Low-order Wave-front Sensing and Control, and Point-spread-function Calibration, for Direct Imaging of Exoplanets

(short title : LOWFSC & PSF for Exoplanets)

Olivier Guyon (University of Arizona)
Wesley Traub (JPL)

Background

2-day meeting held at JPL, Feb 26 & 27

Originally aimed at reporting progress and discussing concepts/techniques related to NASA Space Technology Research Opportunities-Early Stage Innovations (ESI) grant:
"**Wavefront control for high performance coronagraphy on segmented and centrally obscured telescopes**" (PI: Guyon)

Meeting also included a wider discussion on control and calibration of low-order aberration and PSF calibration for NASA mission (AFTA, Exo-C and beyond)

Meeting website:
http://exep.jpl.nasa.gov/lowfsc/

Time	Day 1		
9:00 – 9:15	Introduction/workshop goals	Guyon (UofArizona)	15
	Fundamentals and algorithms		
09:15 – 9:45	Coronagraphs low-order aberrations sensitivity	Krist & Shaklan (JPL)	30
9:45 – 9:55	Fundamental performance limits in the presence of aberration	Belikov (NASA Ames) (Remote)	15
9:55 – 10:05	Fundamentals of low-order wavefront sensing/td>	Kasdin (Princeton)	10
10:00 – 10:15	Photon limit of sensitivity for detecting low-order wavefront changes	Traub (JPL)	15
10:15 – 10:45	Predictive controllers, self-tuning	Poyneer (LLNL) (Remote)	30
10:45 – 11:05	A practical guide to linear quadratic gaussian controllers	Lozi (UofArizona)	20
11:05 – 11:20	break		15
11:20 – 12:20	STRO-ESI effort, low-order wavefront control for high contrast imaging: findings	Guyon (UofArizona)	60
12:20 – 12:35	Fundamentals: Discussion		15
12:35 – 13:30	LUNCH		
	AFTA-WFIRST (2h)		
13:30 – 13:50	Wavefront effects from thermal changes expected for AFTA	Kuan & Content (GSFC)	20
13:50 – 14:10	Wavefront effects from vibration and jitter expected for AFTA	Content (GSFC)	20
14:10 – 14:30	Impact and relevance for WFIRST-AFTA science	Traub/Macintosh (JPL/LLNL)	20
14:30 – 15:00	AFTA coronagraph LOWFS status and trade study, telescope simulator plans	Shi/Wallace (JPL)	30
15:00 – 15:30	Discussion		30
15:30 – 15:45	break		15
	Laboratory pointing/LOWFS/C testbeds, systems and demos (2h)		
15:45 – 16:15	Ames/Lockheed LOWFS system	Lozi/Bendek (UofArizona)	30
16:15 – 16:45	HCIT/PIAA LOWFS system	Kern/Trauger (JPL)	30
16:45 – 17:15	UofA LOWFS testbed (part of STRO-ESI funded effort)	Miller (UofArizona)	30
17:15 – 17:45	Discussion		30

Presentations are available on the website

Time	Day 2		
	Current ground-based systems: Hardware approaches, system-level considerations (2h)		
9:00 – 9:30	Low order aberrations control & PSF calibration on Gemini Planet Imager	Macintosh/Poyneer (LLNL)	30
9:30 – 10:00	Low order aberrations control & PSF calibration on P1640	Vasisht (JPL)	30
10:00 – 10:30	Low order aberrations control & PSF calibration on SCExAO	Jovanovic & Singh (Subaru)	30
10:30 – 11:00	Discussion, relevance to NASA missions		30
11:00 – 12:30	HCIT & Starshade tours		
12:30 – 13:30	LUNCH		
	PSF calibration and resonstruction (2h)		
13:30 – 14:00	Overview/history of PSF calibration, HST experience	Soummer (STScI)	30
14:00 – 14:30	Ground-based : Magellan, LBT	Males (UofA)	30
14:30 – 15:00	PSF calibration with IFUs	Pueyo (STScI)	30
15:00 – 15:30	Discussion		30
15:30 – 15:45	break		
15:45 – 17:15	**Path forward: Future NASA missions, technology development planning (1h30)**		
	Goals, program schedule	Blackwood (JPL)	30
	Discussion, effort planning		60

Outline (roughly follows workshop schedule)

Relevance to Exoplanets Direct Imaging

Coronagraphs sensitivity to low-order aberrations
- **Full apertures**
- **Segmented apertures**

Low order wavefront sensing

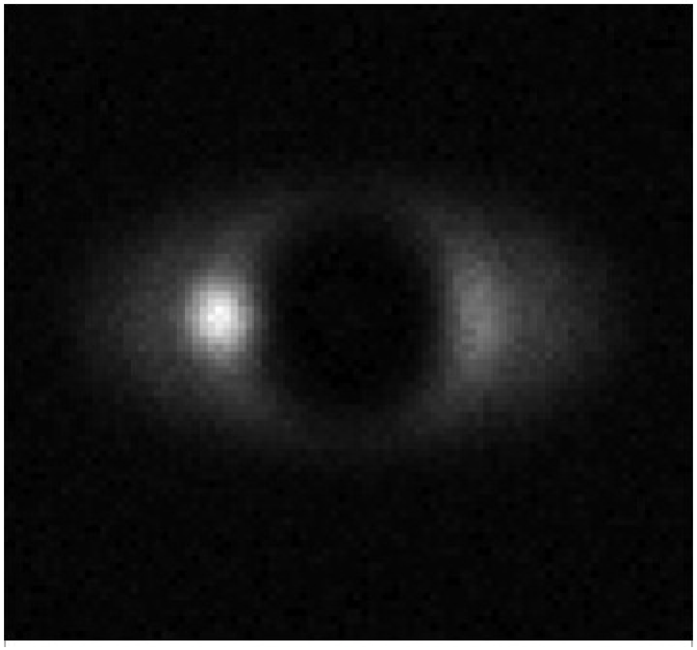
Control algorithms

AFTA-WFIRST

Lab testbeds & Ground-based systems

PSF calibration & reconstruction

Relevance to exoplanet direct imaging



← Simulated image of an exoplanet near the coronagraphs's IWA <u>in the absence of low order aberrations</u>

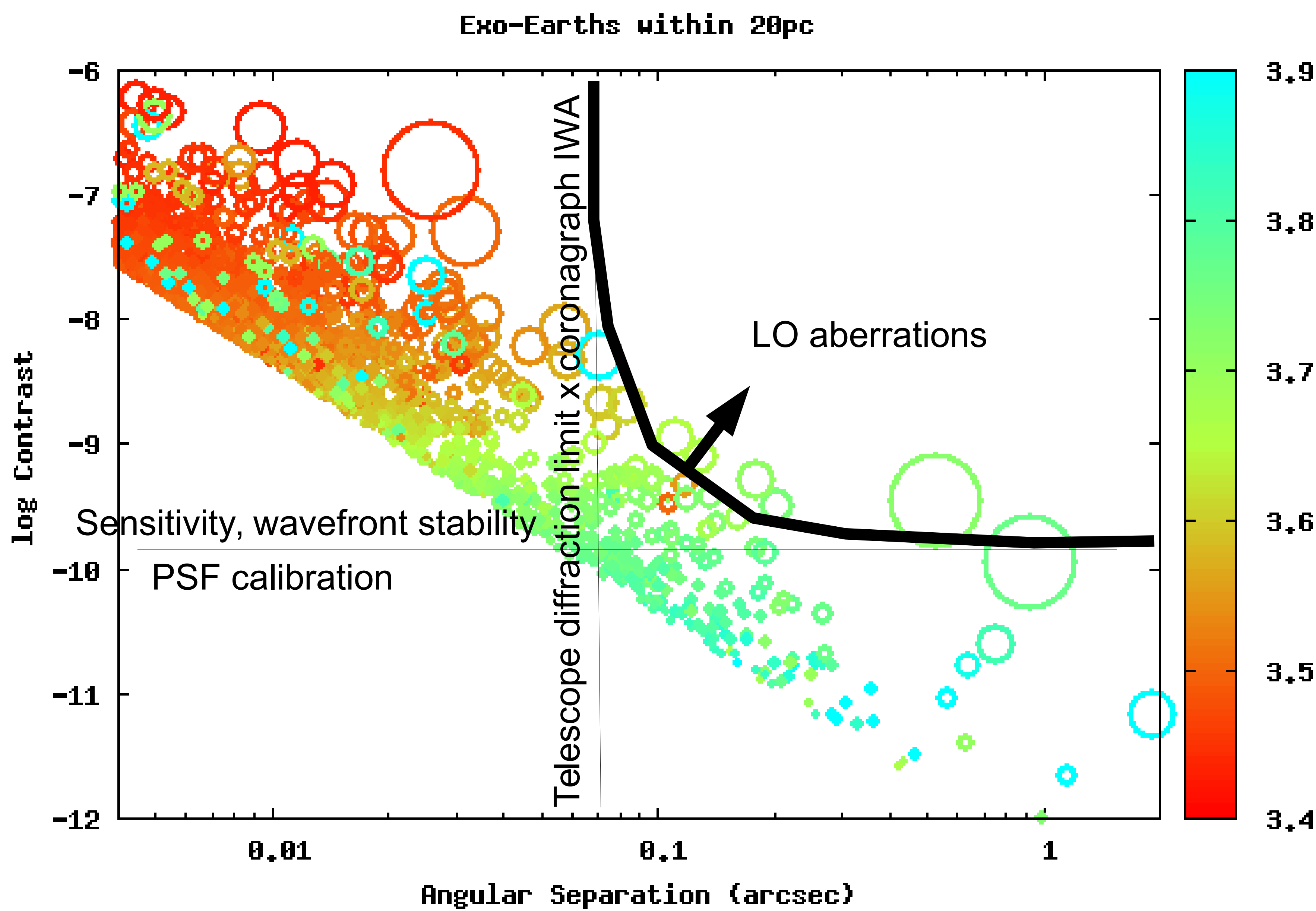
[1] Low-order aberrations will add light in the search region of the coronagraph, and create an uneven ring of light around the focal plane mask (from IWA to IWA+angular resolution)
→ poorer raw contrast
→ confusion between exoplanet(s) and stellar leakage

[2] Low-order aberrations (pointing, focus) are most easily excited in the optical system:
- Telescope pointing jitter induced by reaction wheels
- Ridig body motions of optics induced by thermal effects and vibrations

