UNIVERSITY AT ALBANY
State University of New York

Lithographic characterization of low-order aberrations in the Berkeley MET tool

Patrick Naulleau

CNSE, University at Albany, State University of New York

Jason P. Cain

EECS, University of California, Berkeley

Kim Dean

SEMATECH

Kenneth A. Goldberg

CXRO, Lawrence Berkeley National Laboratory

Supported by SEMATECH

Outline

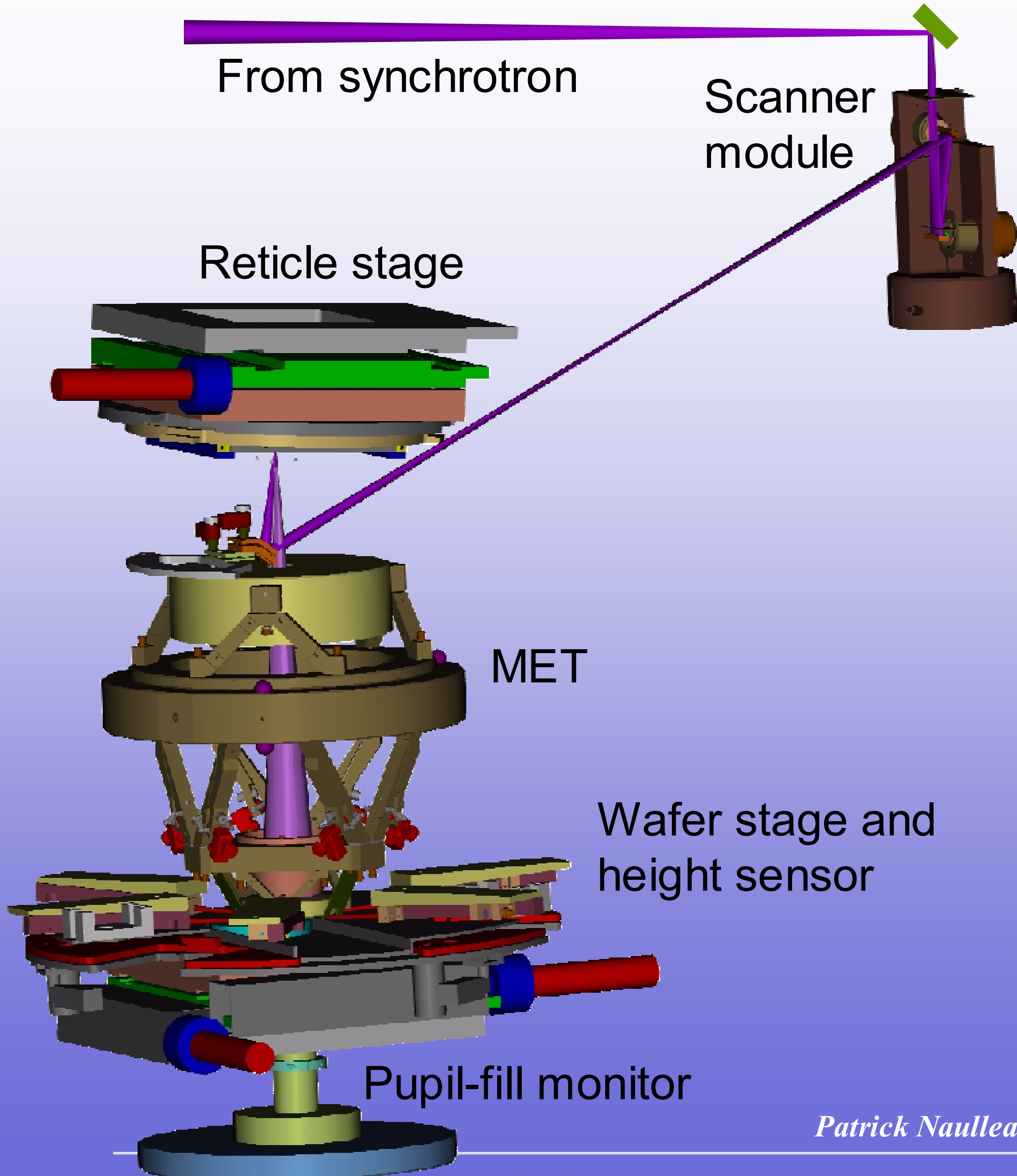
- System description
- Experimental performance limit
- Lithographic measurement of cross-field astigmatism
- Lithographic measurement of spherical error
- Qualitative characterization of coma
- Predicted impact of aberrations on performance

Patrick Naulleau

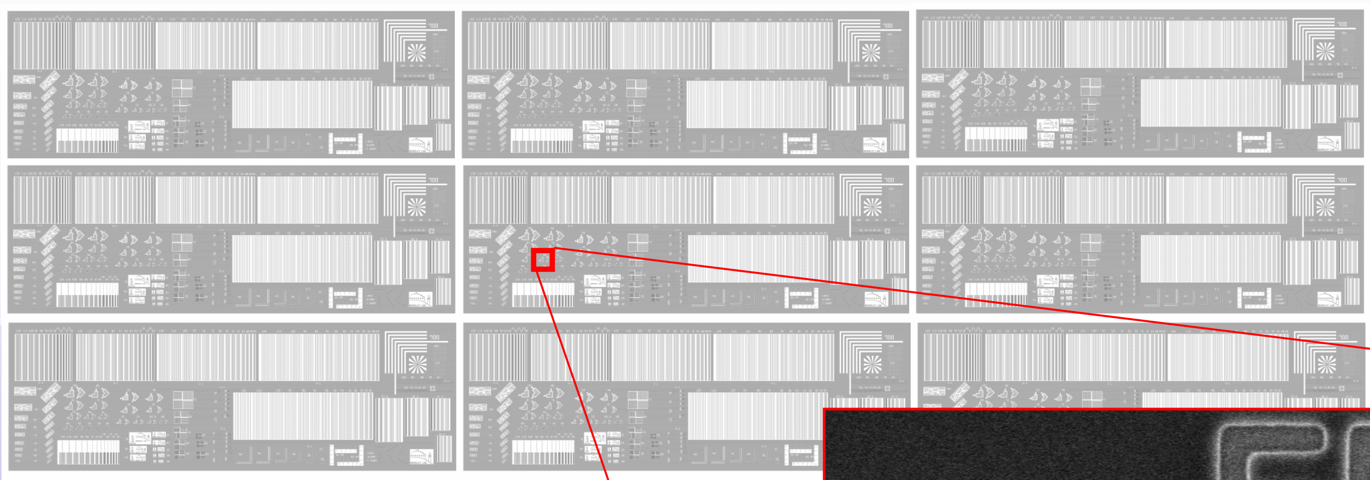
College of Nanoscale Science and Engineering

