Effect of Space Telescope Primary Mirror Segment Errors on Coronagraph Instrument Performance

Bijan Nemati (U. AL. Huntsville),

Mark Stahl (MSFC), Phil Stahl (MSFC)

SPIE Optics and Photonics

August 6, 2017

San Diego, CA

Outline

- Direct imaging of Earth like exoplanets will require a new generation of telescopes and coronagraphs

- Many of the proposed designs will involve a segmented primary mirror

- In the past we have studied the sensitivity of coronagraph raw contrast to segment errors

- Given the importance of the results, we have reviewed the approach and made corrections to the model

- Here we review what are the essential attributes and how we will be modeling the sensitivity to telescope errors, starting with the case of the ATLAST coronagraph.

- This is a work in progress!

ATLAST 9.2 m segmented variant

Direct Imaging of Exo-Earths
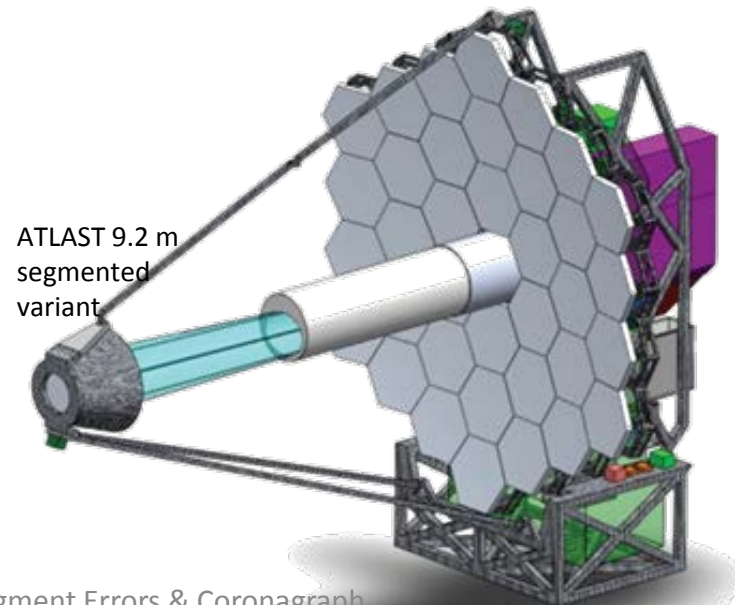
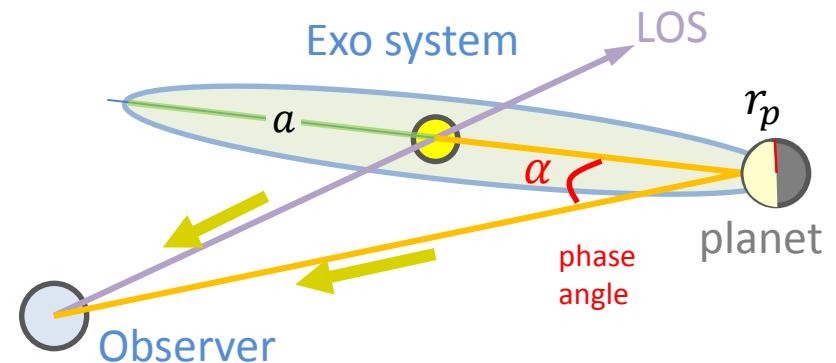- Relative to the star, the light from an exo-Earth is faint!

- Planet flux ratio is the fraction of the light arriving from the planet relative to the star

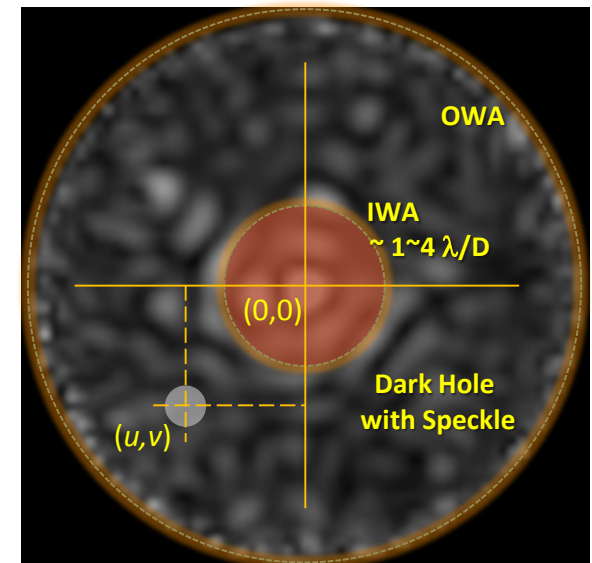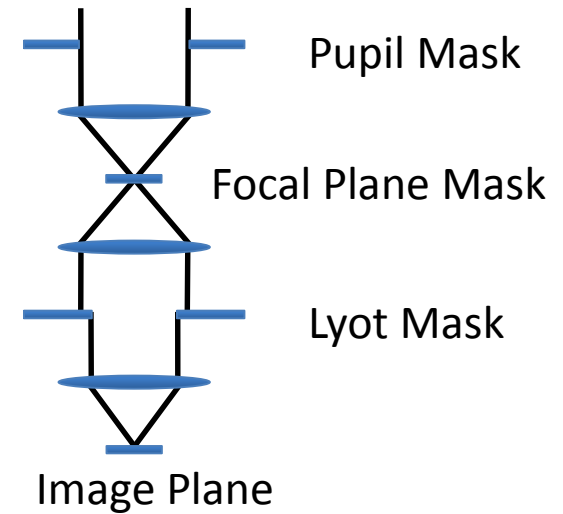albedo

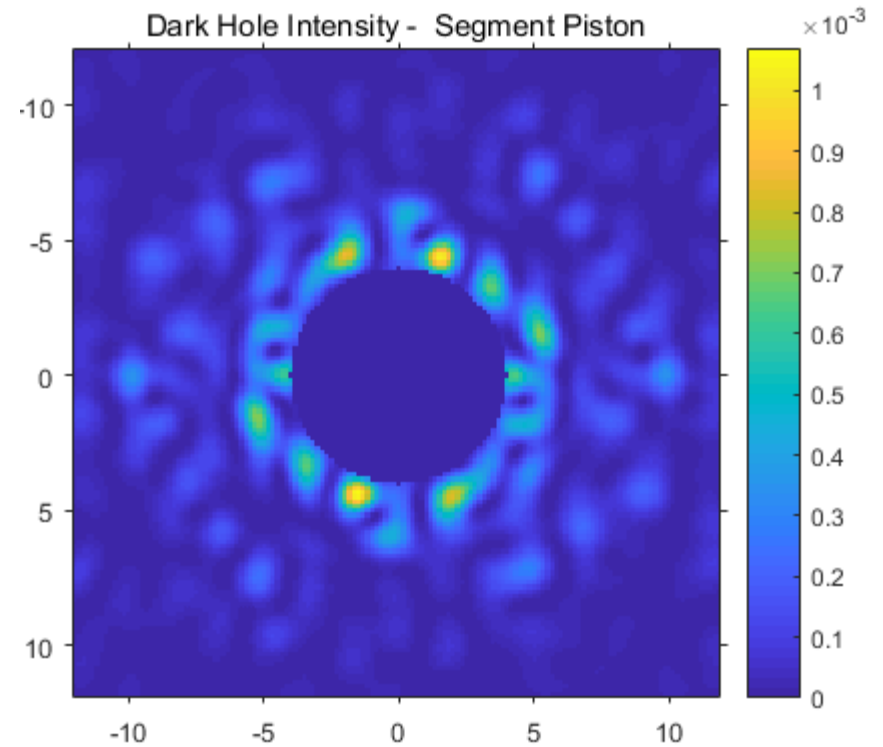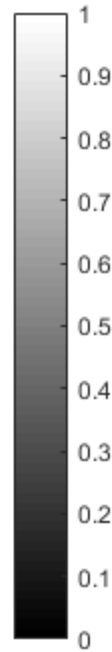$$C_{pl} = A \cdot \phi(\alpha) \cdot \left(\frac{r_p}{a}\right)^2$$

