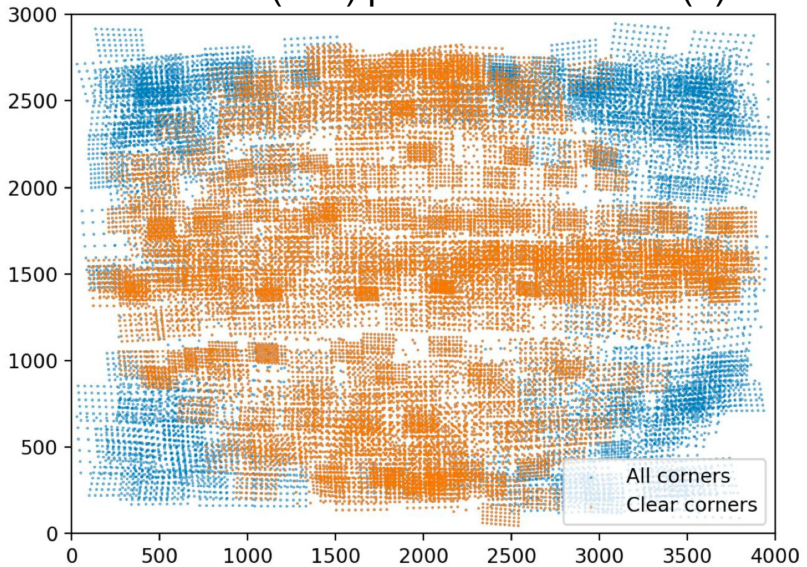




Previous 133 photos for drone 1 only

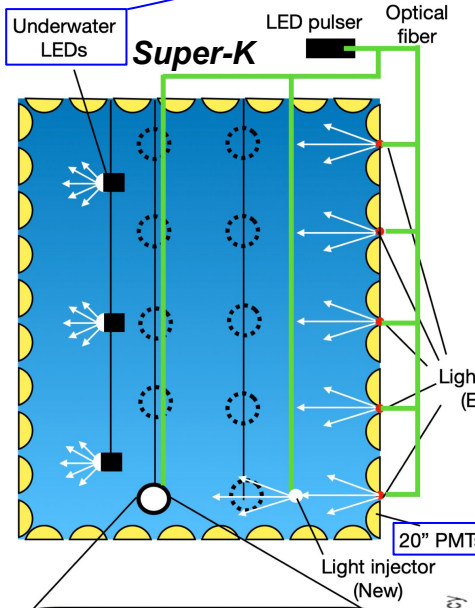


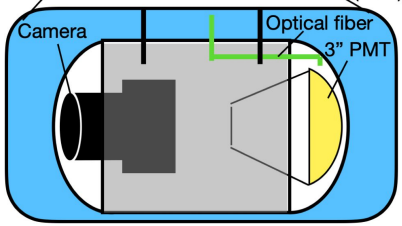
New 800 (650) photos for drone 1 (2)



Underwater Red LED Lamp (for New Calibration Idea)

Y. Nakajima (UTokyo)

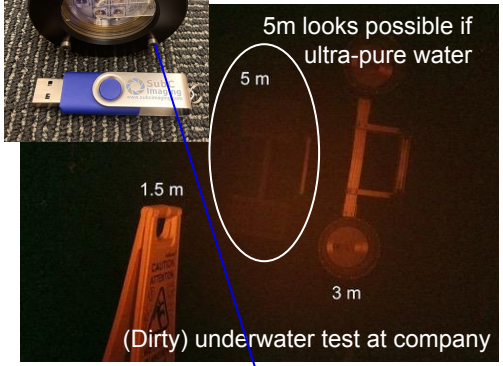




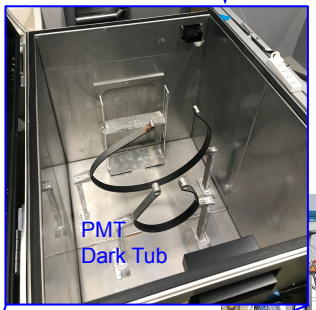
New Module

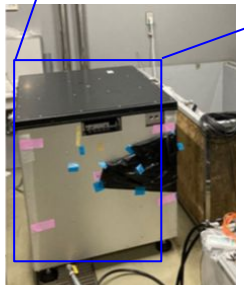
- Characterize spatial dependence of water quality
- Deploy new module:
  - 3" PMT: measures light sources
  - Camera: positioning of module using PG
- Need pressure tolerant LED lamp
  - Also robust for long-term in Hyper-K

Purchased through ICRR IURP



- Need far-red wavelength light to avoid sensitive region of PMTs
  - Allows the calibration and future PG surveys with Super-K/Hyper-K detectors online
- LED to be tested with existing PMT and dark tub at ICRR, Kashiwa





