Effects of Nearby Stars on Wavefront Correction for the WFIRST CGI

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Framing the Problem

Problem:

- Nearby stars will add incoherent light into the dark hole
  - Main concern is binary star systems
- Extra incoherent light in the dark hole:
  - Increases photon shot noise
    - Increases time needed for WFSC
  - Increases subtraction error in image post-processing

Goals of this Study:

1. Determine a formula for the average contrast of incoherent light from a nearby star
   - Parameters: wavelength, separation, relative brightness of neighboring star, coronagraph type
2. Determine the relative increase in time for wavefront correction for a given contrast of the incoherent light

Part 1: Determining Contrast vs Separation

Approach:

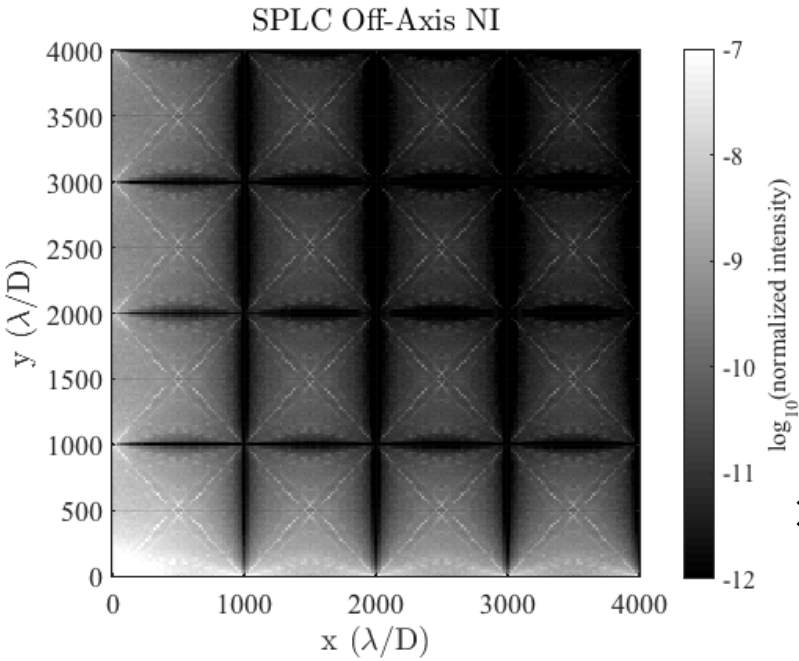
1. Propagate off-axis PSFs through each coronagraph type
   - Pupil planes upsampled to calculate PSF at large separations
   - Performed without aberrations (no aberration data at high spatial frequencies)
2. Calculate the average contrast of the off-axis light in the dark hole
3. Find a functional relationship for the contrast vs separation

Caveats:

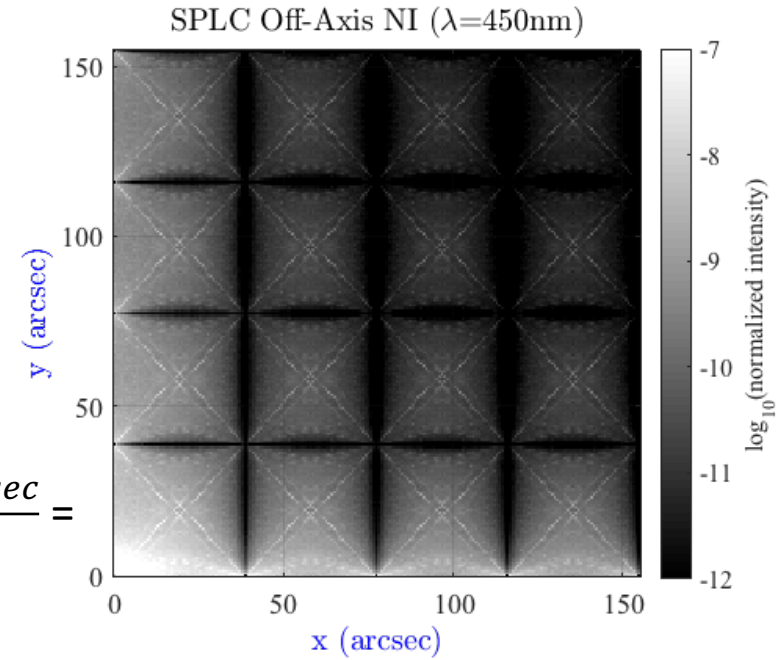
- Not simulated: beam clipping from beamwalk of off-axis sources, finite extent of FPM for HLC
- Aberrations above 200 cycles/aperture not known (largest effect from primary and secondary)
- HLC design only exists at 550nm (results do not necessarily scale with wavelength)