Phase law

Exo system   LOS

a r_p

α

planet

phase angle

Observer

- The Earth seen from many parsecs away would have a flux ratio of approximately 2e-10

Coronagraph Basics

- A coronagraph suppresses the starlight to allow the detection of the planet which is off-axis.

- There are numerous designs, but most involve controlling the diffraction of light by manipulating the phase and amplitude at a number of planes. Most typically, 3 masks and 1-2 deformable mirrors are used.

- The result is a 'Dark Hole' within which starlight is suppressed strongly relative to planet light.

- The inner and outer working angles are the radial limits of a dark hole:
  - IWA is the angle below which the planet light throughput drops to < 0.5 of its peak value within the dark hole.
  - OWA the maximum angle where starlight suppression occurs, limited by the number of deformable mirror actuators.

Pupil Mask

Focal Plane Mask

Lyot Mask

Image Plane

OWA

IWA
~ 1~4 λ/D

(0,0)

Dark Hole
with Speckle

(u,v)

ATLAST Pupil and Coronagraph

ATLAST pupil - Segment Piston

Dark Hole Intensity - Segment Piston

Key Coronagraph Performance Metrics
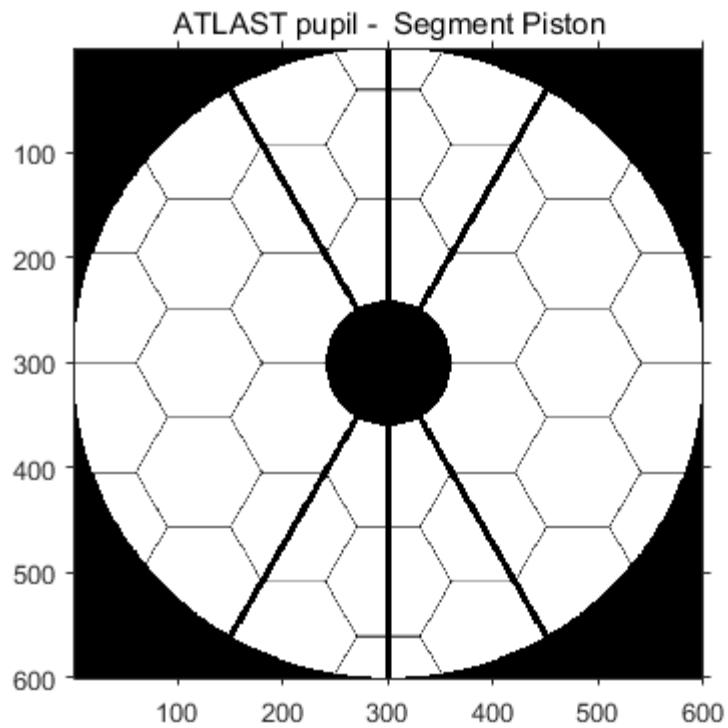
- The most important measure of a coronagraph's performance is its contrast

- Contrast is defined as the fraction of light leaking into the planet location relative to the light arriving if the star was located at the planet location

$$C_{CG}(u,v) \equiv \frac{I_{star}(u,v;0,0)}{I_{star}(u,v;u,v)}$$

evaluate — $I_{star}(u,v;0,0)$

source — $I_{star}(u,v;u,v)$
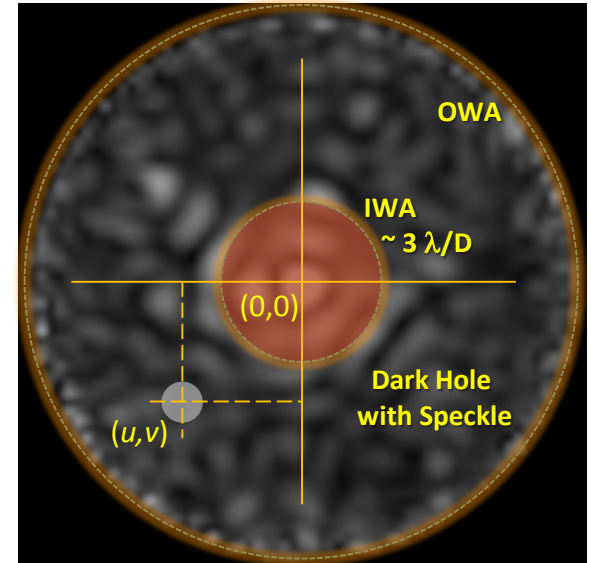
- Another important attribute is throughput.
- Core throughput is the fraction of the entering light from a planet that ends up in the point spread function (PSF) "core"

- Core throughput drops off as we approach the line of sight.

- The Inner Working Angle (IWA) is the angle at which it drops to half of its maximum value in the dark hole

