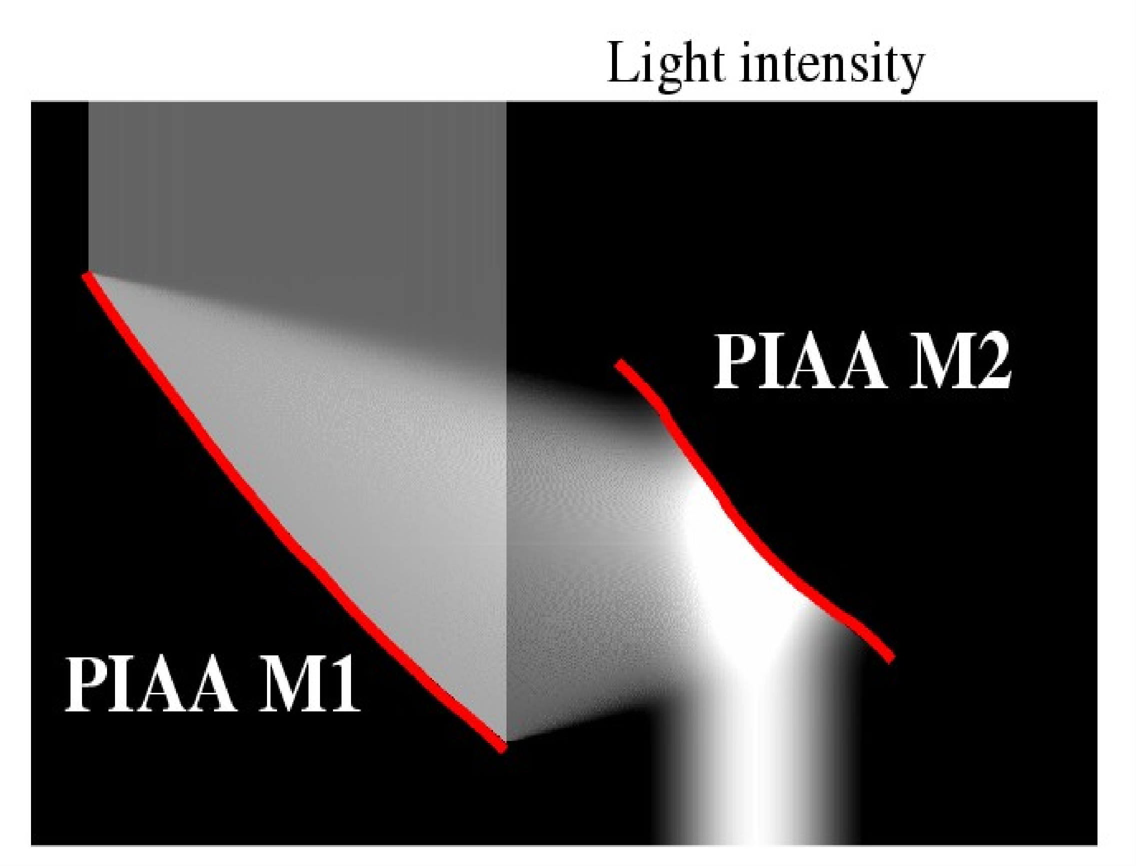
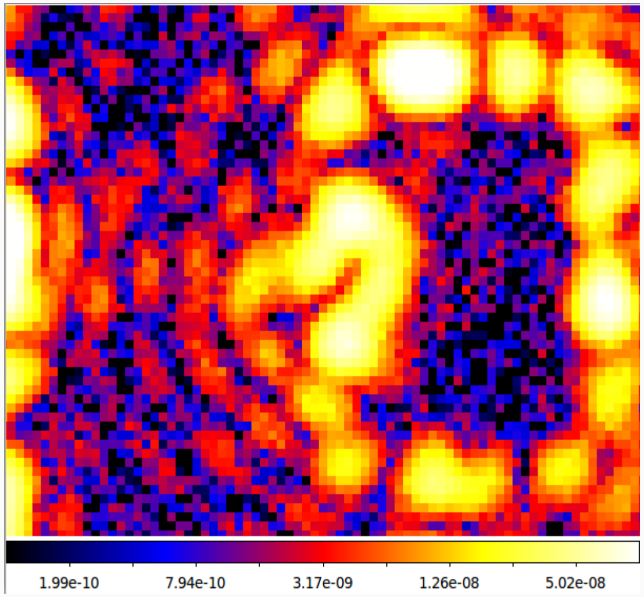
PIAA design for AFTA

Oct 24, 2013
PIAA team

Short intro to PIAA

Has demonstrated high efficiency coronagraphy between 2 and 4 l/D (5e-10 contrast in monochromatic light)





Has achieved 2.1e-8 contrast from 2 to 4 l/D in 10% band (with poor design for chromaticity)

Background

PIAA team recognizes huge importance of TT jitter and PSF calibration on science yield. This is especially relevant for PIAA designs, as they can be optimized for small IWA.

→ PIAA team plans to study 2 point designs:

Low-IWA design based (~1.3 l/D IWA) – design lead: Guyon

Large-IWA design (> 2l/D IWA) – design lead: Belikov

Decision between the two designs should ideally be made with adequate knowledge of TT jitter level post-WFS, and degree to which residual light due to TT jitter and stellar angular size can be calibrated.

→ not possible at present, as final telescope TT jitter level unknown

Due to time & resource constraints, J. Krist only to simulate 1 PIAA design for AFTA, so PIAA team needs to make decision which design to submit.

