

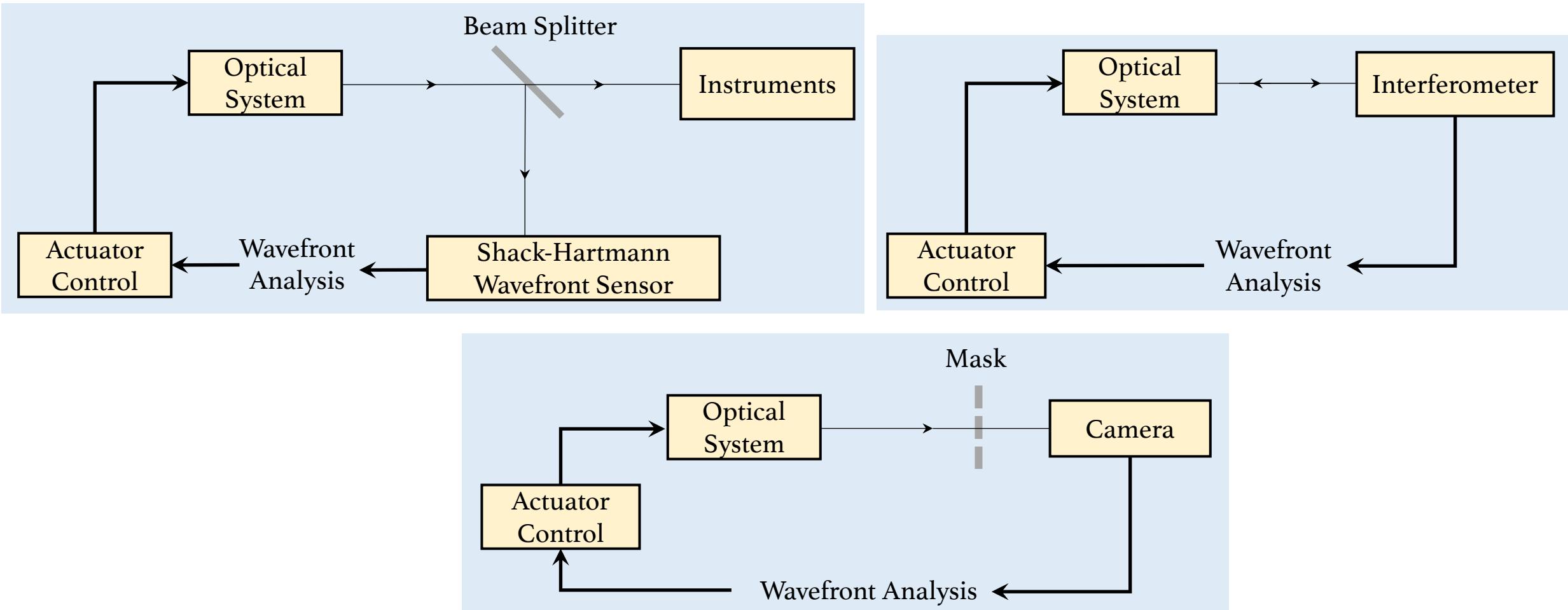
Automated Reflective Optical System Alignment with Focal Plane Sensing and Optimal State Estimation

Duan Li and Dmitry Savransky

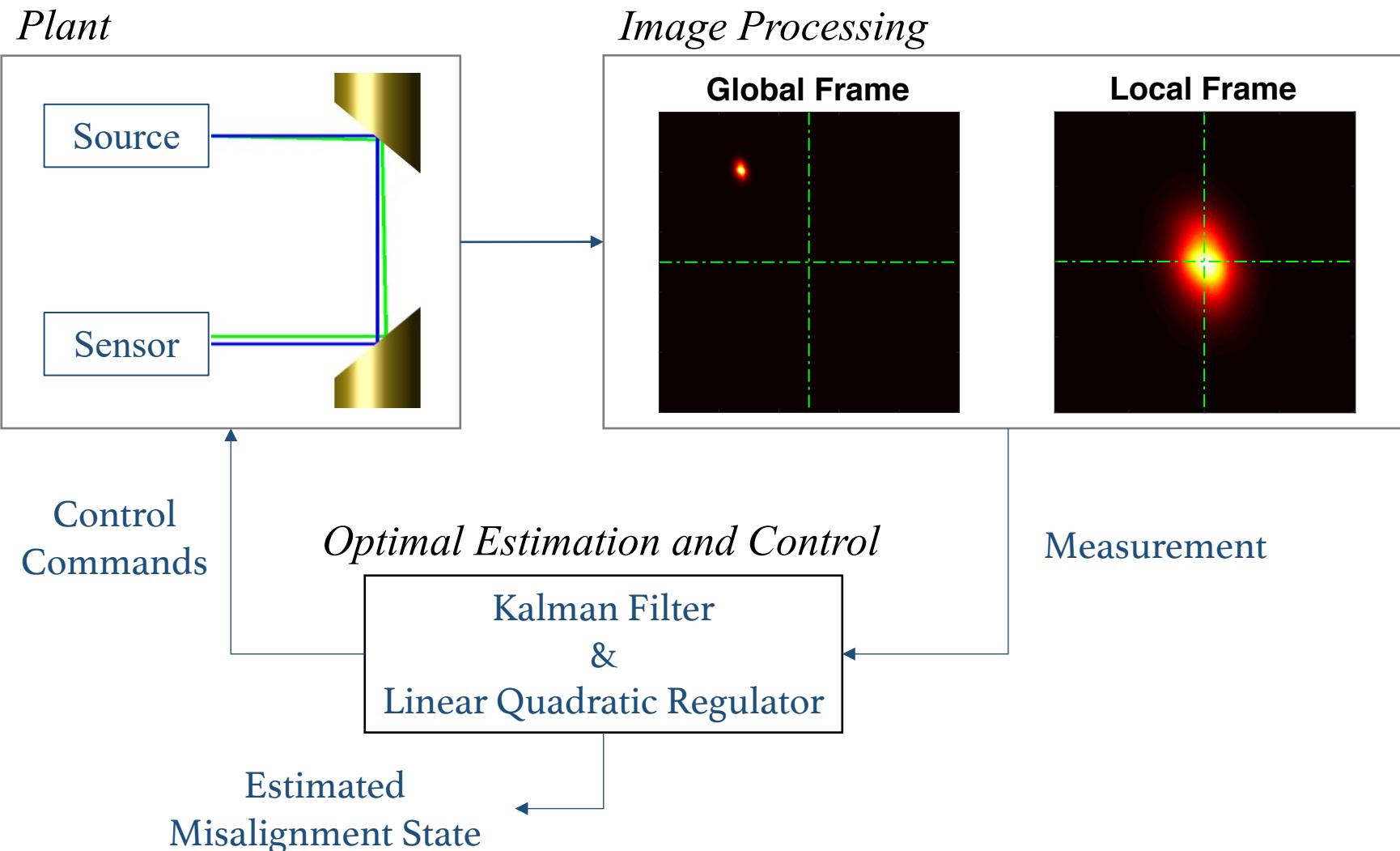
Sibley School of Mechanical and Aerospace Engineering
Cornell University

