The Gemini Planet Imager's Adaptive Optics system: from design to operation

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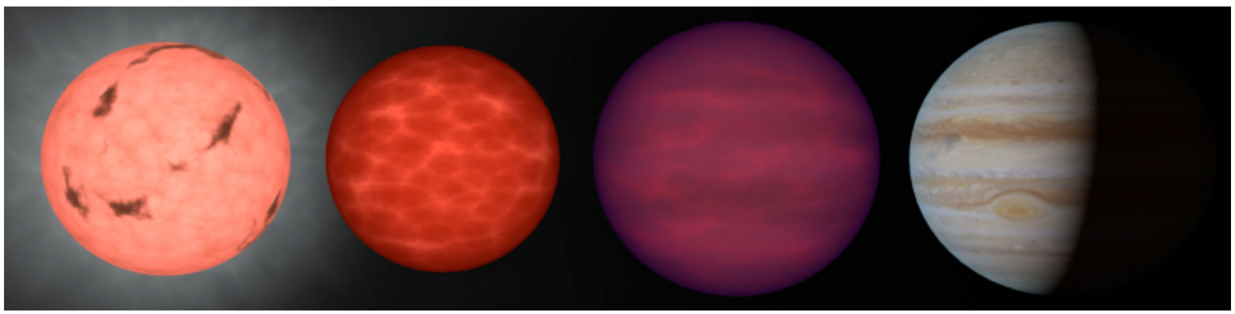
Gemini Planet Imager


Gemini Observatory

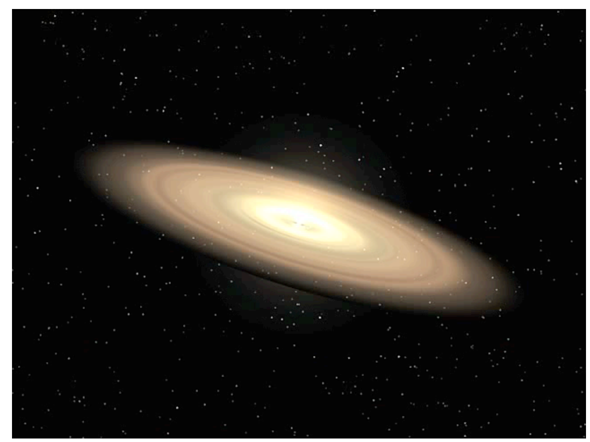
This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

GPI is a science experiment

- Our science team recently was allocated 890 hours for a three-year survey for 600 target stars

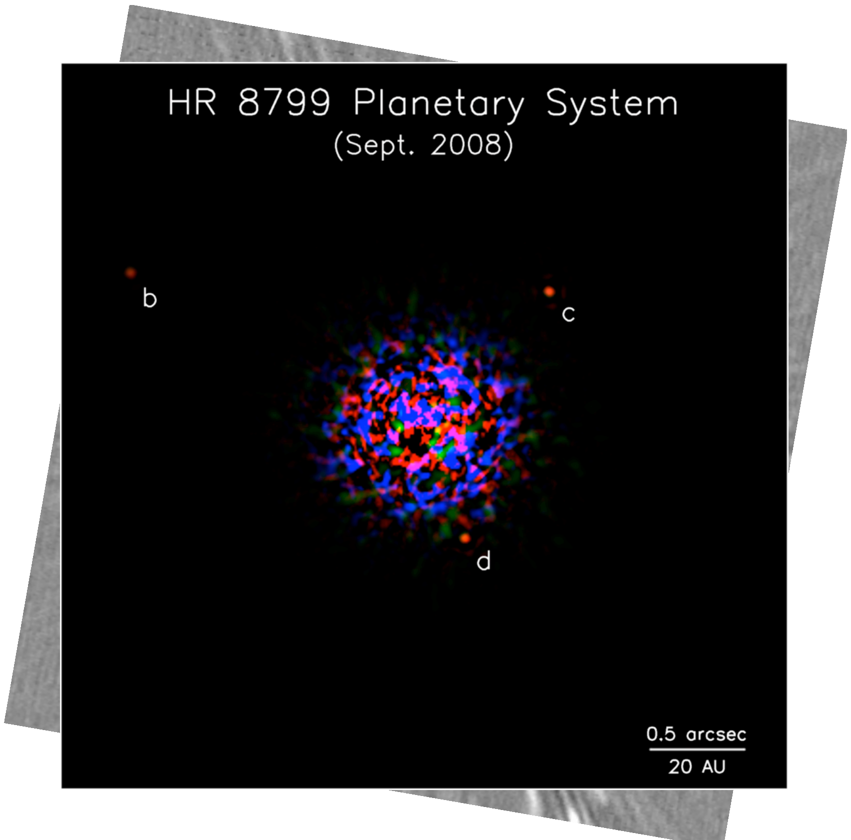


- How do planets form and evolve? (core accretion vs. disk instability)
- What are planetary atmospheres like?
- How do planets migrate? What is their dynamical evolution?

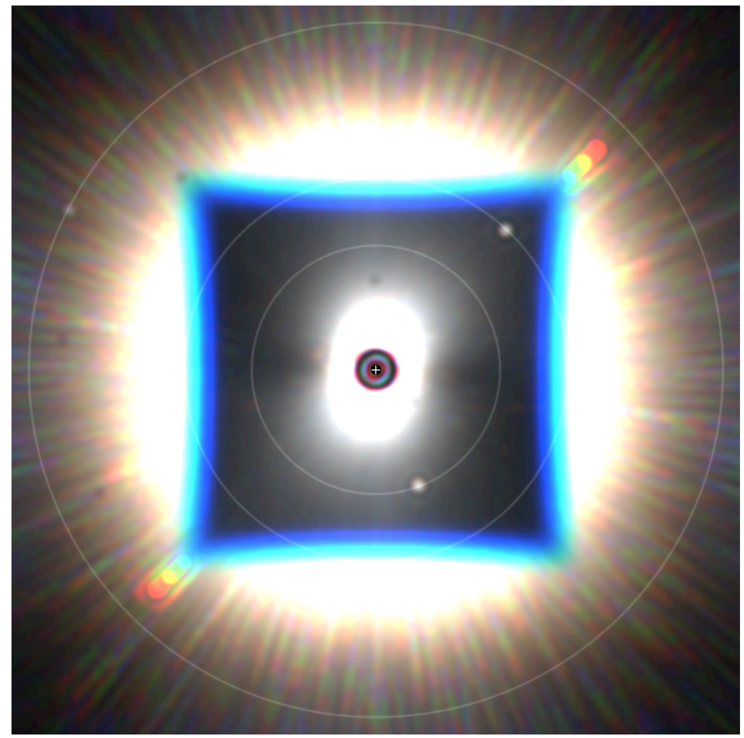


Images from Robert Hurt; NASA Spitzer

HR 8799: discovery & the future



Keck (10 minutes)

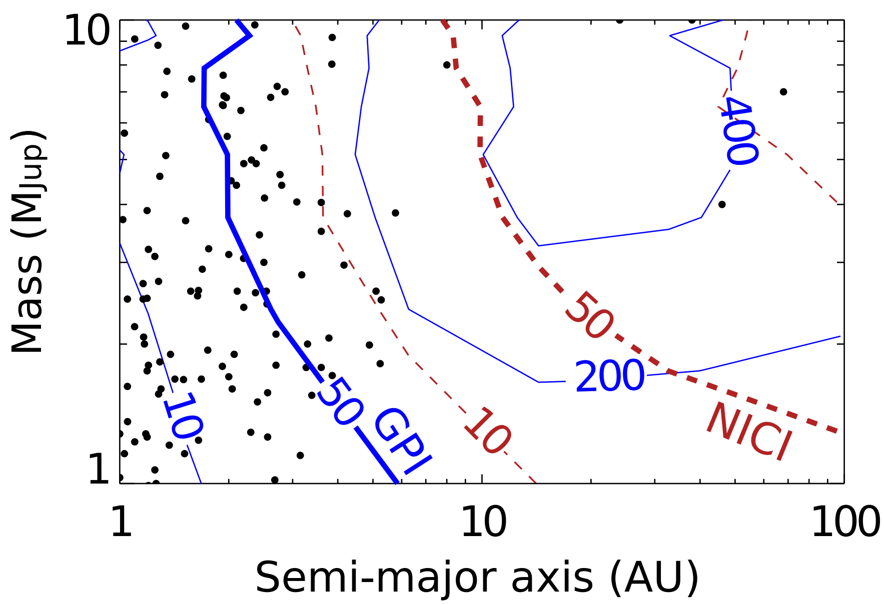


Simulated GPI (10 seconds)

All images/simulations courtesy of Christian Marois (HIA)

GPI can probe closer and fainter

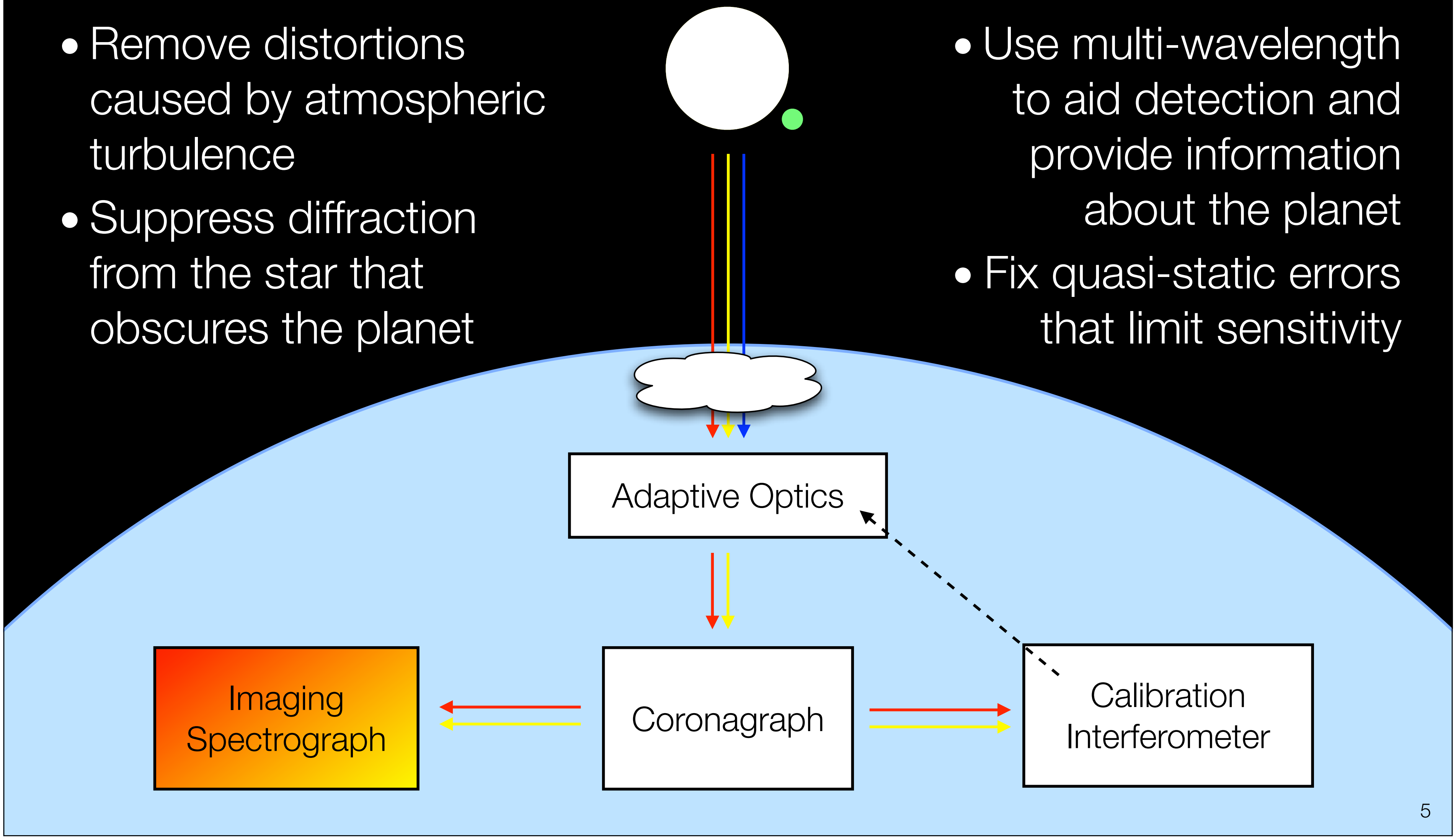
- Start with the 600 star target list and known relevant properties (e.g. age, distance, brightness)
- For a given planet orbit and mass, determine the probability GPI could see it (depends on orbital position, observing conditions, GPI performance, etc)



