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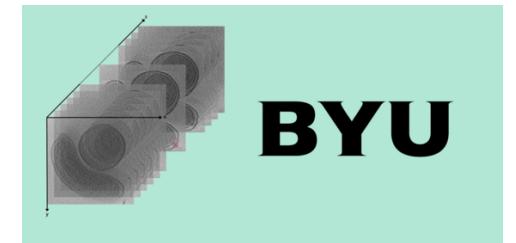
# Internship Project Report

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 16<sup>th</sup>!



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

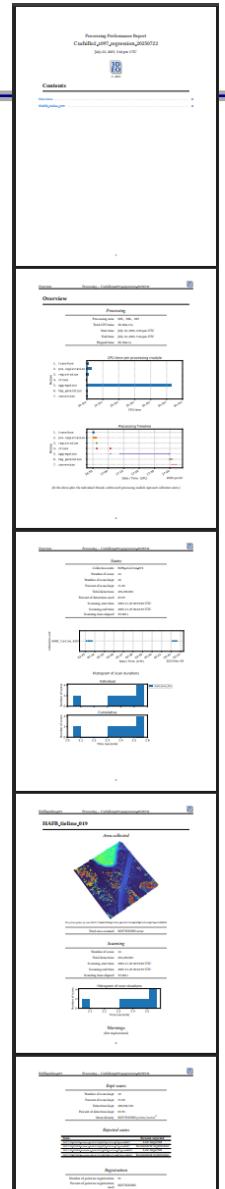
**Not to be confused with sensor performance report!**

# 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



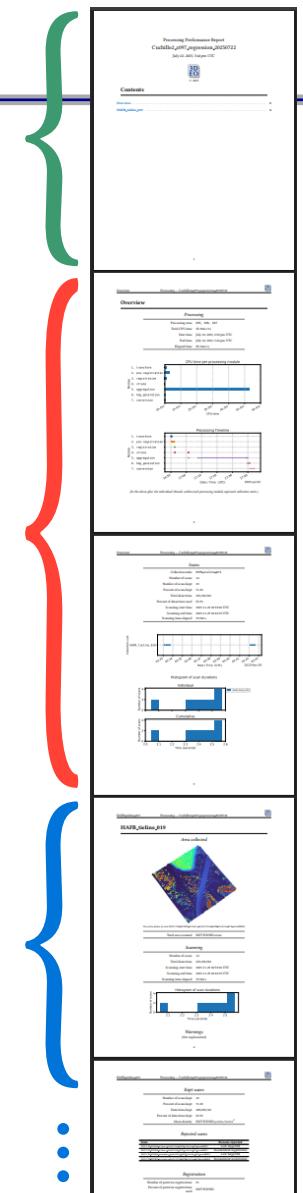
## LATEX report



## PDF report

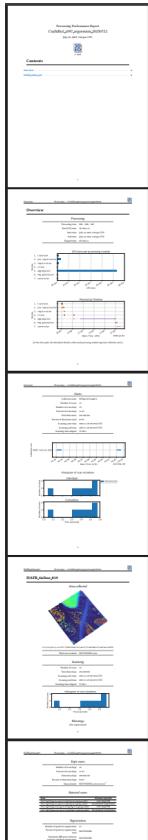
## Report Format

- **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)

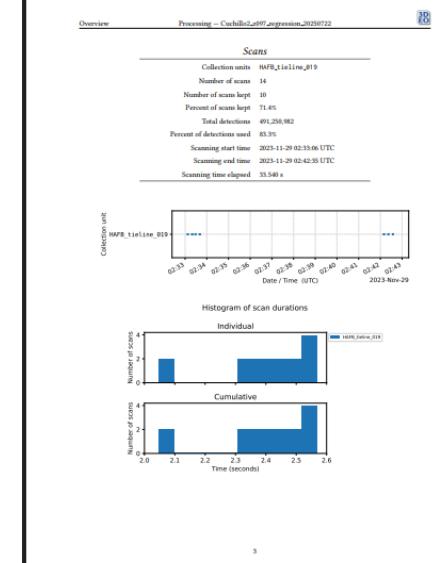
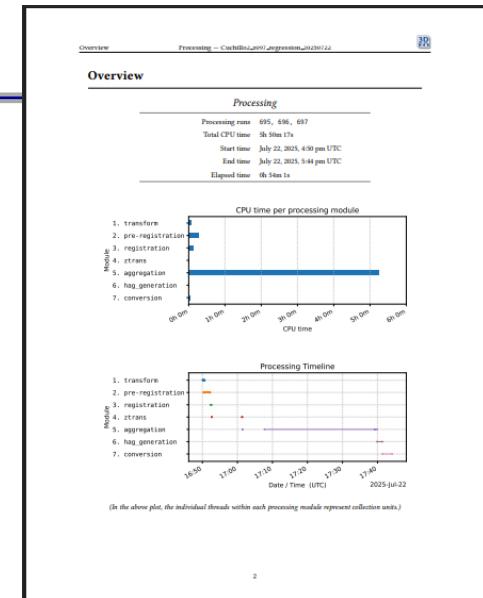
# Overview

- Processing summary**

How long processing took, CPU time, etc.

- Scan summary**

Number of detections, how long scanning took, etc.



# Processing Summary

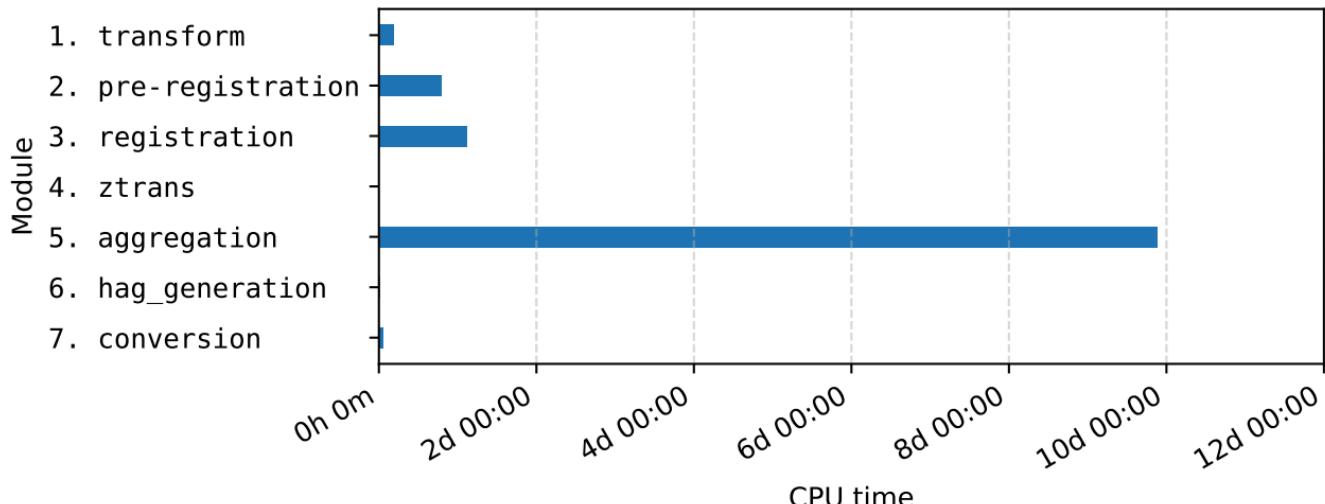
## *Processing*

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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