[3] Low-order aberrations are mostly **restricting the coronagraph's IWA**, which is key to mission science return
- Low-IWA coronagraphs are the most sensitive to low-order aberrations

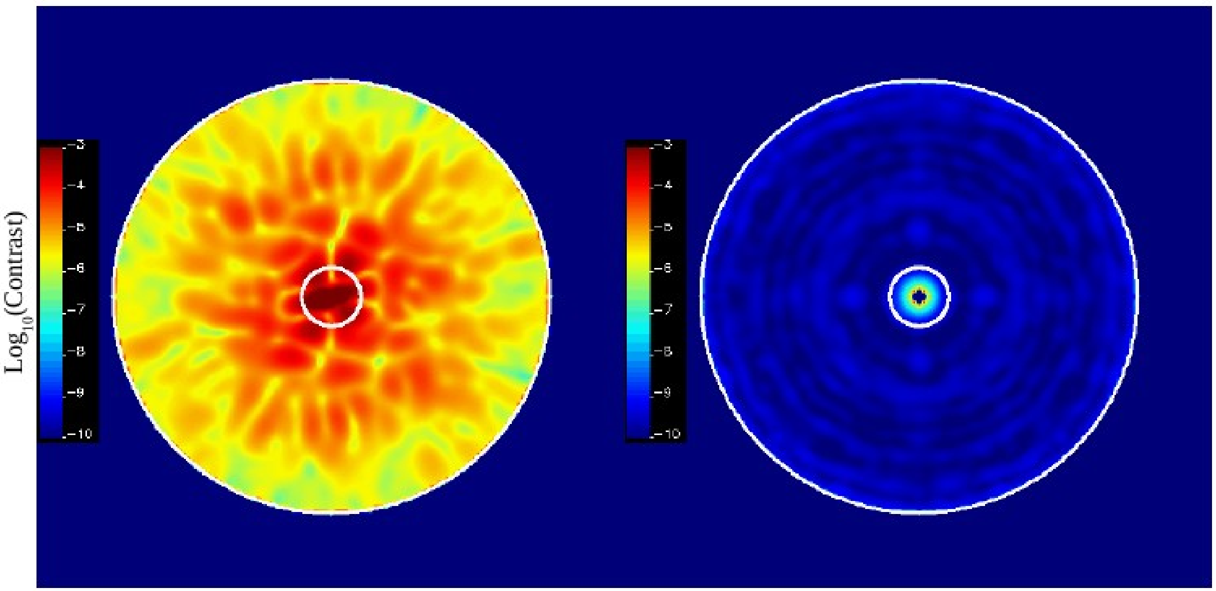
→ Control and calibration (PSF subtraction) of low-order aberrations is key to mission success

Relevance to exoplanet direct imaging



Coronagraph sensitivity to low-order aberrations (Figures from J. Krists' presentation)

Before wavefront control | After wavefront control

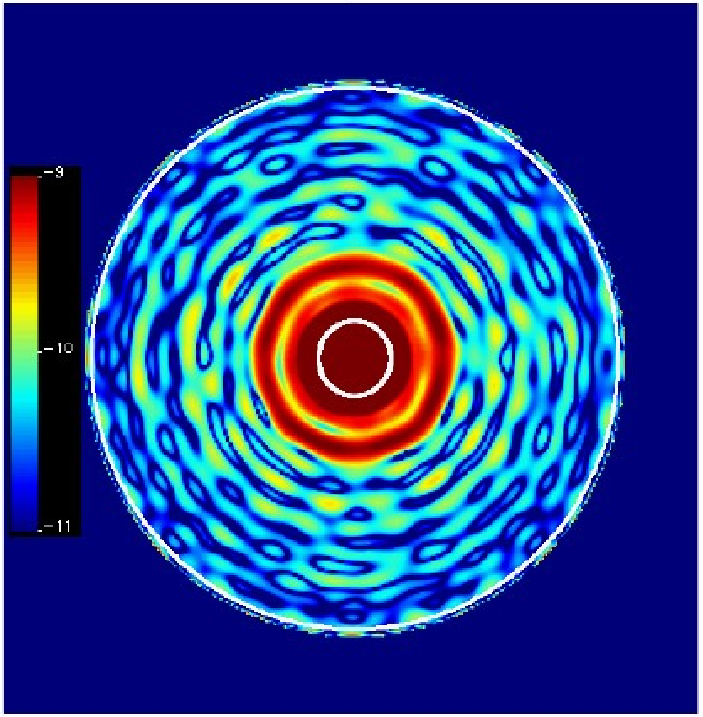


Mean contrast = 2 x 10^{-5}
(at IWA = 2 x 10^{-4})

Mean contrast = 2 x 10^{-10}
(at IWA = 2 x 10^{-10})

Circles are r = 2.2 & 16 λ/D

Δ = 226 pm RMS



- Smaller IWA coronagraphs tend to be more sensitive (there are fundamental reasons for that)
- Coronagraphs can, to some extent, be designed to mitigate LO aberration sensitivity
- There exists a well defined fundamental limit defining how sensitive coronagraphs systems have to be as a function of contrast and IWA (R. Belikov's presentation)

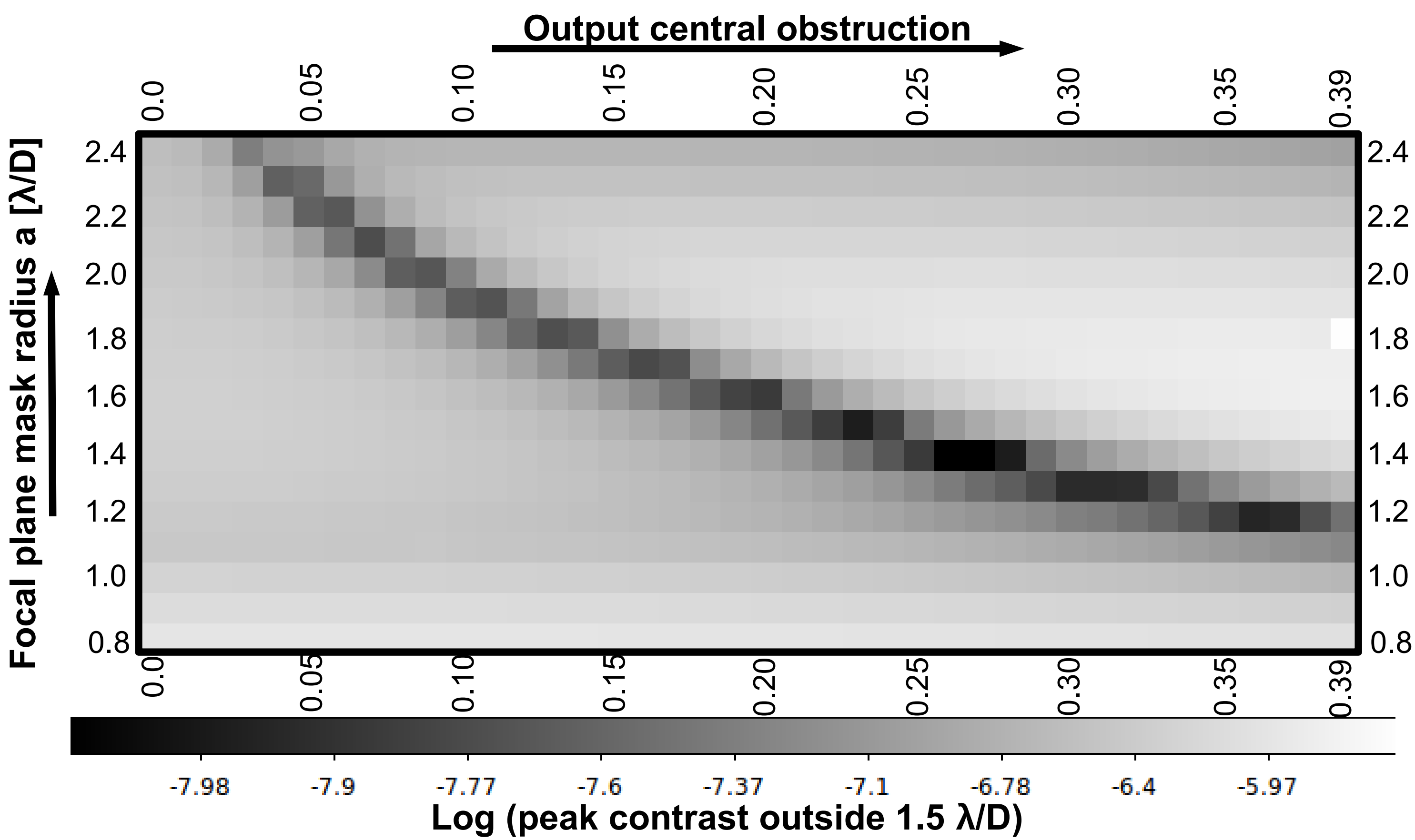
[Presentations: Krist, Shaklan, Belikov, Guyon, Traub]

Coronagraph design can mitigate sensitivity to low-order aberrations

Example: Centrally obscured pupil PIAACMC design optimization, 2% l/D disk

~ two orders of magnitude contrast difference between badly tuned PIAACMC and tuned PIAACMC

For 0.3 output central obstruction, IWA = 1.4 design is much better than IWA = 1.8 l/D design, even when working at ~3 l/D



Segmented abertures (ESI effort, PI: Guyon)

Future large space telescopes, able to take spectra of habitable planets, will likely be segmented and centrally obscured.
Coronagraph solutions exist for such apertures.