Courtesy of McBride & Macintosh from the GPI Expolanet Survey team

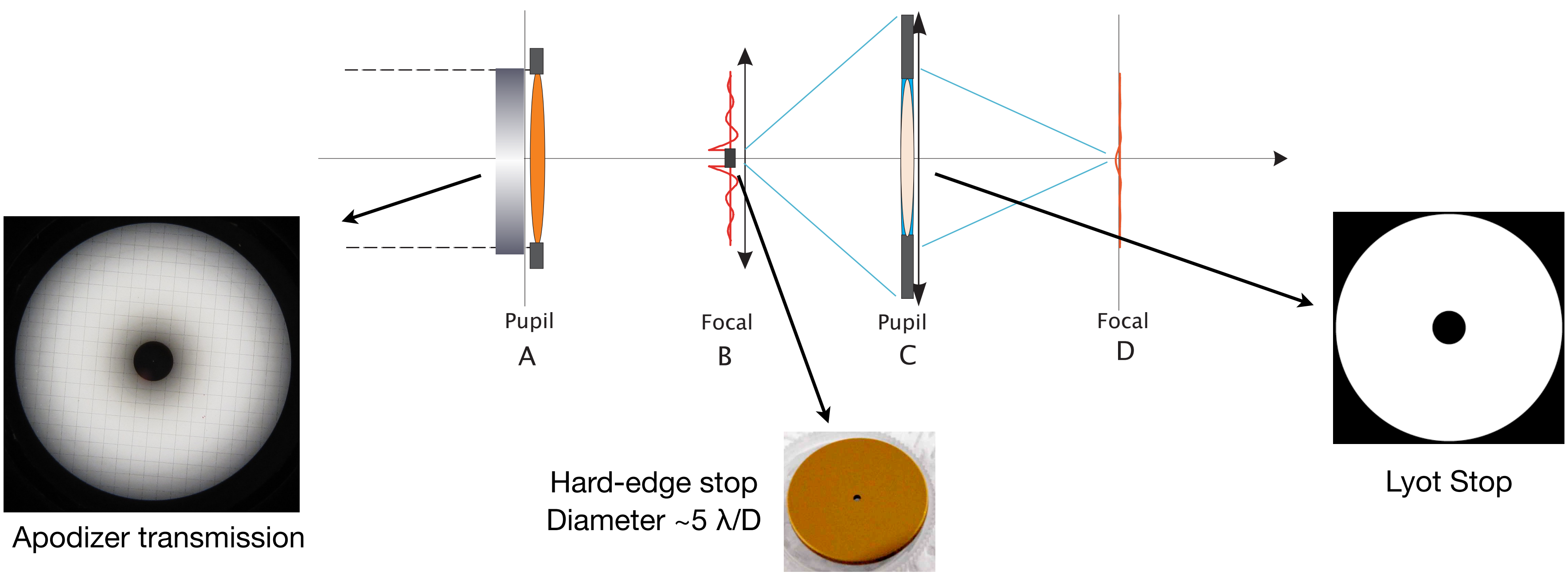
GPI has 4 essential tasks and units

- Remove distortions caused by atmospheric turbulence
- Suppress diffraction from the star that obscures the planet
- Use multi-wavelength to aid detection and provide information about the planet
- Fix quasi-static errors that limit sensitivity



APLC improves Lyot design

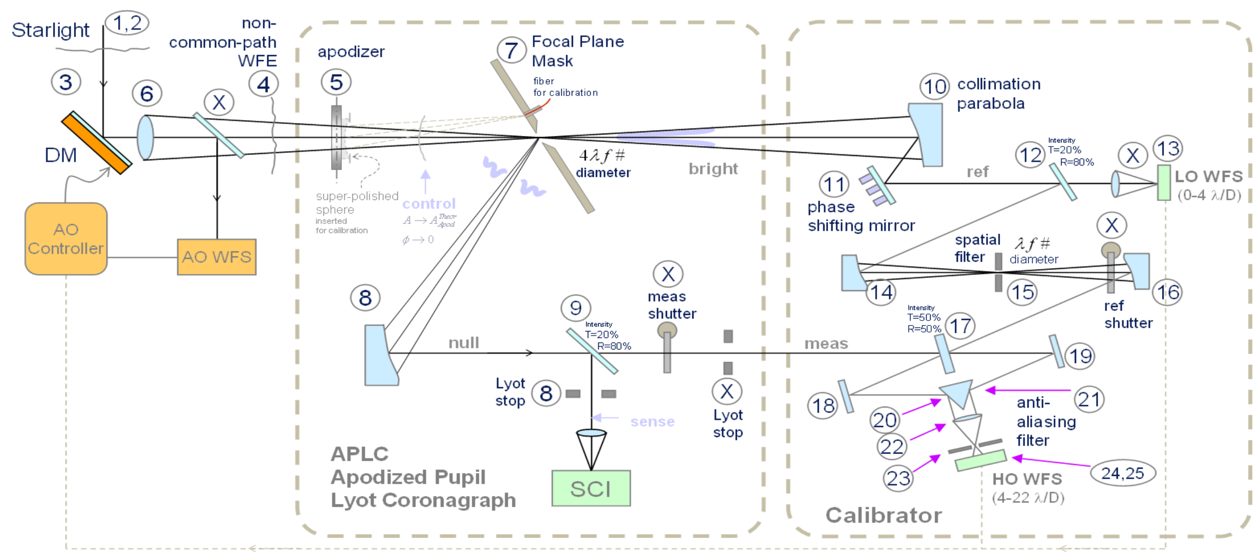
- Apodization allows more efficient destructive interference, providing better cancellation in Lyot plane
- Better throughput and angular resolution
- Built by AMNH (PI: Oppenheimer)



Thanks to R. Soummer for the figure.
See several references, including: Aime et al (2002), Soummer et al (2003) and Soummer (2005)

Cal system measures quasi-static errors

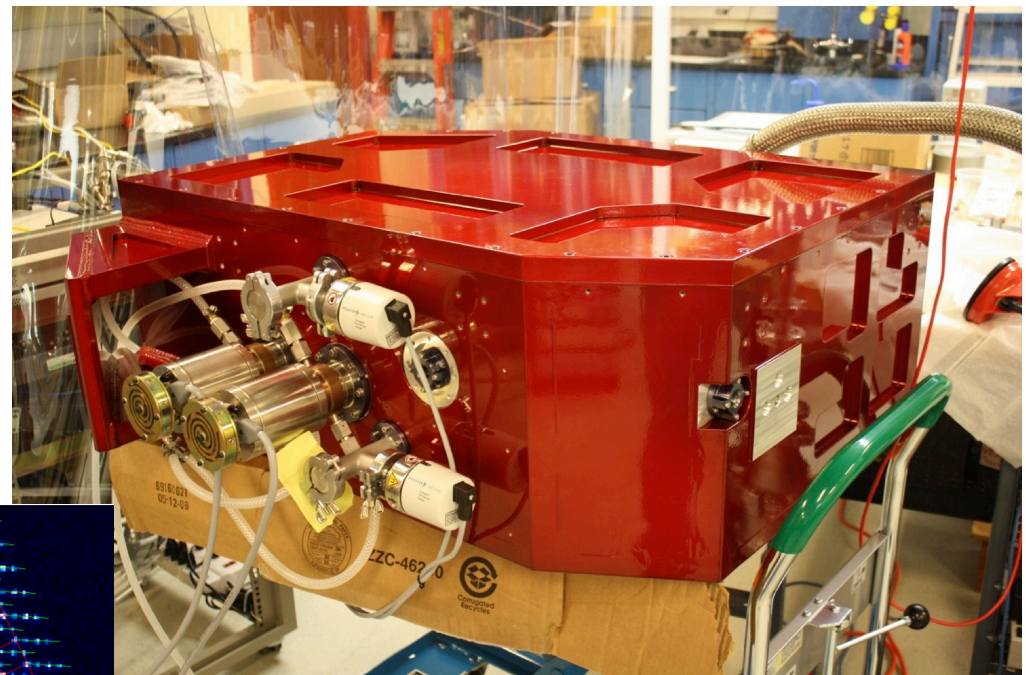
- Calibration system coupled with APLC
- LOWFS uses light from reference arm for low-order modes
- HOWFS is white-light, phase-shiting interferometer using reference and science light
- Built by JPL (PI: Wallace)

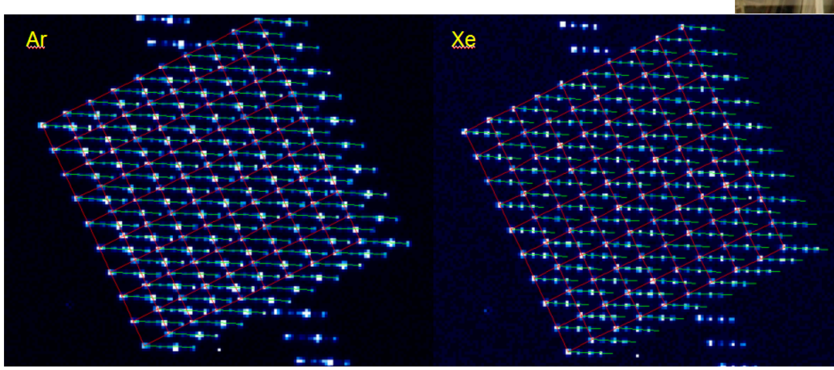


Schematic courtesy of Kent Wallace (JPL)

Dedicated hyperspectral imager

- Lenslet-based Integral Field Spectrograph
- R = 34 to 80 from Y to K
- 2.8” x 2.8” FoV
- 0.014” per pixel
- Built by UCLA (PI: Larkin) with U. Montreal and Immervision





Optics test images courtesy of U. Montreal;
IFS photo courtesy of UCLA

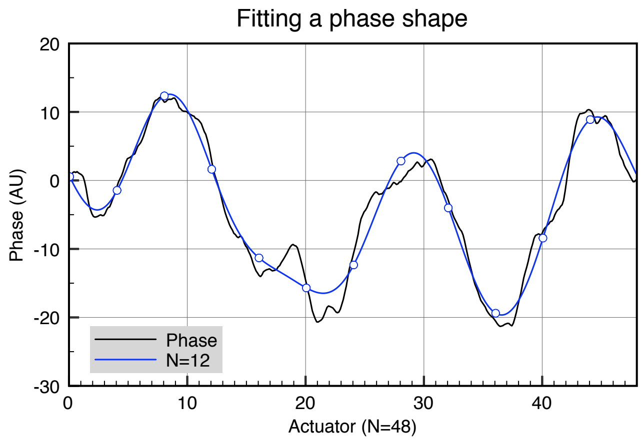
Designed for high-contrast imaging

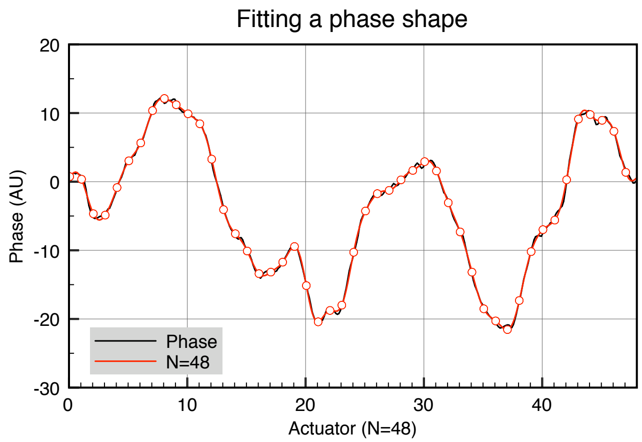
- Compared to current general purpose AO systems on 8-m to 10-m class telescopes, GPI has:
  - **10 times the actuator density per pupil area (18 cm spacing instead of 56-60 cm)**
  - **< 5 nm uncalibrated non-common path error**
  - **a spatially filtered wavefront sensor to produce a "dark hole"**

- Compared to other "extreme" AO systems (Sphere, PALM-3K), GPI has:
  - **computationally efficient wavefront reconstruction and self-optimizing control**
  - **a MEMS deformable mirror**
  - **very high-quality optics**
  - **been designed for near-IR observations with contrast of 10^7 in one hour on NGS I < 8**

GPI has unique DM requirements

- Need thousands of actuators
  - **More actuators means a better fit to atmospheric turbulence**
- Need small form factor
  - **Instrument location and size, plus the cost of other optics, drive us to an actuator pitch < 1 mm**
- Need low power device
  - **Entire instrument power budget (several computers, cyro-coolers, three detectors, etc) is 4 kW**
- At the time of our conceptual design, a DM that met all of requirements did not exist
- Controlling it also challenge...





