WFIRST Coronagraph Milestone #8: PIAACMC contrast demonstration

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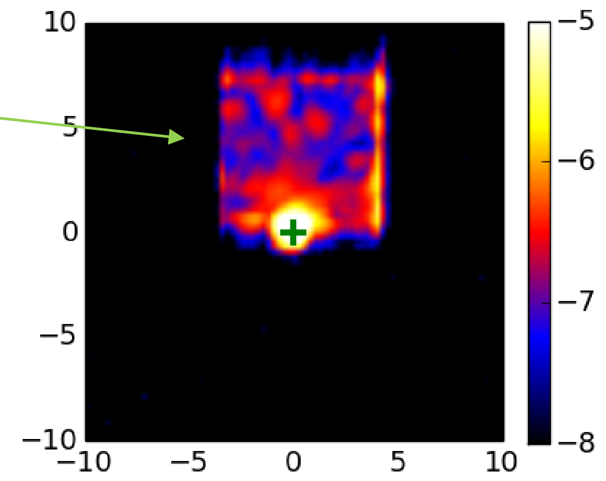
Statement of milestone

- "PIAACMC coronagraph in the High Contrast Imaging Testbed demonstrates 10^{-8} raw contrast with 10% broadband light centered at 550 nm in a static environment; contrast sensitivity to pointing and focus is characterized."

- Status:
  - Monochromatic contrast 2.6×10^{-8}
    - Dominated by incoherent light
    - Mostly tip-tilt jitter
  - Broadband contrast ~ 1.8×10^{-7}
    - Limited by time, not fundamentals
    - Broadband milestone target not yet met



Overview

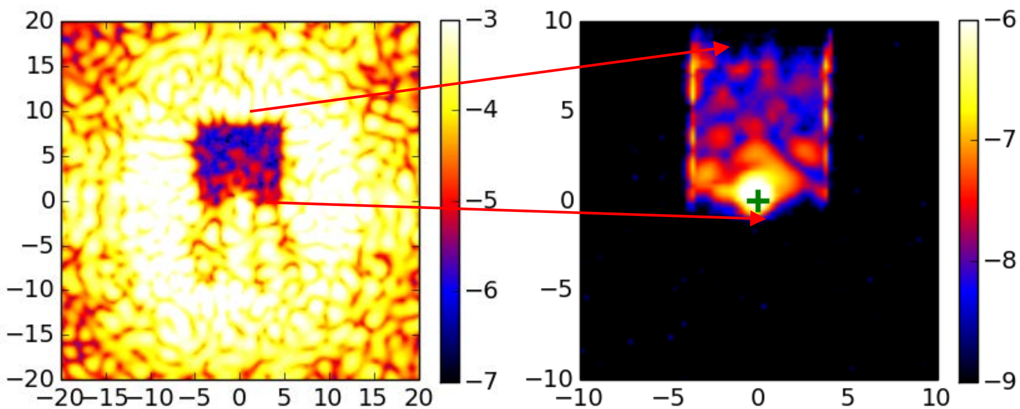
- Monochromatic results summary
- Broadband results summary
- Sensitivities
- PIAACMC functional background
- Testbed components
    - Mirrors
    - Occulter
    - DM
    - Environment
- Modeling topics
- Unfinished topics

Monochromatic results

- 2.6×10^{-8}, dominated by incoherent light
  - Empirical tip-tilt sensitivity and measured tip-tilt jitter expected to produce ~ half this incoherent
    - Tip-tilt jitter is known to vary, may be entirely consistent
  - Should test polarizer (not yet in system)
    - TDEM "classic" PIAA testbed saw polarization problem at ~ 10^{-8}, probably where light source is launched into optical train
    - OMC testbed identified polarization complication from illumination front-end

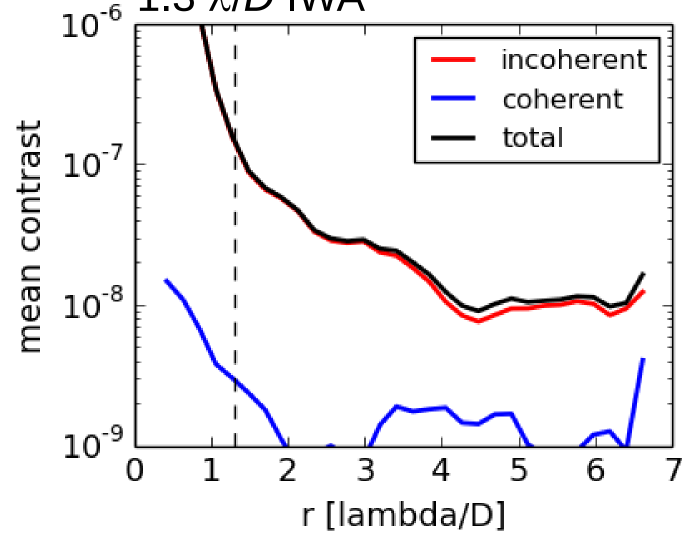
1 DM, 1-sided, $\pm 6.5\ \lambda/D$ before inserting field stop

