Optimal Estimation of Starlight and Incoherent Light

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Overview: High Order Wavefront Sensing & Control

Main Goal: Image faint exoplanets & disks.

HOWFSC Methodology:

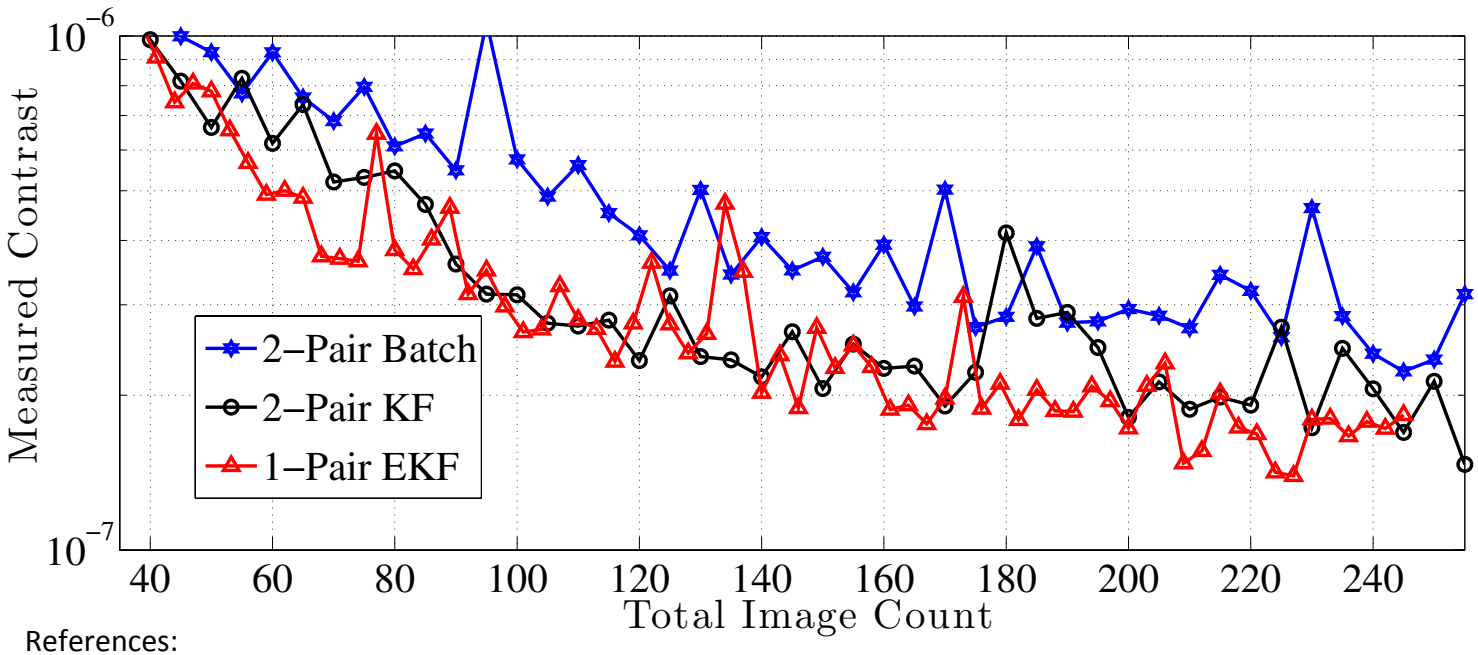
a) Use DMs to provide diversity in focal plane.
b) Estimate focal plane E-field from intensity measurements.
c) Calculate control signal and apply to DMs.
d) Repeat (a)-(c) until desired contrast is reached.

Main Points:

1) Use **recursive estimation** for faster, more robust WFC.
2) Can also **recursively estimate incoherent light** during WFC.

Recursive Wavefront Estimation

- Observations:
  - Most of dark hole acquisition (wavefront correction) time is spent getting last order of magnitude in contrast.
  - Measurements are dominated by readout noise.
- Optimal recursive estimation (Kalman filtering) utilizes all measurements
  - Reduces measurement noise and limits model uncertainty.
  - Less total time is required for correction:



Princeton HCIL: Best Monochromatic Results with Ripple3 SPC

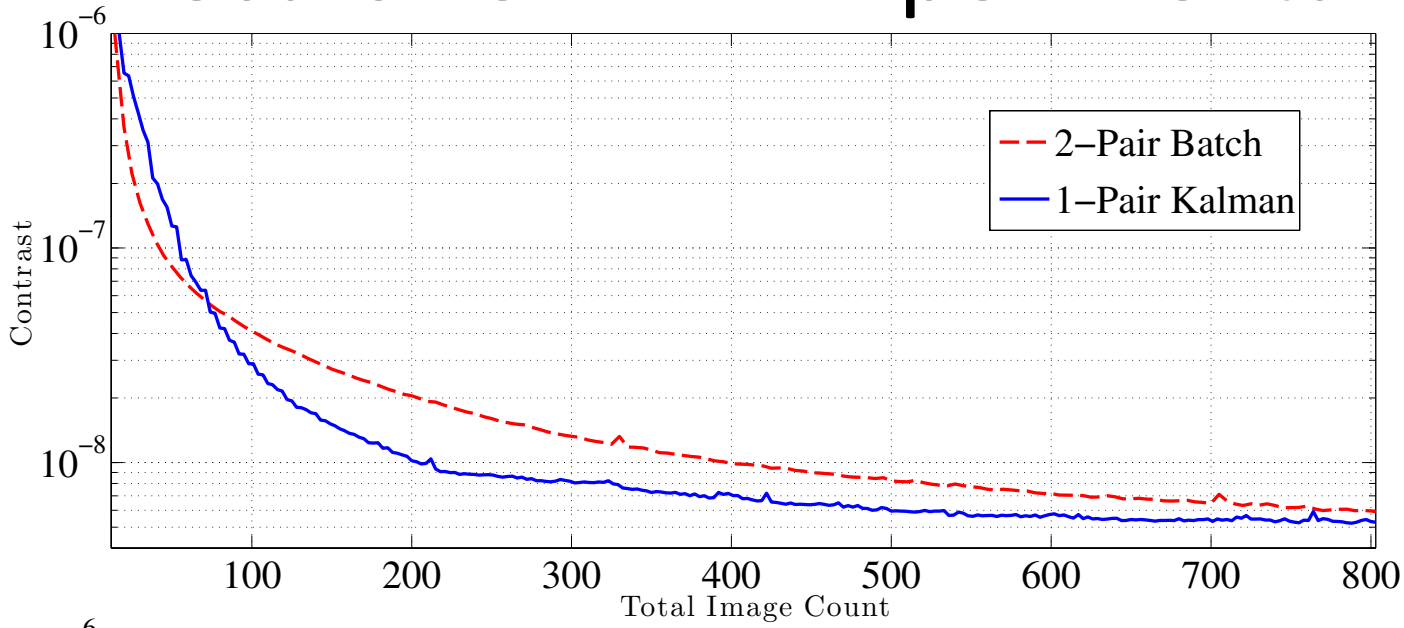
(Riggs, February 3, 2015)

References:

Riggs et al., "Demonstration of Symmetric Dark Holes Using Two Deformable Mirrors at the High-Contrast Imaging Testbed",SPIE, 2013.

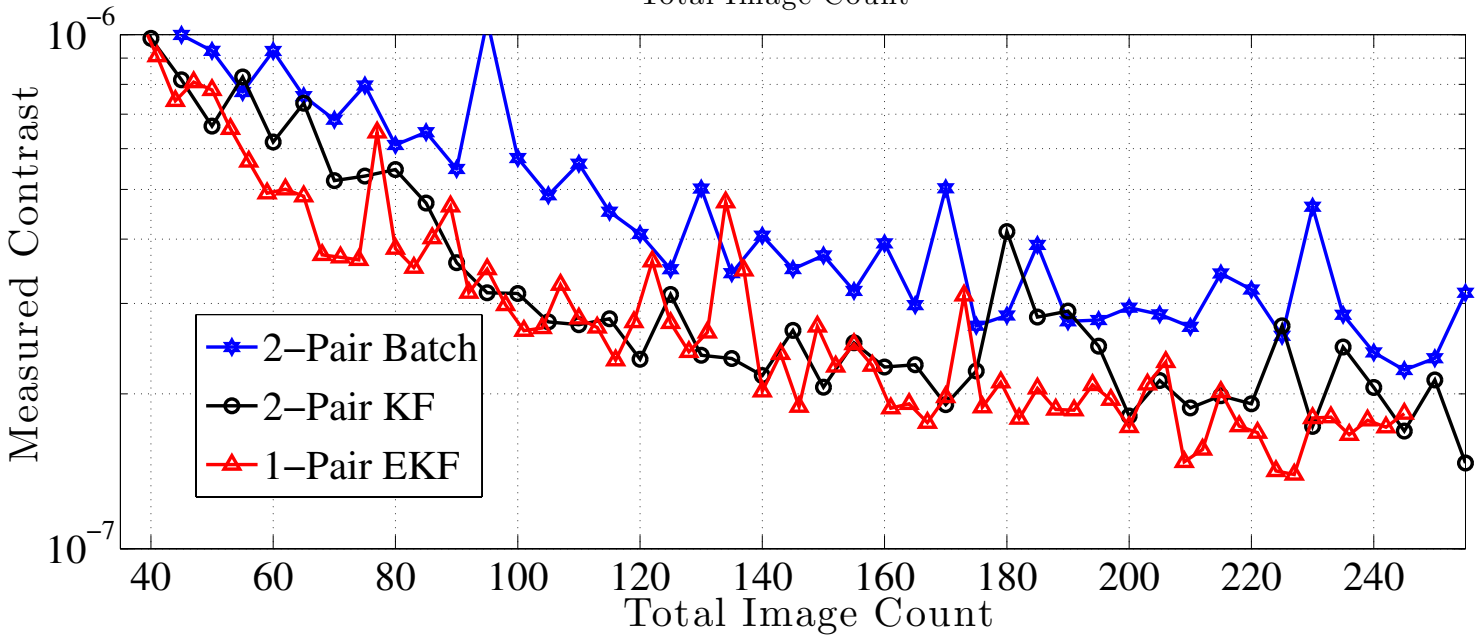
Groff & Kasdin, "Kalman filtering techniques for focal plane electric field estimation", JOSA-A, 2013.

Recursive WFE: Experimental Results



JPL HCIT: Best Monochromatic Results with Ripple SPC

(Riggs, August, 2013) In Riggs SPIE 88640T, 2013.