SPLC Off-Axis PSF

Average DH normalized intensity (NI ≈ contrast) contamination at each off-axis point for a 10^0 contrast star:



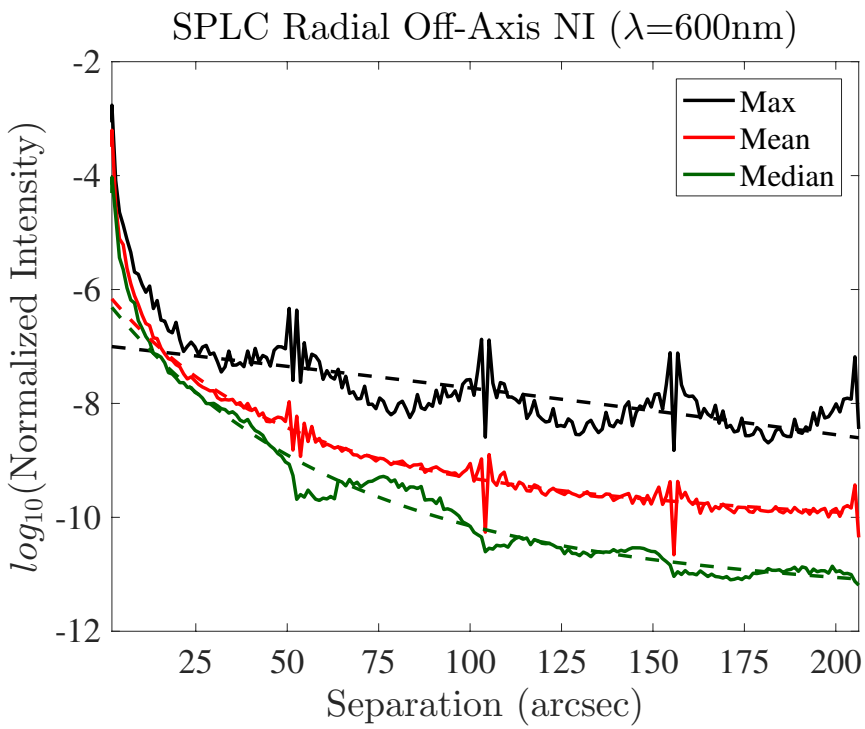
$$\times \frac{\lambda}{D} \frac{180}{\pi} \frac{3600\ arcsec}{degree} =$$



- (Same in each of 4 quadrants, so only 1 computed)
- Periodicity is **real**: from the discrete 1000x1000-point optimization & manufacturing grid of the SP mask
  - Diffraction spikes also periodic
  - NI is worst along x- and y-axes
- Telescope cannot be rotated more than a few degrees because of limited azimuthal FoV for SPLC

SPLC Off-Axis Radial Fits

Radial average/median/max based on previous 2-D plots:



- Three radial fits made: max, mean, and median.
  - Max for worst-case scenario.
  - Median for most likely
  - Fits shown as dashed lines in plot
- Chosen exponential fits monotonically decrease
  - (Exponential fit of log10(NI), not of NI itself)
  - NI can be extrapolated beyond calculated region *(but is only an estimate)*

