Achromatic Optics for Phase Apodization Coronagraphy

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Phase Apodization Coronagraphy

- The halo of an unresolved object is *spatially* coherent.
  - Light from various parts of the PSF can interfere.
- PAC uses a pupil phase mask to scatter the main starlight into the halo, canceling it.
  - *No* focal plane mask
  - *No* Lyot stop
  - *No* careful pointing required.
Why does PAC suppression work?

(n.b. Simplified! The best performance requires more advanced thinking.)

- A phase *ripple* in the pupil is a *diffraction grating*.
- By adjusting the ripple, we can create and control a speckle.
- So, create an “anti-speckle” to cancel each point in the diffraction pattern.
- We also create another speckle on the other side with the wrong phase, so 180° coverage max.
- *(Every part of this has caveats. Phase is a rich topic.)*

This is like the technique of using a pupil DM to clean up residual speckles and coronagraph errors.... Except... *carried to its logical conclusion.*

*We do the whole job* of a coronagraph, aggressively suppressing the diffraction halo.
*Our phase throw requirements are large.*
*The relationship between phase (optic shape) and the starlight EM field is heavily nonlinear.*
Example 1.25 – 8 \( \lambda/D \) “Antihalo Modes” (Phase)

These modes match a selected “region of interest” (ROI).

These are just the first 80 modes.

Depending on how big the phase space is, there can be thousands of modes!
MMT 1.25 – 8  \( \lambda/D \) Phase Solutions

**APPs 40 – 180 modes**

**log-stretch PSFs**
JWST 1.25 – 8 λ/D Phase Masks

APPs 40 – 180 modes

log-stretch PSFs
GMT 1.25 – 8 λ/D Phase Masks

APPs 40 – 180 modes

log-stretch PSFs
Typical Performance Numbers
Unobstructed Circular Aperture

Select best performing case based on next-tier noise source.

Important cases:
- Background
- Speckle halo
- (semi) Static PSF errors

Digging deeper requires a finer calculation mesh and greater care when machining.
Mode Removal: Where should we stop???

**Suppression Modes 2 - 6 \( \lambda/D \)**

- Avg. Halo in "D" (decades)
- Radius (\( \lambda/D \))

**Strehl Cost vs. Halo Suppression Depth (MMT Case)**

- Mean Halo ROI (decades)
- Strehl Ratio

**SNR improvement vs. APP Strehl**

- Normalized SNR metric
- Phase Plate Strehl, \( C_\phi \)

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Spirit of Lyot 2010 Paris
MMT/Clio APP v1 (conservative pupil mask)
MMT/Clio APP v2 (single piece)
Δλ causes the halo to brighten

Mean halo measured over suppressed ROI for a narrowband test.

This becomes steeper in a more highly suppressed halo.
Not exactly the same as the classical achromatic lens problem

Required delay is geometrical, independent of wavelength.

For an achromatic lens, we want all wavelengths to focus to the same point.

This means that an achromatic lens' phase delay is inversely proportional to wavelength.
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For an achromatic lens, we want all wavelengths to focus to the same point.

This means that an achromatic lens' phase delay is inversely proportional to wavelength.

This is **not** what we want! We want the phase to be independent of wavelength.
Two-Glass Solution for wavelength independence

So long as the required phase shift is approximately a linear function of wavelength, we can implement it with 2 glasses.

Wavelength independence
Gives scaled versions of the same shape.

Two-glass solution for wavelength independence

One glass or a mirror

Actual Phase Shift vs. $\lambda$ when designed for 1 radian

actual phase shift

Two glasses: ZnSe/ZnS

wavelength (microns)
Performance of a Broadband APP (BAPP)

5 decade LBT APP, $1^{st}$-$9^{th}$ Airy null

HeNe Interferogram of 5 decade LBT APP, $1^{st}$-$9^{th}$ Airy null

$\lambda_0$ Interferogram of 5 decade LBT APP, $1^{st}$-$9^{th}$ Airy null
Beware of Approximations

Two-Glass BAPP

Actual ray paths cause undesired pupil intensity variations and phase aberrations away from the PAC design.

In extreme cases, TIR can occur.

These problems become more acute as BAPP pupil is scaled down.

LBT: D=8.4 m. BAPP D=8mm.
Fixing problems

- Don't scale the BAPP down so far (not always an option).
- Compute more clever surfaces for the glasses (not likely to help that much, especially over a band).
- Machine more than 2 surfaces (expensive & complicated)
- Extend the theory to allow for 3D BAPP surfaces and actual wave propagation inside the optic (possible)
Avoiding problems *ab initio*

- Don't suppress more than needed.
- Further constrain the phase surface mode space so that high-spatial frequencies are not considered as contributors to the antihalo solution (major winner!)
- Allow for a better optical model of the BAPP in the antihalo servo mathematics. (This is definitely possible, but is quite non-trivial. Only needed for making deep broadband APPs.)
Conclusions

- Broadband Phase Apodization is possible.
- BAPPs for large bands (e.g. joint L&M) can be made using two glasses.
- Care must be taken in the design of the optics.
- Pupil phase manipulation almost certainly holds many more surprises.