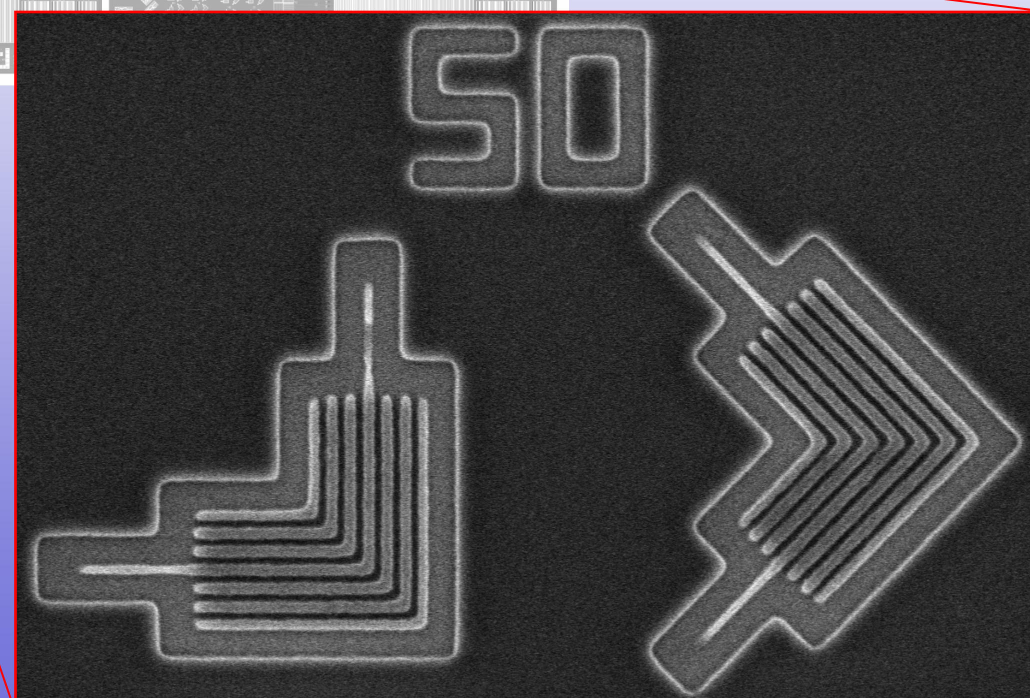
Berkeley MET exposure tool

- **Based on MET optic**
- **Magnification = 5x, NA = 0.3**
- **Rayleigh resolution = 27 nm**
- **Field size = 200x600 μm**
- **Programmable coherence illuminator for low k_1**
- **Reticle and wafer load-lock and manual transfer systems**
- **Wafer-height sensor**
- **nm-resolution wafer-height sensor and focus actuation**
- **Pupil-fill monitor**



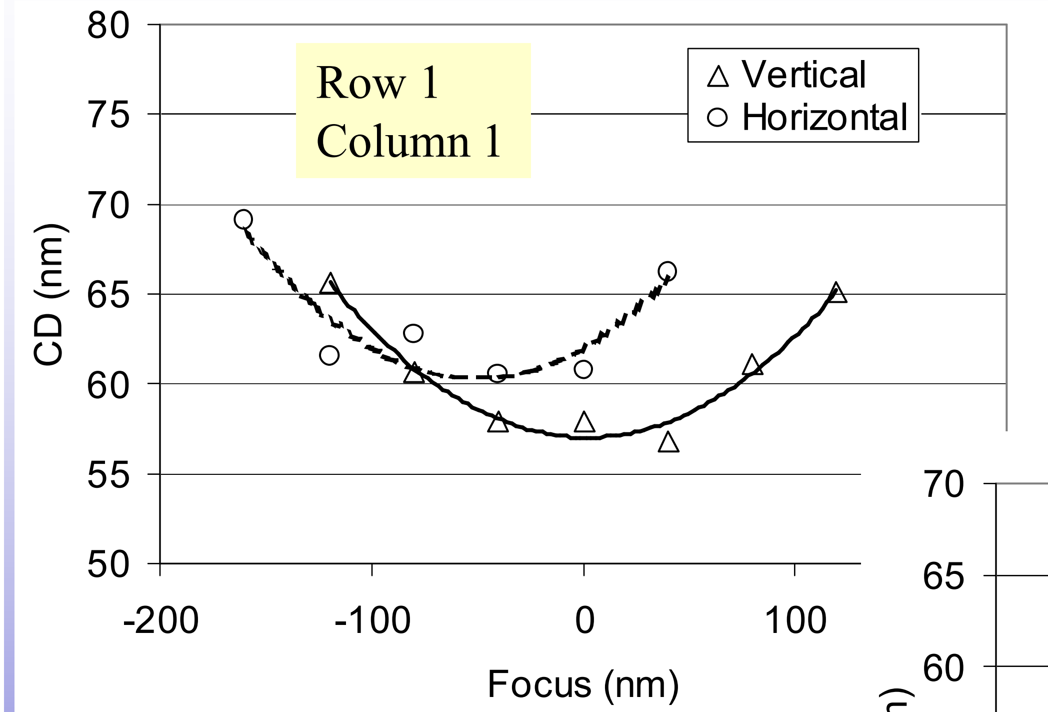
50-nm elbow pattern used to characterize astigmatism across field

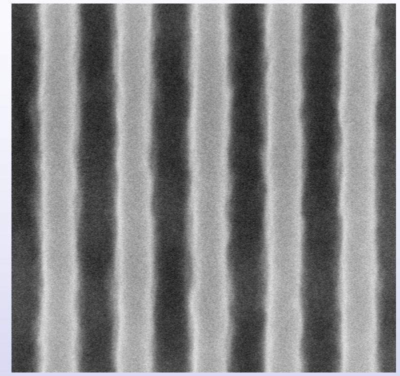




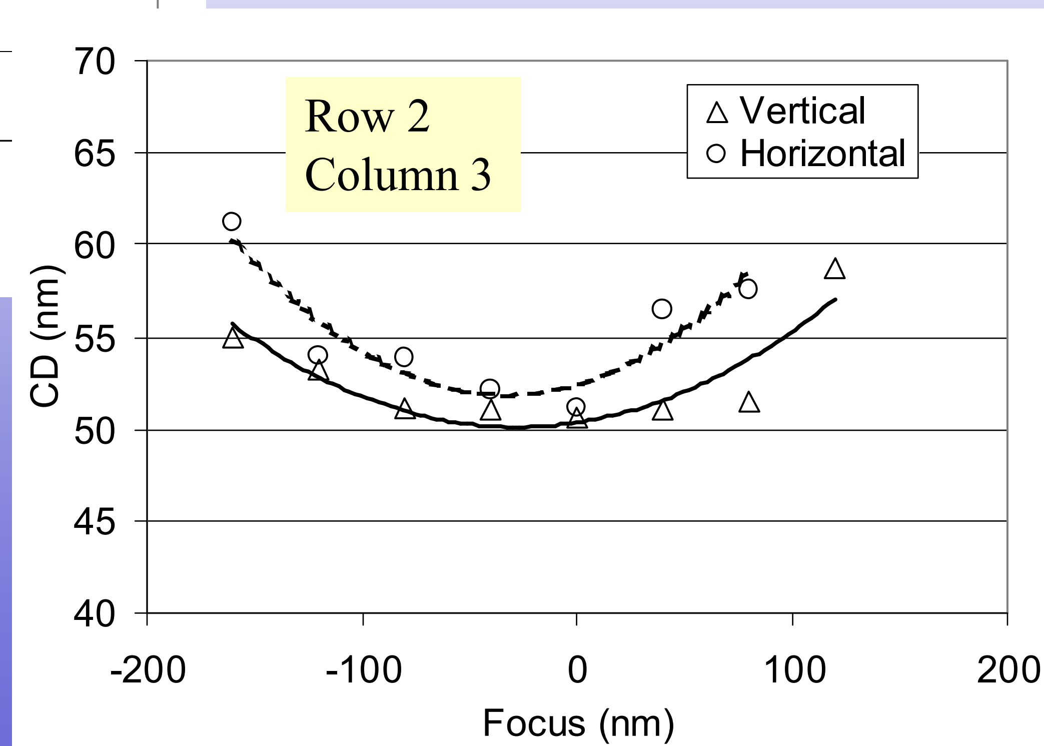
- Elbow feature block provides 4 independent orientations within small area (focus and dose constant over the feature set)
- Orientation dependence of focus used to quantify astigmatism

Orientation dependence of 50-nm performance





Representative image used to determine focus vs orientation



- **Significant astigmatism changes evident**
- **HV bias observed**
  - **Matches orientation expected from mask shadowing**

Cross-field astigmatism

Lithographic measurement

0° astigmatism

-0.467	-0.434	-0.188
-0.518	-0.427	-0.036
-0.481	-0.511	-0.002

45° astigmatism

-0.003	-0.237	-0.314
-0.032	-0.079	-0.216
-0.032	-0.089	-0.160

Total astigmatism magnitude

0.468	0.494	0.365
0.519	0.433	0.219
0.482	0.518	0.160

Field-averaged astigmatism = 0.41 nm rms
Measurement reproducibility better than 0.1 nm