Telescope and coronagraph case ATLAST

r = 3.5 brite = 37.5524

r = 8.5 brite = 1199.064
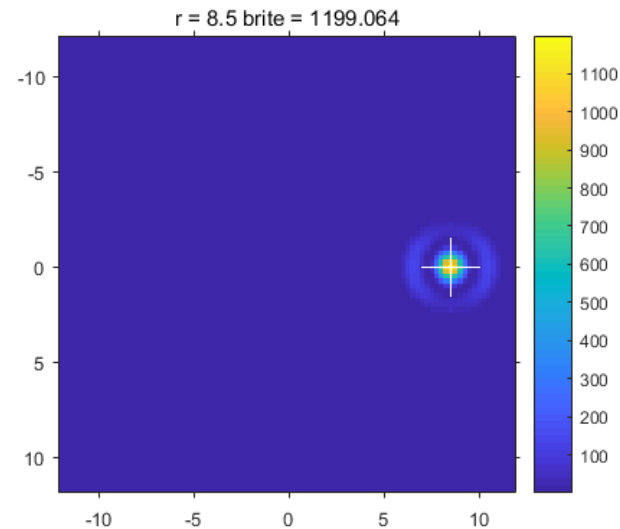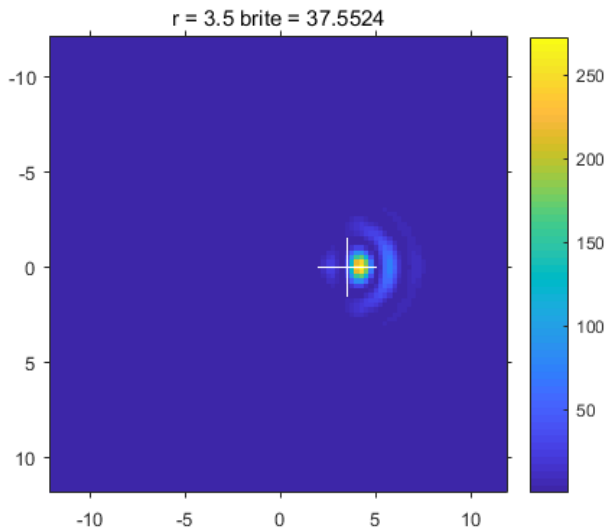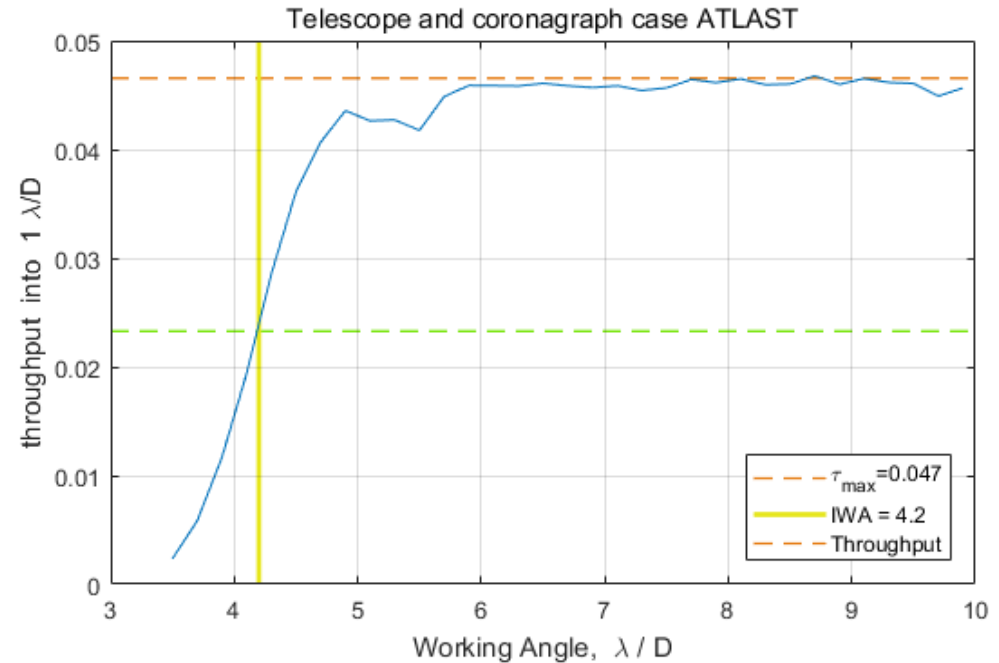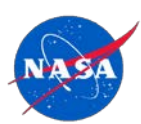
What Contrast is Good Enough?

- We set the goal to be the direct imaging and characterization of an Earth clone at 30 parsecs. Earth flux ratio is about 2e-10.

- Contrast requirement is set by the need to avoid false positives.

- Direct detection needs to have systematic error small enough to avoid false alarms: for example, WFIRST requires SNR > 5

- Characterization would require SNR (>10 for WFIRST) of at least 10 per spectral element

- As a result, a coronagraph for Earth detection will need to have raw contrast in the 1e-10 regime, with stability in the few x 1e-11 in the observation temporal band of interest

- We need to know what are the tolerances on instrument parameters, particularly maximum telescope wavefront errors that are allowable given these contrast requirements

Evaluating Contrast

- One challenge in evaluating contrast, both experimentally and in models, is that many pointings are needed

- Pointings are expensive both in lab testing and in model

- Often, a surrogate for contrast is evaluated instead, called the Normalized Intensity (NI):

$$C_{CG}(u,v) \equiv \frac{I_{CG}(u,v;0,0)}{I_{CG}(u,v;u,v)} \qquad NI(u,v) \equiv \frac{I_{CG}(u,v;0,0)}{I_{no\ FPM}(0,0;0,0)}$$
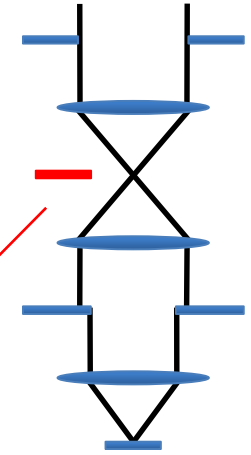
- NI underestimates throughput loss near the IWA

Telescope and coronagraph case ATLAST

Legend:
- IWA = 4.2
- Contrast
- Norm. Int.

X: 4.3 Y: 1.192e-10
X: 4.3 Y: 6.197e-11

Intensity Ratio vs Working Angle, λ / D

Pointings for Contrast 1 / λ/D

Synthesizing A Good Contrast Estimate
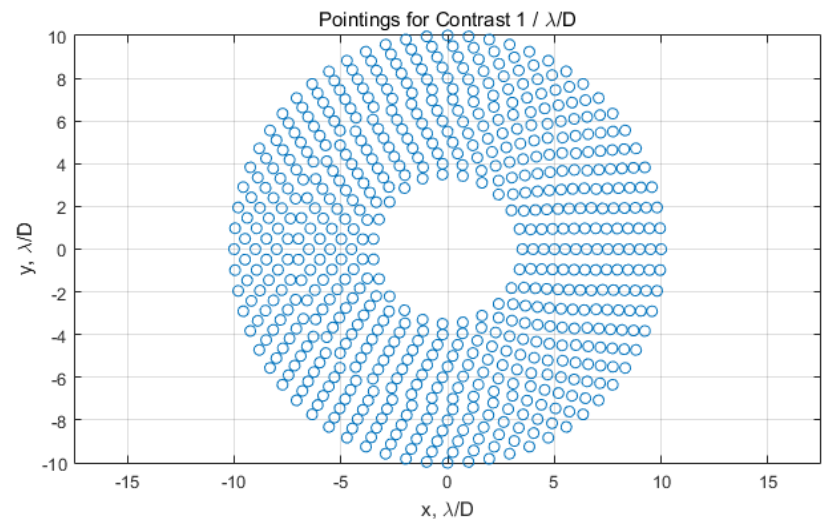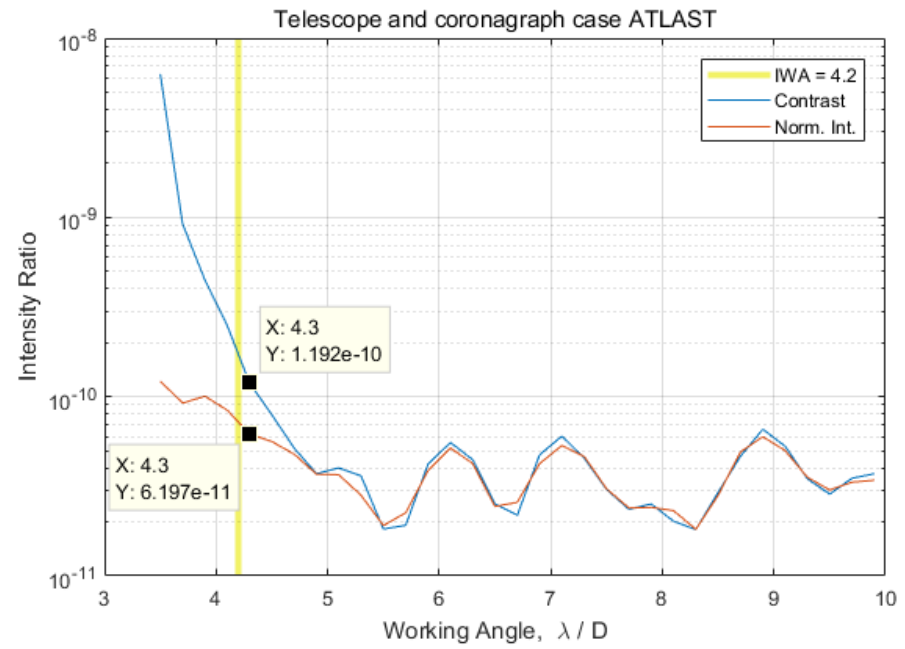
- NI is a good estimate after a few lam/D so only a few pointings are really needed!