field stop in



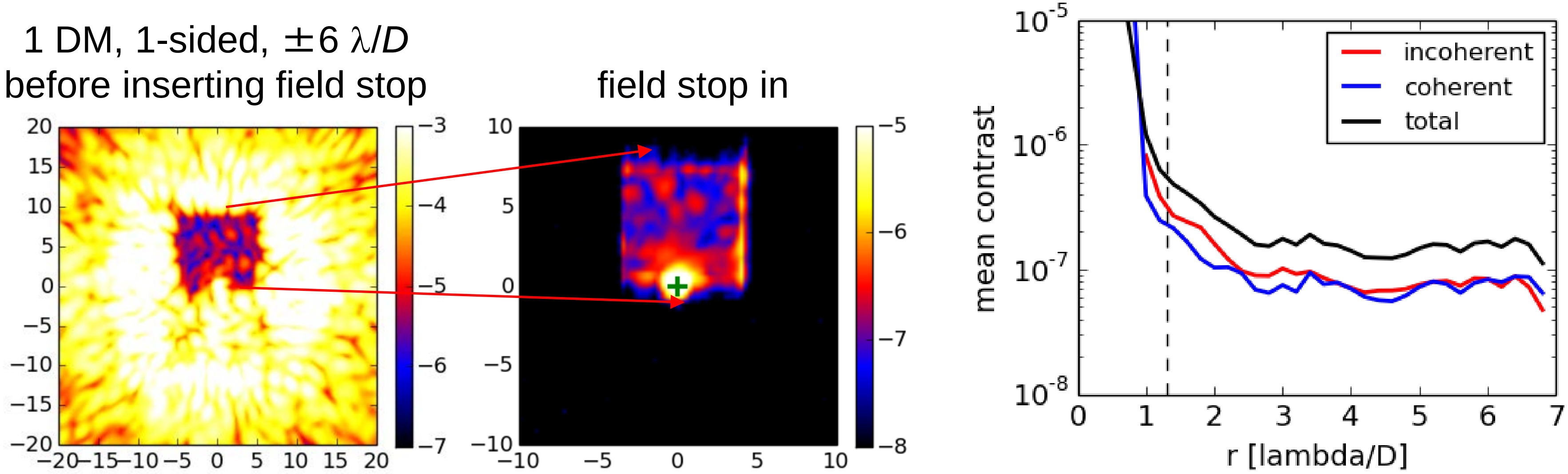
field stop needed below 10^{-7}

1.3 λ/D IWA



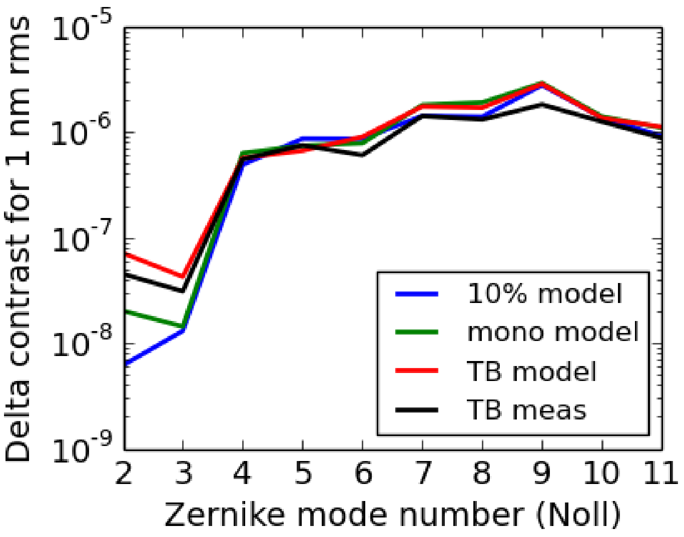
10% broadband results

- 1.8×10^{-7} in 10% broadband light centered at 550 nm
- Not dominated by incoherent light
  - Ambiguous distinction between coherent and incoherent
  - Incoherent decreases with iterations along with coherent to this point
- Wavefront control is realizing improvements more slowly than model
  - Likely a combination of calibration errors of both occulter and DM motion



WFE sensitivities

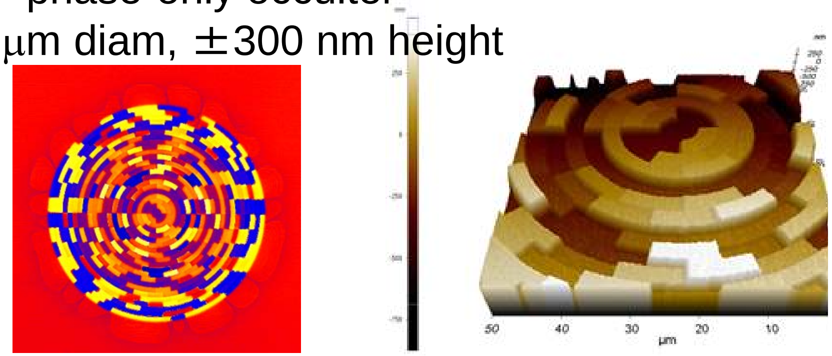
- Test sensitivity to Z2-Z11 on monochromatic solution
- Apply WFE to DM
  - Apply 50 pm – 250 pm rms surface (depending on mode), to produce ~ few 10^{-9} delta contrast
- Model of testbed as best known with testbed DM settings gives good agreement (red vs. black)
- Models run "from scratch" (testbed initial conditions but no feedback from testbed) give lower Z2-Z3 sensitivity
- Likely possible to include tip-tilt sensitivity in control to improve
  - Similar to HLC
  - Certainly potential for 10× improvement