Princeton HCIL: Best Monochromatic Results with Ripple3 SPC

(Riggs, February 3, 2015)

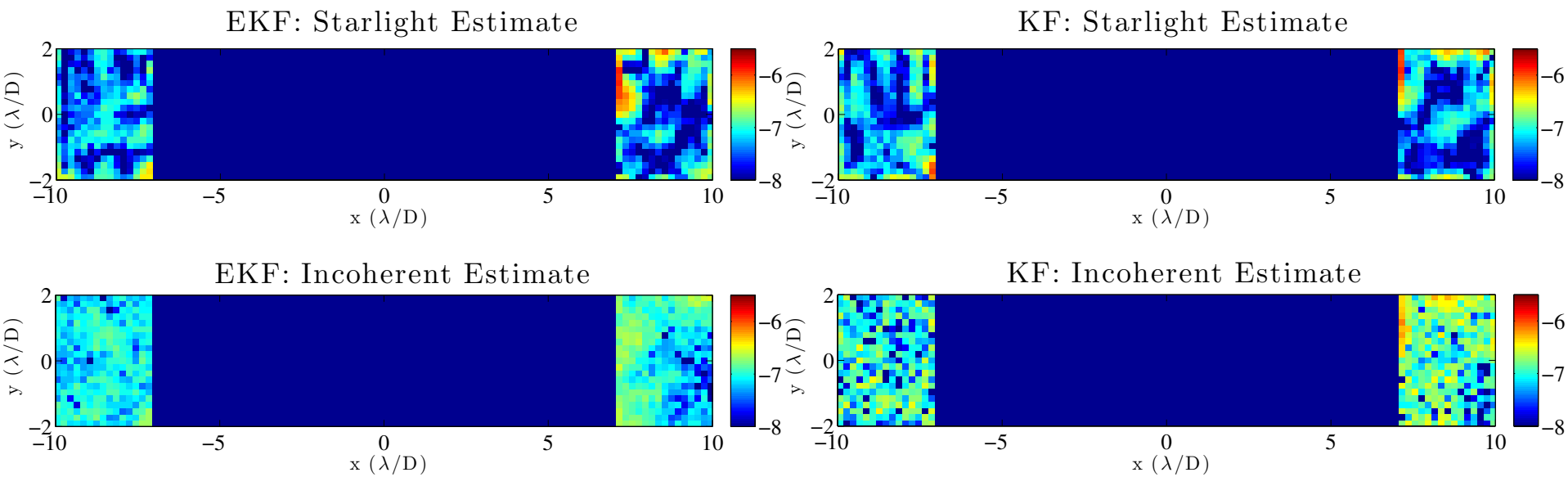
Recursive *Incoherent Light* Estimation

- Can also estimate incoherent light recursively using a nonlinear estimator.
  - Currently trying extended Kalman filter (EKF).
  - EKF just as fast (exposure & computational time) as KF, but also provides less noisy incoherent estimate

- Reason for not using nonlinear estimator: Correction might be done on other, brighter star
  - What if there is zodi or exozodi? Need to estimate incoherent light well and pre-subtract it from nominal PSF (or use just estimated intensity of star)
  - Helpful if any correction iterations required on science target star.

Incoherent Light Estimates

- Recursive incoherent estimate is less sensitive to measurement noise and shot noise.



- Data above are from the final iteration of correction runs in Princeton's HCIL.
- KF and EKF data above are from separate correction runs
- In Princeton's HCIL, unclear if incoherent estimate is stray light or something else.
  - 1-sigma readout noise at 8e-8 contrast (=5 ADU)

HOWFS Comparison

	Batch Process	Kalman Filter (KF)	Extended Kalman Filter (EKF)
Pros	• Computationally fastest • No tuning	• Less exposure time • Uses *all probed* images for recursive estimation • Allows for a dynamic model	• Less exposure time • Uses *all* images recursively • Recursively estimates incoherent light • Allows for a dynamic model • Allows for parameter adaptive estimation
Cons	• More exposure time • Does not utilize previous data • Static model only	• Computationally slower • Must be well tuned	• Computationally slowest • Must be very well tuned • Less stable

Sensor Fusion: LOWFS & HOWFS

Main question:

How best to combine LOWFS and HOWFS for a stable PSF?

Key Points:

- LOWFS sampling *much* faster than HOWFS
- Will LOWFC residuals alter PSF above allowable contrast level? If yes:
  - Major problem for scheme to calibrate on different star
  - Must include in HOWFSC

Possible solutions:

1) HOWFS can be blind to LOWFSC if LOWFSC residuals are negligible.
2) Include known LOWFC residuals and/or extra process noise in recursive HOWFS.

Extra Topics

<u>Best ways to speed up HOWFSC</u>:

- Use broadband light.
- Obtain a better system model.

1. Broadband HOWFSC
   - Crucial for HOWFS to be fast enough.
   - Currently, no alternative to (monochromatic) pairwise estimation and EFC.
   - Limited filter wheel space on AFTA

2. Model-based estimation & control are very sensitive to accuracy of model
   - How to use measurements to improve linear control response matrix?
   - How to obtain DM registration and initial wavefront at DMs without phase retrieval on AFTA?

References

- EKF reference:
  - Riggs et al., "Optimal Wavefront Estimation of Incoherent Sources",SPIE, 2014.

- Kalman filter references:
  - Groff & Kasdin, "Kalman filtering techniques for focal plane electric field estimation", JOSA-A, 2013.
  - Riggs et al., "Demonstration of Symmetric Dark Holes Using Two Deformable Mirrors at the High-Contrast Imaging Testbed",SPIE, 2013.