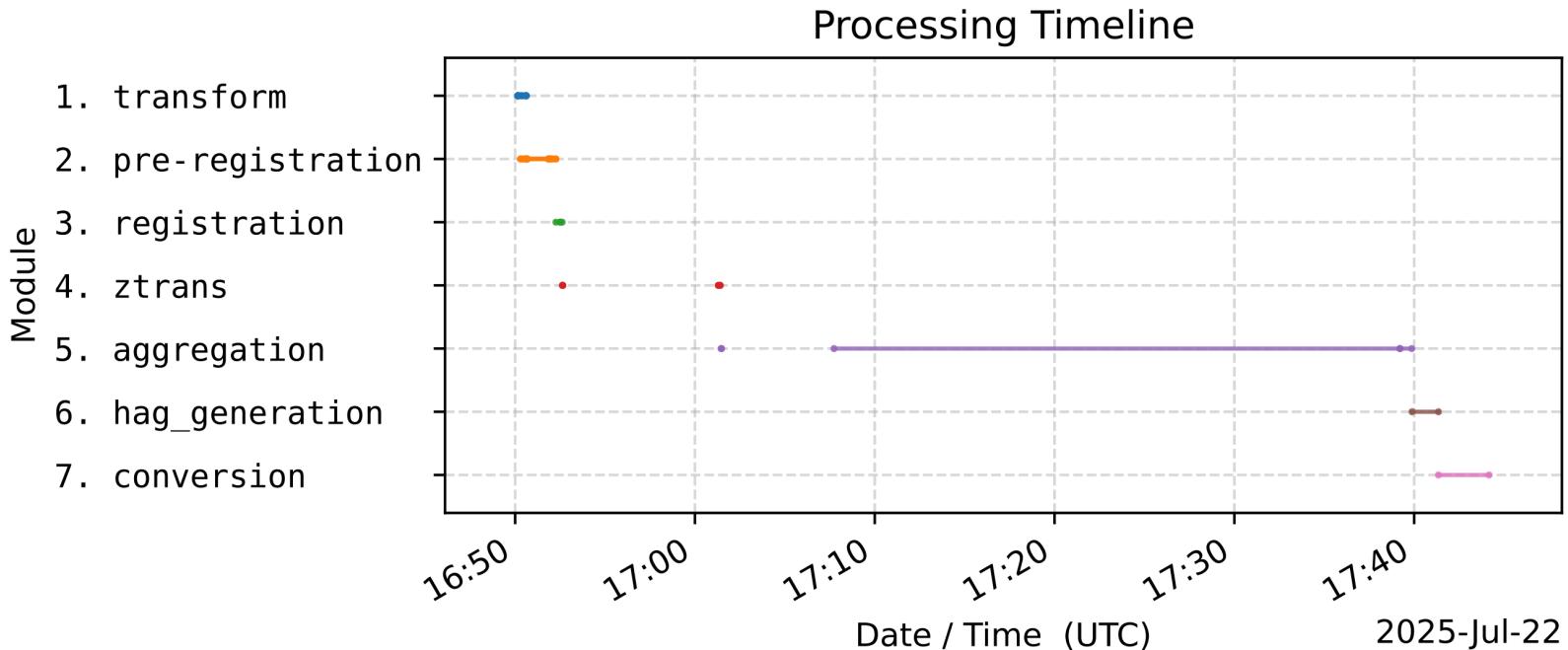
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CPU time per processing module

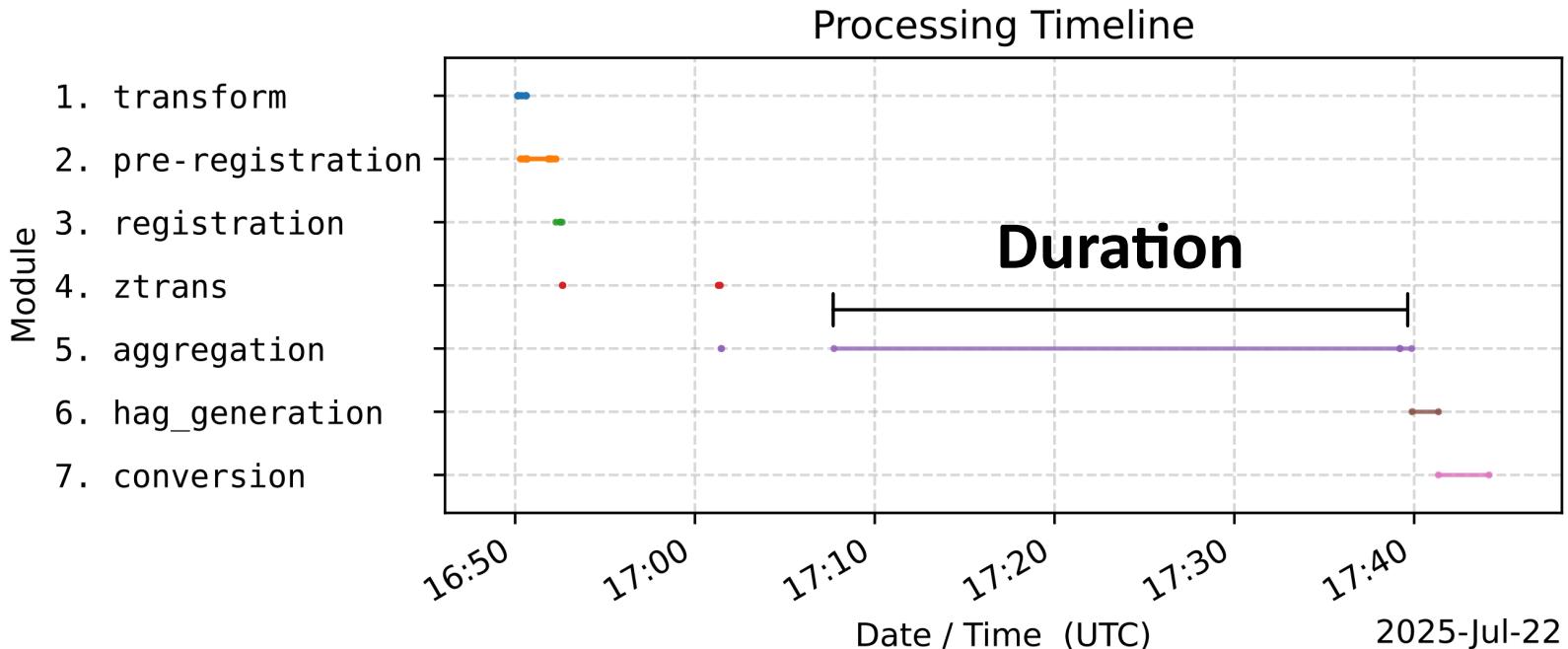


From Mapping Report (56 tiles)

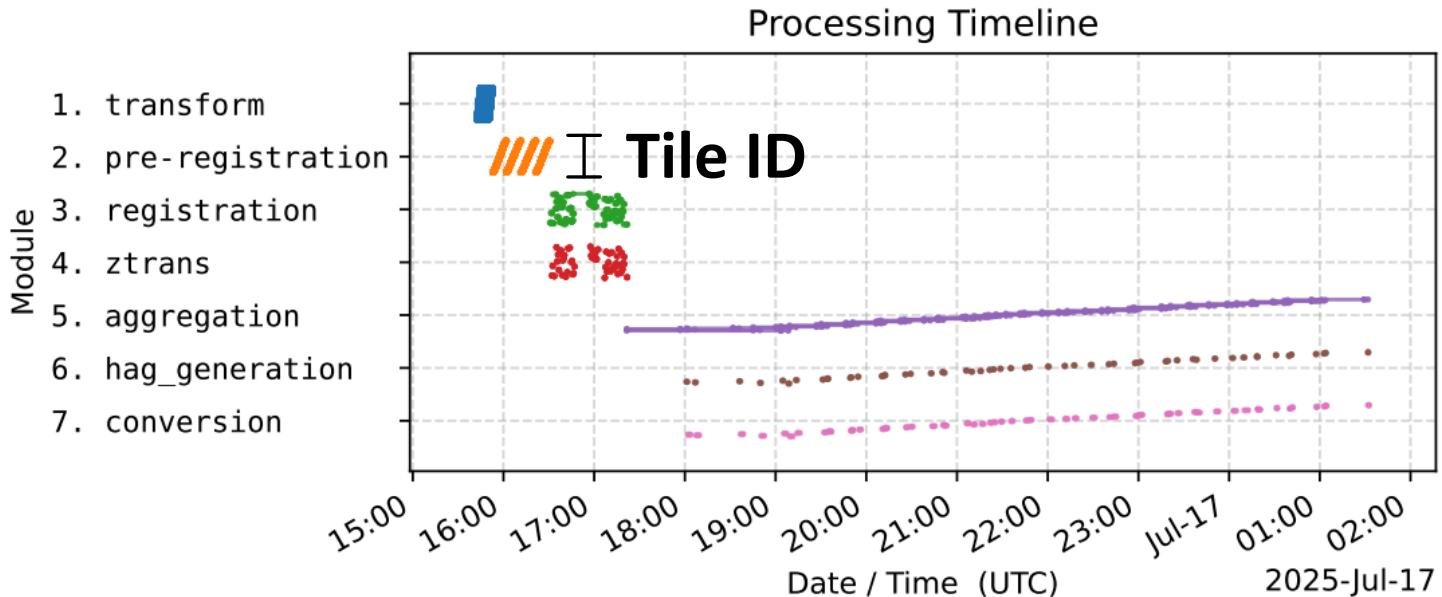
# Processing Timeline



# 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



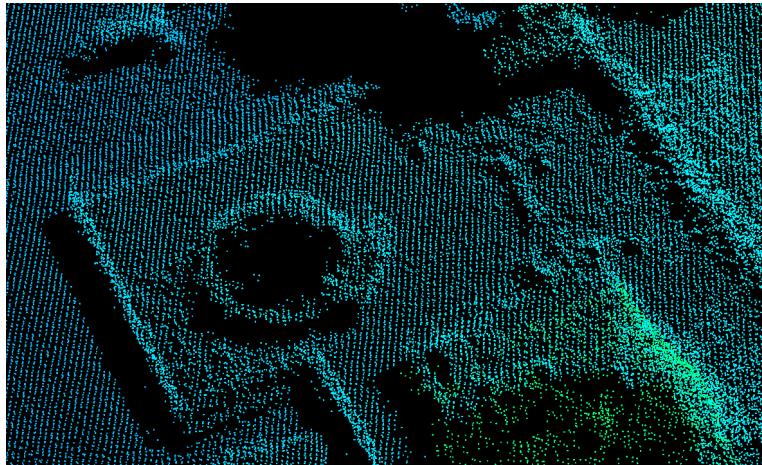
(HAFB\_tieline\_019 from Single Tile Report)