Large-IWA design work delayed due to govt shutdown → low-IWA design submitted to J. Krist on Oct 22, 2013

Low-IWA design submitted offers valuable assessment of :
(1) how PIAA can strongly benefit from reduced TT jitter and
(2) what architecture design features can mitigate impact of TT jitter on an otherwise jitter-sensitive coronagraph system

Design Overview

PIAACMC adopted. Compared to conventional PIAA currently tested in HCIT and Ames, PIAACMC offers some **advantages** and **challenges**:

- **Easier PIAA optics** (manufacturing, alignment)

- **Higher performance, with more flexibility** (more “knobs” can be turned) → can offer small IWA

But... small IWA performance contingent on ability to correct and calibrate low-order WF errors, and PSF subtraction

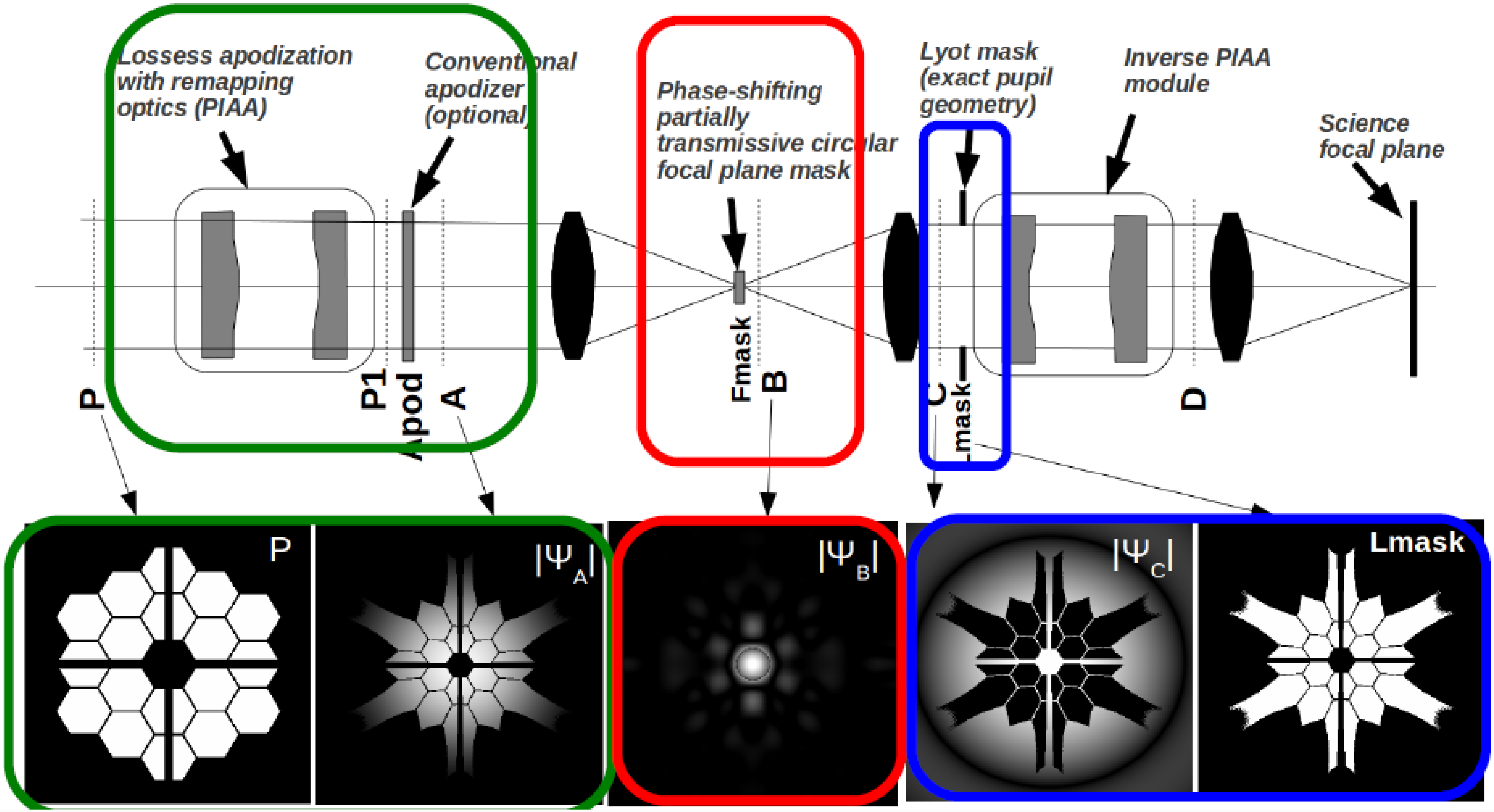
- **Requires variable transmission focal plane mask with phase**

How does PIAACMC work ?

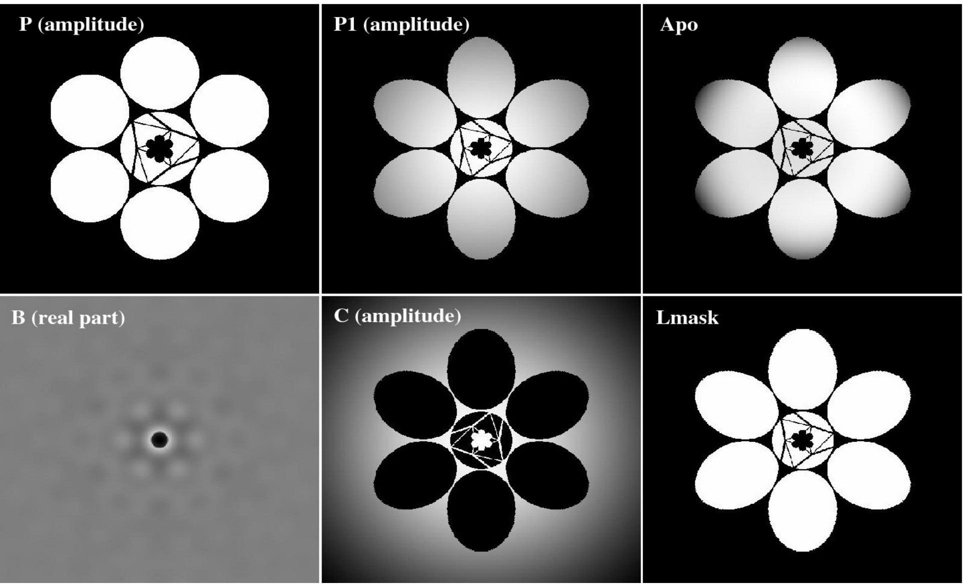
Combines 3 techniques :

