Internship Project Report

Matthew Ward

August 4, 2025

Introduction

- **BYU Applied and Computational Math (DS & ML, April 2026)**
- **Biophysics Simulation Group—computer vision and competition dataset curation with 3D pictures of bacteria (cryo-ET tomograms)**
- **Data engineer intern with you until August 16th!**

Fast, Efficient
3D Imaging

Overview of projects

1. **Generate a processing performance report**
2. **Improve registration pipeline with pose graph optimization**
3. **Model laser spot illumination as a Gaussian from sensor data**

Processing Performance Report

Processing Performance Report

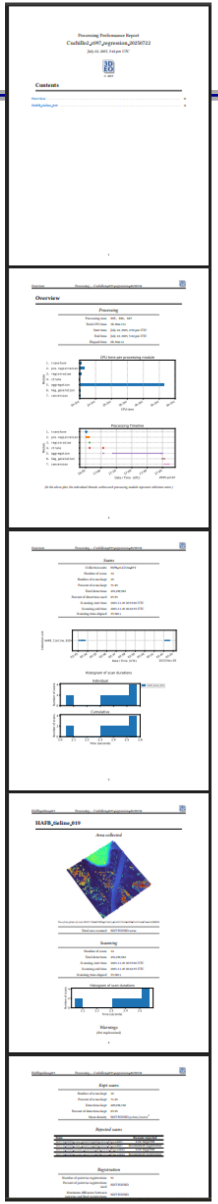
Not to be confused with sensor performance report!

Processing Performance Report

Not to be confused with sensor performance report!

A PDF report summarizing key insights from processing.

Located in `<acadia-output-directory>/qc/processing_report` **after processing is complete**



Processing Report Generation Process

Processing directory

for example, `albert:/shares/processed/cuchillo/flightData/FlatCreek`

↓

JSON of filepaths and statistics

to be used in report

↓

LaTeX report

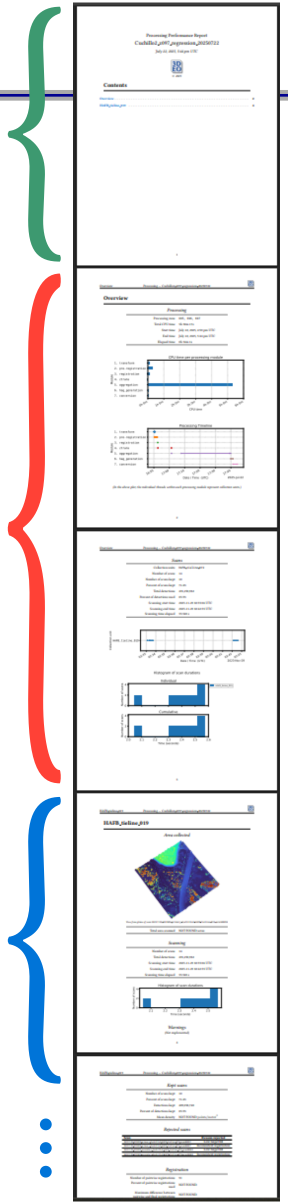
↓

PDF report

Report Format

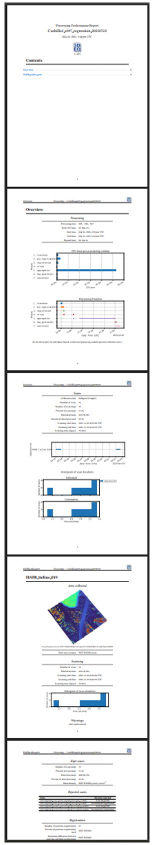
Report Format

- Contents
- Overview (information about all tiles together)
- Tile 1 (information specific to this tile)
- Tile 2
- ⋮
- Tile n



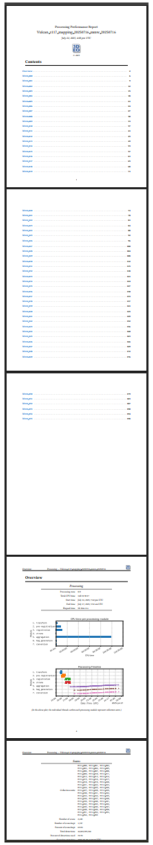
Example Processing Reports

Single Tile Report



(6 pages)

Mapping Report (56 tiles)



(203 pages)

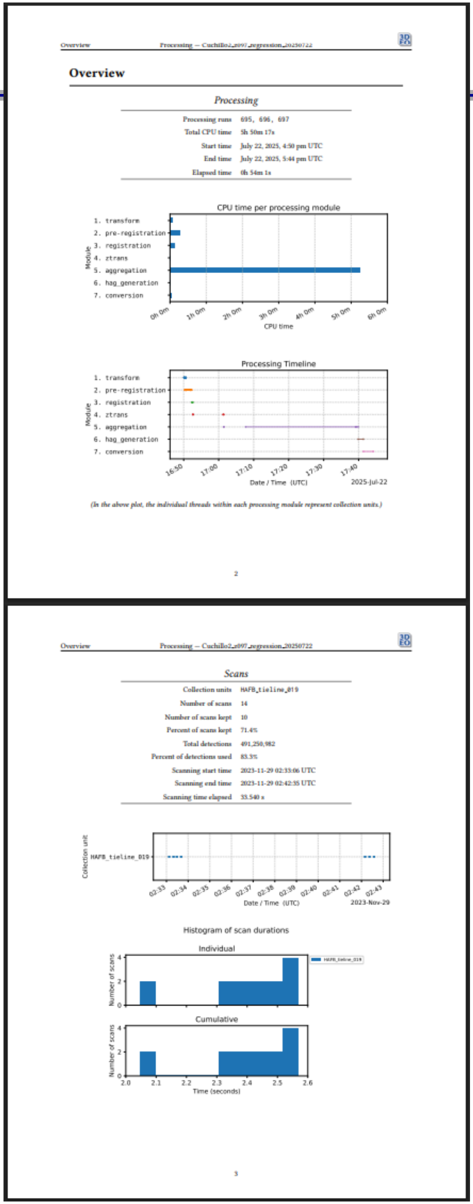
Overview

- **Processing summary**

  How long processing took, CPU time, etc.

- **Scan summary**

  Number of detections, how long scanning took, etc.

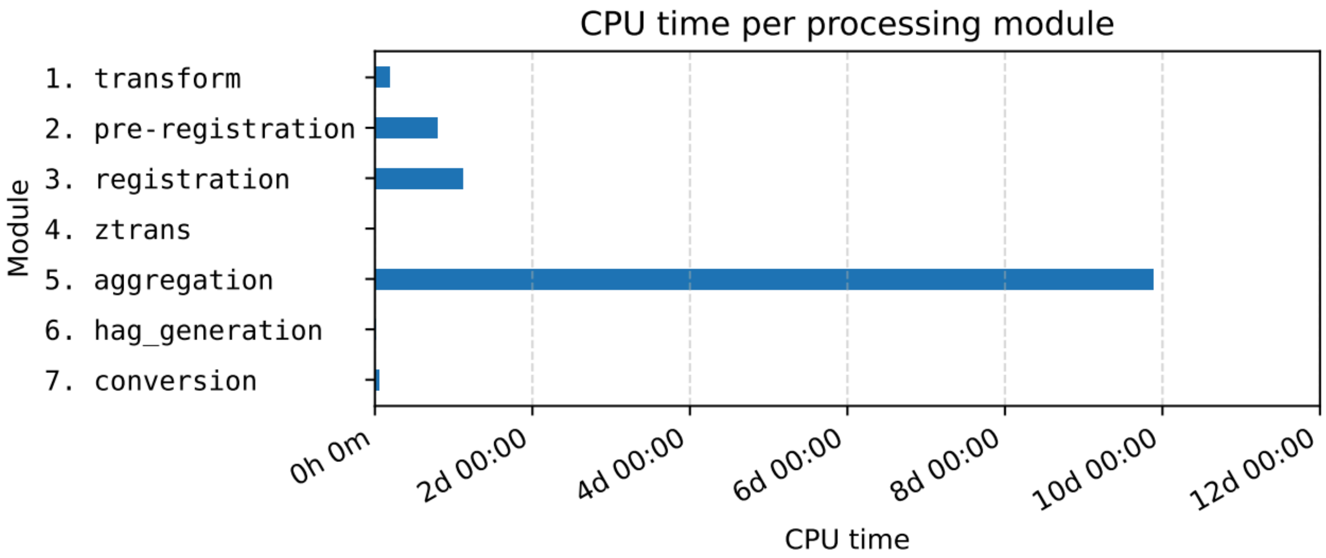


(Overview from Single Tile Report)