Background

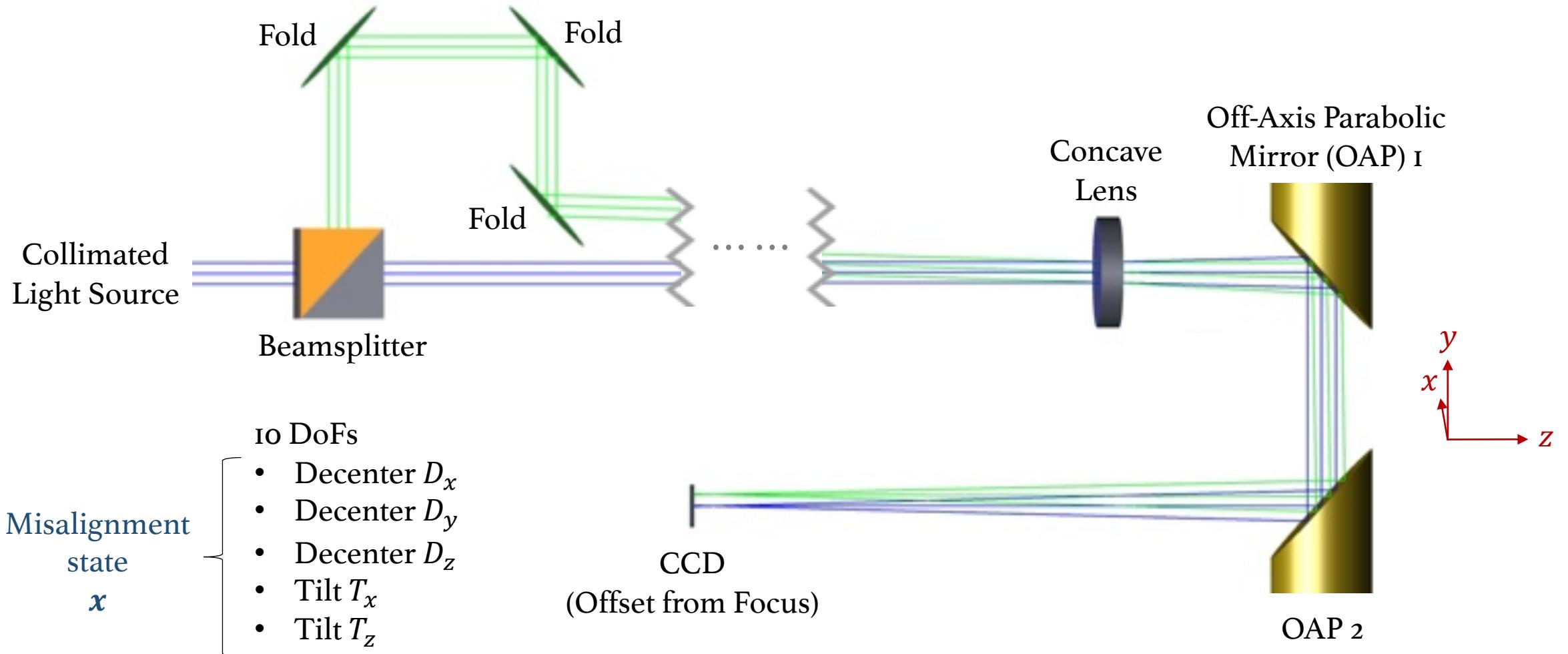
Current alignment methods



Our Approach



Optical Model



Optical Model

Misalignment effect

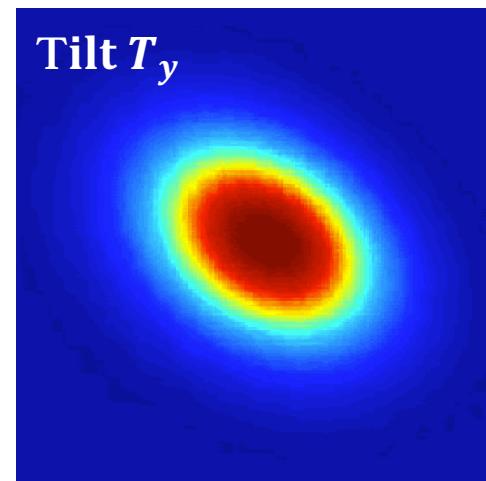
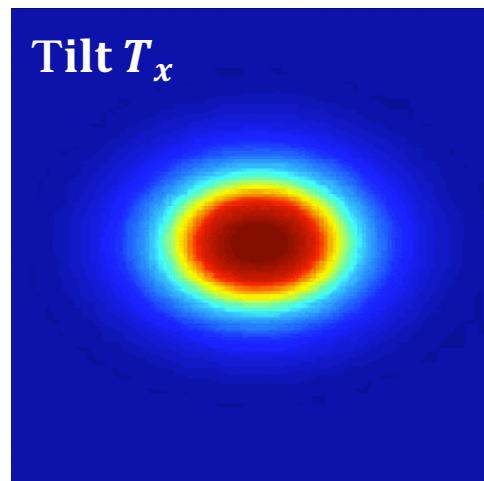
