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

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SESSION 4. . . . . SUN 4:00 PM TO 5:40 PM

LUVOIR/OST

Session Chair: **Makenzie Lystrup,** Ball Aerospace & Technologies Corp. (USA)

The LUVOIR coronagraph instrument: definition and design, Laurent Pueyo, Space Telescope Science Institute (USA). . . . . [10398-15]

Effects of random segment errors on coronagraphs, Mark T. Stahl, H. Philip Stahl, NASA Marshall Space Flight Ctr. (USA); Stuart B. Shaklan, Jet Propulsion Lab. (USA) . . . . [10398-16]

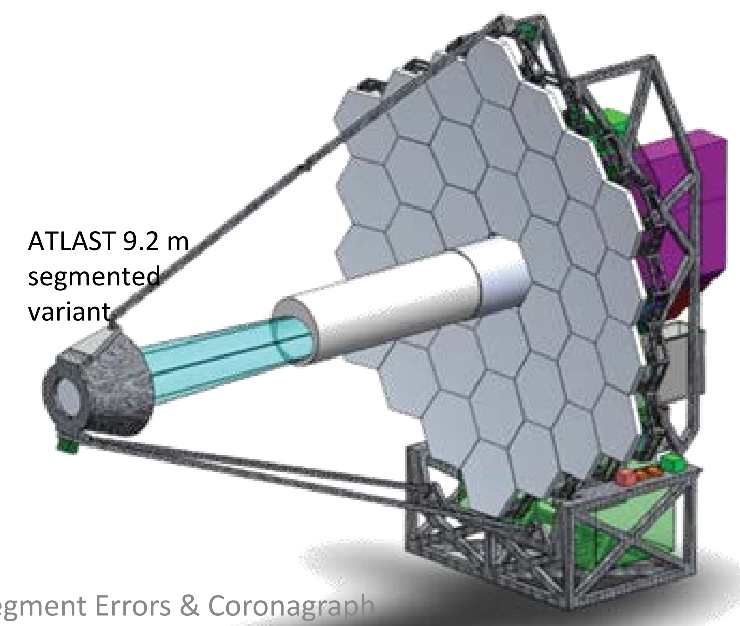
Space technology for directly imaging and characterizing exo-Earths, Brendan P. Crill, Stuart B. Shaklan, Nicholas Siegler, Jet Propulsion Lab. (USA). . [10398-17]

Laser metrology for ultra-stable space-based coronagraphs, Joel A. Nissen, Alireza Azizi, Feng Zhao, Shannon Kian G. Zareh, Shanti R. Rao, Jeffrey B. Jewell, Jet Propulsion Lab. (USA) . . . . [10398-18]

Design considerations for future far-IR observatories, Jonathan W. Arenberg, John Pohner, George M. Harpole, Michael B. Petach, Danny Chi, Perry J. Knollenberg, Northrop Grumman Aerospace Systems (USA). . . . . [10398-19]

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!



Direct Imaging of Exo-Earths

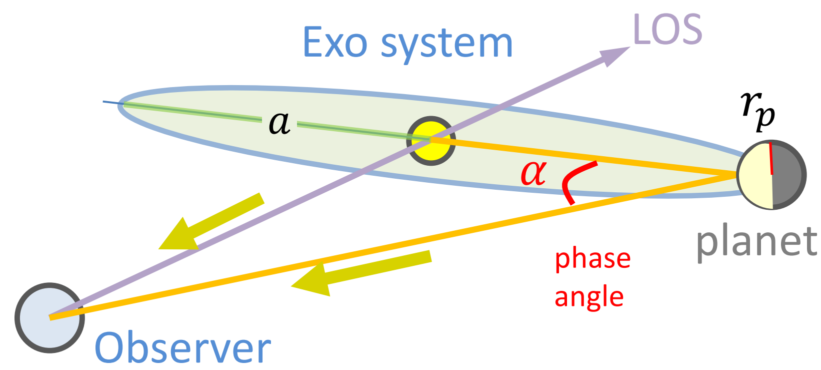
- Relative to the star, the light from an exo-Earth is faint!

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

albedo

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

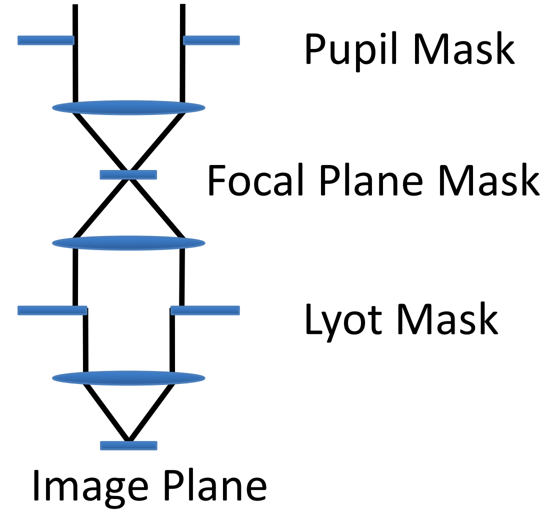
Phase law

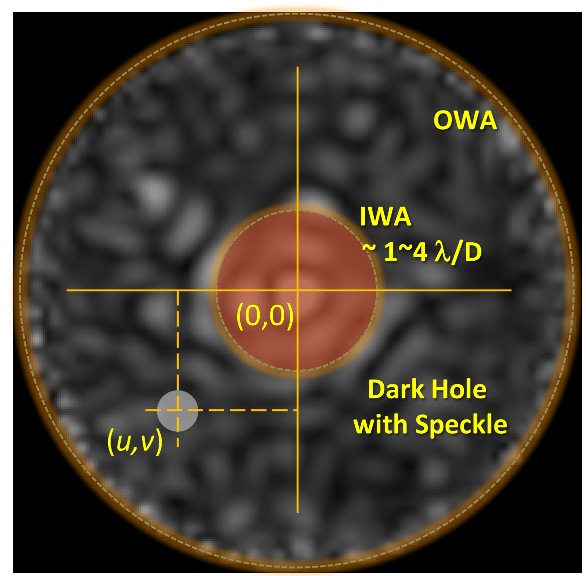


- The Earth seen from many parsecs away would have a flux ratio of approximately 2e-10