- NI and C near IWA can be stitched together

Normalized Intensity

Telescope and coronagraph case ATLAST

Weight functions to make synthetic Contrast

The Context: An Observing Scenario
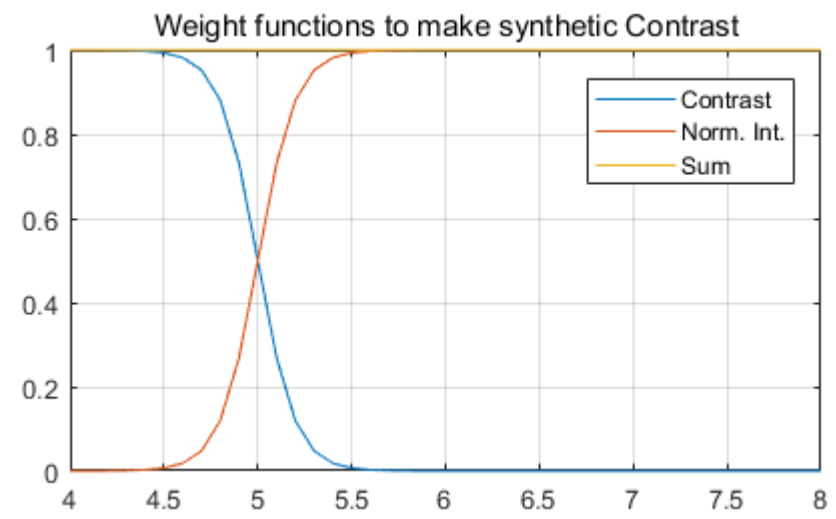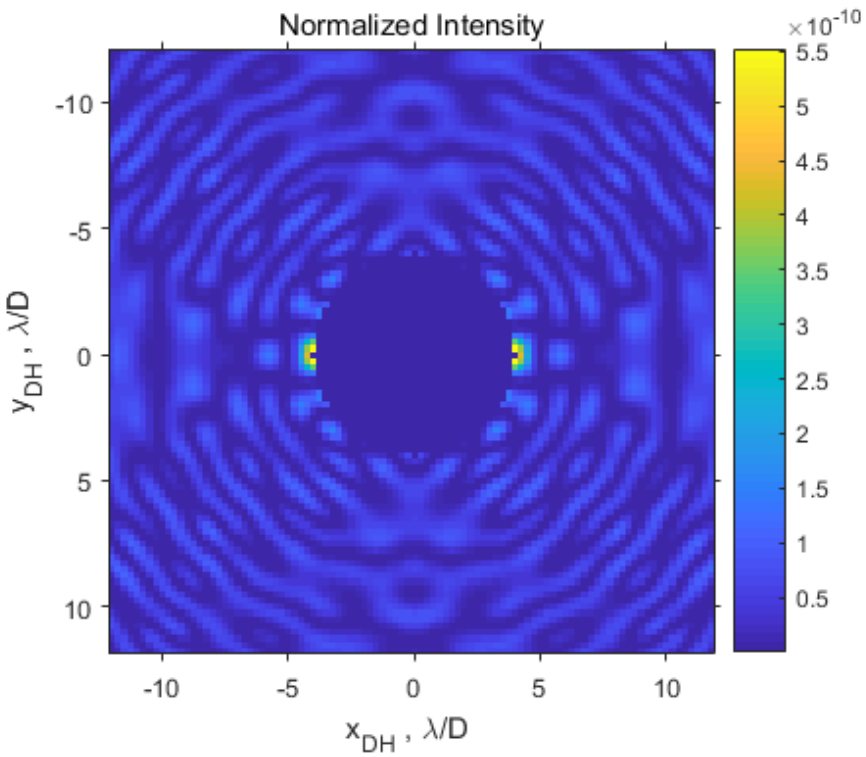
- Requirements on contrast need to into account the temporal structure of the observing scenario

- **Speckle subtraction** is a key step and affects the relevance of different errors

- Reference Differential Imaging Version (based on WFIRST):
  - Generate dark hole on reference star nearby (bright and spectrally similar)
  - Measure dark hole on reference star
  - Slew to target star and settle
  - Integrate on target star
  - Chop back to reference start

- The integration is a **low pass filter** on errors, while the chopping is a **high pass filter**. The result is that only a limited band in frequency matters.

