National Aeronautics and Space Administration

Laboratory testing of a PIAA coronagraph

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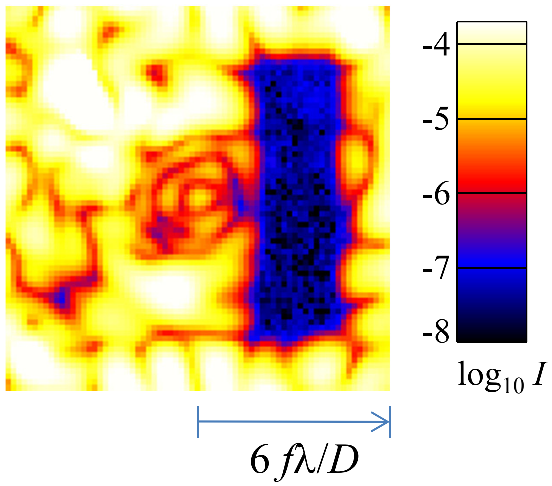
Areas of progress

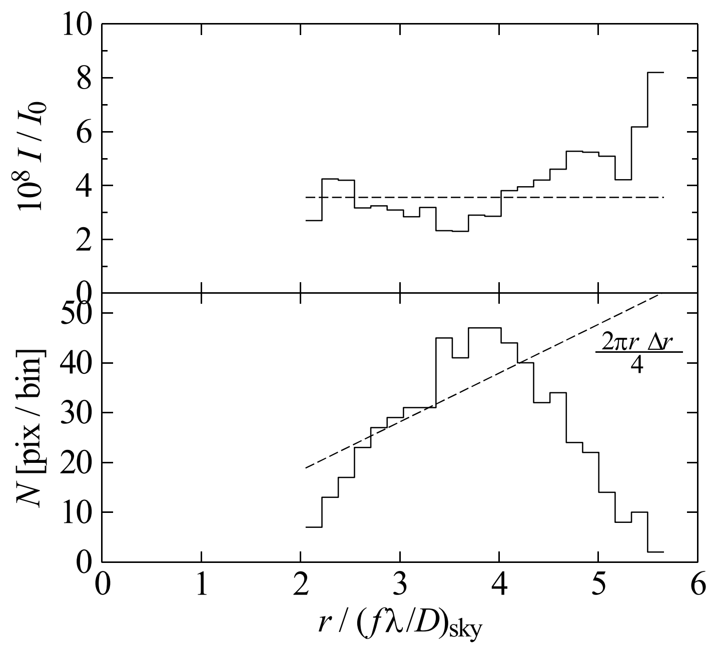
- Dark hole level obtained in lab

  3×10^{-8} with inner working angle $2\ (f\lambda/D)_{\mathrm{sky}}$
- Identification of contrast limits
- Low-order correction
- Simulations to guide architecture choices

Best PIAA contrast

- Best dark hole to date has mean intensity 3.5×10^{-8}
  - Region is $2 < x / (f\lambda/D)_{sky} < 4, -4 < y / (f\lambda/D)_{sky} < 4$
    - Inner edge of dark hole 2.05 $(f\lambda/D)_{sky}$
  - Monochromatic 808 nm freq-stabilized laser





Contrast limits

- Consistently able to reduce light to be dominated by "uncontrollable" light
- Complex E-field estimation is done by modulating DM with "probes"
  - Probes are a pattern of variations in DM surface shape across exposures
  - Pixel-by-pixel, linear effect of DM modulation is to "add" E-field and change its phase (*e.g.*, by $\pi/2$) in successive exposures
  - Equivalent to phase-shifting interferometer at each pixel
  - Some light does not seem to interfere with probe E-field

