The LiCAS LSM System

First measurements from the Laser Straightness Monitor of the LiCAS Rapid Tunnel Reference Surveyor.

Warsaw University

Linear Collider Alignment & Survey

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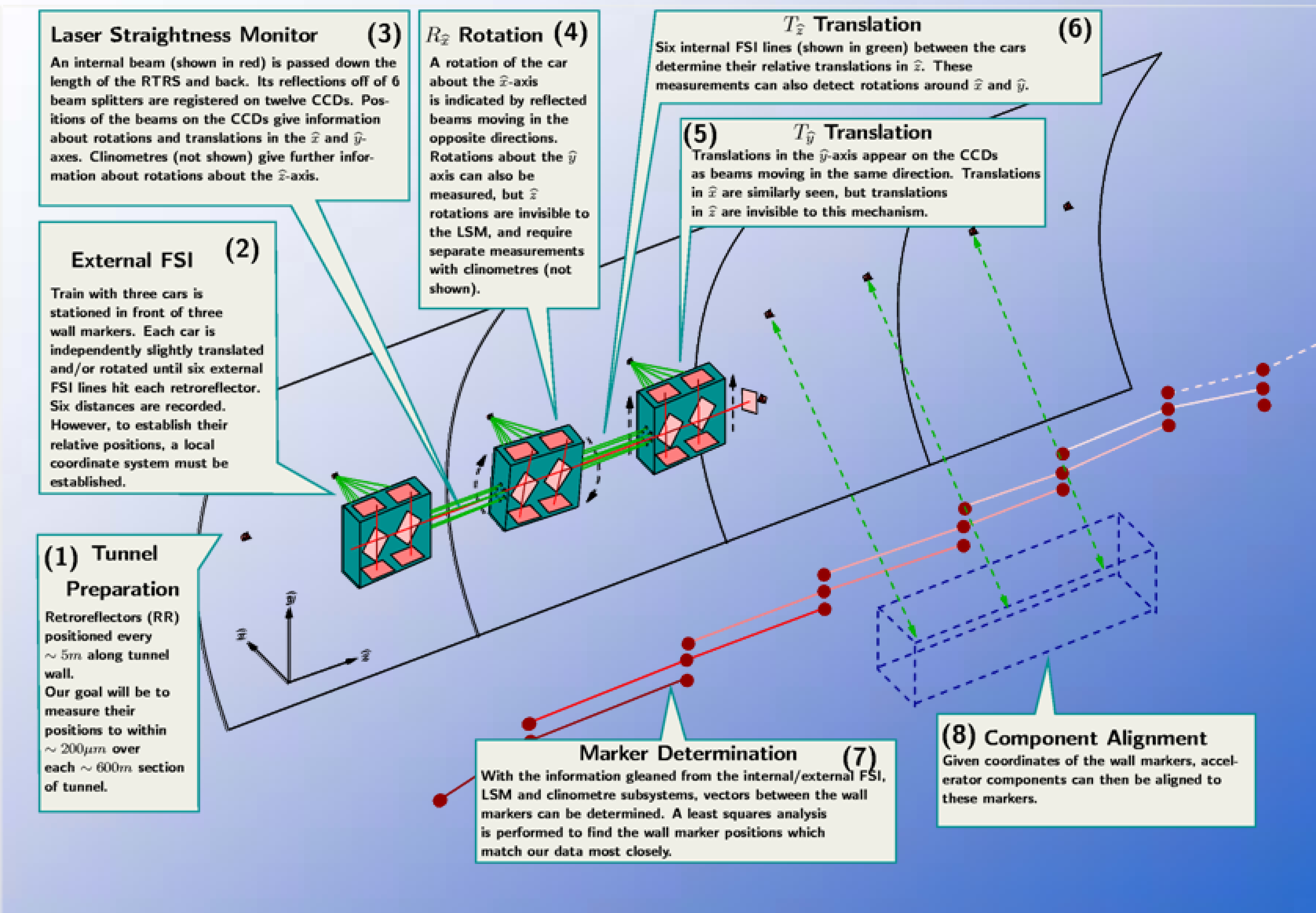
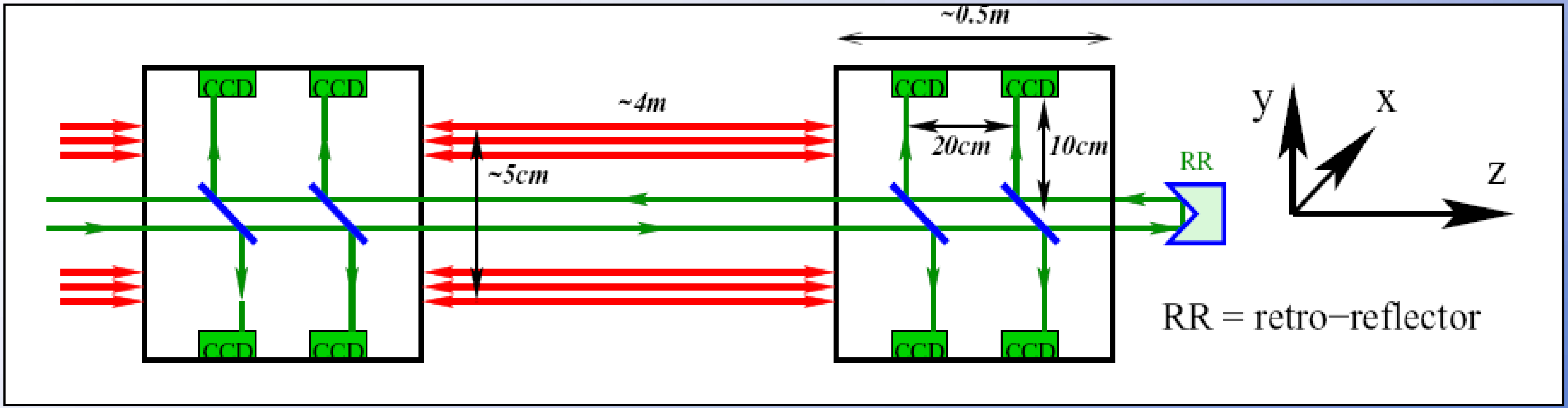
The RTRS


Laser Straightness Monitor (3)
An internal beam (shown in red) is passed down the length of the RTRS and back. Its reflections off of 6 beam splitters are registered on twelve CCDs. Positions of the beams on the CCDs give information about rotations and translations in the $\hat{x}$ and $\hat{y}$-axes. Clinometres (not shown) give further information about rotations about the $\hat{z}$-axis.
$R_{\hat{x}}$ Rotation (4)
A rotation of the car about the $\hat{x}$-axis is indicated by reflected beams moving in the opposite directions. Rotations about the $\hat{y}$ axis can also be measured, but $\hat{z}$ rotations are invisible to the LSM, and require separate measurements with clinometres (not shown).
$T_{\hat{z}}$ Translation (6)
Six internal FSI lines (shown in green) between the cars determine their relative translations in $\hat{z}$. These measurements can also detect rotations around $\hat{x}$ and $\hat{y}$.
(5) $T_{\hat{y}}$ Translation
Translations in the $\hat{y}$-axis appear on the CCDs as beams moving in the same direction. Translations in $\hat{x}$ are similarly seen, but translations in $\hat{z}$ are invisible to this mechanism.
External FSI (2)
Train with three cars is stationed in front of three wall markers. Each car is independently slightly translated and/or rotated until six external FSI lines hit each retroreflector. Six distances are recorded. However, to establish their relative positions, a local coordinate system must be established.
(1) Tunnel Preparation
Retroreflectors (RR) positioned every $\sim 5m$ along tunnel wall.
Our goal will be to measure their positions to within $\sim 200\mu m$ over each $\sim 600m$ section of tunnel.
Marker Determination (7)
With the information gleaned from the internal/external FSI, LSM and clinometre subsystems, vectors between the wall markers can be determined. A least squares analysis is performed to find the wall marker positions which match our data most closely.
(8) Component Alignment
Given coordinates of the wall markers, accelerator components can then be aligned to these markers.