UNIVERSITY AT ALBANY
State University of New York

Cross-field astigmatism

Lithographic measurement

0° astigmatism

-0.467	-0.434	-0.188
-0.518	-0.427	-0.036
-0.481	-0.511	-0.002

45° astigmatism

-0.003	-0.237	-0.314
-0.032	-0.079	-0.216
-0.032	-0.089	-0.160

Total astigmatism magnitude

0.468	0.494	0.365
0.519	0.433	0.219
0.482	0.518	0.160

Interferometric measurement (10/03)

0° astigmatism

-0.239	0.001	0.317
-0.355	-0.073	0.379
-0.275	-0.065	0.688

45° astigmatism

0.157	-0.035	-0.356
-0.173	-0.013	-0.160
-0.030	-0.031	0.211

Total astigmatism magnitude

0.286	0.035	0.476
0.394	0.074	0.412
0.277	0.072	0.719

Field-averaged astigmatism (interferometry) = 0.31 nm rms
Interferometry precision better than 0.1 nm

UNIVERSITY AT ALBANY
State University of New York

Cross-field astigmatism

Lithographic measurement

0° astigmatism

-0.467	-0.434	-0.188
-0.518	-0.427	-0.036
-0.481	-0.511	-0.002

45° astigmatism

-0.003	-0.237	-0.314
-0.032	-0.079	-0.216
-0.032	-0.089	-0.160

Total astigmatism magnitude

0.468	0.494	0.365
0.519	0.433	0.219
0.482	0.518	0.160

Change since interferometry

0° astigmatism

-0.228	-0.436	-0.504
-0.163	-0.354	-0.415
-0.206	-0.445	-0.690

45° astigmatism

-0.161	-0.202	0.041
0.141	-0.065	-0.056
-0.001	-0.059	-0.371

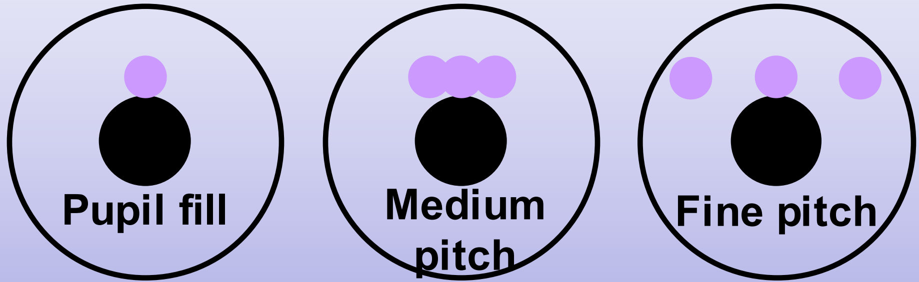
Total astigmatism magnitude

0.182	0.459	-0.111
0.125	0.359	-0.193
0.205	0.446	-0.559

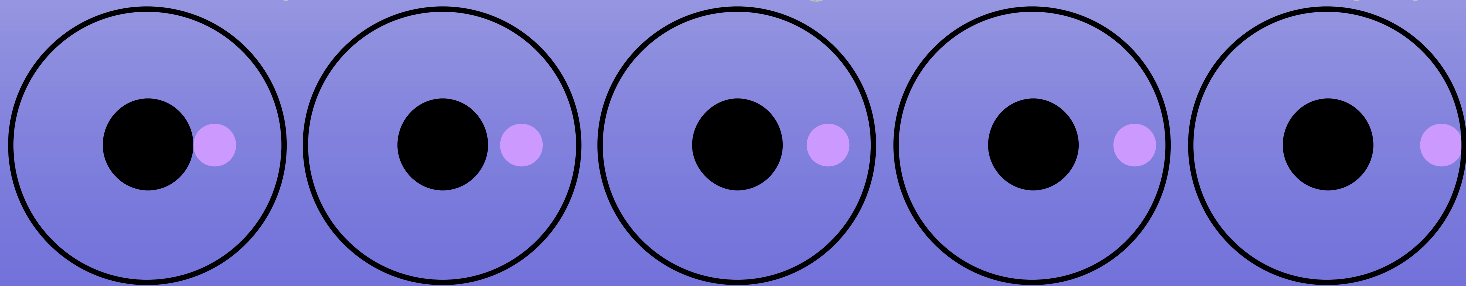
Little change in field-averaged astigmatism
Individual astigmatism terms changed as much as ~0.5 nm

Lithographic quantitative characterization of spherical aberration

- Spherical aberration can be viewed as radially-dependent focus shift
- Programmable illuminator well suited to isolate this error
- Method 1: CD dependent focus shift with y-offset monopole

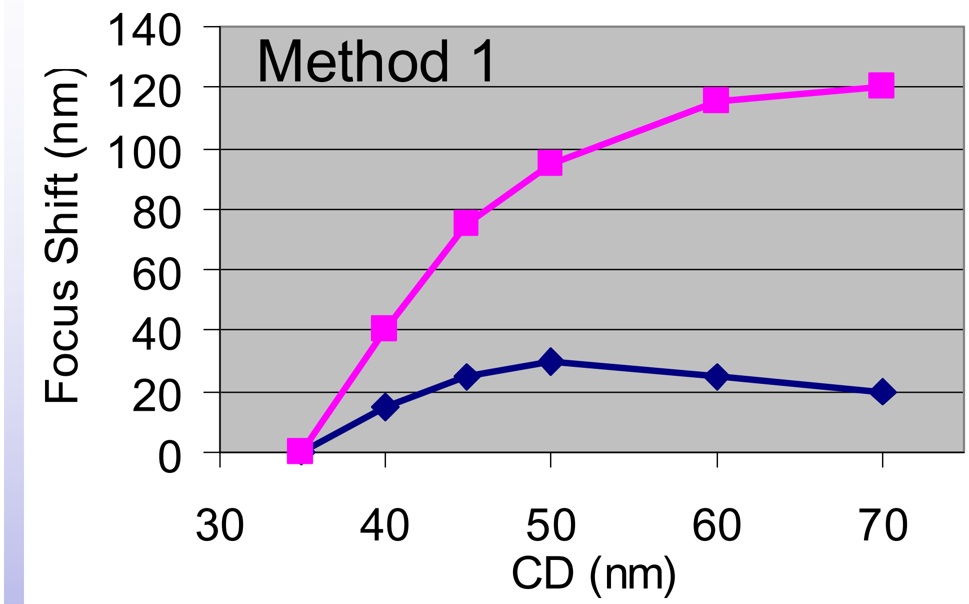


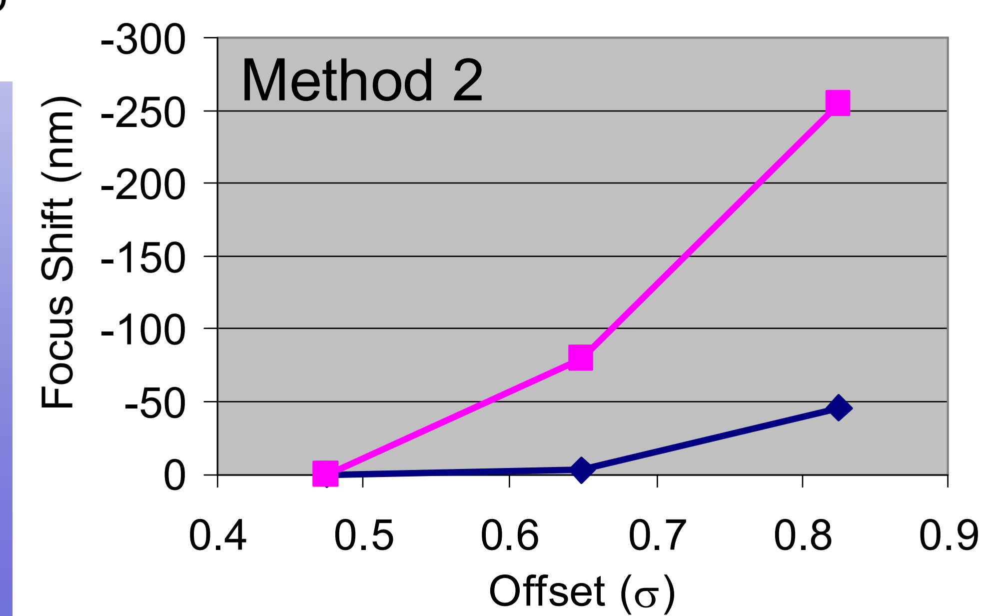
- Method 2: Monopole offset dependent focus shift
  - Shoot multiple small FEMs on single wafer with different pupil fills