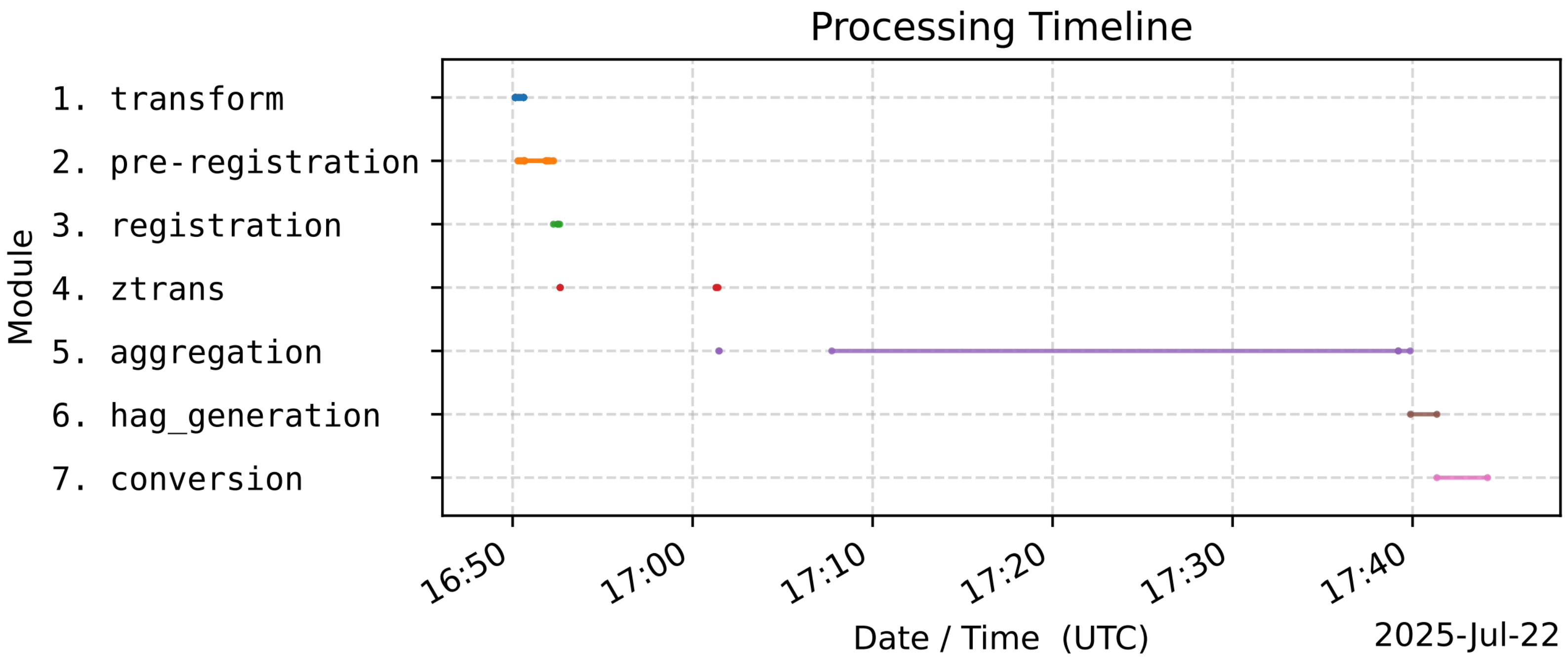
Processing Summary

Processing

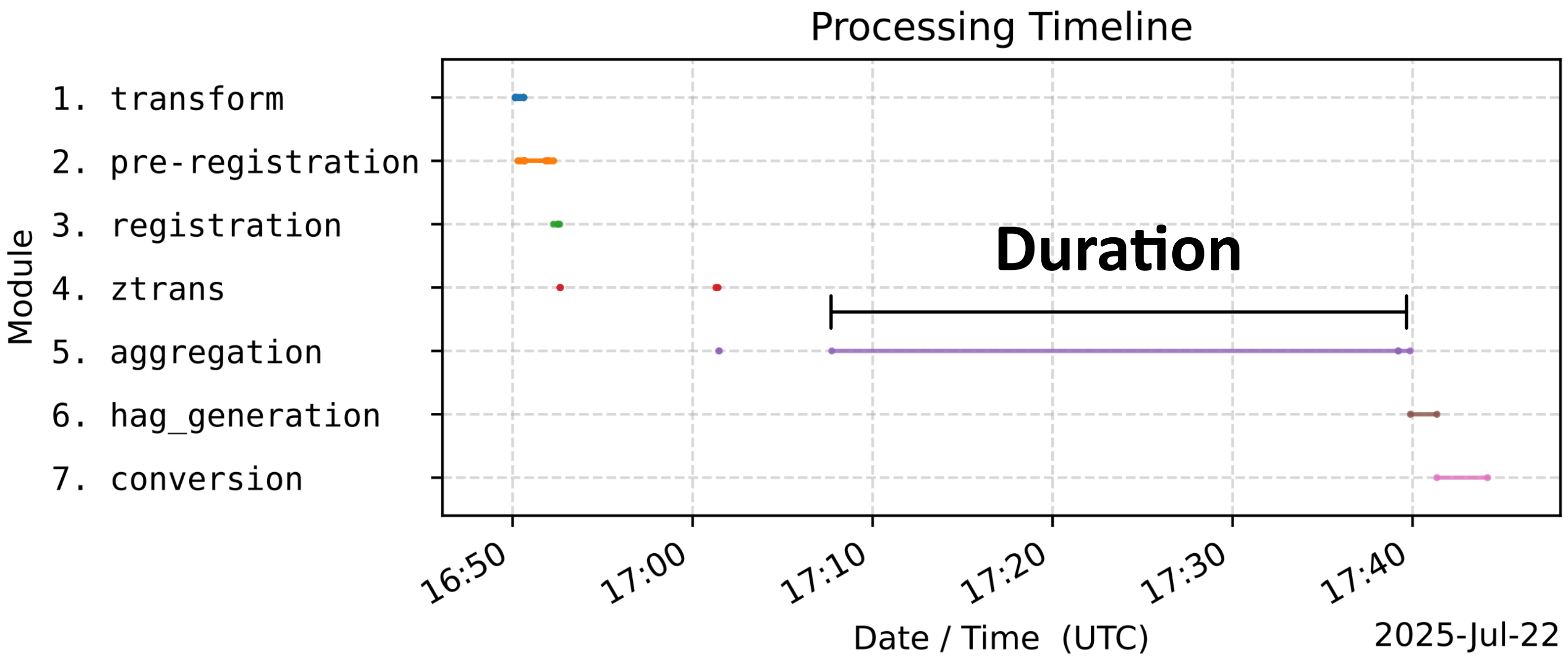
Processing runs	631
Total CPU time	12d 01:30:17
Start time	July 16, 2025, 7:42 pm UTC
End time	July 17, 2025, 5:32 am UTC
Elapsed time	9h 50m 11s



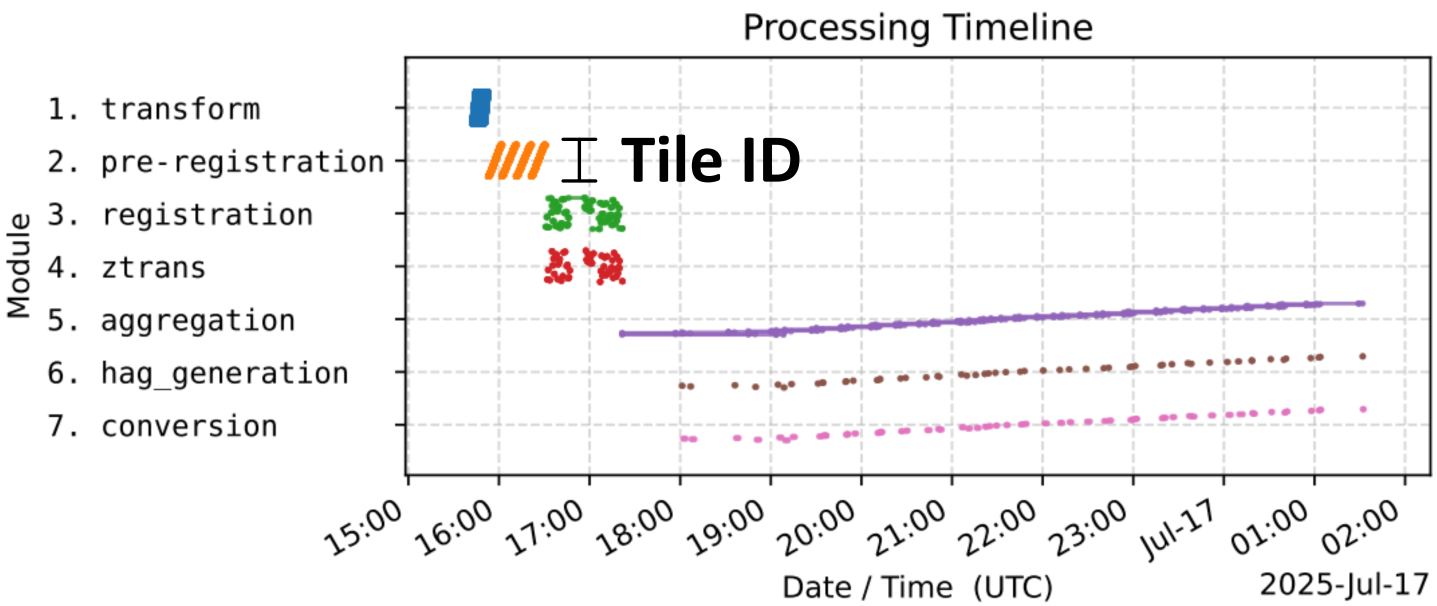
Processing Timeline



Processing Timeline



Processing Timeline



(In the above plot, the individual threads within each processing module represent collection units.)