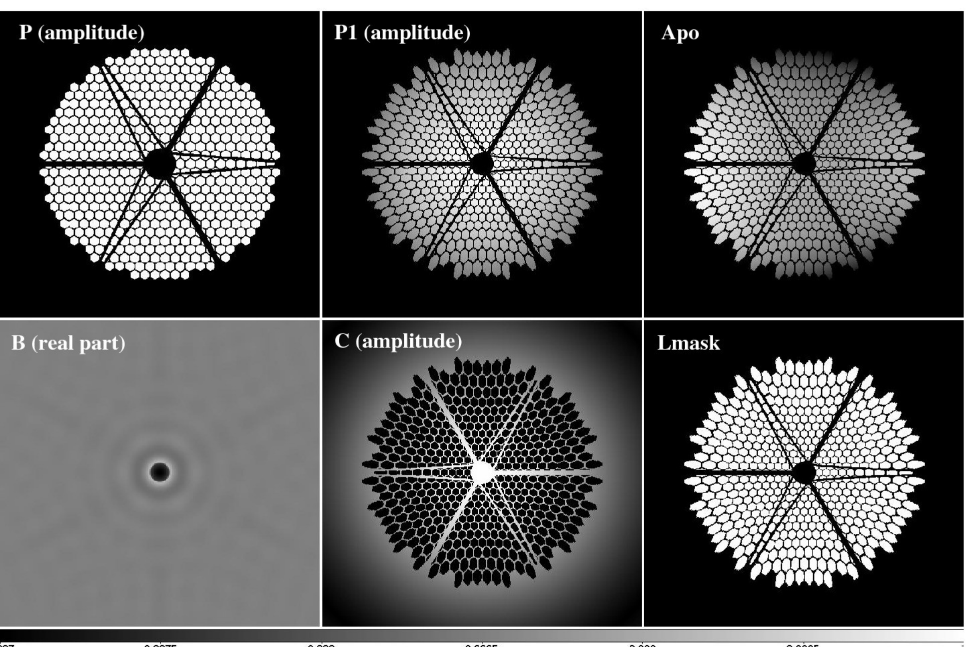
- **Lossless apodization with PIAA optics (beam shaping)**
- **Phase mask coronagraphy (focal plane mask is phase-shifting)**
- **Lyot coronagraphy (Pupil plane Lyot mask removes starlight)**

→ starlight rejection achieved by **destructive interference** between light that passes through the focal plane mask and light that passes outside the focal plane mask