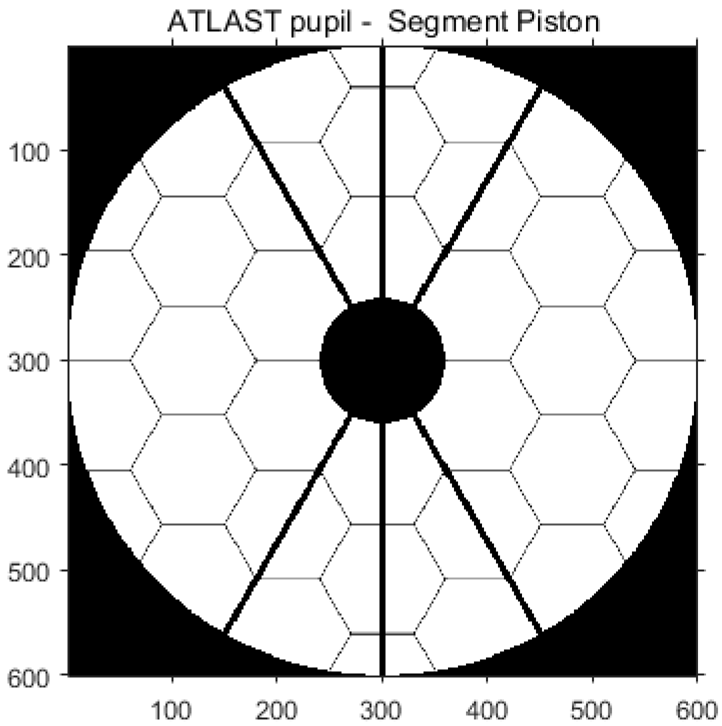
Coronagraph Basics

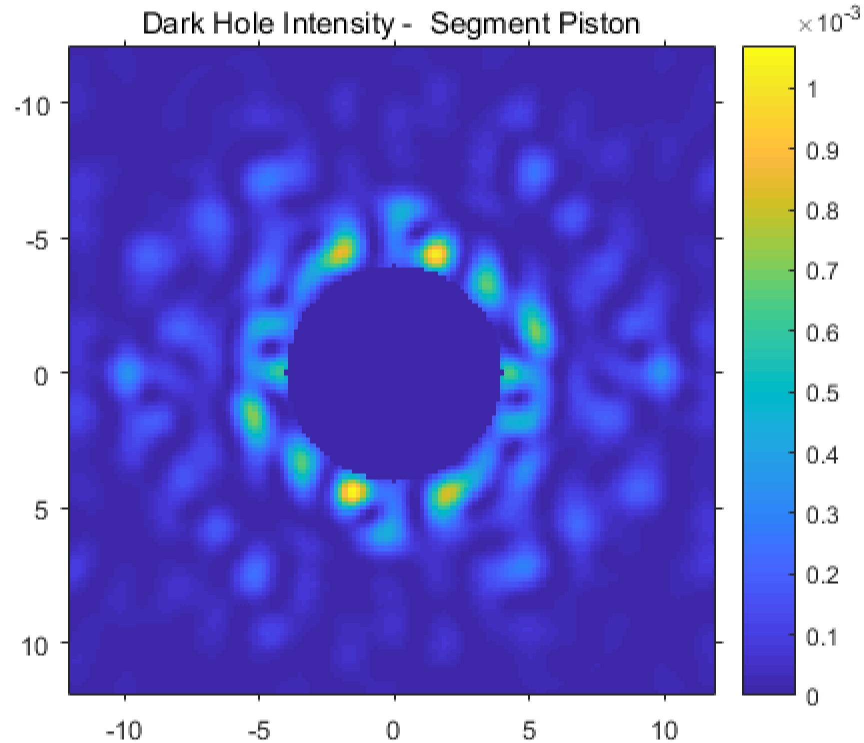
- A coronagraph suppresses the starlight to allow the detection of the planet which is off-axis.
- There are numerous designs, but most involve controlling the diffraction of light by manipulating the phase and amplitude at a number of planes. Most typically, 3 masks and 1-2 deformable mirrors are used.
- 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.





ATLAST Pupil and Coronagraph



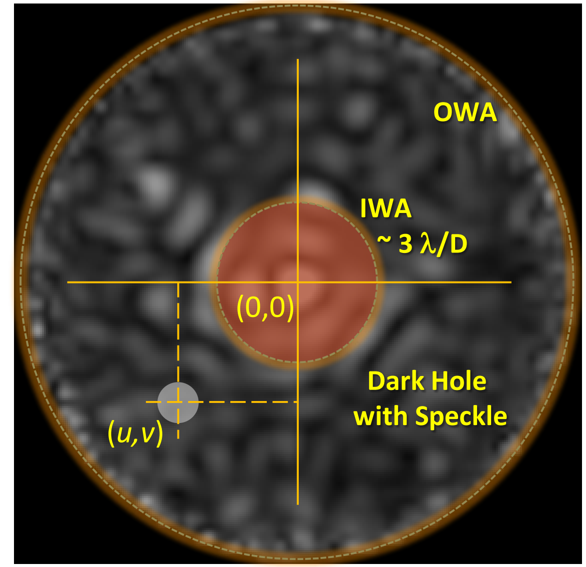


Key Coronagraph Performance Metrics

- 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

$$C_{CG}(u,v) \equiv \frac{\overbrace{I_{star}(u,v;}^{\text{evaluate}}\overbrace{0,0)}^{\text{source}}}{I_{star}(u,v;u,v)}$$