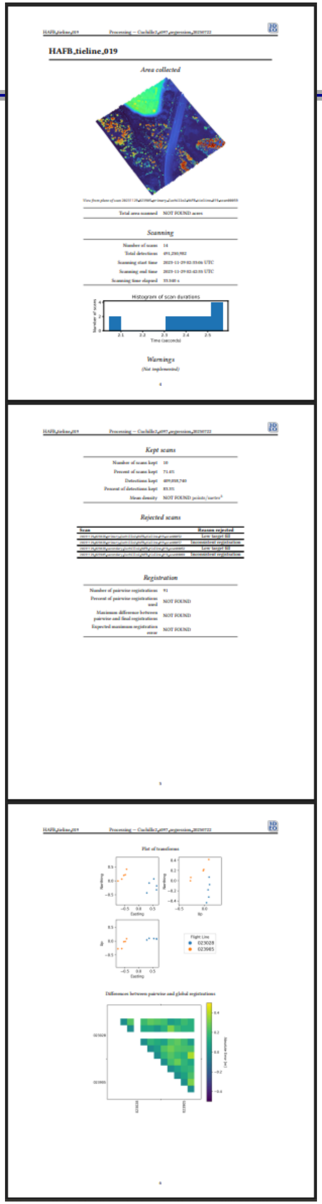
Per Tile Sections

- **Picture of the tile**
- **Scan information**

  Number of detections, how long scanning took, etc.
- **Rejected data**

  Reasons for rejection
- **Registration information**

  To evaluate success of registration



(HAFB_tieline_019 from Single Tile Report)

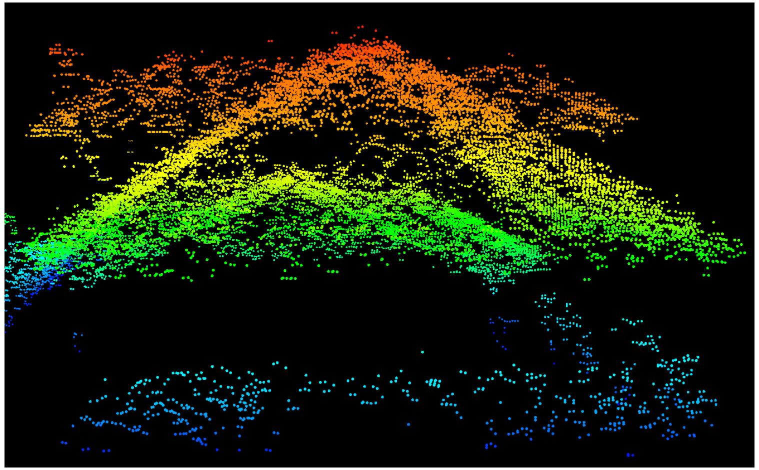
Future Work

- Continue to refine wording and format for clarity
- Finish implementing fields
  - Scan density information
  - Report on more data rejection reasons
  - Registration success metrics
  - Warnings—for example, warn if the beam was dumping
- Get client feedback—what do they want to see in the report?
- Make LaTeX compilation container smaller

Pose Graphs for Registration

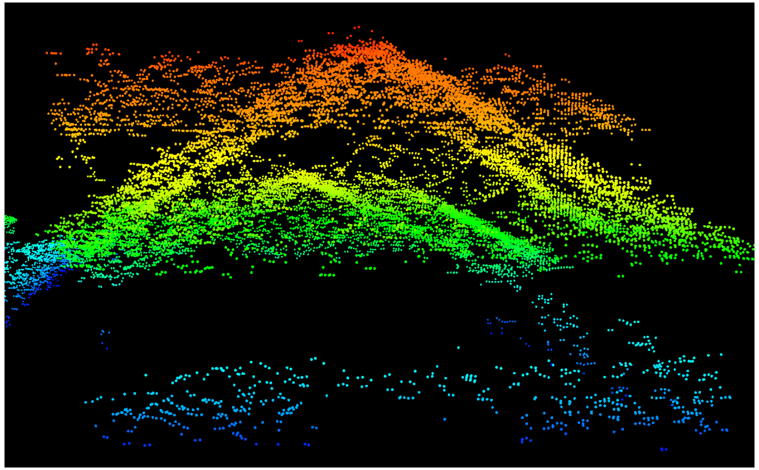
Ghosting

Good registration



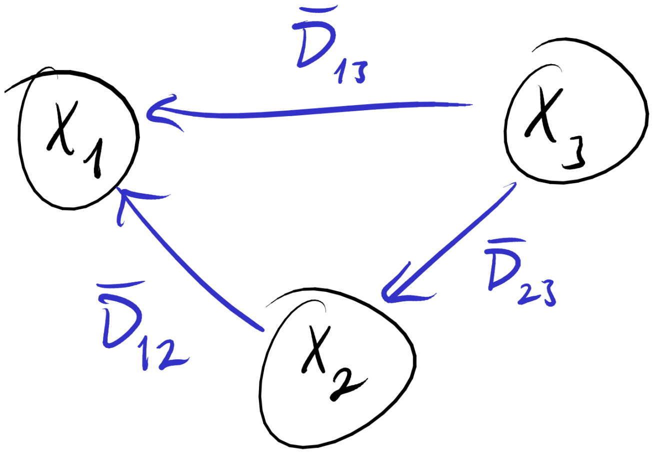
Bad registration

notice that the roof is doubled here



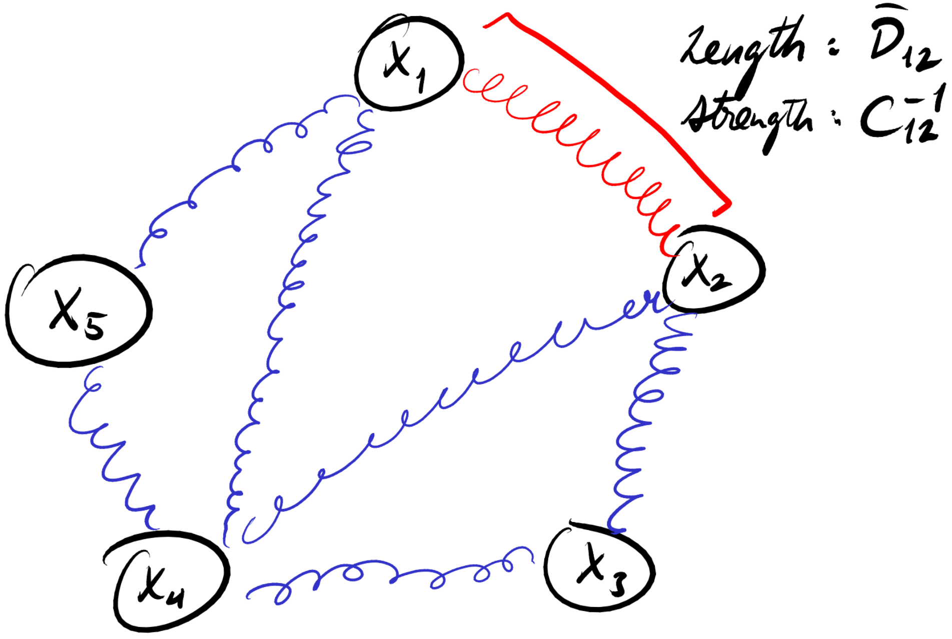
Pose Graph

We have ways to move one scan to align with another, with some uncertainty. How can we move n scans to align with each other?



In practice, $\bar{D}_{13} \neq \bar{D}_{12}\bar{D}_{23}$.

Pose Graph as Springs



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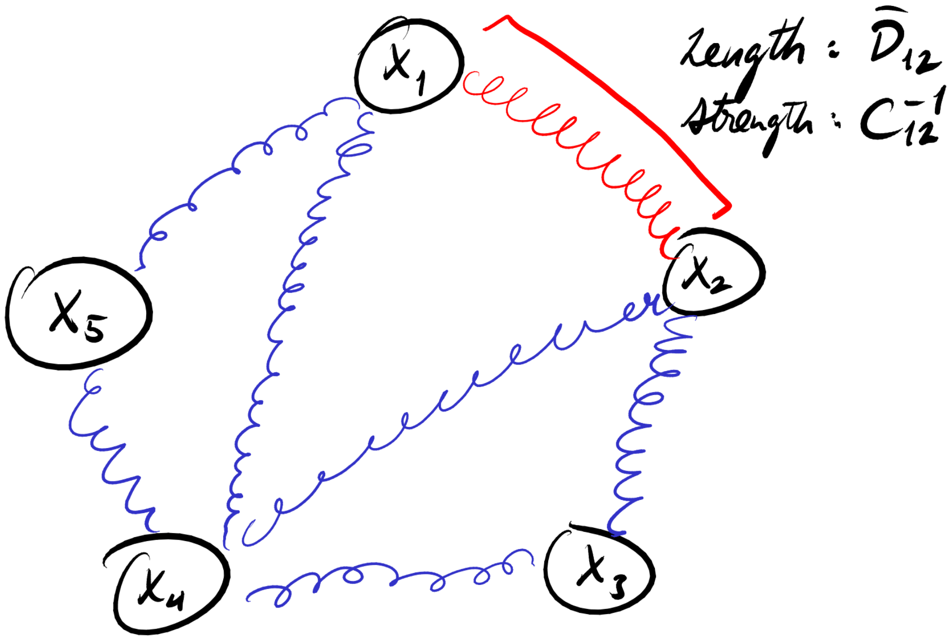
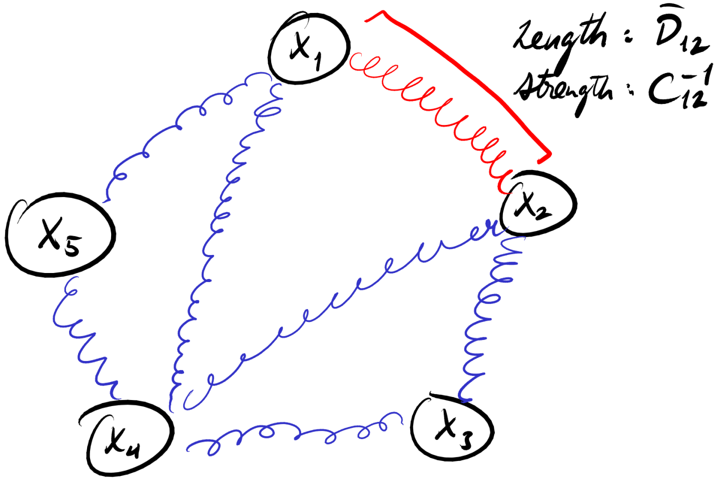


$$\underset{\{X_1,\ldots,X_n\}}{\text{minimize}} \quad \sum_{i,j} \left(\bar{D}_{ij} - \left(X_i - X_j\right)\right)^T C_{ij}^{-1} \left(\bar{D}_{ij} - \left(X_i - X_j\right)\right)$$