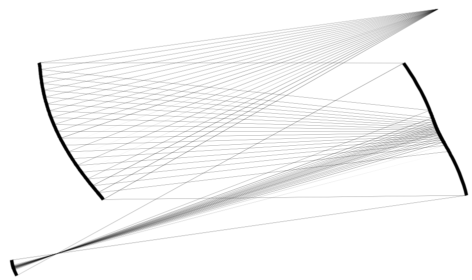
Pic of incomplete modulation

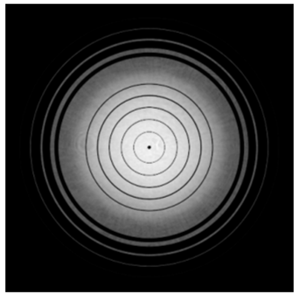
Descriptions of uncontrollable light

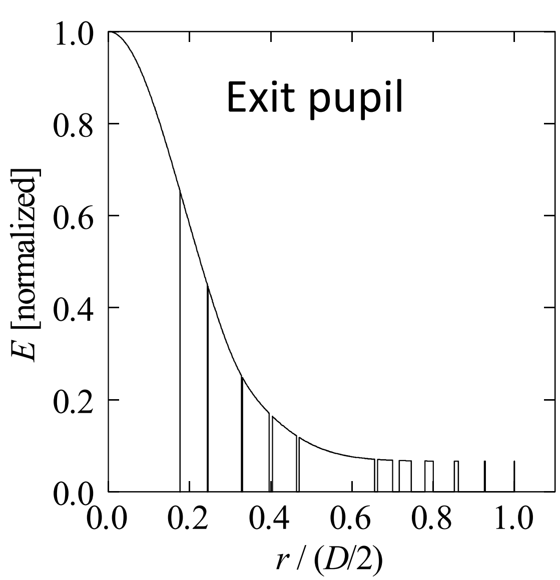
- Uncontrollable light can be considered "unresolved" in one of many ways
  - Temporally unresolved – interference patterns that change with time
    - Mechanical motion, vibration
  - Spatially unresolved – fringes whose spacing is < 2 pixels
    - Ghost with tilted wavefront w.r.t. direct wavefront
  - Spectrally unresolved – incoherent light
    - OPD > coherence length defined by spectrum
      - Ghosts with large OPDs may be partially coherent
    - Quasi-monochromatic light with center wavelength varying during exposure
  - Unresolved by polarization state
    - Mutually orthogonal polarization states will not interfere with one another
  - Measurement errors
    - Random errors statistically underestimate uncontrollable light
    - Poor dark subtraction can increase or decrease measured uncontrollable light

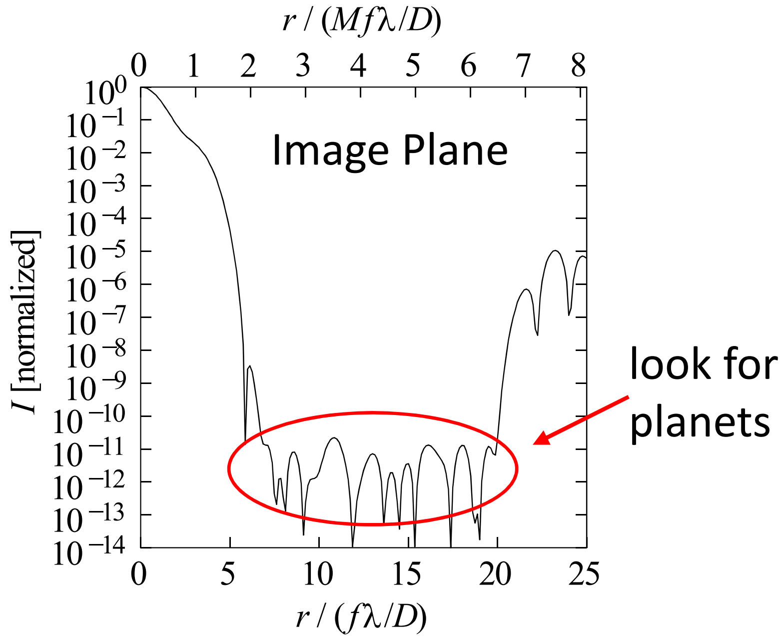
Optical description relevant to tests

- PIAA losslessly constructs pupil-plane amplitude pattern with useful image-plane PSF
  - Many designs call for absorbing post-apodizer
  - Can be binary annuli