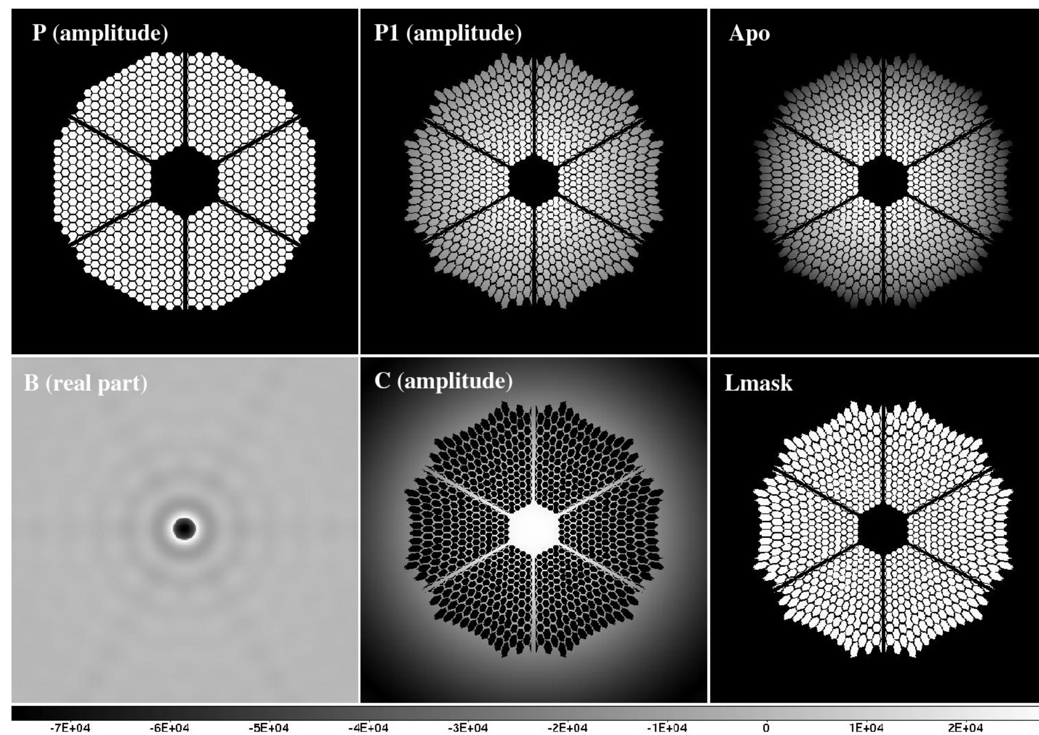


PIAACMC gets to < 1 l/D with full efficiency, and no contrast limit

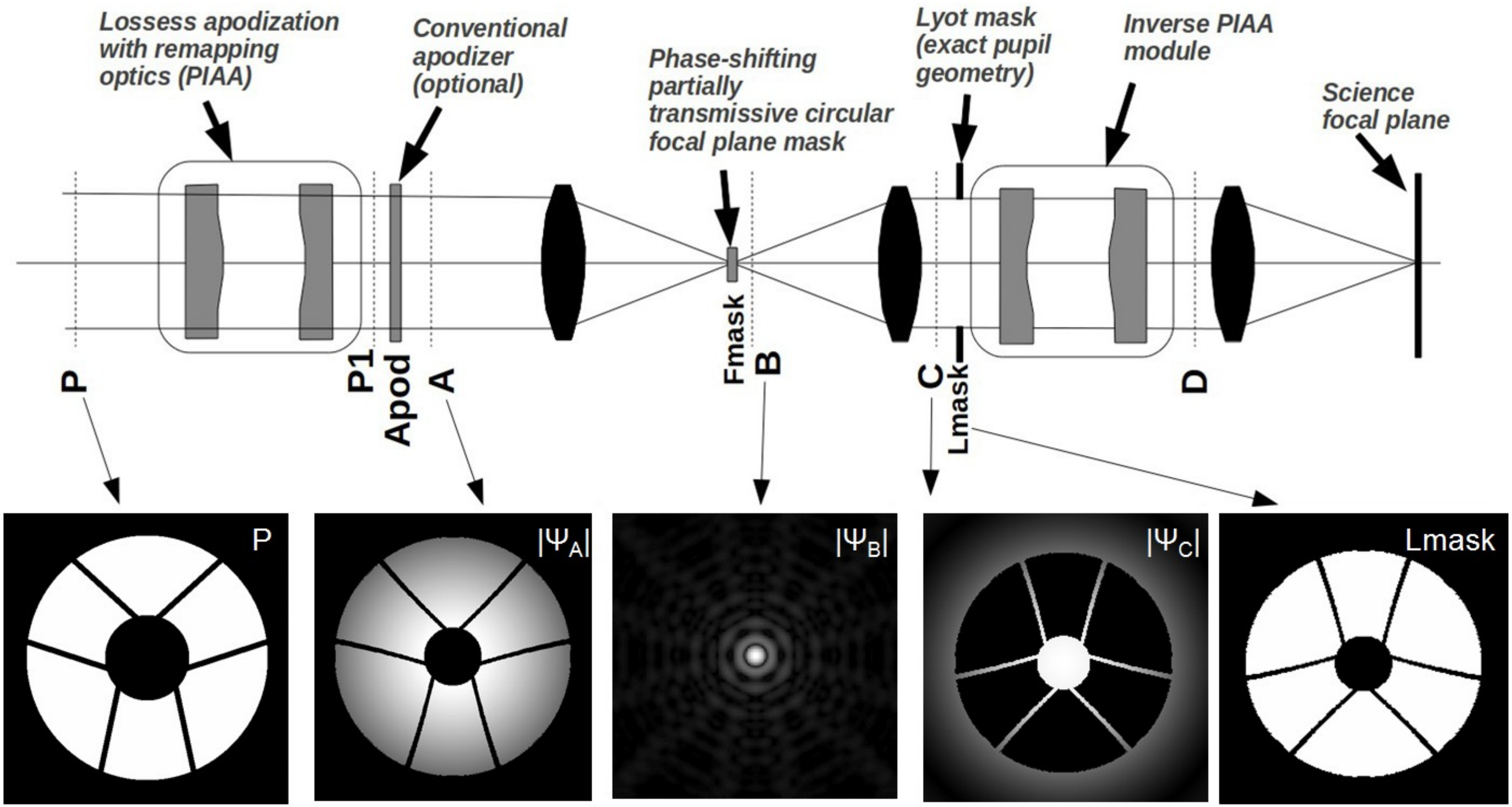




<u>Pupil shape does not matter !!!</u>



Phase Induced Amplitude Apodized Complex Mask Coronagraph (PIAACMC)



Scientific motivation

PIAACMC provides a low-IWA, high throughput solution for AFTA.

Scientific motivations:

- preserving the ability to **image small (1-2 Re) planets** in habitable zones to 0.8 um around the most favorable stars (***contingent on PSF calibration and subtraction level, to be discussed in this document***)

- Providing **high efficiency for giant planets and disks** observations: high throughput, sharp PSF → high data quality (astrometry, spectra)

Performance:

IWA<1.5 l/D
~90% throughput
1 l/D PSF sharpness

Table 1. Most favorable targets for the direct imaging of an Earth analog, ranked by decreasing SNR. The planet is assumed to be observed at maximum angular separation (given both in arcsec and λ/D) at 0.8 μm. The light contribution are given in contrast unit for the source, the background flux (zodi+exozodi) and stellar leak due to the star finite angular size. The SNR for a 10hr observation is given assuming only photon noise, with a 20% system efficiency and a 20% wide spectral band.

Target	Teff [K]	Dist [pc]	L_{bol} [L_{sun}]	max sep. ["]	max sep. [λ/D]	m_V	star Diam [mas]	star Diam [λ/D]	Contrast source	Contrast background	Contrast star	10hr SNR (R=5)
α Cen A	5809	1.34	1.52	0.92	13.39	0.01	8.47	0.1232	1.15e-10	3.05e-11	2.95e-09	43.4
α Cen B	5259	1.34	0.50	0.53	7.68	1.34	5.93	0.0862	3.48e-10	8.92e-11	1.13e-08	39.7
ϵ Eri	5104	3.21	0.34	0.18	2.64	3.73	2.16	0.0314	5.12e-10	7.44e-10	7e-09	24.0
ϵ Ind	4621	3.62	0.22	0.13	1.88	4.68	1.88	0.0274	7.91e-10	1.47e-09	1.16e-08	20.4
τ Cet	5527	3.65	0.55	0.20	2.95	3.49	2.06	0.0300	3.18e-10	6.67e-10	5.2e-09	18.2
40 Eri	5311	4.98	0.46	0.14	1.98	4.43	1.50	0.0218	3.78e-10	1.49e-09	4.21e-09	14.7
61 Cyg A	4530	3.50	0.15	0.11	1.63	5.20	1.69	0.0246	1.14e-09	2.13e-09	4.7e-08	12.8
Procyon	6546	3.51	6.93	0.75	10.91	0.37	5.44	0.0791	2.51e-11	5.1e-11	1.21e-09	11.4
82 Eri	5418	6.04	0.74	0.14	2.07	4.26	1.51	0.0219	2.35e-10	1.39e-09	3.1e-09	10.7
70 Oph	4857	5.10	0.69	0.16	2.36	4.21	2.14	0.0311	2.53e-10	1.14e-09	6.96e-09	9.6
η Cas A	6105	5.94	1.29	0.19	2.78	3.46	1.59	0.0231	1.35e-10	7.88e-10	3.32e-09	8.6
δ Pav	5582	6.11	1.22	0.18	2.63	3.55	1.80	0.0262	1.43e-10	7.44e-10	4.86e-09	8.0
σ Dra	5418	5.75	0.47	0.12	1.74	4.67	1.26	0.0184	3.69e-10	1.92e-09	1.61e-08	7.2
Altair	7524	5.12	10.60	0.64	9.25	0.77	3.49	0.0507	1.64e-11	9.03e-11	8.96e-10	6.3
ξ Boo A	4761	6.78	0.83	0.13	1.96	4.67	1.85	0.0268	2.08e-10	1.98e-09	6.4e-09	5.9
36 Oph B	5104	5.95	0.40	0.11	1.55	5.08	1.27	0.0184	4.35e-10	2.66e-09	2.63e-08	5.7
β CVn	5638	8.44	1.15	0.13	1.85	4.24	1.24	0.0180	1.51e-10	1.53e-09	5.05e-09	5.5
ζ Tuc	5926	8.59	1.44	0.14	2.03	4.23	1.24	0.0180	1.21e-10	1.54e-09	2.87e-09	5.3
β Com	5926	9.13	1.36	0.13	1.85	4.23	1.13	0.0164	1.28e-10	1.51e-09	4.17e-09	5.0
χ^1 Ori	5926	8.66	1.08	0.12	1.74	4.39	1.06	0.0154	1.61e-10	1.77e-09	6.63e-09	4.8
χ Dra	6105	8.06	2.34	0.19	2.76	3.55	1.58	0.0230	7.45e-11	8.47e-10	3.27e-09	4.6
γ Pav	6105	9.26	1.52	0.13	1.93	4.21	1.11	0.0161	1.14e-10	1.57e-09	4.02e-09	4.5
γ Lep A	6417	8.93	2.69	0.18	2.67	3.59	1.39	0.0201	6.46e-11	9.2e-10	2.7e-09	4.1
ι Per	5985	10.54	2.55	0.15	2.20	4.05	1.31	0.0191	6.83e-11	1.31e-09	2.26e-09	3.6
61 Vir	5582	8.56	0.85	0.11	1.57	4.74	1.07	0.0156	2.05e-10	2.25e-09	1.89e-08	3.4
θ Per	6045	11.13	2.70	0.15	2.15	4.10	1.25	0.0182	6.45e-11	1.44e-09	2.06e-09	3.3