Pose Graph as Springs



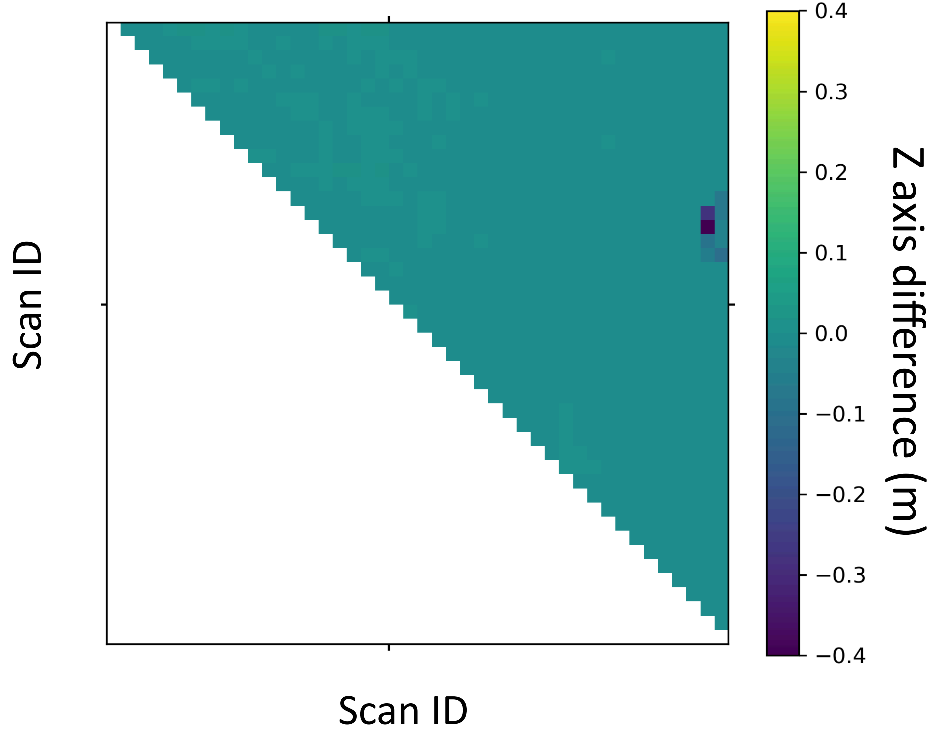
Ways to Set Spring Elasticities (covariances)

- **Constant elasticity**
- **Model elasticity using pairwise features**
  $(i, j) \rightarrow C_{ij}^{-1}$

$$\underset{\{X_1,\ldots,X_n\}}{\text{minimize}} \quad \sum_{i,j} \left(\bar{D}_{ij} - \left(X_i - X_j\right)\right)^T C_{ij}^{-1} \left(\bar{D}_{ij} - \left(X_i - X_j\right)\right)$$

Rooting out Bad Pairwise Registrations

Comparing pairwise and global registrations



- After optimization, some springs (pairwise registrations) are stretched
- Lots of redundancy in the graph reveals poor pairwise registrations
- Weight those springs less in optimization step or remove them entirely

Lu-Milios Implementation

- **Implemented registration optimizer using the closed-form least squares pose graph solution described in Lu and Milios' 1997 paper**

$$\mathbf{X} = \left(\mathbf{H}^T\mathbf{C}^{-1}\mathbf{H}\right)^{-1}\mathbf{H}^T\mathbf{C}^{-1}\bar{\mathbf{D}}, \qquad \mathbf{C}_{\mathbf{X}} = \left(\mathbf{H}^T\mathbf{C}^{-1}\mathbf{H}\right)^{-1}$$

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- **Parameters:**
  - **Expected translational error of 1 meter, 2 mrad (constant covariance of** $\mathrm{diag}\left(1, 1, 1, 0.002^2, 0.002^2, 0.002^2\right)$**)**
  - **Prune edges (pairwise registrations) whose optimized Mahalanobis distance has z-score higher than 1.5 among all edges**

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  - **Prune edges (pairwise registrations) whose optimized Mahalanobis distance has z-score higher than 1.5 among all edges**
- **Note: Improper to perform linear least squares on Euler angles, but works alright since angles are very small (no more than a few mrad)**

Comparing Old Optimizer with Lu-Milios

Optimization Time (Barrett Park)

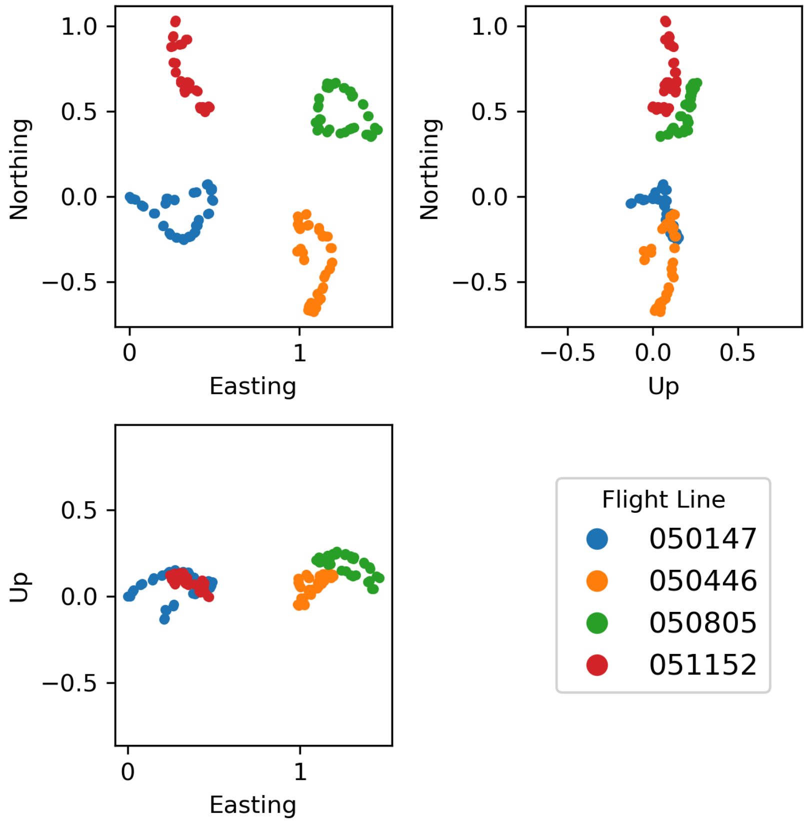
Old ncc_nxn Optimizer	*Lu-Milios Optimizer*
2m 54s	0m 3s
	(58 times faster)

See *References* for link to old optimizer

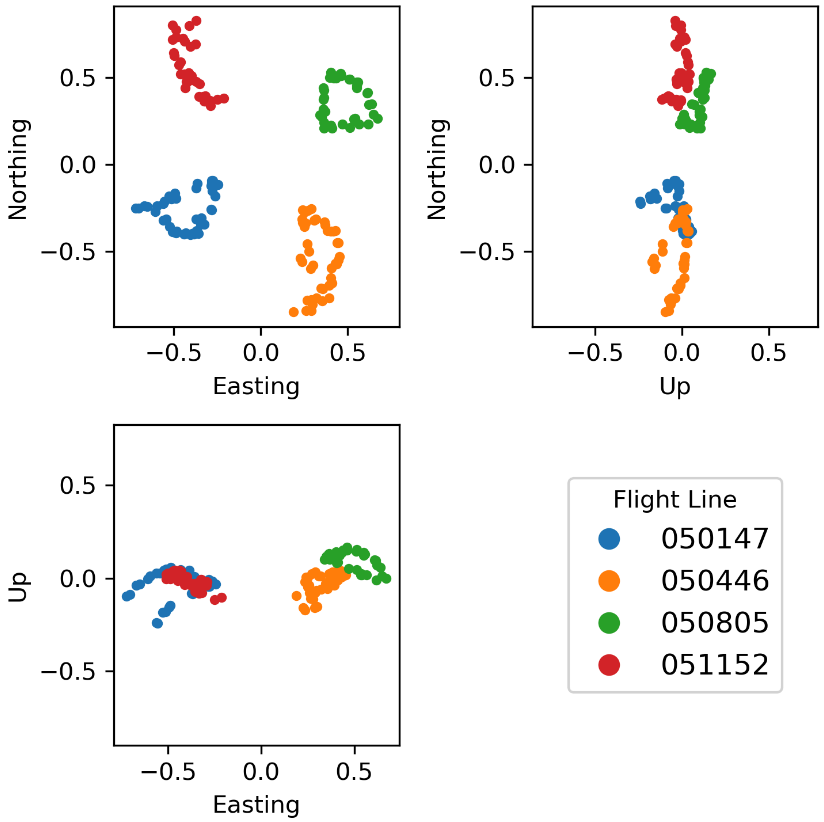
Comparing Old Optimizer with Lu-Milios

Optimized Translation Plots (Barrett Park)