Bright star for acquisition of DH

$V \leq 3\ mag$

~ 100 available stars

~20 deg

$V \sim 6\ mag$

Target star and planet

t_{chop} t_{LOWFS} t_{stare}

How Instability Affects Contrast
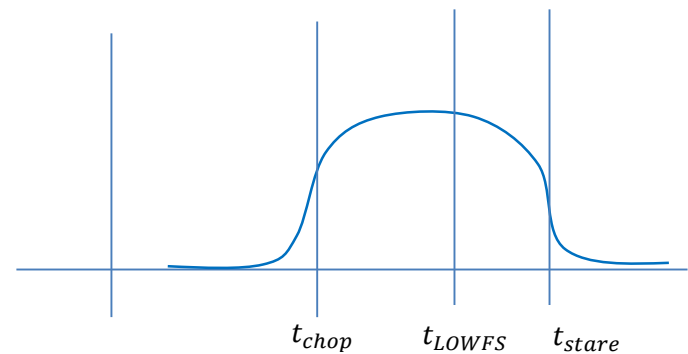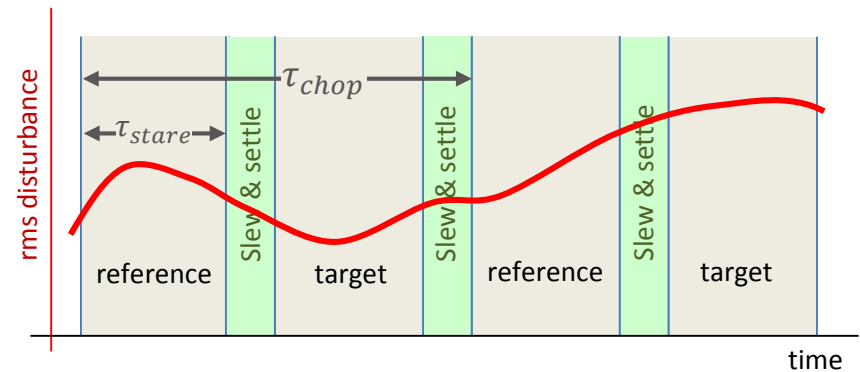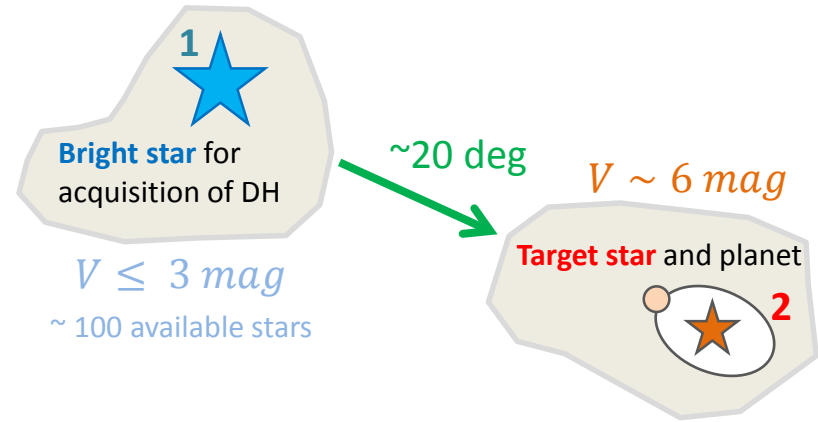
- How does the error affect the speckle pattern?

$$C \propto |E + \Delta E|^2 = |E|^2 + |\Delta E|^2 + 2\,\mathcal{R}\{E^* \Delta E\}$$

existing field   perturbation   Cross term
(static field)   (instability)

- Instability is amplified by the existing field in the cross term
- However, the cross term is not positive-definite: it *can* be negative. An oscillating cross term can become attenuated if there are many oscillations during an integration.
  - In that case, the $|\Delta E|^2$ term will be the next term to consider
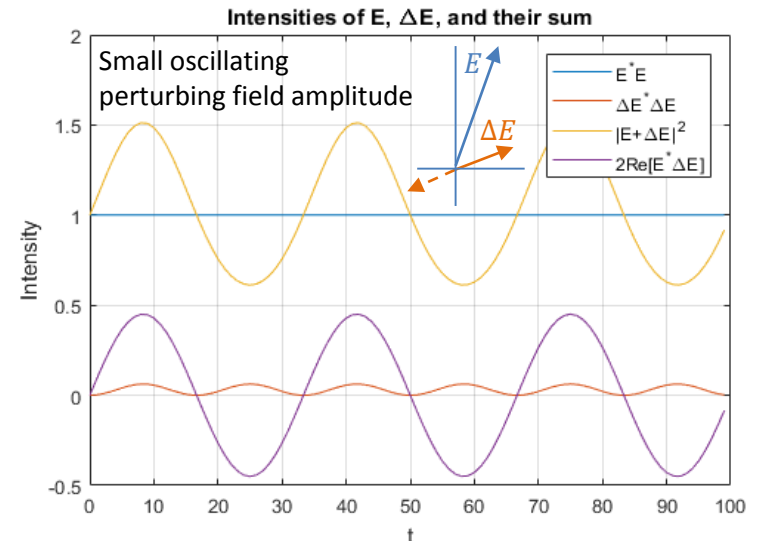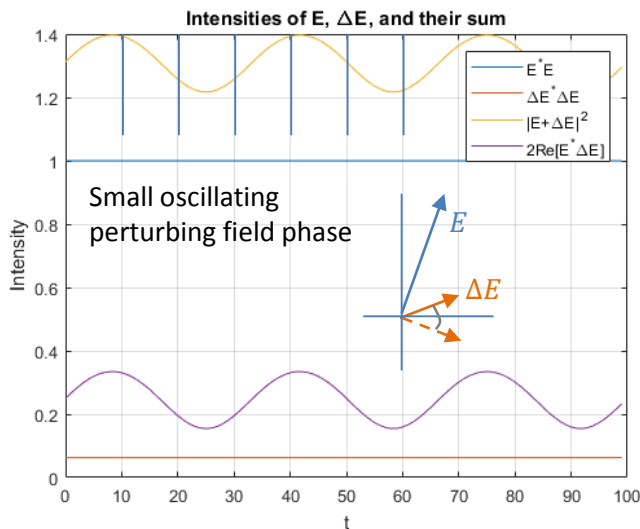
Small oscillating perturbing field phase

Small oscillating perturbing field amplitude

Chopping

Intensities of E, ΔE, and their sum

B

1000 s integration

100 s frame

A

Chop period

Small oscillating
perturbing field phase

E

ΔE

Legend:
- $E^* E$
- $\Delta E^* \Delta E$
- $|E + \Delta E|^2$
- $2\mathrm{Re}[E^* \Delta E]$