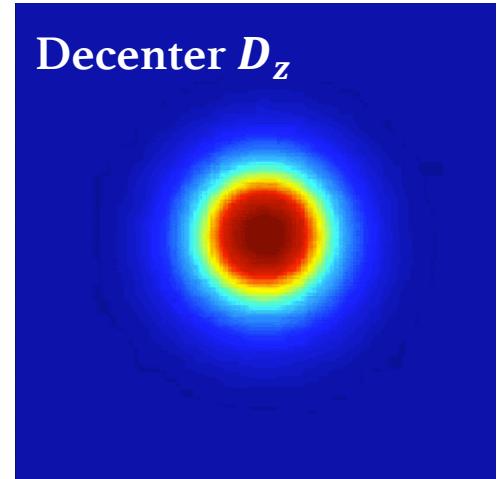
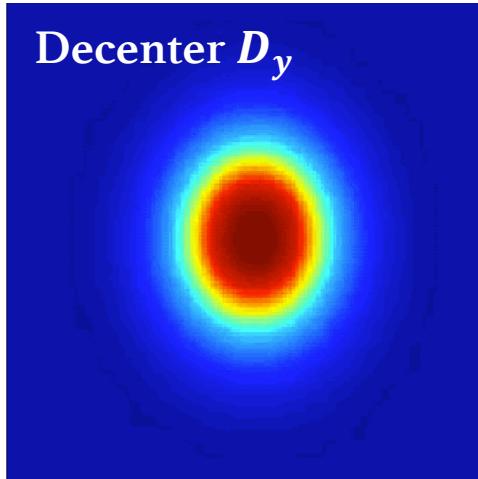
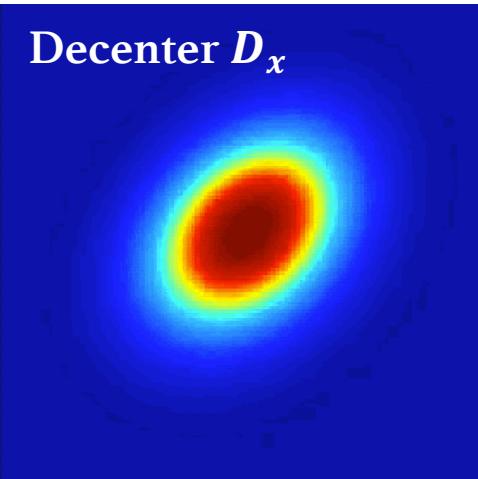
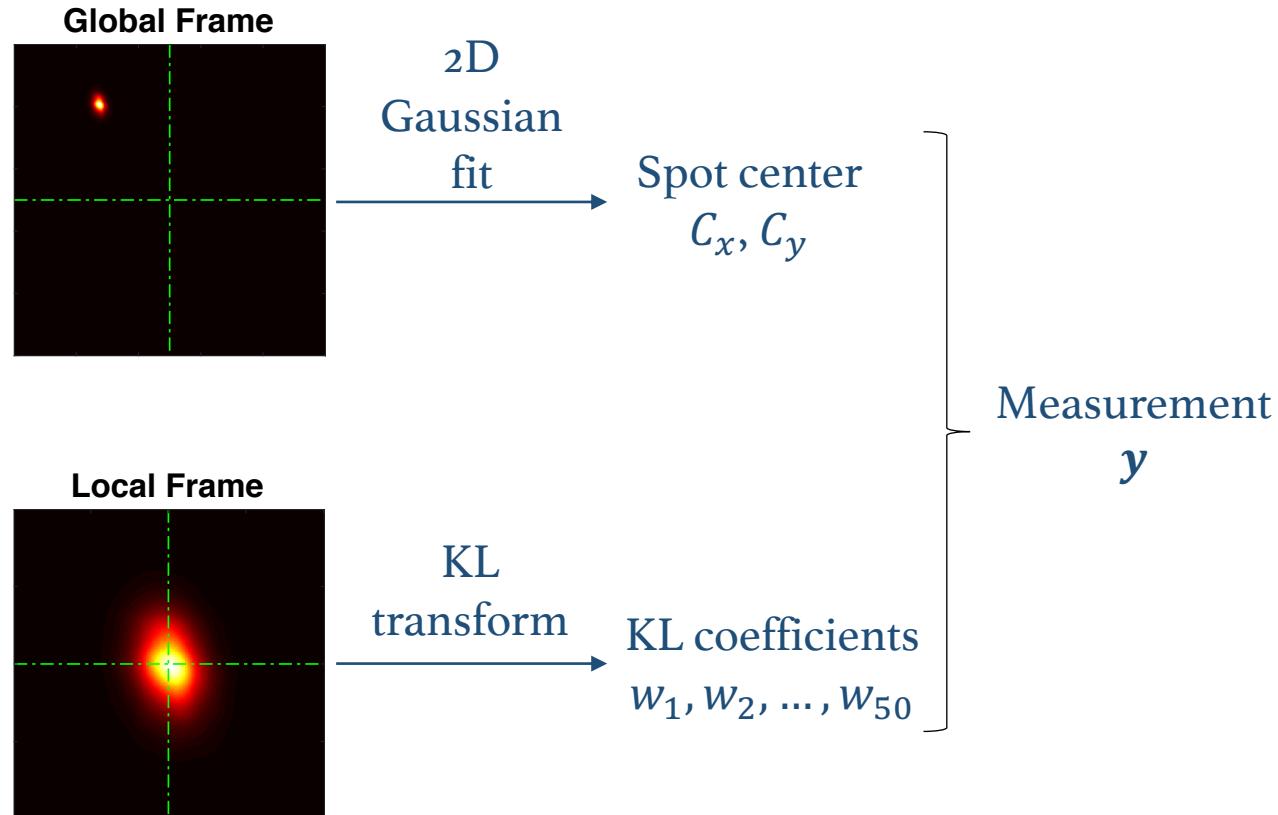
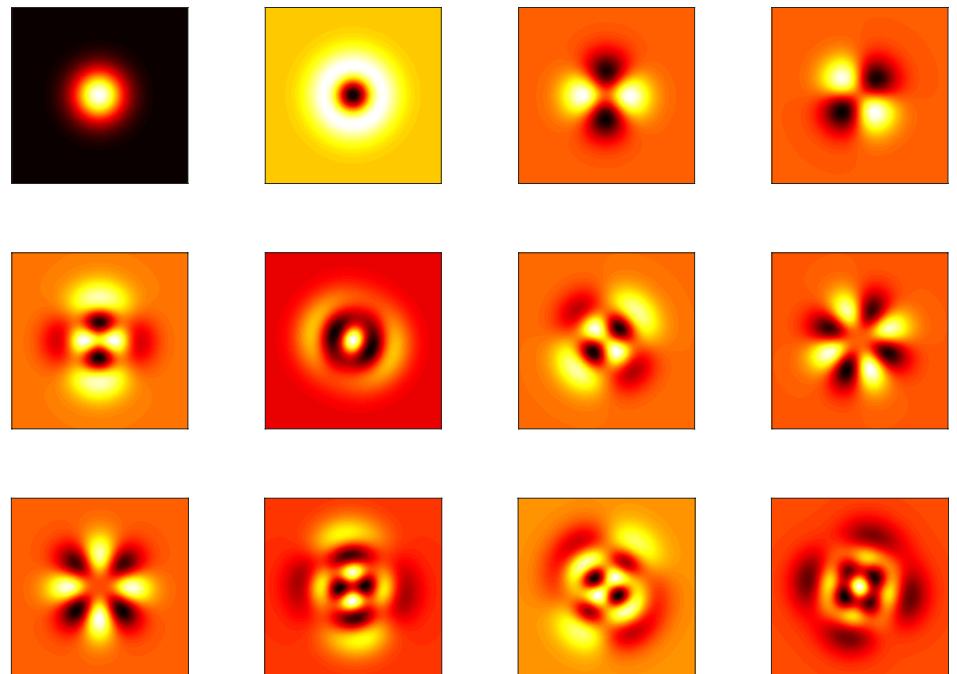