Matrix-based recon is expensive

- The slope vector $\mathbf{s}$ contains x- and y-slopes for all valid subapertures in the pupil
- The phase vector $\boldsymbol{\phi}$ contains all controllable actuators
- We model the WFS measurement process as

$$\mathbf{s} = \mathbf{W}\boldsymbol{\phi}$$

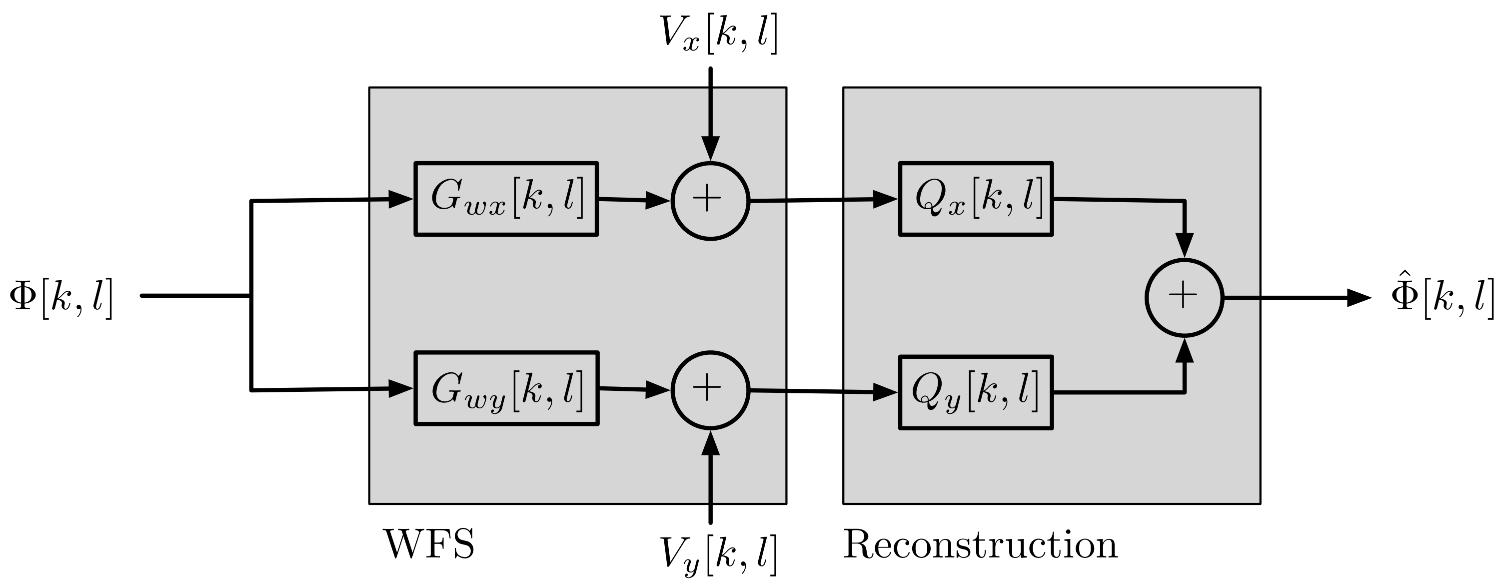
- With the matrix pseudo-inverse $\mathbf{E} = \mathbf{W}^+$, the reconstruction is obtained by a matrix-vector multiplication

$$\hat{\boldsymbol{\phi}} = \mathbf{E}\mathbf{s}$$

- Full application of the matrix is $\mathcal{O}(n^2)$, where n is the number of actuators

View this as a filtering problem

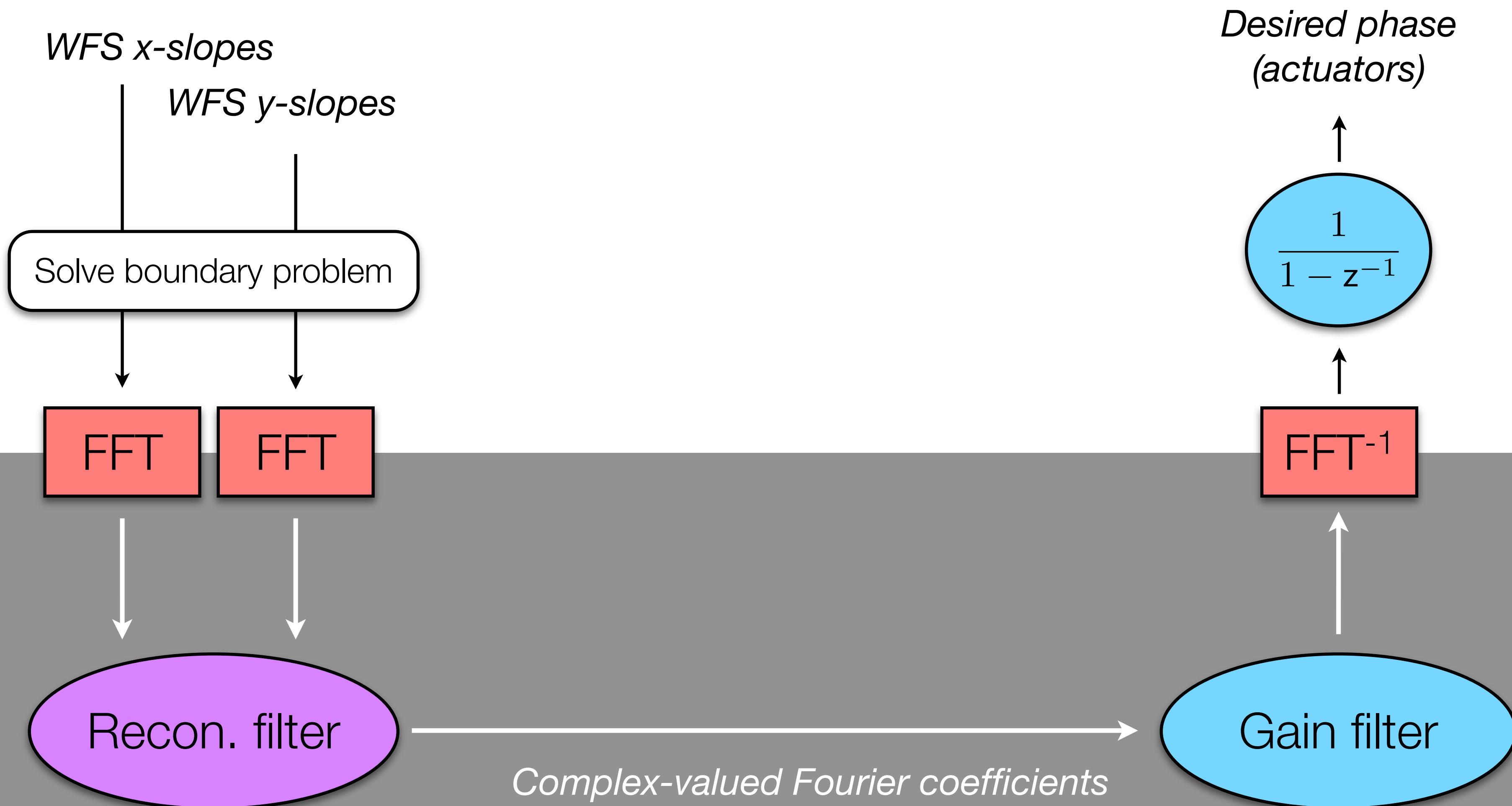
- Fourier modes are eigenfunctions of LSI systems - for each mode the filter is simply multiplication by a complex number



- FFTWs are $\mathcal{O}(n \lg n)$. That's 50 times more efficient for GPI.

- Weiner filter is equivalent to MVU matrix methods.

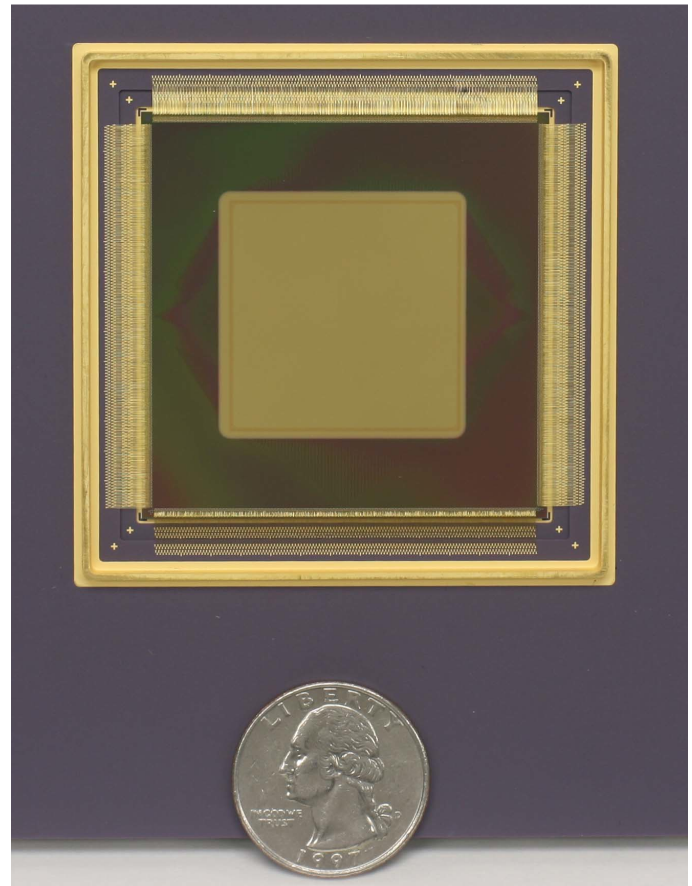
Fourier Transform Reconstruction



Poyneer, Gavel, and Brase, "Fast wave-front reconstruction in large adaptive optics systems with use of the Fourier transform," J. Opt. Soc. Am. A 19, 2100–2111 (2002).

4K deformable mirror developed for GPI

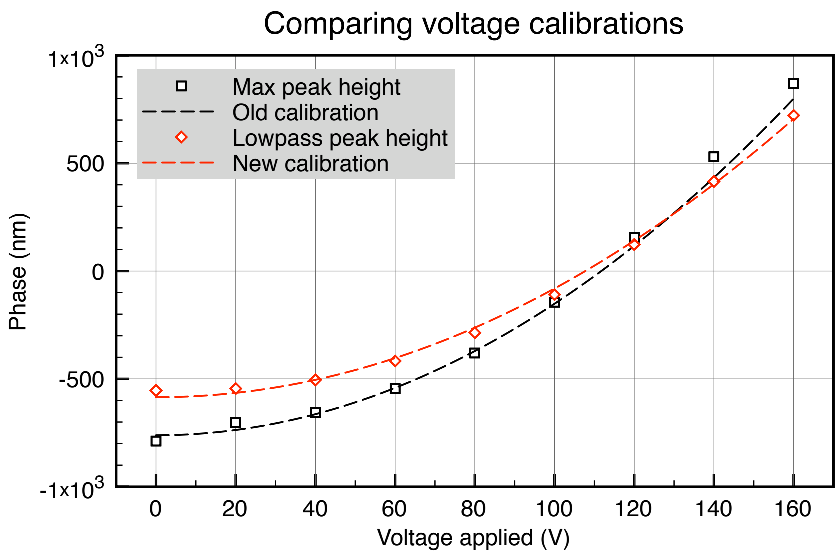
- Microelectromechanical system (MEMS) mirrors are produced with silicon semi-conductor fabrication techniques
- Developed by Boston MIcromachines in multi-year process with CfAO and Gemini
- Two specific advantages for GPI
  - **small form factor: 400 micron actuator spacing**
  - **4096-actuator MEMS dissipates only 4 W**



Photograph courtesy of Steven Cornelissen, Boston Micromachines Corp.

Characterizing MEMS actuator response

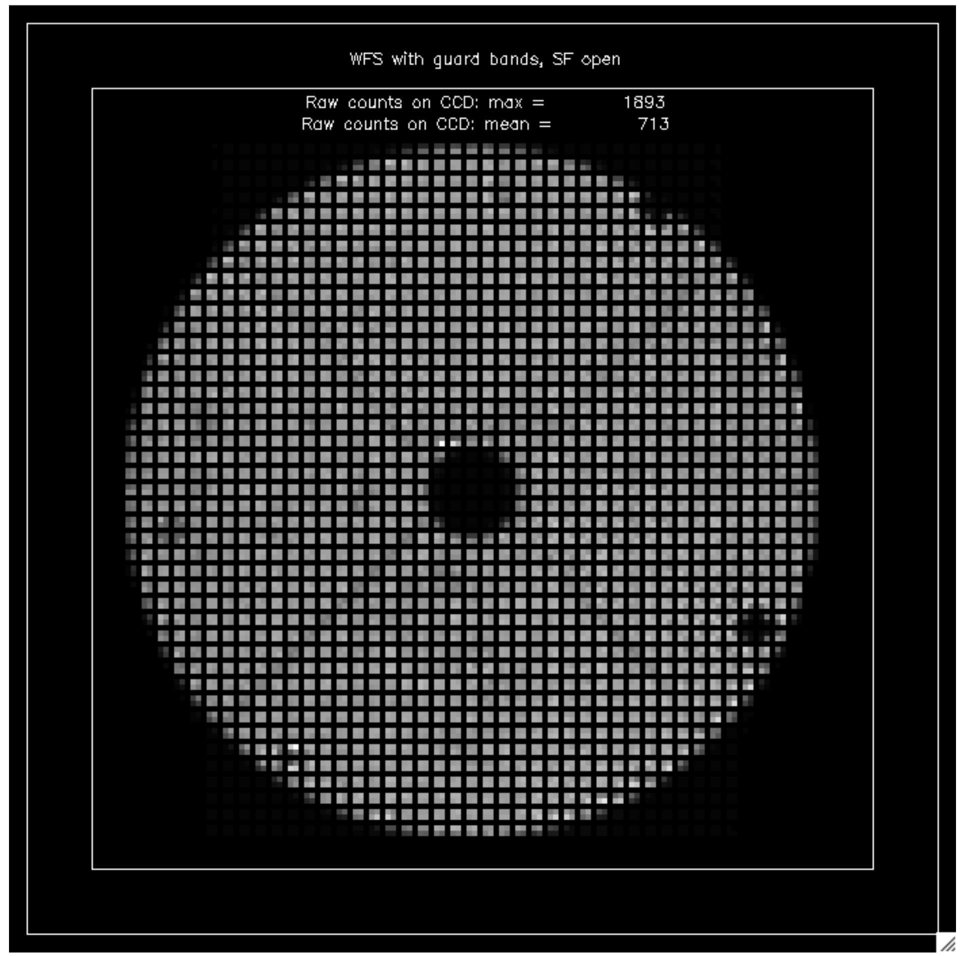
- Single actuators go where you want and stay there
  - **essentially no hysteresis: < 1 nm over full > 1 micron stroke range**
  - **excellent temporal stability: < 0.35 nm RMS motion over 40 minutes**
  - **excellent repeatability: go-to capability with < 1 nm position error**
- Actuator stroke is quadratic function of commanded voltage
  - **calibrate each actuator using low-pass peak height**



For more information on single-actuator tests see:
Morzinski et al, "Characterizing MEMS deformable mirrors for open-loop operation: high-resolution measurements of thin-plate behavior," Proc. SPIE 6888, p. 68880S.
Morzinski, et al, "Characterizing the potential of MEMS deformable mirrors for astronomical adaptive optics," Proc. SPIE 6272, p. 627221.