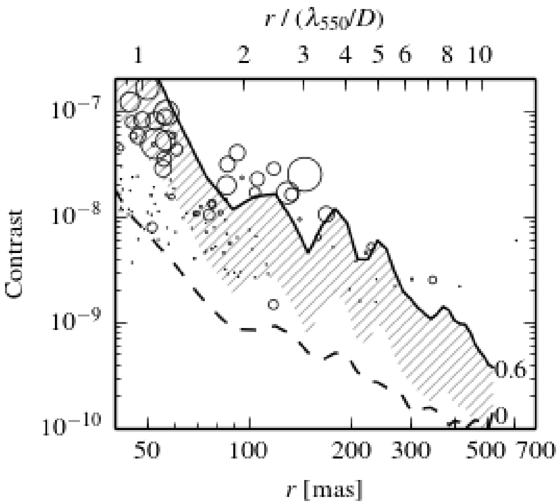


PIAACMC basics

- PIAACMC is high-throughput, small IWA coronagraph
  - IWA = 1.3 λ/D
- "Gen 3" system design was optimized for low (good) tip-tilt sensitivity
- Novel components are aspheric PIAA mirrors and phase-only occulter (reflective)
- As designed, with low tip-tilt errors, science return was modeled to be very good

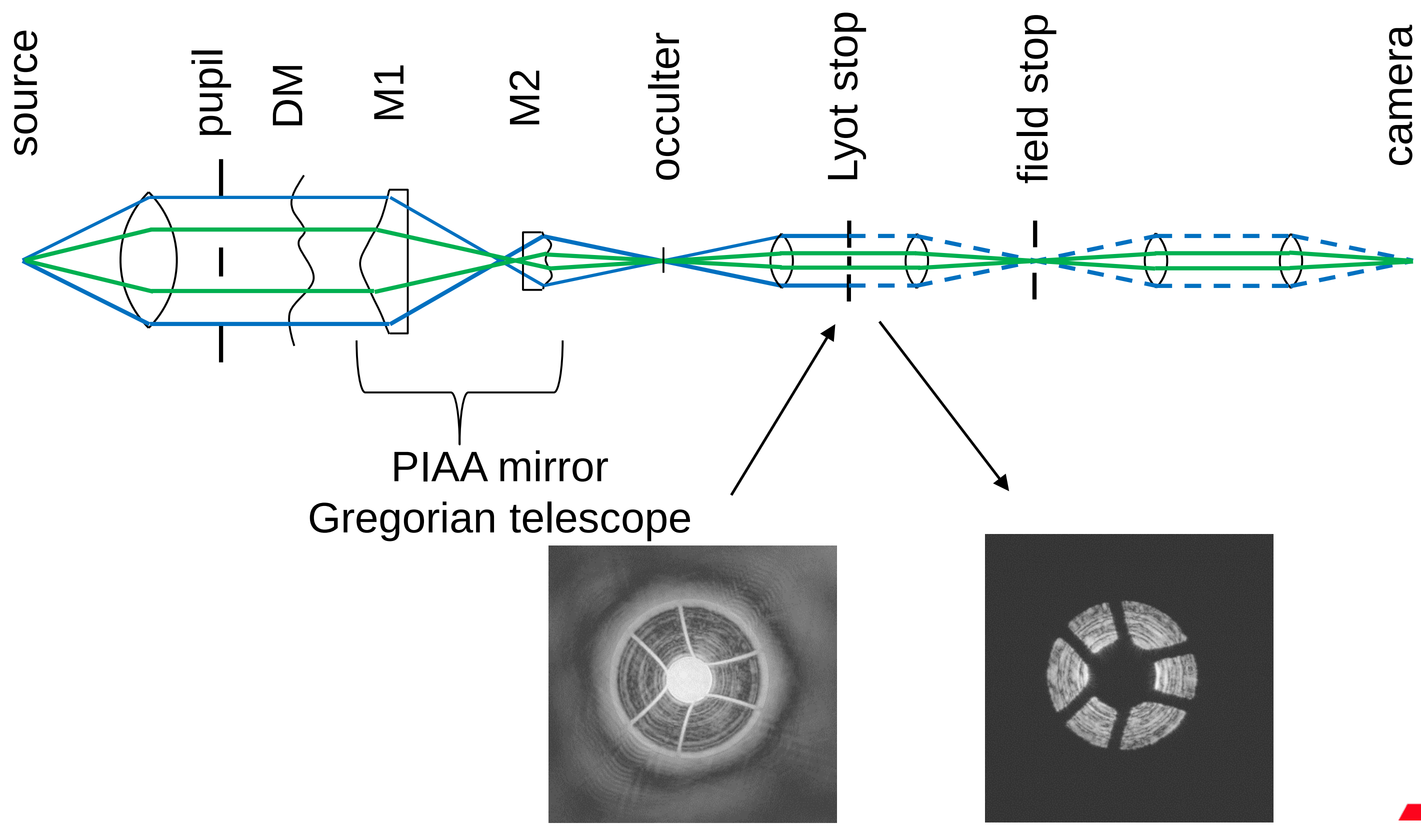
phase-only occulter
150 μm diam, $\pm$300 nm height