Stellar leak is ~15x brighter than Earth-size planet

But SNR not hopeless if in photon noise regime

→ We need to:

- Control pointing at the mas RMS level (<star diam)

and

- Calibrate stellar leak+TT at the ~1% level

Wavefront control, PSF calibration

PIAACMC's ability to image low-mass planets at 1.5-3 l/D is contingent on sensing & control of low order aberrations and PSF calibration

PIAACMC instrument design addresses this by:

[1] Diverting almost ALL starlight to high sensitivity LOWFS which is integrated within the coronagraph architecture

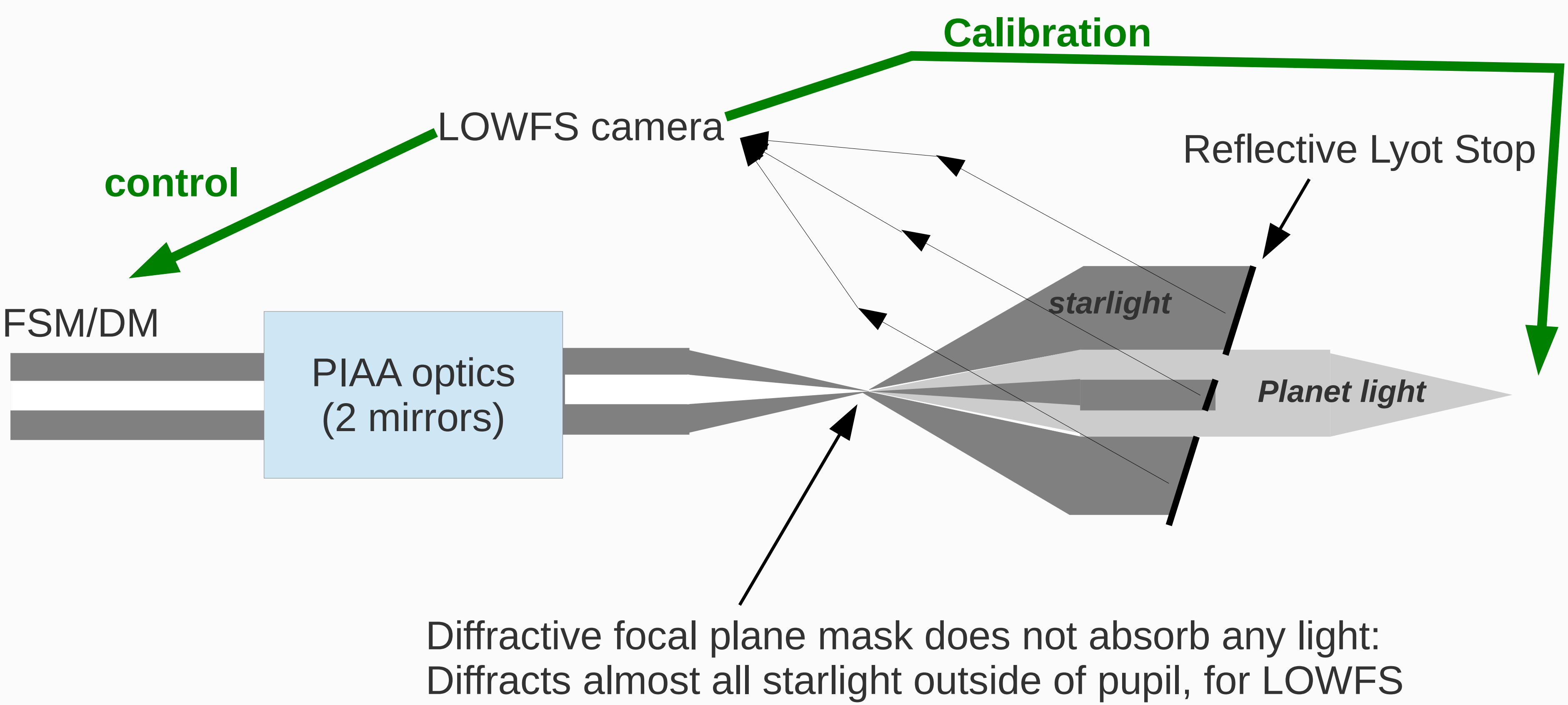
[2] Adopting a LOWFS architecture with no non-common path errors (this is essential to hope to suppress stellar leakage from science image)

[3] Using telemetry from LOWFS to calibrate residual science image starlight

Design architecture

Key components:

PIAA optics
Transmissive Focal plane mask designed for LOWFS
Reflective Lyot Stop → feeds LOWFS camera



PIAACMC LOWFS architecture

Maximizing efficiency

Use pure phase-shifting mask → no light lost at focal plane mask

Mask at focal plane → full diffraction sensitivity, no pupil segmentation (as in SH)

Eliminating non-common path errors

Insensitive to LOWFS camera motion: TT is ***NOT measured as a centroid***, it is measured as a PSF shape modulation

→ postprocessing calibration removal of TT errors is possible

Current TRL:

Lab demo at Meudon Observatory (Singh et al. 2013, in prep)