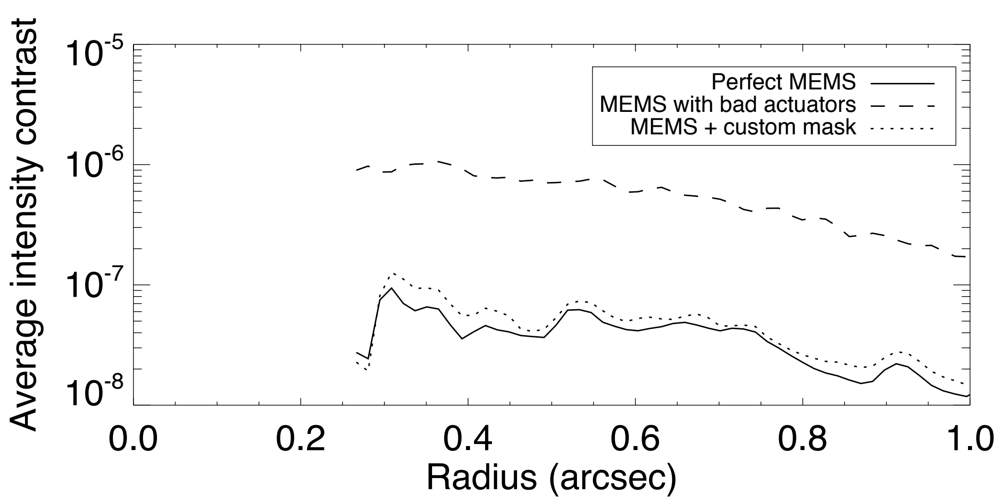
Final MEMS has defects

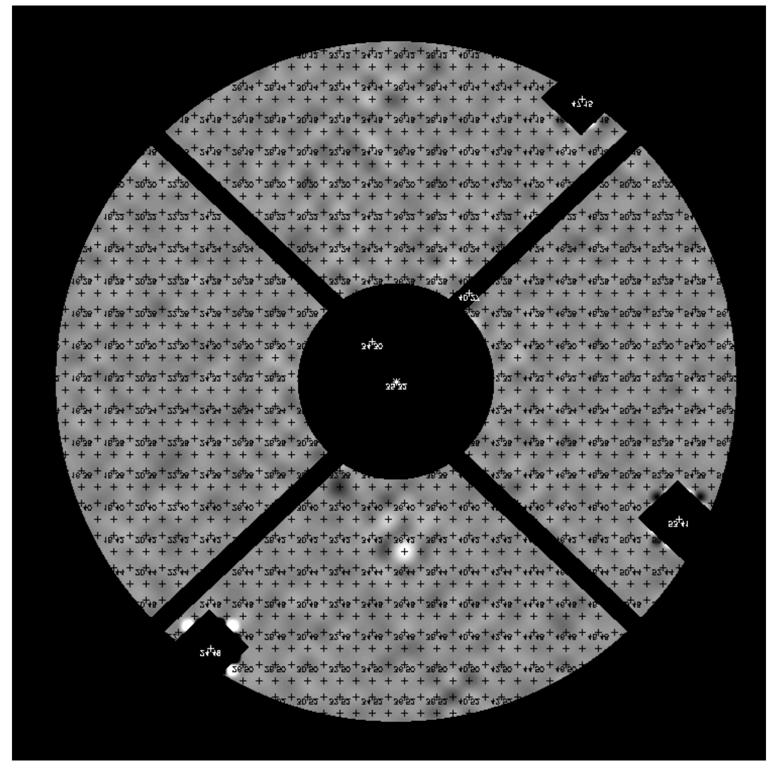
- Four dead actuators that are unresponsive
- For each, the four surrounding subapertures are numerically masked
- Two pairs of coupled actuators slightly underperform, but not enough so that we need to do anything special to control them



Mask defects inside APLC

- Phase errors on the scale of one actuator cause bright spots in the Lyot plane
- We have fabricated custom modified Lyot stops to block these locations



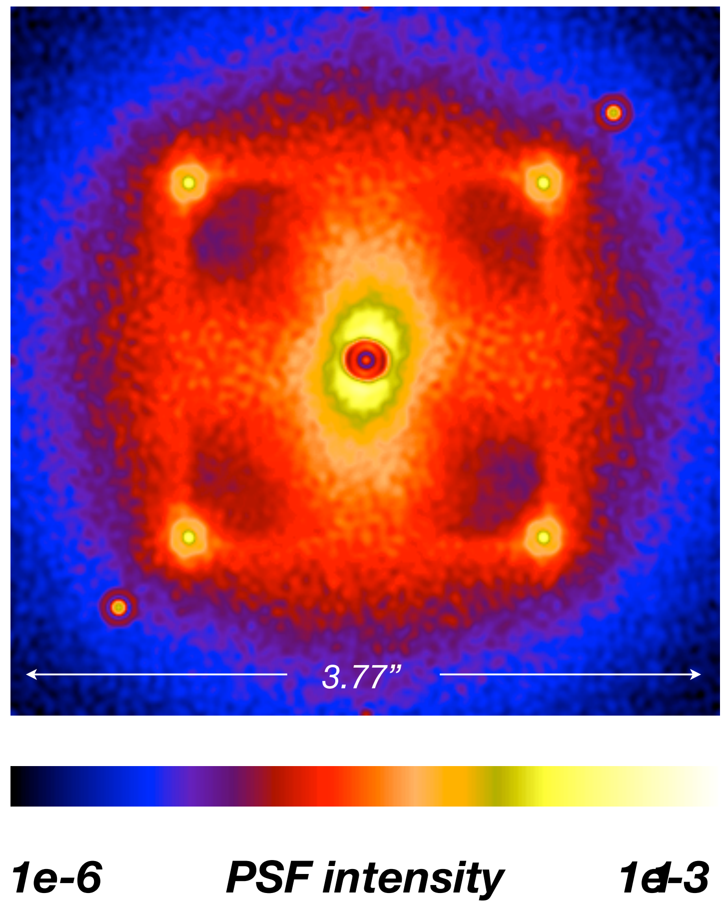


Figures courtesy of Bruce Macintosh and Josh Isaacs

MEMS and FTR enable “extreme” AO

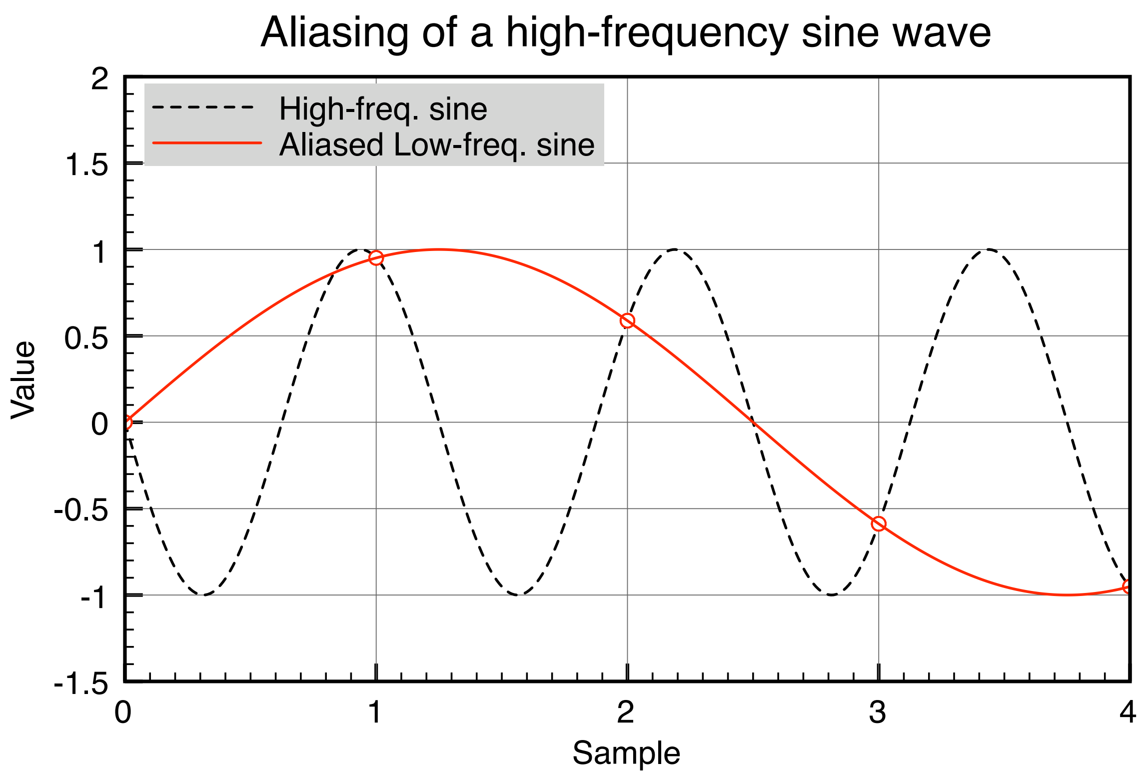
- More actuators and 1 kHz frame rate gets us higher Strehl
- Dominant error term in controllable region is due to aliasing
- In classic AO, aliasing error has one-third the power of fitting error

I=7, eight sec composite



Wavefront sensors sample the phase

- Signal above Nyquist will not be accurately sampled and reconstructed



Anti-aliasing filter is a field stop

Phase in pupil plane

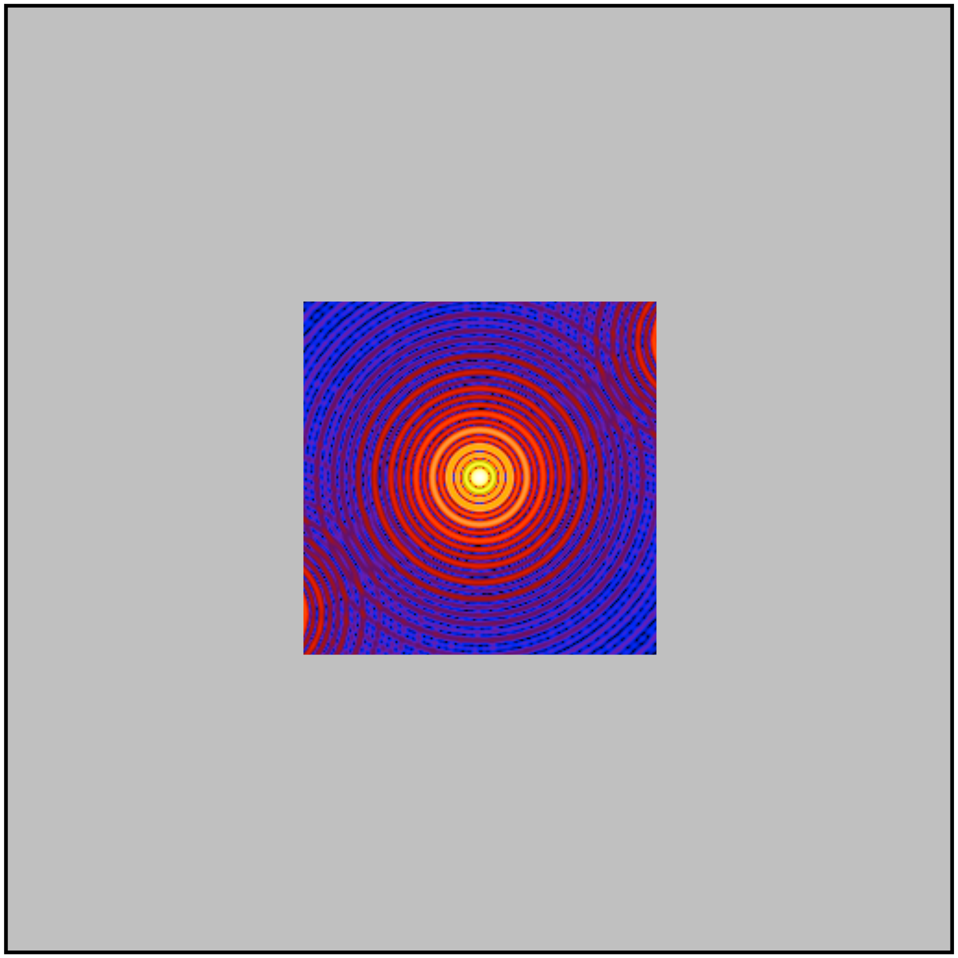
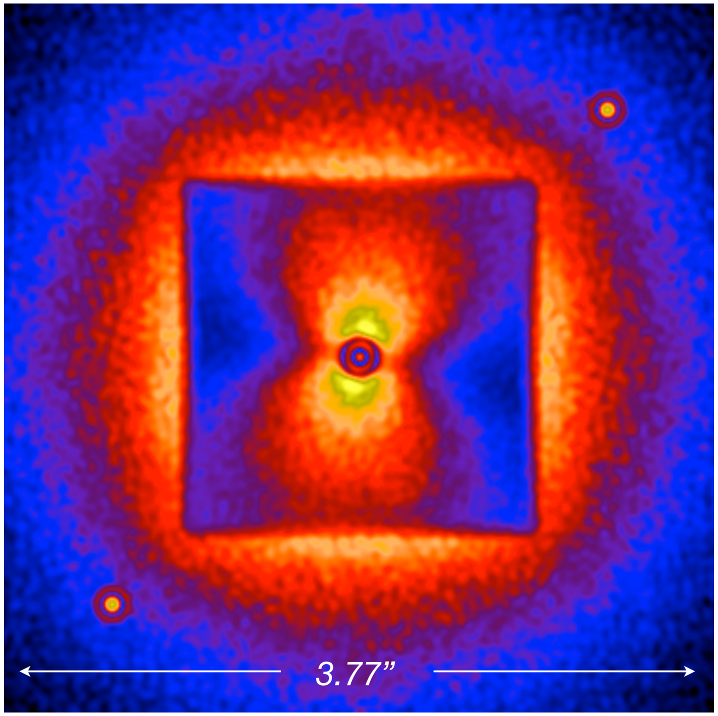