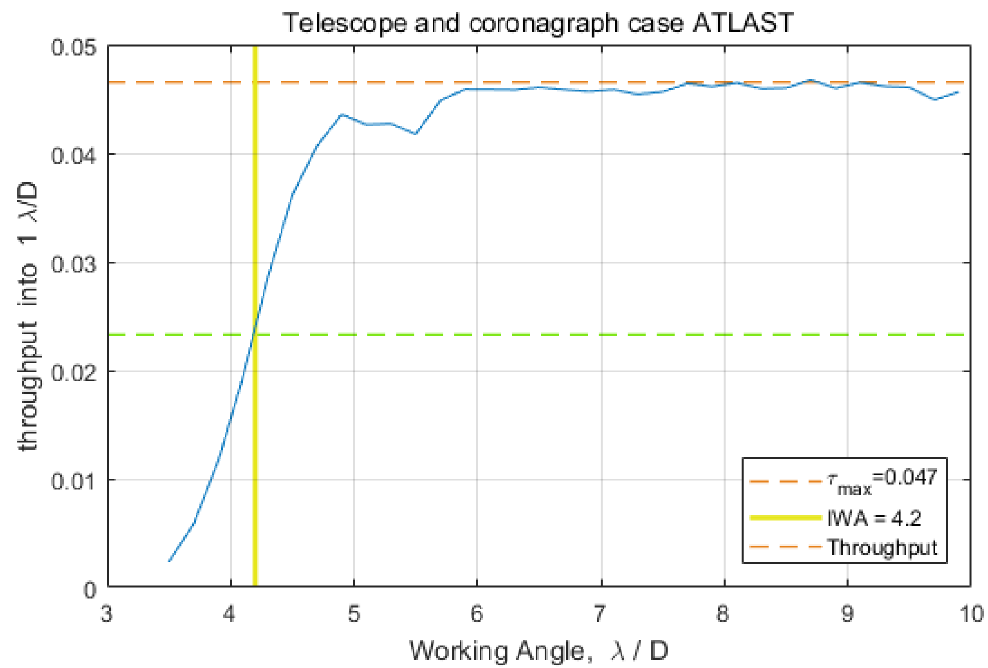


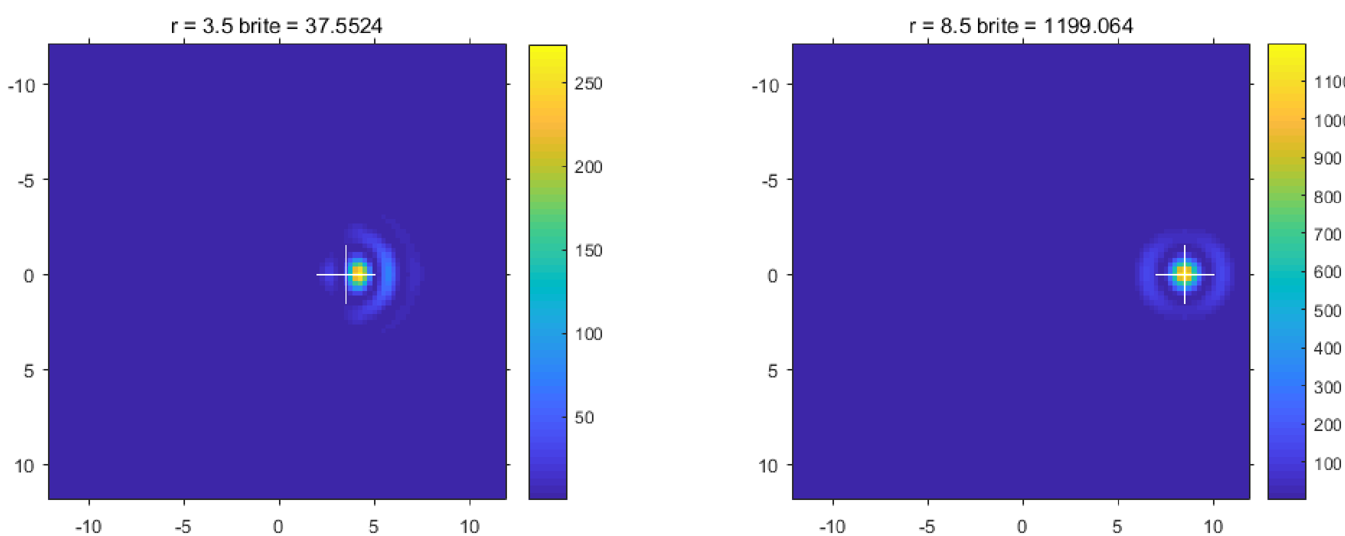
- Another important attribute is throughput.
- Core throughput is the fraction of the entering light from a planet that ends up in the point spread function (PSF) "core"

Core Throughput Vs. Working Angle

- 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



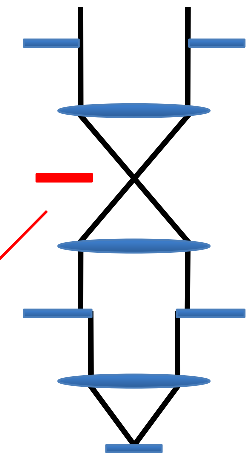


What Contrast is Good Enough?