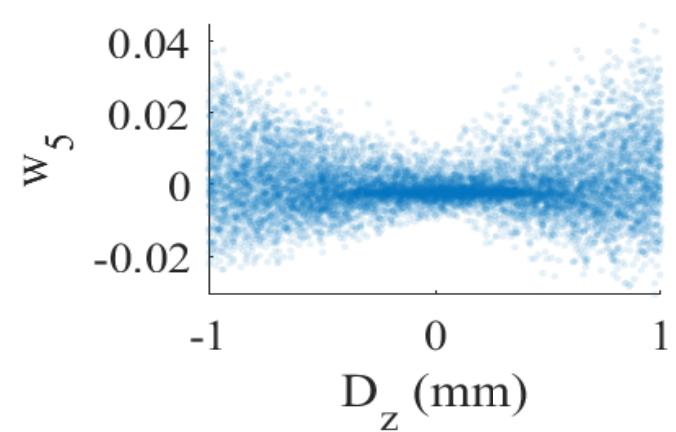
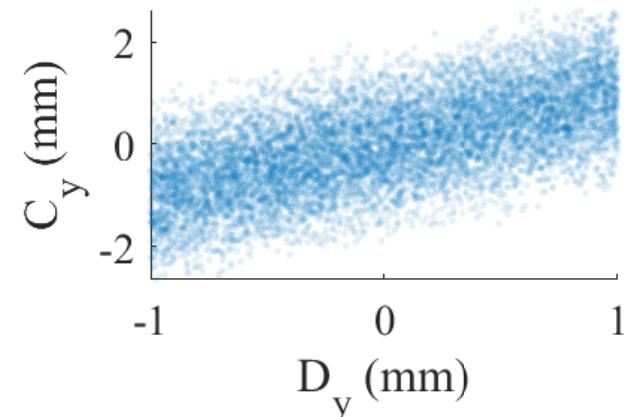
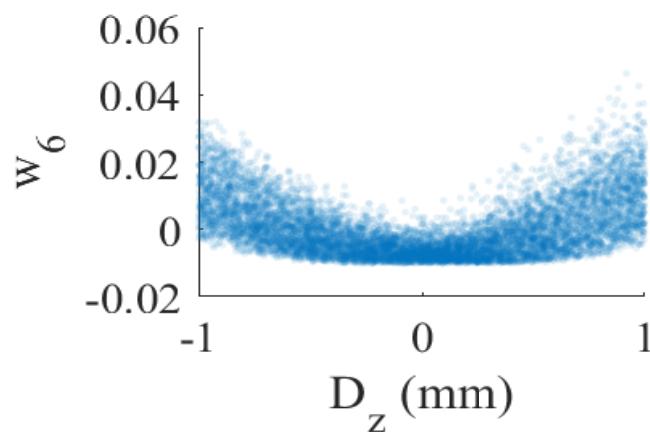
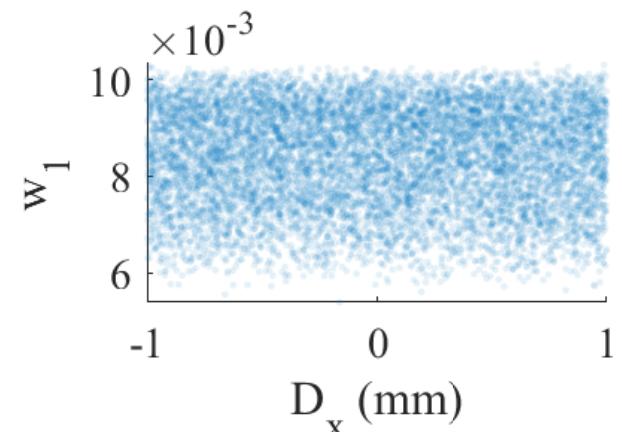
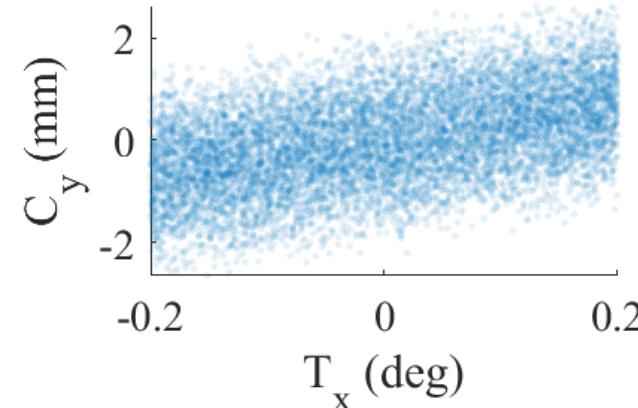
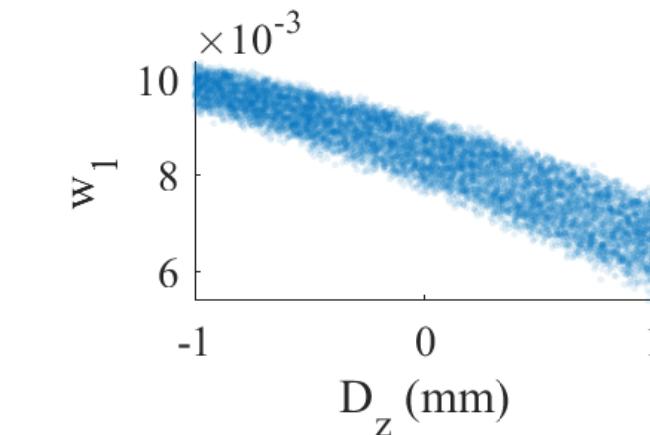
Image Processing