Image plane

“Dark hole” essential for high performance

- SFWFS attenuates high-spatial frequency phase power by 1000 times, eliminating the aliasing error
- Operation with the spatial filter reveals the true error from the uncorrected atmosphere and WFS noise

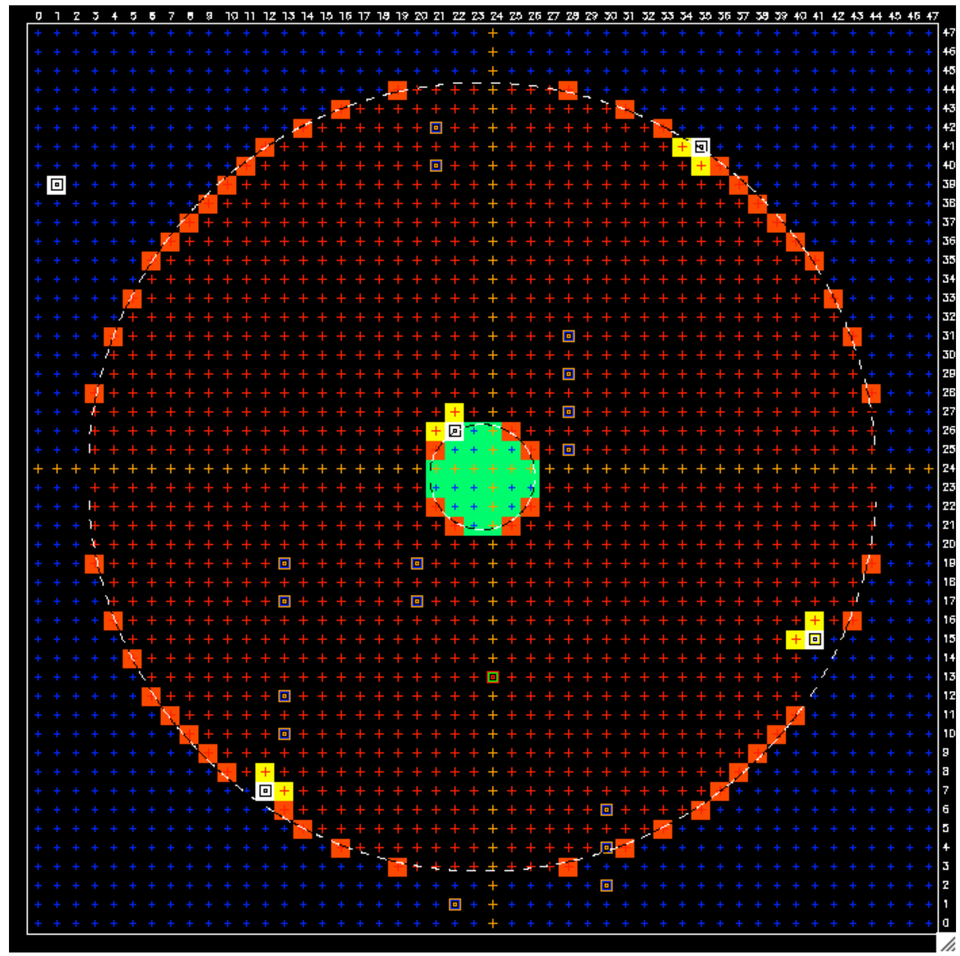
I=7, eight second composite



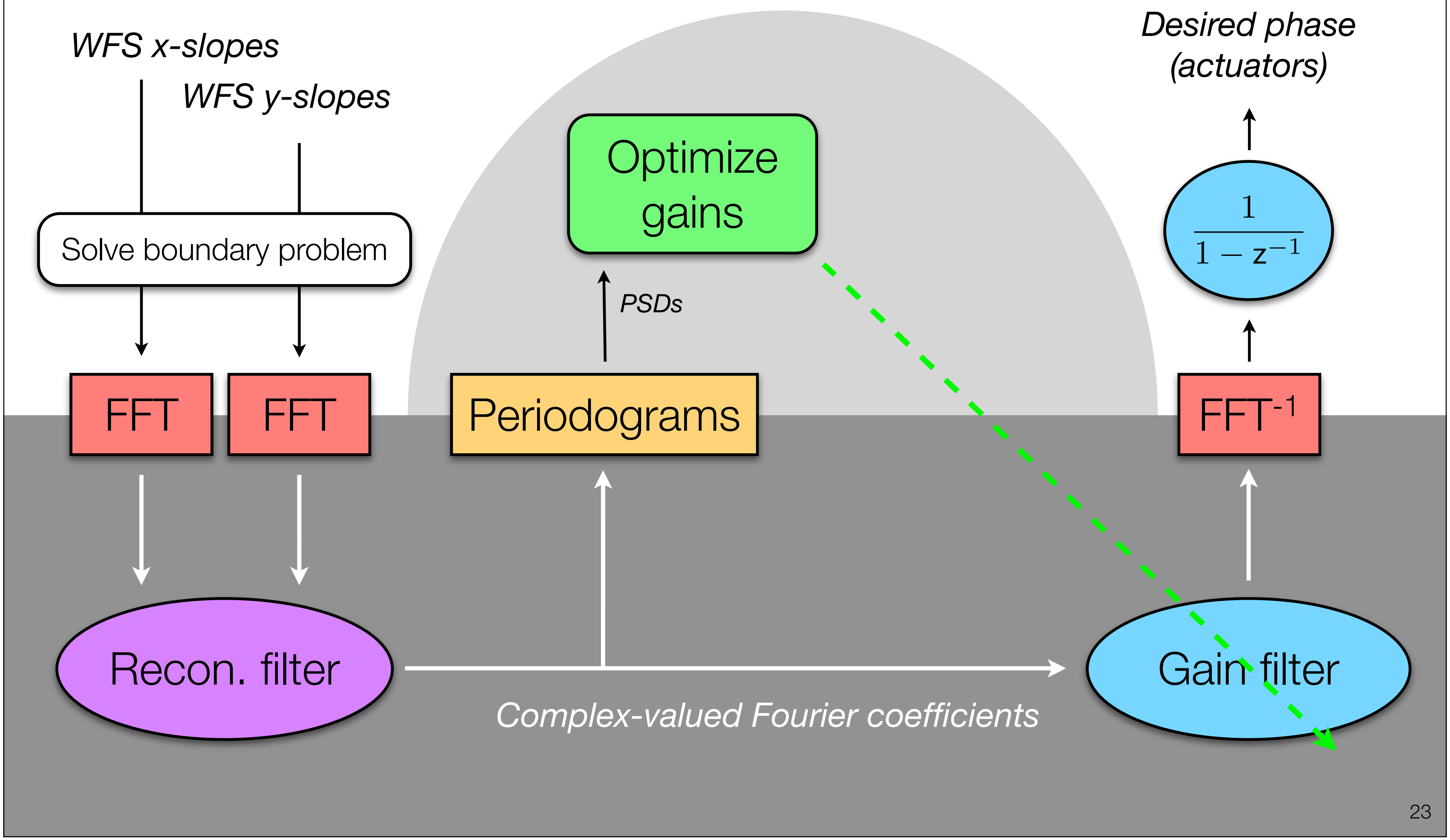
Poyneer & Macintosh, “Spatially filtered wave-front sensor for high-order adaptive optics,” J. Opt. Soc. Am. A 21, 810–819 (2004).

Slaving essential to SF stability

- Large inter-actuator phase excursions lead to intensity drop-outs and slope errors
- Preventing unnecessary excursions is essential
- The following had to be slaved for stability
  - **nearest neighbors of dead actuators**
  - **the central obscuration**
  - **actuators at pupil edge that touched only 1 valid subap**

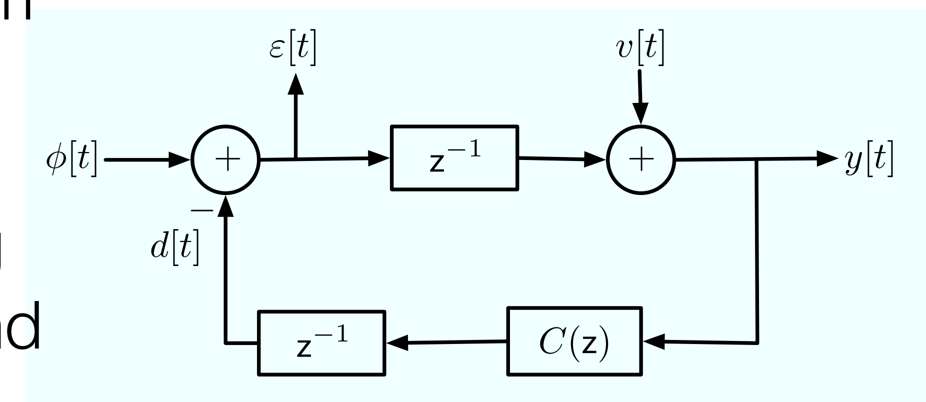


Optimized-gain Fourier Control



Know control system; measure conditions

- Model and verify control system behavior using Z- or Laplace transforms
- Use wavefront residuals during operation to estimate signal and noise temporal power spectra
- Find best gain by minimizing error power



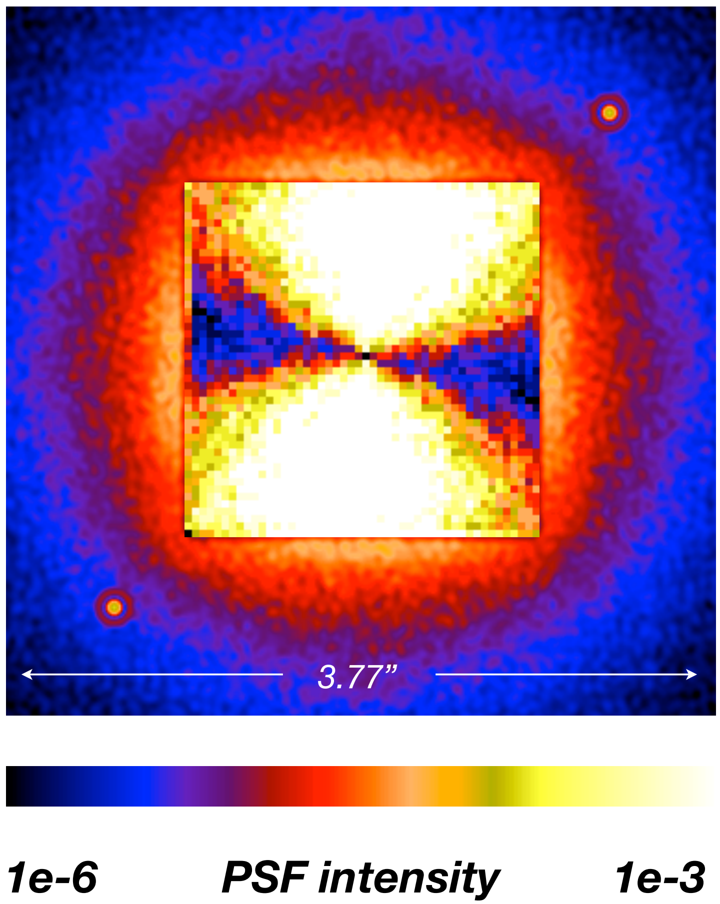
$$\underset{C(z)}{\operatorname{argmin}} \left\{ \int_{-\pi}^{\pi} \left| \frac{1}{1+\exp(-2j\omega)C(\omega)} \right|^2 |1+\exp(-j2\omega)C_0(\omega)|^2 \, \hat{P}_{y,cl}(\omega)\, d\omega \right\}$$

For original modal gain optimization concept see Gendron and Léna, "Astronomical adaptive optics I. Modal control optimization," Astron. Astrophys. 291, 337–347 (1994).
For the application to Fourier reconstruction see Poyneer and Véran, "Optimal modal Fourier transform wave-front control," J. Opt. Soc. Am. A 22, 1515–1526 (2005).