Existing PMT HV and readout electronics

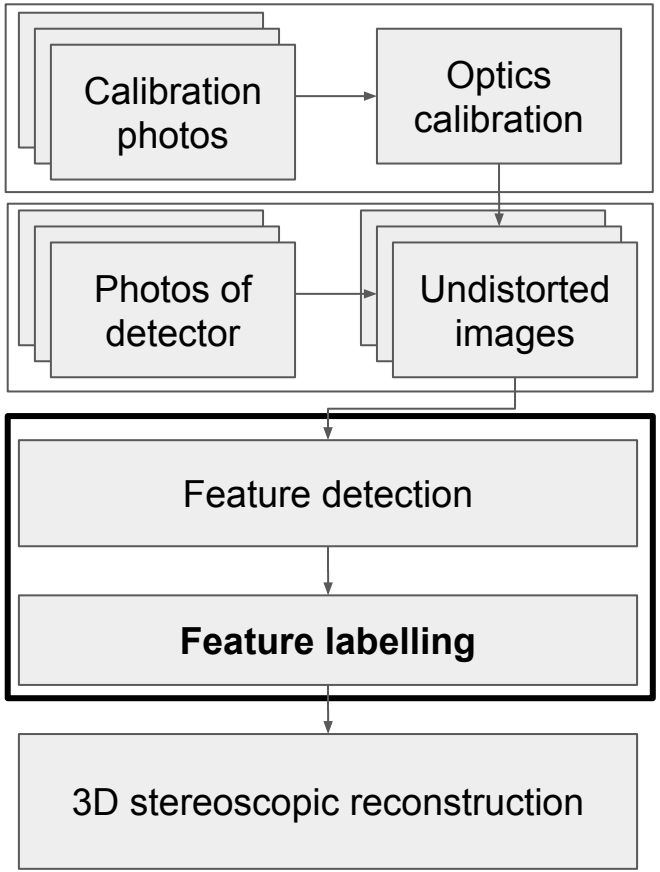
Summary

- New photogrammetry geometry survey result on segment of Super-K detector
- Significant R&D progress towards Hyper-K and associated detectors
- Ongoing work to improve and finalize Super-K analysis
- Synergy with new Super-K calibration idea
- *Many thanks to ICRR-IURP for your support in making this possible!!*

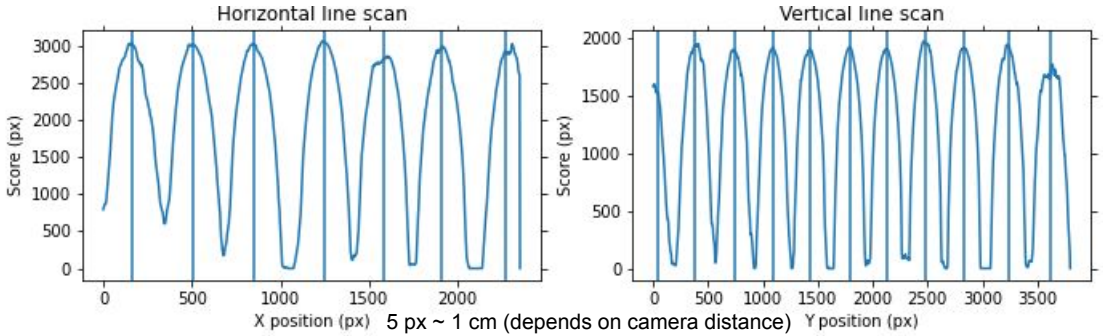
Appendix

Automated Feature Labelling

Dan Martin, Imperial College London



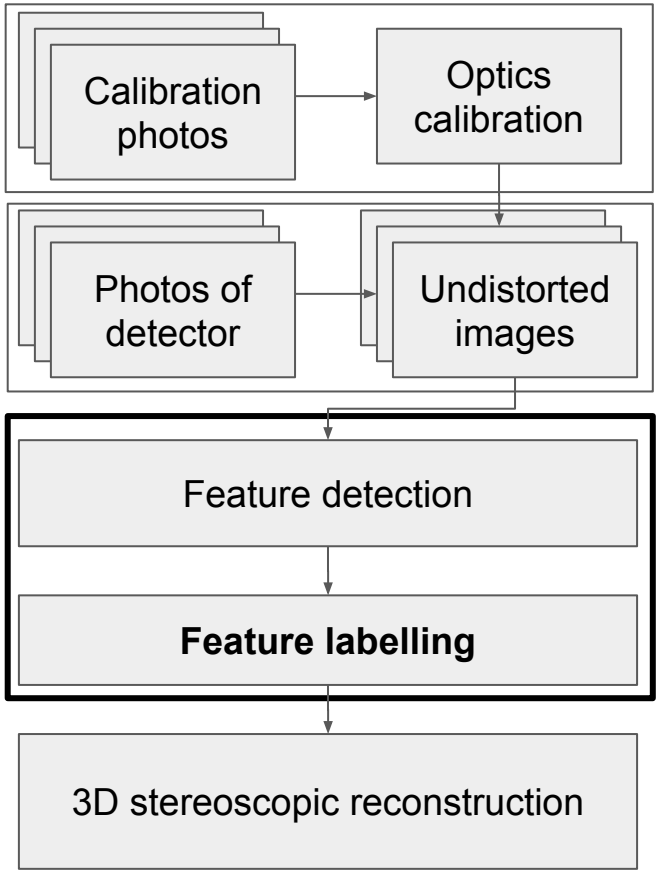
- Submarine depth & direction sensors, and gaps between supermodules used to identify which row / column is which
  - To allow matching the same PMTs between different images



  - Scans each row / column of pixels and assigns score as amount of pixels assigned to PMTs
  - Clearly shows positions of PMTs and gaps between them