Karhunen-Loèeve (KL) Basis



Mapping function $y = h(x)$



Misalignment state x $\left\{ \begin{array}{ll} \text{Decenter} & D_x, D_y, D_z \\ \text{Tilt} & T_x, T_z \end{array} \right.$

Measurement y $\left\{ \begin{array}{ll} \text{Spot center} & C_x, C_y \\ \text{KL coefficients} & w_1, w_2, \dots, w_{50} \end{array} \right.$

Optimal Estimation and Control

Extended Kalman filter

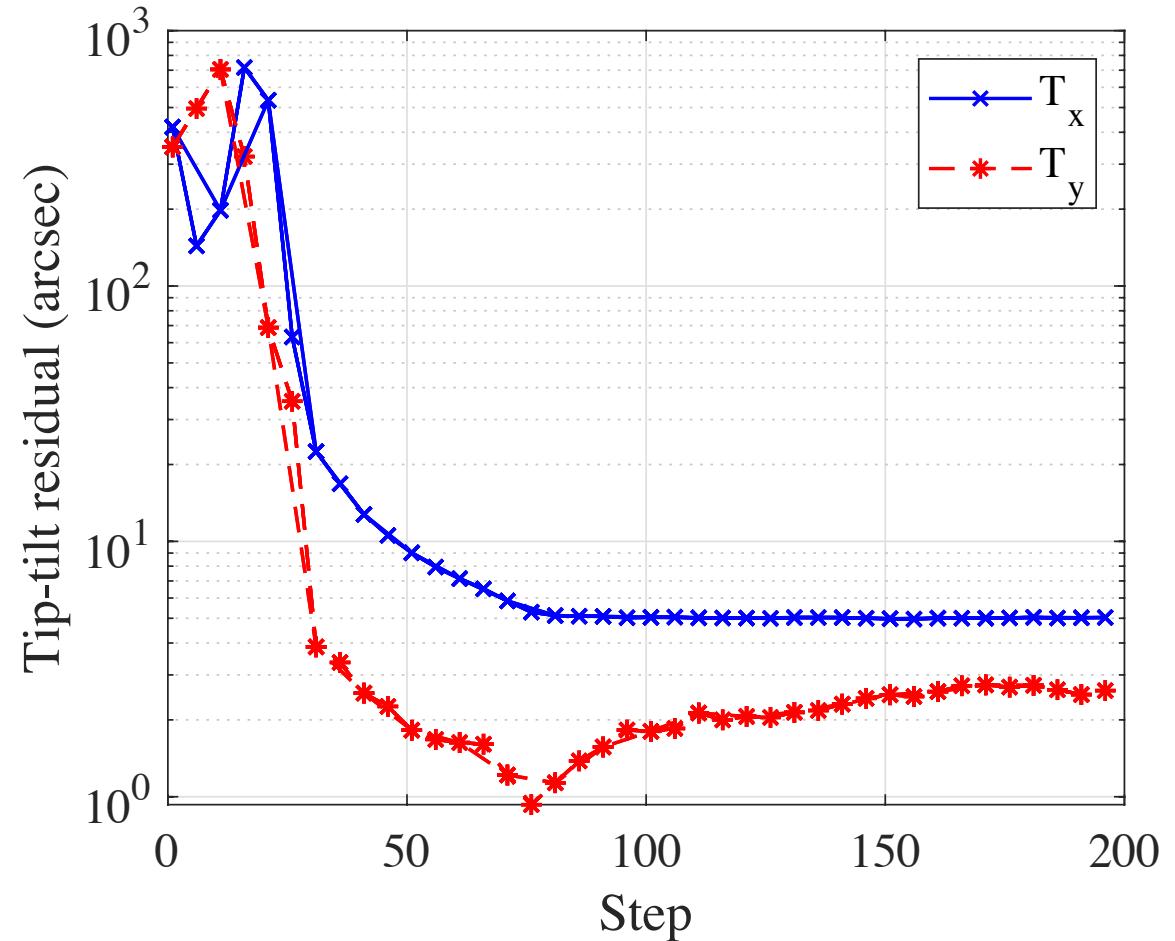
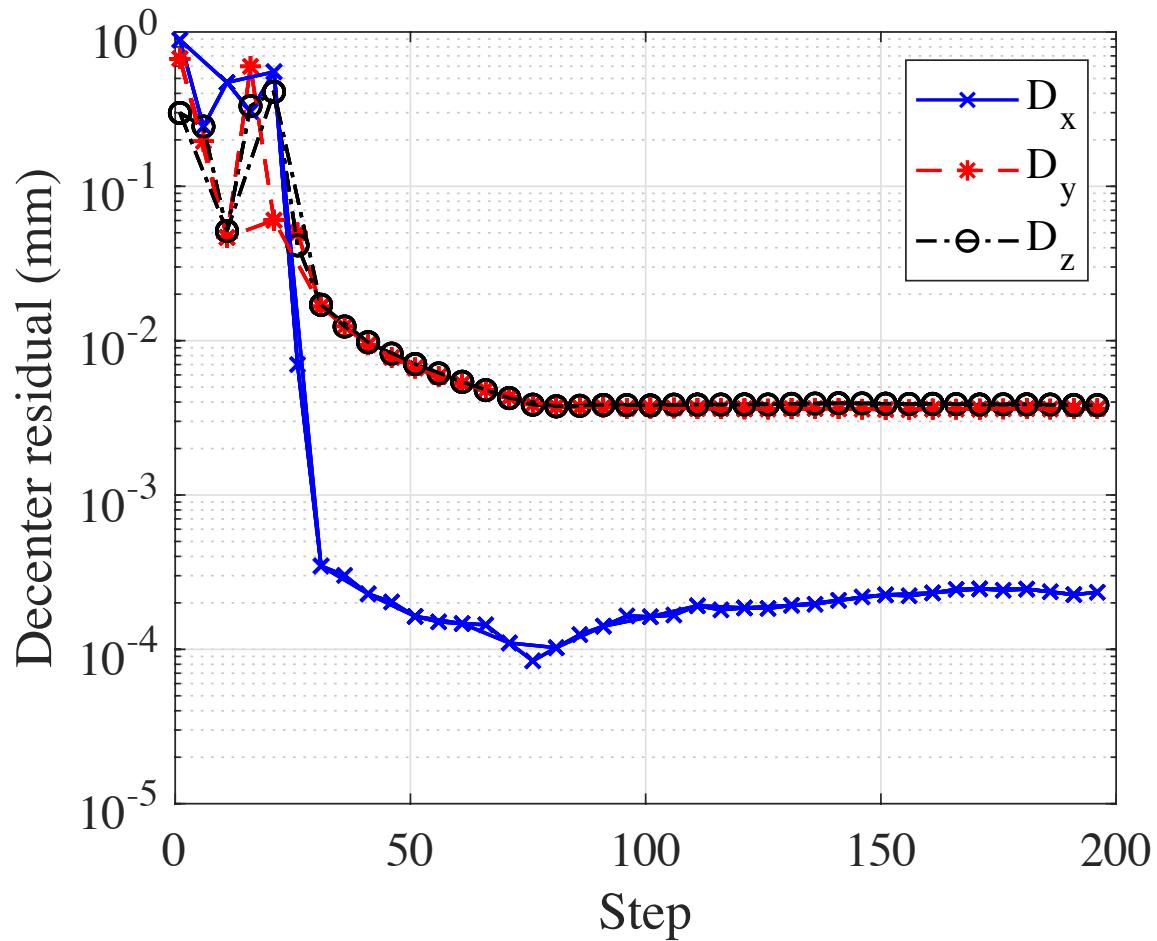