- Stroke minimization:
  - Pueyo et al., "Optimal dark hole generation via two deformable mirrors with stroke minimization", Applied Optics, 2009
  - Groff & Kasdin, "Kalman filtering techniques for focal plane electric field estimation", JOSA-A, 2013

- Pair-wise estimation and EFC
  - Give'on et al., "Pair-wise, deformable mirror, image plane-based diversity electric field estimation for high contrast coronagraphy", SPIE, 2011

Backup Slides

Princeton HCIL Layout

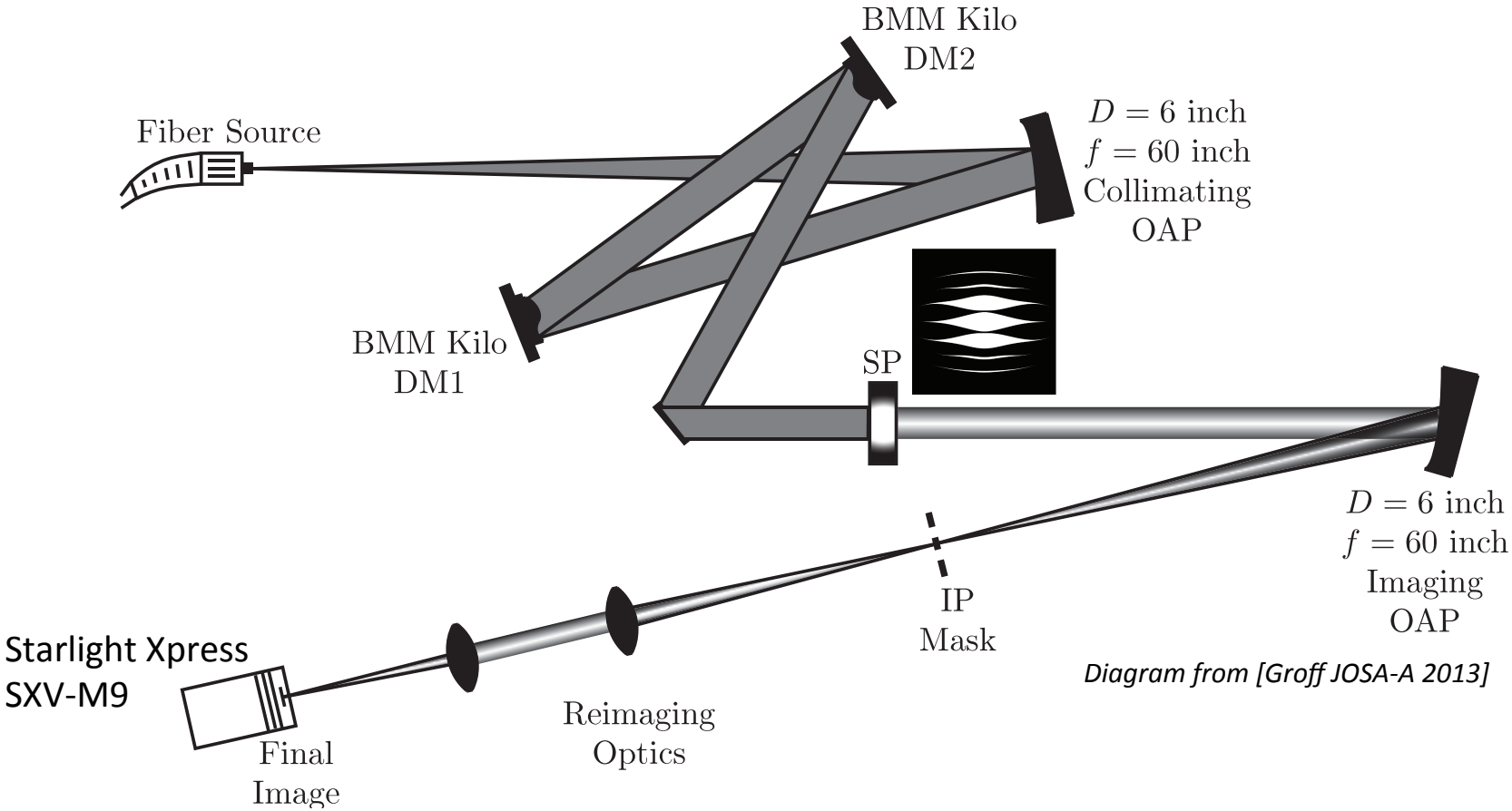
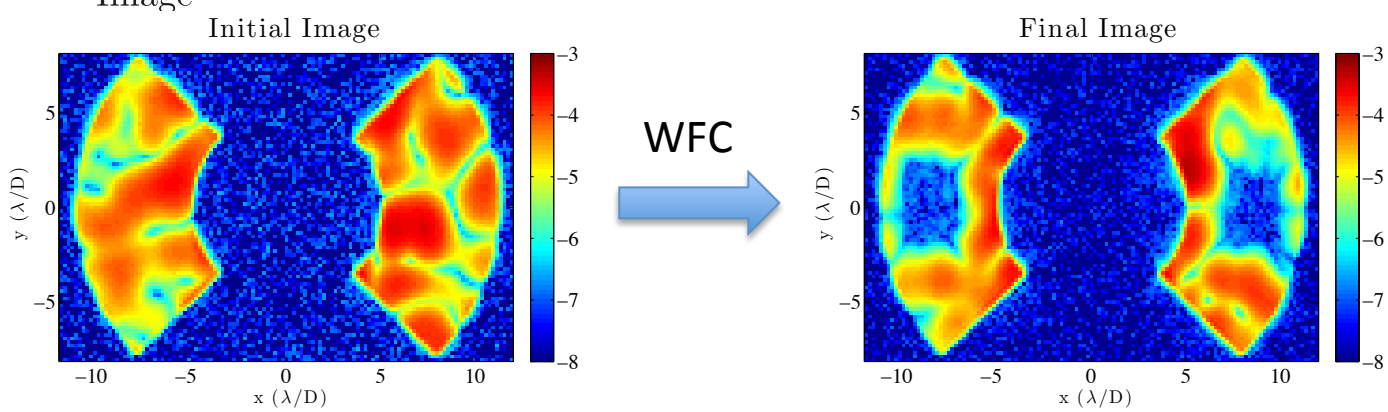
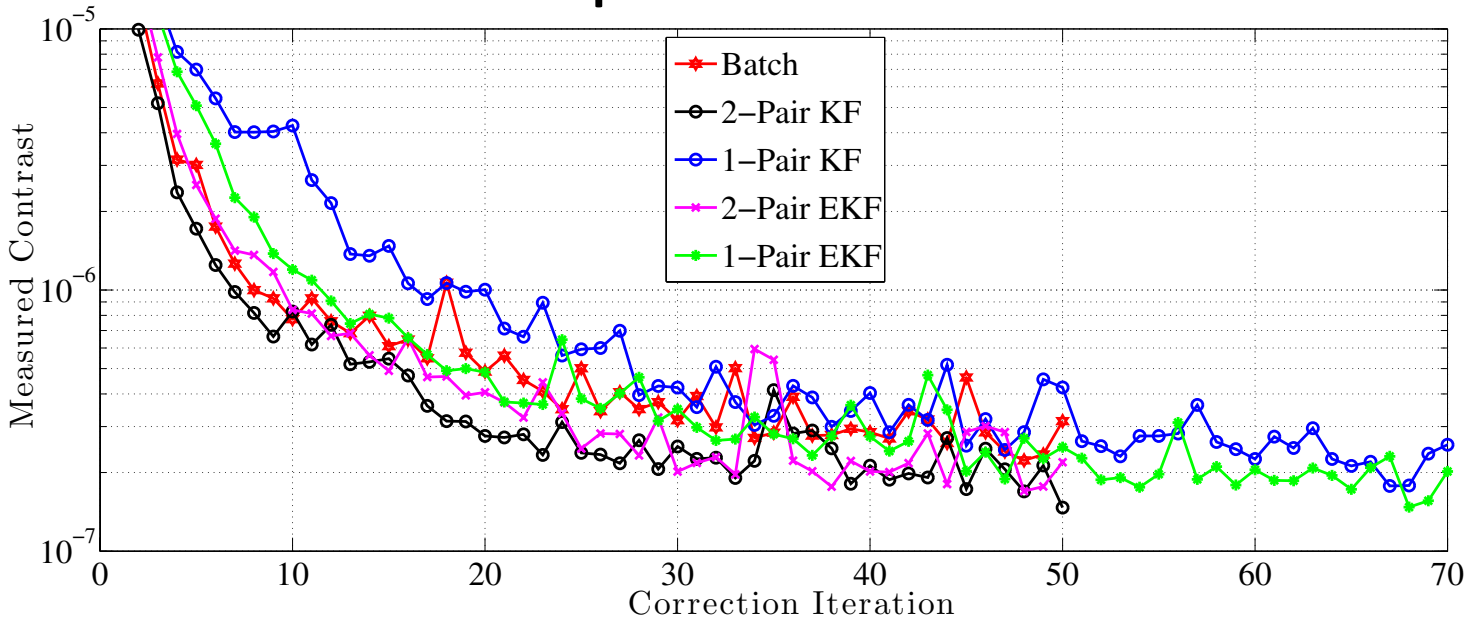