Sensitivity of Internal Components



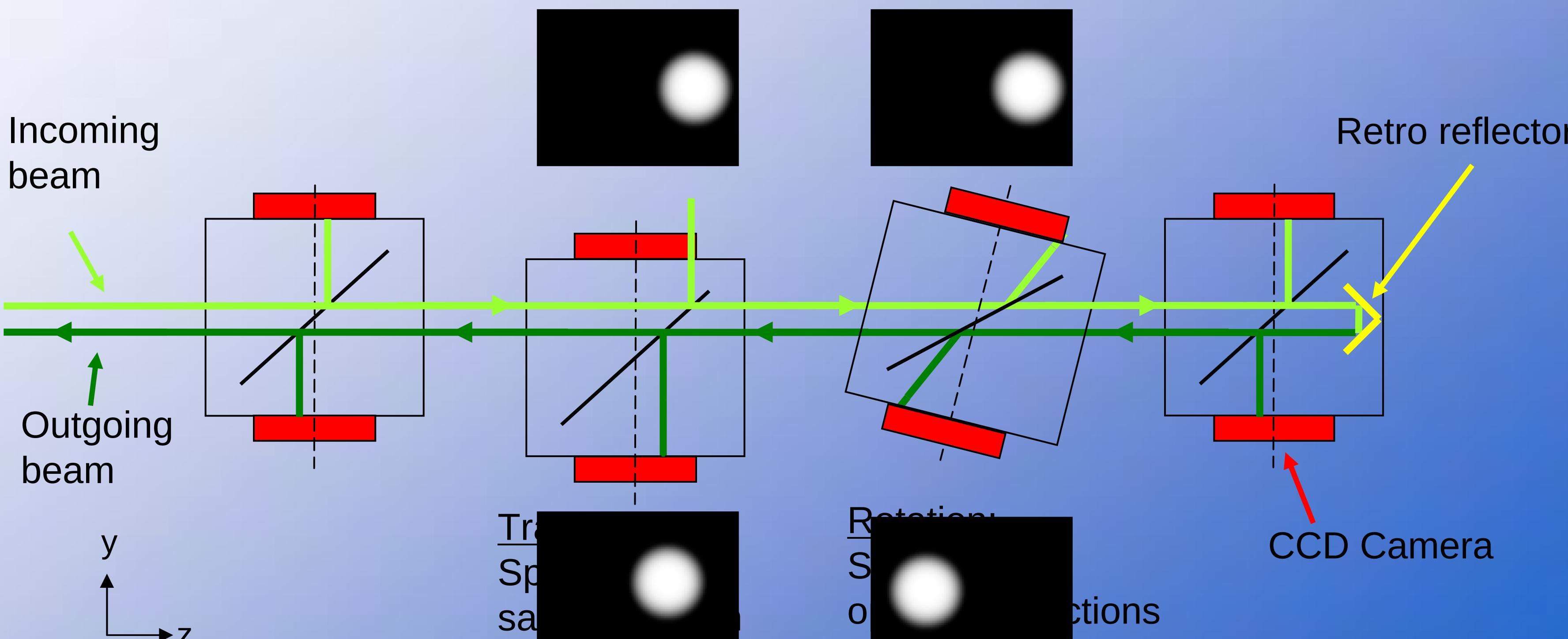
Component	TrX	TrY	TrZ	RotX	RotY	RotZ
LSM	√	√		√	√	
FSI	±	±	√	±	±	
Inclinometer				√ (not used)		√

Straightness Monitor Basics

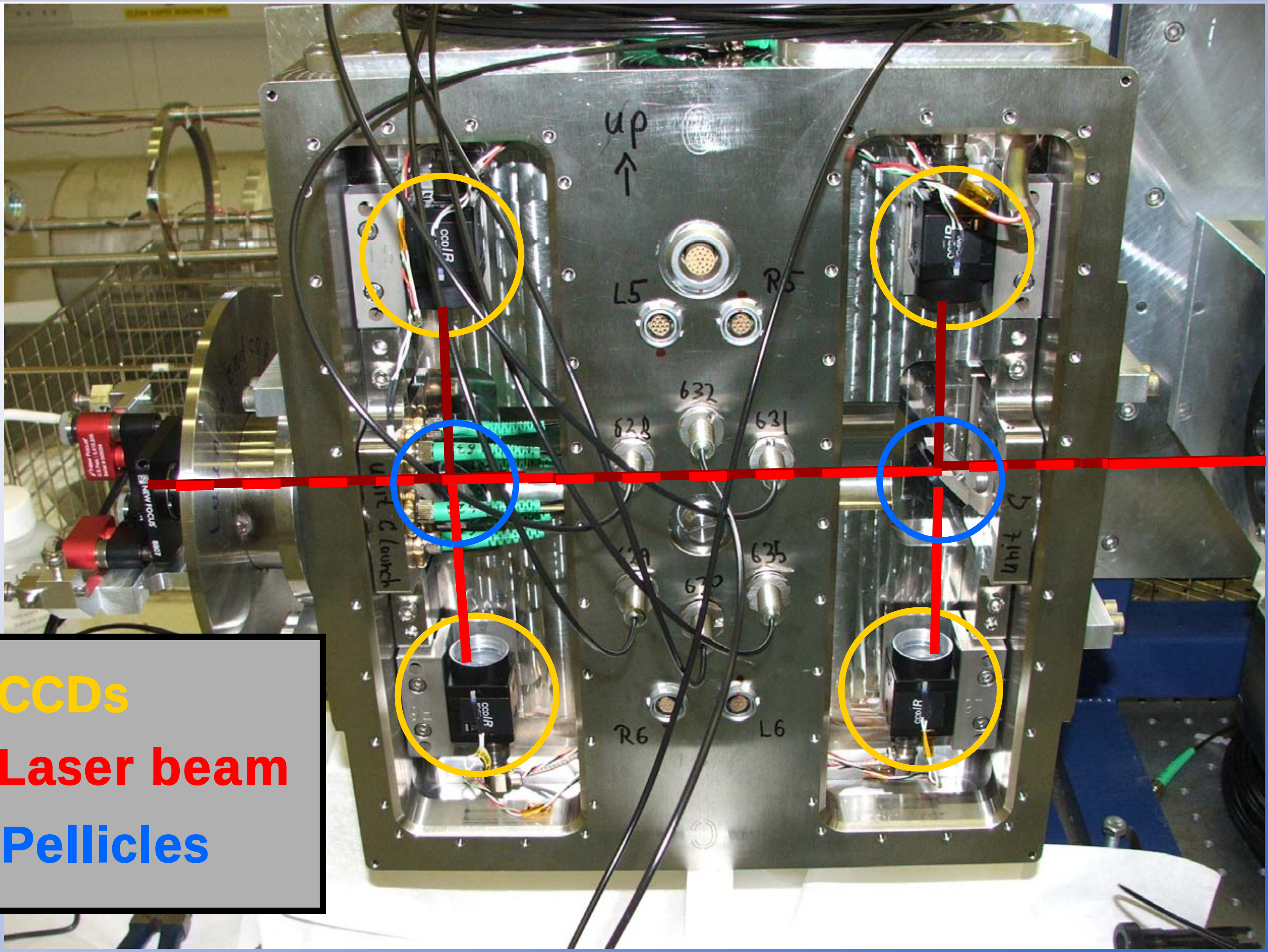
The train needs to know how it is aligned internally.

Achieved by internal FSI and the Laser Straightness Monitor.

- LSM is used to measure:
  - Transverse translations
  - Rotations
- Require 1µm precision over length of train



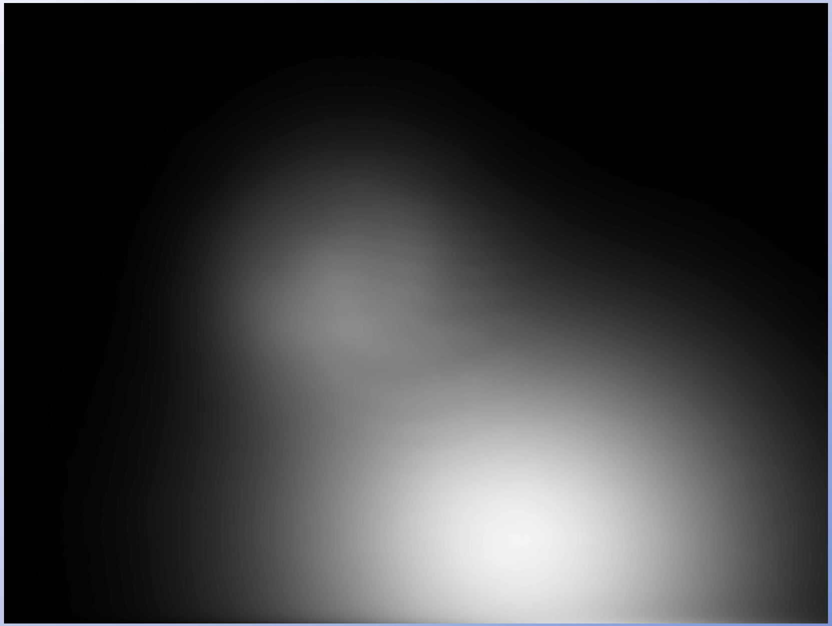
Produced System



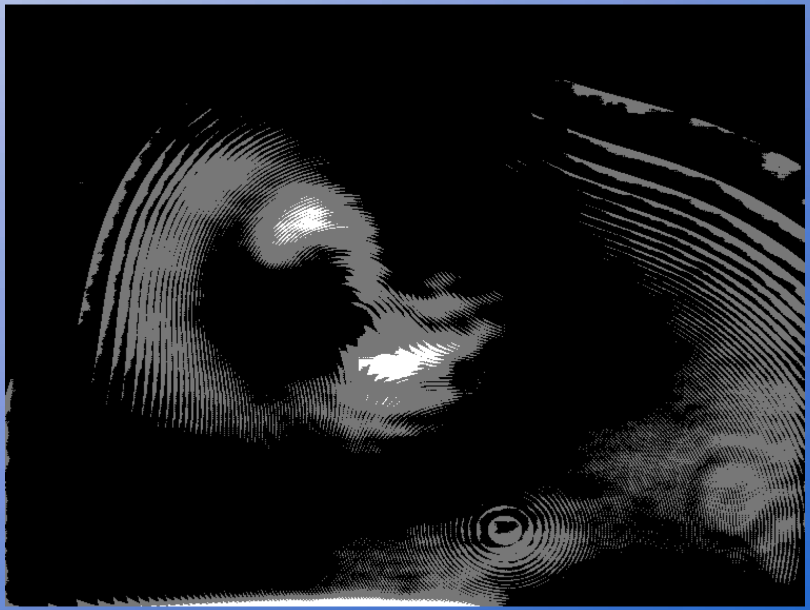
Beam Fitting

Multiple beams fitted on each image
(to deal with reflections)