Automated Feature Labelling

Dan Martin, Imperial College London



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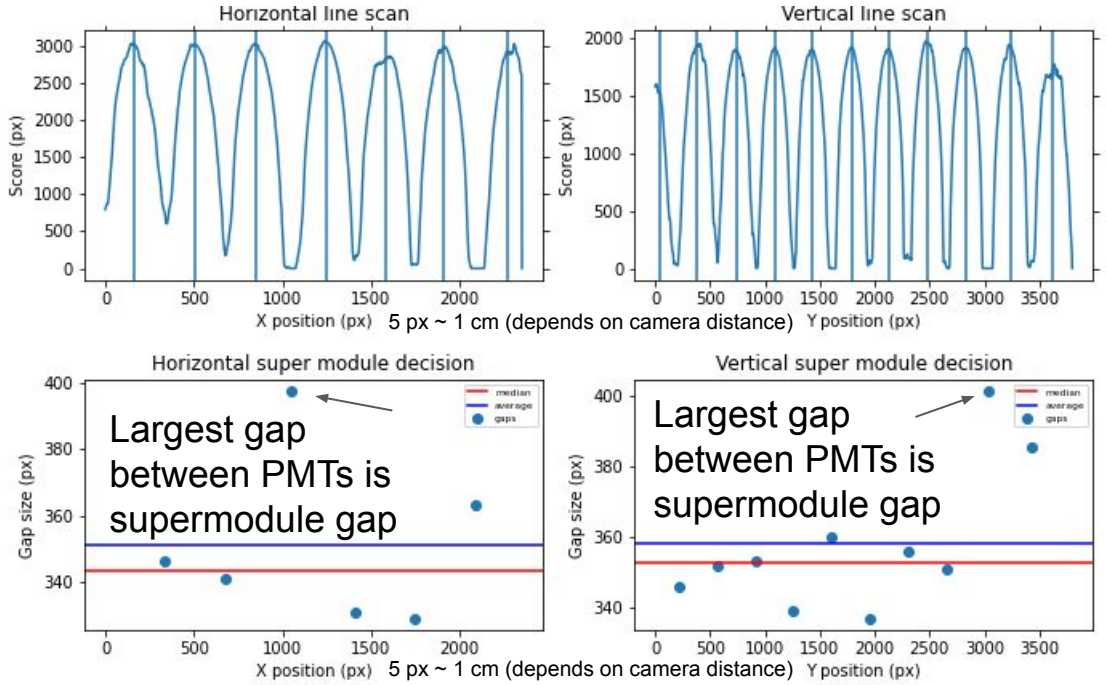
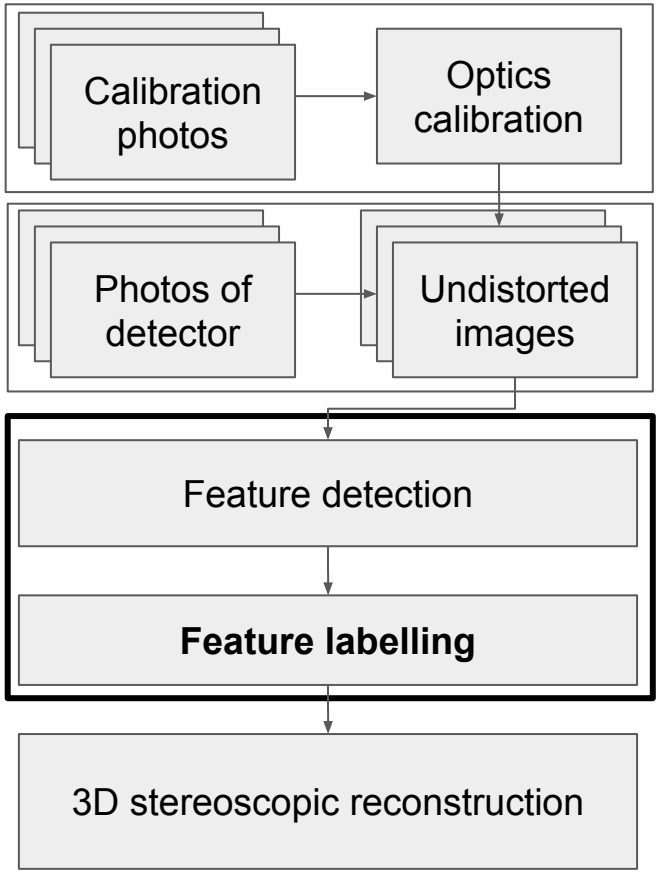