# 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  $\text{\LaTeX}$  compilation container smaller

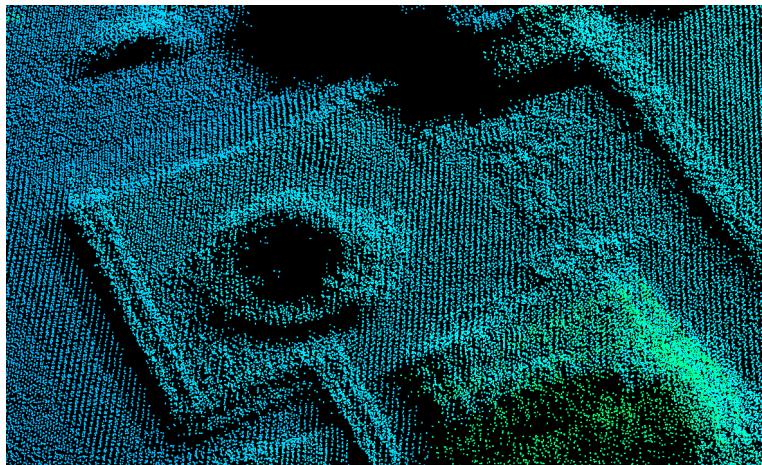
# Pose Graphs for Registration

**Good registration**



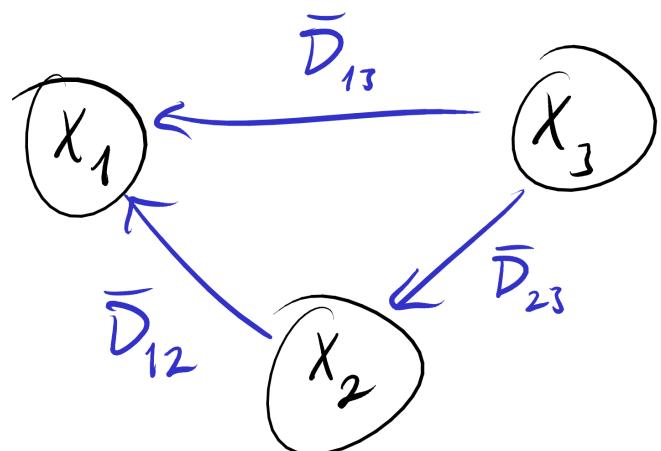
**Bad registration**

notice that the building is doubled here



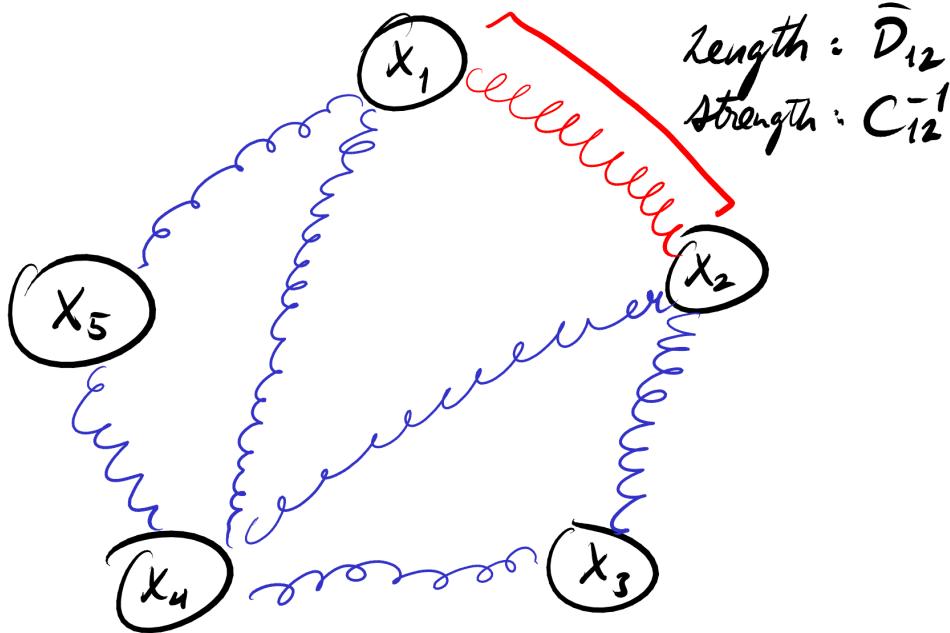
# Pose Graph

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?

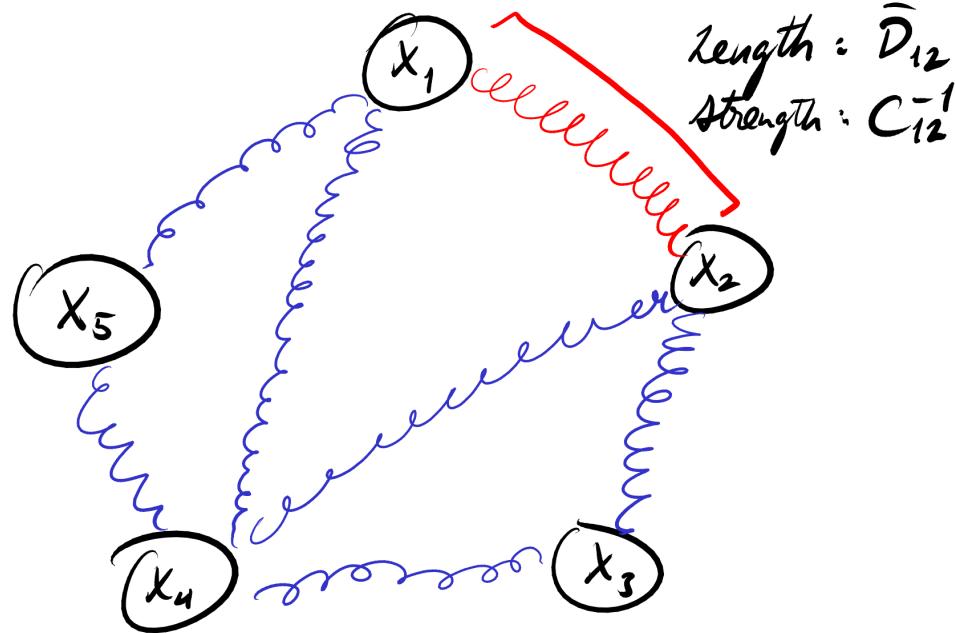


In practice,  $\bar{D}_{13} \neq \bar{D}_{12}\bar{D}_{23}$ .