Old ncc_nxn Optimizer



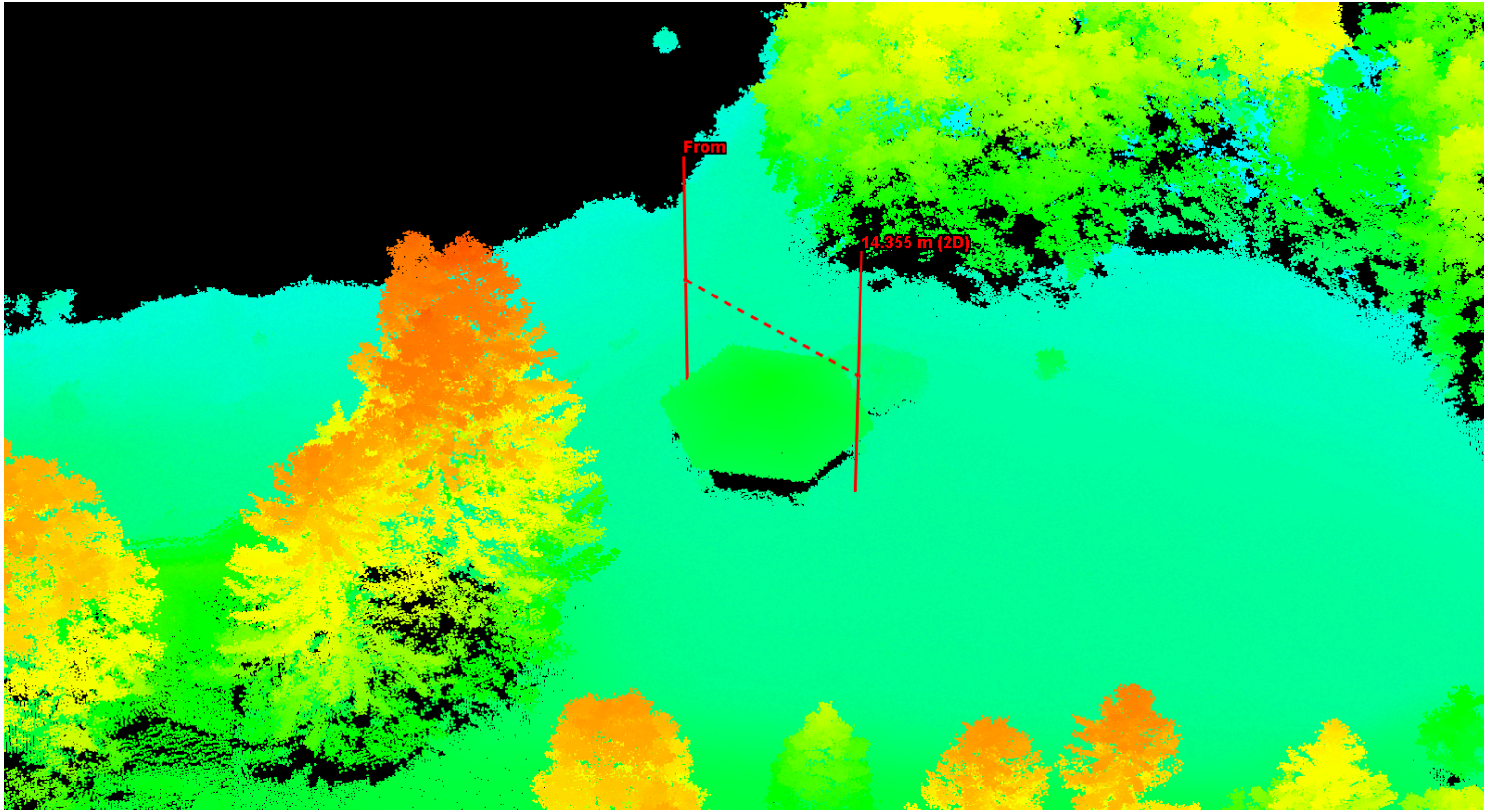
Lu-Milios Optimizer



Comparing Old Optimizer with Lu-Milios

Profile Analysis (Barrett Park, gazebo)

(only scans ending in `scan00010`)



Comparing Old Optimizer with Lu-Milios

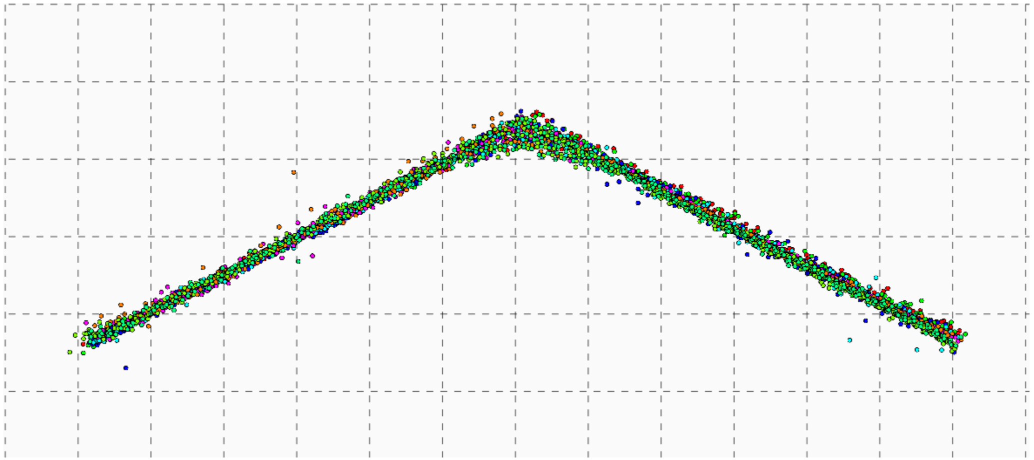
Profile Analysis (Barrett Park, gazebo)

(only scans ending in `scan00010`)