Automated Feature Labelling

Dan Martin, Imperial College London



- Submarine depth & direction sensors, and gaps between supermodules used to identify which row / column is which
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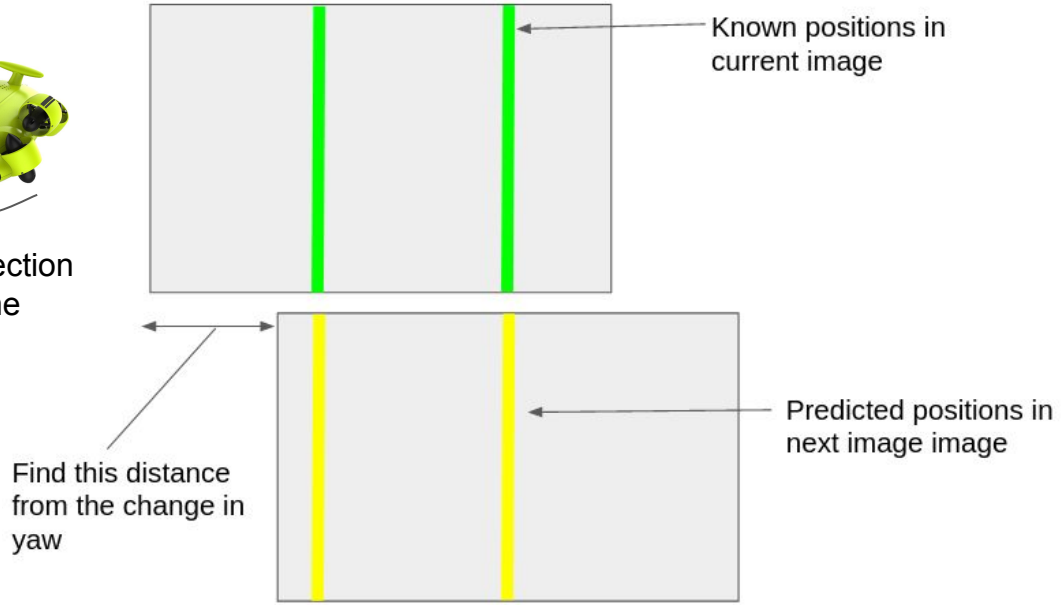
“yaw” direction from drone sensor



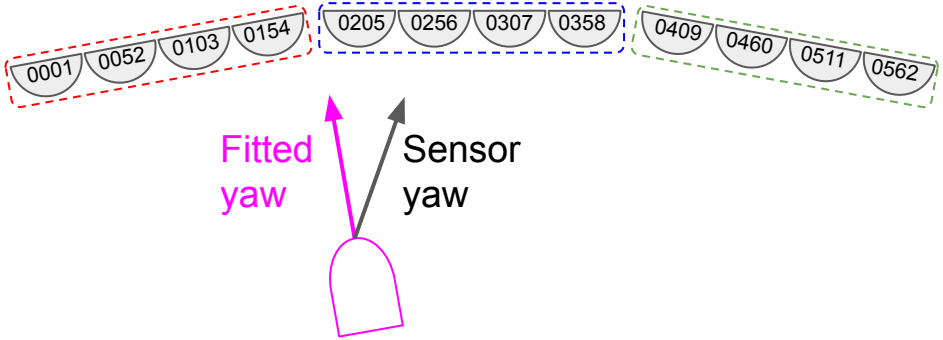
Care needs to be taken at half super-module location

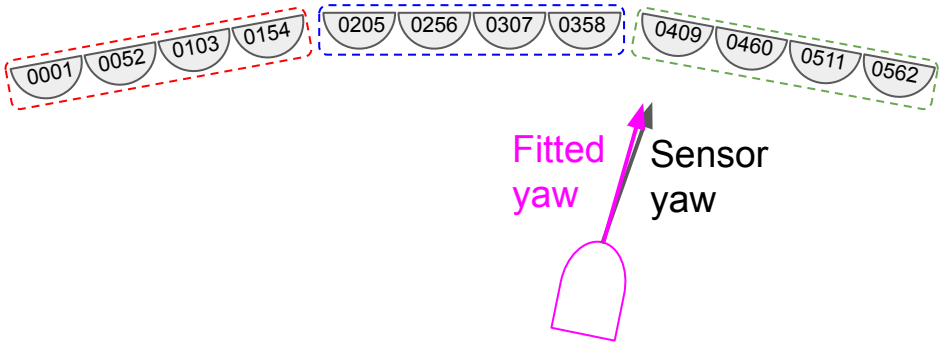
Automated relabelling to improve matching

We can use initial fit output and drone yaw to produce improved matching

- Assume that locations of supermodule boundaries in each image are correct
- Try relabelling images by ‘shifting’ the PMT labels by multiples of 4 columns (whole supermodules)
- Repeat initial photogrammetry fit to find new fitted camera yaw values
- Compare new yaw values to drone yaw values
- Choose labelling that gives the best match

