SCDA / PIAACMC status

University of Arizona:
  Olivier Guyon
  Johanan Codona
  Alex Rodack
  Justin Knight

NASA Ames:
  Ruslan Belikov
  Stephen Bryson
  Christopher Henze
  Dan Sirbu

JPL:
  Brian Kern
PIAACMC principle, theoretical performance

PIAACMC provides, for any aperture shape, full rejection (infinite contrast), 1.0 I/D IWA and 100% throughput under the following assumptions:

- No wavefront error
- On-axis point source
- Ideal focal plane mask
- Fourier Optics (no propagation of edge diffraction through finitely sized optical elements)

Our SCDA effort goes from ideal concept to realistic implementation by taking into account these 3 effects.
Focal plane mask

*Ideal PIAACMC calls for a phase-shifting disk with a fixed l/D radius*

*There is no demonstrable way to make such a mask in broadband light → we approximate it by a multi-zone physical device (mirror), which can be manufactured*

Multiple zones (sectors or hexagons) phase-shift light

Multiple zones interfere destructively inside the pupil across the science spectral bandwidth

No light is absorbed → ALL starlight sent to the LOWFS for efficient sensing of low-order aberrations

*Much of our SCDA activity has been to design manufacturable FPMs for PIAACMC FPM co-optimized for broadband performance, stellar angular size (+ optional resilience to known aberrations)*
PIAACMC SCDA design uses same approach as WFIRST
PIAACMC (some hardware, technology heritage)

On-axis PIAACMC system (Gregorian telescope)

Single Lyot Stop → easy feed to LOWFS

Zygo phase

ZeMapper

AFM

Reflective multi-zone focal plane mask

1 DM, 1-sided, $\pm 6 \lambda/D$ before inserting field stop

field stop in

![Graph showing mean contrast over r [lambda/D]](image)
PIAACMC science trade space

**Key advantages**

- High throughput, “undisturbed” PSF
- Access to small IWA (~1.0-1.5 l/D) … but comes with high sensitivity to stellar angular size
- Maintains high performance on segmented aperture

→ Brings additional potential science capabilities not accessible to “classical” coronagraph approaches working at larger IWA:

- **Longer wavelength science (near-IR):** star is smaller, planet is closer in (in I/D units), planet may have thermal emission (kicks in @ ~3+ um)
- **Provides access to later-type stars.** Proxima Cen b -like targets: moderate contrast (~1e-7) but small angular separation
- **Provides access to distant targets.** Small angular separation, small stellar size

→ PIAACMC/SCDA effort key goals:

(1) Demonstrate viable architecture for segmented aperture: managing edge diffraction with realistic optical design and manufacturable components

(2) Demonstrate/quantify additional science capabilities enabled by small IWA access

(3) Can PIAACMC @ segmented aperture **ALSO** operate in the more conventional performance regime (contrast ~1e-9 / 1e-10 at 4 I/D)?
Key findings

(1) Demonstrate viable architecture for segmented aperture → Completed to 1e-8 level, now pushing deeper
We have produced designs that deliver PIAACMC key IWA & throughput advantages: ~1 I/D IWA, 70% throughput in broadband light
Designs are matched to realistic optical design and components manufacturing capabilities, as demonstrated on HCIT with PIAACMC testbed

(2) Demonstrate/quantify additional science capabilities → Ongoing, promising... but needs further improvement (stellar angular size)
Performance limited by stellar angular size
With stellar size = 2% I/D, raw contrast ~1e-7. Smaller stellar size → deeper contrast
→ does bring in unique near-IR science, planets around M-type stars
... but needs further improvement

(3) Can PIAACMC @ segmented aperture ALSO (simultaneously) operate in the more conventional performance regime (contrast ~1e-9 / 1e-10 at 4 I/D) ? → Optimization of high perf solution at 4 I/D not been seriously started yet. Likely requires changes in architecture/hybrid (some progress with APLC / PIAACMC hybrid).
Stellar angular size is a significant issue even at >3 I/D → we have not yet demonstrated deep contrast with small-IWA PIAACMC
Does an architecture offering simultaneously access to small IWA and deep contrast at > 3I/D exist ?
Promising avenues currently under investigation, but with reduced throughput:
   APLCMC architecture does offer improved sensitivity to stellar angular size
   APLC + PIAACMC : apodize pupil to deliver deep contrast @ > 3 I/D, use PIAACMC for < 3 I/D
PIAACMC design process

Design is a 2-step process

(1) Design PIAACMC (or APLCMC) in monochromatic light, point source, and ideal focal plane mask

(2) Add chromaticity, stellar angular size and physical mask → optimize mask zone thicknesses