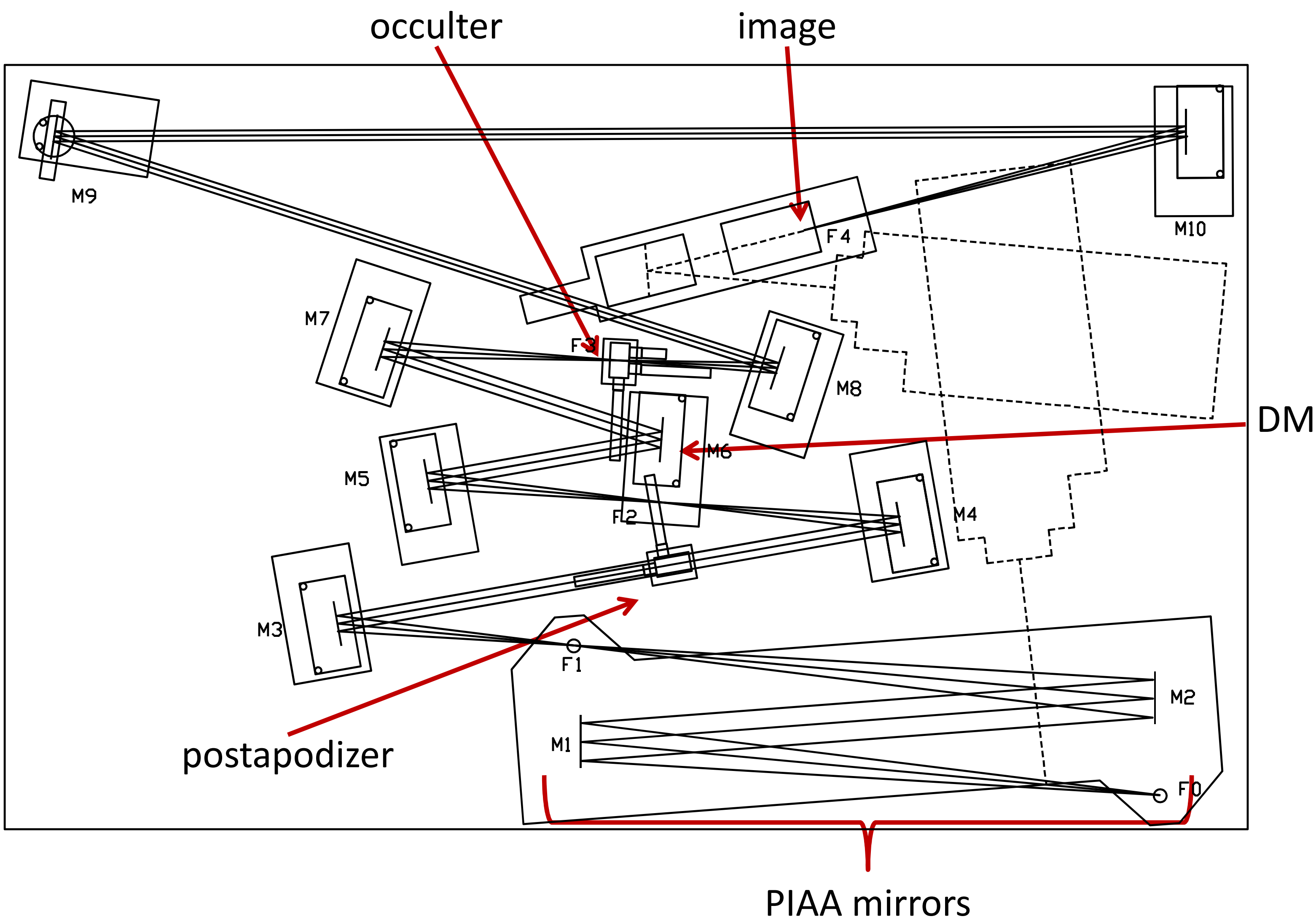








Optics in testbed

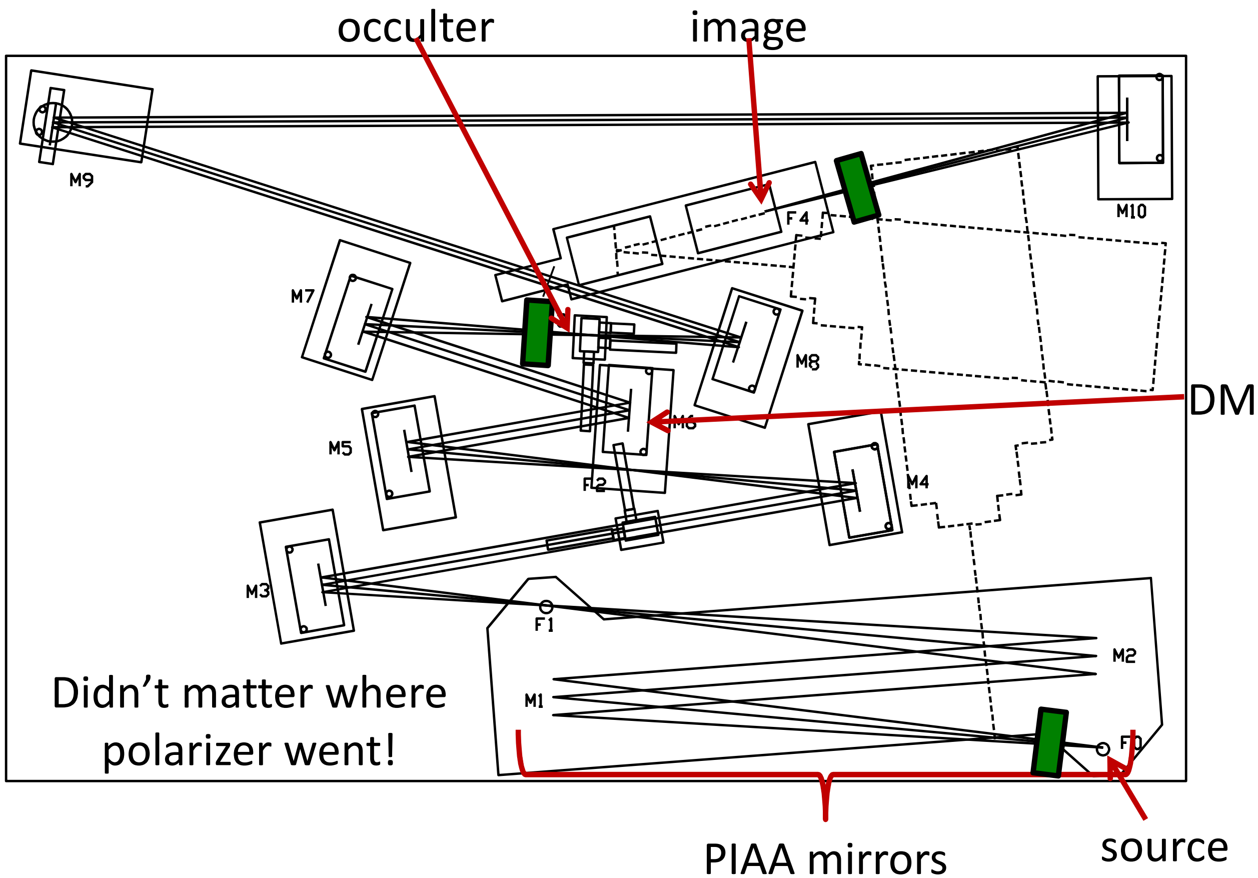


Physical sources for limits

Origin	Mechanism	Test	$\log_{10}$ limit
Poor occulter image	Finite optics / truncation	Add Lyot stop	-8
	Scattering	Add Lyot stop	-8
Temporal variability	Low freq drift (<< iterations)	Repeat unchanged	< -7
	High freq vibration (>> iter)	Change flux & exp	< -7
Fiber / pinhole as source	Source wavefront morphology	Add / change pinhole	< -8
Camera pixel size	Misinterpret DM probes	Numerical analysis	< -9
Ghosts	OPDs by glass/air reflect, CCD, source partially incoherent	Move optics / occ	
Scattered Light	Poor baffling	Add baffling	
Polarization	Incoherent states at source	Add / change pinhole	< -8
	Ghost with altered pol. State	Move optics / occ	-8?