Fitted pose using original labels

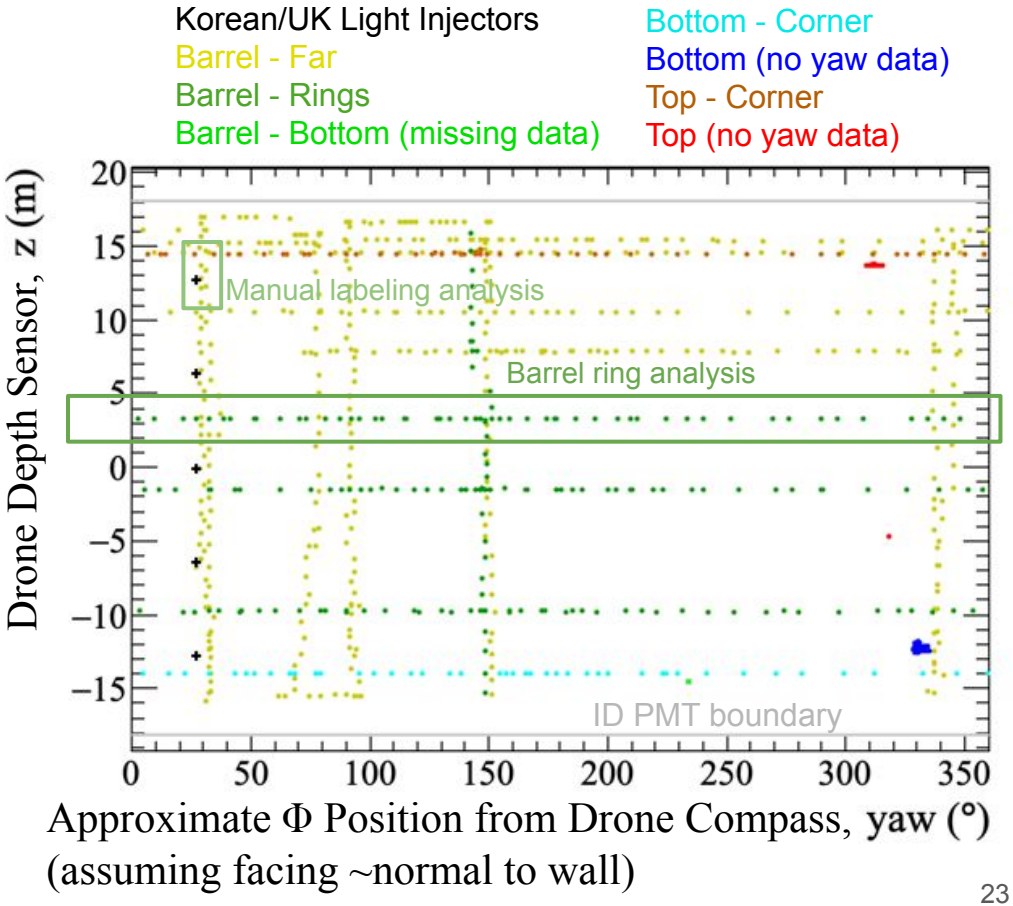




Fitted pose using proposed labels

Geometry Survey for Photogrammetry

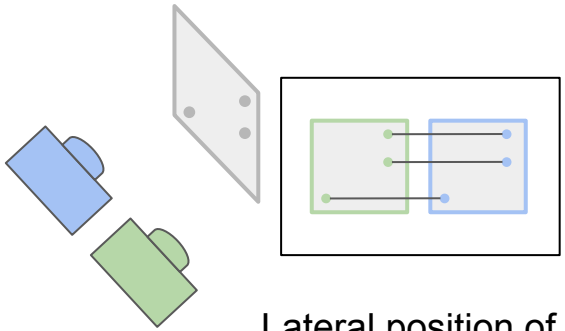
- Fairly good coverage of whole detector
  - Including top and bottom caps
  - ~1800 positions, ~13000 photos
- Potentially undersampled regions
  - Limited time: 5.5 hours total
  - Difficult to track during piloting
    - Sensor plots were not available during TOW
- Analysis will tell if this current photo set is sufficient



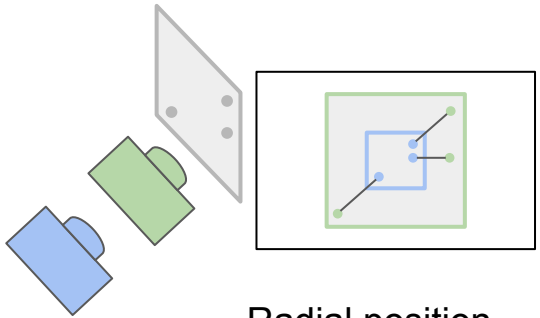
3D reconstruction: Determining (Seed) Camera Poses

Use seed 3D positions from expected geometry

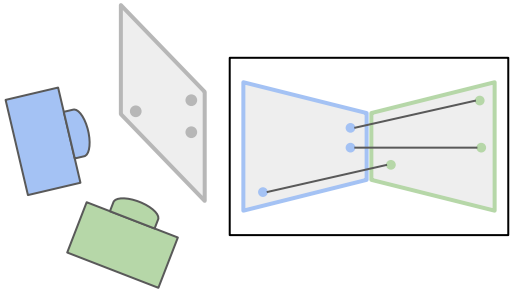
1. Load pixel coordinates of identified features in images
2. Determine camera poses from assumed ‘expected’ 3D feature positions
    - Camera poses: relative position and orientation in 3D space