OFC improves performance in dark hole

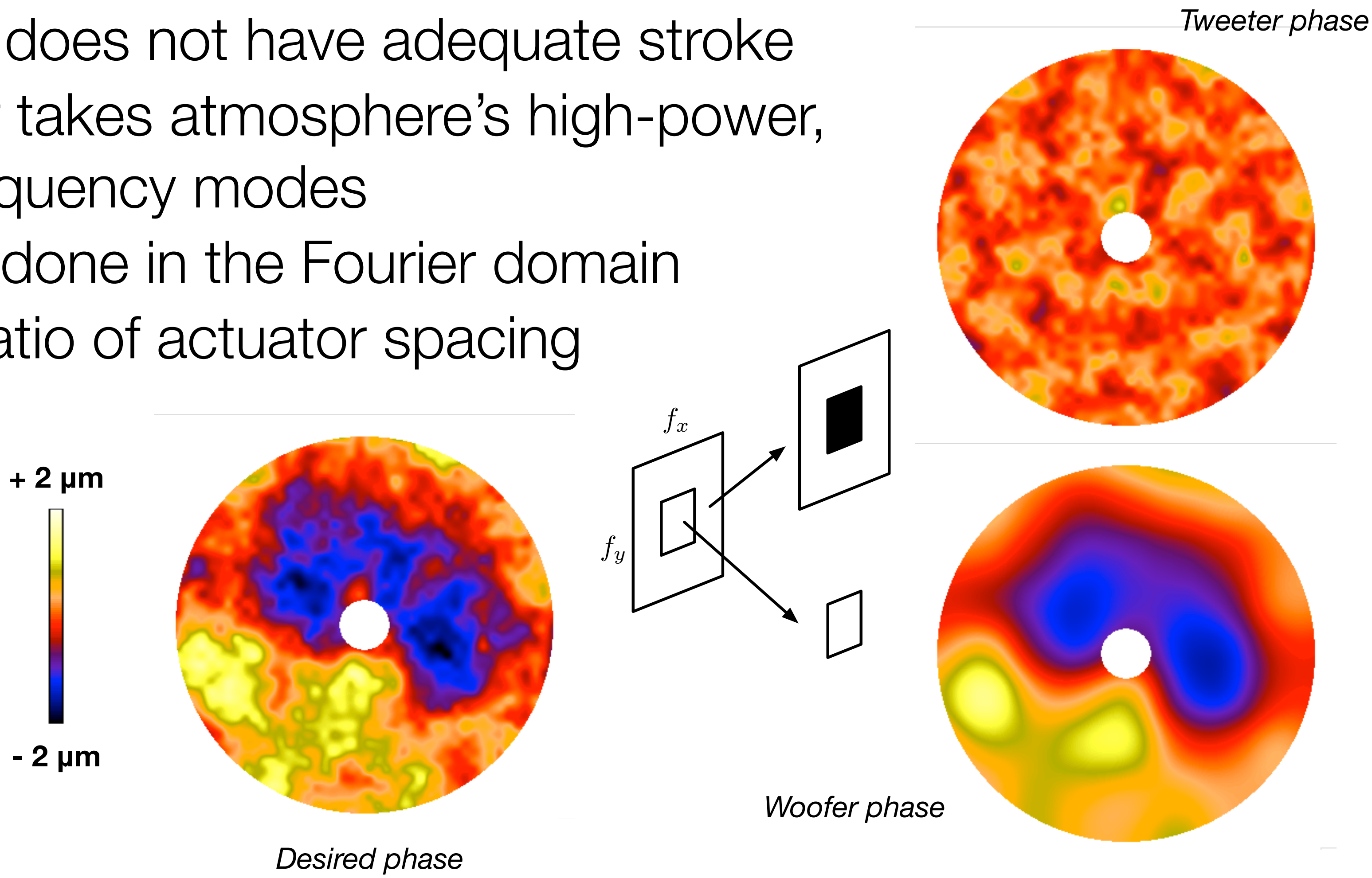
- Large range of gains required by variations in atmospheric and WFS noise power with spatial frequency
- PSF intensity reduced nearly everywhere in dark hole
- System self-optimizes several times a minute

I=7, eight second composite



Woofer-Tweeter control

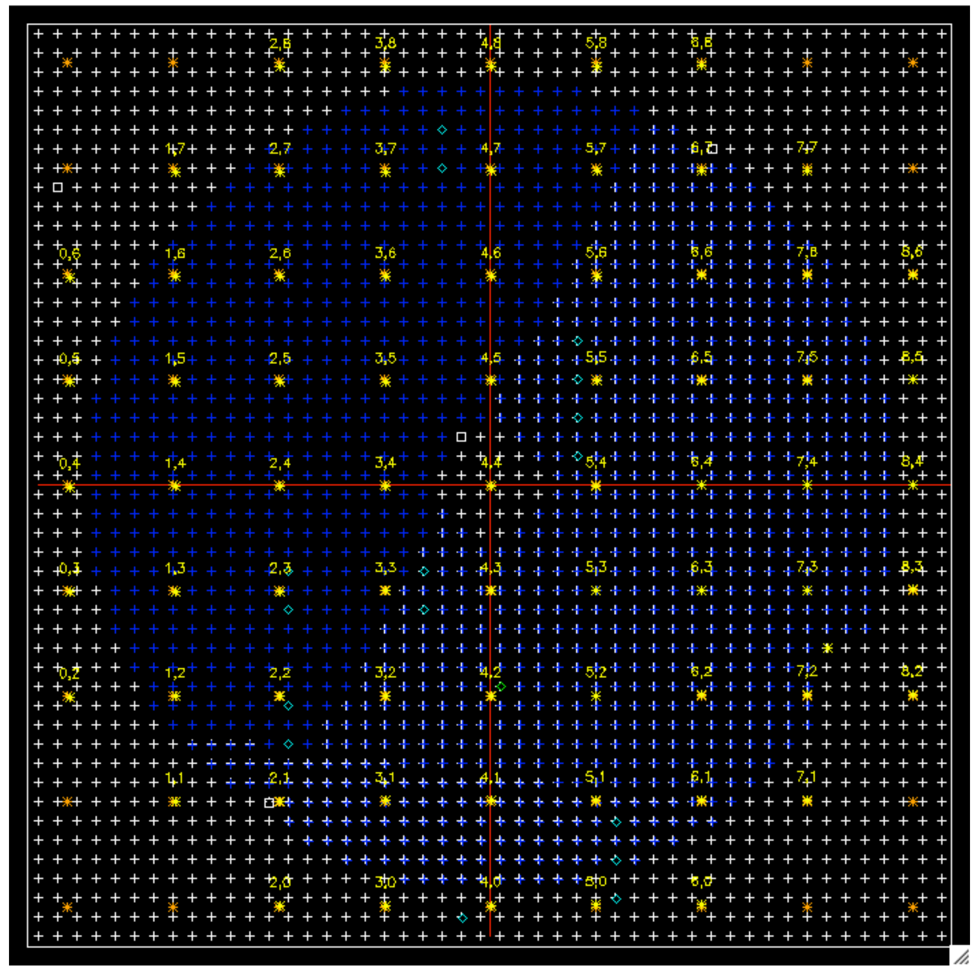
- MEMS does not have adequate stroke
- Woofer takes atmosphere's high-power, low-frequency modes
- Split is done in the Fourier domain
- 5.5:1 ratio of actuator spacing



Lavinge and Véran, "Woofer-tweeter control in an adaptive optics system using a Fourier reconstructor," J. Opt. Soc. Am. A 25, 2271–2279 (2008).

Very precise alignment of DMs

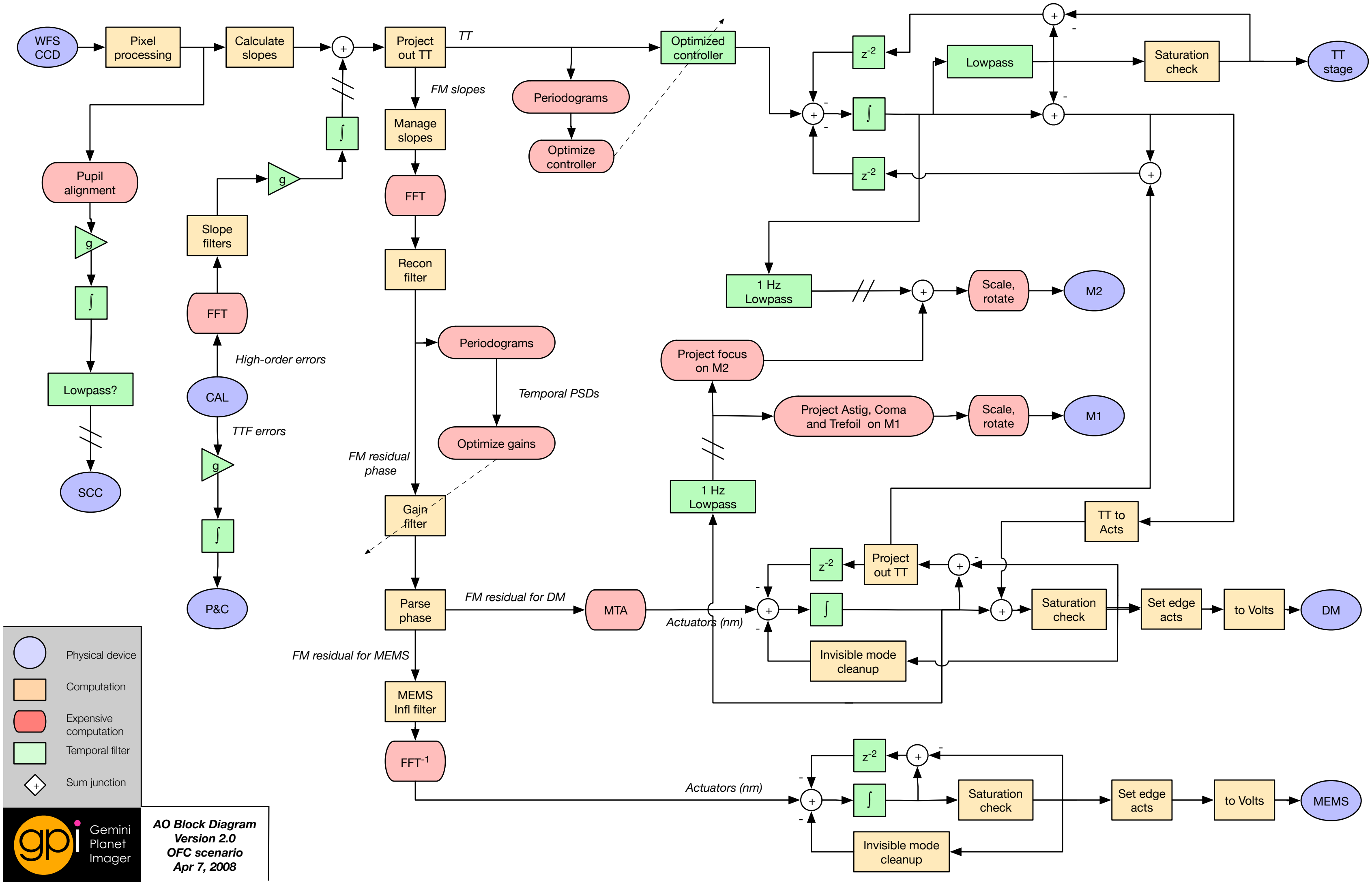
- Woofer is aligned to MEMS once for rotation, magnification and translation
- MEMS is aligned with magnification and rotation to lenslets once
- P&C pair adjusts drifts in translation (centering) of MEMS on lenslets