Improvement 1: Polarization

- Add linear polarizer anywhere in the system (3 places), uncontrollable light went down by ~ $2\times$

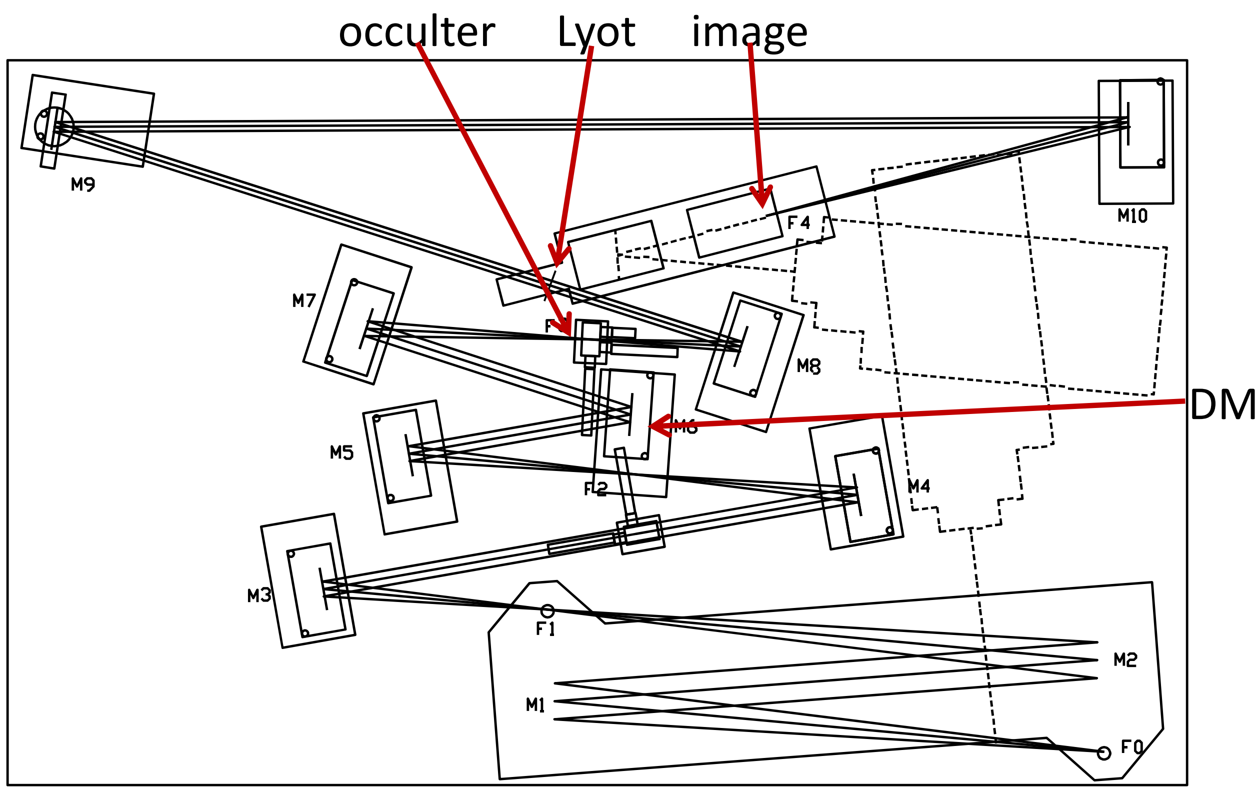


Improvement 2: Spatial filter at source

- Began with bare high-NA single-mode fiber as source
  - Should give achromatic illumination
- Switch to $5\ \mu m$ pinhole, contrast improved by ~ $2\times$
- Must be non-single-mode behavior of fiber
  - Could be coupled to polarization