# Pose Graph as Springs

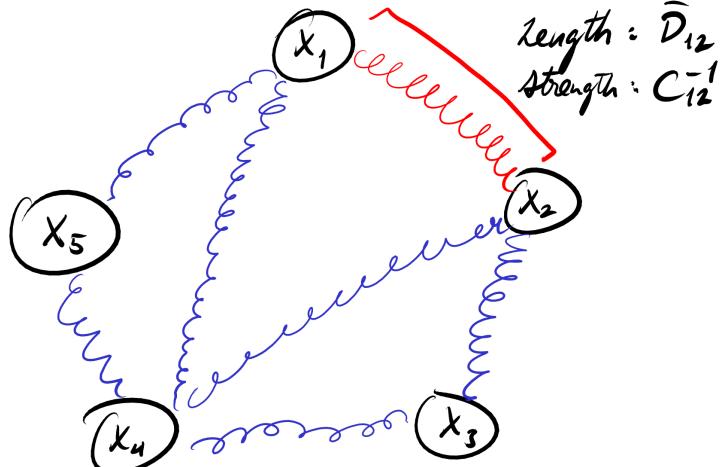


# Pose Graph as Springs



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

# Pose Graph as Springs



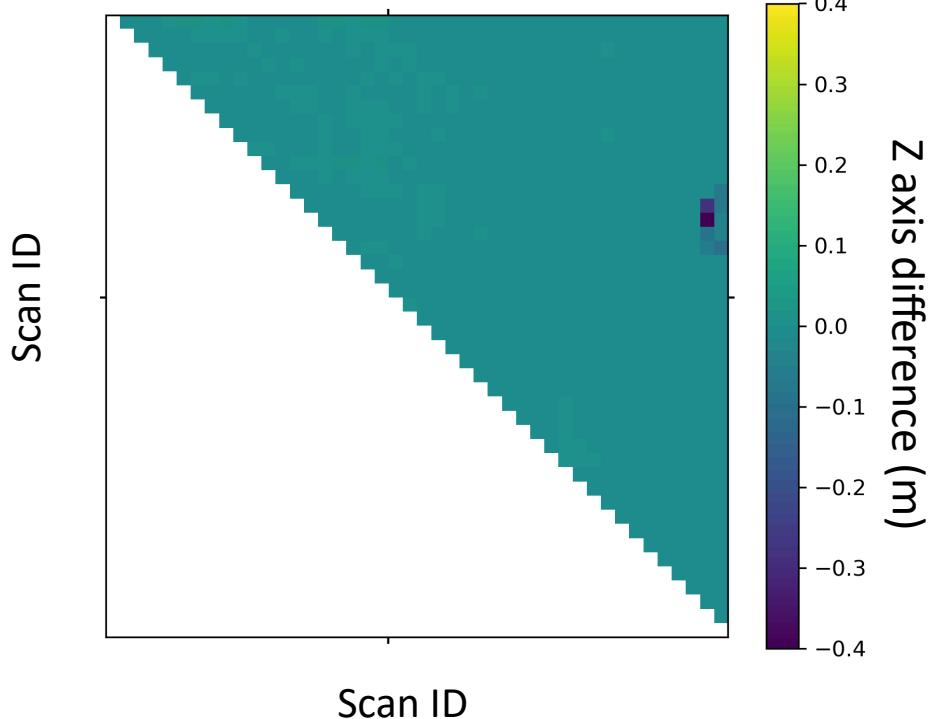
## Ways to Set Spring Elasticities (covariances)

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

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

# Rooting out Bad Pairwise Registrations

Comparing pairwise and final 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

$$\mathbf{x} = (\mathbf{H}^T \mathbf{C}^{-1} \mathbf{H})^{-1} \mathbf{H}^T \mathbf{C}^{-1} \bar{\mathbf{d}}, \quad \mathbf{C}_{\mathbf{x}} = (\mathbf{H}^T \mathbf{C}^{-1} \mathbf{H})^{-1}$$

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- Parameters:
  - ▶ Expected translational error of 1 meter, 2 mrad  
(constant covariance of  $\text{diag}(1, 1, 1, 0.002^2, 0.002^2, 0.002^2)$ )
  - ▶ 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*

2m 54s

*Lu-Milios Optimizer*

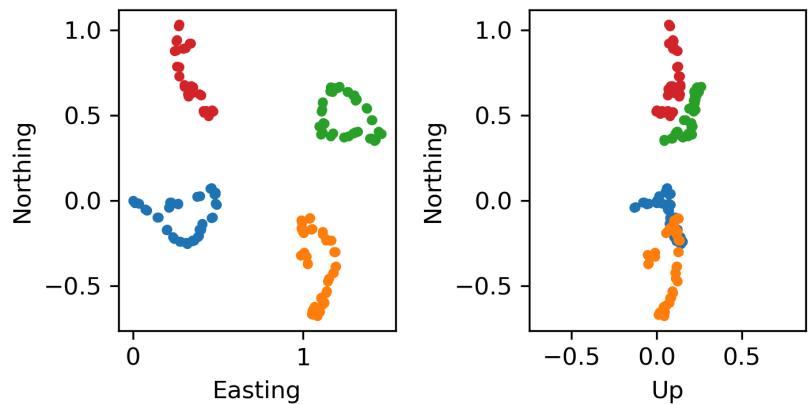
0m 3s

(58 times faster)

# Comparing Old Optimizer with Lu-Milius

## Optimized Translation Plots (Barrett Park)

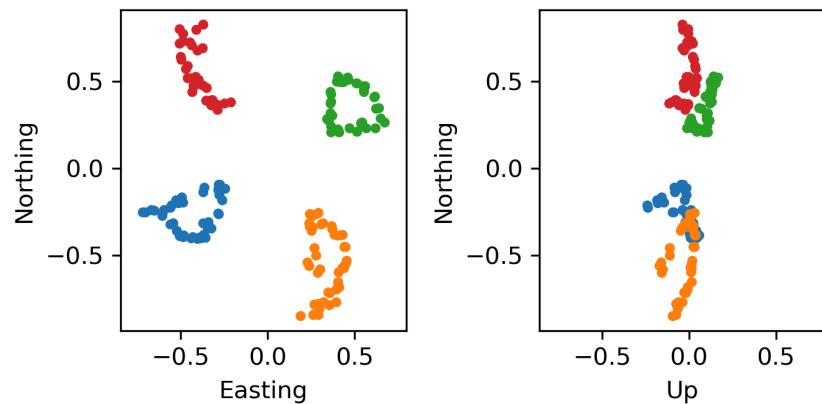
*Old ncc\_nxn Optimizer*



Flight Line

- 050147
- 050446
- 050805
- 051152

*Lu-Milius Optimizer*



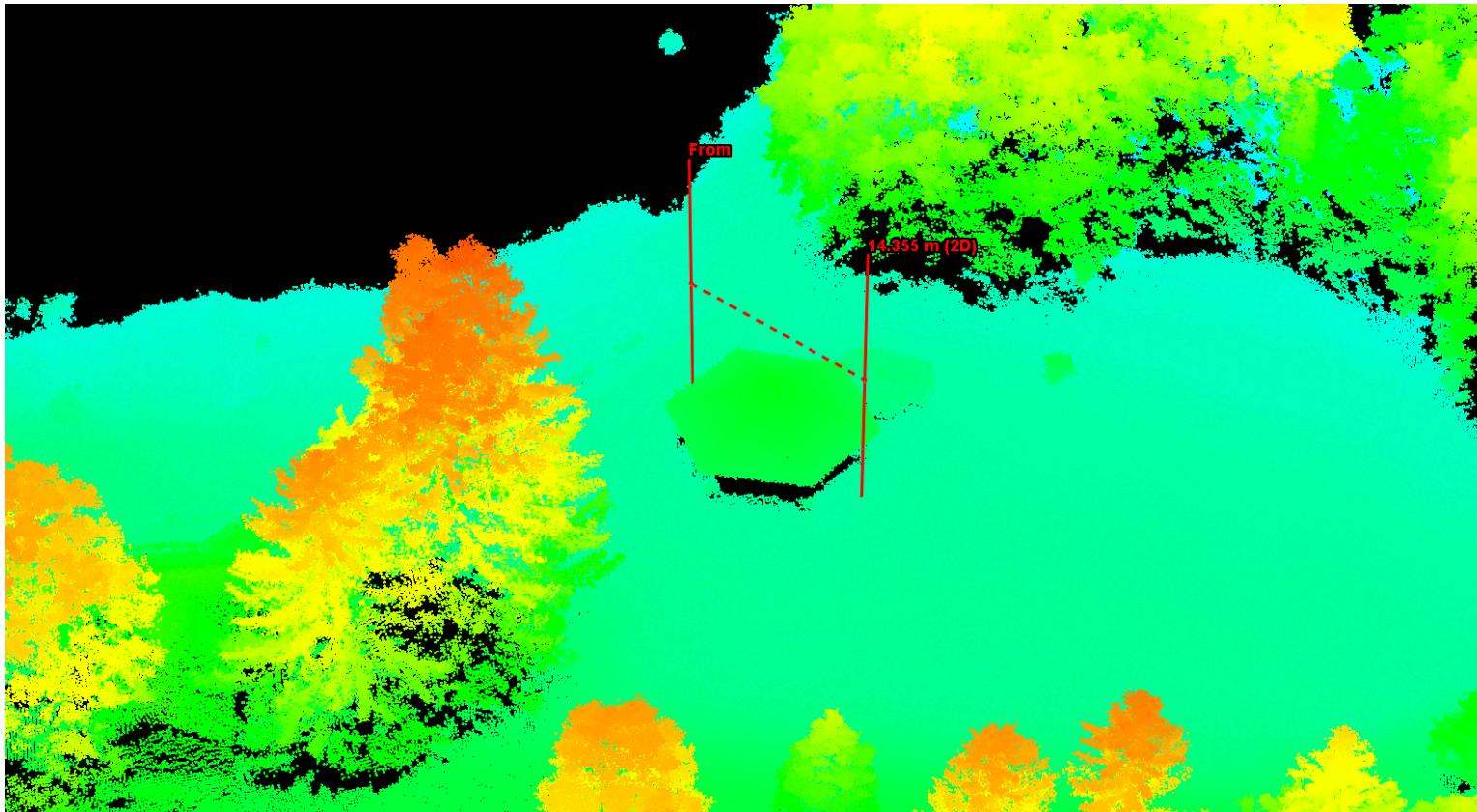
Flight Line

- 050147
- 050446
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# Comparing Old Optimizer with Lu-Milios