Typical difficult image

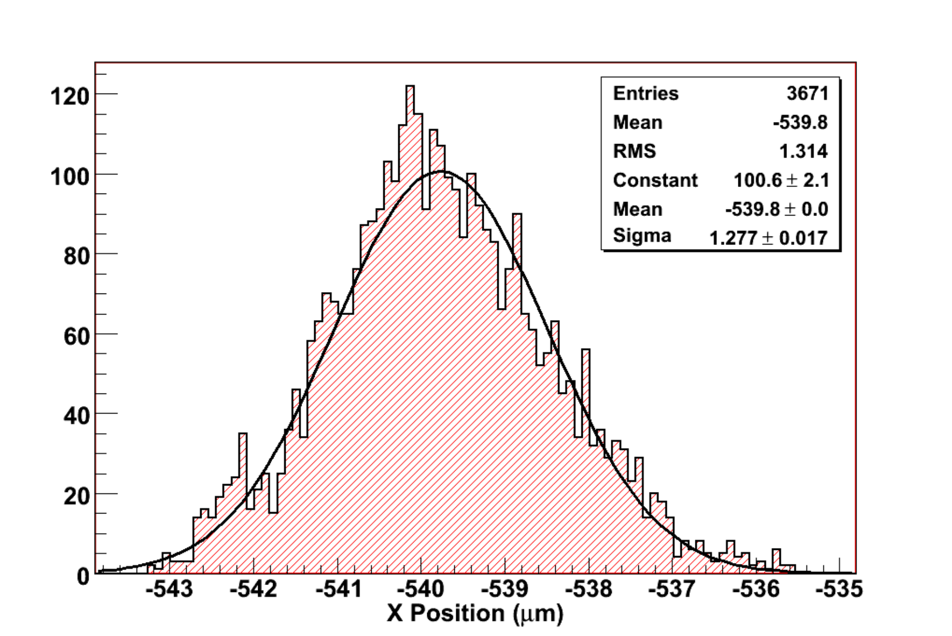


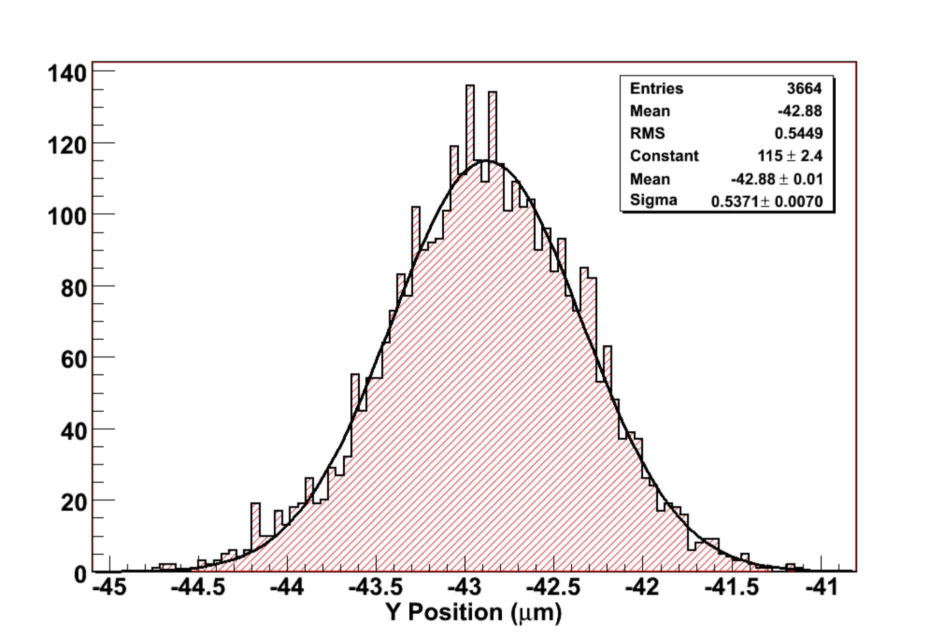
Differences from data and fit
(range of 2/256)



Beam Fitting

- Real life beams fitted over 40 hours to:
- 1.28µm horizontally
- 0.54µm vertically
- Difference not understood – possibly beam jitter





Stability

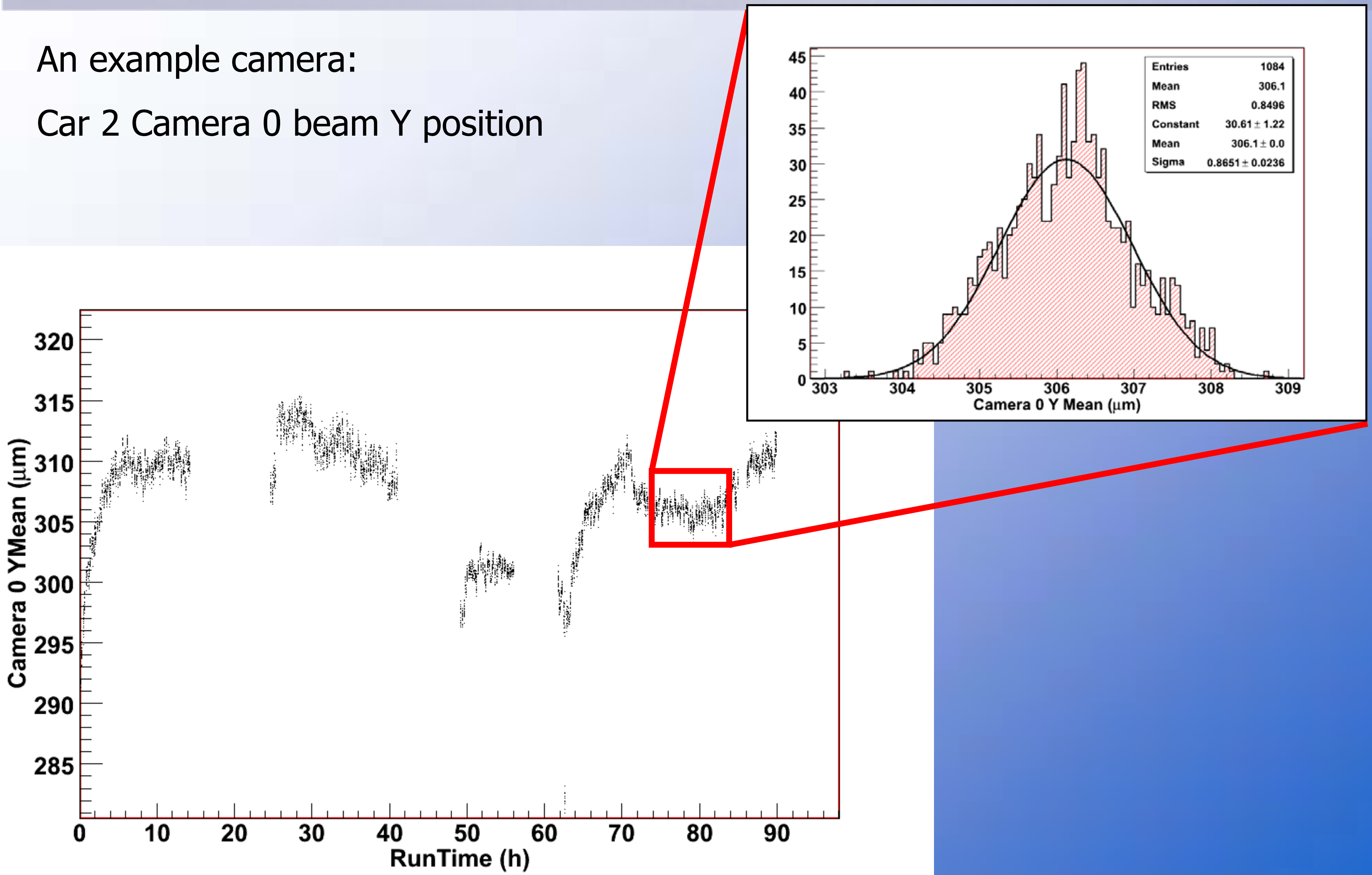
- Large amount of data taken with no planned movement