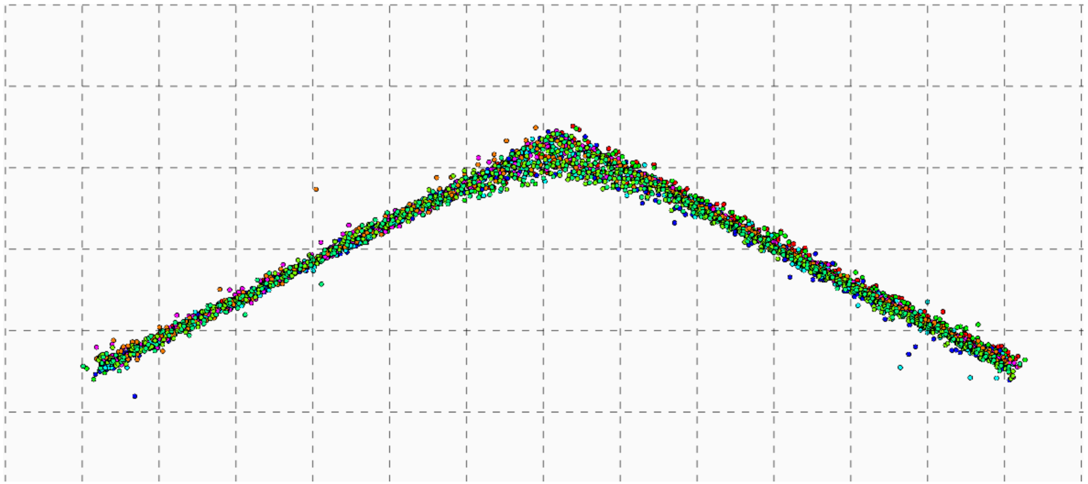
Old ncc_nxn Optimizer

Lu-Milios Optimizer

1 m



1 m



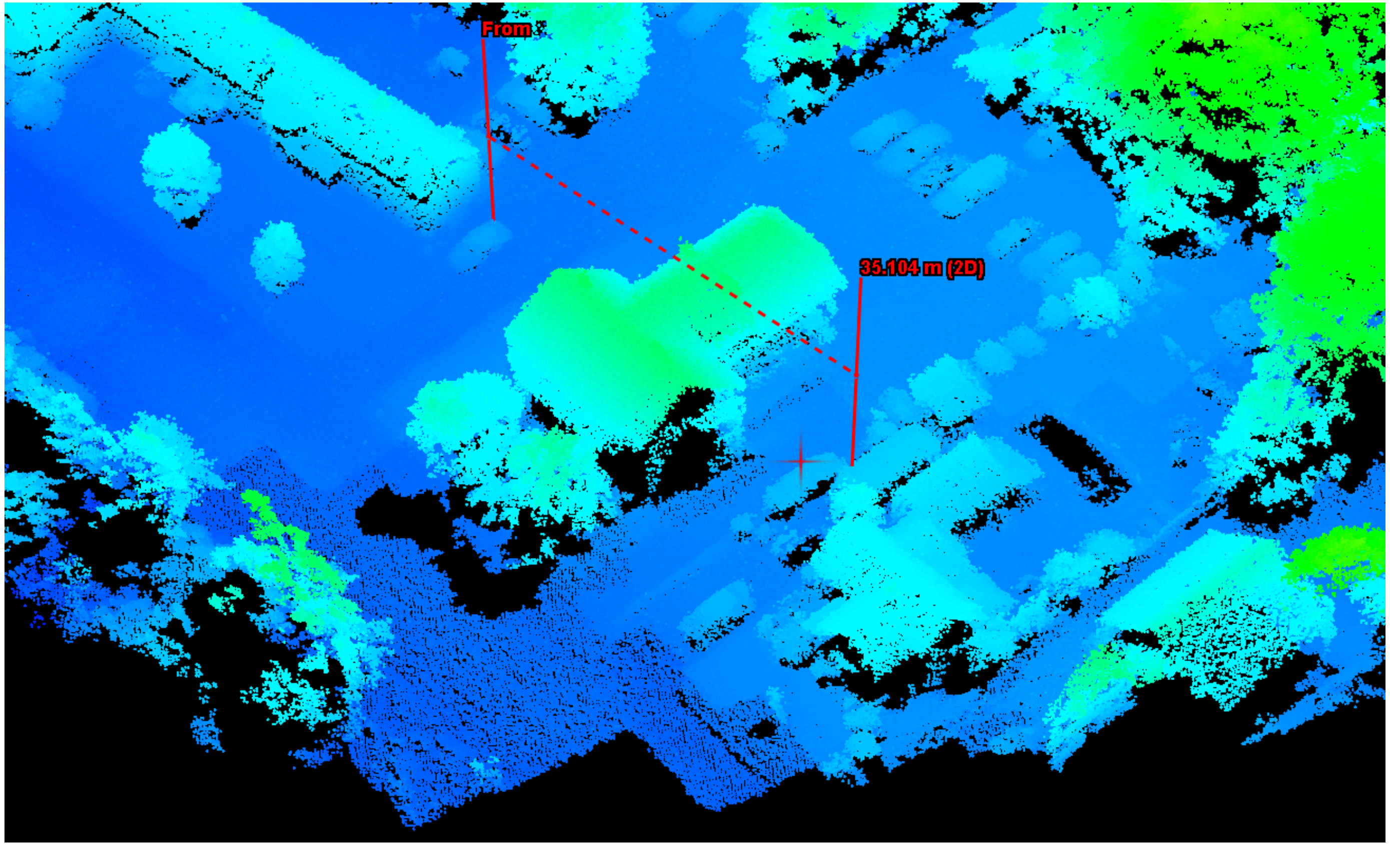
1 m

(notice ghosting at upper left in both images)

Comparing Old Optimizer with Lu-Milios

Profile Analysis (Barrett Park, building on northeast)

(only scans ending in `scan00010`)

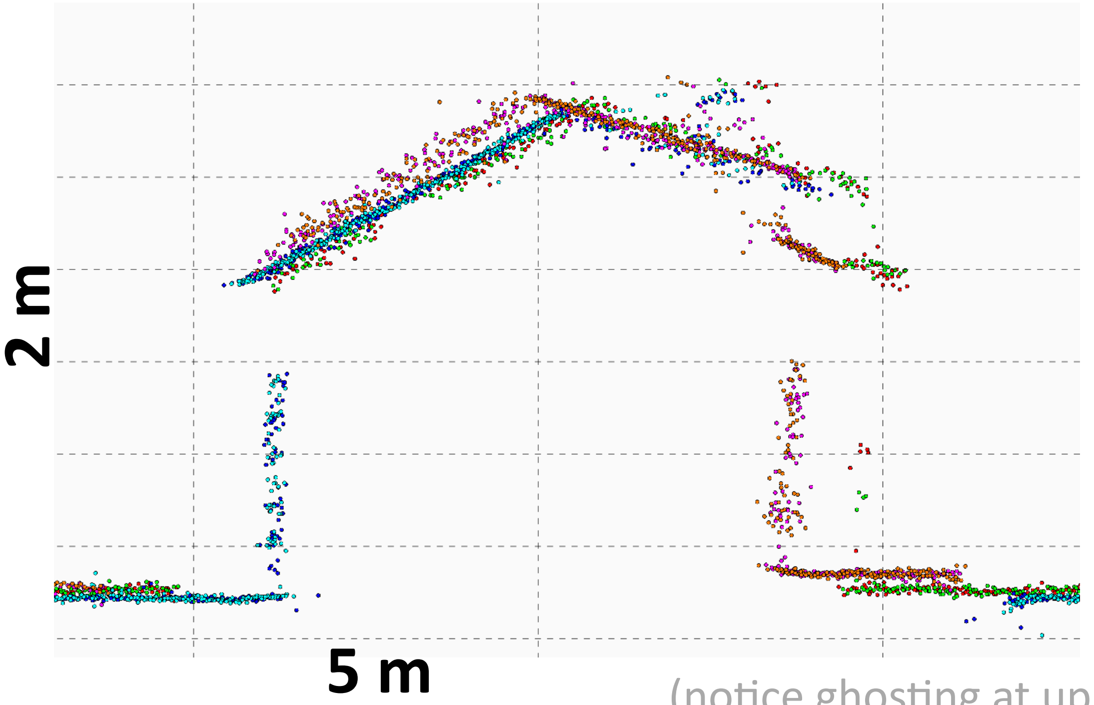


Comparing Old Optimizer with Lu-Milios

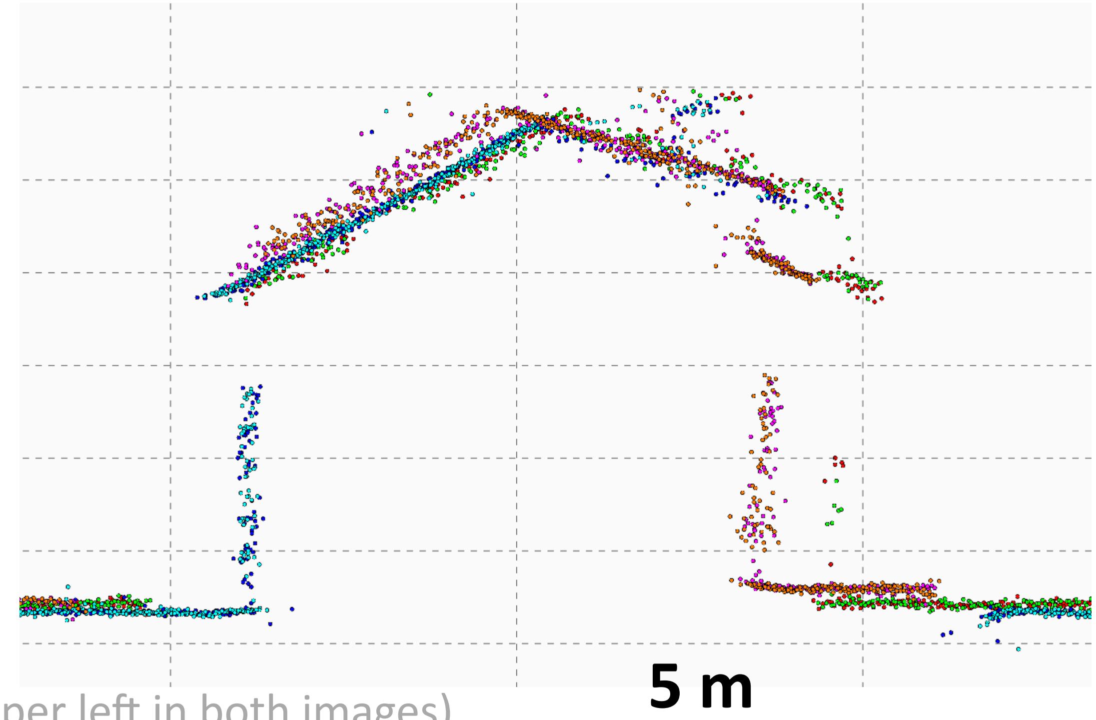
Profile Analysis (Barrett Park, building on northeast)

(only scans ending in `scan00010`)

Old ncc_nxn Optimizer



Lu-Milios Optimizer



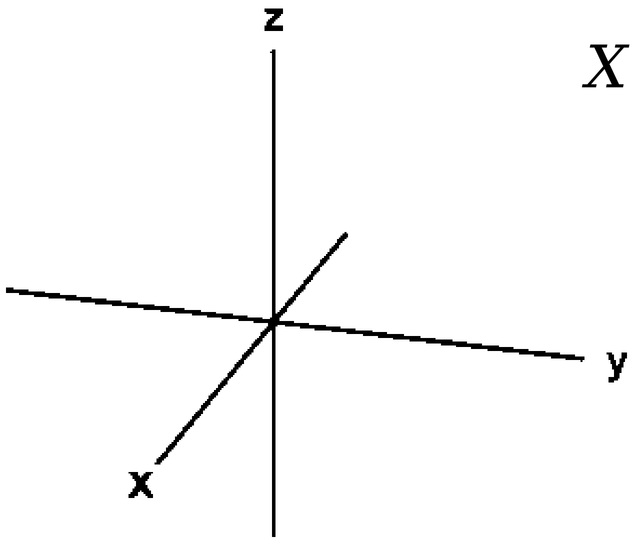
(notice ghosting at upper left in both images)

Ongoing and Future Work

$$X_i = \begin{pmatrix} x_i \\ y_i \\ z_i \\ \theta_i \\ \phi_i \\ \psi_i \end{pmatrix} \in \mathbb{R}^6$$

$$\underset{\{X_1, \ldots, X_n\}}{\text{minimize}} \quad \sum_{i,j} \left(\bar{D}_{ij} - \left(X_i - X_j \right) \right)^T C_{ij}^{-1} \left(\bar{D}_{ij} - \left(X_i - X_j \right) \right)$$