## Profile Analysis (Barrett Park, gazebo)

(only scans ending in scan00010)



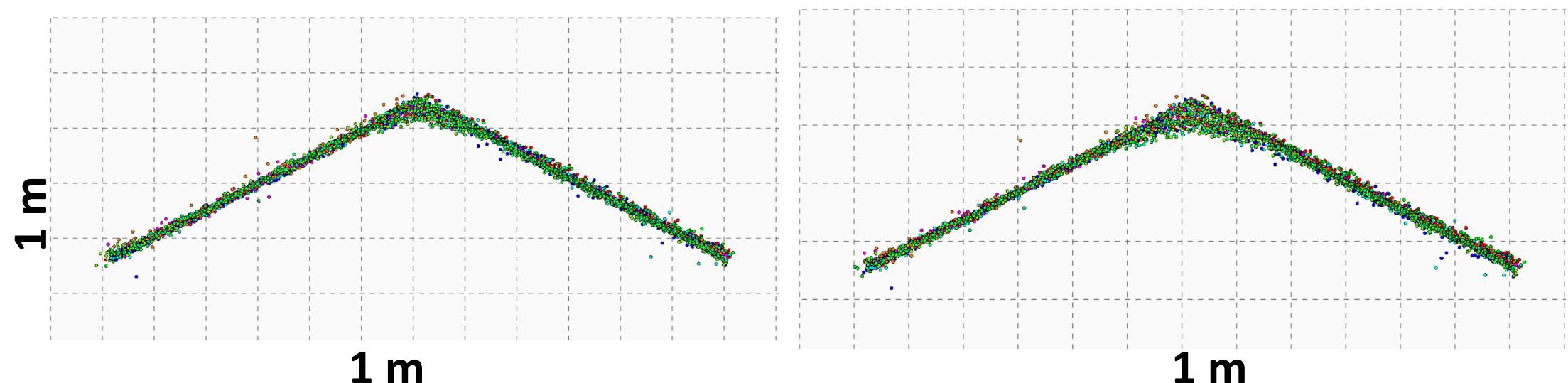
# Comparing Old Optimizer with Lu-Milios

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(only scans ending in scan00010)

*Old ncc\_nxn Optimizer*

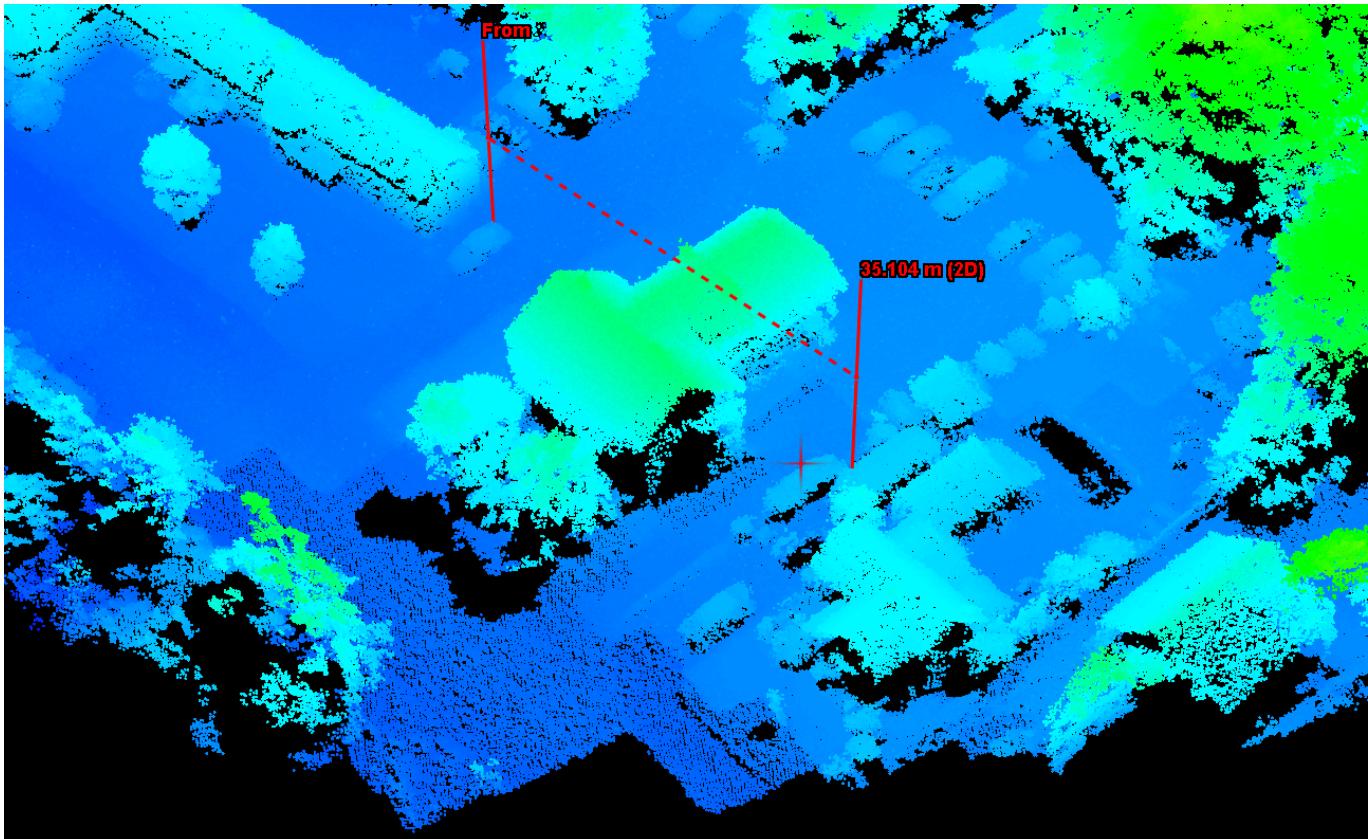
*Lu-Milios Optimizer*



# Comparing Old Optimizer with Lu-Milios

## Profile Analysis (Barrett Park, building on northeast)

(only scans ending in scan00010)