- 2 x 10 images every 10 minutes
- Data taken for 4 days

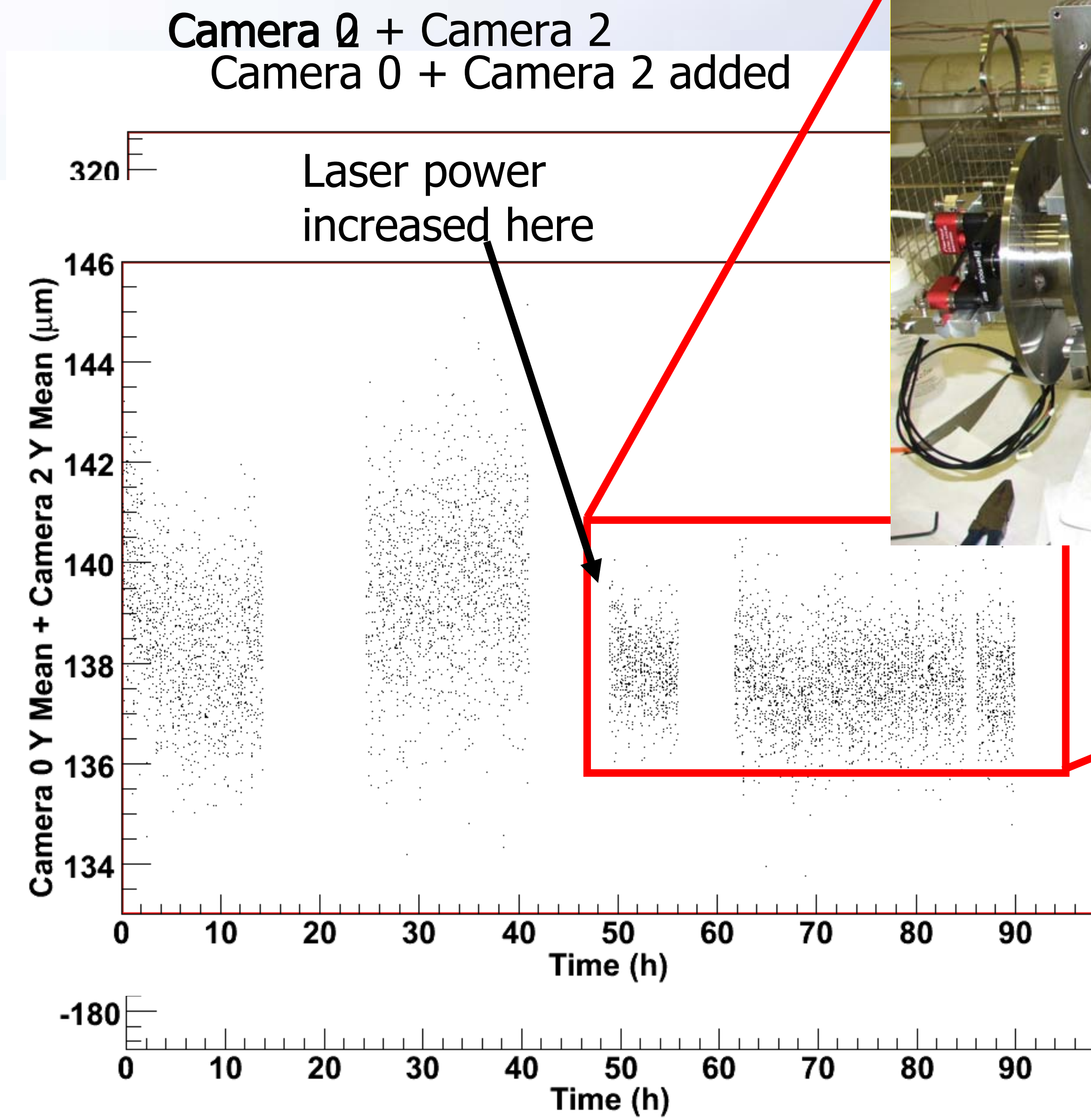
Stability

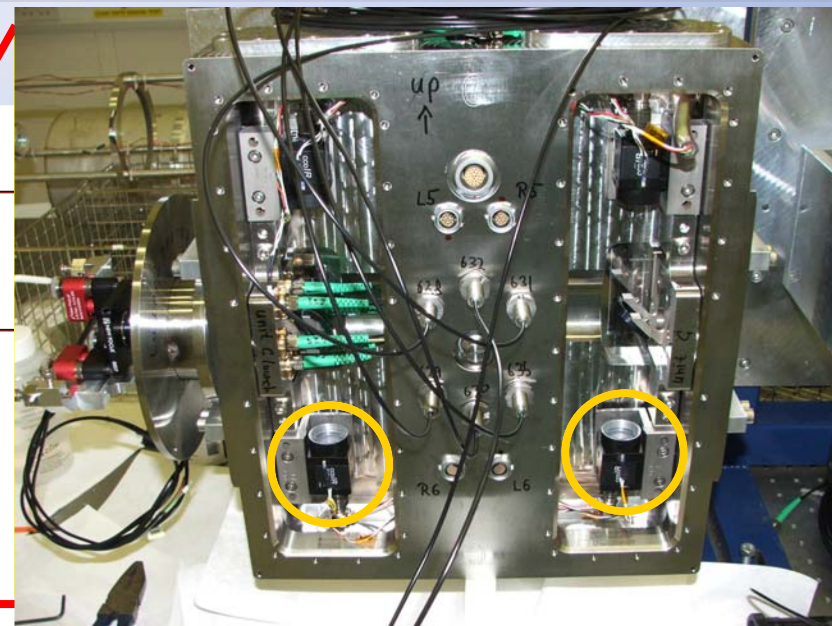
An example camera:

Car 2 Camera 0 beam Y position



Stability

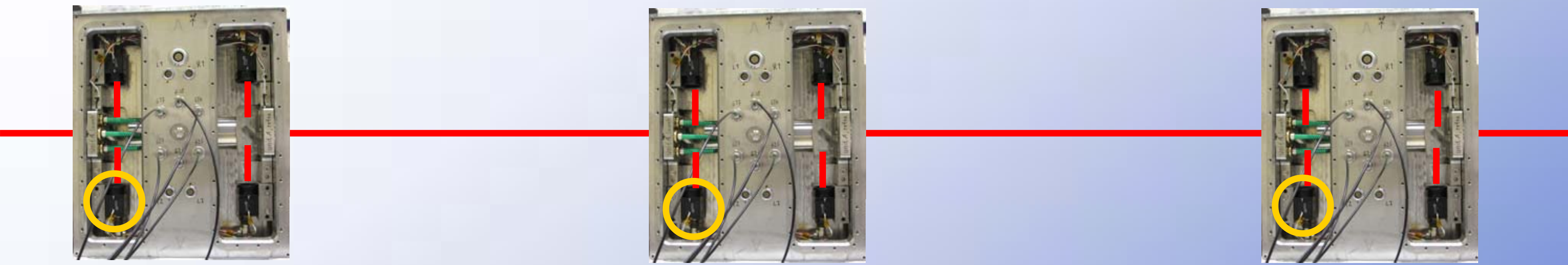


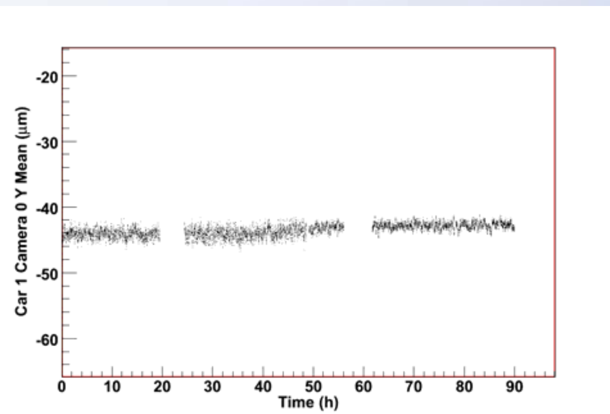


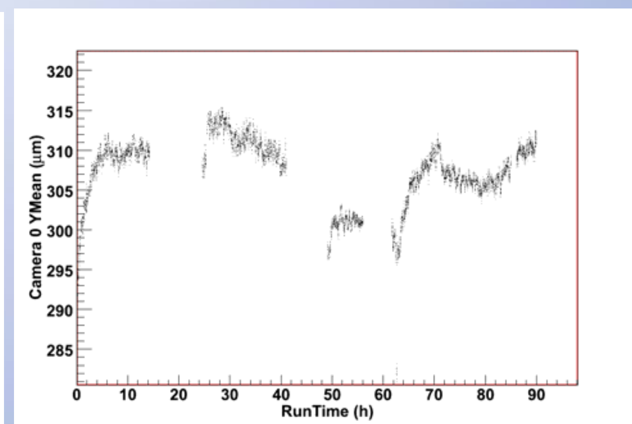
0.78μm Standard deviation

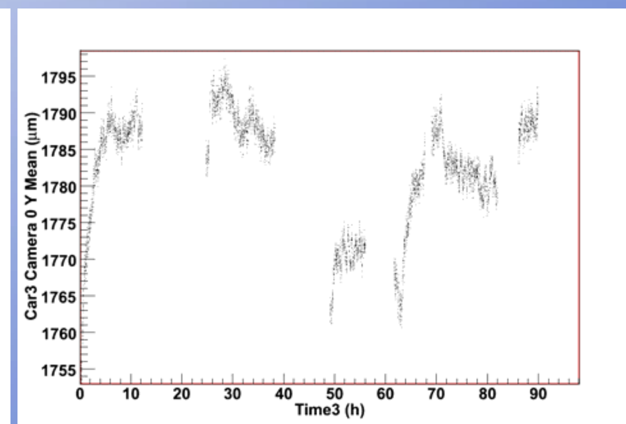
0.55μm Standard deviation per camera. (Same as earlier)