PIAACMC schematic

- Layout is single DM
  - Single-sided dark hole
- All light is absorbed at Lyot stop
- Field stop is available for high dynamic range
  - See dark hole near bright outer PSF / uncorrected half



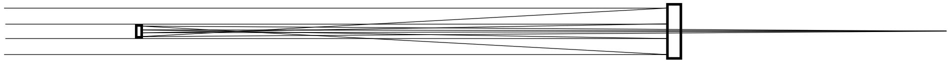
Modeling overview

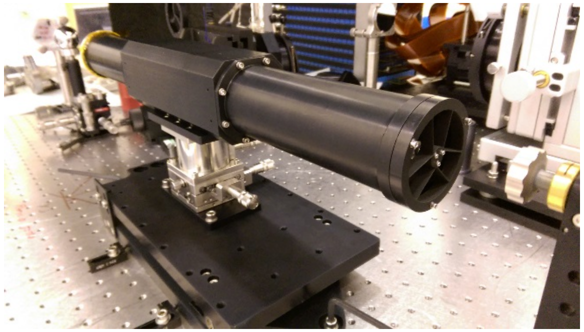
- What components are well characterized and / or well modeled?
  - Modeling impacts do not include effects of errors in control model w.r.t. testbed

	Characterized	Modeled	Impact mono	Impact BB
PIAA mirrors	well	well	no	no
occulter	medium	low	tip-tilt sens?	?
DM	well	low	no	?
environment	medium	medium	tip-tilt?	no

Individual components: PIAA mirrors

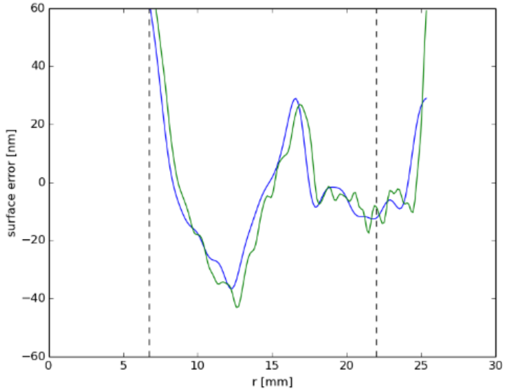
- Mirrors were fabricated to spec
  - Single-point diamond turned
    - Inexpensive, fast
  - Measured against CGH
  - 20 nm rms surface requirement met
  - Gregorian telescope assembly



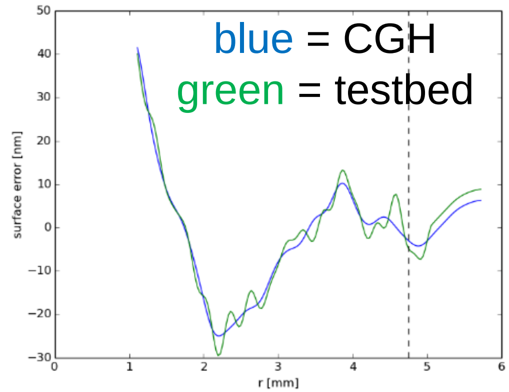


- Measurements on testbed refine interferometric testing
- Models say mirrors are fine