Patrick Naulleau
College of Nanoscale Science and Engineering

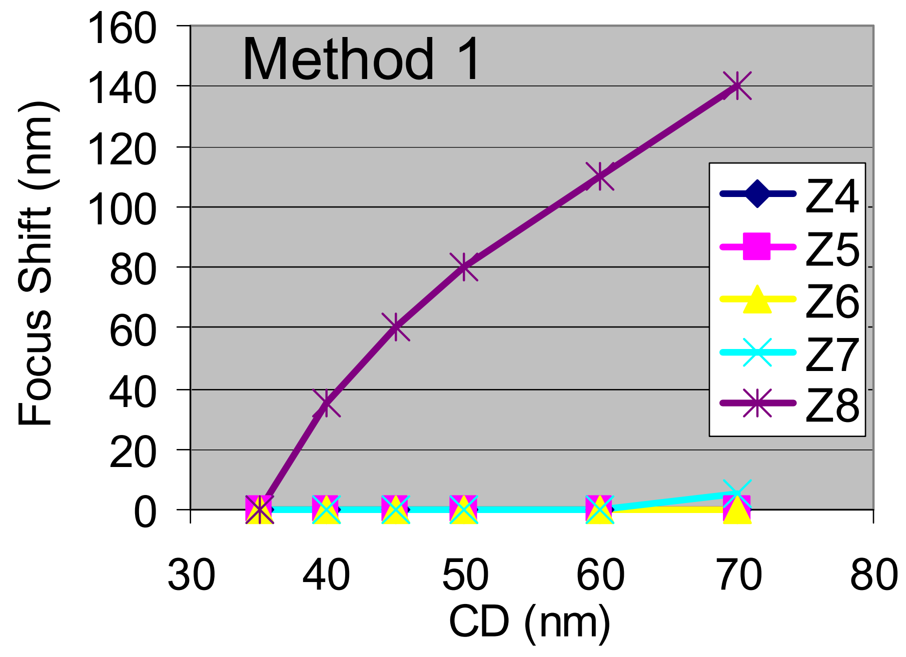
Prolith modeling demonstrates feasibility of measurement of spherical error





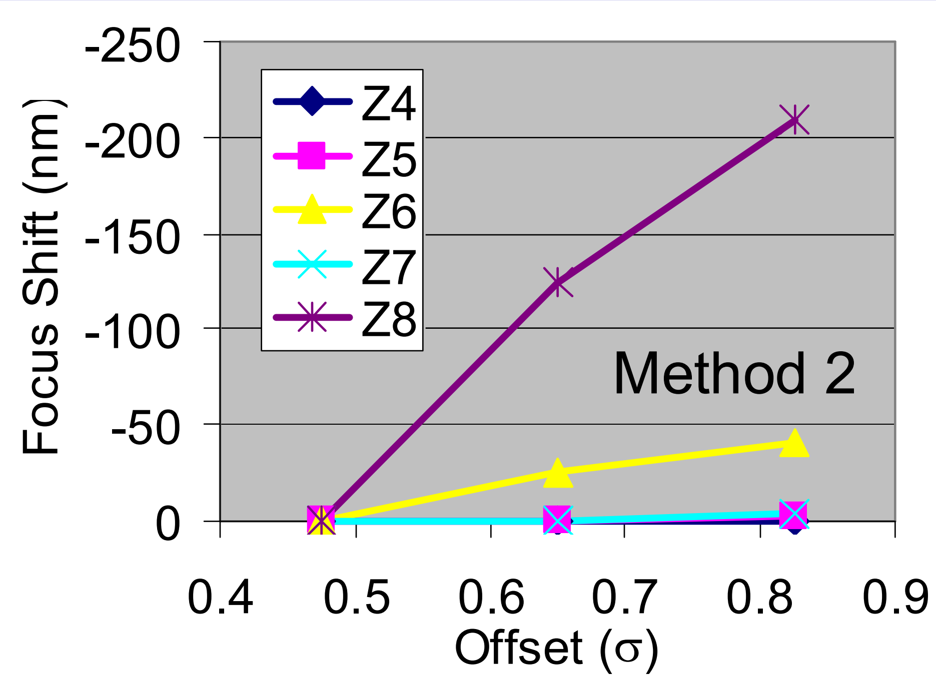
- Both methods provide high sensitivity to spherical error and selectivity from other aberrations in interferometric wavefront