Ongoing and Future Work



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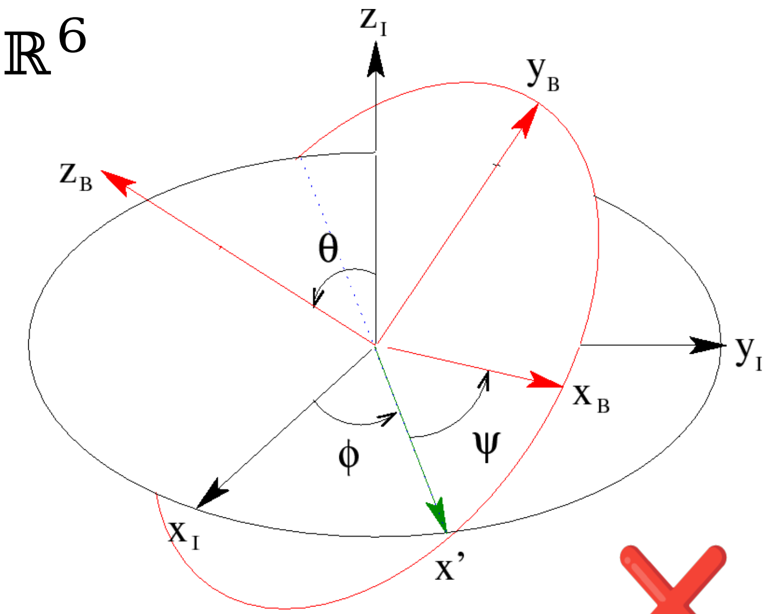


✅ ❌

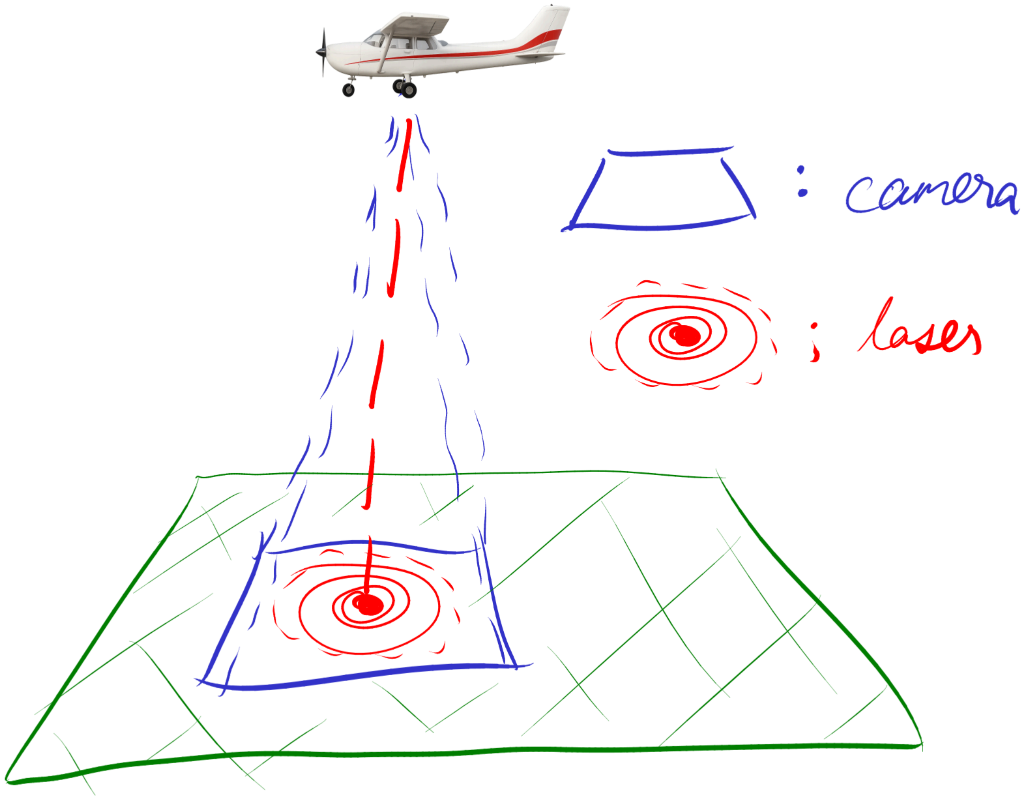
$$\underset{\{X_1,\ldots,X_n\}}{\text{minimize}} \quad \sum_{i,j} \left(\bar{D}_{ij} - (X_i - X_j)\right)^T C_{ij}^{-1} \left(\bar{D}_{ij} - (X_i - X_j)\right)$$

Ongoing and Future Work

- Use non-linear least squares optimization to better handle orientation
- [lie algebra graph results]
- Be smarter in choosing pairwise registration covariance (uncertainty)
  - Automatically determine covariance using properties of the sensor or the data
  - Use pairwise registration features to determine covariance

Modeling the Laser Illumination Spot

Laser Illumination Spot



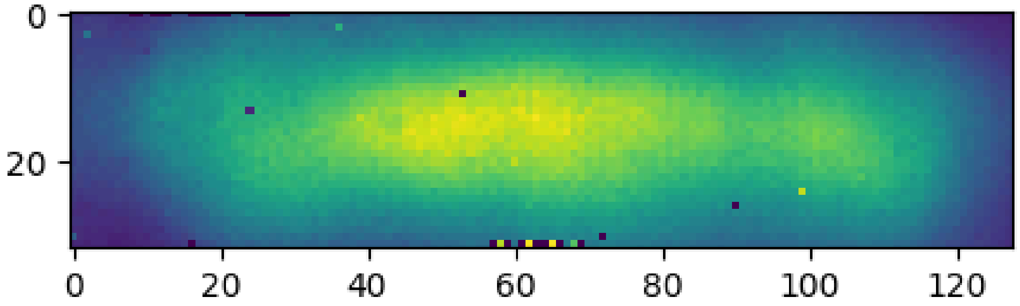
Why Model the Spot

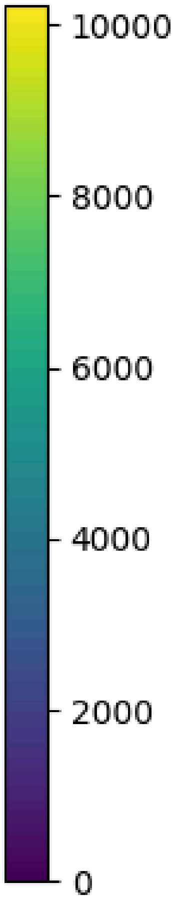
- **More accurate pointwise reflectivity estimate**
- **Validate or refine alignment in-flight**
- **Track defective pixels**

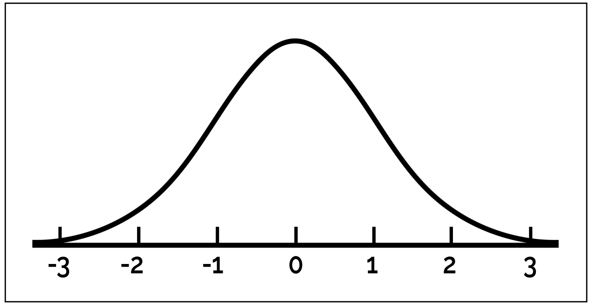
Spot is Approximately Gaussian

Total photon detections per pixel during

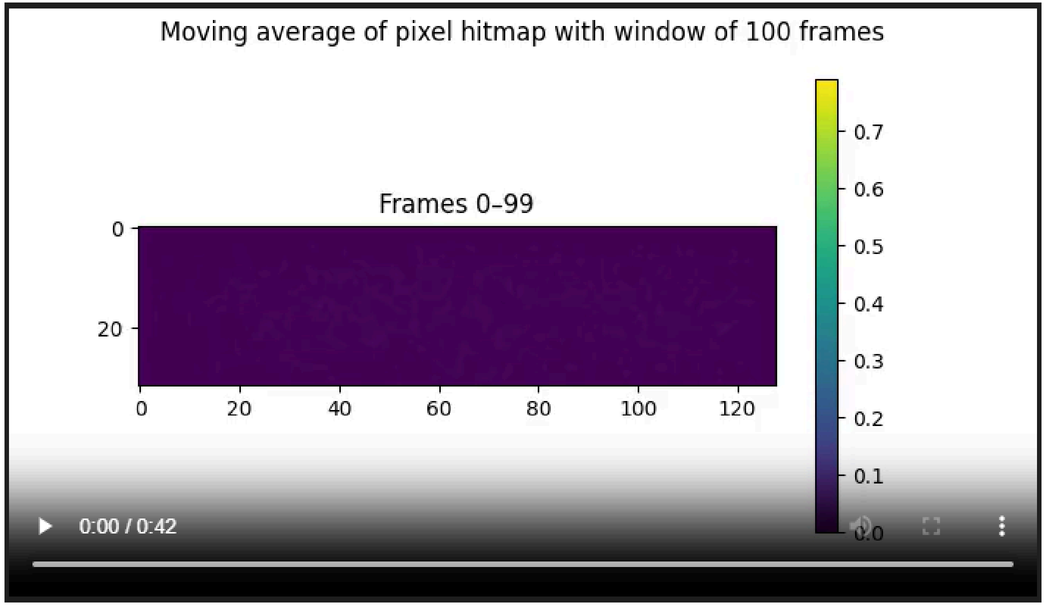
`20230627_095732_cuchillo1_scan00091.bpf`