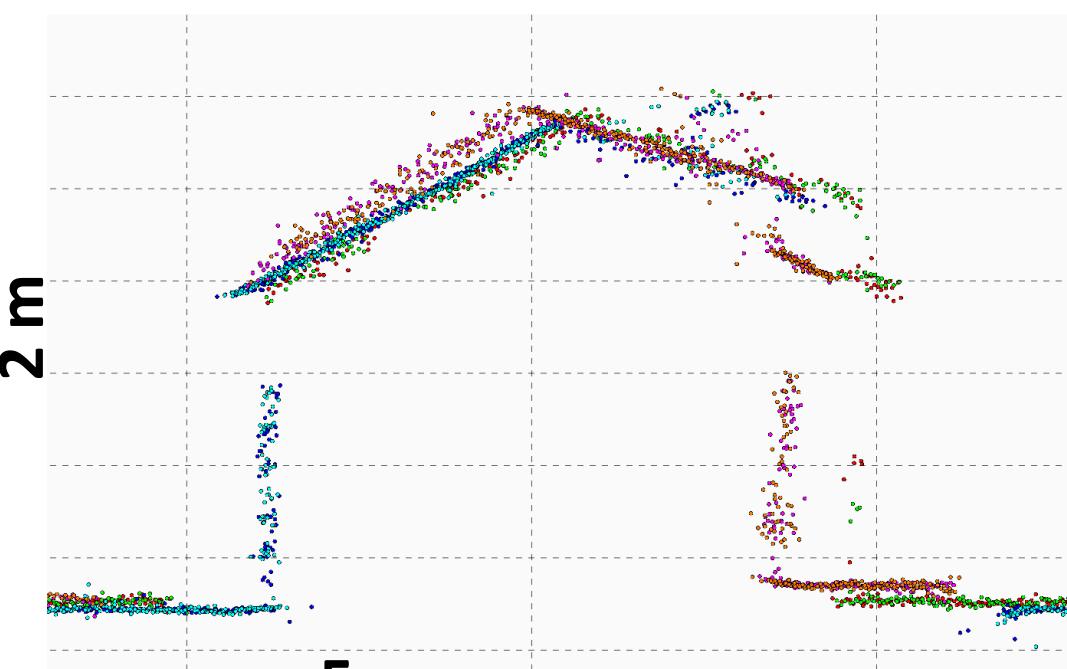


# Comparing Old Optimizer with Lu-Milios

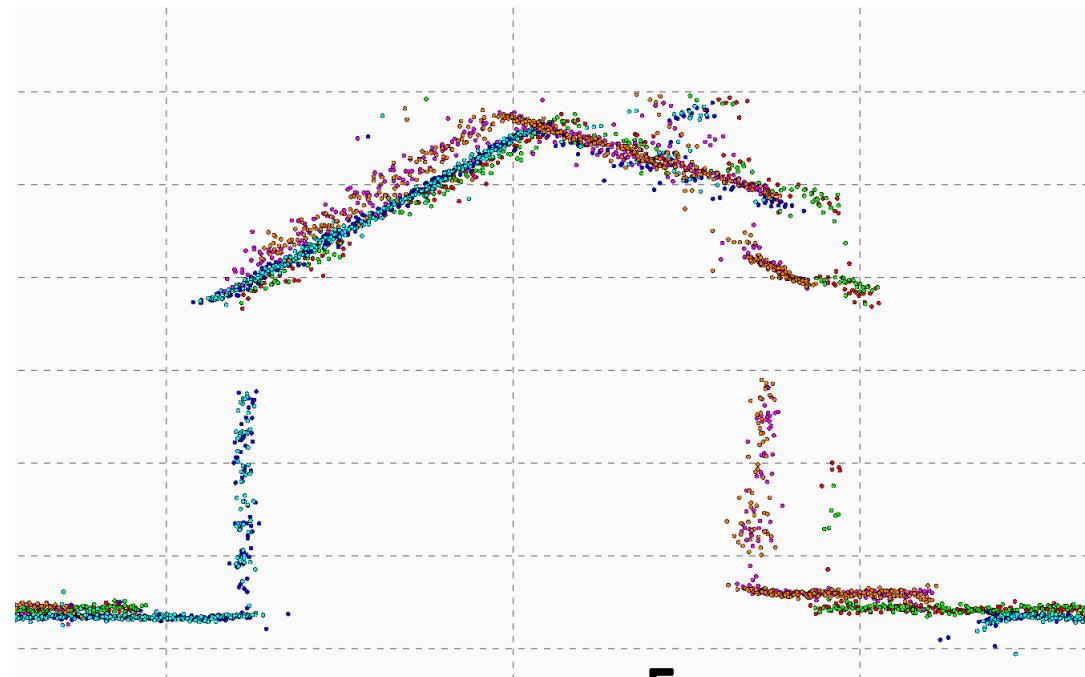
## Profile Analysis (Barrett Park, building on northeast)

(only scans ending in scan00010)

*Old ncc\_nxn Optimizer*



*Lu-Milios Optimizer*



(notice identical ghosting at upper left in both images)

5 m

# Ongoing and Future Work

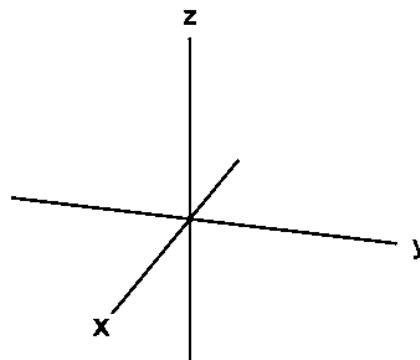
$$X_i = \begin{pmatrix} x_i \\ y_i \\ z_i \\ \theta_i \\ \phi_i \\ \psi_i \end{pmatrix} \in \mathbb{R}^6$$

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

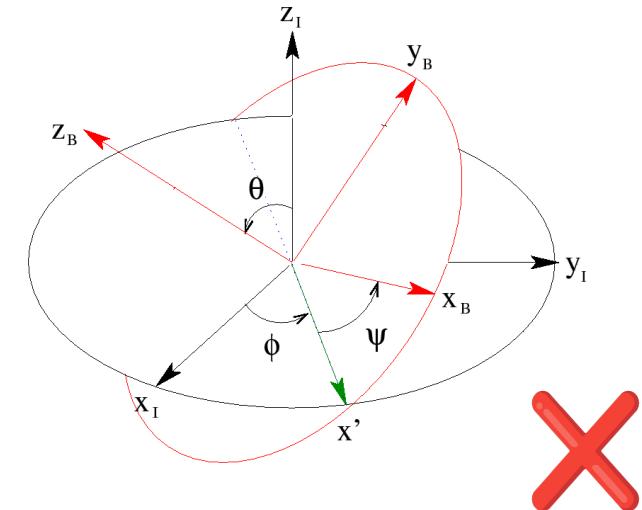
- **Use non-linear least squares optimization to better handle orientation**

Existing implementation spun its wheels for 3 hours on Barrett Park and failed...

# Ongoing and Future Work



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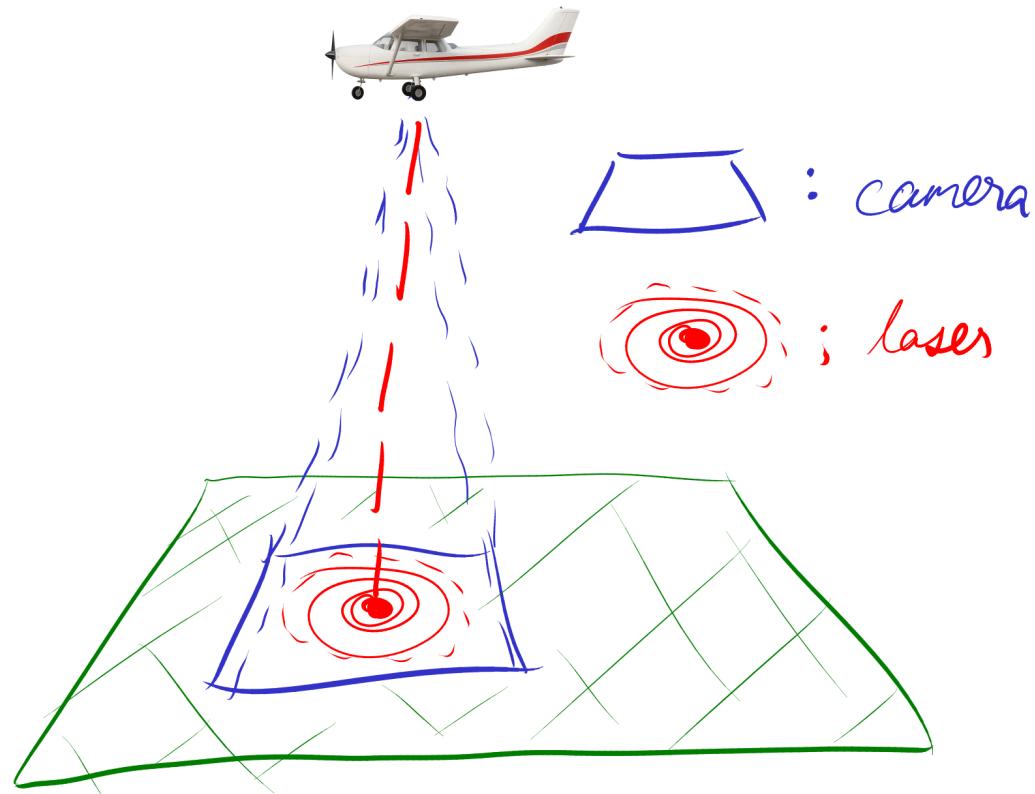
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# Ongoing and Future Work