Prolith modeling demonstrates generalized selectivity of measurement

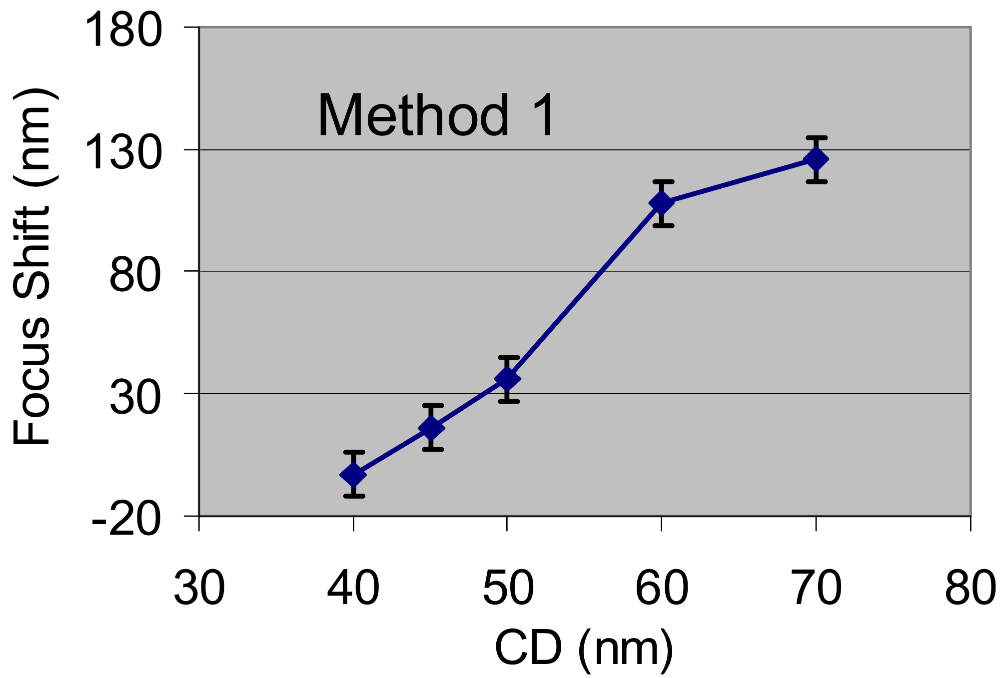


Response to isolated low-order aberrations of magnitude 0.8-nm rms

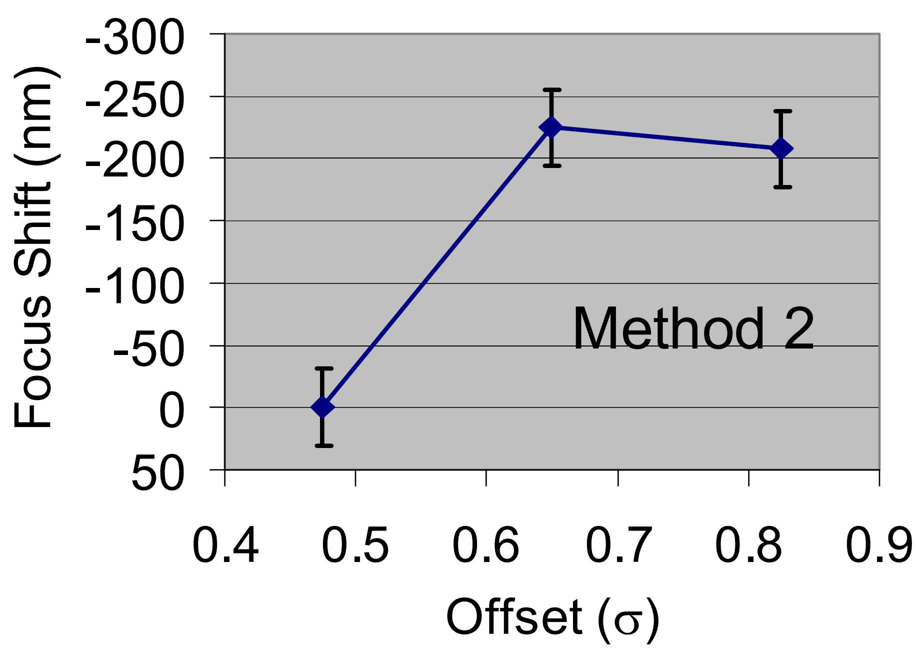
- Good selectivity to spherical error relative to other low order aberrations makes test insensitive to low-order errors in interferometric data



Experimental measurement of spherical error signature in MET optic



- The presence of spherical error is evident
- Spherical error significantly larger than final alignment state