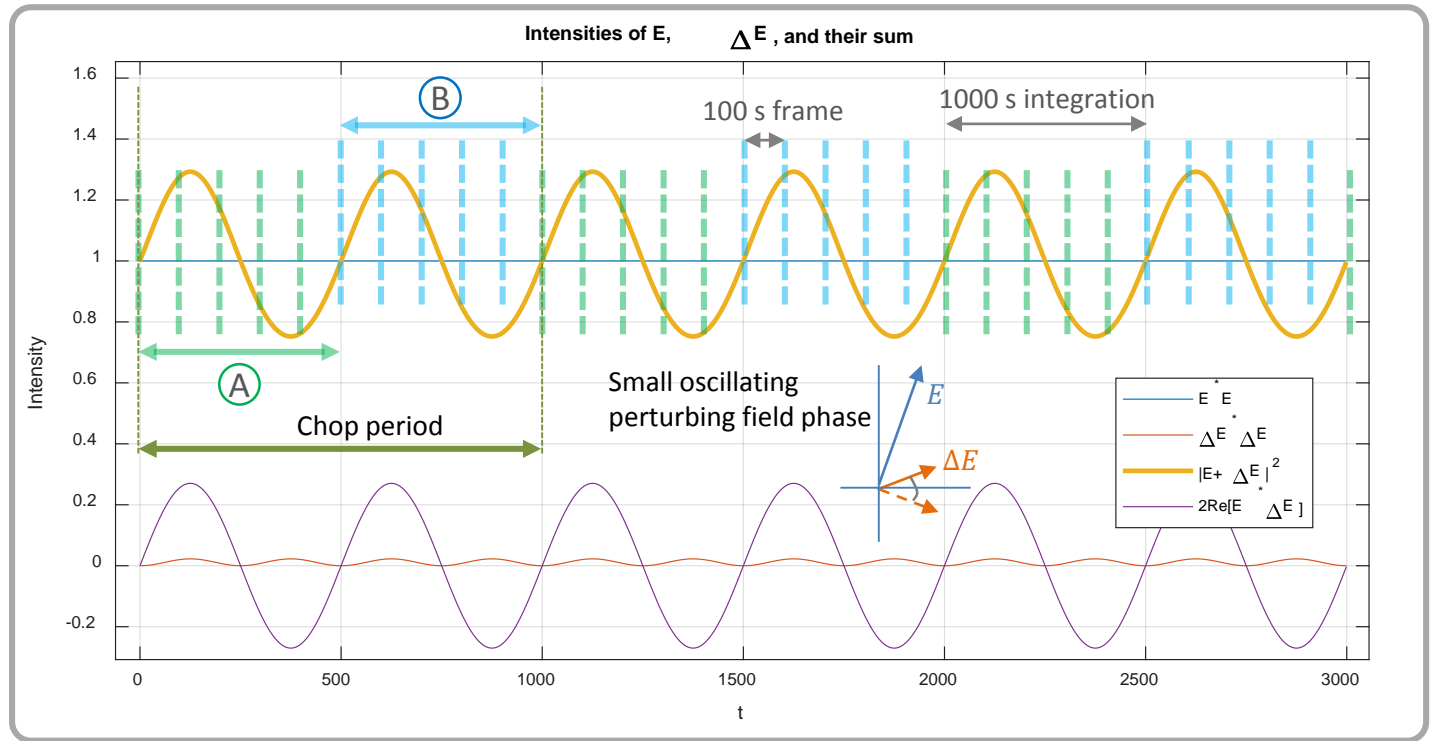Intensity

t

$$C \propto |E + \Delta E|^2 = |E|^2 + |\Delta E|^2 + 2\,\mathcal{R}\{E^* \Delta E\}$$

existing field   perturbation   Cross term
(static field)   (instability)

Applying Segment Errors

- Segment errors evaluated in this study:
  - Piston
  - Tip/Tilt
  - And the Next 15 Zernikes
  - Global Aberrations: Tip/Tilt, Power, Spherical Seidel Coma, Bending
  - Segment Aberrations: Piston, Tip/Tilt, Power, Astigmatism, Trefoil

Sample Phase Map - Segment Tilt

Sample Phase Map - Segment Hexfoil

Segment Piston
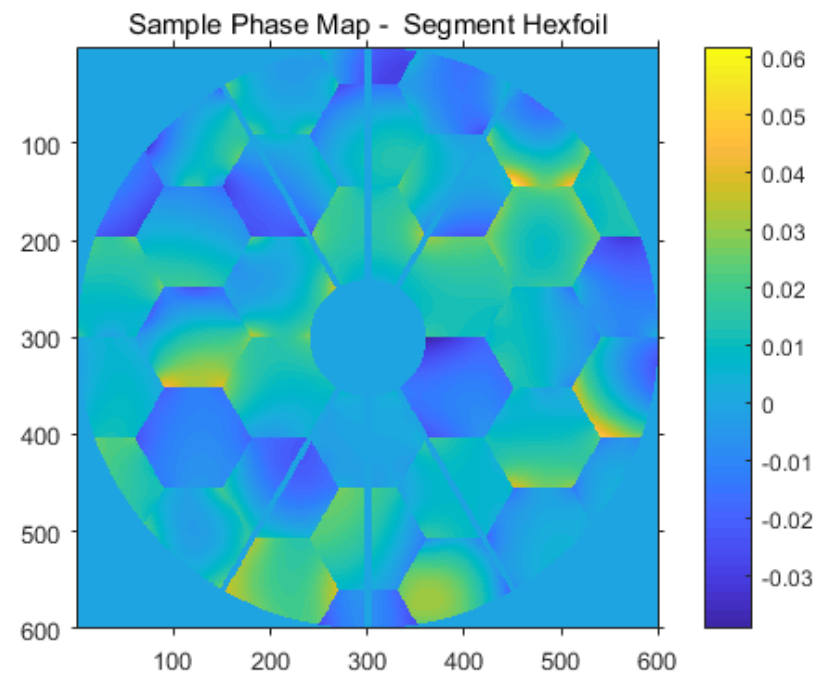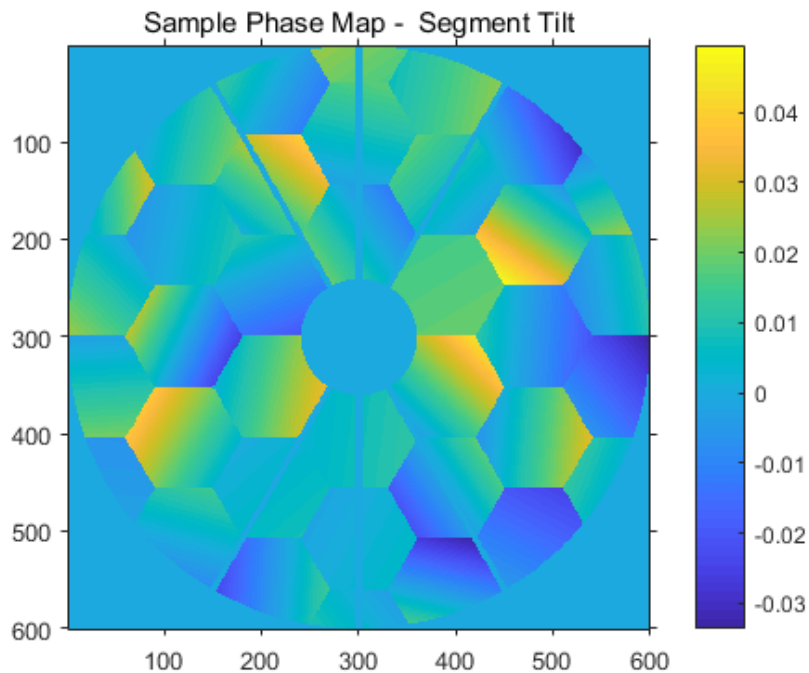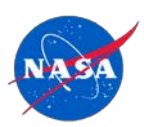
Contrast (solid) and NI (dashed) - ATLAST Segment Piston

Segment Tilt

Contrast (solid) and NI (dashed) - ATLAST Segment Tilt

Legend:
- 1 pm rms
- 6 pm rms
- 32 pm rms
- 178 pm rms

y-axis: Contrast (10^{-8} to 10^{-5})
x-axis: Working Angle (λ/D) (4 to 8)