Lateral position of camera



Radial position (distance) of camera

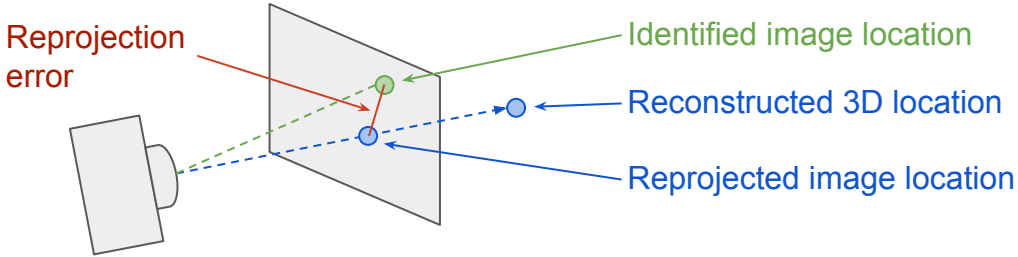


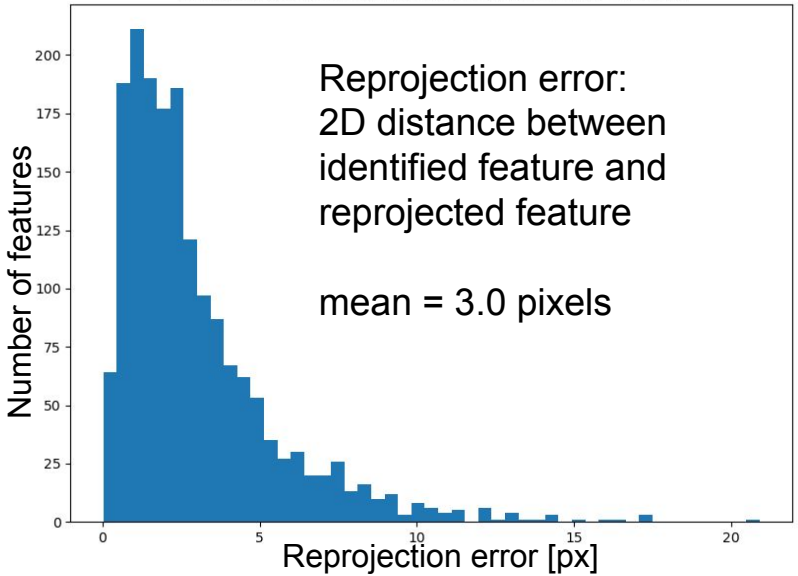
Orientation of camera

https://en.wikipedia.org/wiki/Perspective-n-Point

Reconstruction Analysis

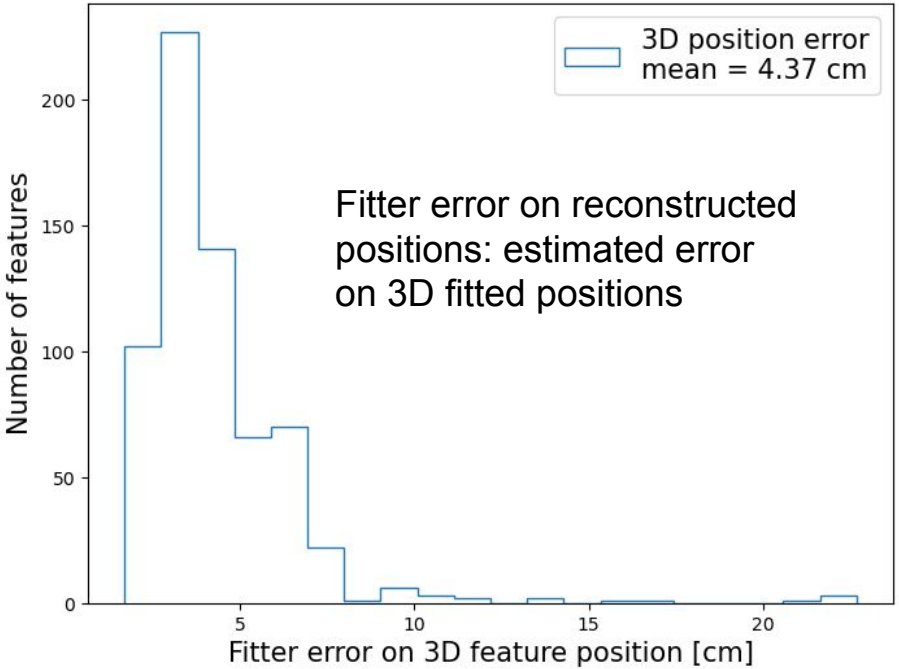
- Reconstruction fit minimises “reprojection errors”
  - Mean error: 3.0 pixels
  - 1 px error ~ 1 cm position error
  - Manual image processing by eye had ~ 1.6 pixel error
- Reprojection errors provide measure of fit quality, due to:
  - Errors in feature position identification in images
  - Errors in feature labelling
  - Errors in camera calibration
  - Bad fit convergence