- 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

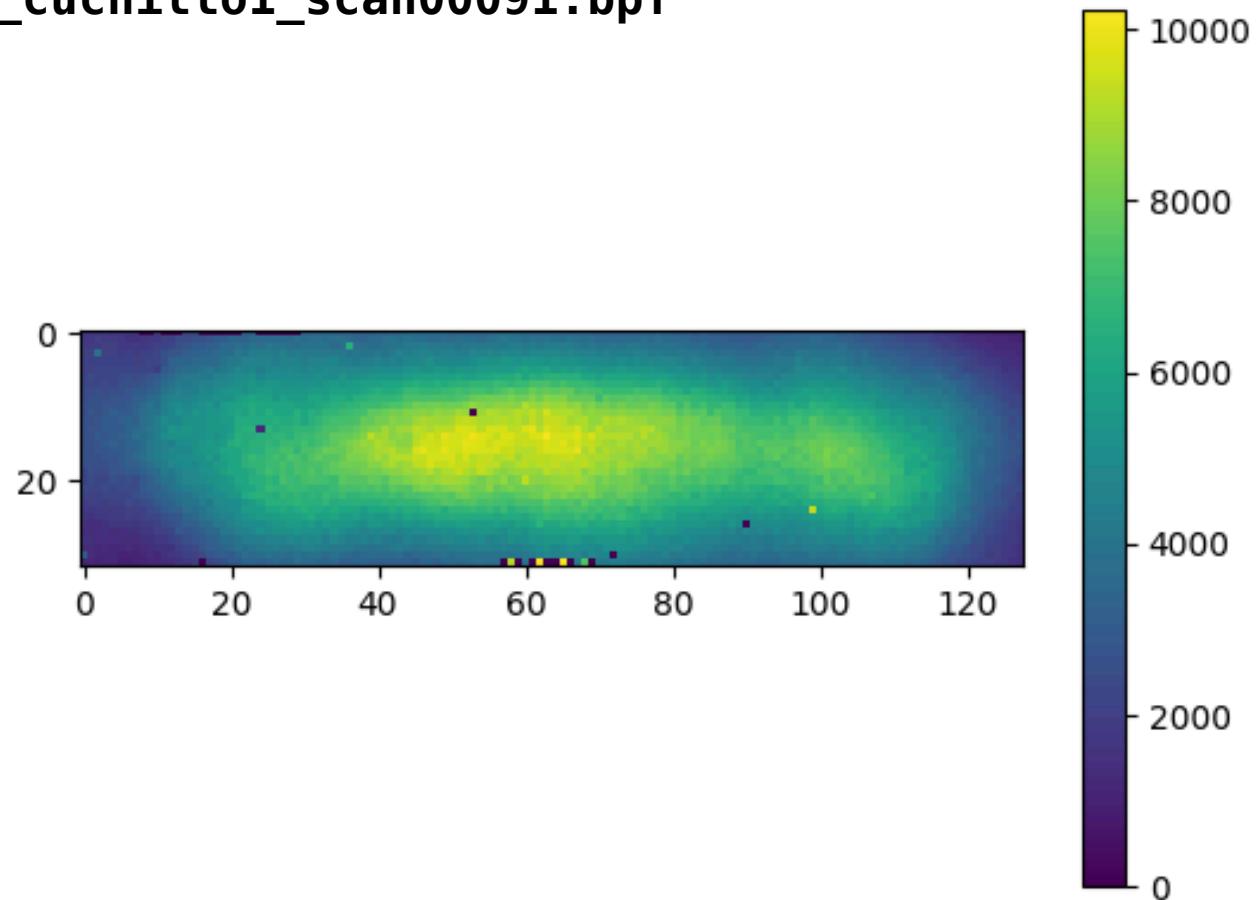


# Why Model the Illumination Spot

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

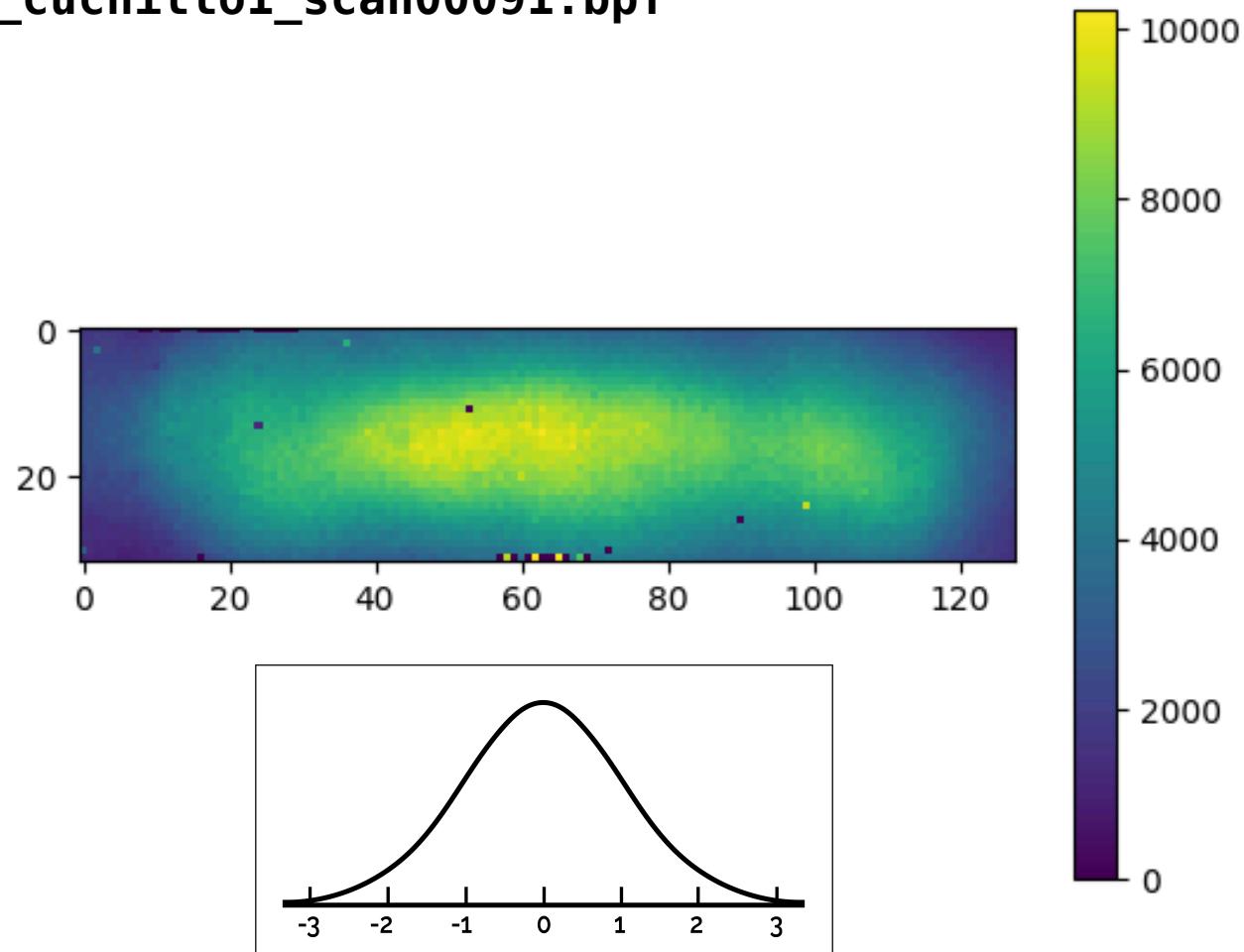
# Laser Illumination Spot

Total photon detections per pixel during  
**20230627\_095732\_cuchillo1\_scan00091.bpf**