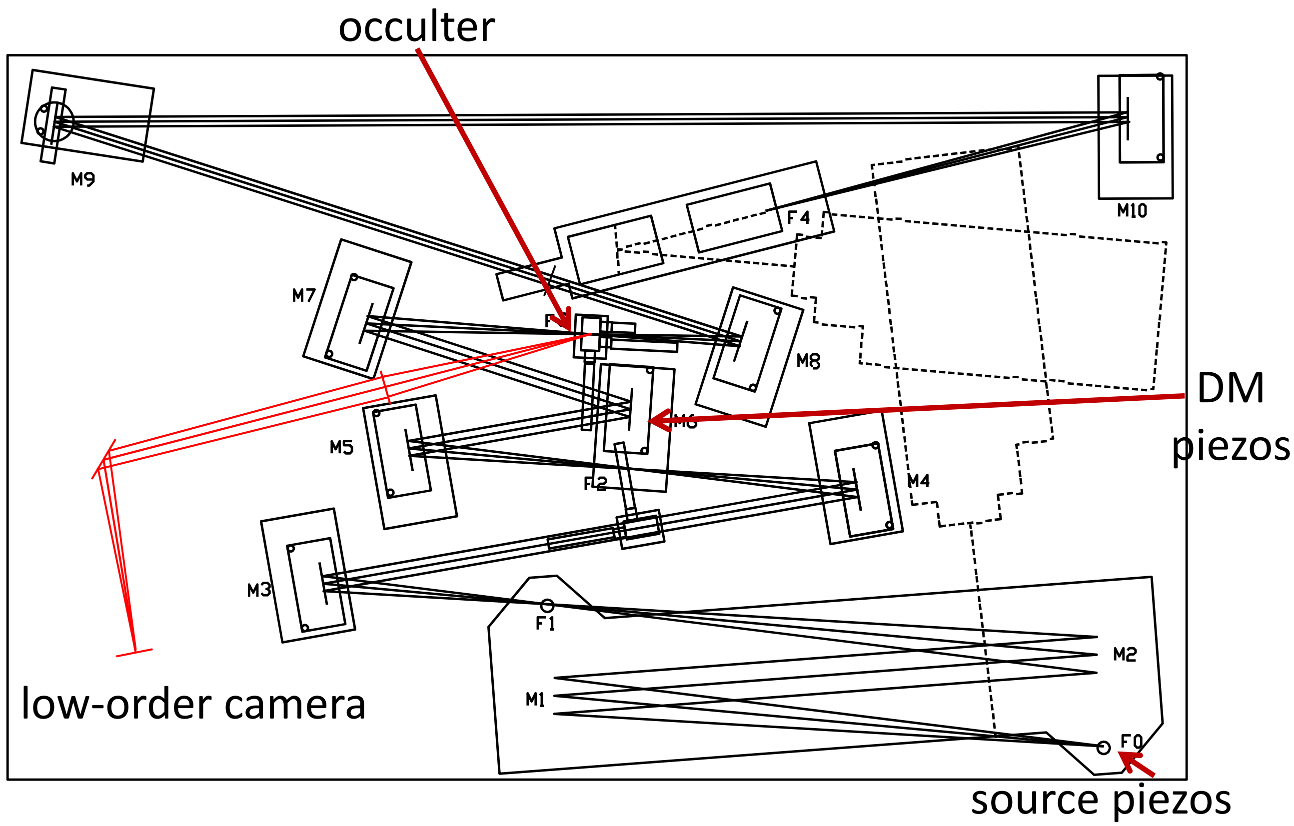
Improvement 3: Lyot stop

- Added Lyot stop after occulter, improved by several ×
- Raises size question – what size to use?
- Becomes APLC



Improvement 4: Low-order correction

- Introduced camera to look at light reflected from occulter
- Lots of light, can operate at high speed
  - Currently 10 Hz, not difficult to reach 50 Hz



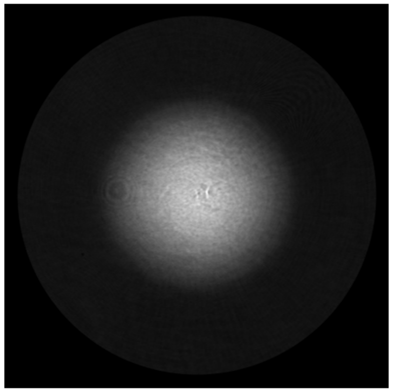
Preliminary results from low-order camera