M1 surface errors



M2 surface errors

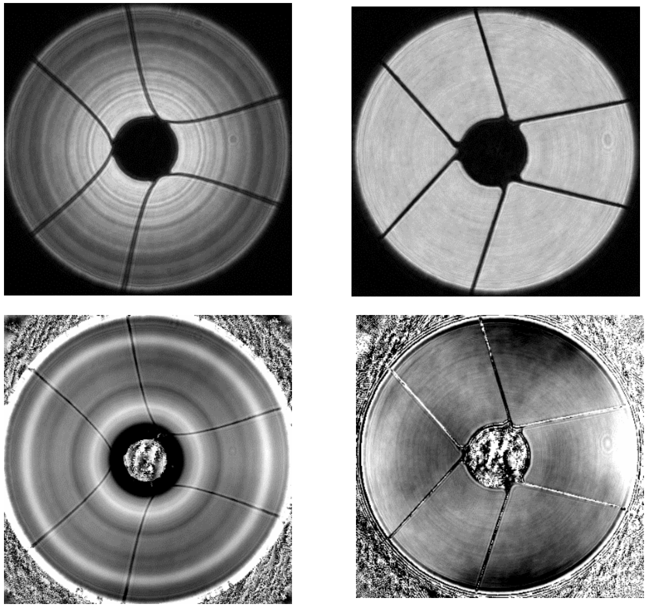


at camera

upstream of PIAA

amplitude

phase

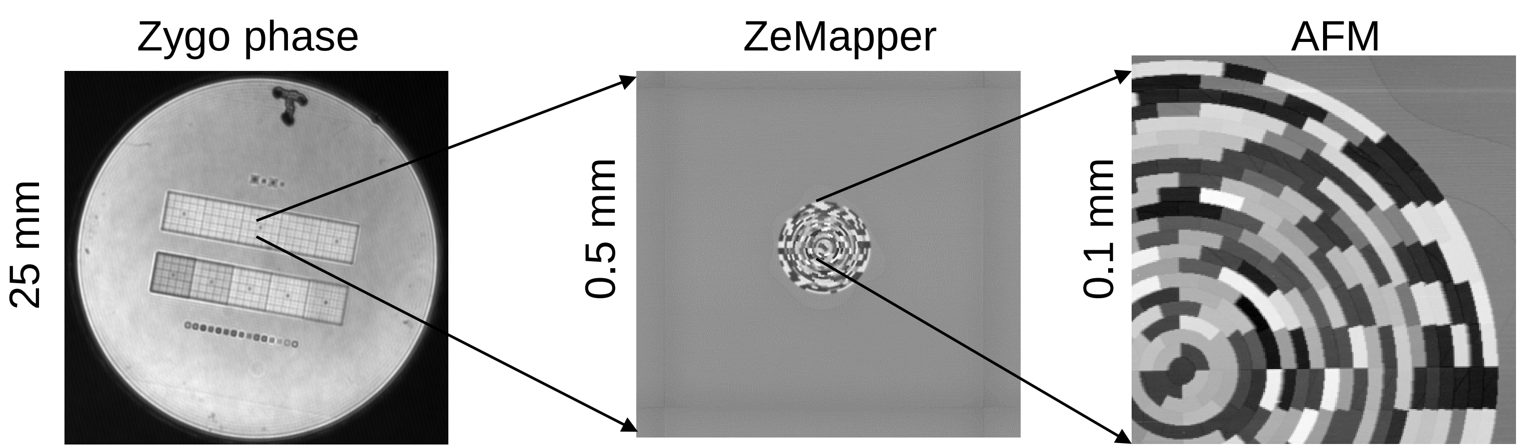


330 nm P-V wavefront stretch

82 nm P-V wavefront stretch

Individual components: PIAA occulter

- Gen 3 occulter fabricated at JPL Micro Devices Lab
  - PMMA on 2 mm thick fused silica, coated with Al
    - All-reflective, phase-only
  - 8 occulters on same substrate
- Occulter suite on testbed now has “global” +12% height scale factor error
  - Additional occulters on substrate with −20%, −10%, +10%, +20% scale factors relative to nominal, using −10% relative to +12% nominal error
- Detailed Gen 3 modeling to date only for scale errors

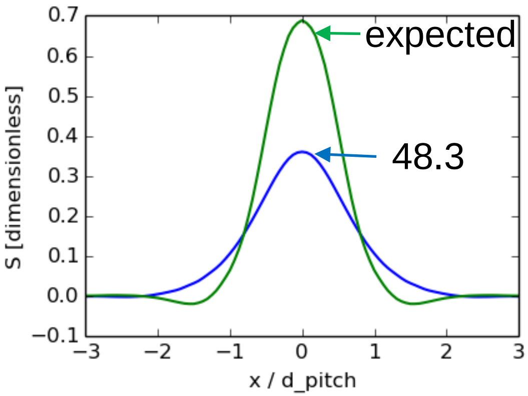


JPL

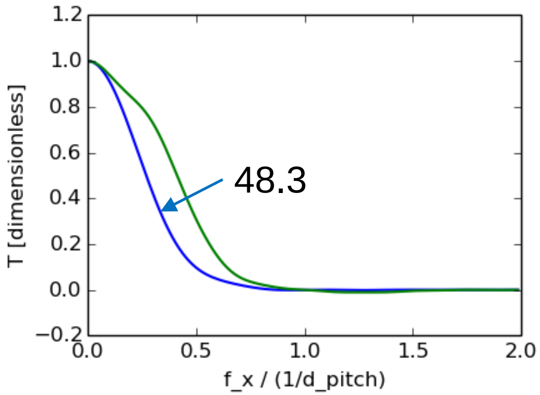
Individual components: DM

- Using Xinetics 48 × 48.3 DM
  - New DM, not used prior to WFIRST PIAA testbed
- Influence function consistent with thicker facesheet
  - Requires larger voltage swings to produce high spatial frequency features ("stiff")
  - At mid spatial frequencies, transfer function is 2-3× lower than earlier modeling had been based on
- BB WFC solutions are seeing more voltage constraints than thin-facesheet models expected
  - Lesson learned for flight CGI DM is to clearly specify influence function req'ts