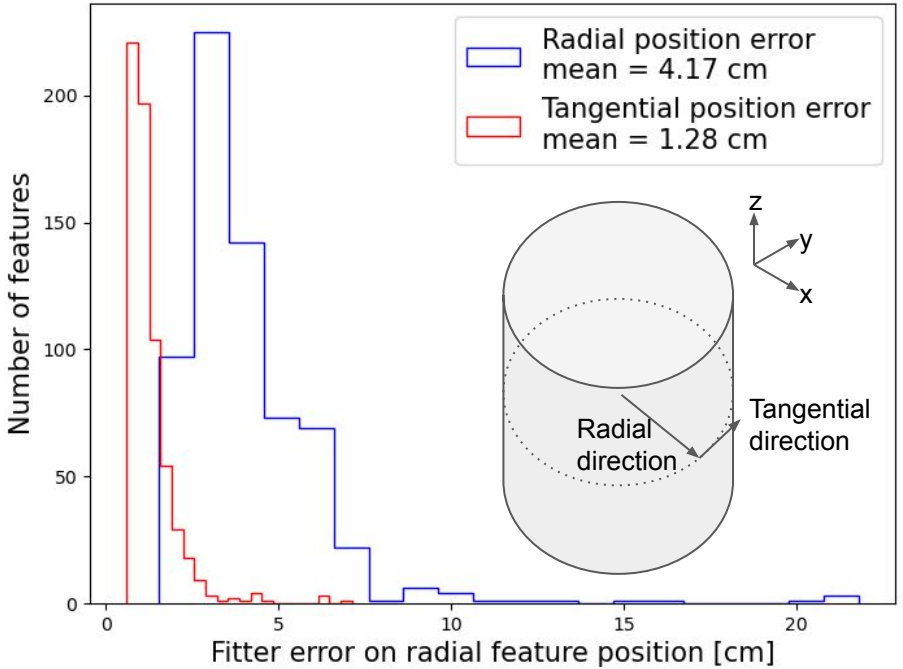




Reconstruction Analysis

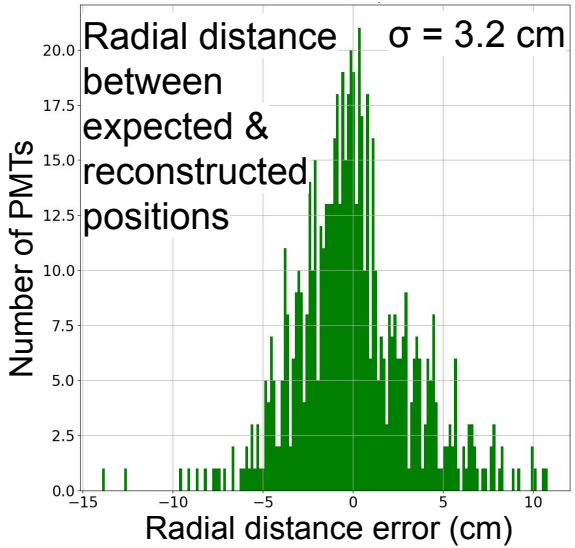
- Fit also provides estimated measurement errors on fitted position values
- Interpreted like reprojection errors, but in cm instead of pixels
  - Currently ~ 4 cm errors, but hope to reduce through improvements to image processing