Other tweaks that we've had to make

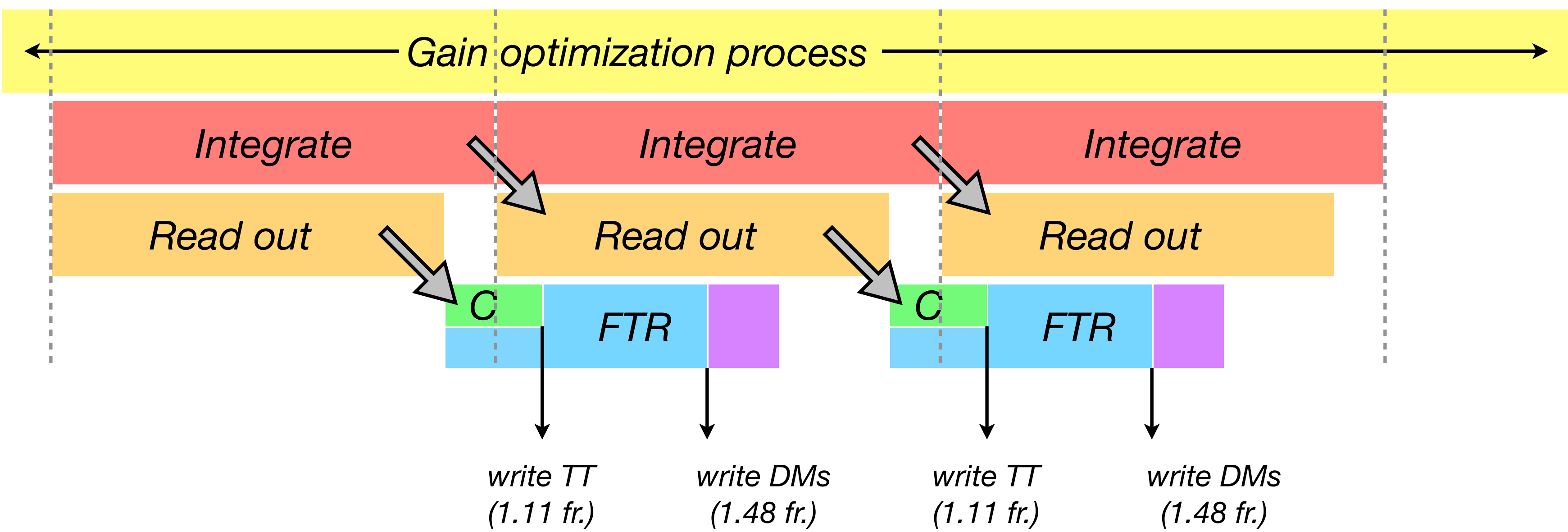
- Use a local waffle suppression filter by reducing the MEMS influence function pre-compensation for highest spatial frequencies around waffle
- Woofer-Tweeter split does not behave well when large amounts of focus are present in the phase
  - **manually implement on testbed the offloading to M1/M2 that will occur at Gemini**

Real-time control processing tasks



RTC timing - self-report

- All loops closed, optimizer on; times via system clock
  - **WFS read: 890 µsec (fixed read time for camera mode 3 -> max 1.12 kHz)**
  - **Time from end of read to TT write: 220 µsec (17% throughput)**
  - **Time from end of read to DM writes: 590 µsec**
  - **Time from end of read to all processing done: 750 µsec (average)**
- WFS stare depends on frame rate: this example is 1.0 kHz

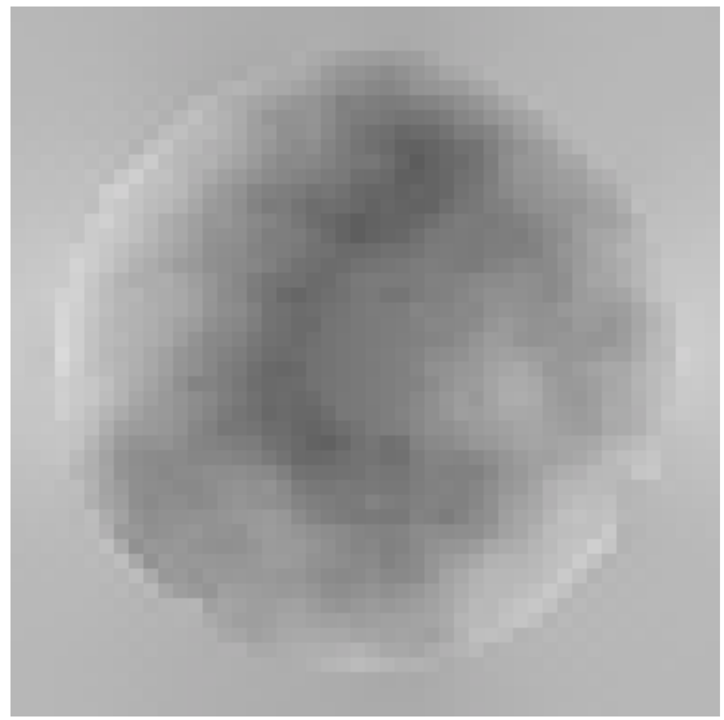


Experimental setup

- Spinning phase plate
  - **due to quality problems, could not used the phase plates we were supposed to**
  - **used plate with only one-half the RMS phase error of median seeing**
  - **plate spun to effective 15 m/s wind**
- 700-900 light source (filtered white)
- Spatial filtered irised down to designed size when Woofer loop closes
- No science camera yet (IFU delayed) so all performance analysis done from **telemetry of measured residual Fourier coefficients**

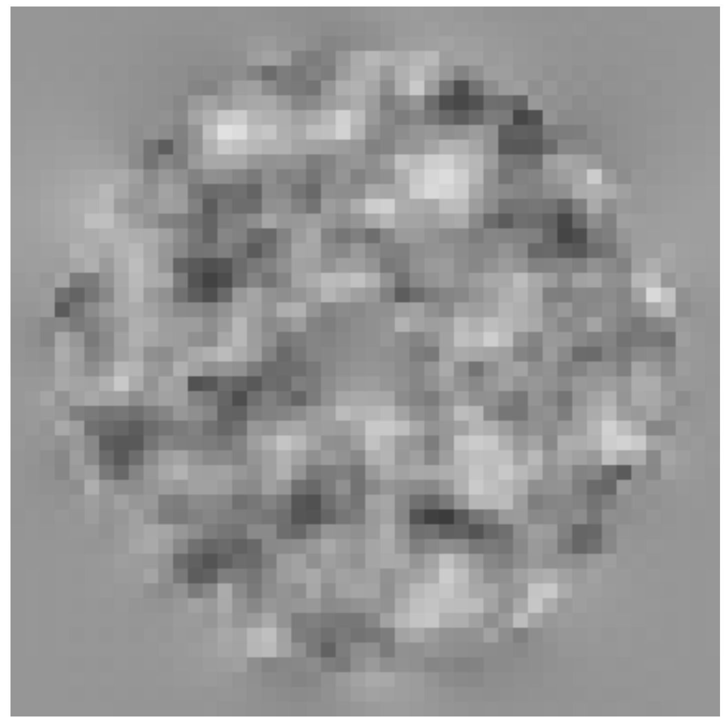
Loop closing sequence

- Initial control loop gains = 0.1
- Spatial filter open
- Close TT loop
- Close Woofer loop and iris down spatial filter
  - **WFS measures 92 nm RMS**
- Close Tweeter loop
  - **WFS measures 45 nm RMS**



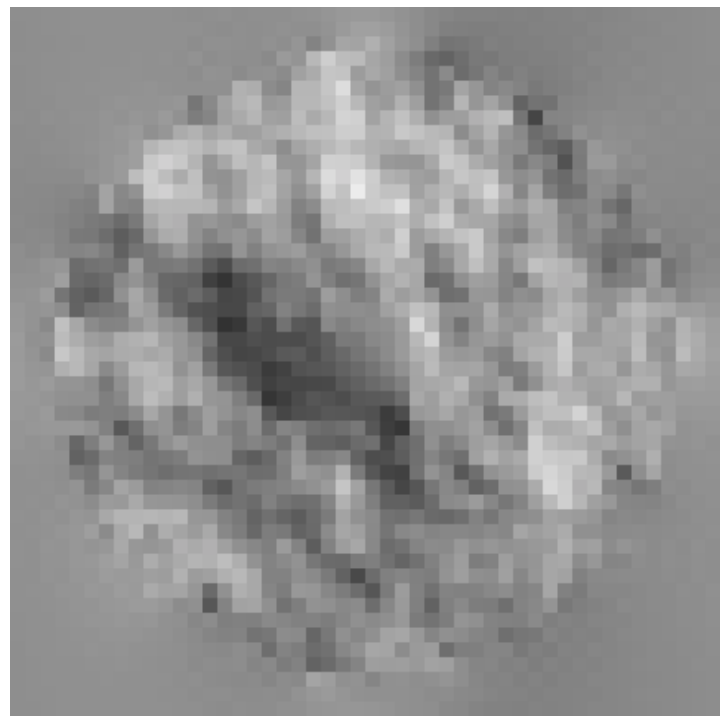
Closer look at Tweeter closing step

- Start Woofer loop closed and spatial filter irising down
  - **WFS measures 92 nm RMS**
- Tweeter loop then closes
  - **WFS measures 45 nm RMS**



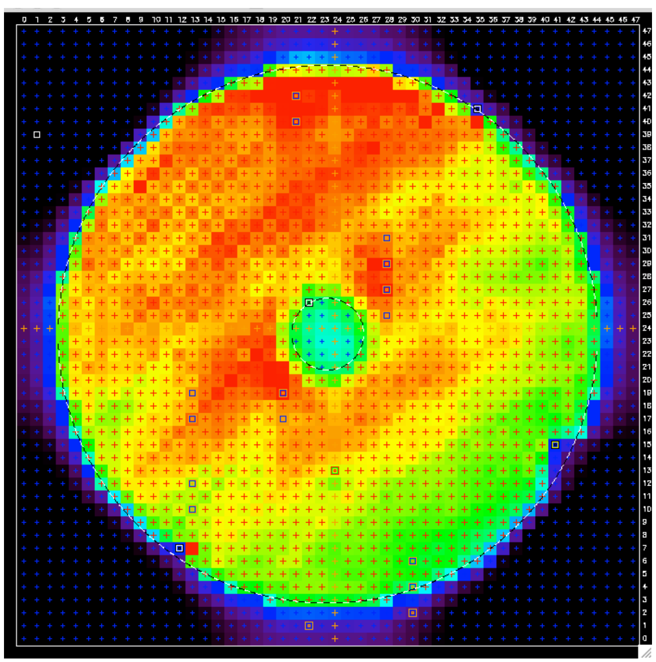
Impact of gain optimization

- Bright star case
- Gains 0.1 to start
  - **WFS measures 45 nm RMS**
- OFC cranks up gains to 0.3 for nearly all modes
  - **WFS measures 24 nm RMS**

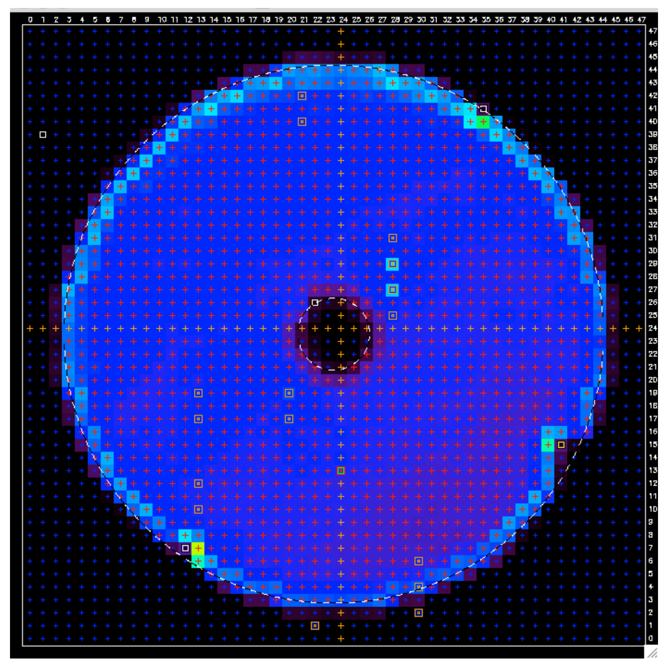


Wind & defects visible in error per actuator

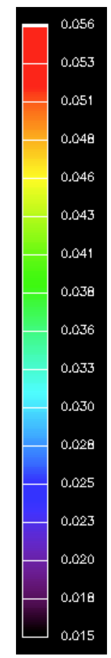
- Calculate RMS error per actuator as measured in closed loop
- This example is the bright-star case



Before optimization (gains = 0.1)

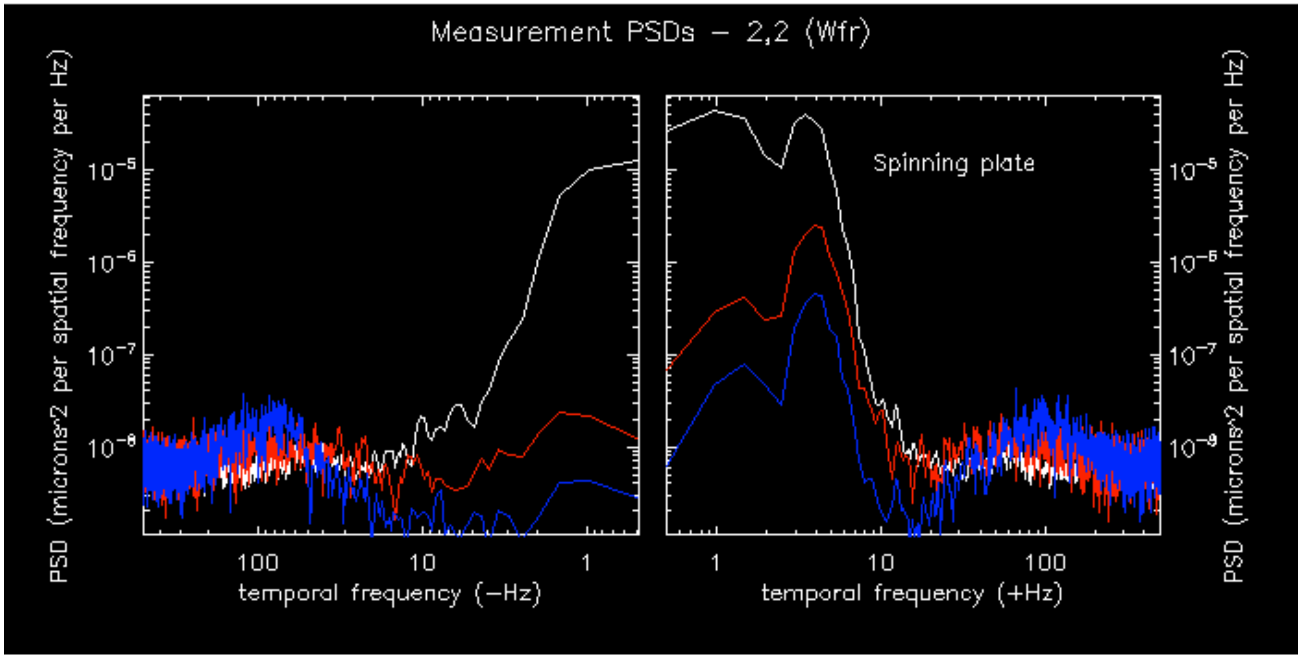


After optimization (most gains = 0.3)