Segment Astigmatism
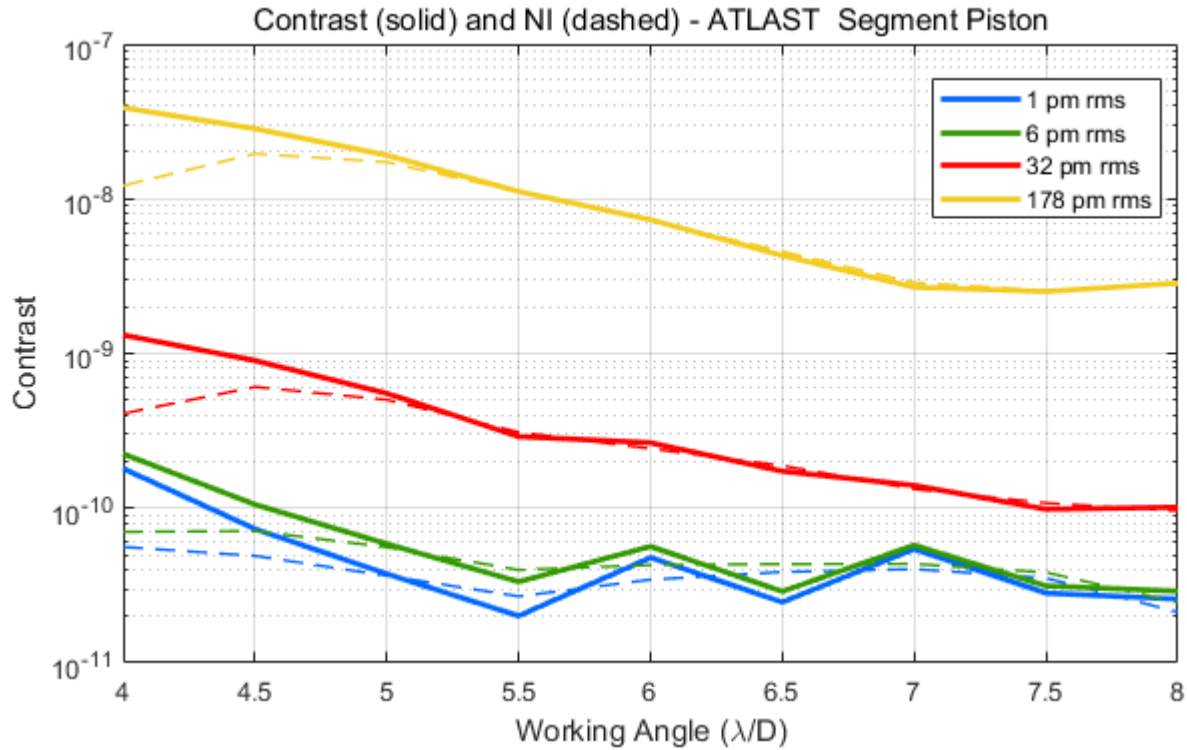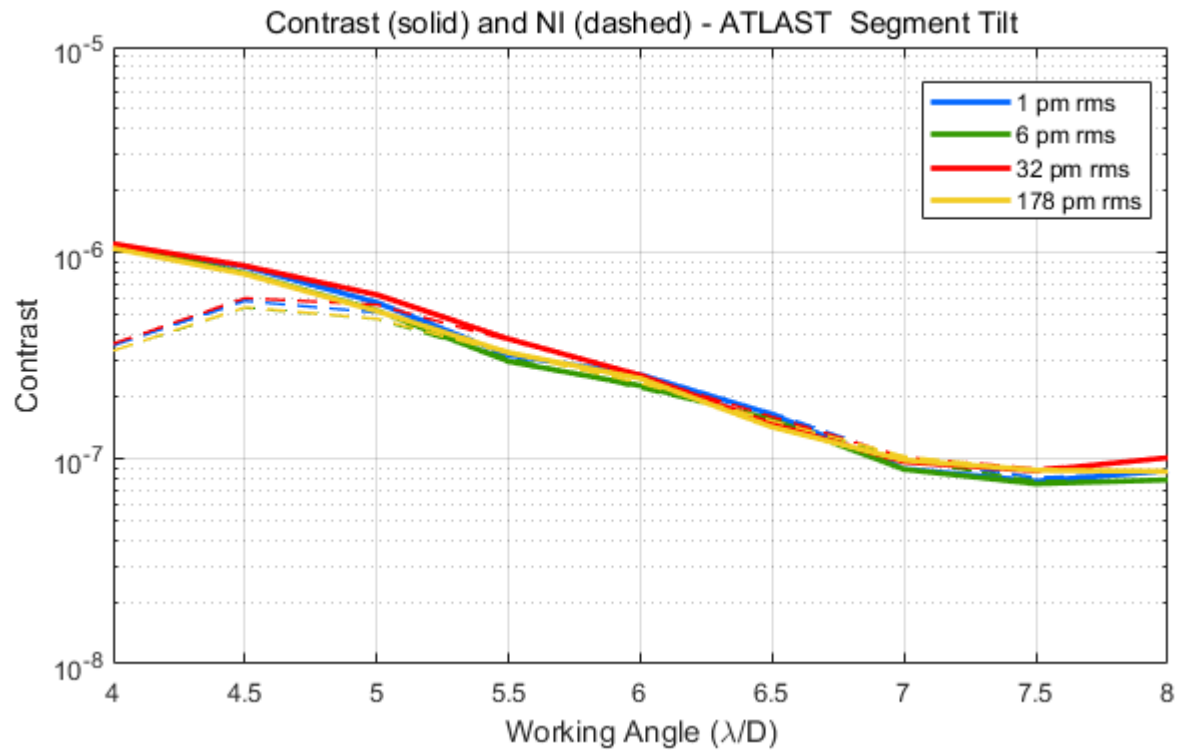
Contrast (solid) and NI (dashed) - ATLAST Segment Astigmatism

Summary

- The ATLAST coronagraph design for an obscured segmented primary has been modeled to find the sensitivity to various segment error modes.

- Temporal processing and speckle subtraction are an important part of the story, and will be incorporated into the model next.

- We will also be evaluating monolithic and unobscured telescope options and coronagraphs.