Stability









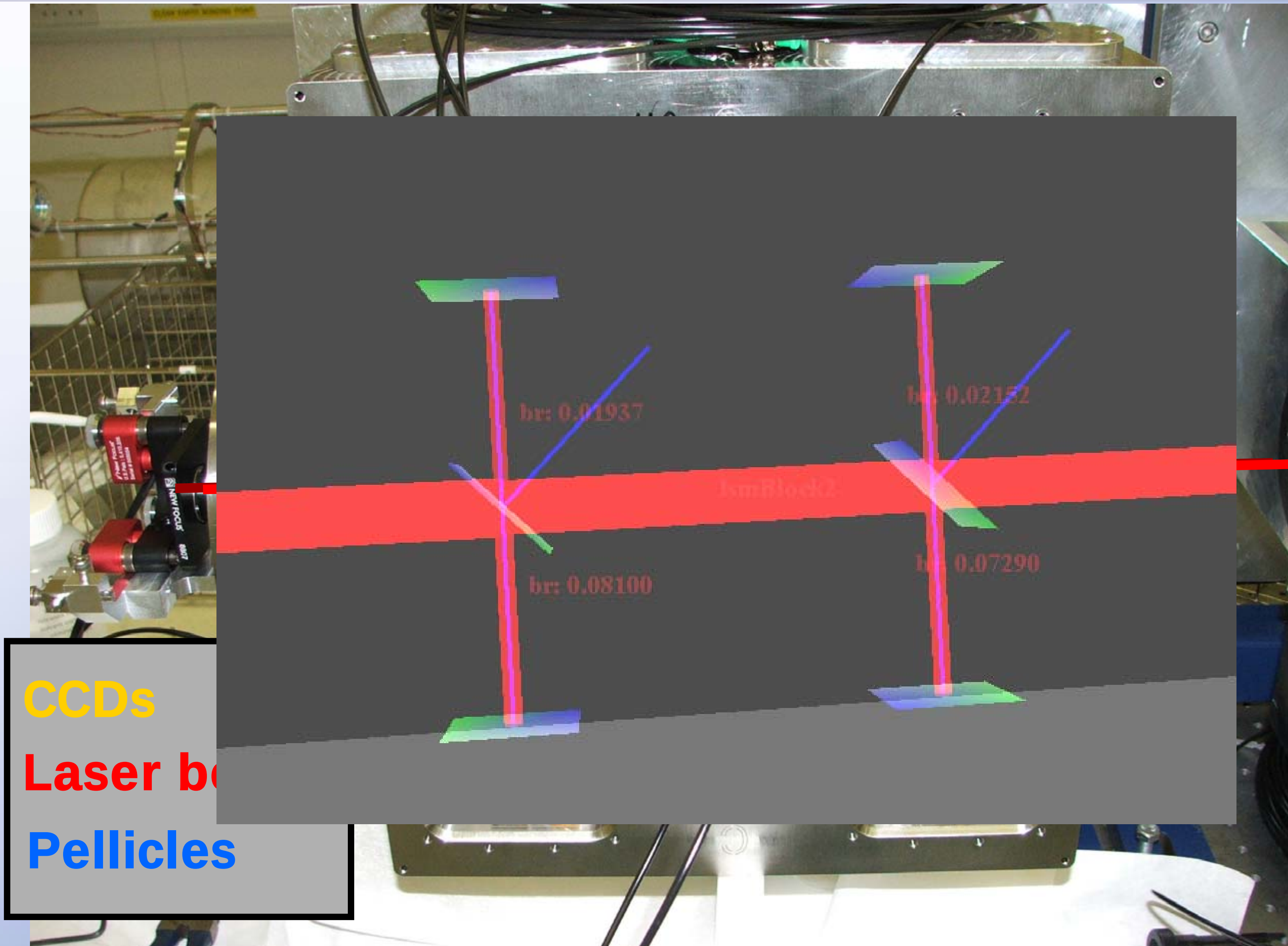
Motion of ~1µm on car1 (0.2m away & attached)

Motion of ~15µm on car2 (4.7m away)

Motion of ~35µm on car3 (9.2m away)

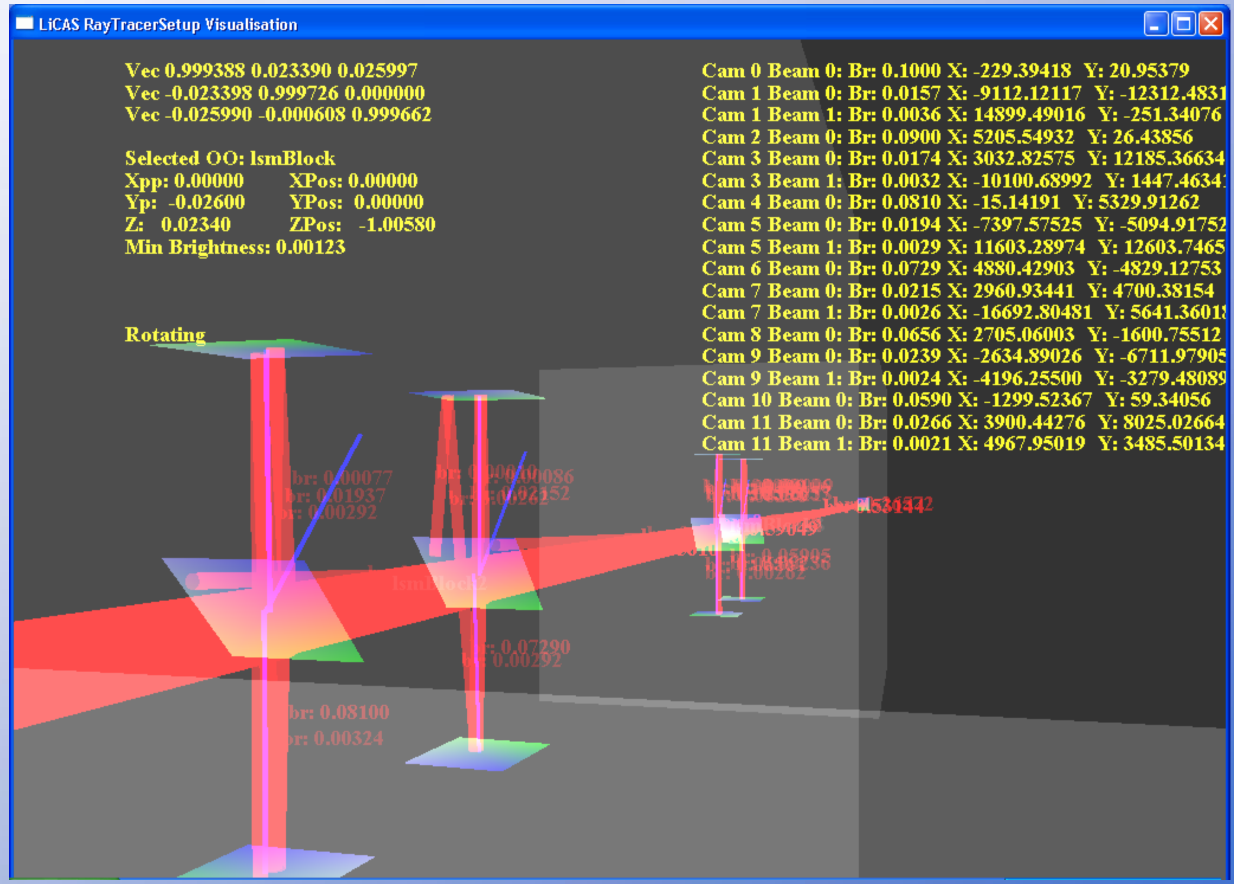
Launch/car1 are unstable to the order of 4 micro-radians over 4 days.

The LSM



Ray Tracer

- Ray tracer used to calculate spot positions
- Highly flexible
- Agrees with completely independent Simulgeo simulation