Use temporal PSDs to evaluate loops

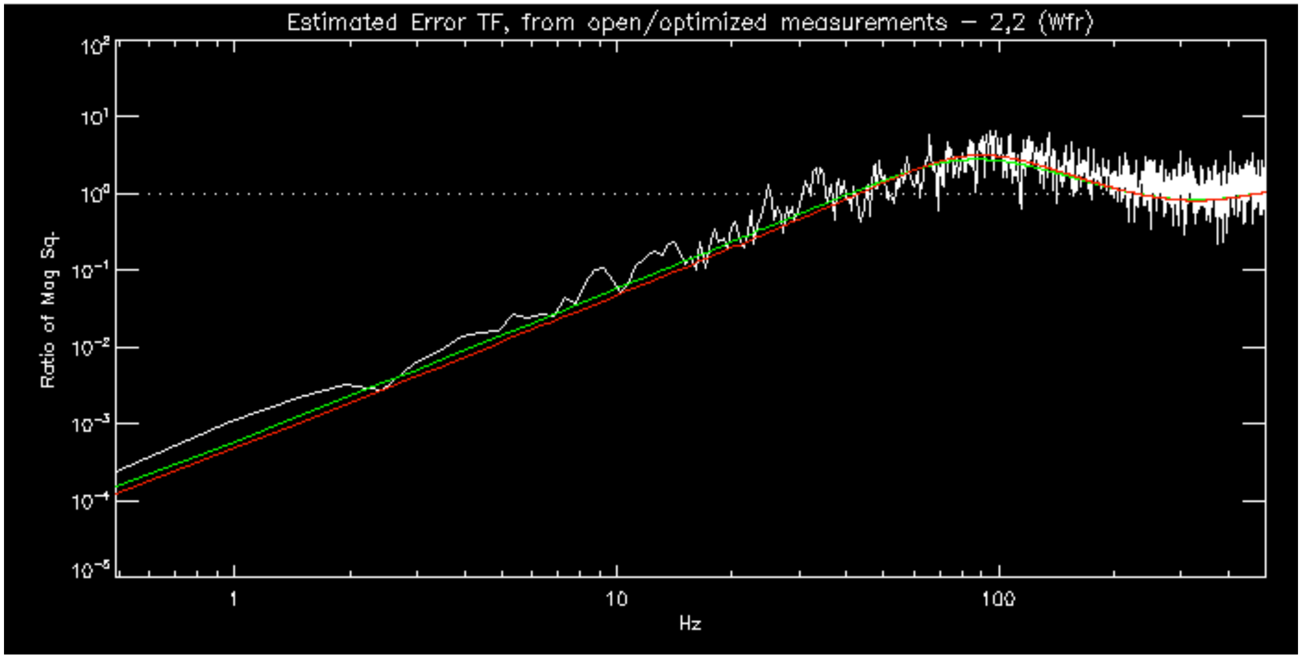
- We have access to the measured Fourier coefficients.
- For each complex-valued Fourier coefficient, estimate the temporal PSD (just like AOC does for OFC)



From I=7.2 test case

System temporal response matches model

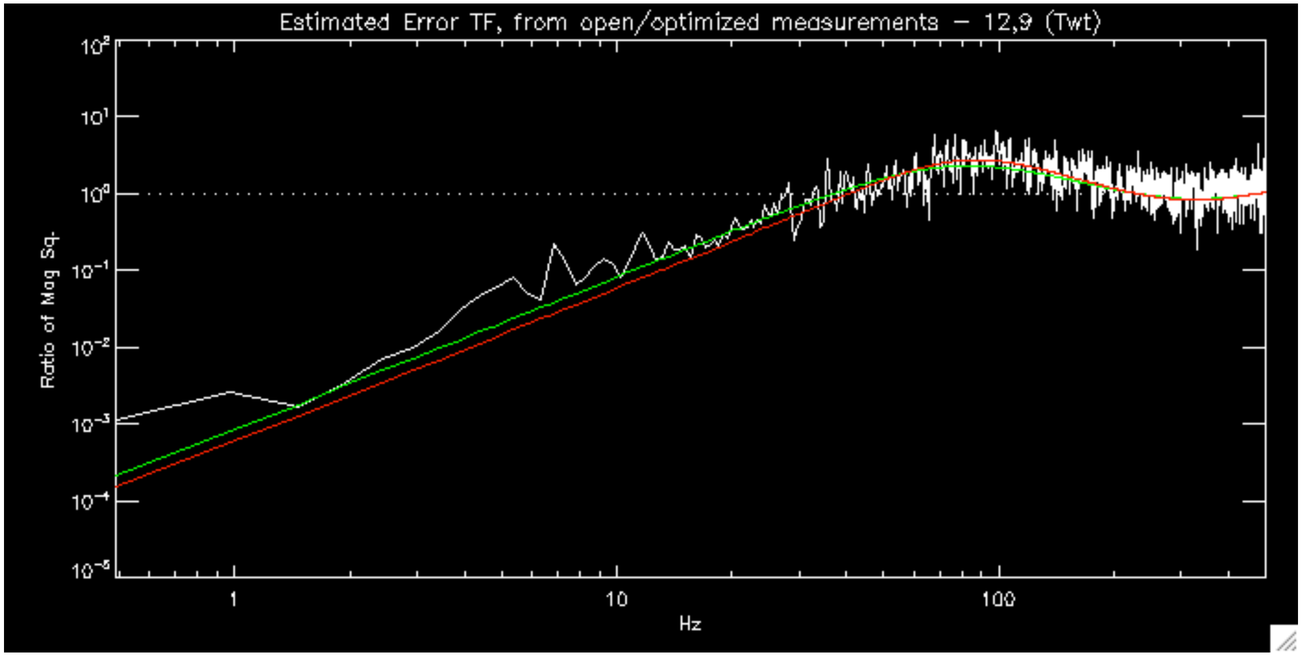
- Estimate ETF as ratio of open/closed loop measurements
- We have a detailed Laplace model of system dynamics
- Excellent agreement of model and calibration with measured data



From I=7.2 test case

High-order modes also well-behaved

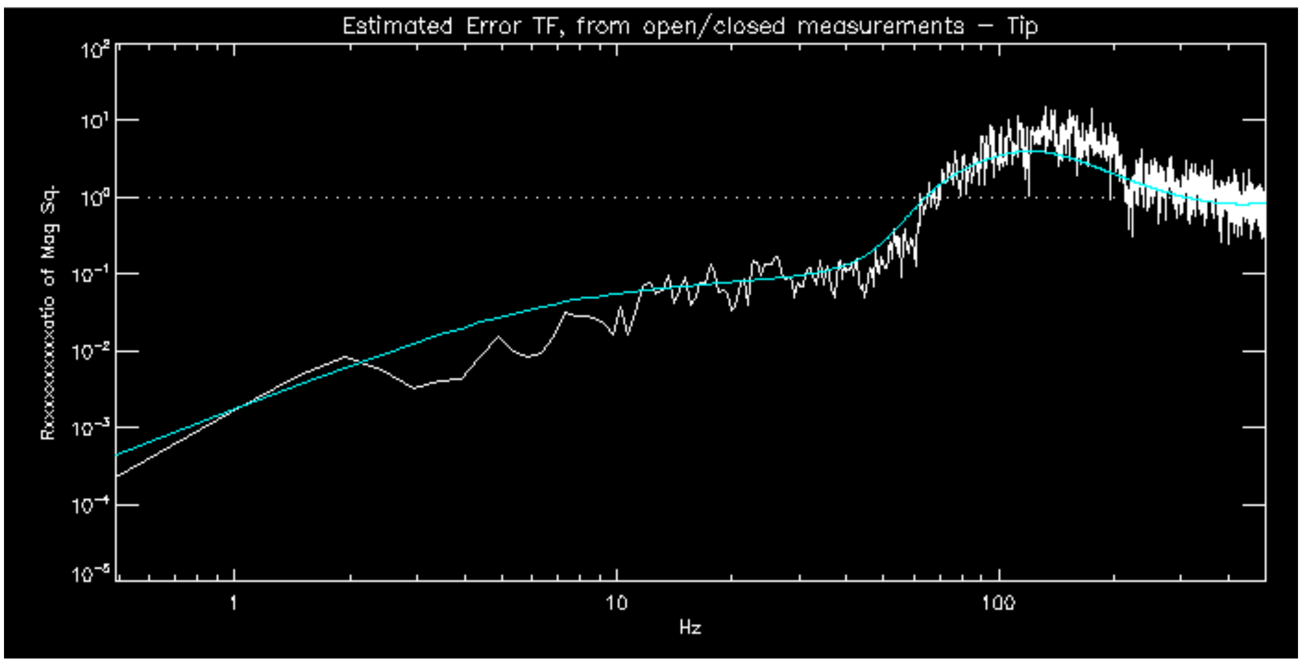
- Fourier modes being controlled independently
- MEMS influence function filtering is correctly calibrated



From l=7.2 test case

Dual surface TT control working well

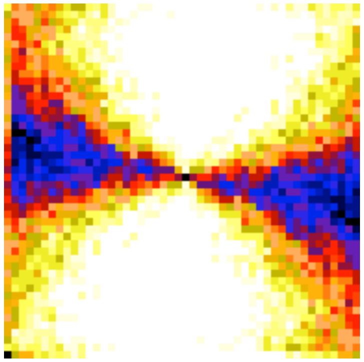
- TT split between two surface with a low-pass filter
- TT Stage has high stroke, but is slow and has low bandwidth
- Woofer surface (actuators) has low stroke but is faster



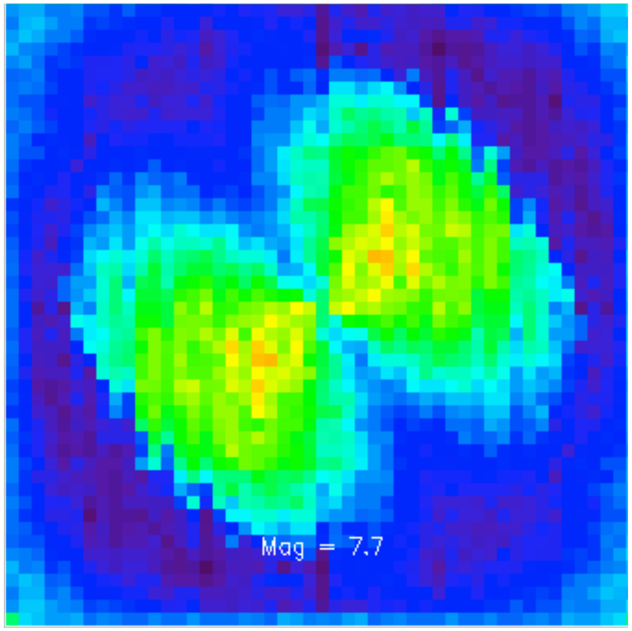
From I=7.2 test case

Gain optimizer working correctly

- Updates gains every 10 seconds
- Converges rapidly to correct modal gains and stays there
  - **Even did the right thing when we accidentally spun the phase plate to make 80 m/s wind!**



From simulation of three-layer atmosphere with one dominant wind direction (different color table)



Testing with same spinning phase plate

Lab test performance

	Estimated science-leg in-band residual error (nm), optimized gains, SF closed, 1 kHz	
I mag	WFS noise	Temporal
4.5	6.0	14.6
6.0	10.8	23.7
7.2	15.5	46.0
7.7	18.5	66.0
8.0	still testing	

- Estimates obtained from “noise only” and “noise + plate” runs and WFS telemetry using PSD methods
- Temporal error on phase plate with one-half RMS of median r_0

Huge effort by GPI AO team

- Lawrence Livermore (AO design, simulations, algorithms, and real-time computer)
  - **Brian Bauman, Steve Jones, Bruce Macintosh, Dave Palmer and Lisa Poyneer**
- HIA (AO optical bench)
- UC Santa Cruz LAO (integration)
  - **Daren Dillon, Don Gavel and Sandrine Thomas**