On-sky demo at Subaru Telescope with phase masks

Focal plane reflected light-equivalent at HCIT, Ames

PSF calibration using LOWFS has been demonstrated to 1% level at IWA in lab

(see "Coronagraphic Low-Order Wavefront Sensor: Postprocessing Sensitivity Enhancer for High-Performance Coronagraphs" Vogt, Frederic P. A.; Martinache, Frantz; Guyon, Olivier; Yoshikawa, Takashi; Yokochi, Kaito; Garrel, Vincent; Matsuo, Taro, Publications of the Astronomical Society of the Pacific, Volume 123, issue 910, pp.1434-1441 (12/2011))

PSF calibration with LOWFS: lab demo (Vogt et al. 2011)

Conventional PSF subtraction:
~5x contrast improvement

PSF subtraction with LOWFS :
>100x contrast improvement

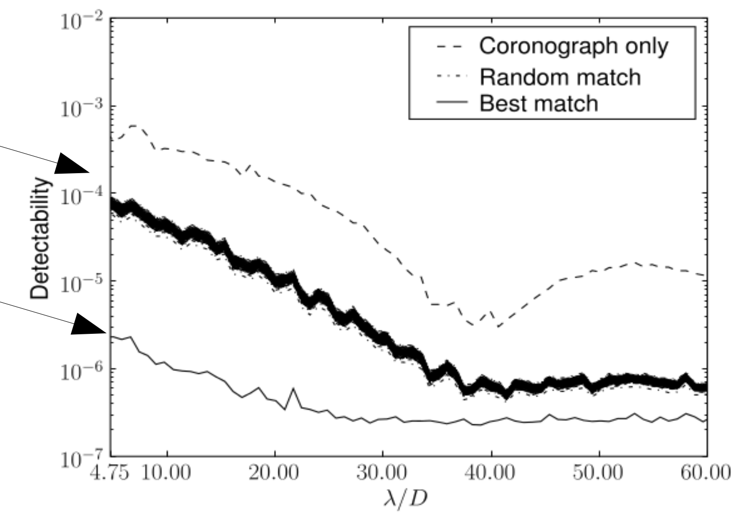


Fig. 7.— Standard deviation of the image profile as a function of angular separation. The figure compares three types of profiles: the raw science image (dashed line), the best-fit cleaned science image (solid line) using the proposed post-processing procedure and 200 random-match cleaned science images (dot-dashed line) simulating the standard PSF subtraction.

Raw coronagraphic image

PSF subtraction

PSF subtraction with LOWFS telemetry

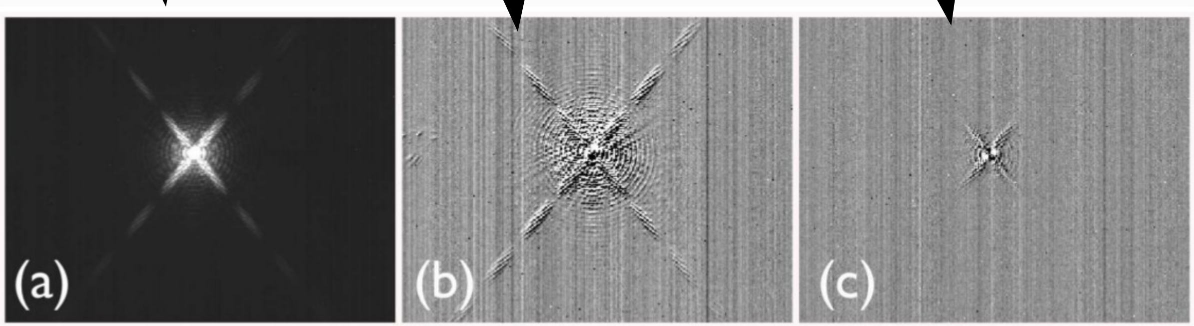


Fig. 4.— a) Long-exposure "science camera" image, non-linear intensity scale. Airy rings and diffraction spikes due to the peculiar Subaru Telescope pupil are clearly visible. b) Image after standard subtraction of a PSF without using the proposed CLOWFS image selection procedure. c) Image after CLOWFS post-processing calibration. Panels b and c use the same intensity scale.

Pointing control
Expected LOWFS performance

Assumptions:

Simple integrator controller, with a gain between 0 and 1 (no PID, no Kalman filter, no on-board processing of PSDs to optimize loop controller)

CCD camera, 10 MHz pixel readout rate max, 5e- RON

LOWFS is 5x5 pix, readout frame area is 30x30 pix → 10 kHz max frame rate

LOWFS is taking diffracted starlight from Lyot stop (as done on SCExAO) to eliminate non-common path errors, and offer high efficiency

Star is mV=5, 50% bandpass (LOWFS before filter), 20% system efficiency -> 2e8 ph/s -> 4e6 ph/s/pix

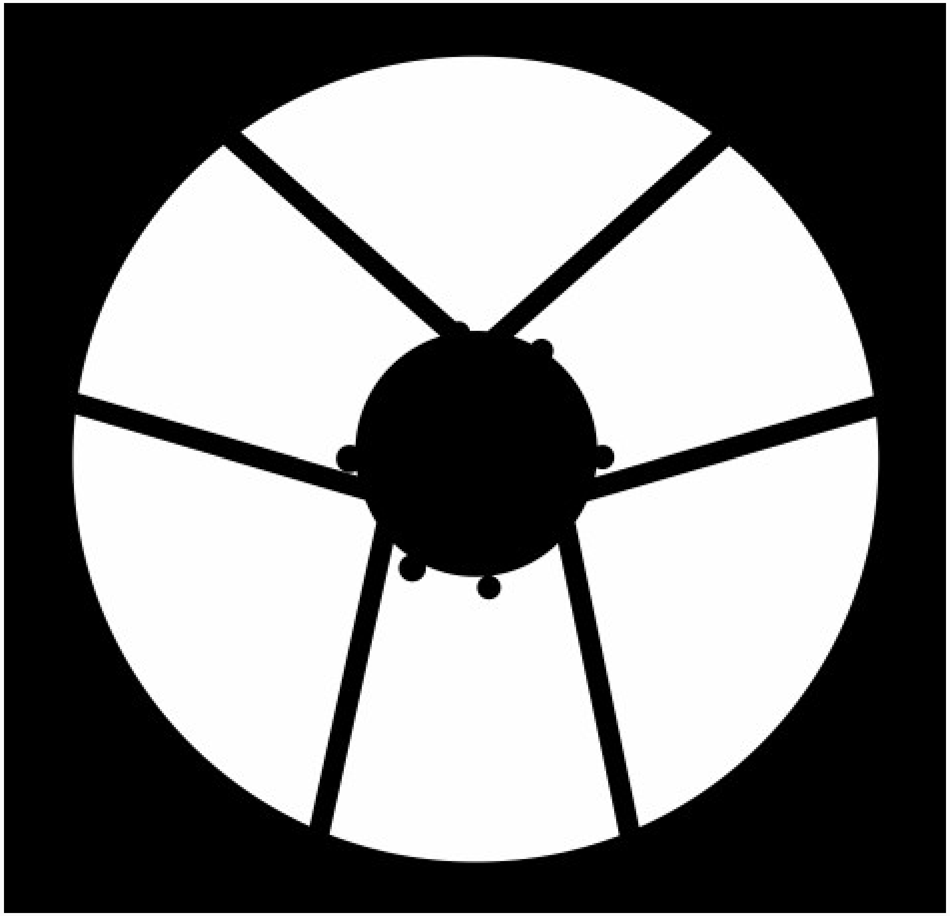
10 kHz frame rate: 400 ph/pix/exposure, which is OK for RON
single measurement precision at 10 kHz (photon noise):
2/sqrt(2e4) rad = 0.014 rad RMS = 1/112 lambda/D = 0.42 mas