- Predict
 - Predicted state:
 $\hat{\mathbf{x}}_{k|k-1} = \mathbf{F}_k \hat{\mathbf{x}}_{k-1|k-1} + \mathbf{B}_k \mathbf{u}_k$
 - Predicted covariance:
 $\mathbf{P}_{k|k-1} = \mathbf{F}_k \mathbf{P}_{k-1|k-1} \mathbf{F}_k^T + \mathbf{Q}_k$
- Update
 - Kalman gain: $\mathbf{K}_k = \mathbf{P}_{k|k-1} \mathbf{H}_k^T (\mathbf{H}_k \mathbf{P}_{k|k-1} \mathbf{H}_k^T + \mathbf{R}_k)^{-1}$
 - Updated state: $\hat{\mathbf{x}}_{k|k} = \hat{\mathbf{x}}_{k|k-1} + \mathbf{K}_k \tilde{\mathbf{y}}_k$
 - Updated covariance: $\mathbf{P}_{k|k} = (\mathbf{I} - \mathbf{K}_k \mathbf{H}_k) \mathbf{P}_{k|k-1}$

State transition matrix \mathbf{F}_k
Control input matrix \mathbf{B}_k
Process noise covariance \mathbf{Q}_k
Mapping function $\mathbf{y} = \mathbf{h}(\mathbf{x})$
Mapping Jacobian $\mathbf{H}_k = \frac{\partial \mathbf{h}}{\partial \mathbf{x}} \Big|_{\hat{\mathbf{x}}_{k|k-1}}$
Measurement noise \mathbf{R}_k

Simulation Result

State residual



Simulation Result

Final stage positions



OAP 1

State	RMS Residual
D_x	0.24 ± 0.097 μm
D_y	3.2 ± 0.9 μm
D_z	3.4 ± 0.7 μm
T_x	4.4 ± 1.3 arcsec
T_y	2.6 ± 1.1 arcsec

OAP 2

State	RMS Residual
D_x	0.37 ± 0.15 μm
D_y	2.5 ± 0.7 μm
D_z	1.8 ± 0.4 μm
T_x	4.5 ± 1.3 arcsec
T_y	2.6 ± 1.1 arcsec