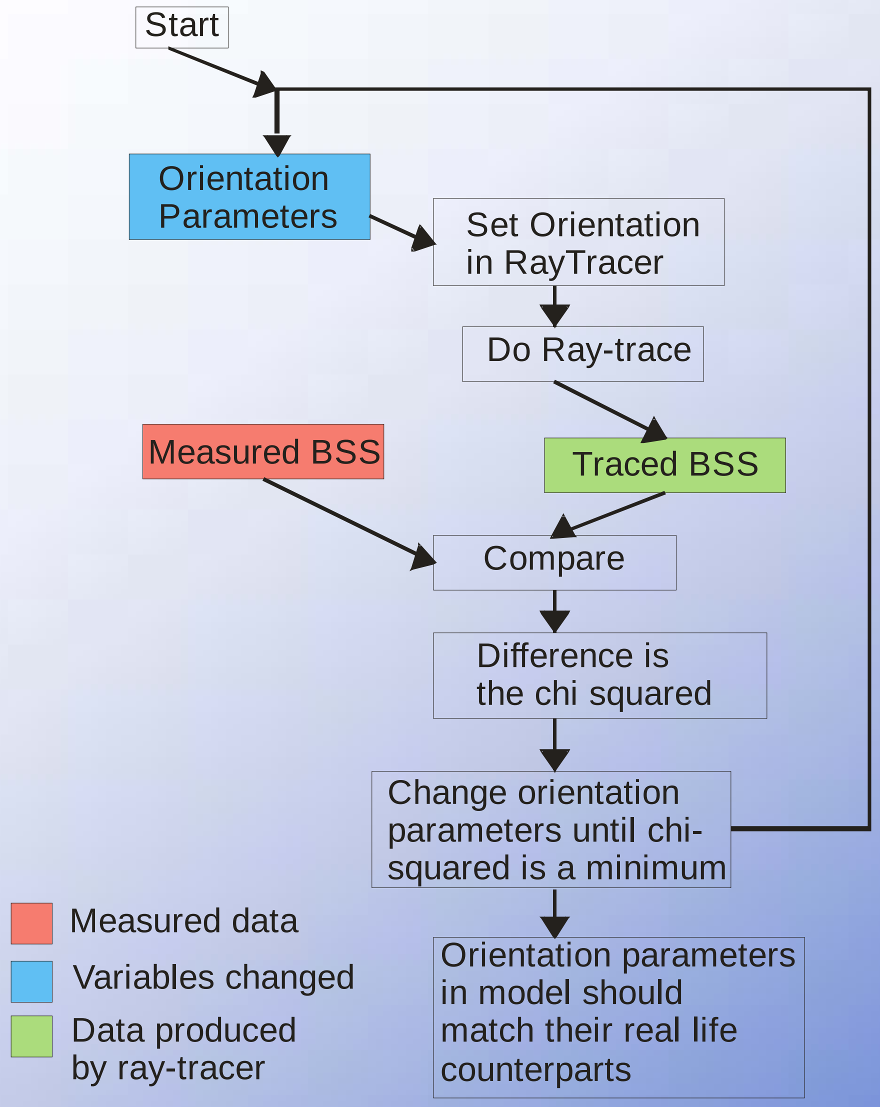


Reconstruction

Ray tracer is used as a part of a fit function for the Minuit fitting package

- Position & orientation of each LSM unit used as the fit parameters
- CCD spots fitted by Chi-squared Minimisation
- Precise to ~0.5xSpot uncertainty for translations
  - ~0.3 microns
- Precise to ~5xSpot uncertainty for rotations
  - ~3 microradians
- Easy to take many images, average, then fit or fit then average.

Reconstruction



Internal Geometry

- Model used needs correct geometry
  - Camera positions & orientations
  - Pellicle positions & orientations

- These are the calibration constants
- Measured to 5-10 microns with CMM
- Need to know some better

Constant Importance

Important Constants

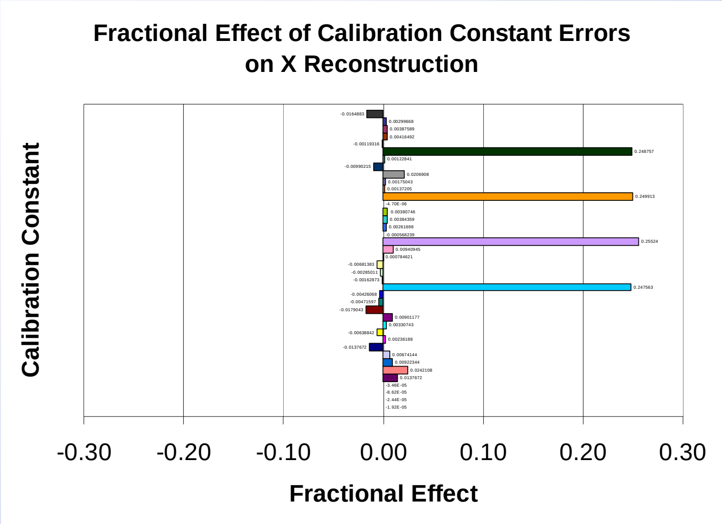
CCD Y positions

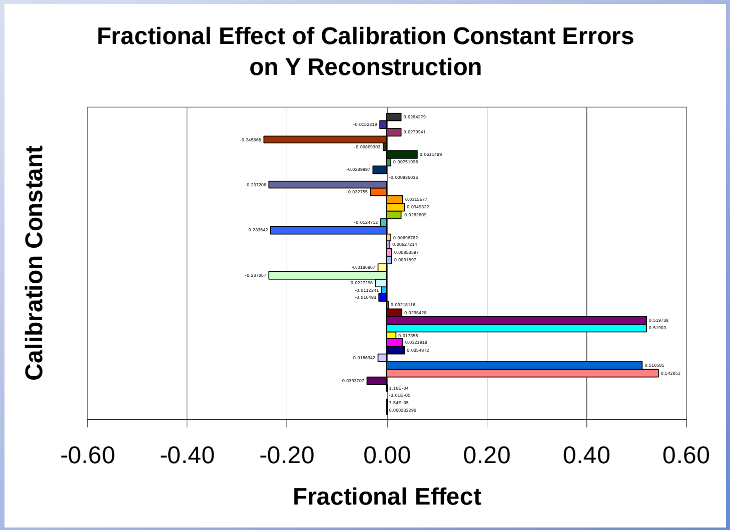
CCD Z positions

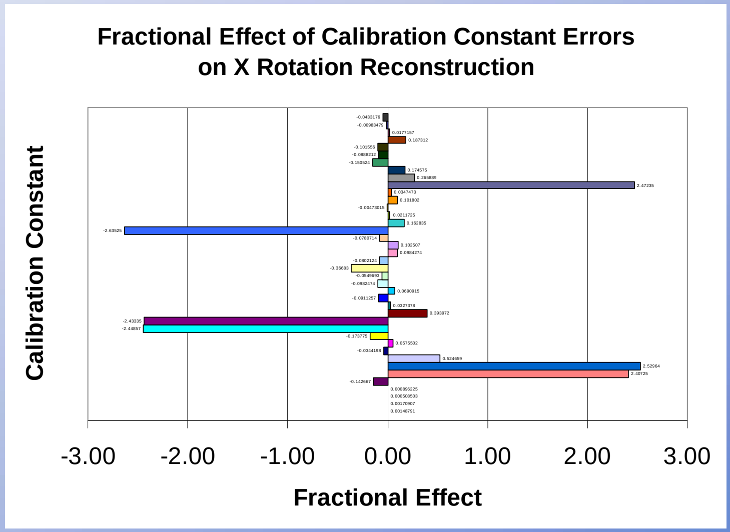
Pellicle Y positions

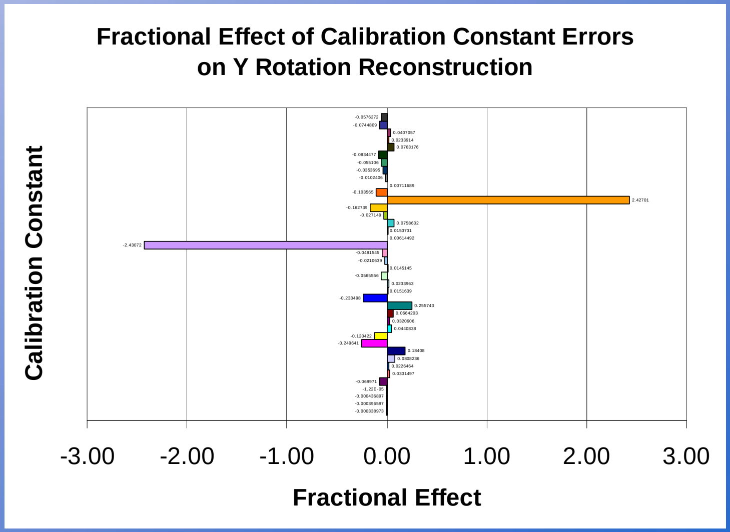
Pellicle Z positions

1 micron error in parameter gives 0.25 – 0.5 micron / 2.5 – 5.0 milliradian error in reconstructed parameter