Segment motion / cophasing is significant challenge: segments would need to be held / calibrated at pm level for 1e10 contrast

$$\text{Contrast}(r<\lambda/d) = d\varphi^2 / N$$

Number of segments

Cophasing error [rad]

Important scaling rules:

More segments = relaxed requirement if motions are uncorrelated

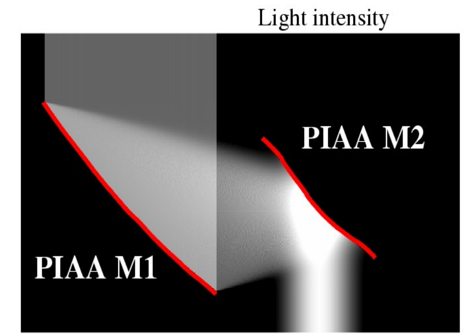
But, stability timescale is identical

TABLE 1: Segment cophasing requirements

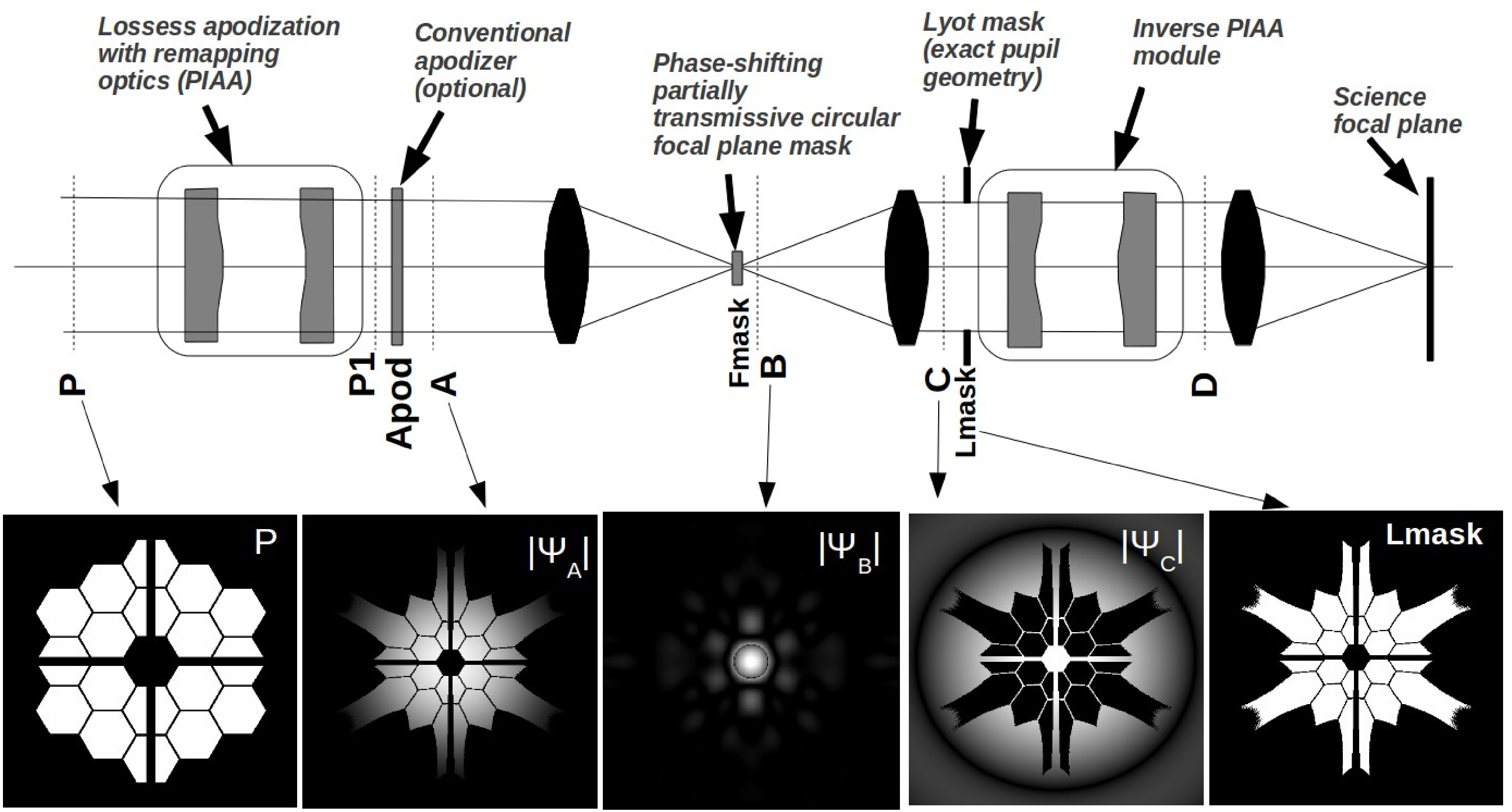
Telescope diameter (D) & λ	Number of Segments (N)	Contrast	Target	Cophasing requirement	Stability timescale
Ground-based telescope					
10 m, 1.6 μm	36	1e-6	m_V=8	1.5 nm	21 ms
30 m, 1.6 μm	10	1e-6	m_V=8	0.8 nm	2.3 ms
30 m, 1.6 μm	1000	1e-6	m_V=8	8.1 nm	2.3 ms
Space-based telescope					
4 m, 0.55 μm	10	1e-10	m_V=8	2.8 pm	22 mn
8 m, 0.55 μm	10	1e-10	m_V=8	2.8 pm	5.4 mn
8 m, 0.55 μm	100	1e-10	m_V=8	8.7 pm	5.4 mn

[Presentation: Guyon]

PIAACMC : example coronagraph for segmented aperture



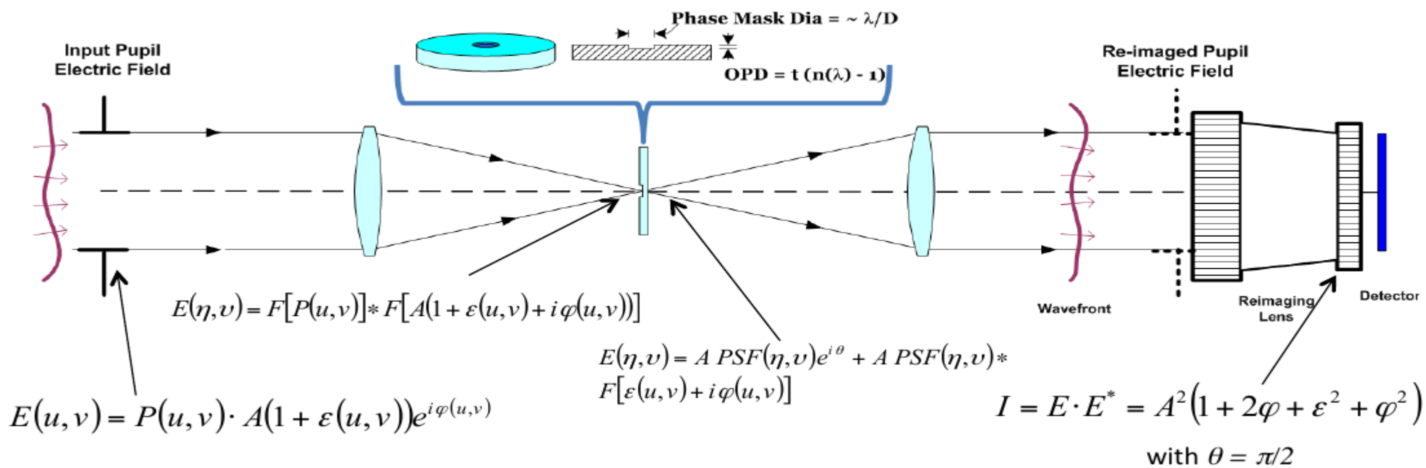
Phase Induced Amplitude Apodized Complex Mask Coronagraph (PIAACMC)

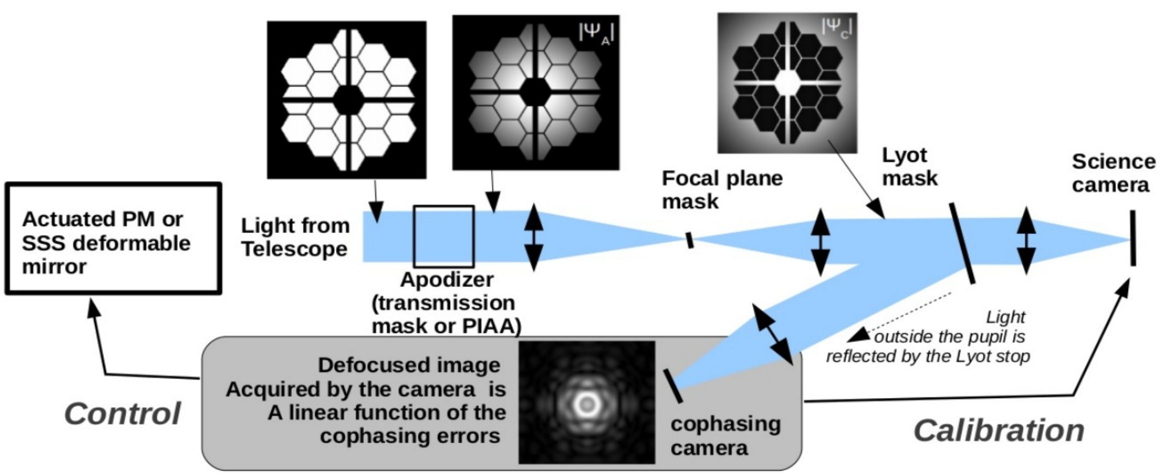


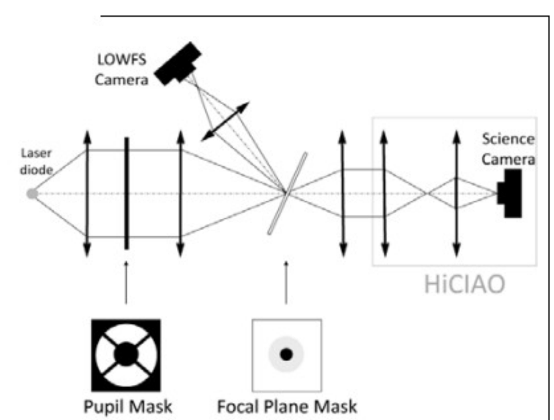
Low Order Wavefront Sensing

Approach:
Use startlight that the coronagraph rejects to measure pointing errors and other low order modes: direct imaging of the light spot, or phase constrast reveals low-order aberrations

- Opaque focal plane mask: use light reflected by the focal plane mask
- Phase mask: use light reflected by the Lyot stop