- See motion that was unresolved with slower science images (< 0.1 Hz)
- Cross-correlation between successive science images shows ~ $0.5\ \mu\text{m}$ shifts over minutes timescales
- Roughly matches power spectrum from low-order camera
- Calibration not yet in place to discriminate pre- and post-remapping aberrations
  - Without discrimination, limits correction to $2\times$ improvement

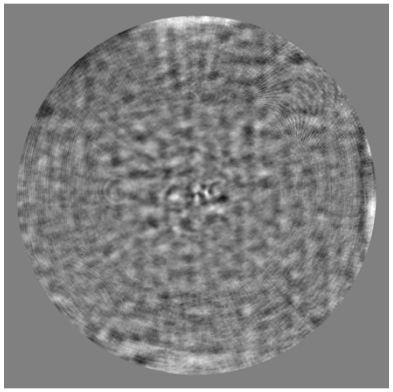
Effect of Lyot stop

- Lyot stop had significant effect compared to no-stop configuration
- Use simulations to find best Lyot stop size, and to determine interaction with postapodizer
- Use measured testbed wavefront instead of "perfect" wavefront

measured



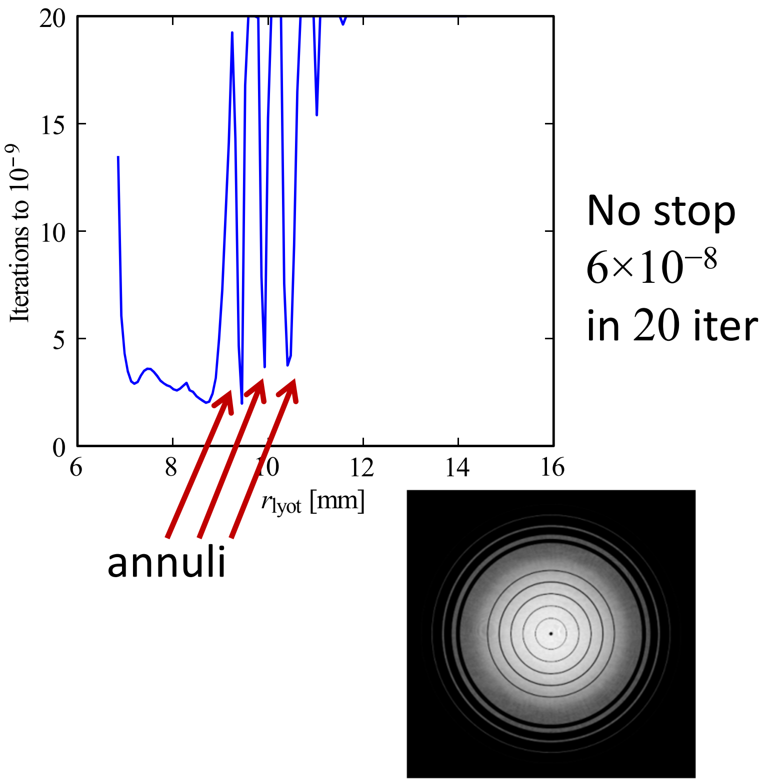
amplitude

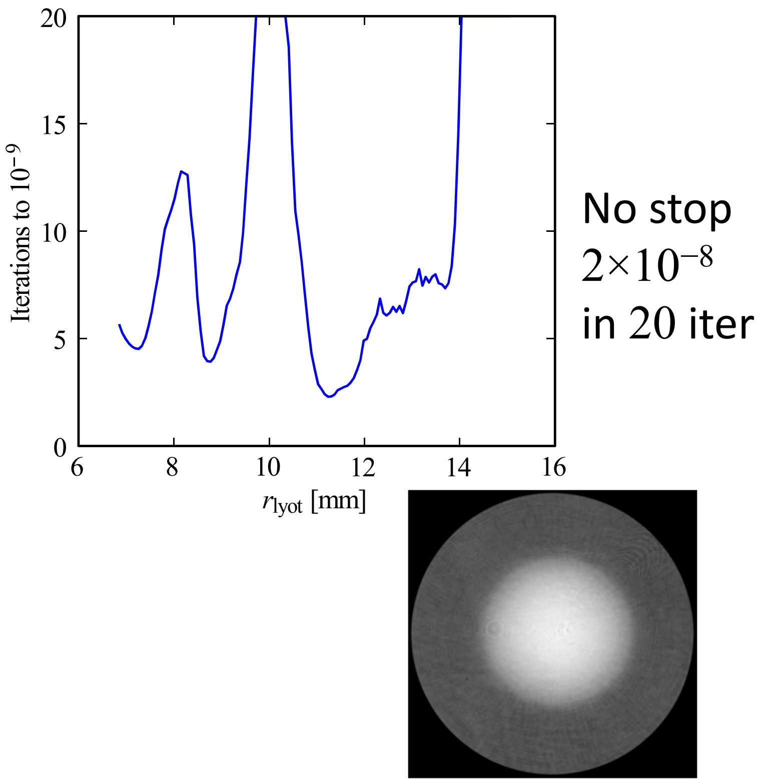


phase

Simulations of Lyot sizes

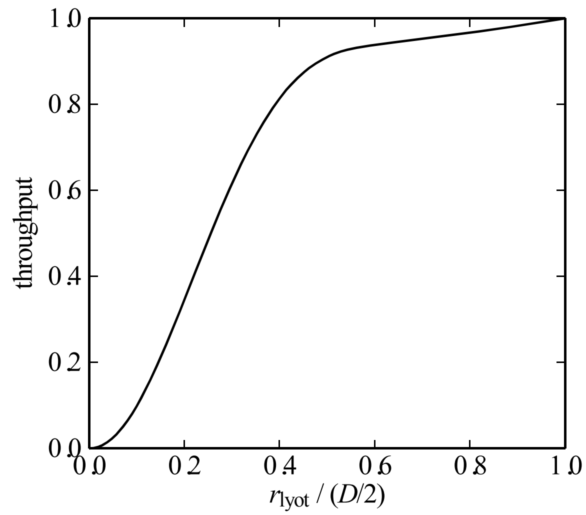
- Choose figure of merit for architecture choices
  - Number of iterations to 10^{-9} (best cases ~ 10^{-11} in 20 iterations)
  - Some arrangements take > 20 iterations





Lyot size / postapodizer choice

- Monochromatic simulations suggest that annular postapodizer does not help wavefront control reach 10^{-9}
- Lyot stop is necessary for good contrast