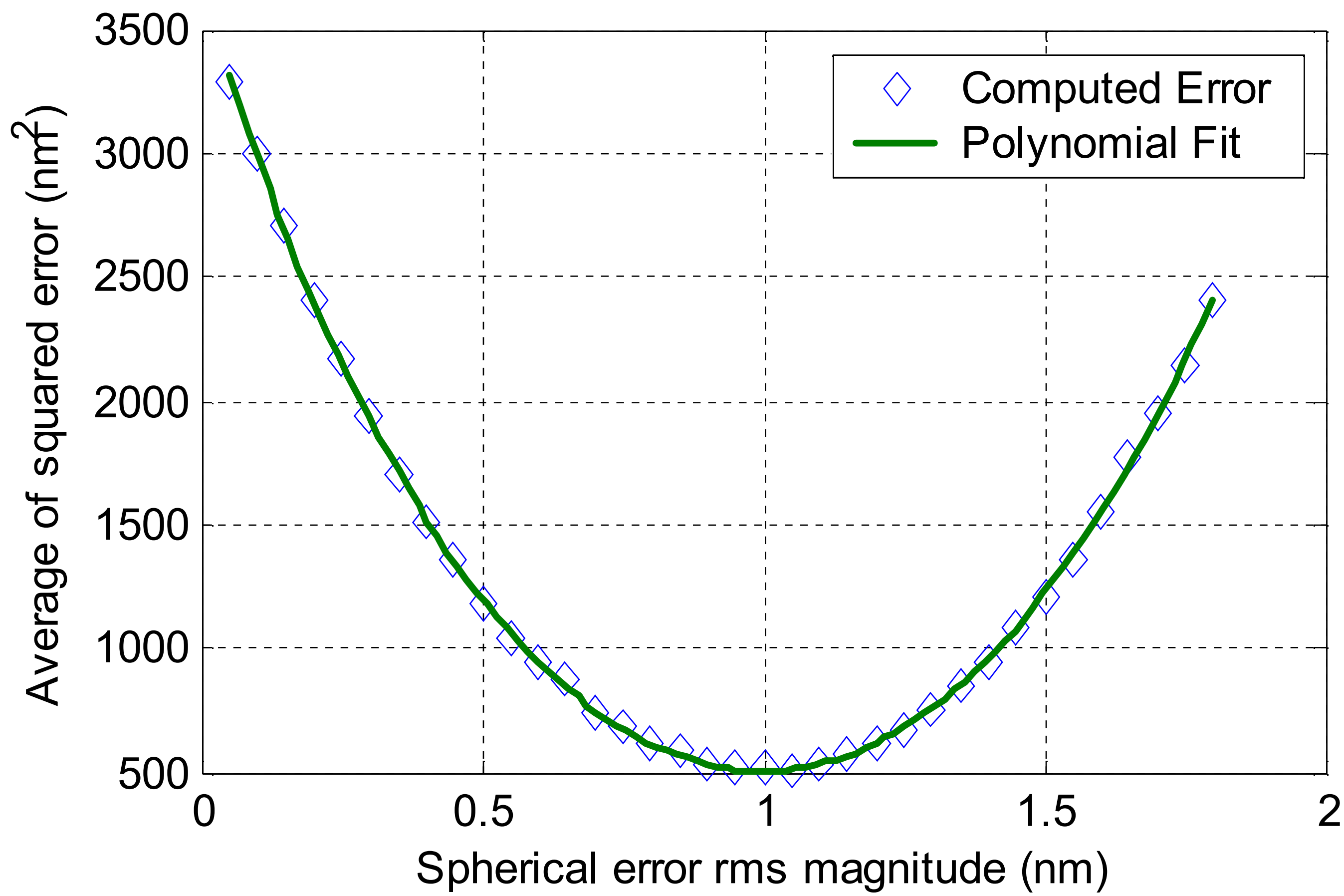


Patrick Naulleau

College of Nanoscale Science and Engineering

MET optic determined to have 1-nm rms spherical error

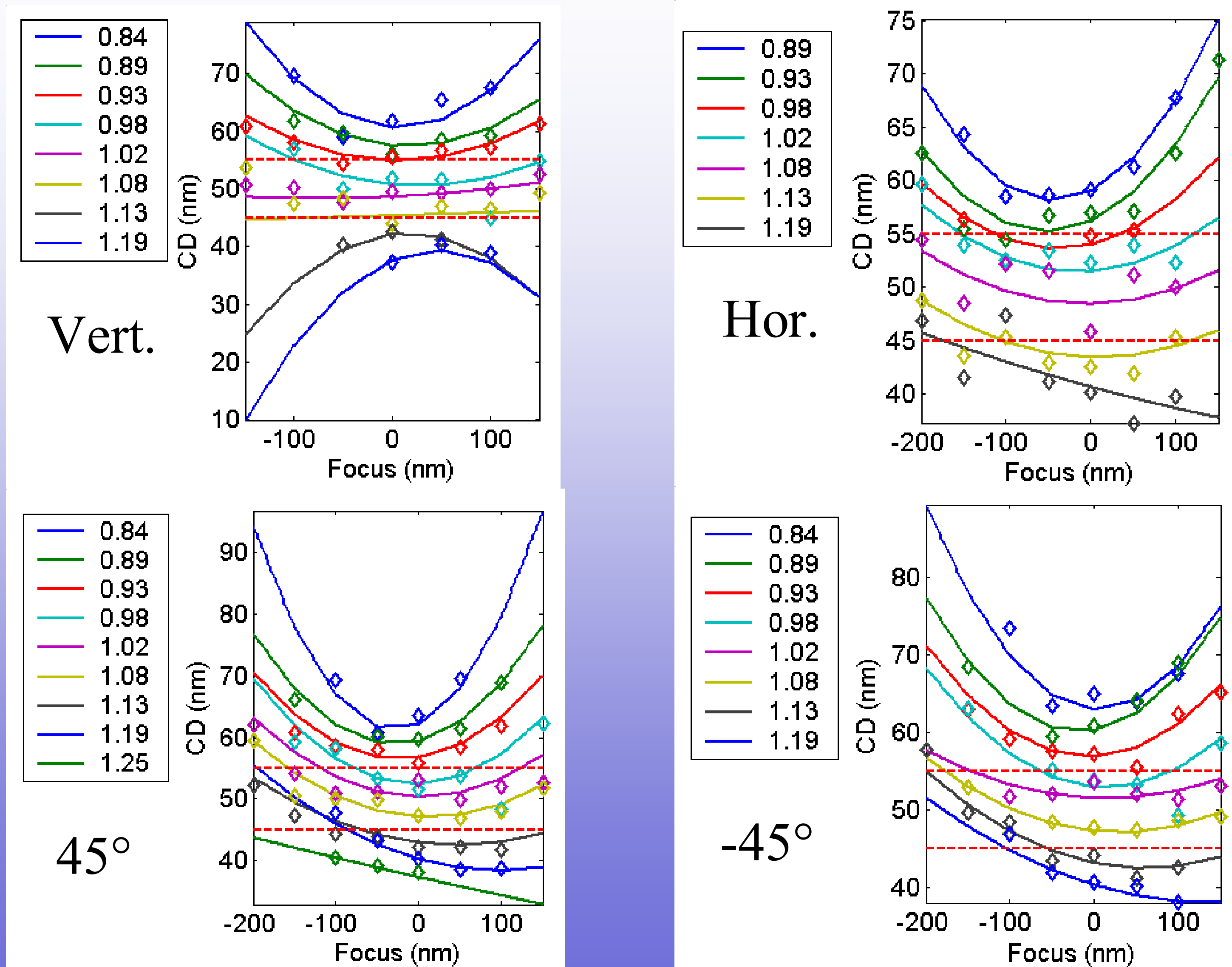
UNIVERSITY AT ALBANY
State University of New York



- Least squares data regression to *Prolith* based modeling yields a measurement of 1-nm rms spherical error
- From interferometry, spherical error was expected to be < 0.1-nm rms

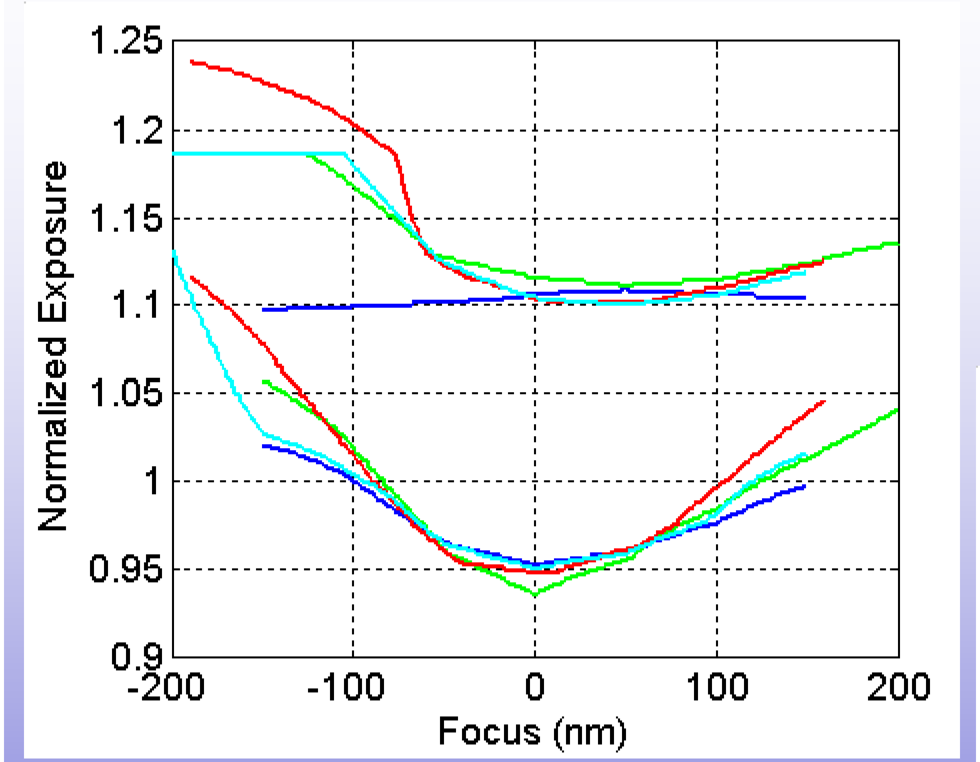
Orientation dependence of performance used for qualitative coma characterization

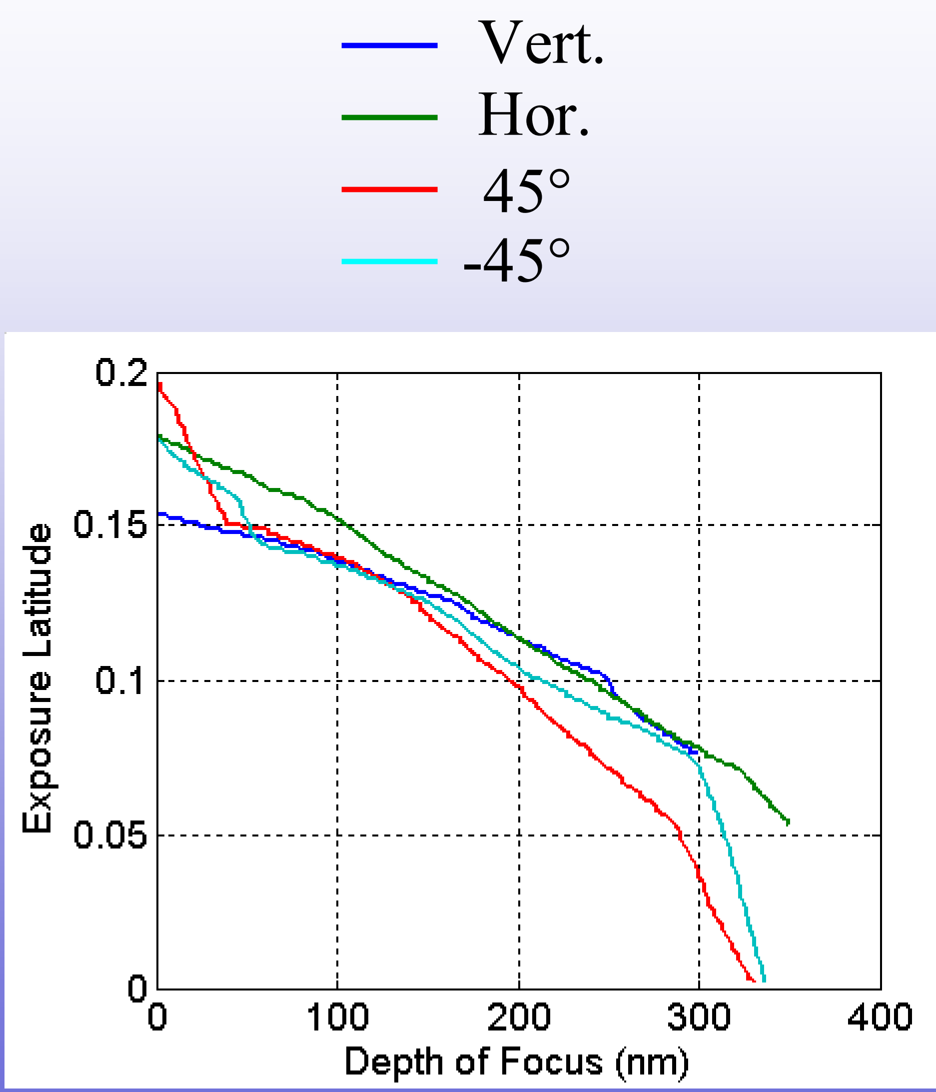
UNIVERSITY AT ALBANY
State University of New York