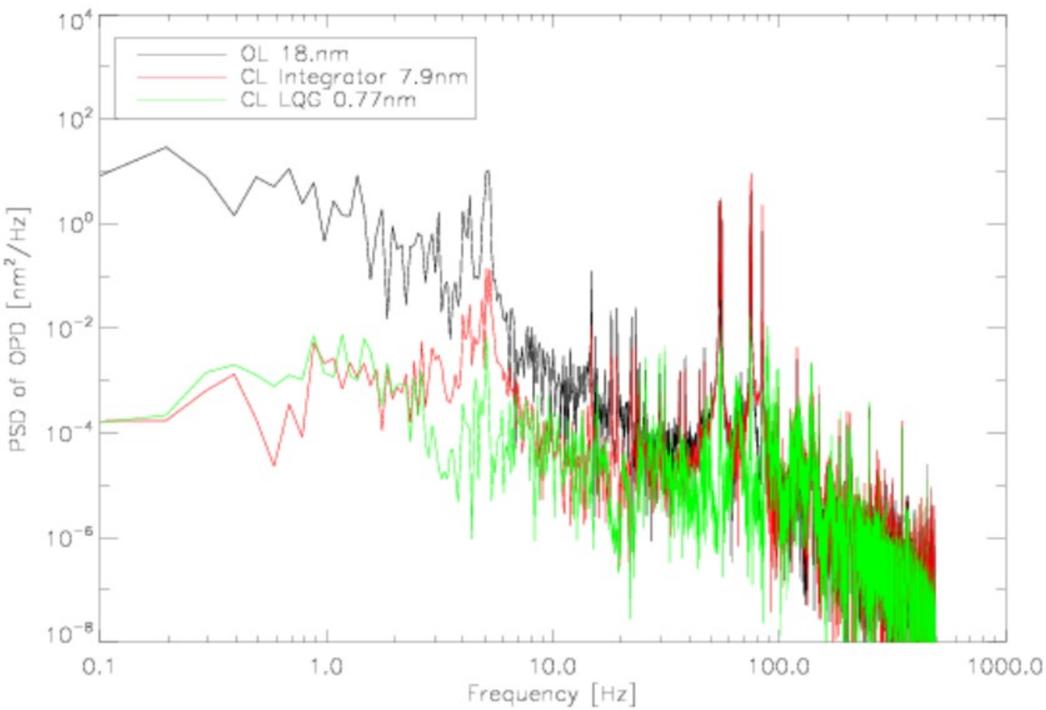


[Presentations: Guyon, Traub, Kern, Trauger, Lozi, Miller, Shi, Wallace]

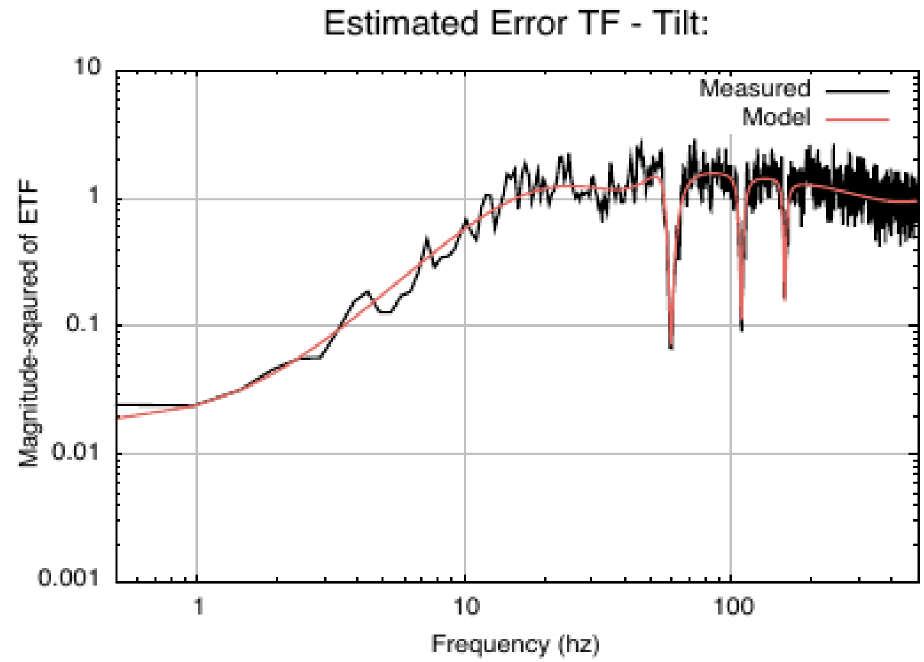
Control algorithms

Tuning control loop to disturbances is essential for high performance control of low-order modes

Vibrations can be efficiently removed



Example performance on lab bench (Lozi)
Input disturbance: 18nm
Standard integrator control: 7.9nm
Linear Quadratic Gaussian / Kalman filter: 0.77nm

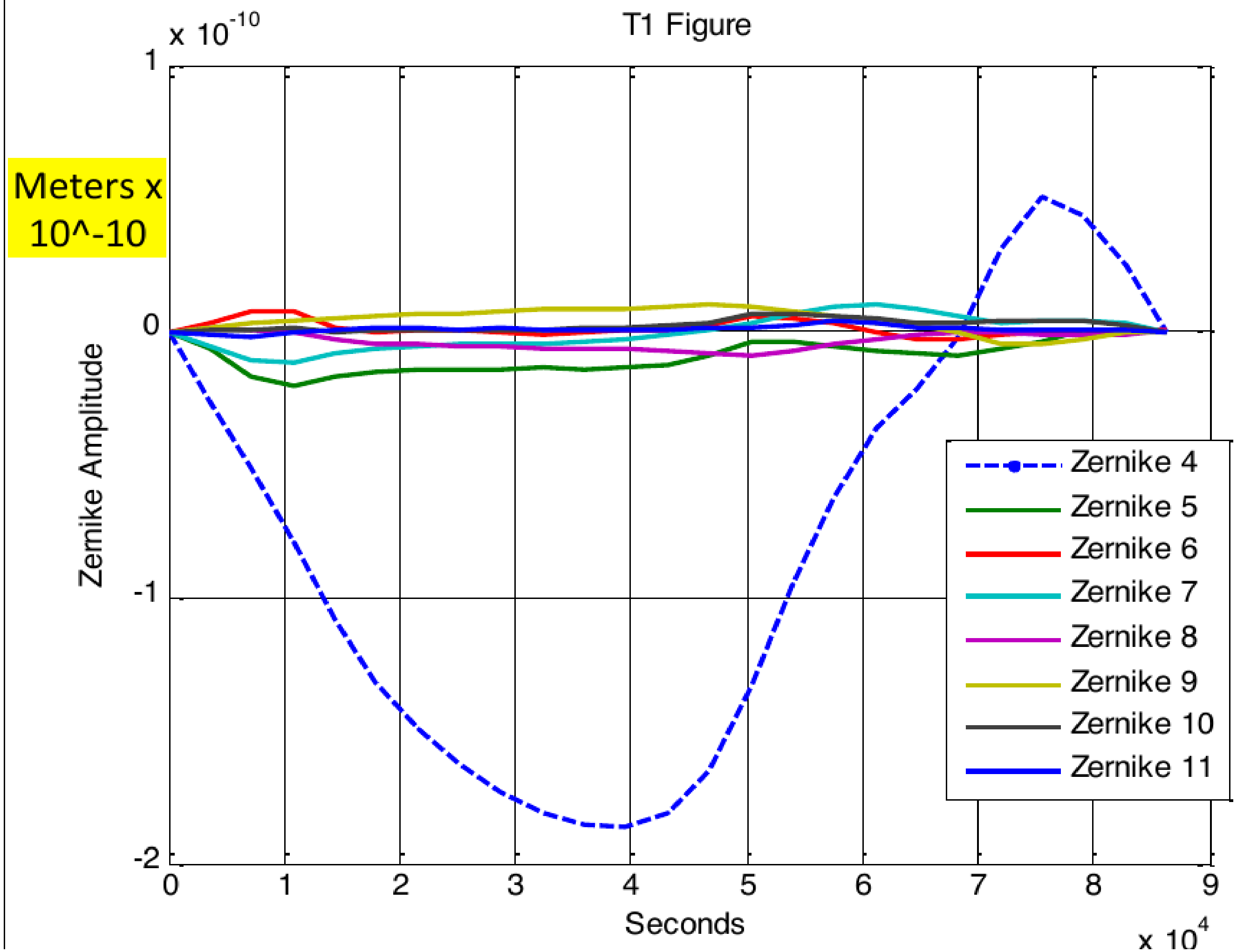


Example: GPI testing in lab demonstrates ability to notch out vibration frequencies

[Presentations: Poyneer (overview), Lozi (LQG practical guide)]

AFTA-WFIRST : Thermal disturbances are slow, and relatively easy to control

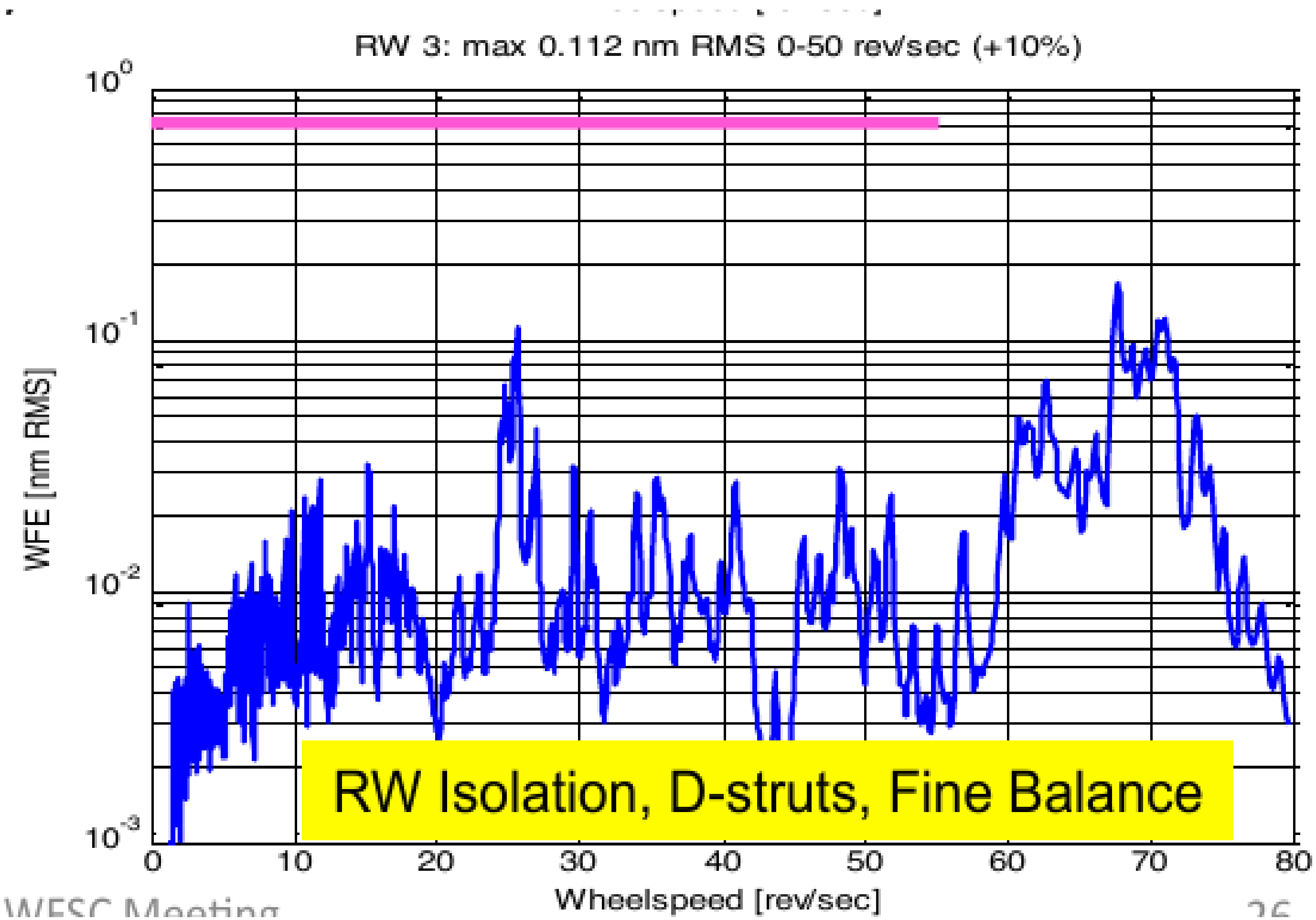
T1 Zernike Amplitudes Over 24 Hours for STOP Fixed Attitude Case