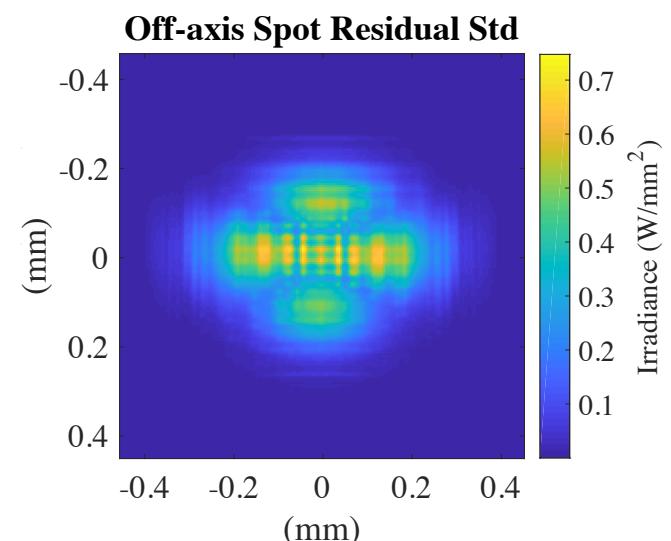
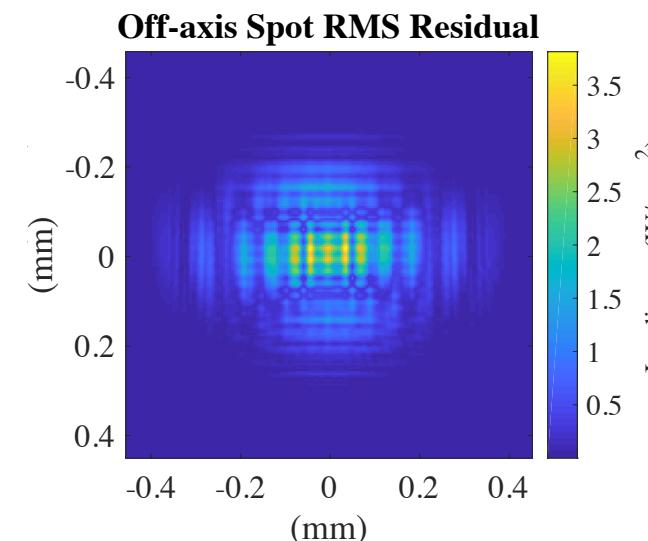
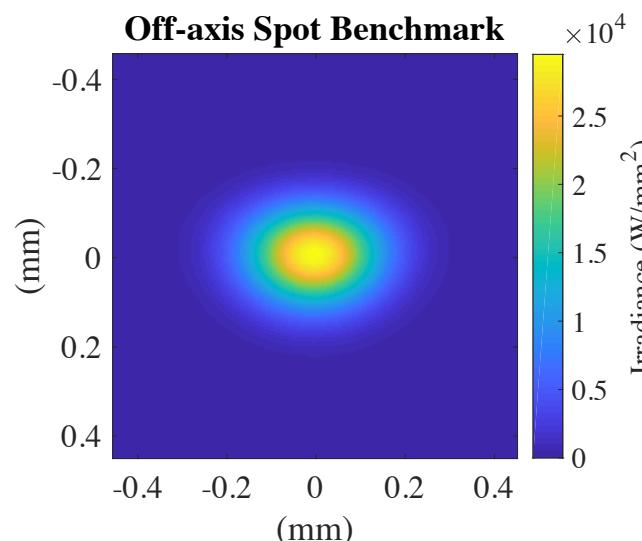
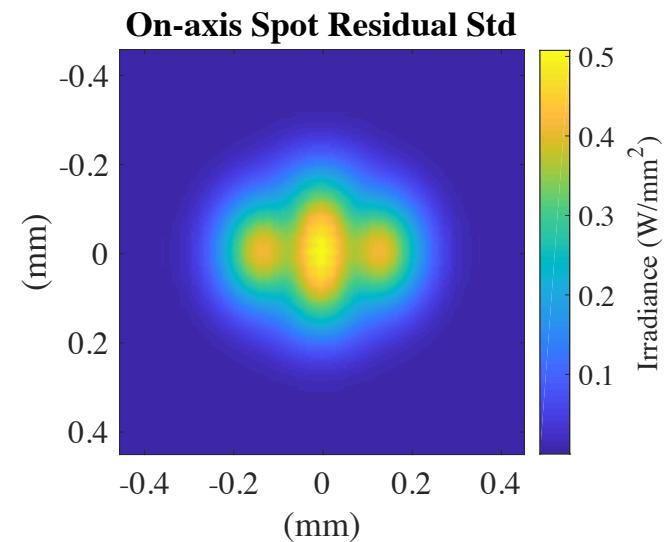
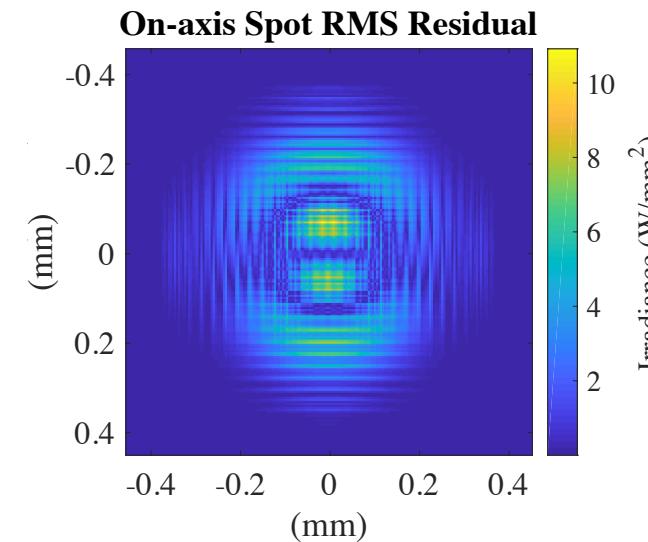
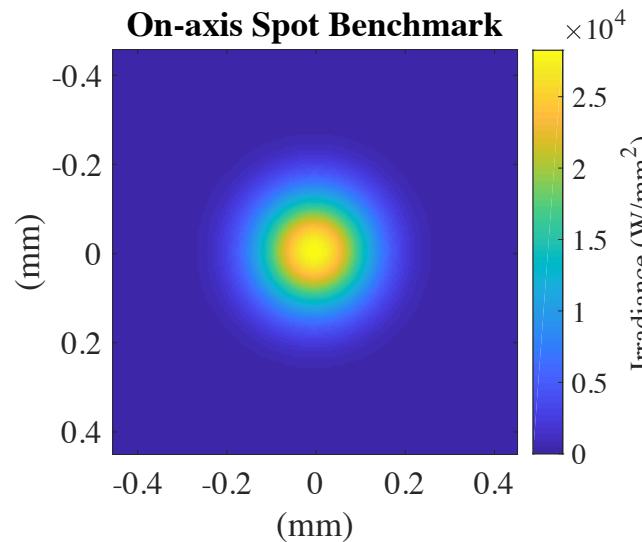
Simulation Result