Patrick Naulleau

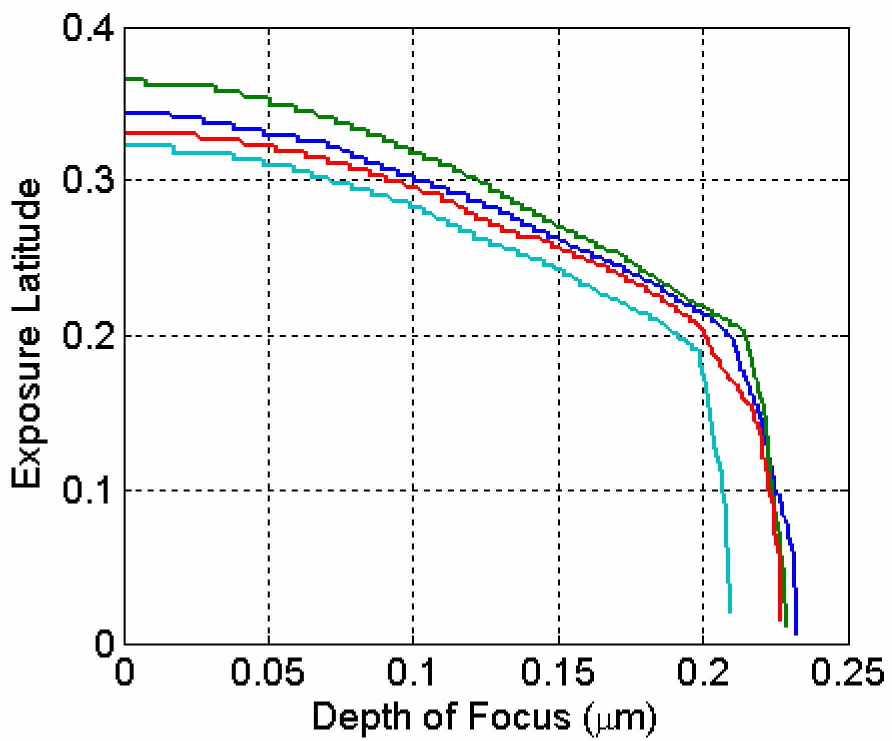
Orientation dependence of 50-nm performance

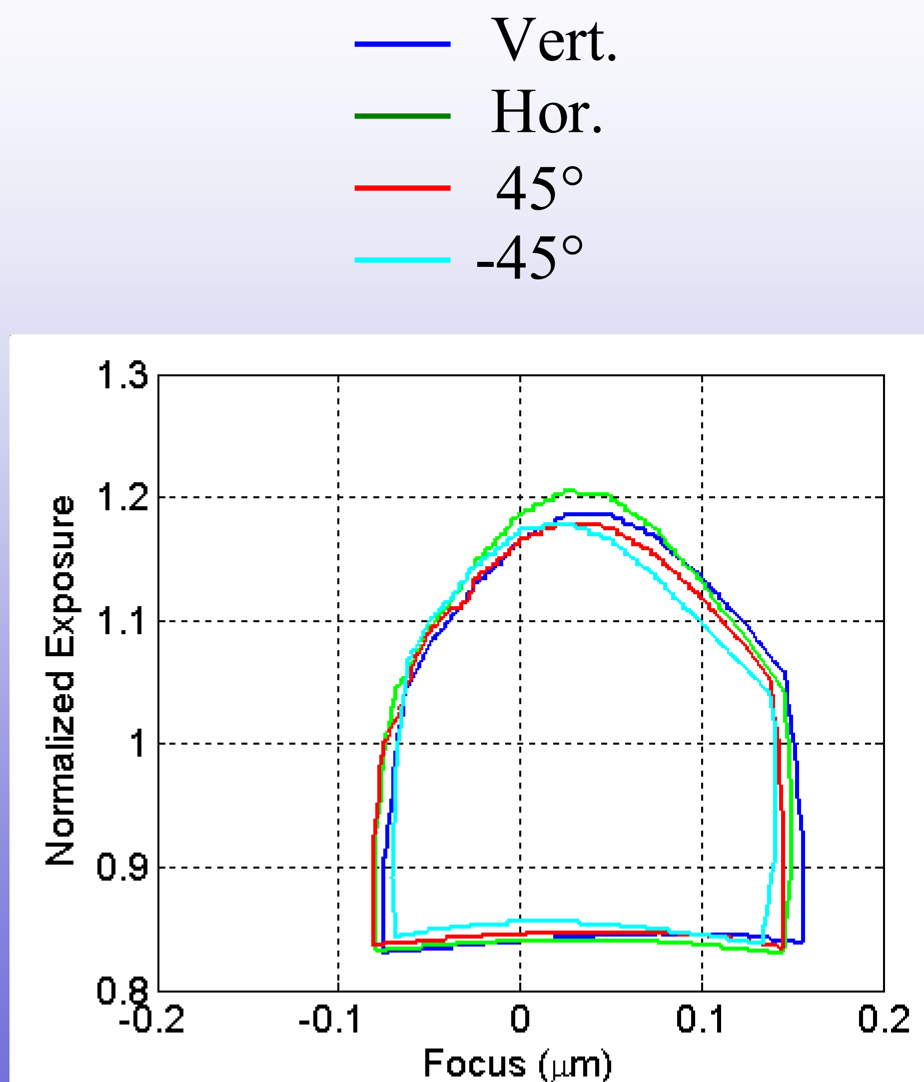




- Possible 50-nm spread in DOF at 10% EL
- Not sure that it statistically relevant

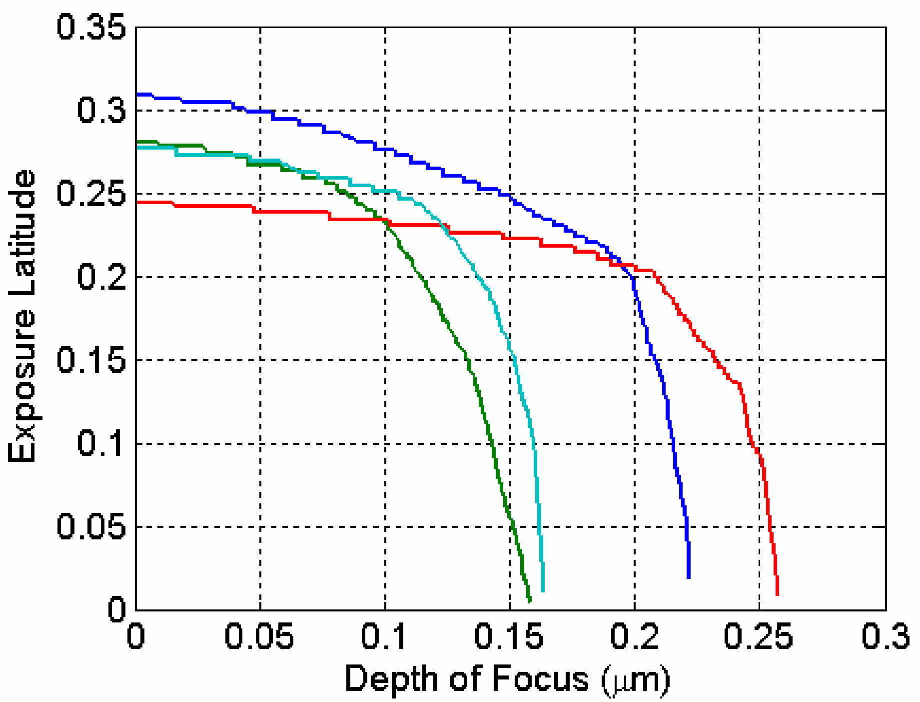
Modeled orientation dependence using lithographically measured wavefront