- T1 WFE is also very stable
- Dominant term is focus, ~0.2 nm Δ over 12 hours (easily correctable by LOWFS/C)
- Other low order WFE terms <20 pm over 12 hours
- Well received by Coronagraph Team

[Presentations: Kuan & Content (thermal), Content (vibration/jitter), Shi/Wallace (LOWFS)]

AFTA-WFIRST : Vibrations induced by reaction wheels require fast LOWFS / correction



Controlling vibrations > ~50Hz is challeniging with LOWFS

Ongoing modeling suggests this is an issue that will affect coronagraph performance Can be addressed by LOWFS optimization, control algorithm and PSF calibration

Integrated modeling of LOWFS under way (Shi/Wallace)

[Presentations: Kuan & Content (thermal), Content (vibration/jitter), Shi/Wallace (LOWFS)]

Testbeds, systems

Sensing and control of low-order aberrations for high contrasting imaging developped and demonstrated on multiple testbeds and systems:

Lab:

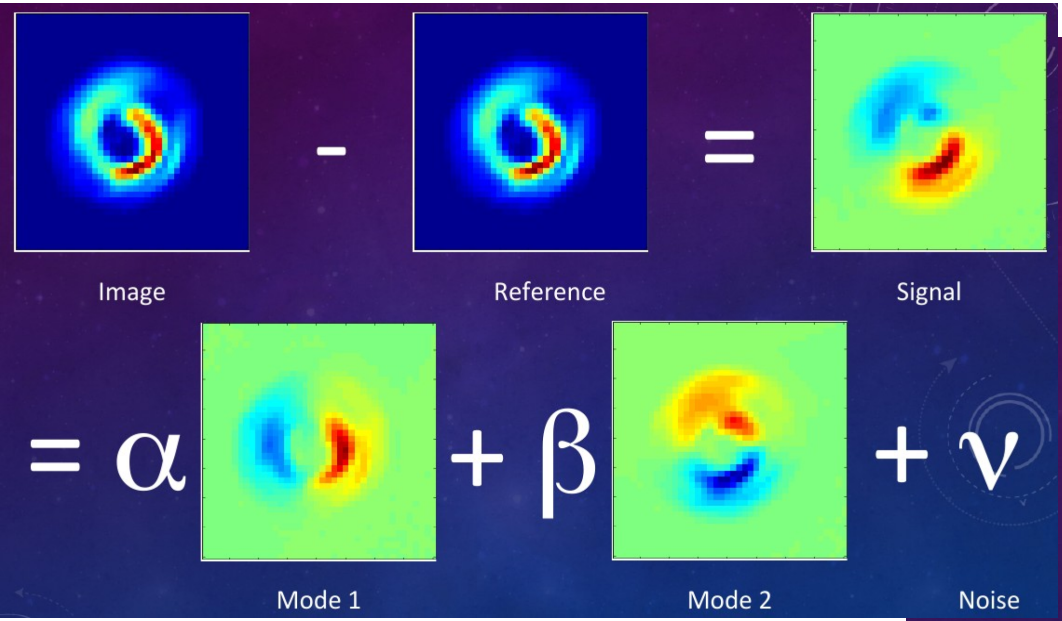
- JPL HCIT LOWFS on PIAA coronagraph
- NASA Ames LOWFS (EXCEDE, AFTA-FIRST)
- UofA (for segmented and centrally obscured systems)

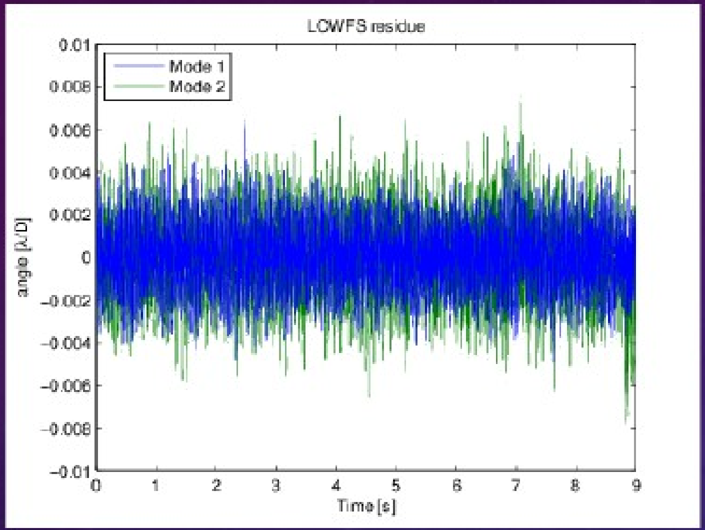
Ground:

- LOWFS on Subaru system
- Low order control on GPI
- Low order control on P1640

[Presentations: Lozi, Kern, Trauger, Bendek, Miller, Jovanovic, Singh, Macintosh, Poyneer, Vasisht]

Ames testbed: ~2e-3 l/D closed loop control





- Open-loop:
  - X-axis: 6×10^{-3} λ/D rms
  - Y-axis: 9×10^{-3} λ/D rms
- Closed-loop:
  - X-axis:

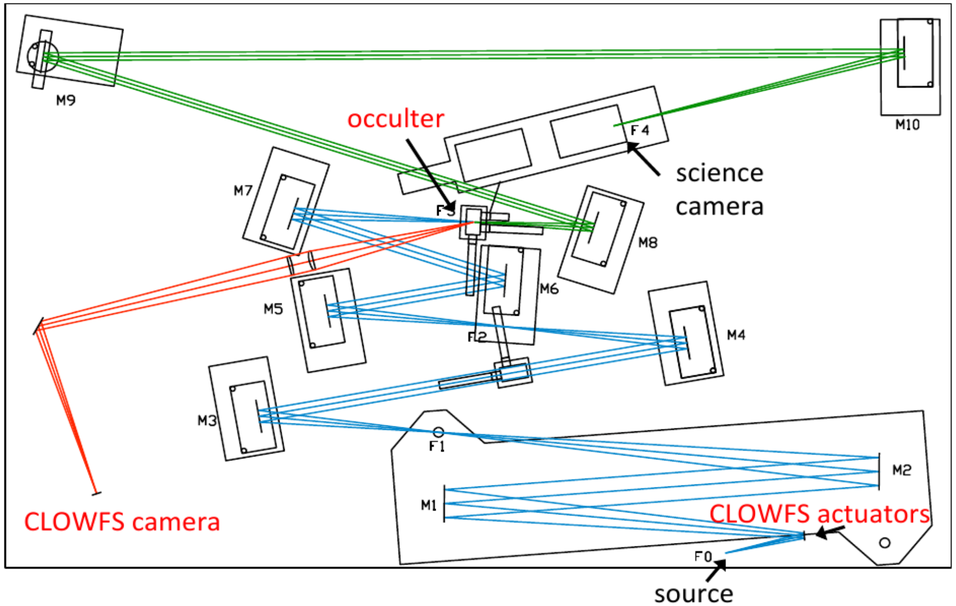
    1.5×10^{-3} λ/D rms
  - Y-axis:

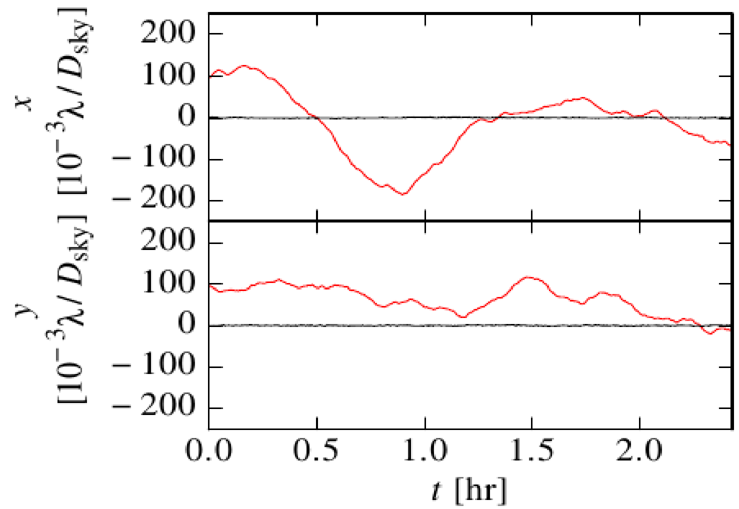
    2×10^{-3} λ/D rms

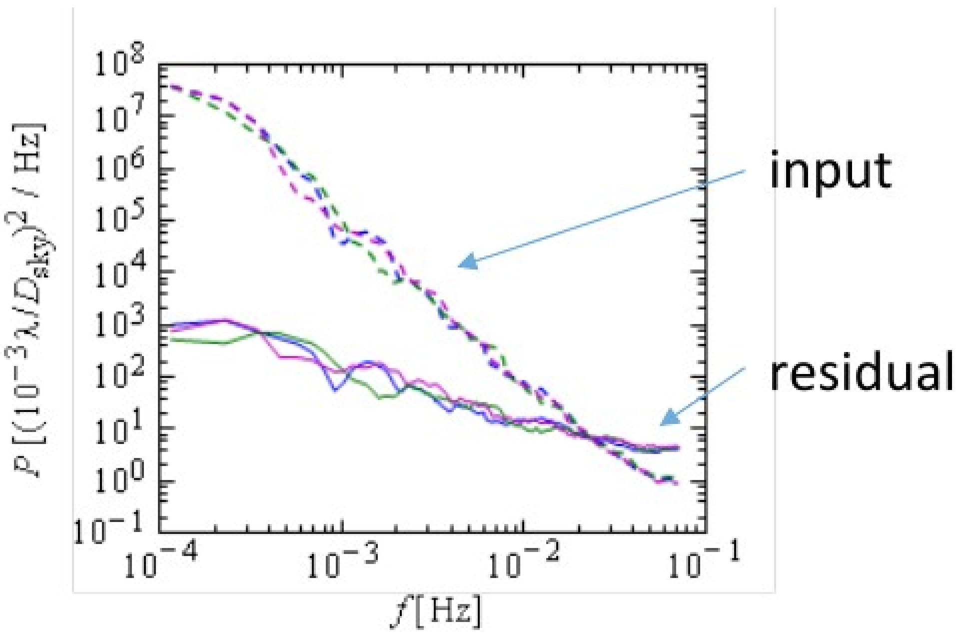
- Limited by vibrations
  - 25 Hz: vibration of the testbench
  - 50 Hz, 120 Hz: vibrations of mounts
  - 60 Hz: electronics
- A LQG controller could reduce those vibrations (x: 10^{-3} λ/D, y: 1.5×10^{-3} λ/D)

[Presentation: Lozi & Bendek]

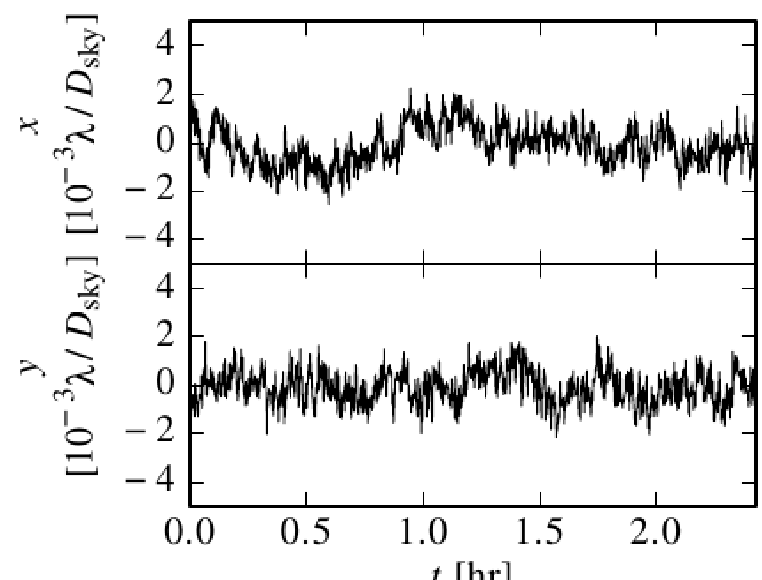
HCIT system with PIAA





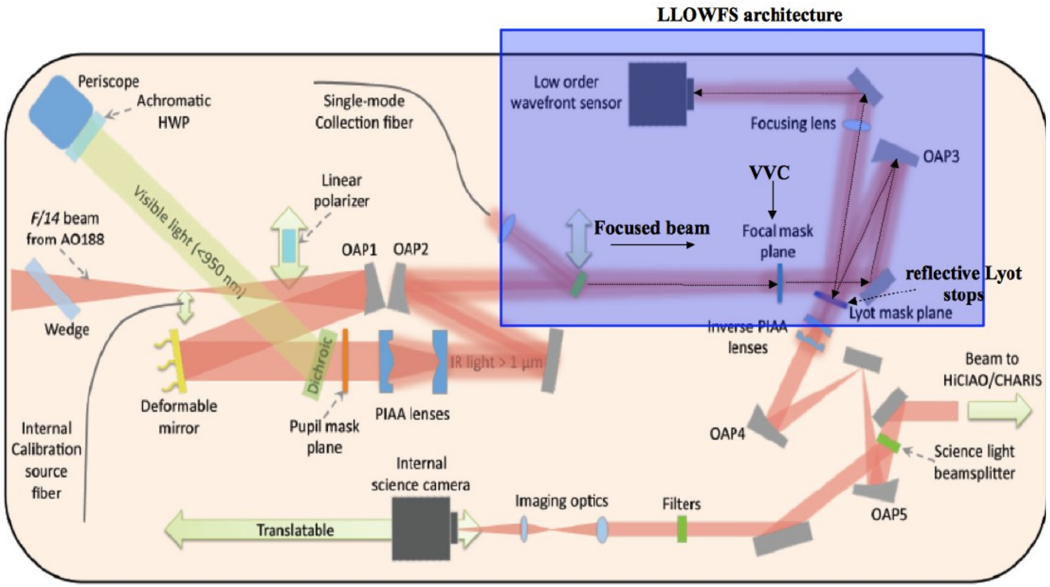


90 e-3 l/D disturbance
→ 1.1 e-3 l/D

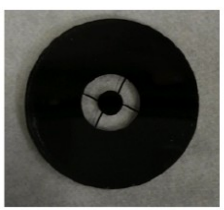


[Presentation: Kern]

Subaru LOWFS System (Light reflected by Lyot stop – demonstrated with Vortex, 4QPM, PIAA)



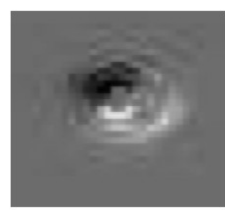
(a) Reflective Lyot Stop for VVC



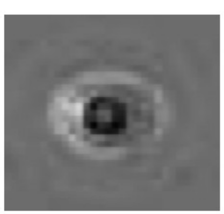
(b) Reference image

(c) Tip (30 nm rms)

(d) Tilt (30 nm rms

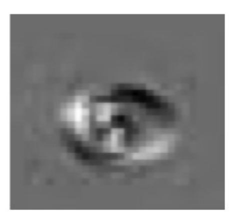


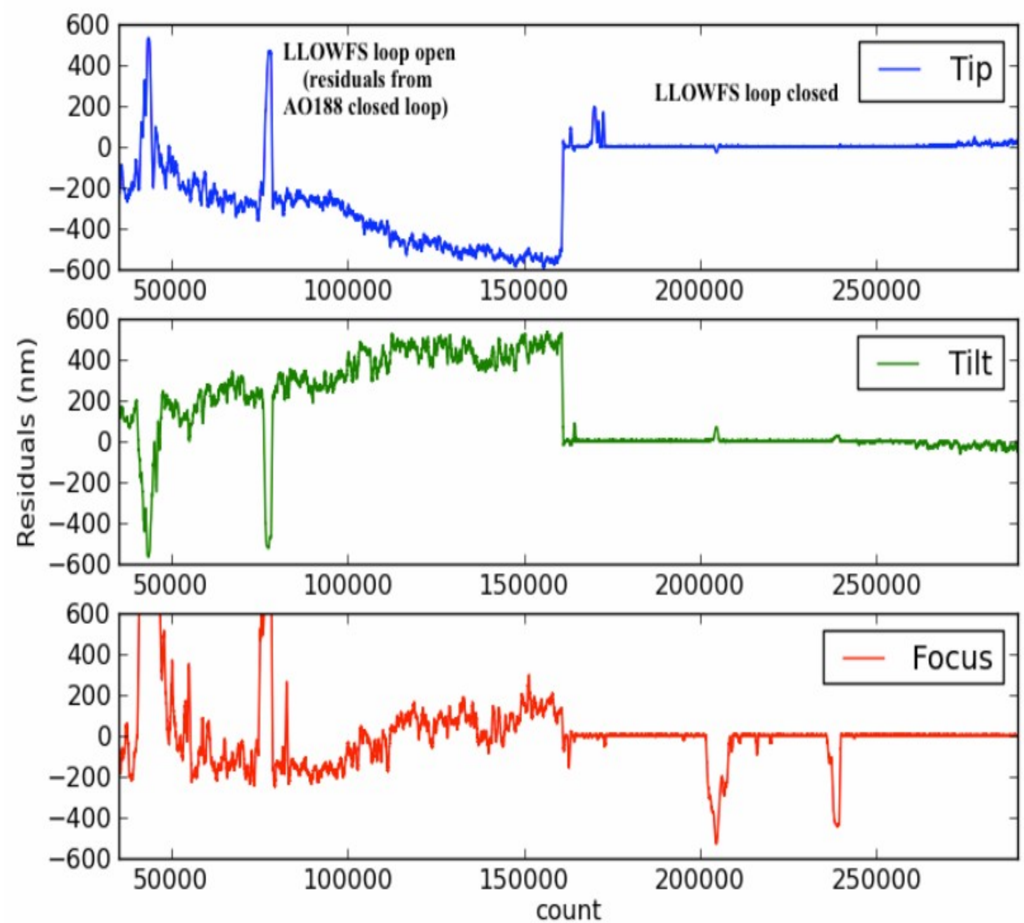
(e) Focus (30 nm rms)



(f) Oblique Astigmatism (30 nm rms)

(g) Right Astigmatism (30 nm rms)