Final spot positions

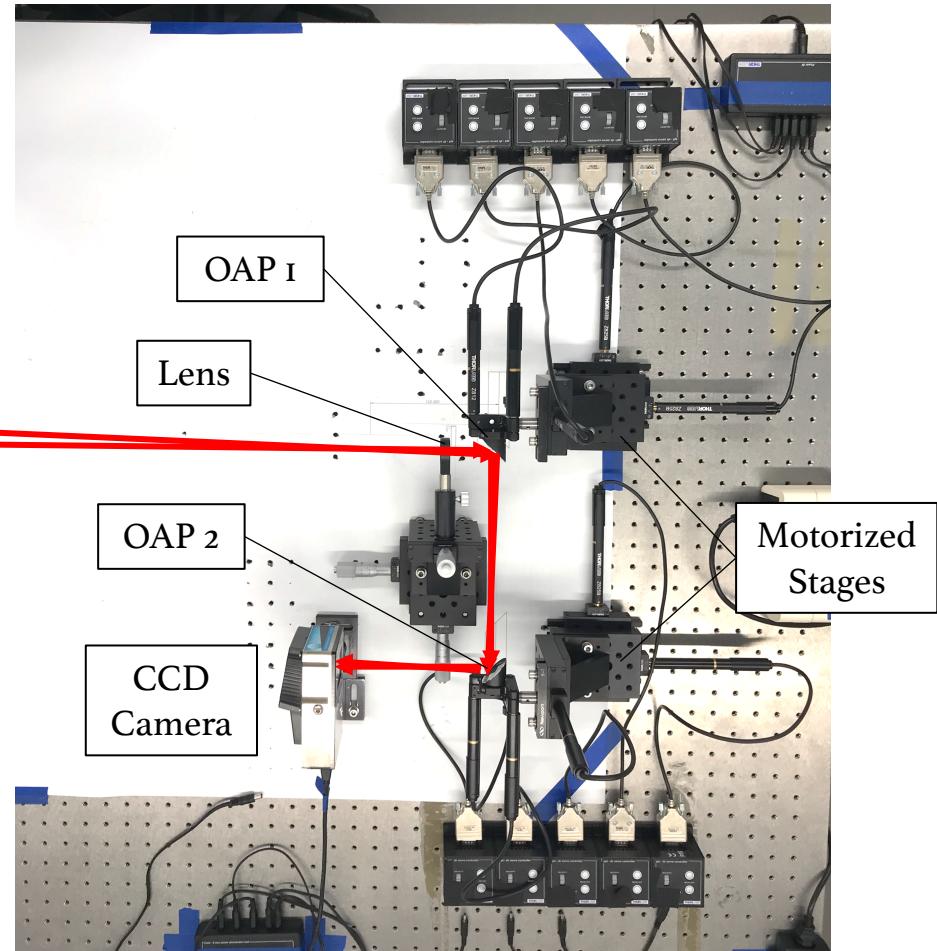
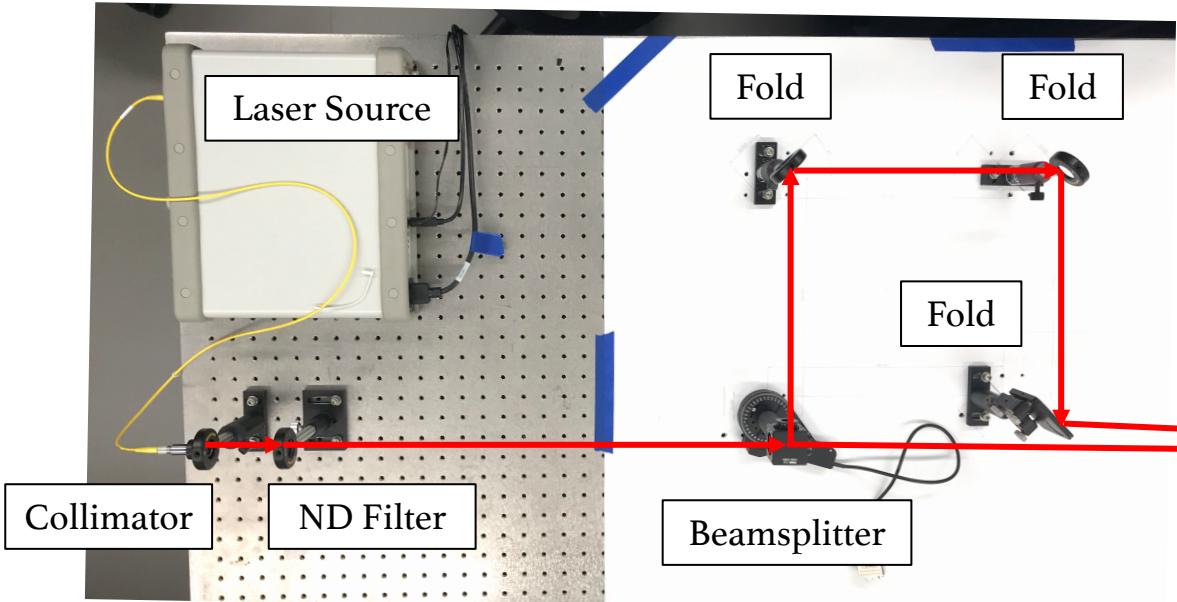
	Measurements	RMS Residual	
On-axis spot	C_x	0.36 ± 0.31	nm
	C_y	19 ± 0.06	nm
Off-axis spot	C_x	84 ± 35	nm
	C_y	49 ± 20	nm

Simulation Result

Image quality



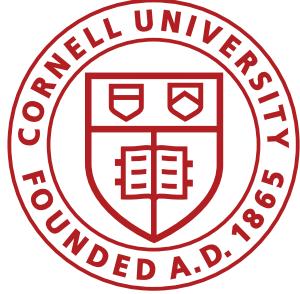
Experiments



Conclusion and Future Work



- Simulated automated alignment of a reflective system using only focal plane sensing
- Methodology
 - Image Processing
 - Optimal Control and Estimation
- Simulation Results
 - Final misalignment error $\sim \mu\text{m}/\text{arcsec}$
 - Applications on imaging systems with $< 0.05\%$ error
- Future work
 - Experiments to validate simulation results
 - Improving mapping function to reduce error and misalignment coupling



Thank You!