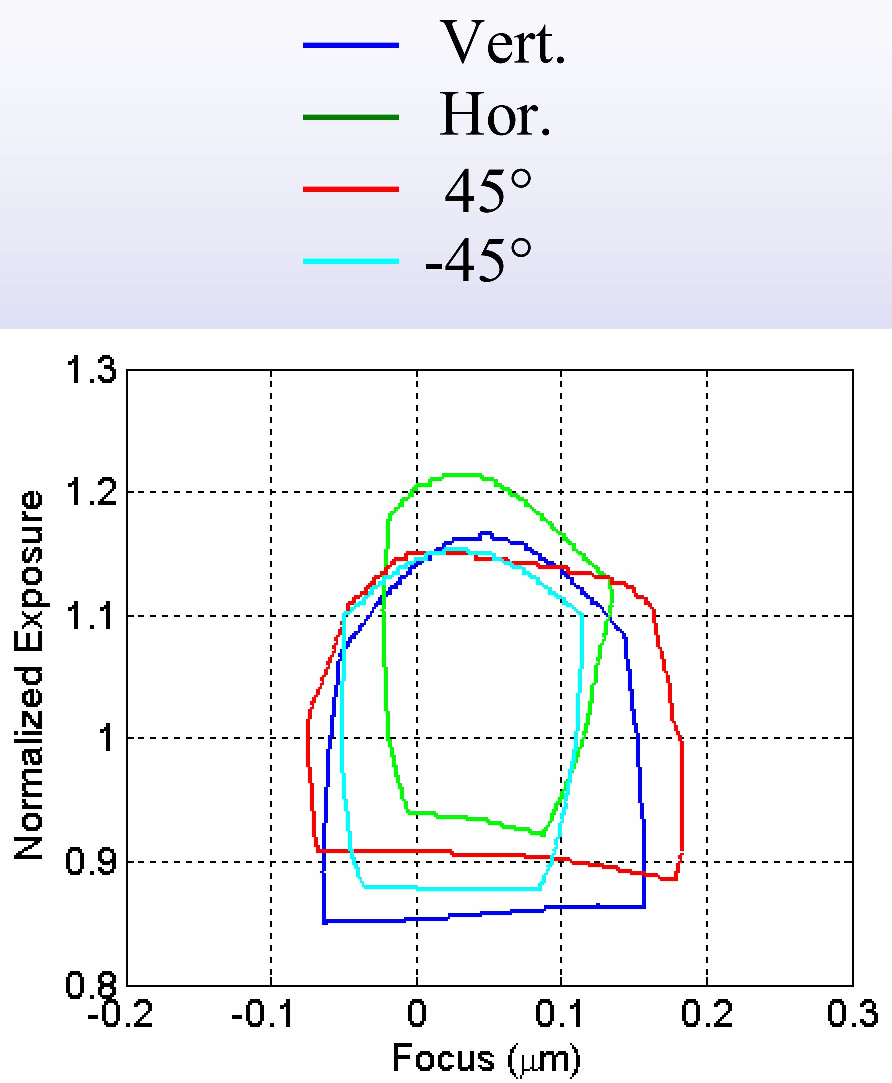




- ~25-nm spread in DOF at 10% EL
- Interferometrically measured coma ~0.5 nm rms

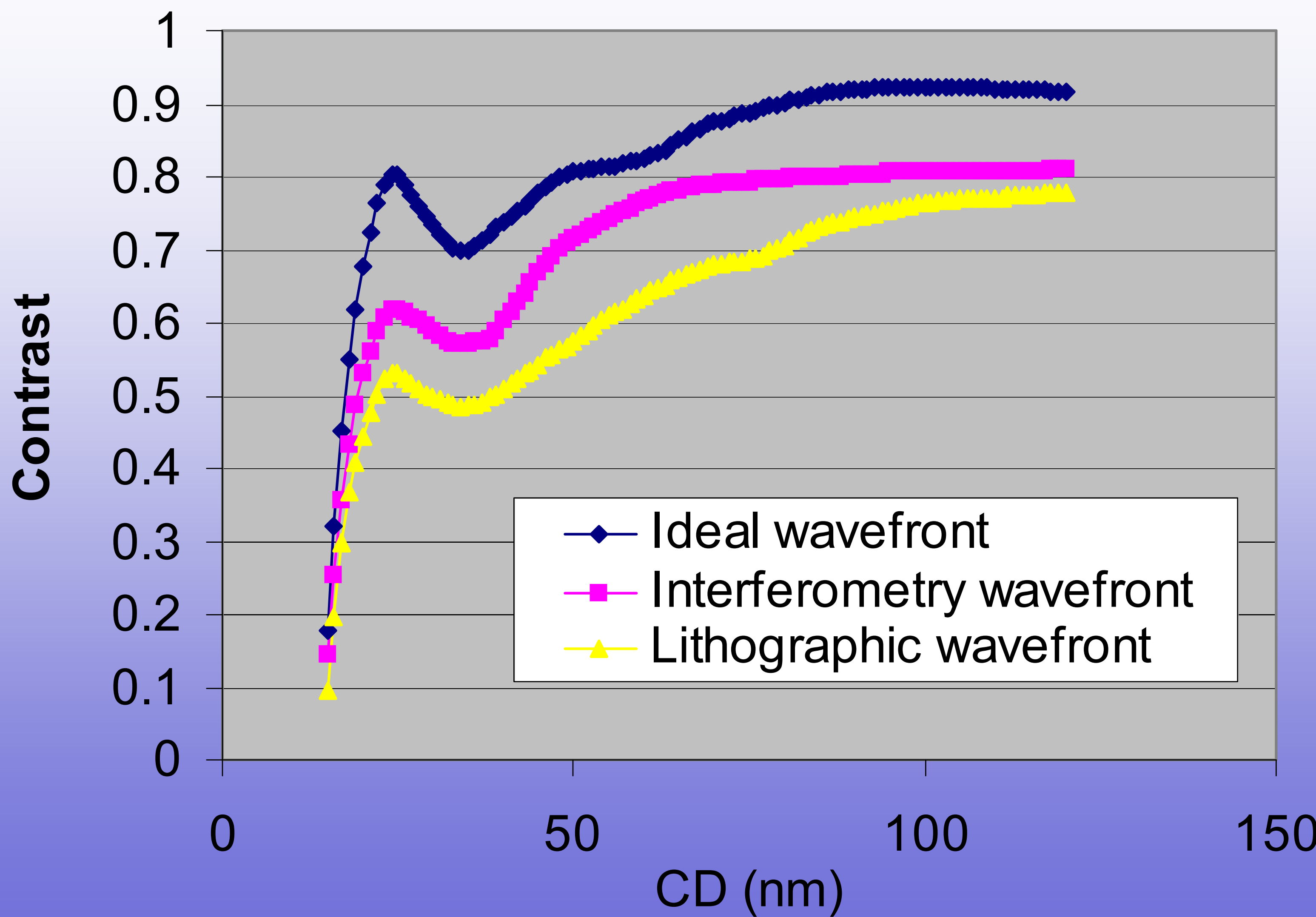
Modeled orientation dependence assuming 1-nm rms coma error





- ~100-nm spread in DOF at 10% EL
- We can safely say that optic has <1 nm coma error

Wavefront difference has significant impact on predicted imaging performance



Summary

- Cross-field astigmatism measurement completed
  - ~0.5-nm rms drift observed since alignment
  - No significant change in field-averaged value
- Spherical aberration measured at center of field
  - 1-nm rms error found
  - ~0.9-nm rms change since alignment
- Qualitative coma measurement reveals no significant change in coma since alignment
  - Final value ~0.5-nm rms
- Results still resist limited

Acknowledgments

Erik Anderson
Paul Denham
Brian Hoef
Keith Jackson
Seno Rekawa
LBNL

Supported by SEMATECH