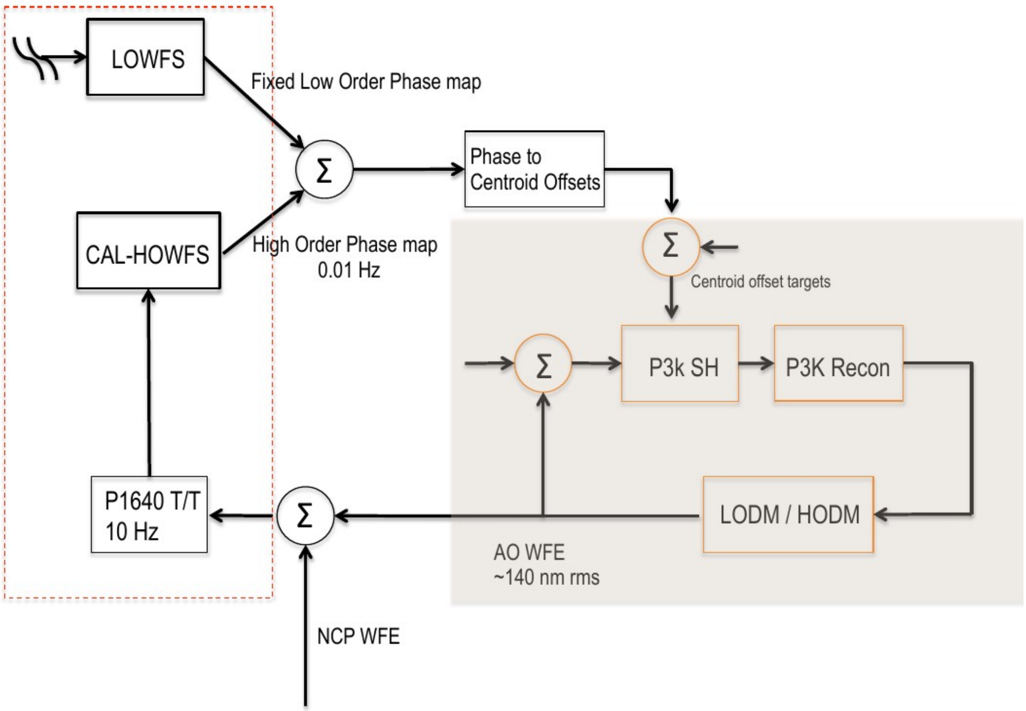


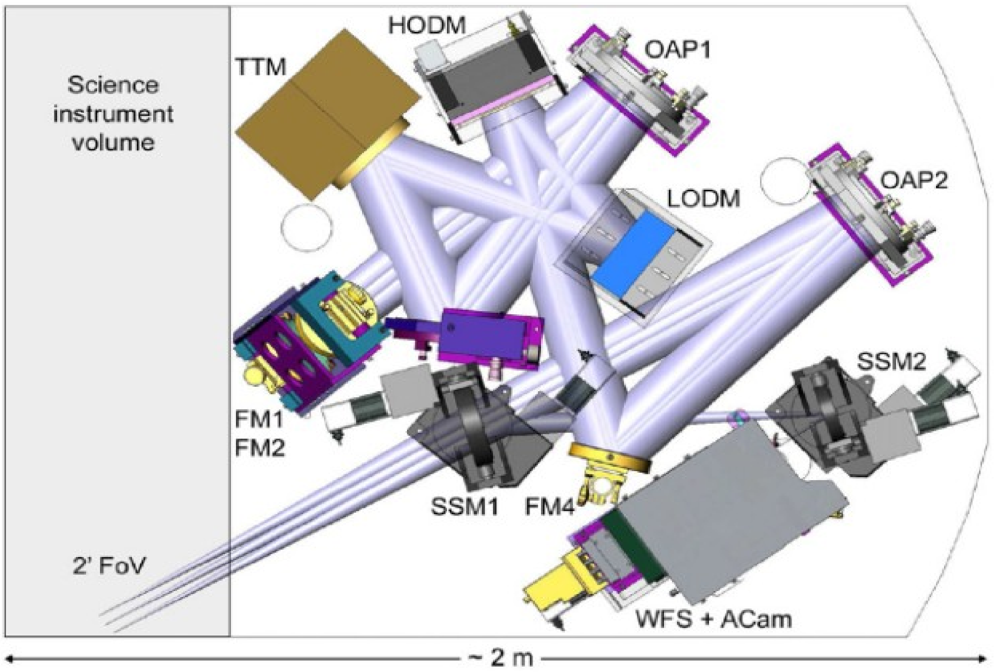
On-sky LOWFS control of TTF Residual <mas

[Presentation: Jovanovic & Singh]

PALM3000 / P1640 system

TT quad cell sensor + LOWFS (to dial out fixed low order aberrations) + high order sensor





[Presentation: Vasisht]

PSF calibration

This is a very large unknown in link between instrument design and science return.

Both ground-based and space (HST) systems have demonstrated the ability to perform PSF subtraction at the sub-% level
Currently using passive calibration (database of PSFs): ADI, LOCI

Active speckle control in dark field can be quite different problem. Active control may make PSF databases less relevant, but adds precious telemetry (speckle modulation)

More study needed to understand how well PSF can be calibrated on future space-based high contrast imaging systems

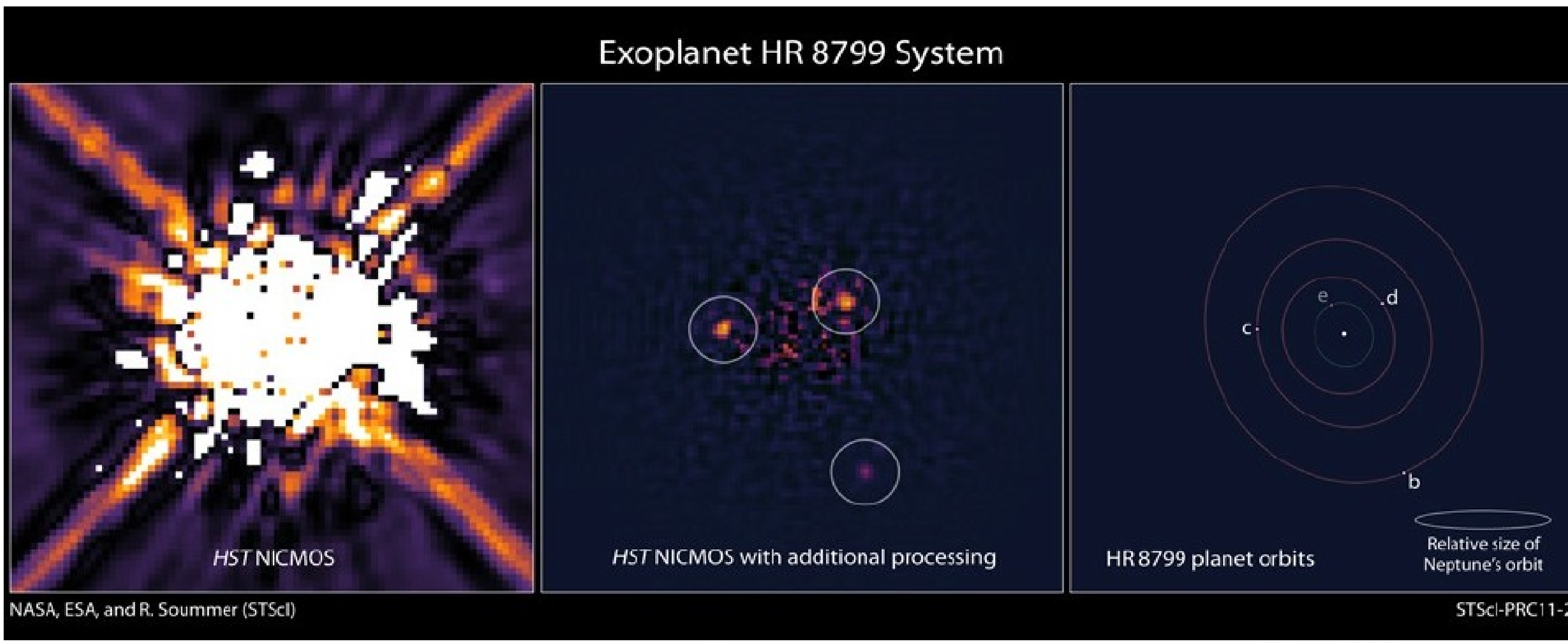
Experience from ground and HST will be helpful, but holds little predictive power at present.

[Presentations: Soumer, Males, Pueyo]

HST experience

HR8799 planets (imaged first from ground based telescopes) recovered in 1998 HST images
PSF calibration tools and experienced developed after years of HST experience