PIAACMC design software

Source code: www.github.com/oguyon/PIAACMCdesign
- C code, runs on Linux & OS-X systems, uses GPU acceleration
- Development & single/few design(s) evaluation on computers at UofA, Hawaii & Ames
- Preparing for use of NASA Ames hyperwall cluster for rapid parameter exploration (128-node cluster, each: 20 cores + GPU, 64GB mem, 646 Tflop/s)
- Independent verification process of results @ Ames under development
Extensive parameter scan @ Ames hyperwall (example shown here for WFIRST/polarization study)

~3 I/D on sky

system l/D units (sky is ~1.5x smaller)
Design #1: “Aggressive” PIAACMC, 3-ring SCDA aperture
High perf. near IWA for point source, but very sensitive to stellar angular size

- 1.0 I/D IWA
- 70% throughput
- Single Lyot stop (Performance improves with >1 Lyot stop)
- No invPIAA (simpler)

Optimized for:
- 10% band centered at 565nm
- point source
- Optics diam = 2x beam size

Focal plane mask:
- 0.9 I/D nominal size
- 32 rings, 3.6 I/D outer zone

**broadband (10%) averaged raw contrast (design NOT optimized for stellar angular size)**

Curves do not include wavefront control, which should improve contrast further
Brightness scale is different between images
Multiple Lyot Stops help
Focal plane mask design (mirror)

Sag +/- 600nm

Little sag outside 1 I/D
540 nm – diffraction effects due to segments, beam truncation, PIAA
590 nm – diffraction effects due to segments, beam truncation, PIAA
Off-axis image quality @ 5 I/D
(contrast reference)

Off-axis PSF has similar core throughput to full aperture nominal PSF
Fainter Airy ring (thanks to apodization), but some off-axis coma
High contrast PSF is strongly chromatic

- Effect of numerical sampling to be evaluated

- Wavefront control is unlikely to have significant leverage on chromatic residual

  → need to adopt finer sampling (more computing time)
Design #2: APLCMC, 3-ring SCDA aperture

Lower throughput, improved sensitivity to stellar angular size

- ~1.1 l/D IWA
- 46% throughput (pupil apodizer)
- Single Lyot stop

Optimized for:
- 10% band centered at 565nm
- 0.02 l/D source
- Optics diam = 2x beam size

Focal plane mask:
- 1.0 l/D nominal size
- 32 rings, 4.0 l/D outer zone

**broadband (10%) averaged raw contrast**
*(design is optimized for stellar angular size)*

10x improved contrast @ 3 l/D
100x improved contrast @ 16 l/D
Design #2: APLCMC, 3-ring SCDA aperture
Lower throughput, improved sensitivity to stellar angular size

Warnings:
• This design was not simulated using truncated optics in intermediate planes
  (uses Fourier transforms, not actual physical propagations)
  → Does not fully capture segment edge diffraction effects in realistic optical design
• Ideal apodizer assumed (how to manufacture it? Binary mask?)
Preparing for lab demo:
Exploring FPM manufacturing options @ UofA

UA Link Award → A small graduate-led (J. Knight) team will generate pilot data for coronagraph mask manufacturing efforts during the 2016-2017 academic year

Major Tasks:

Manufacture coronagraph focal plane masks
Focus on in-house capabilities: binary etching e-beam lithography into Si with a mask-aligner (MA6)
Testability: Subaru telescope, etching into Si wafer; master silicone mold-to-UV epoxy → AR coatings are important for multi-wavelength performance!
Draw from previous/current device manufacturing efforts, e.g. JPL MDL Gen 3 PIAACMC, SNF achromatic PIAACMC FPMs (K. Newman), Subaru masks at Cornell

Survey local and national manufacturing capabilities
Create a database of nanofabrication facility processes/tools geared toward FPM creation
Establish collaborative relationships with coronagraph research groups around the world – here’s what we do, what do you do? How can we help?

There are multiple ways to make masks already, yet the space of manufacturing is relatively unexplored such that a “best” process has been developed, esp. for PIAACMC masks. While there is a path forward from design to manufacturing of these devices, we have the flexibility to take different approaches presently.
Conclusions & Next Steps

Demonstrated PIAACMC design on segmented aperture in realistic optical system, 10% band
Achieves ~1.0 l/D IWA, 70% throughput
Contrast floor at 1e-8 may be due to sampling effects (under investigation)
Contrast limited by stellar angular size
→ PIAACMC can deliver low IWA + high throughput, but sensitivity to stellar angular size
increases as IWA decreases
Implementation is compatible with realistic optical design and manufacturing capabilities

PIAACMC unlikely to have strong aperture geometry preference (will confirm by running
designs on all apertures)

Demonstrated that hybridization with APLC and focal plane mask optimization can mitigate sensitivity
to stellar angular size
→ Encouraging step toward coronagraph solution offering simultaneously small IWA and
maintains deep contrast at larger separations

Next steps:
- Simulate less aggressive PIAACMC (larger IWA)
- Investigate sampling effects
- Include wavefront control
- Explore Hybrids
- Code improvements, validation and verifications → run batch scans on Ames HyperWall
- Compare results with fundamental limits