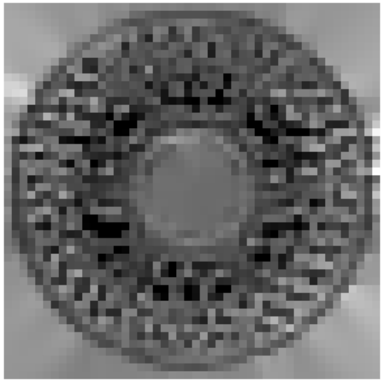
influence function



transfer function



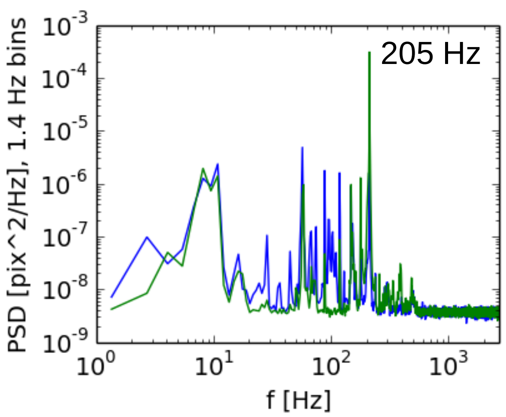
BB WFC voltage map
230 actuators hit
constraints (1703 visible)



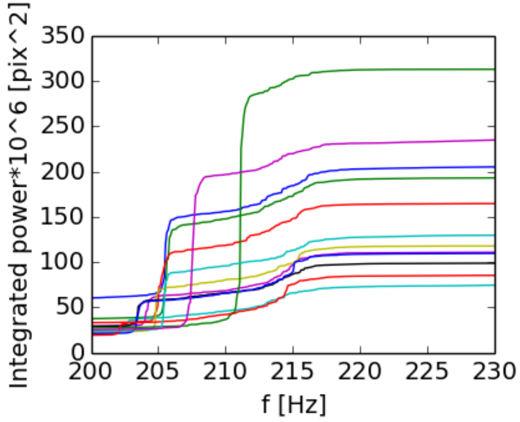
Testbed environment

- Measurement of star centroid with occulter out shows dominant 205-210 Hz power
  - 0.2 mas rms table-horizontal, 0.1 mas rms table-vertical
- 205-210 Hz line strength varies over ~ 10 minute timescales
  - Integrated power in line changes by 2-3×
- Incoherent light in monochromatic dark hole also varies on similar timescales