- 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

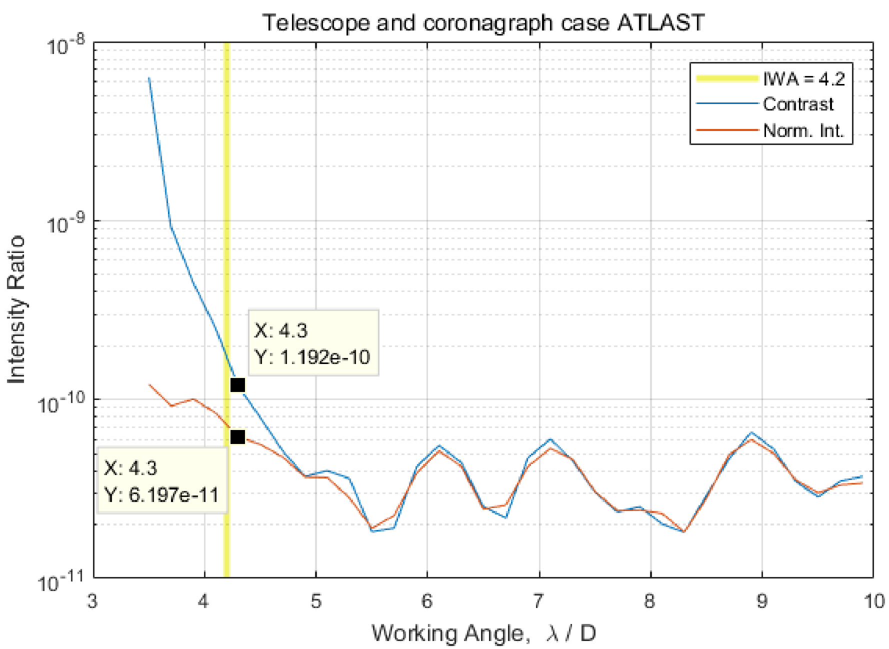
Evaluating Contrast

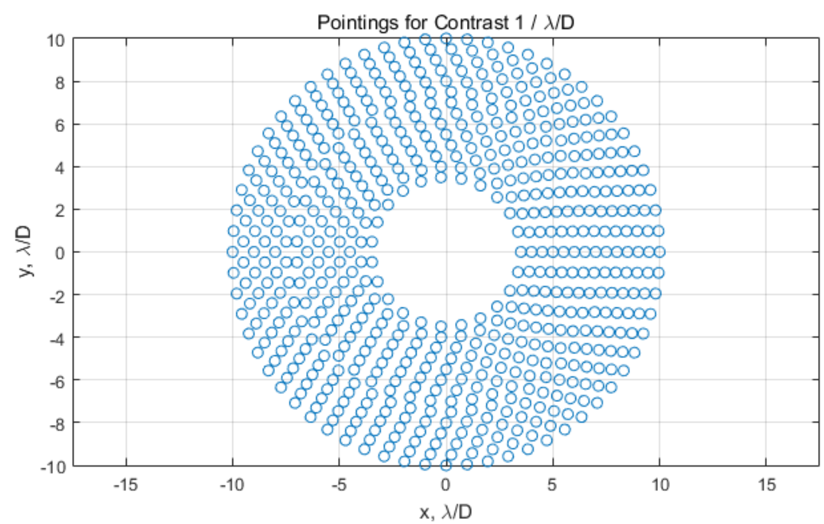
- One challenge in evaluating contrast, both experimentally and in models, is that many pointings are needed
- Pointings are expensive both in lab testing and in model
- Often, a surrogate for contrast is evaluated instead, called the Normalized Intensity (NI):



$$C_{CG}(u,v) \equiv \frac{I_{CG}(u,v;0,0)}{I_{CG}(u,v;u,v)} \qquad NI(u,v) \equiv \frac{I_{CG}\,(u,v;0,0)}{I_{no\ FPM}(0,0;0,0)}$$

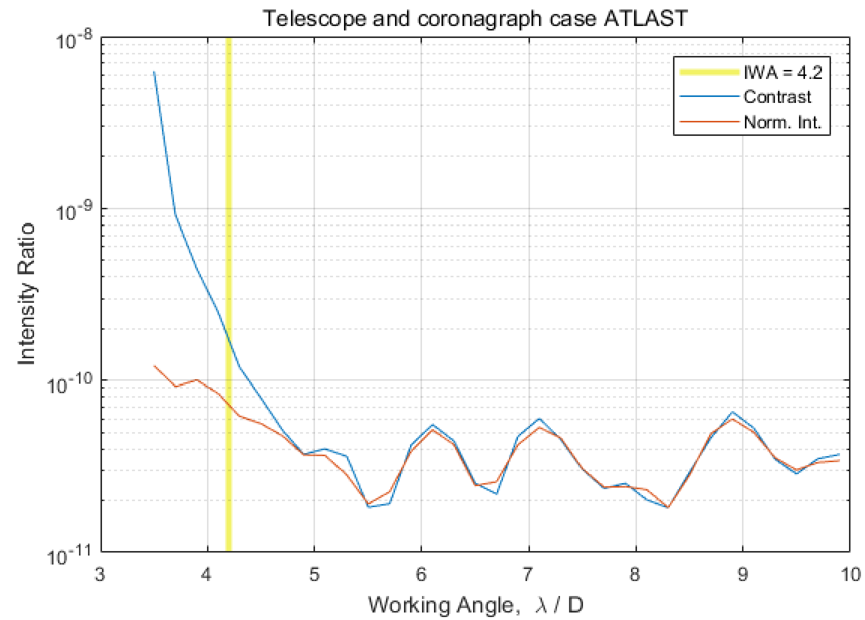
- NI underestimates throughput loss near the IWA