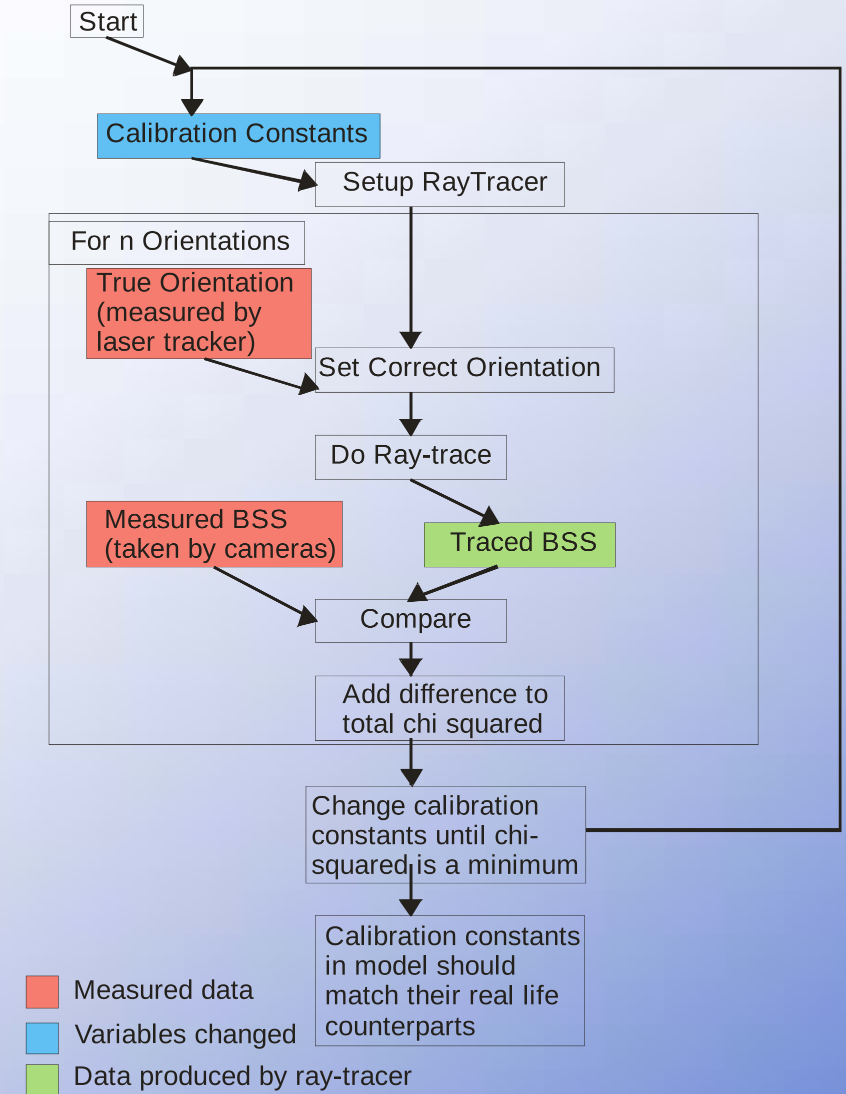








Classical Calibration



- This method compares spot positions generated using a set of calibration constants, to the measured values (knowing the correct orientation).
- Many orientations are used
- It changes the calibration constants until the difference between the measured spots is minimised.
- Complements linear algebra method (see presentation by A. Reichold.)

Classical Calibration

- Simulation run with typical values:
  - 1μm camera resolution
  - 3μm/10μradian observation error
  - 80 orientations used
  - 1mm component uncertainty

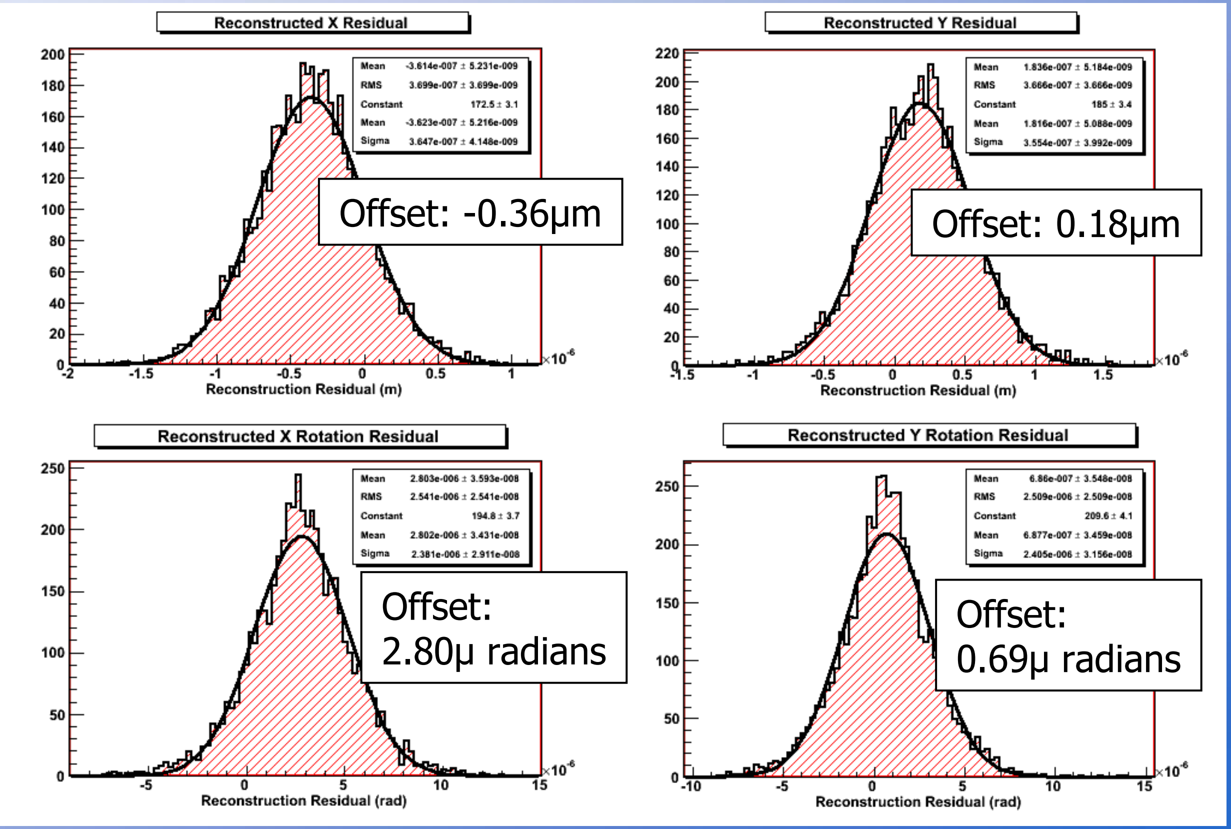
- Important constants found to < 1 μm
- Other constants found to <100 μm (not that useful)

Classical Calibration

- Now USE the fitted constants
- Reconstruct many times and compare to the truth
- Mean residual gives systematic error of that system
- Standard Deviation is dominated by camera resolution – gives statistical error of that system

Example run shown on right.

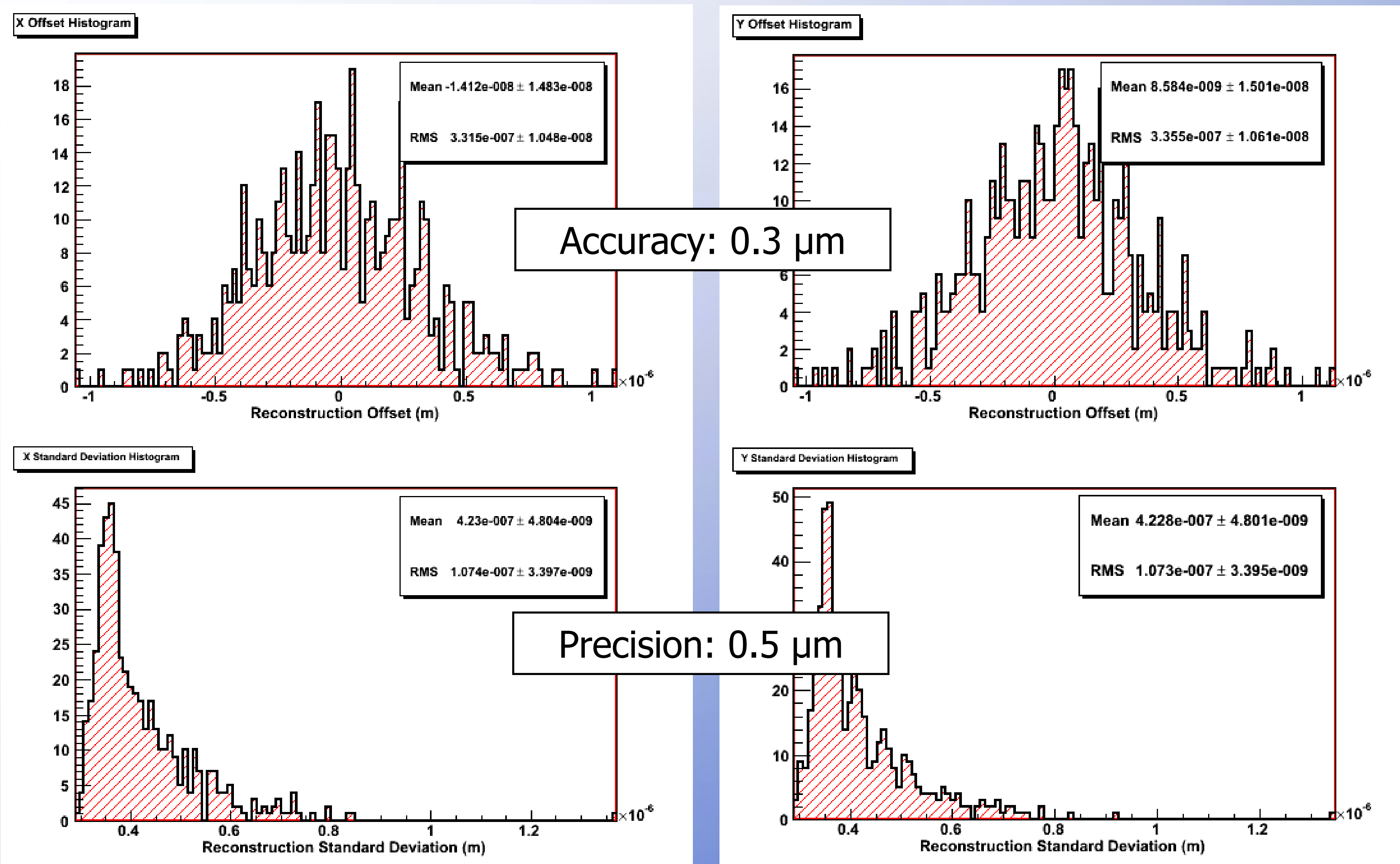
However – this is only one example. Would like to know what to expect in general.