Diagram from [Groff JOSA-A 2013]

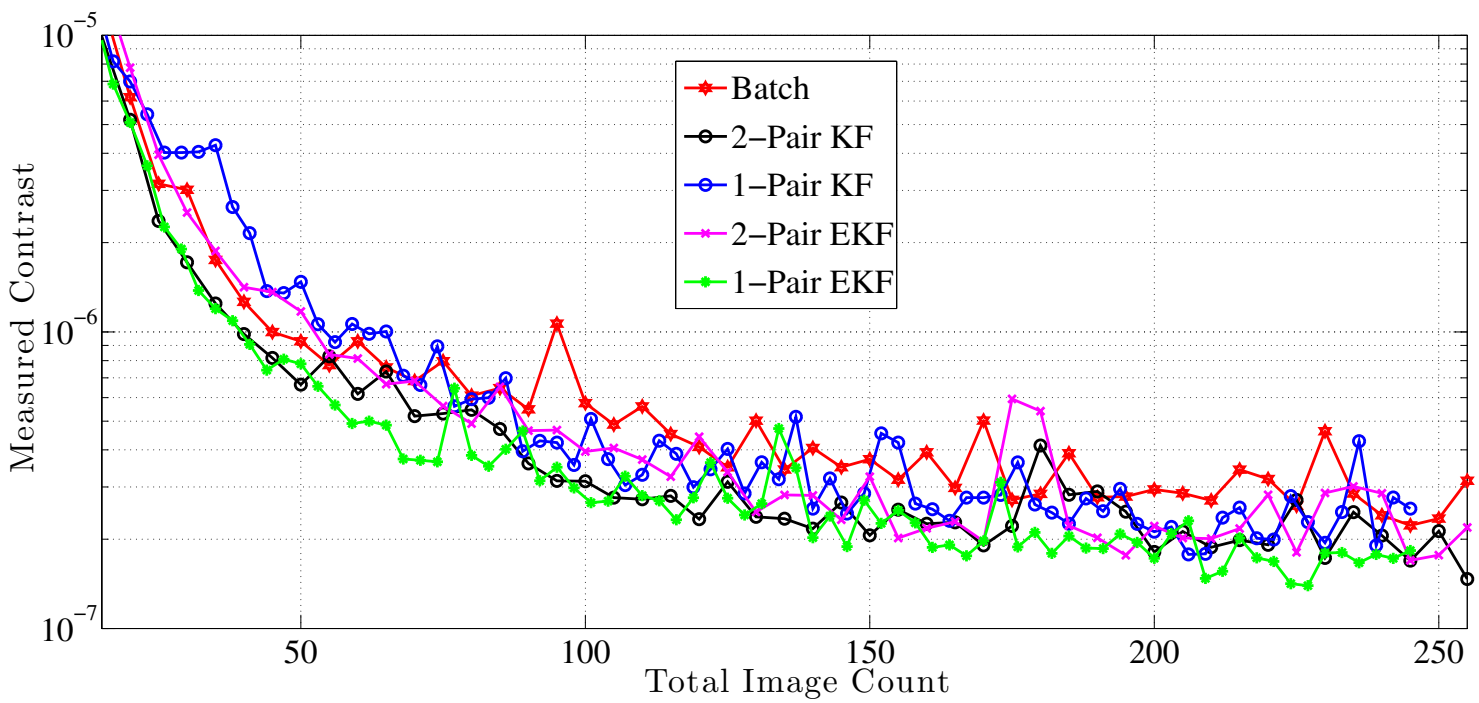


Estimator Comparison: Princeton HCIL Results



Exposure time is constant for all images.

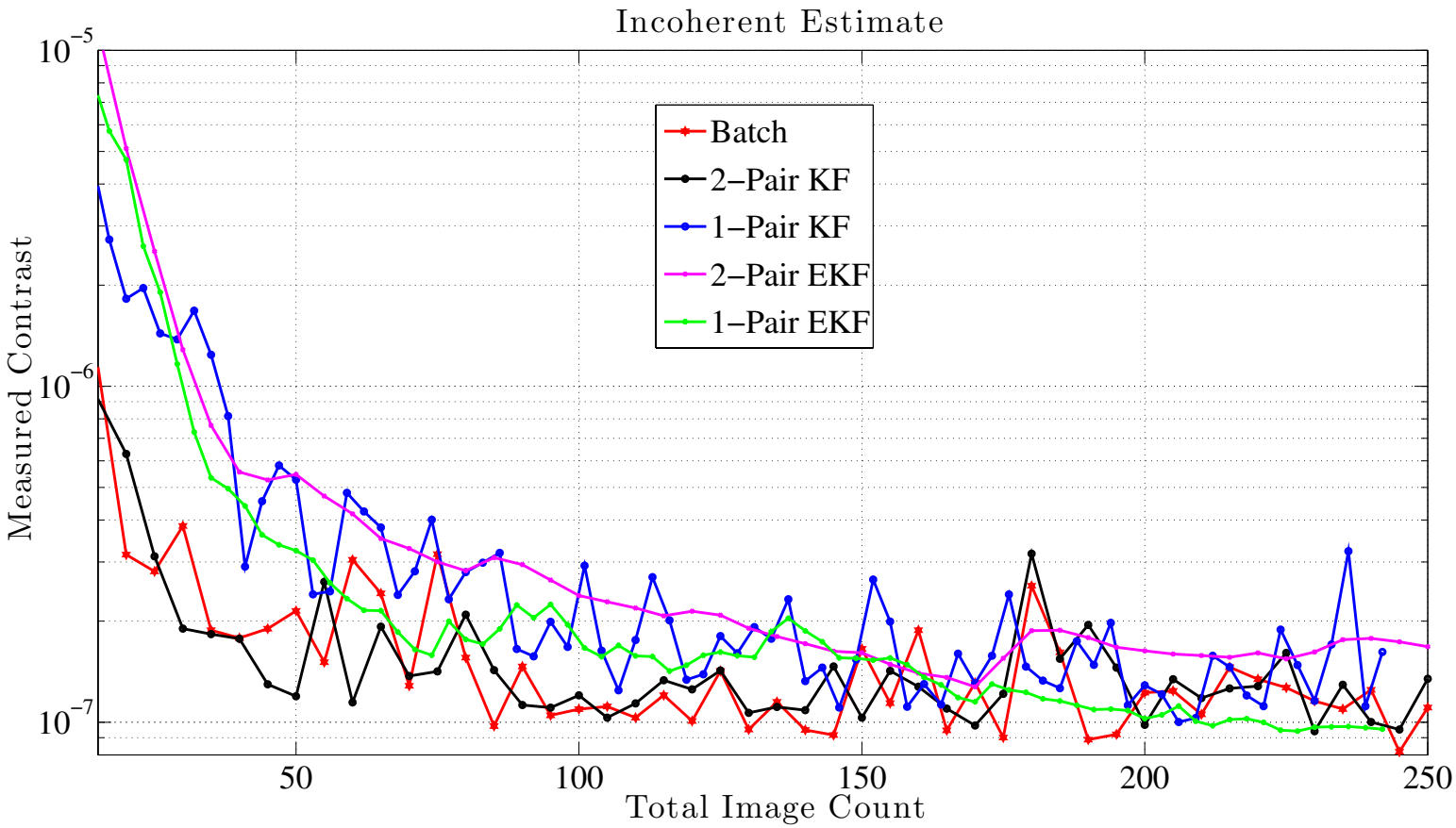
One-sigma measurement noise at 8e-8 contrast.