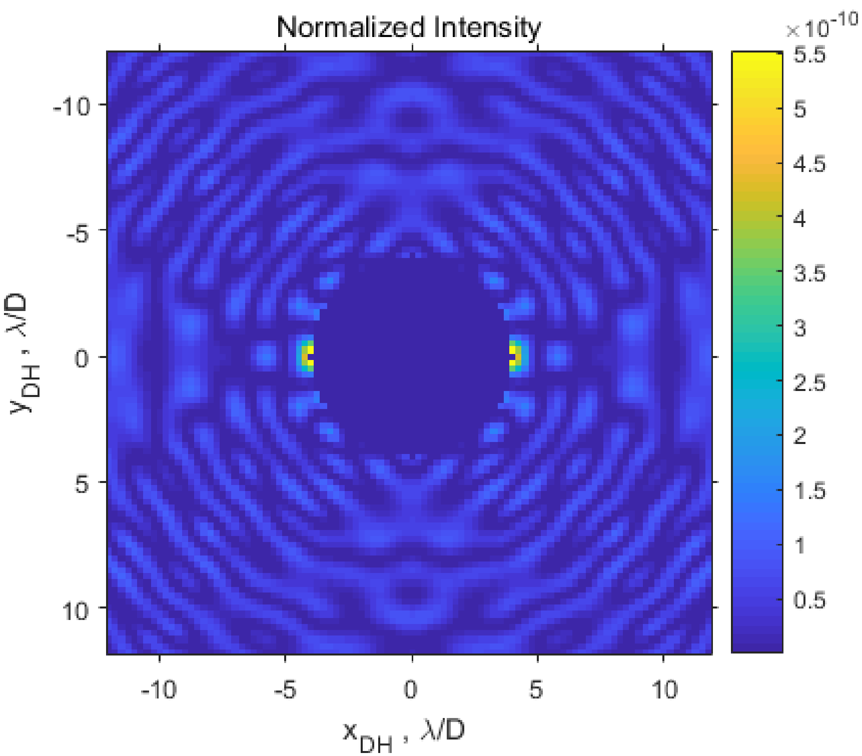


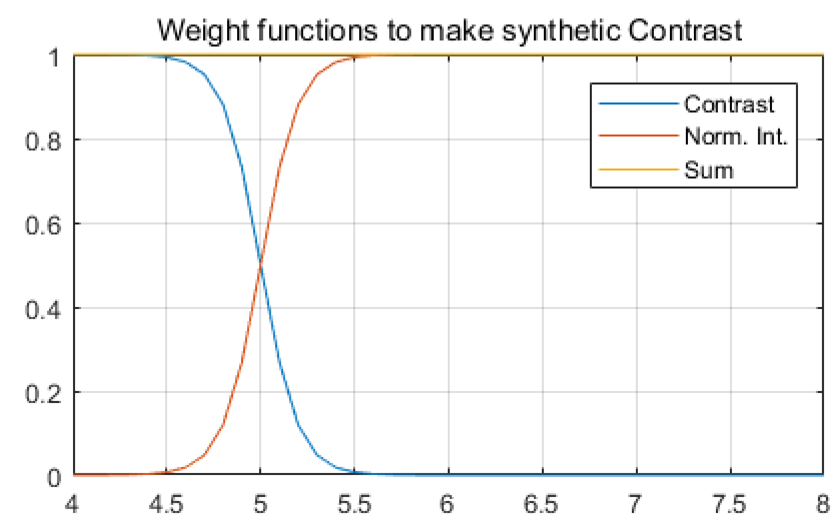


Synthesizing A Good Contrast Estimate

- 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

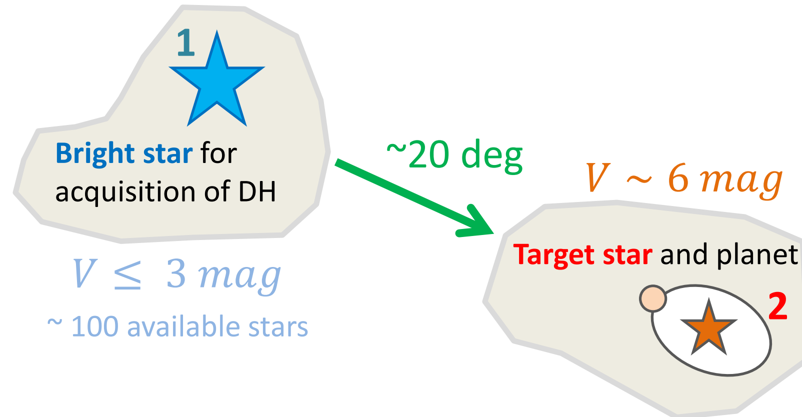


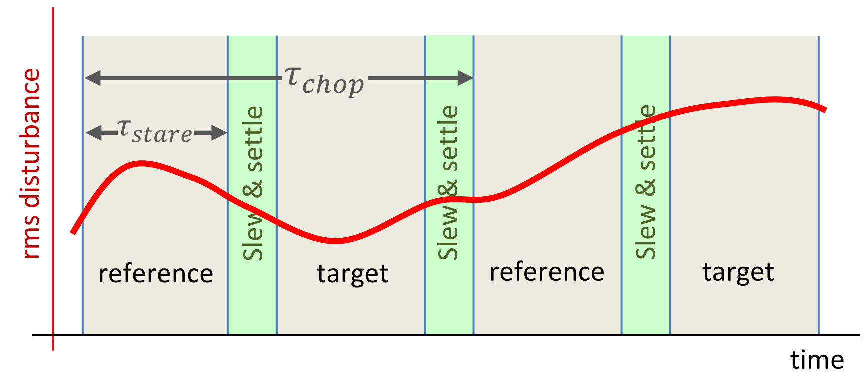


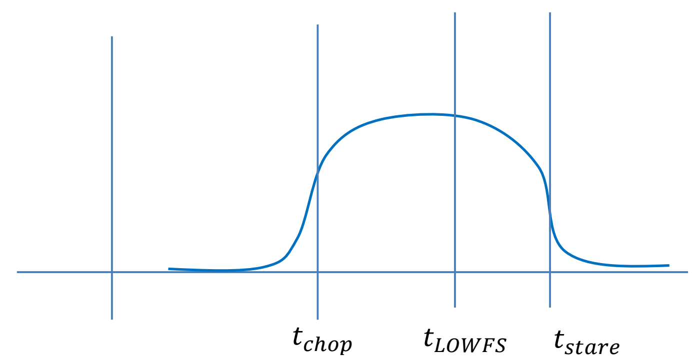


The Context: An Observing Scenario

- 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.