<u>Formulas for NI vs separation (at λ=600nm):</u>

$$NI_{max}(r) \approx C_{nbr} 10^{-6.988 \exp(0.001008r)}$$

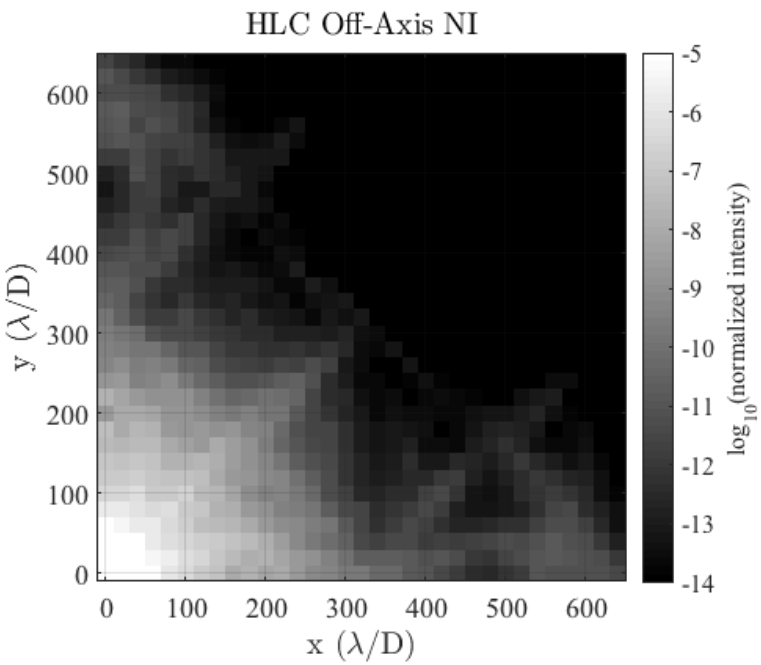
$$NI_{mean}(r) \approx C_{nbr} 10^{-9.393 \exp(0.0002863r) + 3.386 \exp(-0.02247r)}$$

$$NI_{median}(r) \approx C_{nbr} 10^{-10.82 \exp(0.0001785r) + 4.671 \exp(-0.01681r)}$$

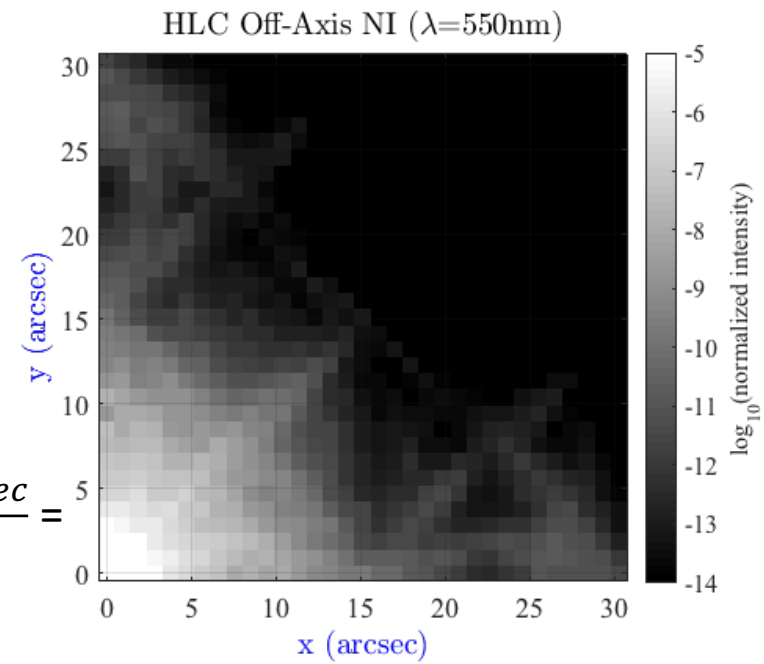
- Radial coordinates scale with wavelength for SPLC. For longer wavelengths, multiply separation *r* by wavelength/(660nm)
- C_{nbr} is the contrast ratio of the *neighbor* star to the on-axis star (without a coronagraph)
- *NI ≈ contrast. Contrast/NI ratio is usually 0.8 to 0.9.*