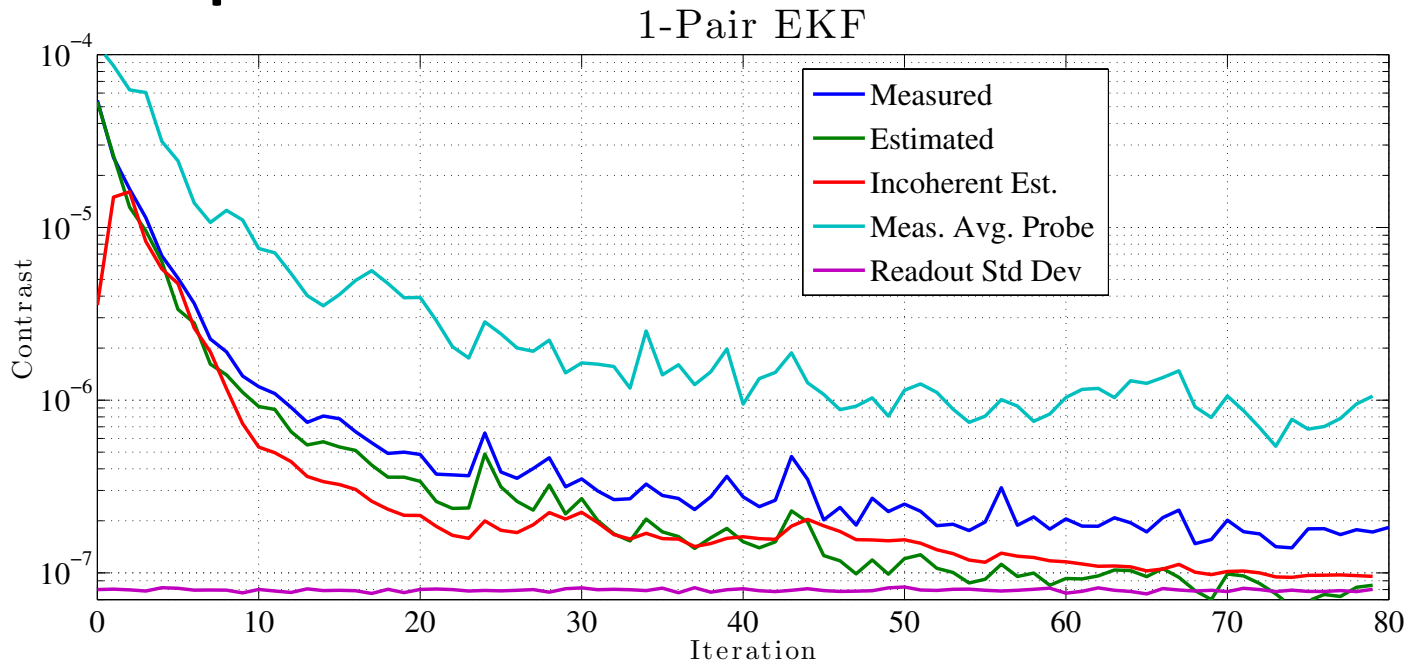
All recursive estimators are faster than the batch process estimator.