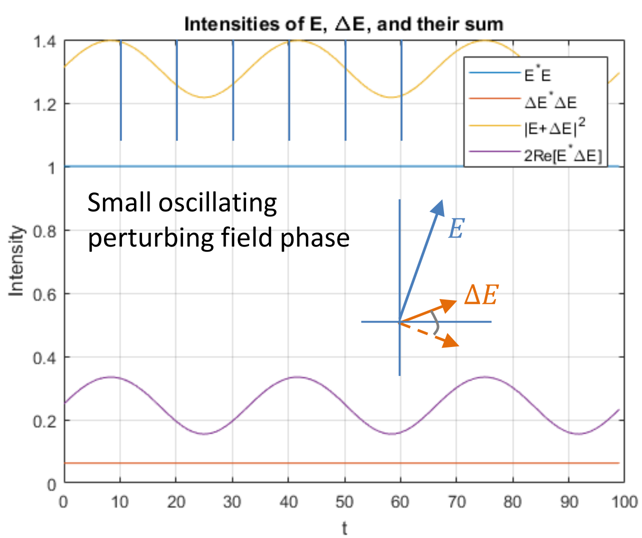


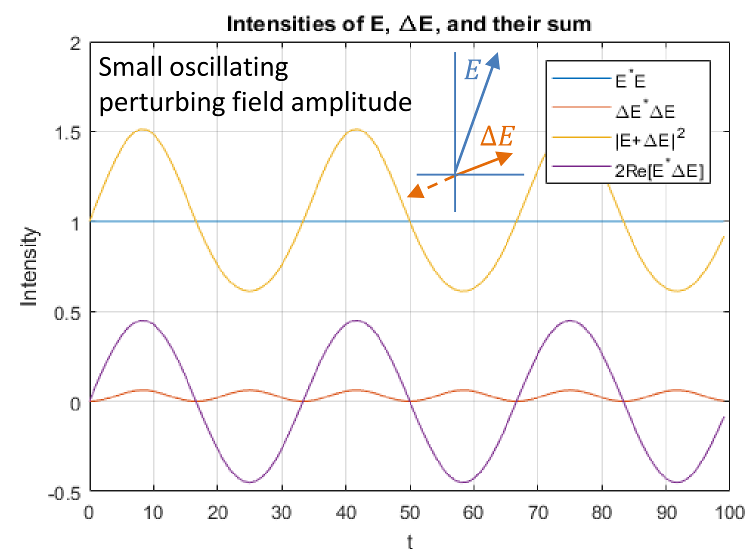
How Instability Affects Contrast

- How does the error affect the speckle pattern?

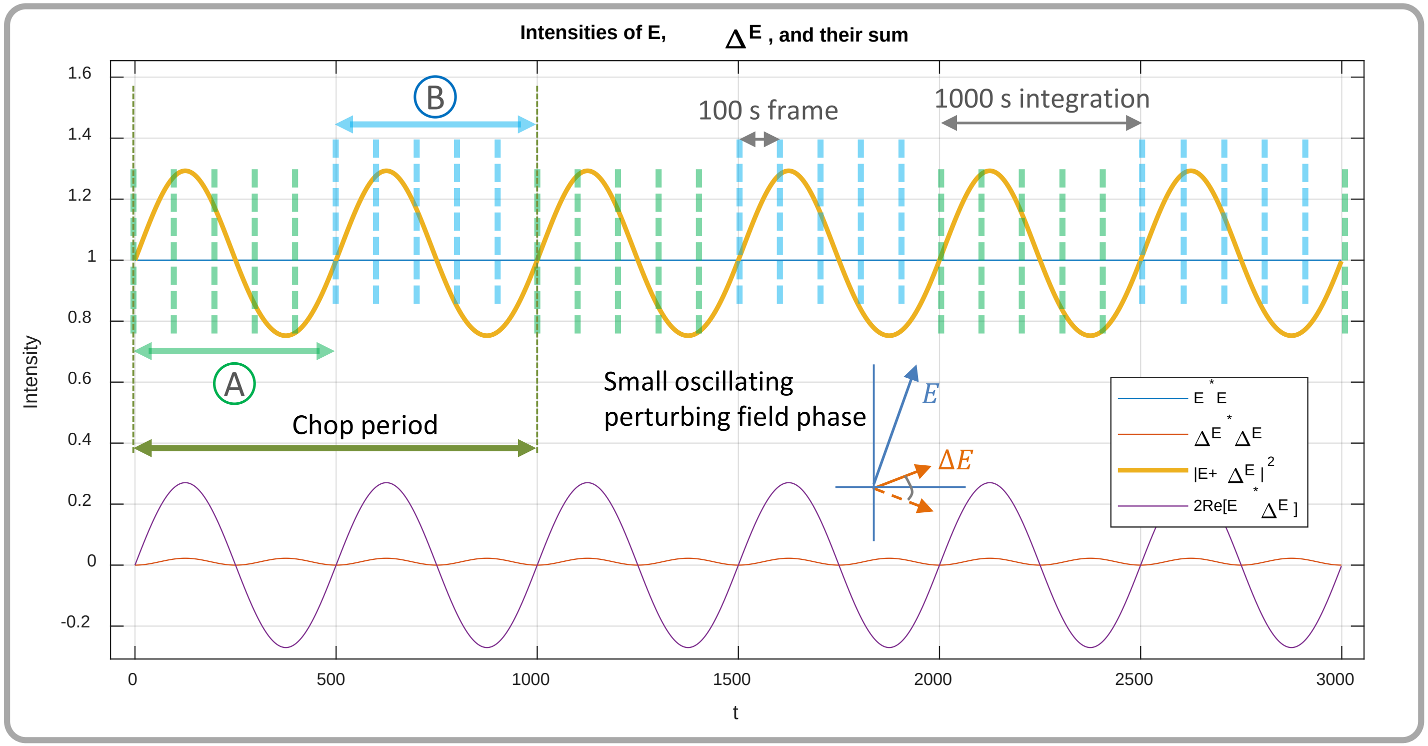
$$C \propto |E + \Delta E|^2 = \underbrace{|E|^2}_{\substack{\text{existing field} \\ \text{(static field)}}} + \underbrace{|\Delta E|^2}_{\substack{\text{perturbation} \\ \text{(instability)}}} + \underbrace{2\,\mathcal{R}\{E^* \Delta E\}}_{\text{Cross term}}$$