BACKUP

Example: WFIRS Control Steps

$V \leq 3\ mag$
~ 100 available stars
1
Bright star for acquisition of DH

~20 deg

$V \sim 6\ mag$
Science star
2

1. **Coarse Acquire Bright Star ($V \leq 3$)**
   1. ACS places the star within the imager FOV
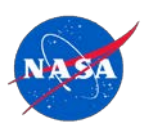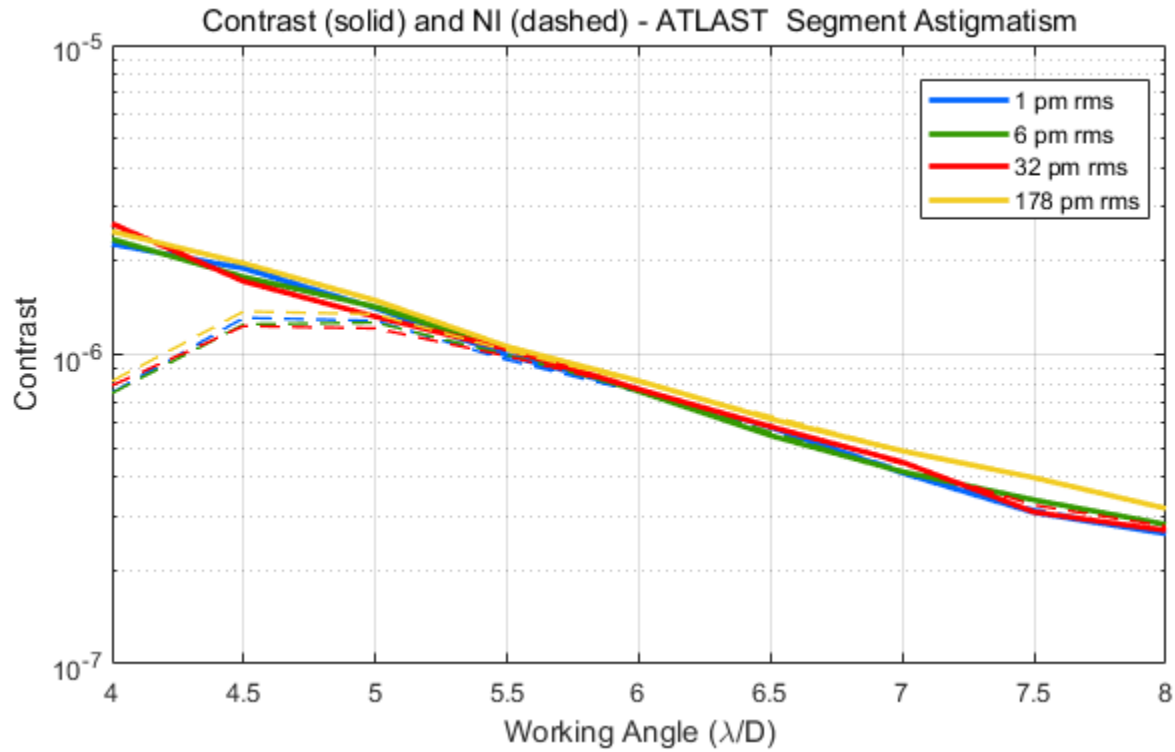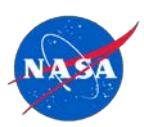   2. CGI sends pointing error as sensed by imager to S/C for correction

2. **Preconfigure for Dark Hole**
   1. The LOWFS determines the tip tilt (T/T), focus (FOC), and LOWF modes
   2. LOWFC actuates the FSM to zero out the measured T/T
   3. LOWFC initially zeros out focus and LOWF using FocM and DM1
   4. CGI configures masks and filters, and presets DM1 and DM2

3. **Generate Dark Hole**
   1. DM1 and DM2 generate probe fields for dark hole (DH) generation
   2. The system computer iteratively updates DM1,2, re-probes, and makes the DH deeper until delta Contrast is low enough
   3. CGI sets target FOC, LOWF for LOWFS/C based on current state; T/T setting is stored (≡TTDH)
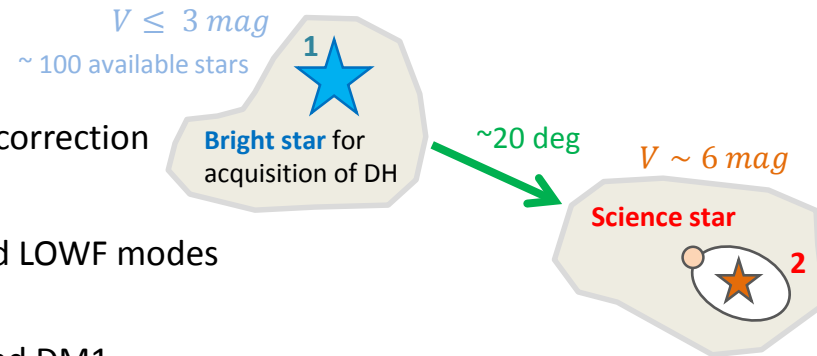
4. **Slew to Science Star**
   1. ACS used to slew S/C to science star: FocM, DM1, DM2 frozen, TTDH saved

5. **Acquire Science Star**
   1. Similar to Bright Star Acquisition, then:
   2. LOWFC actuates the FSM targeting T/T → TTDH from best dark hole

6. **Set Dark Hole and Integrate**
   1. LOWFSC maintains T/T FOC, LOWF at targeted values
   2. DM1, DM2 are only modified to maintain LOWF

The HabEx WF sensitivity paper

1. We are evaluating a number of options for the HabEx telescope. The baseline option currently is the monolith 4m off axis
2. The dominant sensitivities of this design are to
   1. LOS error (via beamwalk on secondary)
   2. Seidel power and coma ?
3. Our plan is to ultimately create a feasibility assessment using integrated modeling of the HabEx instrument. For now we are taking initial steps.
4. In the present paper, we are simply checking a few coronagraph design variations on the baseline design (4m monolith) [and possibly one segmented variation]
5. For each case, we start with
   1. An amplitude of aberration
   2. Existing surface power law or other aberration specification
   3. (Temporal frequency of the aberration change)
6. We do EFC on the static error (contribution from Garreth Ruane)
   1. This is our initial field in the dark hole
7. We then apply the deformation, and compute the delta field and mix it with the existing field
8. We then report the resulting contrast per amplitude of the delta aberration
9. What we are working on right now is implementing the nominal coronagraph for VVC charge 6 and above
10. The paper can include VVC 6 and 8
11. It will be a work in progress
12. Later work will include the temporal analysis and observing scenario integration
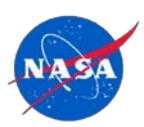
Effects of Space Telescope Primary Mirror Segment Errors on Coronagraph Instrument Performance

Mark T. Stahl, H. Philip Stahl, NASA Marshall Space Flight Ctr. (USA);
Stuart B. Shaklan, Jet Propulsion Lab. (USA). [10398-16]
Bijan Nemati, The University of Alabama in Huntsville. (USA)

Abstracts:

Long Version
Direct imaging of potentially habitable planets is challenging because of the relative proximity of the planet to the star and the low flux ratio (typically well under 1e-9 in the visible) of the planet relative to the star. Future exoplanet direct imaging telescopes like the Habitable Exoplanet Imaging Mission (HabEx) will hence require large collecting apertures with very low wavefront errors. The feasibility of these missions is in a large part dependent on the sensitivity of the achieved contrast at small working angles to imperfections and motions of the telescope optics. In past studies, we explored the effect of applying specific modes to segmented and monolith telescopes on the contrast leakage of a coronagraph. Here we extend the results to combined modes and incorporate some of the latest coronagraph designs.

Short Version
Direct imaging of potentially habitable exoplanets is challenging because of the small planet-star angle and the low flux ratio of the planet relative to the star. The feasibility of future direct imaging missions like HabEx is in a large part dependent on the sensitivity of the achieved contrast at small working angles to imperfections and motions of the telescope optics. In past studies, we explored the effect of applying specific modes to segmented and monolith telescopes on the contrast leakage of a coronagraph. Here we extend the results to combined modes and incorporate some of the latest coronagraph designs.