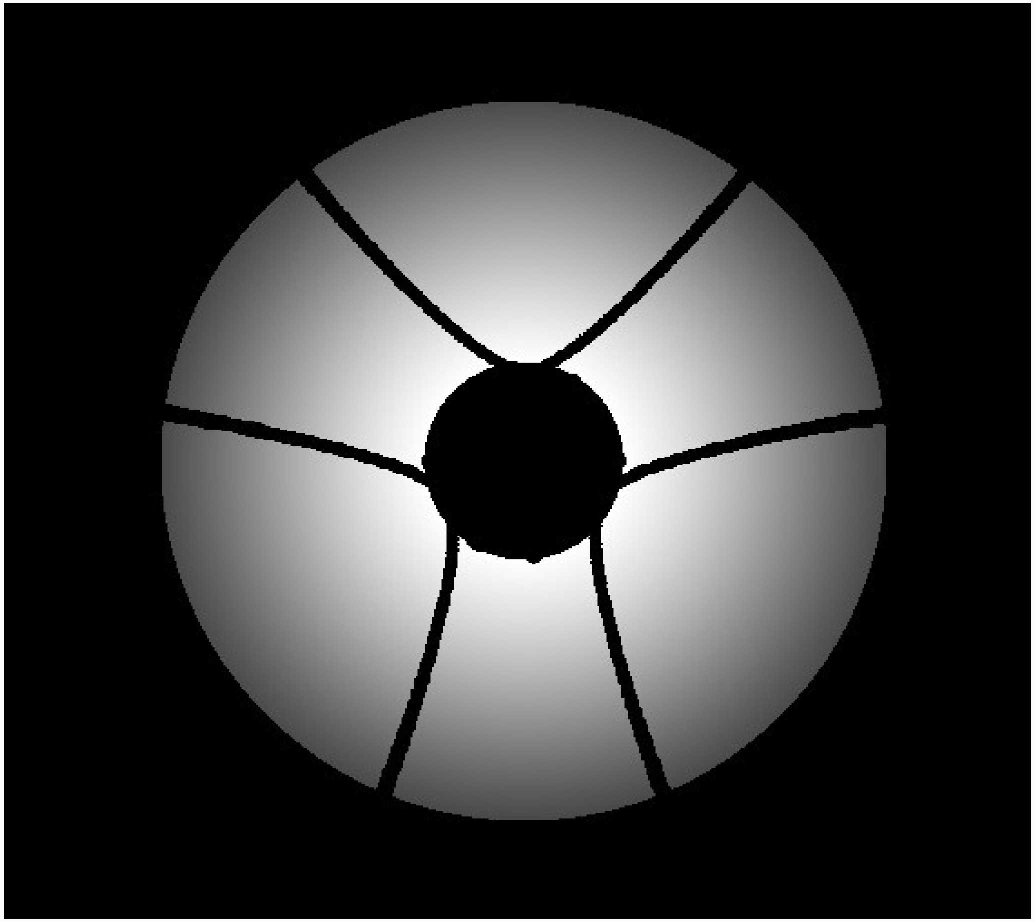
→ Loop should run at full speed, gain ~1. We assume gain = 0.5 (1.0 for HCIT)
Photon noise contribution = 0.27 mas RMS
0 dB point in transfer function at ~500 Hz
Rejection at 50 Hz = 10x, Rejection at 5 Hz = 100x
14mas at 50 Hz → RMS tip = 1.426 mas (single axis)
14mas at 10 Hz → RMS tip = 0.389 mas (single axis)

See analysis by R. Belikov for more details

Apodization

Apodization is within 2% of being radially symmetric
Surface brightness at edge ~1/10 of center (about 10x brighter than current PIAA at HCIT)