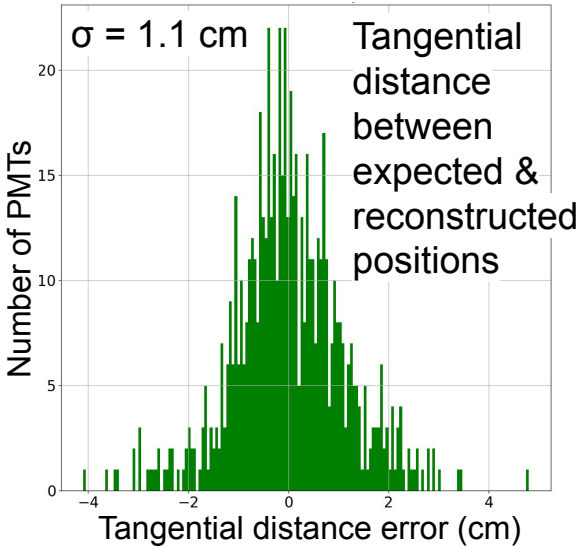


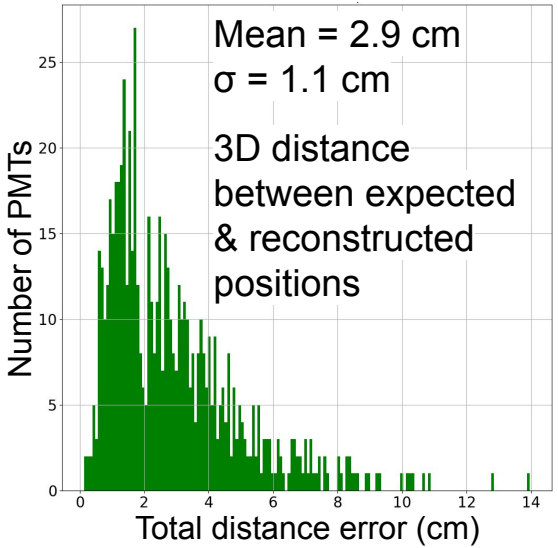


Reconstruction Analysis

Difference between reconstructed PMT positions and SKDETSIM PMT positions





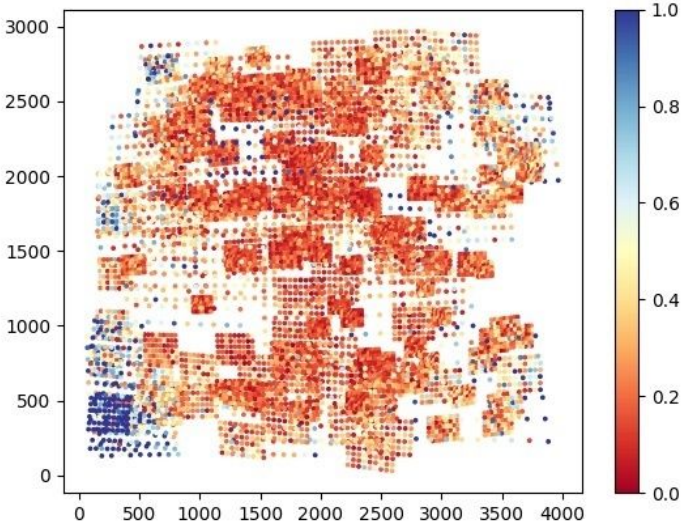


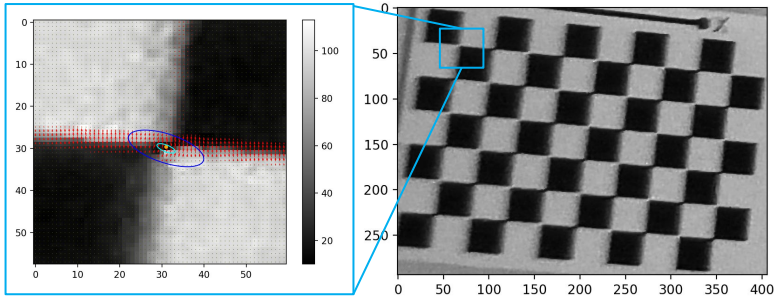
- So far, this dataset and analysis shows no evidence of deformations of SK geometry
  - Deviations are smaller than estimate of errors due to photogrammetry procedure
- Hope to reduce errors by improving feature identification and reconstruction
  - Future analysis to look for systematic deviations may find differences to assumed geometry
- No absolute scale information yet, but plan to determine from known length scales
  - e.g. use known distance between neighbouring bolts around PMT covers

New underwater drone camera calibration

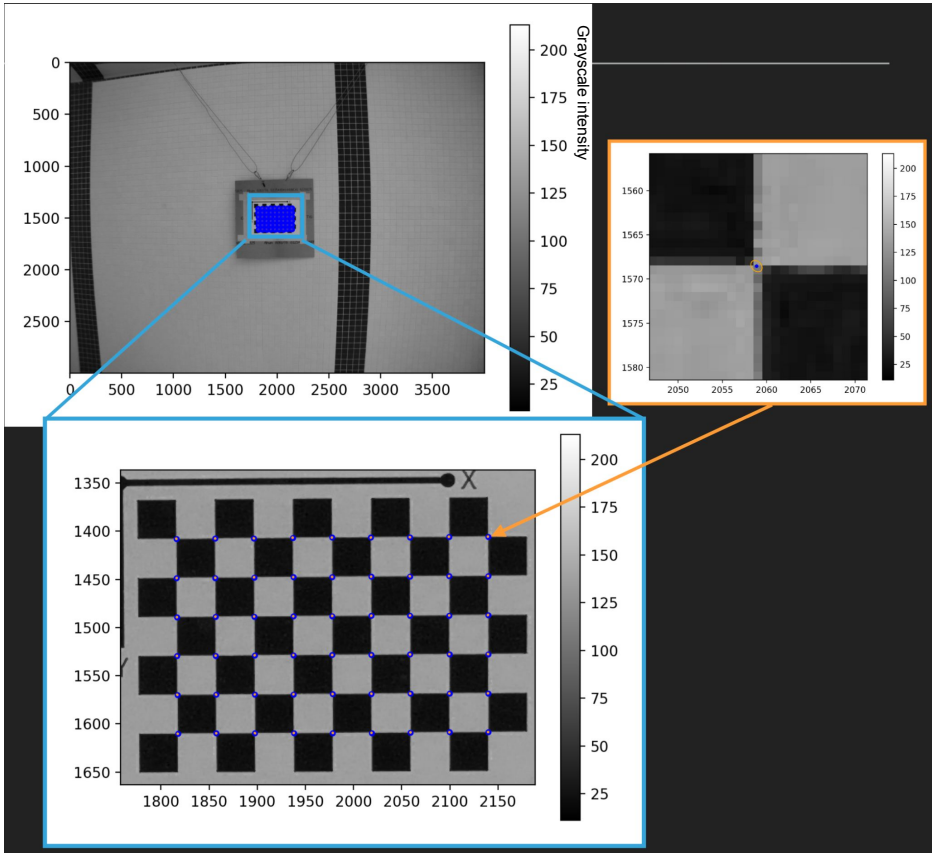
- More images are taken at 1-5 m away from the calibration pattern, with a larger FOV coverage compared to previous analysis
  - Improve camera calibration
  - Study the effect that such a distance has on the camera model
  - Compare results between two Fifish V6 drones
- Near-term plans
  - Larger calibration patterns for easier and better calibration at 4-5 m (the distance at which photos were taken in SK by the drones for photogrammetry analysis)
  - Assign corner finding uncertainties in the camera calibration analysis, and obtain camera model with correlated errors as results, which will be propagated to SK photogrammetry analysis

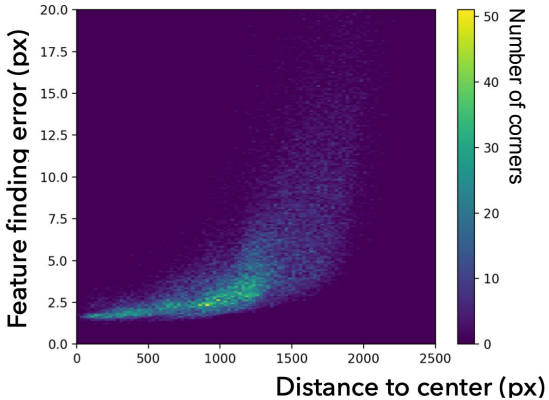
Reprojection error w/ 300 images





Feature Detection Uncertainty Estimation





UBC Pool Underwater Camera Calibration

Testing hemispherical dome port candidates and cameras:

1) PVC prototype camera housing deployed underwater using ladder support and metal wire, to sit flush against pool wall.
2) Calibration pattern deployed and maneuvered using Fifish V6 drone.
3) Systematic image acquisition at set distances of 2m, 3m and 4m to imitate meaningful distances for IWCD