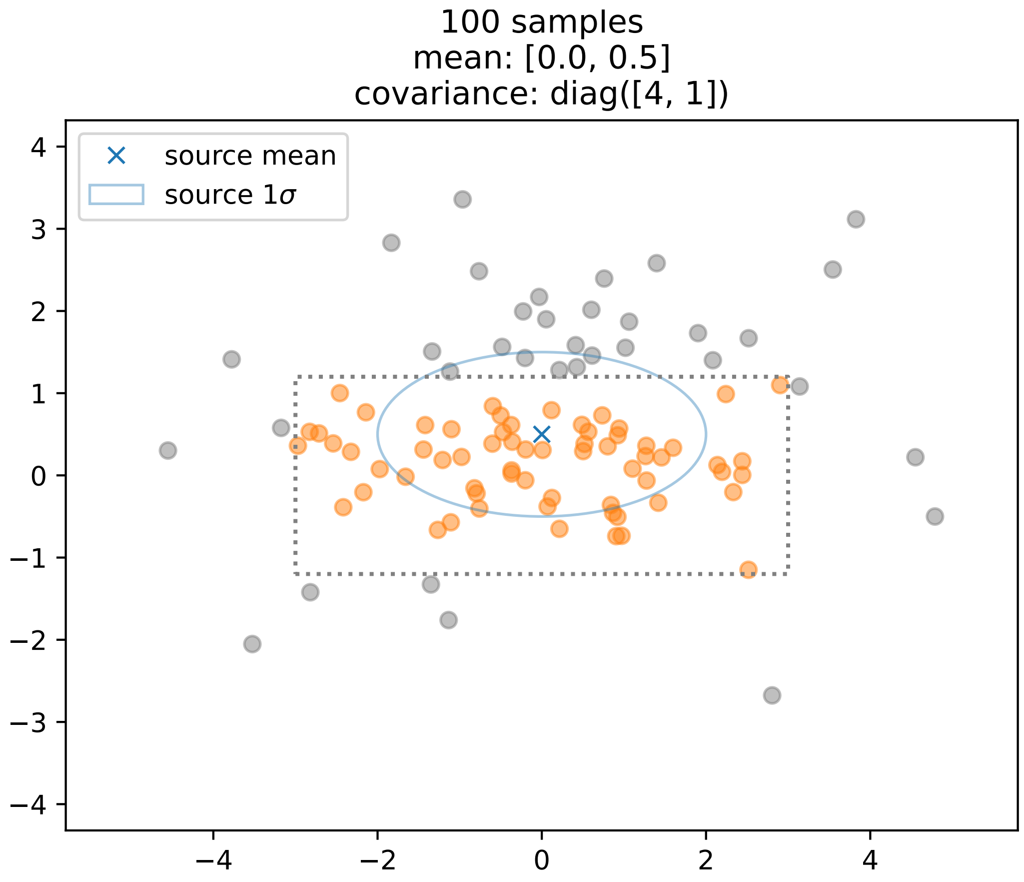




Cannot Assume the Spot Stays Still

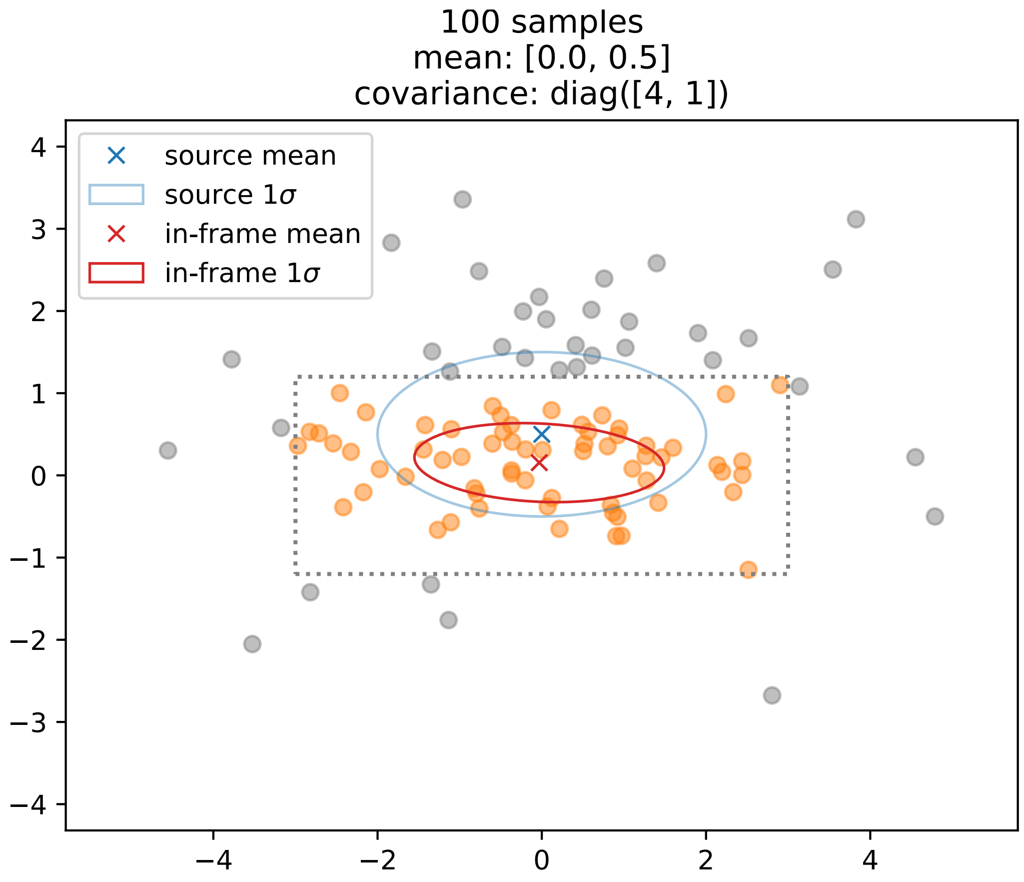


Cannot Use Sample Mean and Covariance



- **100 random Gaussian samples representing photons, not all of which are in-frame**
- **Ring represents 1 standard deviation**
- **We only see the samples within the frame**

Cannot Use Sample Mean and Covariance



- 100 random Gaussian samples representing photons, not all of which are in-frame
- Ring represents 1 standard deviation
- We only see the samples within the frame
- Fitting Gaussian with sample mean and covariance doesn't work

Attempts

For each 100-frame pixel hitmap average,

- **Sample mean and covariance with Gaussian Mixture Models**

Attempts

For each 100-frame pixel hitmap average,

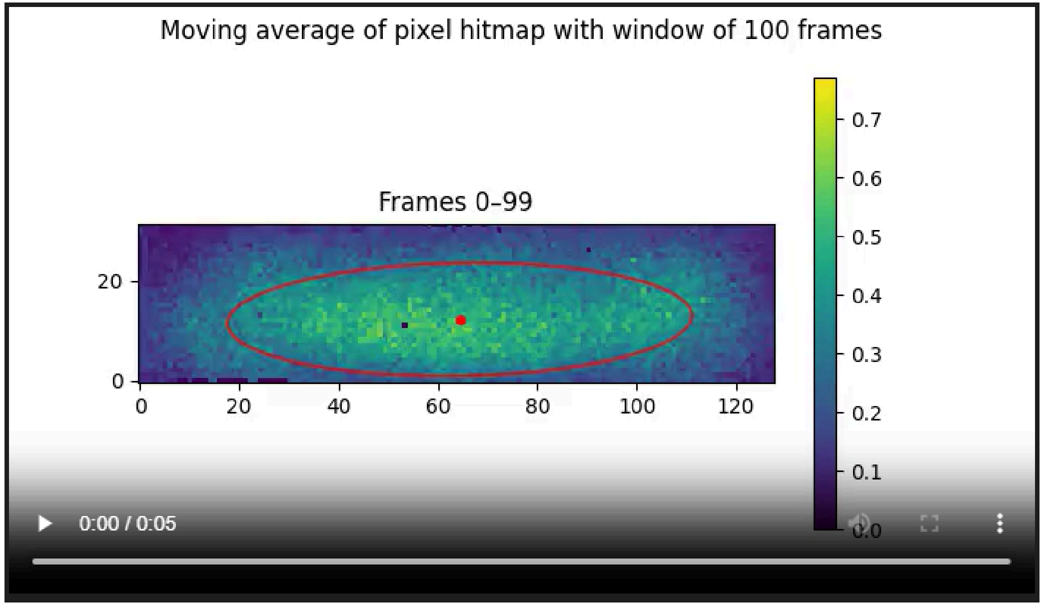
- **Sample mean and covariance with Gaussian Mixture Models**
- **Bayesian inference to fit Gaussian parameters given camera frame bounds**

Attempts

For each 100-frame pixel hitmap average,

- **Sample mean and covariance with Gaussian Mixture Models**
- **Bayesian inference to fit Gaussian parameters given camera frame bounds**
- **`pygmmis`—Gaussian Mixture Models for occluded data**
  - **Written by Princeton astronomers to model luminosity of galaxies from truncated camera data (like ours)**
  - **Gaussian Mixture Models (GMMs) that can handle occluded data**
  - **Under the hood, uses Expectation Maximization (standard for GMMs), but also generates mock samples to handle occluded regions**

Successful Fit



Future Work

- Continue investigating faster alternatives, using `pygmmis` as ground truth
  - Blur pixel heatmap to quickly track spot center without having to recalculate covariance
  - Fit to some subset of the data—random subset works surprisingly well
- Test on more scans
- Implement reflectivity estimate normalized by spot illumination model

References

Processing Performance Report

- processing-performance (master) on Bitbucket
- acadia (master) on Bitbucket Apptainers in apptainer_creation and slurm bricks in processing_workflow
- python_3deo/fileIO/readGSOF.py Used to collect certain scanning information

Pose Graphs for Registration

- Presentation I gave on pose graph registration
- Ideas related to the above presentation
- Lu and Milios paper "Globally Consistent Range Scan Alignment for Environment Mapping", April 1997. Introduces these ideas in the context of robotics
- Old optimizer Replaced by Lu-Milios in zreg_ncc commit 2b6d0d4 on July 18th
- Lu-Milios implementation zreg_ncc, python/lu_milios.py

Modeling the Laser Illumination Spot

- Write-up Describes background and my work thus far on this