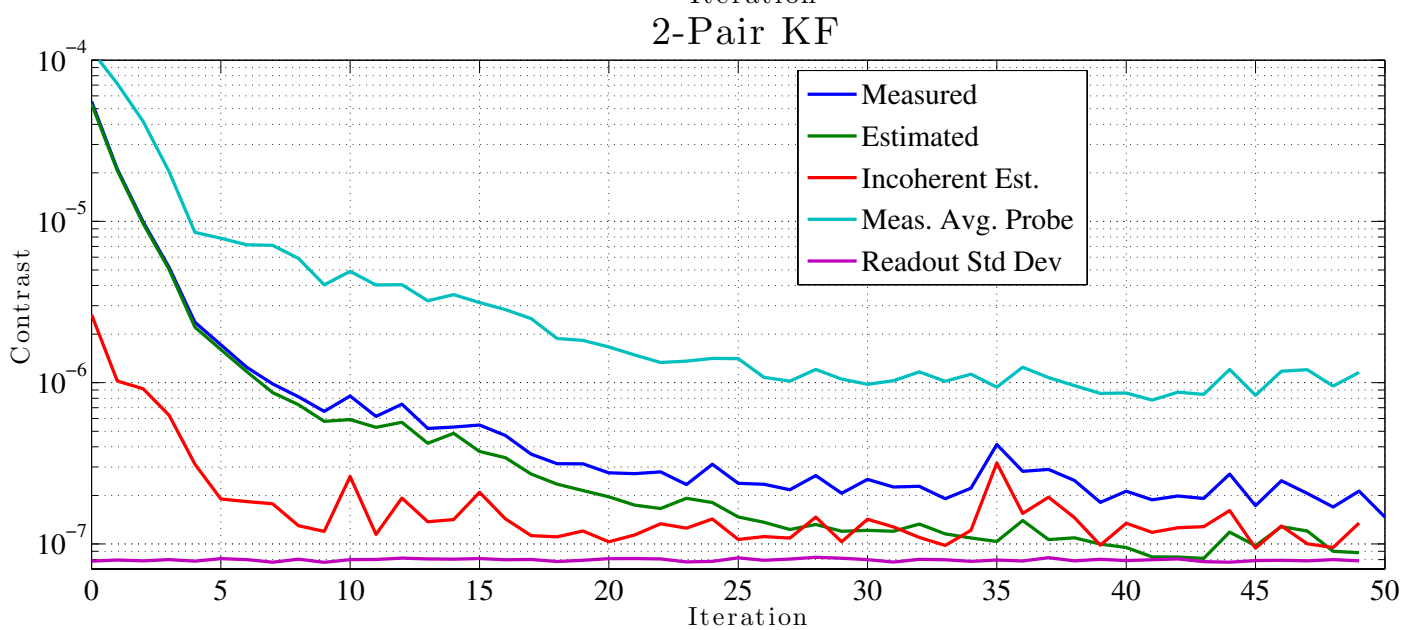
Incoherent Light Estimates

- In Princeton's HCIL, unclear if incoherent estimate is readout noise or stray light.
  - 1-sigma readout noise at 8e-8 contrast (=5 ADU)

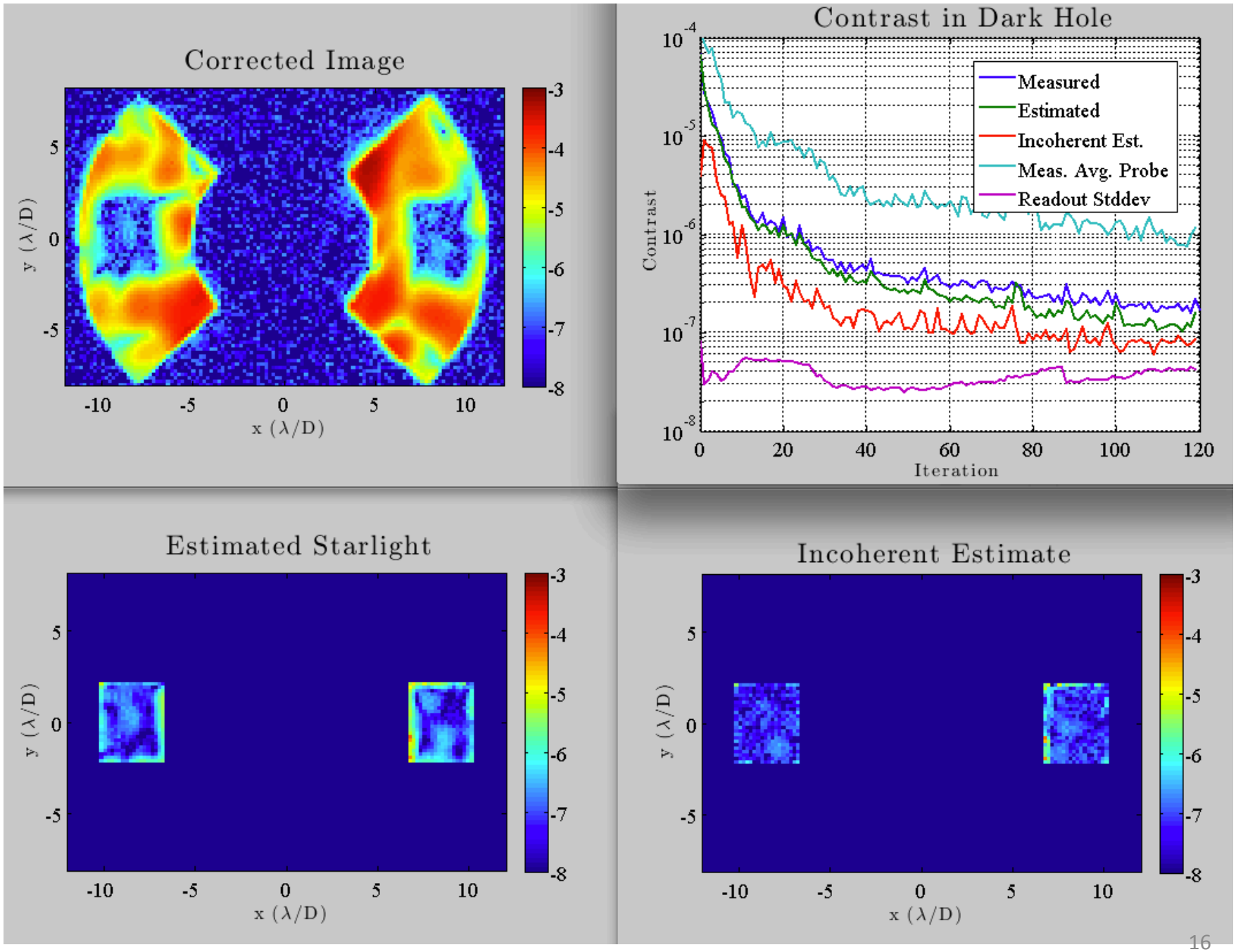


Example Contrast Correction Curves





Princeton HCIL:
3 Feb 2015


Corrected Image
y (λ/D)
x (λ/D)
Contrast in Dark Hole
Contrast
Iteration
Measured
Estimated
Incoherent Est.
Meas. Avg. Probe
Readout Stddev
Estimated Starlight
Incoherent Estimate