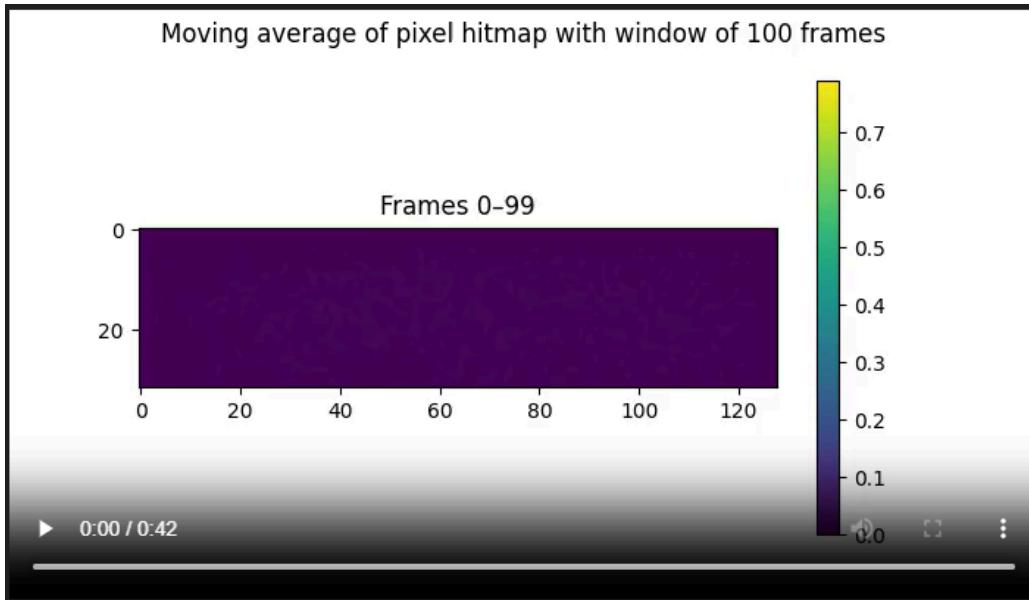


# Spot is Approximately Gaussian

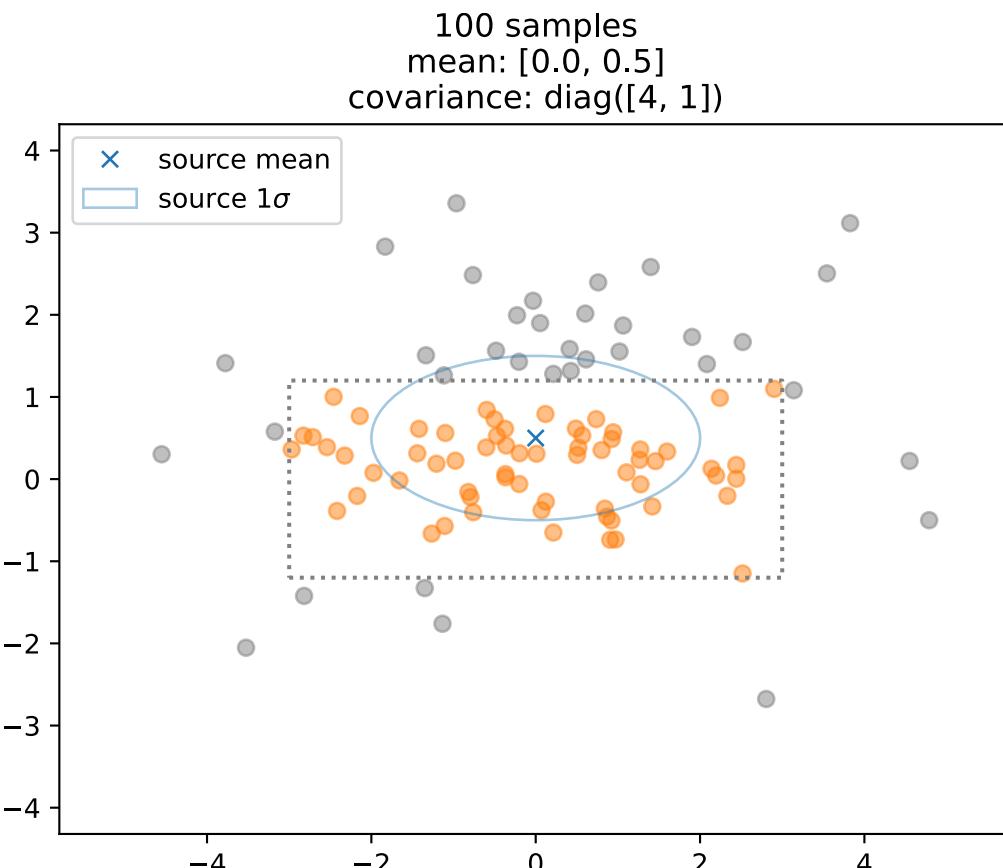
Total photon detections per pixel during  
**20230627\_095732\_cuchillo1\_scan00091.bpf**



# Cannot Assume the Spot Stays Still

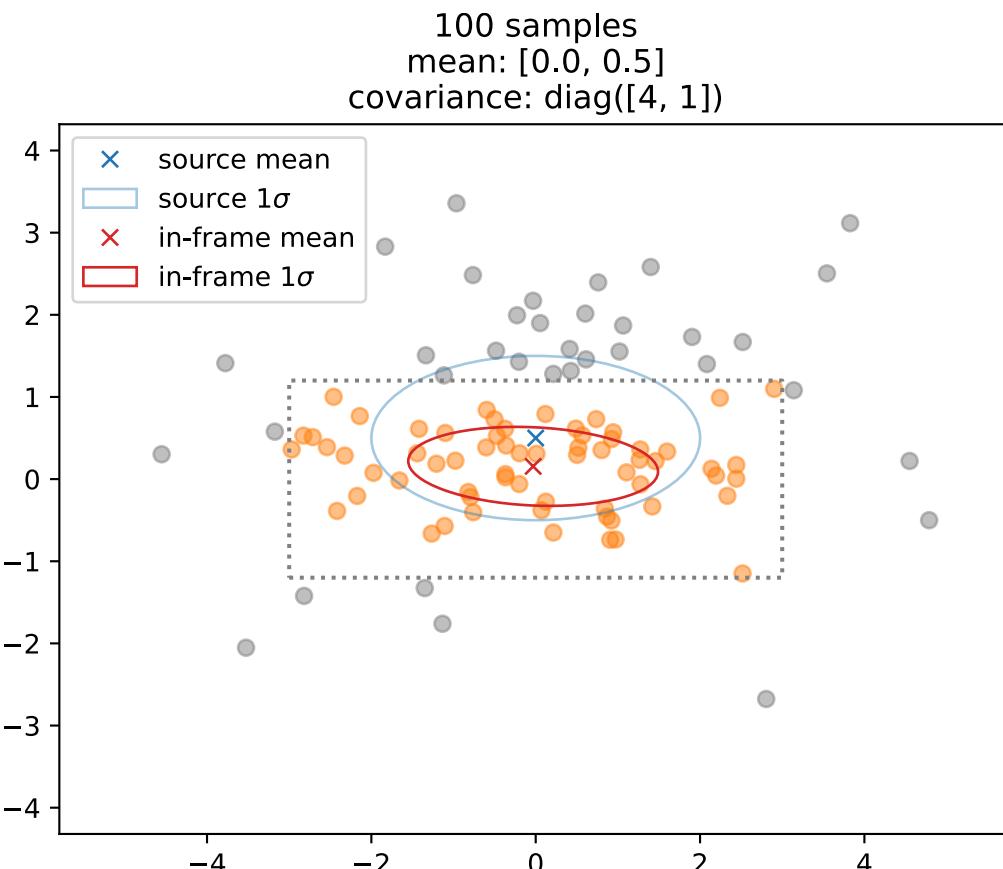


# Cannot Use Sample Mean and Covariance



- 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 bitmap average, fit Gaussian parameters with:

- **Gaussian Mixture Models**

Dealt with problem just described—sample is occluded, means and covariances are off

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- **Bayesian inference**

Necessary PyMC tools (cumulative distribution function of multivariate normal) [not fully implemented](#)

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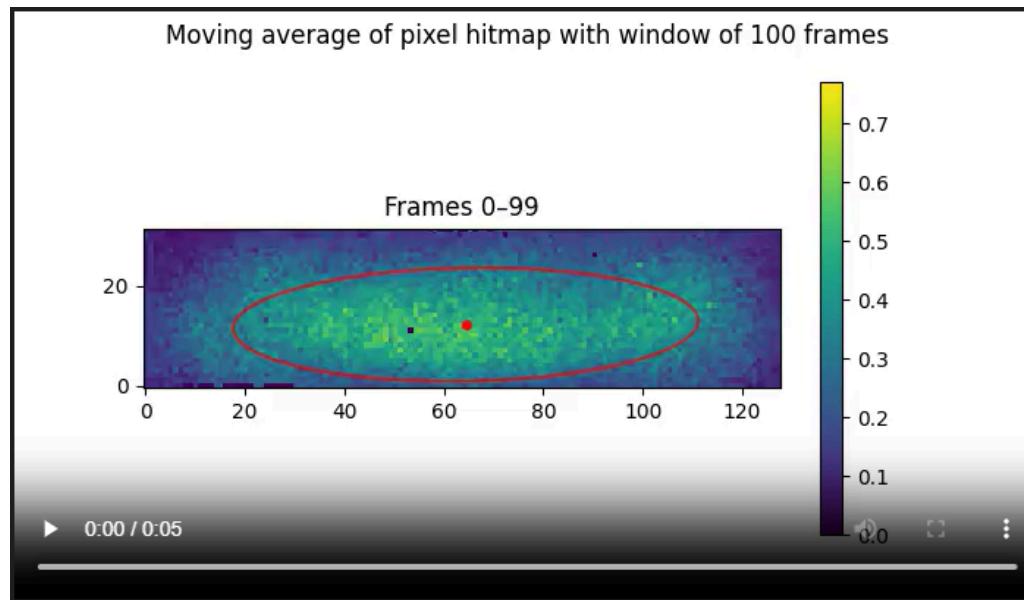
- **Bayesian inference**

Necessary PyMC tools (cumulative distribution function of multivariate normal) [not fully implemented](#)

- **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 Single-Gaussian 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 (if single Gaussian)
  - 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\_miliros.py
- [PyMC forum discussion](#) I asked about using Bayesian inference—necessary tools not implemented

## Modeling the Laser Illumination Spot

- [Write-up](#) Describes background and my work thus far on this
- [laser\\_illumination\\_spot \(master\) on Bitbucket](#) Work in progress