- 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





Chopping

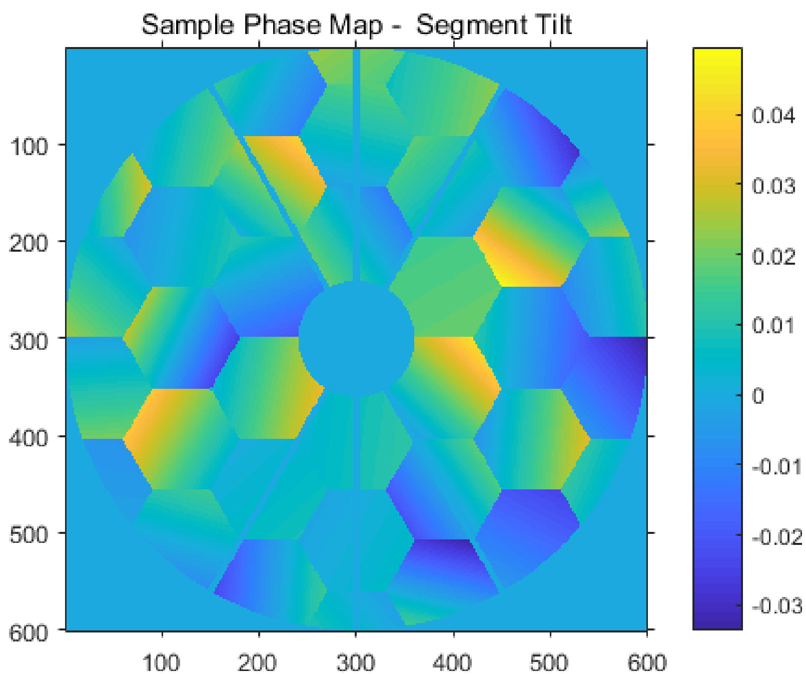


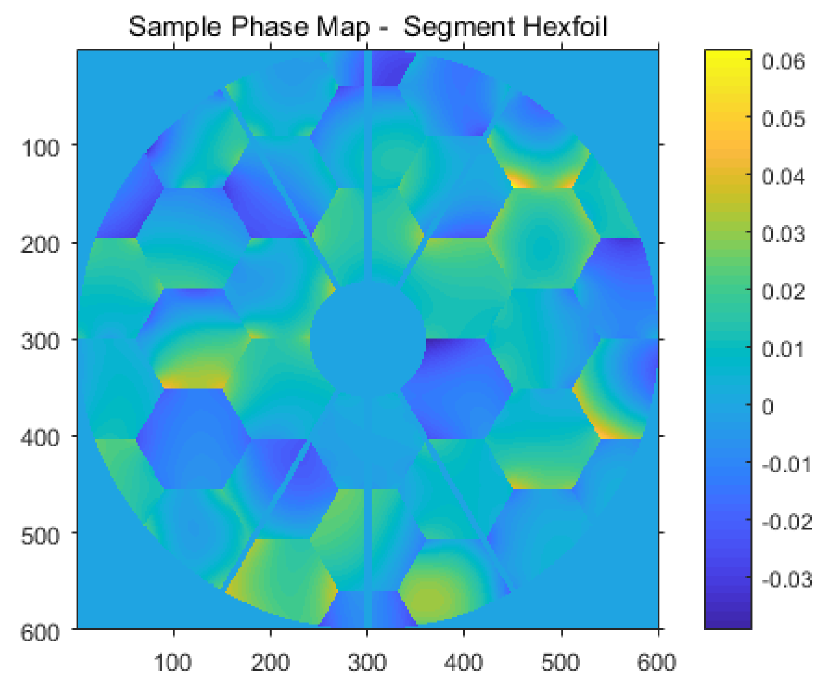
$$C \propto |E + \Delta E|^2 = |E|^2 + |\Delta E|^2 + 2\,\mathcal{R}\{E^* \Delta E\}$$

