Phase-Induced Amplitude Apodization Complex Mask Coronagraphy (PIAACMC) for Large Segmented Apertures

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Scientific Motivation for small IWA

Spectroscopic characterization
Near-IR (~ 0.7 - 2.5 um) is the most valuable spectral range for atmospheric characterization of habitable planets

Planet diversity
Small IWA enables access to HZs of cooler stars (smaller HZ)

Yield
Small IWA = large number of targets

Earth atmosphere transmittance illustrates value of near-IR
Our Approach: PIAACMC … without PIAA

We adopted APLCMC (= PIAACMC without PIAA) for convenience

Pupil amplitude apodizer → Focal plane mask → Lyot stop

Apodization loss → Low throughput (~30%), Some loss in IWA, Larger PSF core (FUTURE designs will use PIAA → ~2-3x gain in efficiency expected)

Easier to design, faster numerical simulation → rapid exploration of design optimization & trades (THIS presentation)

Design process:
(1) Design ideal monochromatic APLCMC: complete suppression of on-axis light in monochromatic light, small IWA
(2) Replace ideal focal plane mask with multi-zone mask. Optimize zones for broadband light and stellar angular size.

For both APLCMC and PIAACMC, the multi-zone focal plane mask is the most critical element (Can it be manufactured?)
Baseline APLCMC design

Apodization throughput = 34.13%
(Note: few % could be regained by removing circular constraint on inner and outer edges)

Outer edge intensity transmission = 4%

Lyot stop directs nearly ALL starlight to LOWFS

Focal plane mask has 1237 zones over a 3 l/D radius at central wavelength
Throughput & PSF quality

**30% throughput** at 2.5 l/D
15% throughput at **1.45 l/D = IWA**

Clean PSF outside ~2 l/D, but ~11% wider than unapodized PSF
PSF is dominated by stellar angular size

PSF dominated by incoherent spots due to stellar angular size → contributes to photon noise, but does not interfere coherently with wavefront errors → can be removed in post-processing. Instead of radial average contrast, we use 50-percentile (search) and 20-percentile (spectroscopy) radial contrasts for performance evaluation: we avoid the bright spots.

Source radius = 0.01 l/D

Source radius = 0.03 l/D

568 nm shown 10% bandwidth optimized.
APLCMC design – Raw Contrast

(20 percentile along each radius)
How does pupil geometry affect performance?

In theory...

APLCMC and PIAACMC do not care about pupil geometry. Performance should be the same for segmented and non-segmented apertures.

We find that...

This holds true when considering point source, but there is a coupling between stellar angular size and segment/spiders diffraction features:

Partially resolved star + segmented aperture → incoherent bright “spots” and lines appear in PSF
Stellar Angular Size Study

What is the impact of stellar angular size on planet characterization?
Stellar angular sizes strongly correlate with HZ angle.
Median stellar diameter in this box = 0.4 mas
LUVOIR 12m V-band sample: 781 stars
Median stellar diameter = 0.598 mas
80% of stars < 0.955 mas
Spectroscopic Characterization

Assumptions (see APLCMC design details):
• 12m aperture, 50% efficiency, 30% Airy throughput, FWHM=1.11 l/D, IWA=1.45 l/D
• Exozodi has same dust density as local zodi. 3x brighter (incl + double pass). Color effects are taken into account.

Following slides quantify planet yield for spectroscopic characterization.

We assume 1 Earth-like planet around each star, and count:
- **# of SNR-accessible targets**: stars around which an Earth analog is bright enough to be characterized assuming ALL starlight is removed (perfect coronagraph)
- **# of characterizable targets**: Takes into account coronagraph contrast, due to combination of stellar angular size and chromatic effects

Difference between the 2 numbers = targets lost due to coronagraph leak
B band ExoEarth spectral characterization (436nm)

Targets suitable for ExoEarth spectral characterization (B band)

Detected (SNR=10, R=40 in < 24hr exposure time)

370 planets SNR-accessible (no starlight)
206 planets characterizable

Circle size proportional to stellar angular size
V band ExoEarth spectral characterization (545nm)

Targets suitable for ExoEarth spectral characterization (V band)

Detected (SNR=10, R=40 in < 24hr exposure time)

461 planets SNR-accessible (no starlight)
268 planets characterizable

Circle size proportional to stellar angular size
I band ExoEarth spectral characterization (797nm)

Targets suitable for ExoEarth spectral characterization (I band)

Detected (SNR=10, R=40 in < 24hr exposure time)

356 planets SNR-accessible (no starlight)
222 planets characterizable

Circle size proportional to stellar angular size
J band ExoEarth spectral characterization (1.22µm)

Targets suitable for ExoEarth spectral characterization (J band)

Detected (SNR=10, R=40 in < 24hr exposure time)

179 planets SNR-accessible (no starlight)
124 planets characterizable

Circle size proportional to stellar angular size
H band ExoEarth spectral characterization (1.63um)

Targets suitable for ExoEarth spectral characterization (H band)

Detected (SNR=10, R=40 in < 24hr exposure time)

95 planets SNR-accessible (no starlight)
74 planets characterizable

Circle size proportional to stellar angular size

Angular Separation (arcsec)

log10(Contrast)

log(Teff)

B8
A5
F5
G5
K5
M0
M5

3.4
3.5
3.6
3.7
3.8
3.9
4.0
4.1
K band ExoEarth spectral characterization (2.19um)

Targets suitable for ExoEarth spectral characterization (K band)

Detected (SNR=10, R=40 in < 24hr exposure time)

51 planets SNR-accessible (no starlight)
39 planets characterizable

Circle size proportional to stellar angular size
Fraction of light due to coronagraph leak (B band)

Targets suitable for ExoEarth spectral characterization (B band)

370 planets SNR-accessible (no starlight)
206 planets characterizable
Fraction of light due to coronagraph leak (V band)

Targets suitable for ExoEarth spectral characterization (V band)

461 planets SNR-accessible (no starlight)
268 planets characterizable

Angular Separation (arcsec)
Fraction of light due to coronagraph leak (I band)

Targets suitable for ExoEarth spectral characterization (I band)

356 planets SNR-accessible (no starlight)
222 planets characterizable
Fraction of light due to coronagraph leak (J band)

Targets suitable for ExoEarth spectral characterization (J band)

179 planets SNR-accessible (no starlight)
124 planets characterizable

Angular Separation (arcsec)
Fraction of light due to coronagraph leak (H band)

Targets suitable for ExoEarth spectral characterization (H band)

95 planets SNR-accessible (no starlight)
74 planets characterizable
Fraction of light due to coronagraph leak (K band)

Targets suitable for ExoEarth spectral characterization (K band)

51 planets SNR-accessible (no starlight)
39 planets characterizable
CONCLUSIONS

APLCMC provides coronagraph solution compatible with any segmented aperture. Throughput is low (~30%), but IWA is good (< 1.5 I/D). Note: PIAACMC should recover throughput … future work

For most targets, coronagraphic leak due to stellar angular size has small effect on SNR
For most targets, about 20% contribution to total light in the planet PSF (other contributions: planet, zodi, exozodi) → SNR is comparable to ideal SNR (no starlight) that a perfect coronagraph or starshade would obtain.

Stellar angular size is a concern for planets at large angular separation observed at short wavelength. APLCMC / PIAACMC is not the ideal coronagraph for these observations, but other solutions exist in this regime.

For 12m aperture, spectroscopy can be obtained on Earth-like planets around a sample of 74 stars to H-band (1.65um)

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