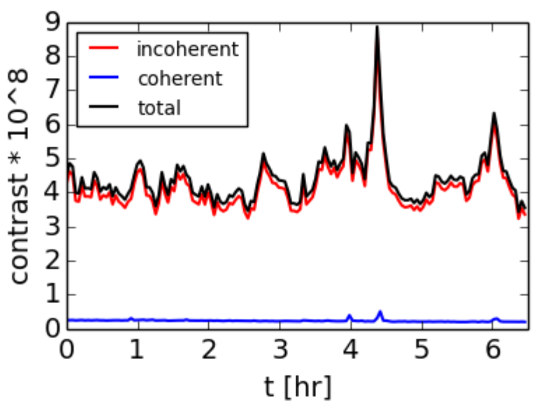
centroid temporal PSD



cumulative centroid power at different times



monochromatic dark hole contrast vs time

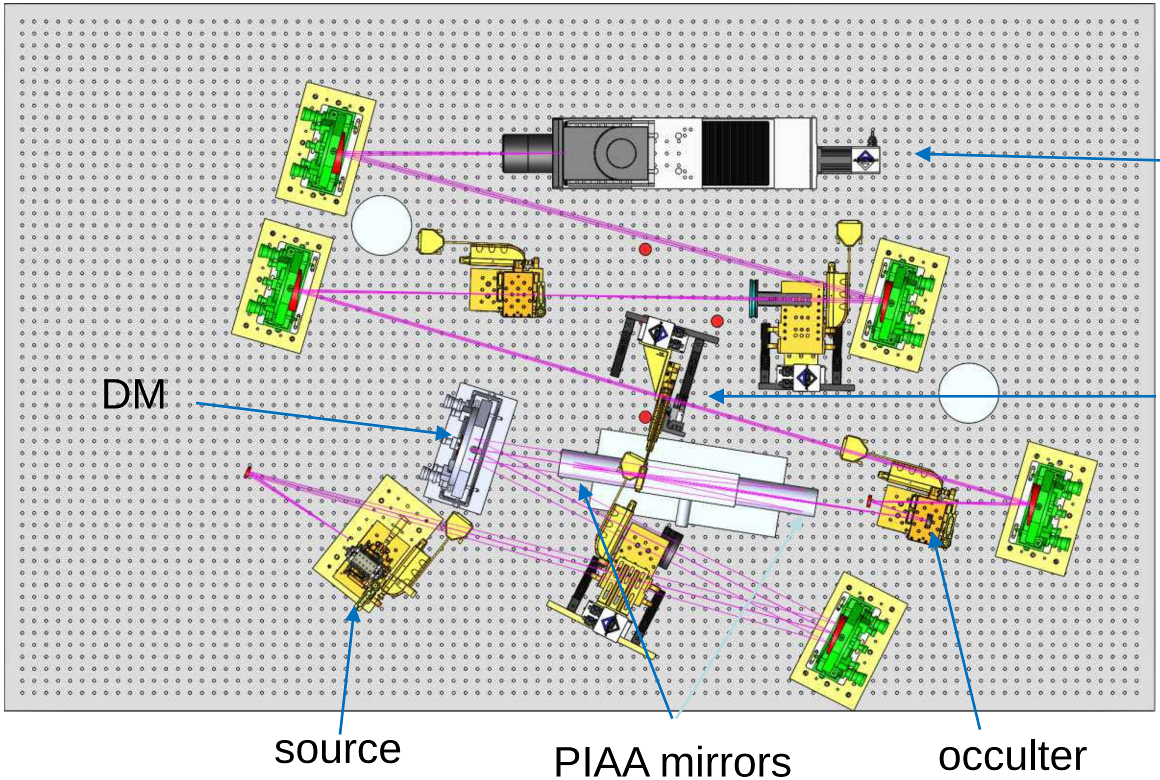


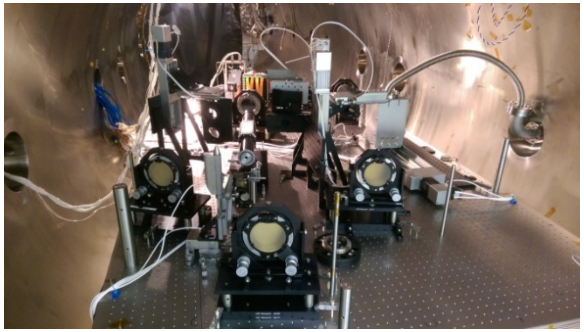
Unfinished topics

- Continued BB wavefront control
  - May see significant improvement with “standard” operation
    - Factor of ~ 7 improvement in last week
  - Include Strehl / stroke mitigation in EFC
  - Revisit DM gain calibration
  - Feedback on model of occulter
  - Explore more of the existing occulters / different height scale factors
- Tolerance more varieties of occulter errors
  - Additional occulter with more test data is available
- Null with occulters using different scale factors
  - Milestone #3 style analysis should be repeated for Gen 3
  - Tolerance ability to calibrate the rest of the coronagraph for WFC

BACKUP

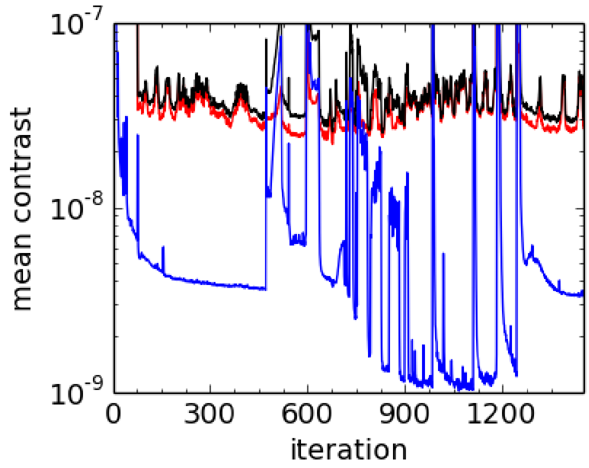
Table

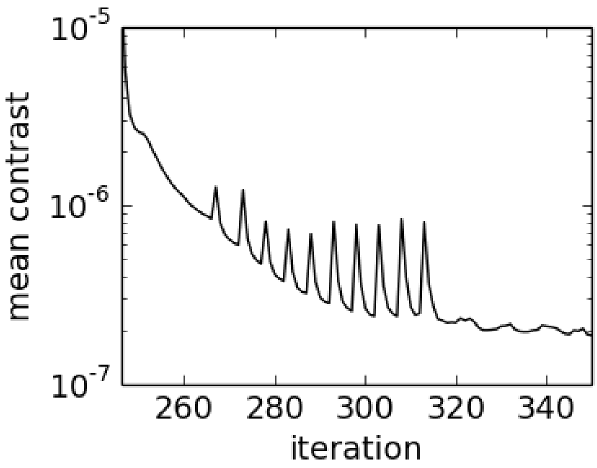




Rate of convergence

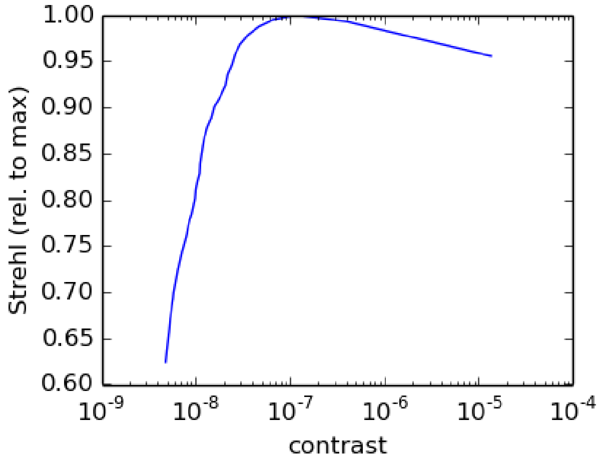
- New investigations into most effective wavefront control strategies
- How much of existing dark hole E-field to null in a single iteration
- When trying to null bulk of E-field, residual E-field in next iteration is higher, but contrast is reduced over long-term