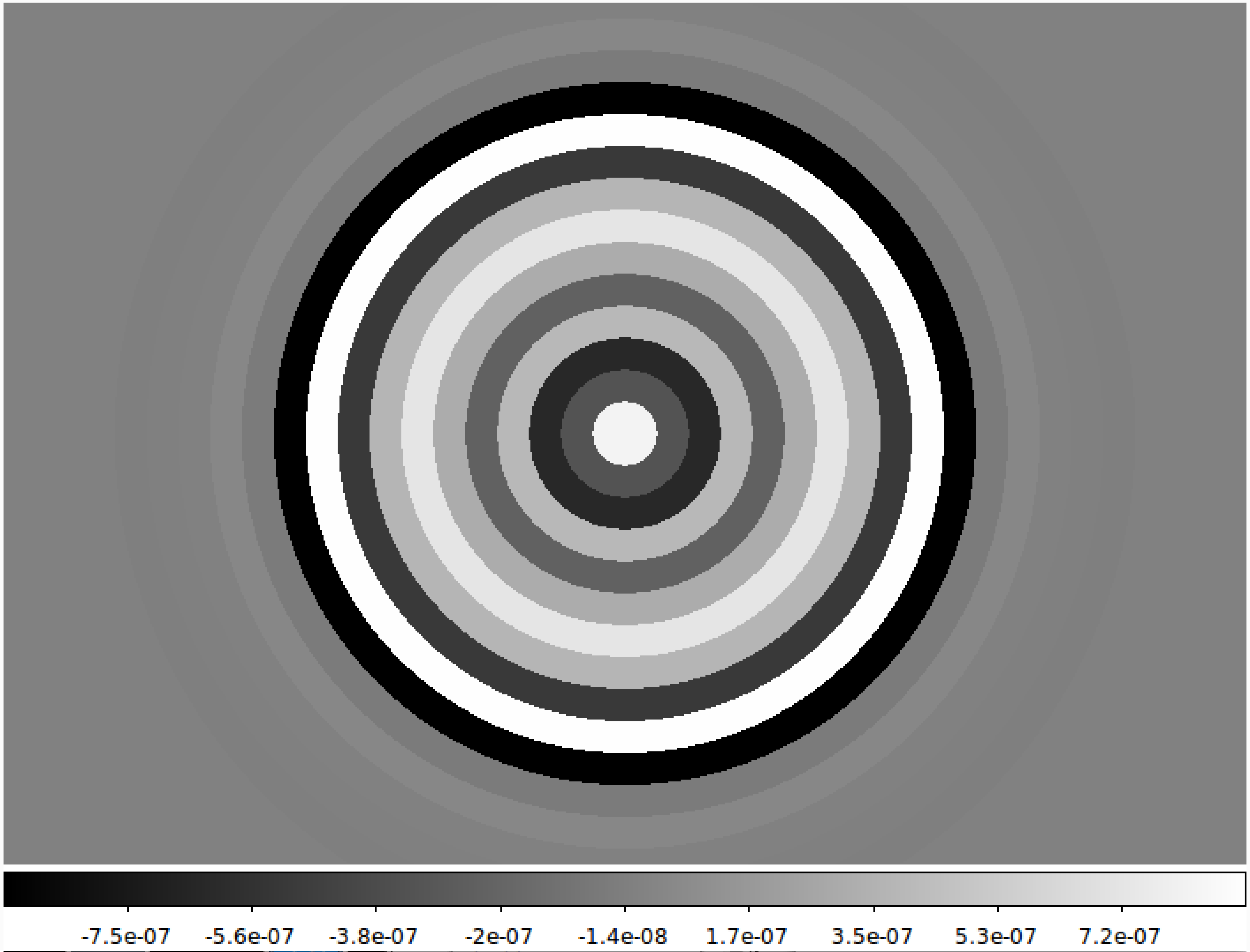


Focal plane mask design

PMGI material, 16 circular rings, each with a different thickness, 2 l/D outer radius

Peak to Valley = 1.8 um

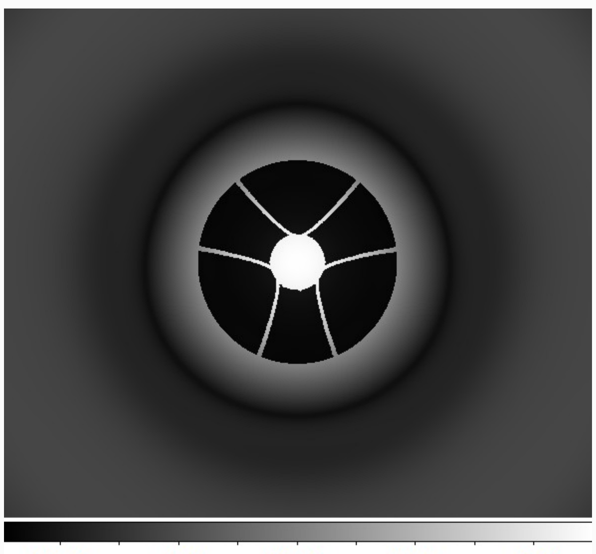
More rings:
Better chromaticity
Harder to manufacture
Larger Lyot stop mirror



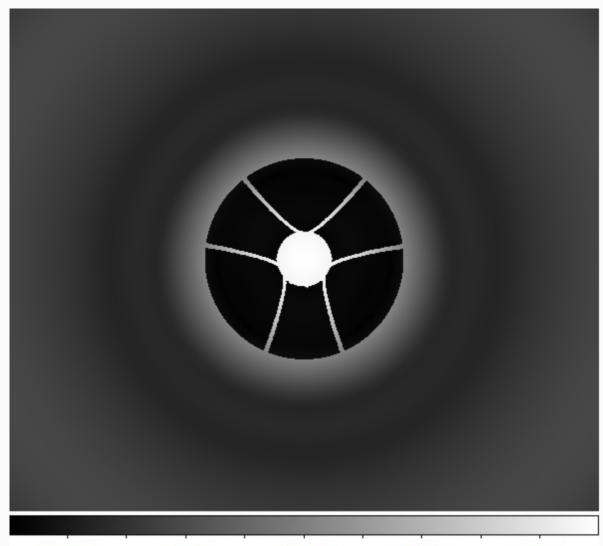
Light distribution on Lyot stop

10% wide band, assumes no wavefront control

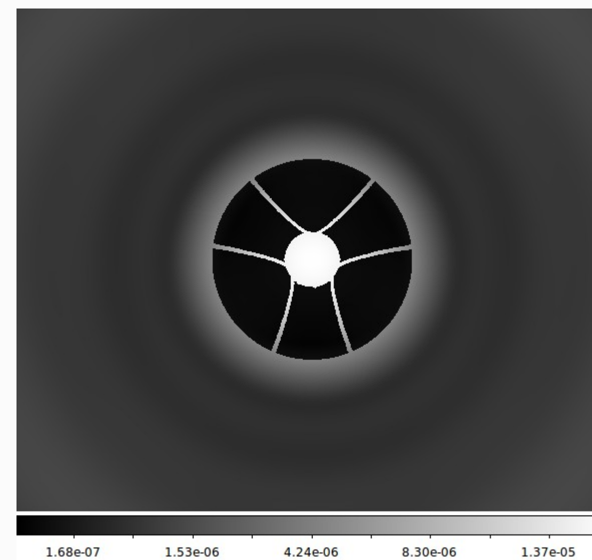
522.5 nm



530.6 nm



577.5 nm



Performance (without WFC)

1.3 l/D IWA
85%~90% throughput (not 100%, due to slightly larger central obstruction adopted and outer edge clipping)
Sharp PSF