HR8799 b,c,d imaged by HST in 1998



planet b: Δm=12.3 at 1.72 arcsec

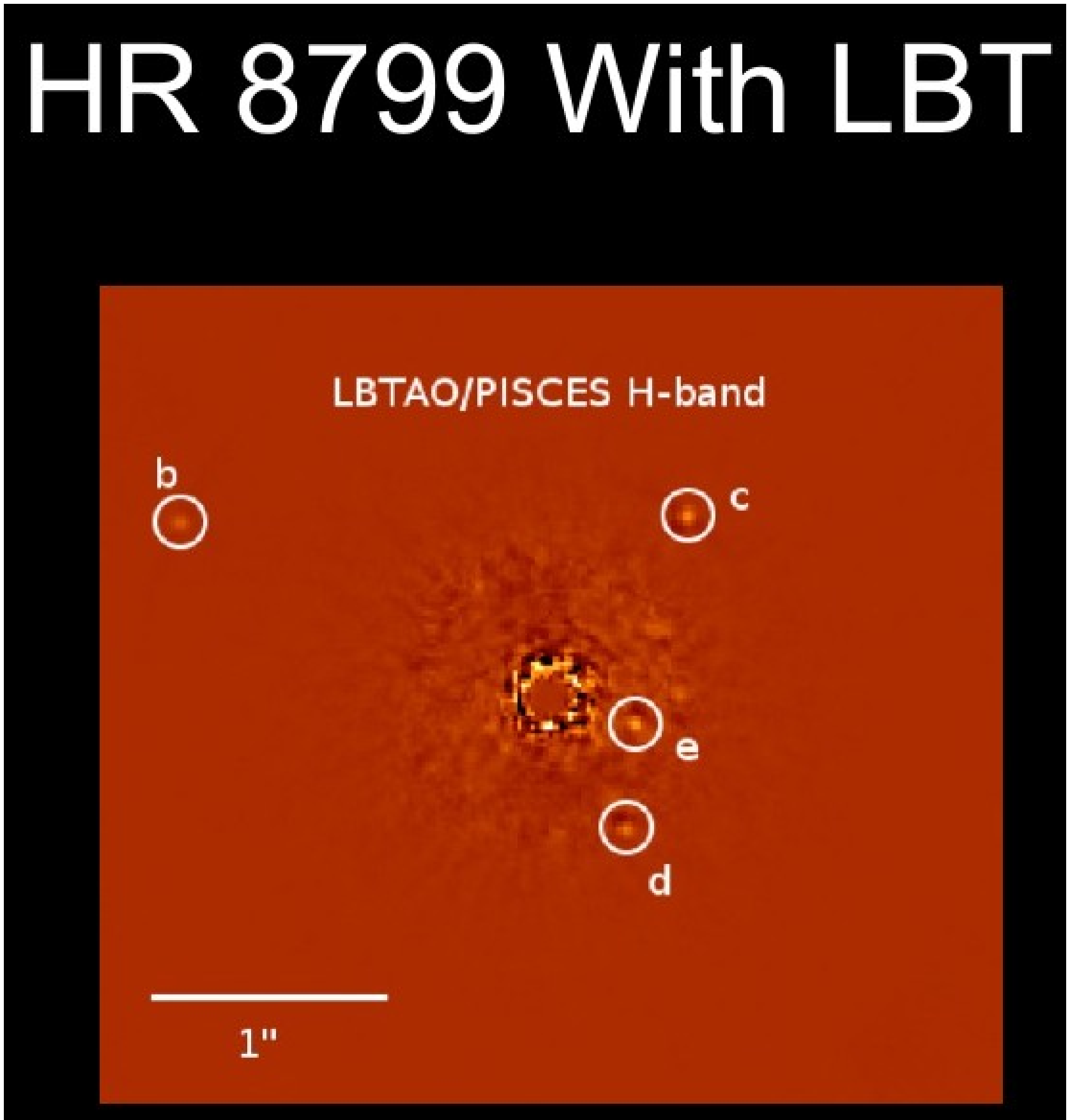
planet c: Δm=11.4 at 0.96 arcsec

planet d: Δm=11.3 at 0.60 arcsec

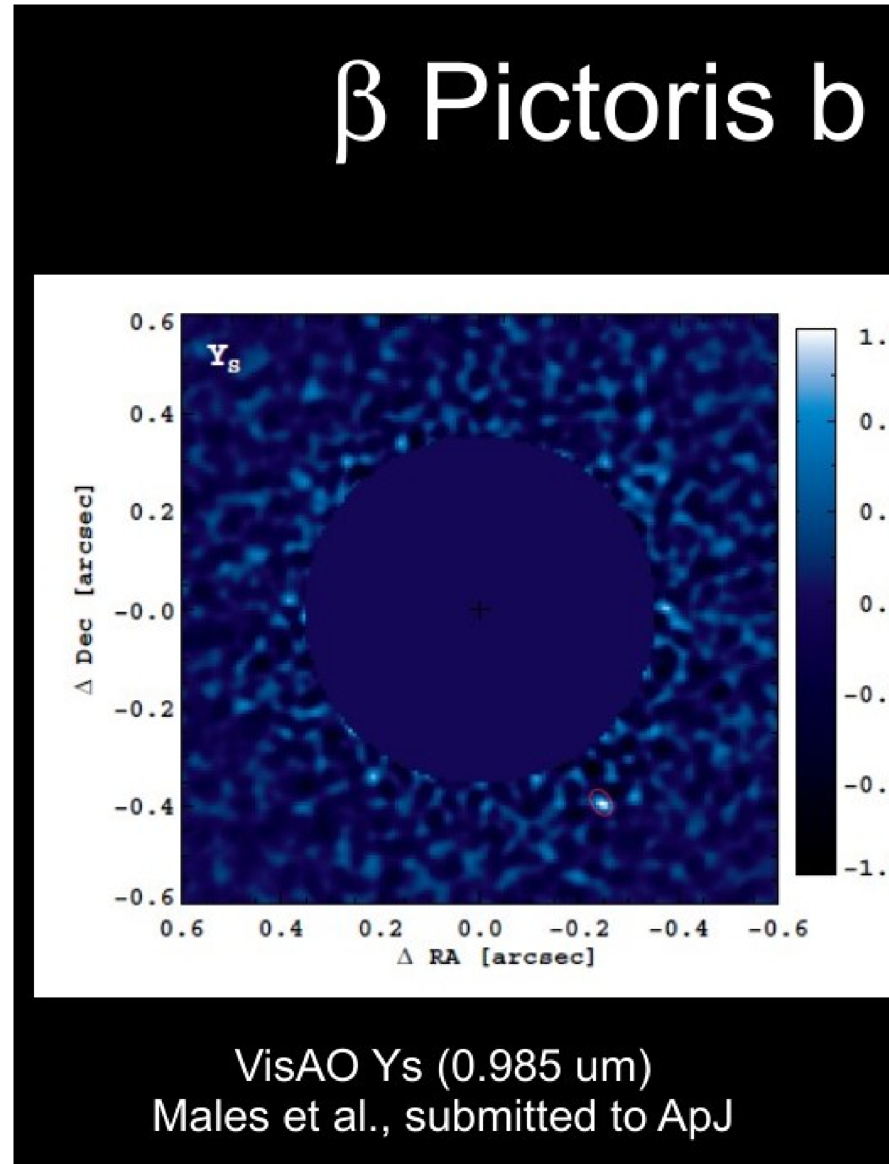
These results were made possible by post-processing speckle subtraction and achieve an order magnitude contrast improvement over the state of the art when the data was taken in 1998

Soummer et al. 2011

Ground experience : detection limit ~100x below raw contrast level thanks to post-processing

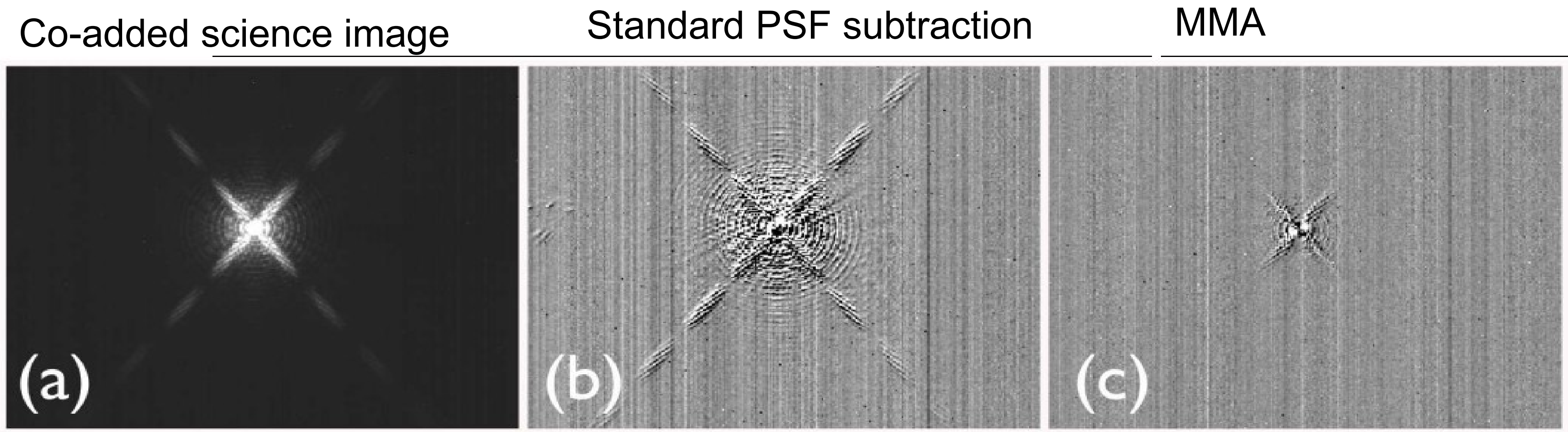


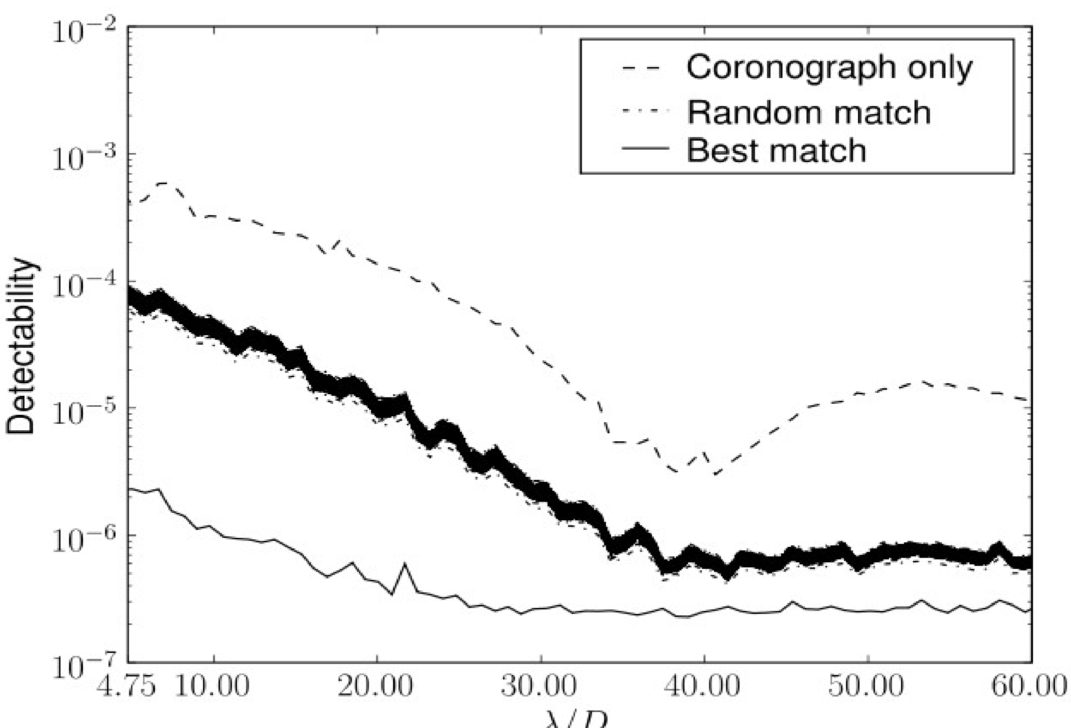
Skemer et al 2012



First CCD image of Beta Pic B

Using telemetry from LOWFS and speckle control can greatly improve PSF calibration





PSF calibration improved ~10x using LOWFS telemetry (Vogt et al. 2011)

Conclusions

Low-order aberrations pose a serious challenge to high contrast imaging

It is important to MEASURE low-order aberrations during observations:
- measurement can drive a control loop
- measurement will be used for PSF calibration, possibly in ways we do not yet understand

Thanks to a combination of disturbance modeling, LOWFS design/optimization, and PSF calibration modeling, we are now, for the first time, becoming able to PREDICT the detection limit for a future space telescope

Experience from HST and ground-based system will be precious: while working at different contrast levels, the fundamental challenges and solutions are similar.

Next workshop to be announced soon (late 2014)