Classical Calibration

- Run simulation many times (with 0.1 mm component uncertainty)
- Collect the mean and standard deviation values of the histograms produced
- Create a histogram of these values
- For the mean histogram the standard deviation gives the accuracy
- For the standard deviation histogram the mean gives the precision

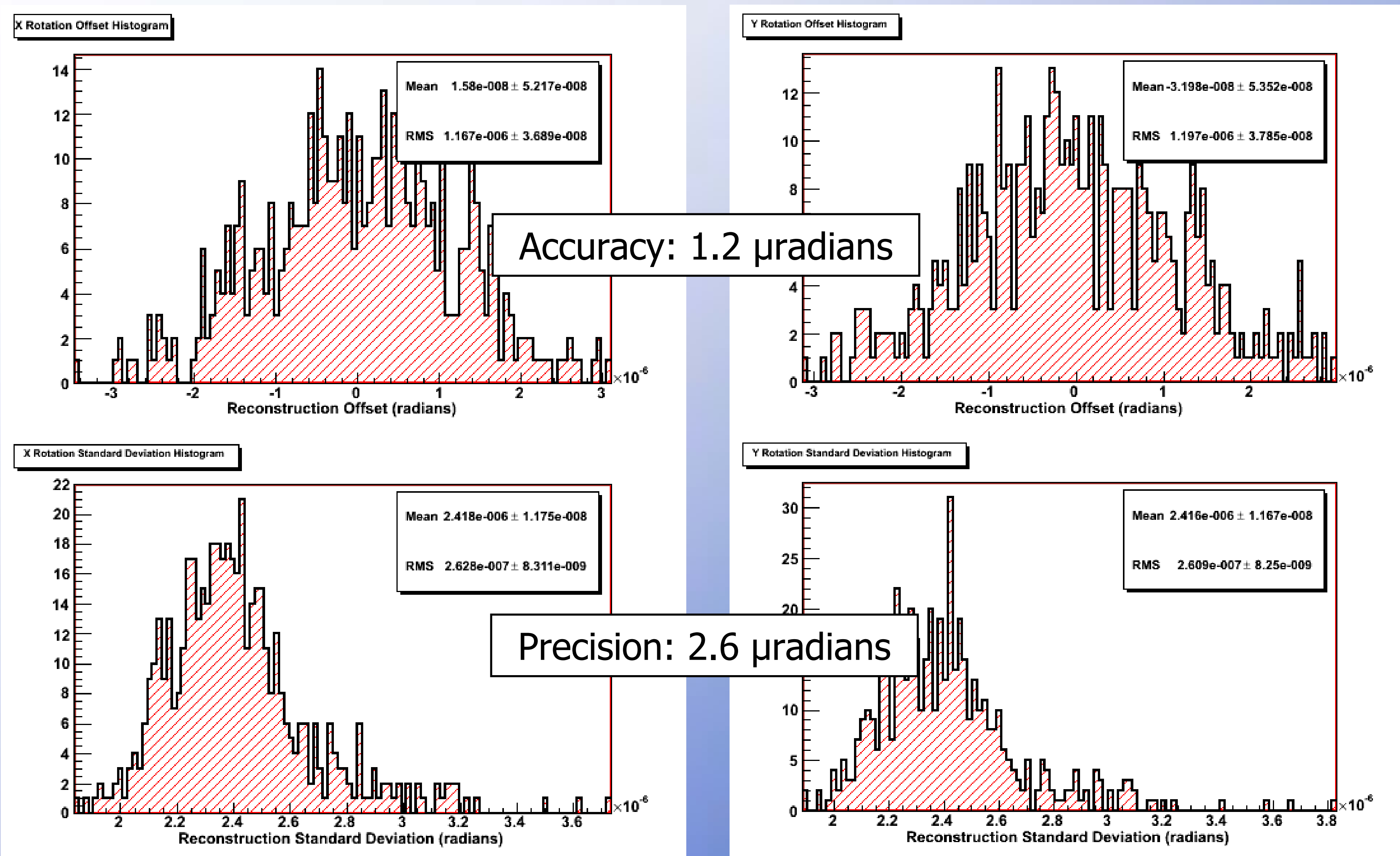
Classical Calibration



Accuracy: 0.3 µm

Precision: 0.5 µm

Classical Calibration



Accuracy: 1.2 μradians

Precision: 2.6 μradians

Auto-Calibration

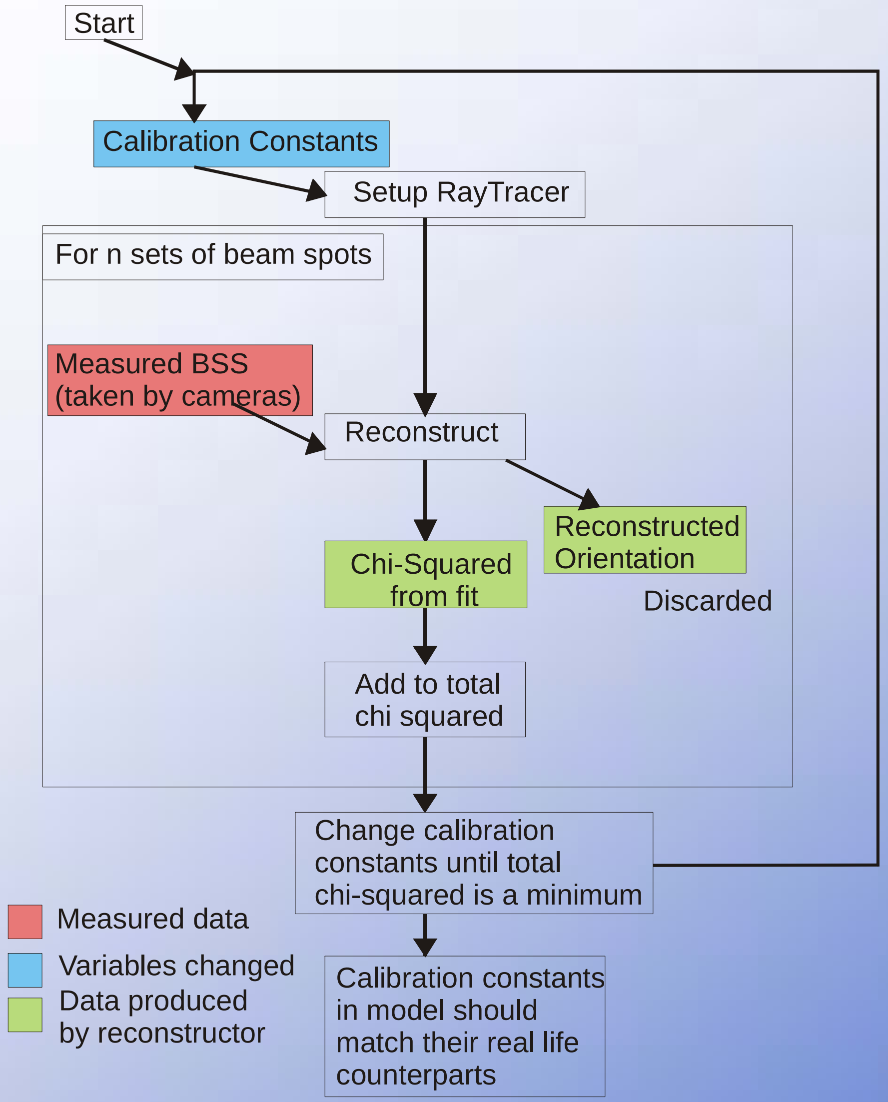
- E = External unknowns (reconstructed variables)
- I = Internal unknowns (calibration constants)
- M = Measurements

- M = F(E,I)
- Eg for a single LSM reading
  - 8 measurements (CCD spot positions)
  - 4 external unknowns
  - 18 internal constant unknowns
    - (this is underconstrained)
- For 10 readings
  - 80 measurements
  - 40 external unknowns
  - 18 internal constant unknowns

    (This is overconstrained by 22 DoF)

- We use the large overconstraint found with many readings to determine the calibration constants.
- Complements both classical calibration methods
- Can be used with much more data and can show how constants change.

Auto-Calibration



- This method incorporates the calibration constants as part of the fitting process
- Many runs are fitted en-masse and the individual chi-squareds summed
- The constants that give the lowest total chi-squared are chosen.

Auto-Calibration

- Simulations have been performed using typical uncertainties
  - 40 runs
  - 1μm camera resolution
  - 0.1mm constant uncertainty

- Find most important constants to <0.3μm (after corrections)
- Problems (as expected) with scaling & offsets
- Still a useful addition to calibration

Conclusions

- Working LSM system
- Beam fitting now mature
- Stability under investigation
- Ray tracer well developed
- Reconstruction effective
- Calibration predicted to work well
- Autocalibration predicted to compliment well