Part 2: HLC

Average DH normalized intensity (NI ≈ contrast) at each off-axis point for a 10^0 contrast star:



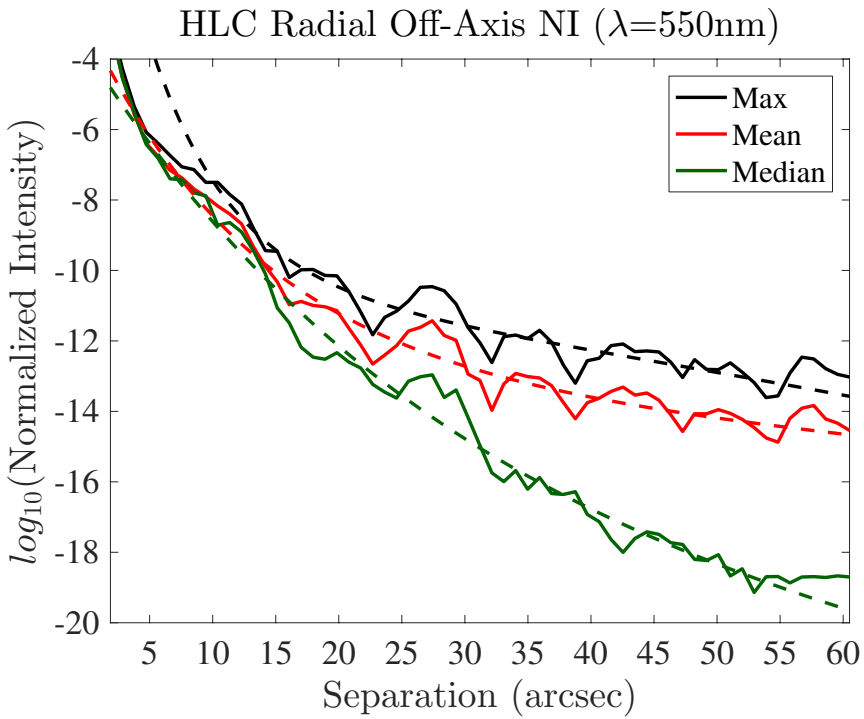
$$\times \frac{\lambda}{D} \frac{180}{\pi} \frac{3600\ arcsec}{degree} =$$



- Only 1 quadrant used (negligible error in assuming other 3 quadrants the same)
- NI fall-off is *much* faster than for SPC
- Can be well approximated with radial formula

HLC Off-Axis Radial Fits

Radial average/median/max based on previous 2-D plots:



- Three radial fits made: max, mean, and median.
  - Max for worst-case scenario (along diffraction spikes)
  - Median for most likely scenario
  - Fits shown as dashed lines in plot
- Chosen exponential fits monotonically decrease
  - Can be extrapolated beyond calculated region *(but is only an estimate)*
- HLC design is different at different wavelengths, but for now can approximate NI vs separation as scaling inversely with wavelength

Formulas (at λ=550nm):

$$NI_{max}(r) \approx C_{nbr} 10^{-10.14\exp(0.004823r)+14.72\exp(-0.1531r)}$$

$$NI_{mean}(r) \approx C_{nbr} 10^{-12.91\exp(0.002233r)+9.923\exp(-0.07354r)}$$

$$NI_{median}(r) \approx C_{nbr} 10^{-18.29\exp(0.002523r)+14.51\exp(-0.03585r)}$$

For different bandpasses, multiply separation *r* by *center wavelength*/(550nm)

Part 3: Effect on Wavefront Correction Time

Approach:

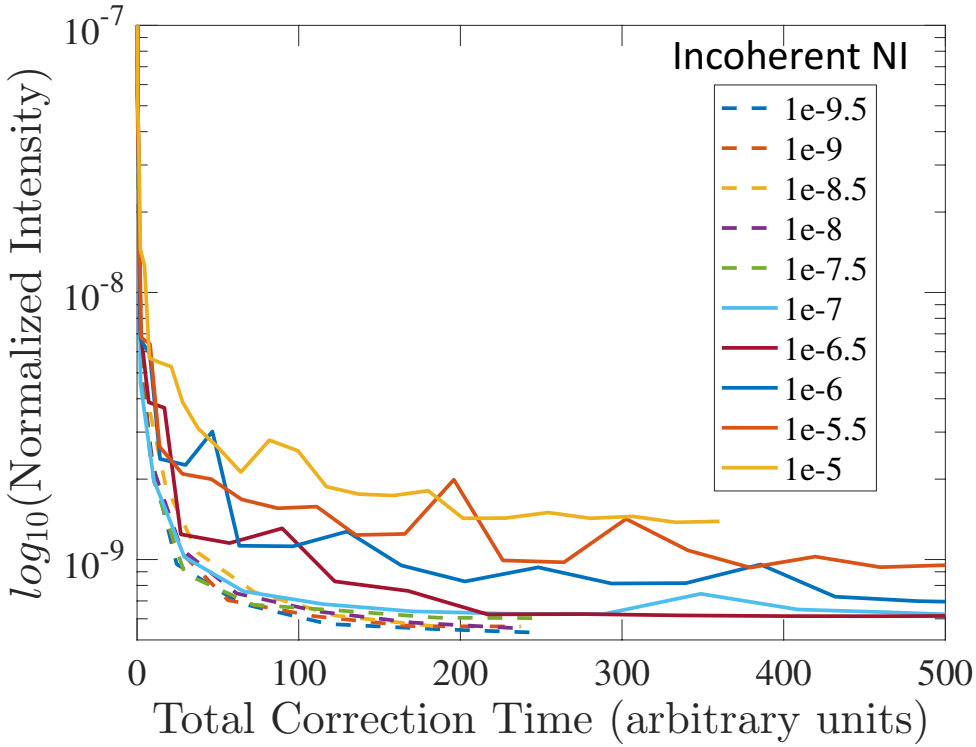
1. Approximate the incoherent light from the neighboring star as uniform across the dark hole
2. Perform broadband wavefront estimation and control with different levels of incoherent light.
3. Compare the relative times necessary to achieve the final contrast for different levels of incoherent light.

Notes:

- SPLC results only (10% BB; estimation+control in 3 sub-bandpasses)
- Model: phase errors on optics, photon shot noise, and 0.2e- readout noise. (Dark current noise, CIC, etc. not included).

Increase in Wavefront Correction Time

Correction Curves for Different Incoherent Light Levels



Results:

- ***Correction negligibly slower for incoherent light <= 10^{-7} NI.***
- Correction ≈2x slower for $10^{-6.5}$ NI incoherent light.
- Correction >5x slower for 10^{-6} NI incoherent light.
- Final achievable contrast is several times worse for >10^{-6} NI incoherent light

Summary and Next Steps

Summary

- Fast fall-off of HLC's off-axis PSF means that any stars >≈30 arcsec shouldn't contaminate the dark hole above the 10^{-10} NI level.
- Slow roll-off and periodic bright features of the (IFS-version) SPLC's off-axis PSF are more worrisome.
  - Similar brightness stars (compared to the on-axis star) along the x- or y- coronagraph axes need to be several *arcminutes* away.
- Wavefront correction can still be efficiently performed in the presence of bright (<≈3×10^{-7} NI) incoherent light.

Follow Up Activities

1. Determine if high spatial frequency (e.g., 200-4000 cycles/aperture) aberrations will make the PSF tails brighter than the nominal contrast already shown
   - Effect will be dominated by the primary and secondary. Data on those might not be available.
2. Determine the effect of azimuthal instability
   - How rotationally stable does the spacecraft pointing have to be for the binary star's PSF wings not to shift during a correction iteration? (Sensitivity increases with radial separation)
3. Determine how well post-processing can do.
   - Even though correction can be done with bright (e.g., 1e-7 NI incoherent light), the extra shot noise will have a worse effect on the planet estimate.
   - Can the non-uniform field that is different at different angles be subtracted out.