  - Testbed results indicate uncontrollable light issues as well, which improved with Lyot stop
- Loss of throughput for reasonable Lyot sizes is very modest
- All this needs to be revisited for broadband simulations



Simulations of sensitivity to tip/tilt

- Simulations of tip/tilt show about 10^{-8} mean dark hole effect for offsets of $1\ \mu\mathrm{m}$ at occulter
  - $1\ \mu\mathrm{m}$ at occulter is $(f\lambda/D)_{\mathrm{sky}}\ /\ 30$
  - $1\ \mu\mathrm{m}$ at occulter is $0.4\ \mu\mathrm{m}$ at source
- Sensitivity to tip/tilt depends on specific DM solution and starting dark hole level
  - Deeper dark holes (10^{-11} vs. 10^{-9}) have worse contrast after tip/tilt, by factor of $2{-}3\times$
  - Quadratic sensitivity (mean intensity vs. offset) to tip/tilt at these levels
- If remapped tip/tilt is corrected by ordinary tip/tilt, effect is half of uncorrected value

Summary

- Search continues for factors limiting contrast at 10^{-8} levels
- Low-order wavefront control upgrade underway, could be responsible for large part of uncontrollable light limit
- Lyot stop is needed
  - Coronagraph becomes APLC
- With Lyot stop, no advantage to annular postapodizer
  - Monochromatic result