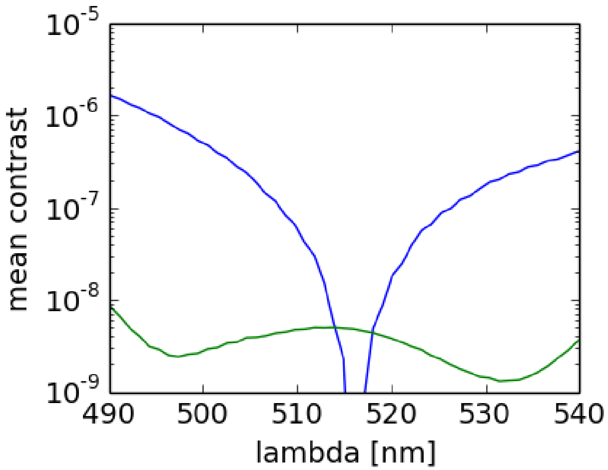




Strehl

- Need to be aware of Strehl ratio changes as wavefront control proceeds
- Broadband solution uses more stroke
  - Strel ratio lower by ~40% for broadband relative to mono
  - P-V ~ 50 V off of "flat"
  - Model does not predict as large stroke at high spatial frequencies as seen on testbed
- If only single wavelength is controlled, system is strongly chromatic, ~ 10^{-6} over 10%
  - Assumes as-built mirror errors, known occulter global scale error, measured system phase and amplitude

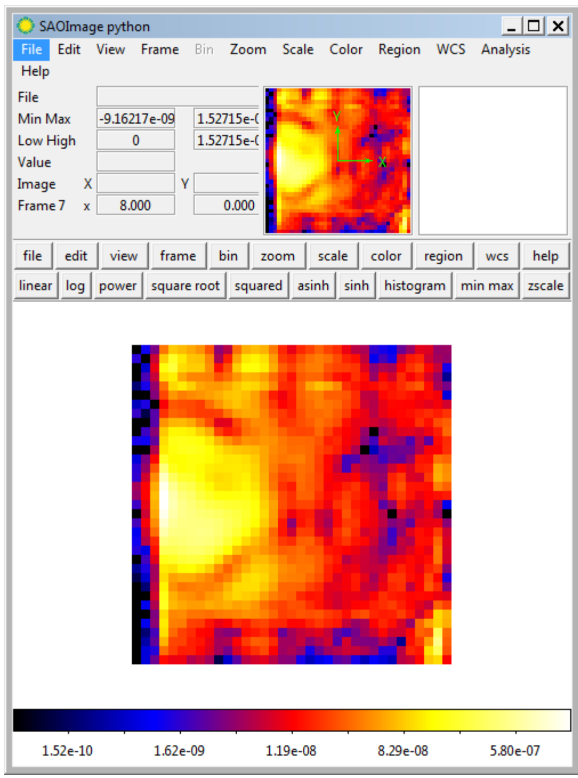




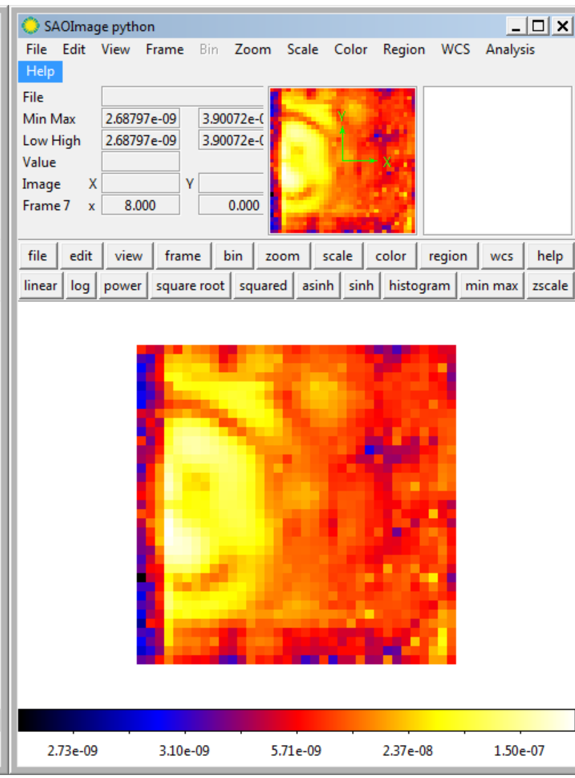
Monochromatic contrast 8/31/16, +12% occulter

- Some incoherent intensity is not temporal variability at f < kHz

total normalized intensity



temporal variance



temporal minimum