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

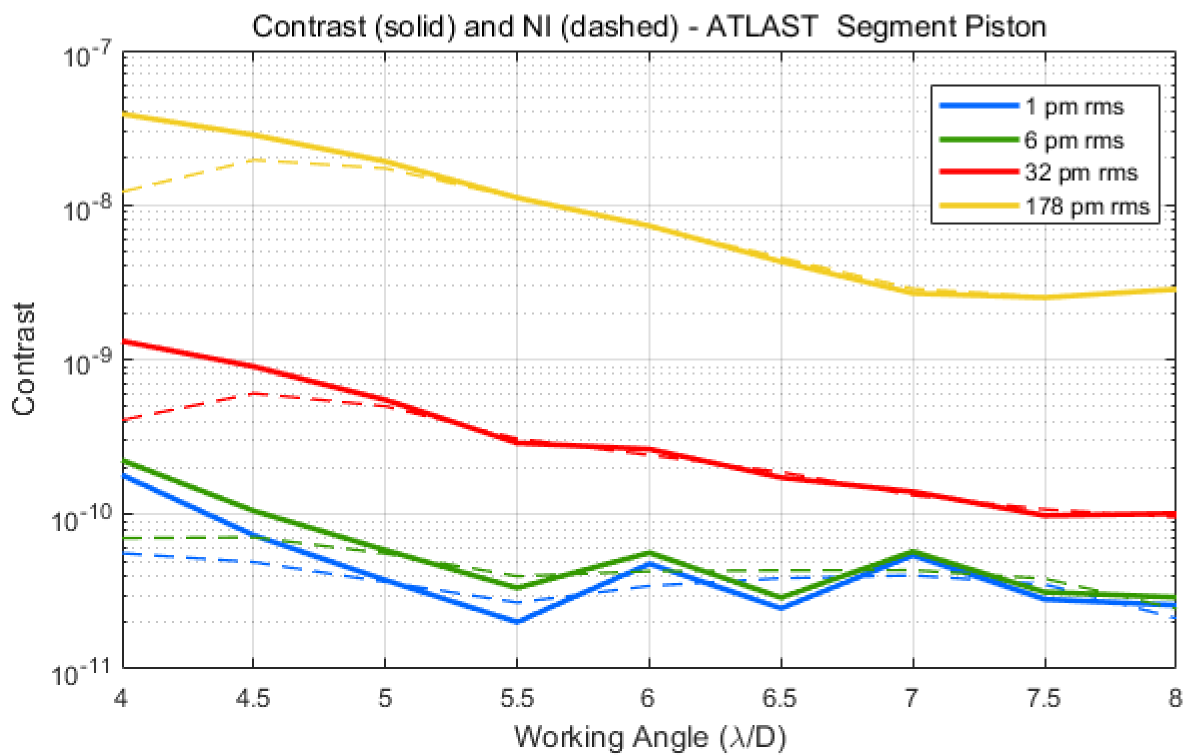
Applying Segment Errors

- 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

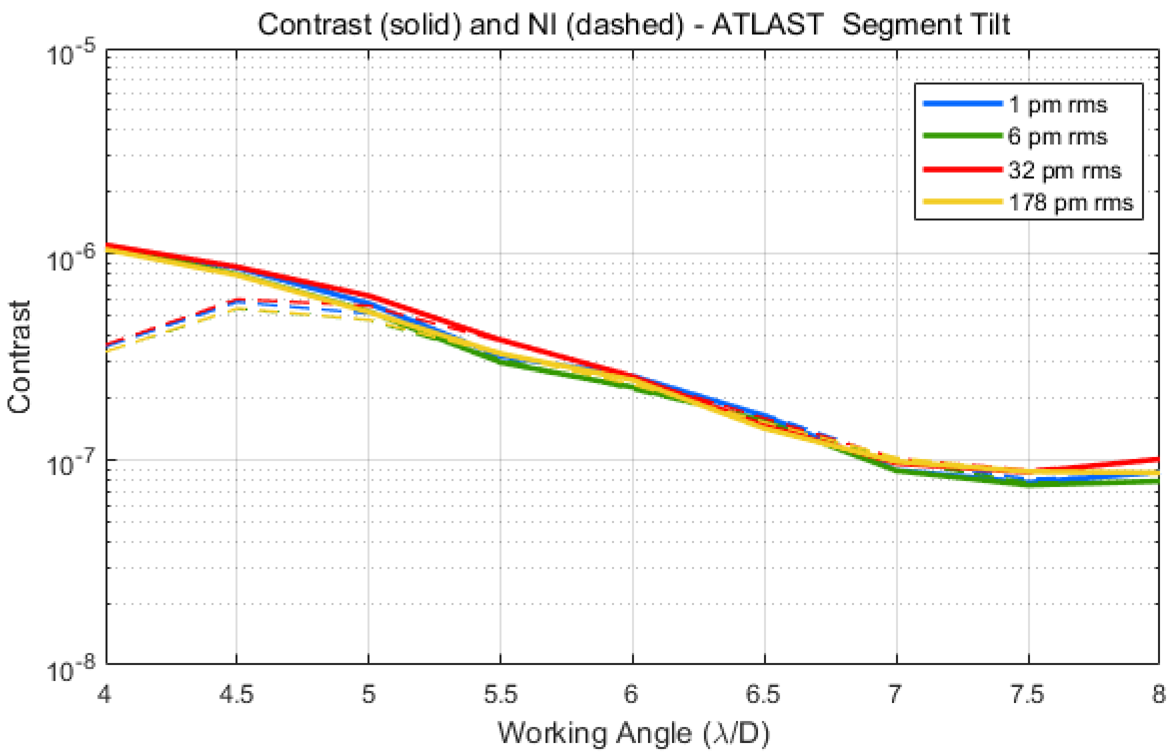




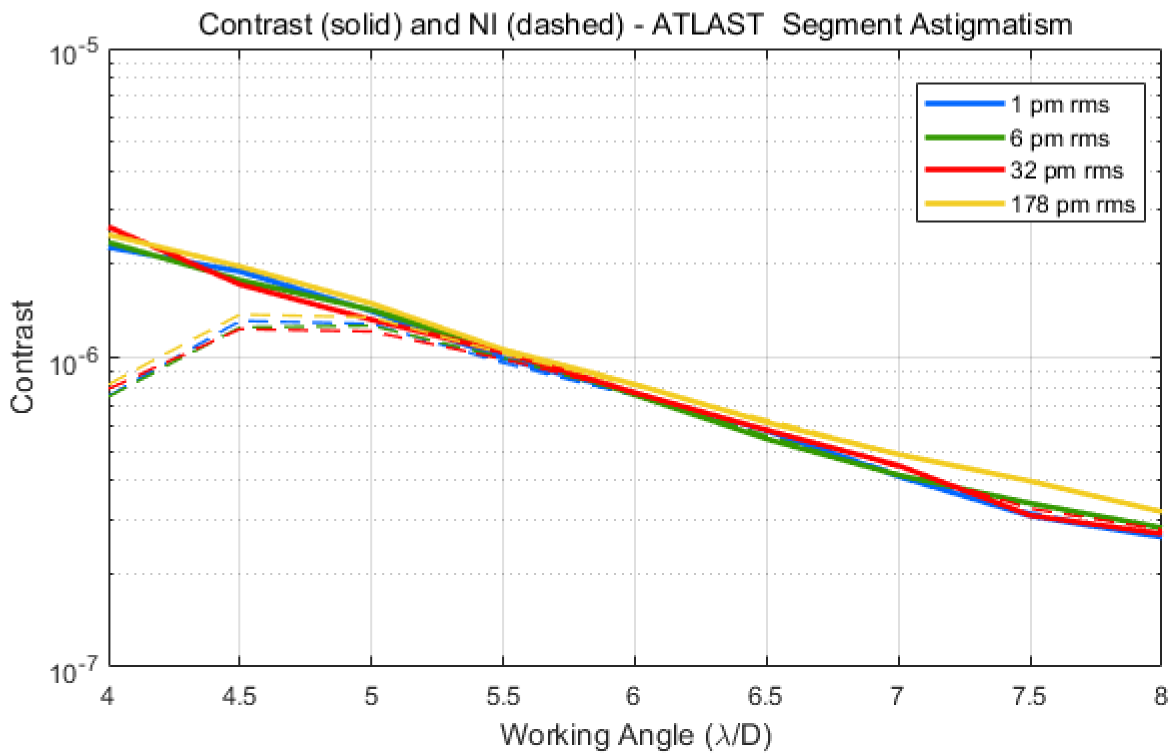
Segment Piston



Segment Tilt



Segment Astigmatism

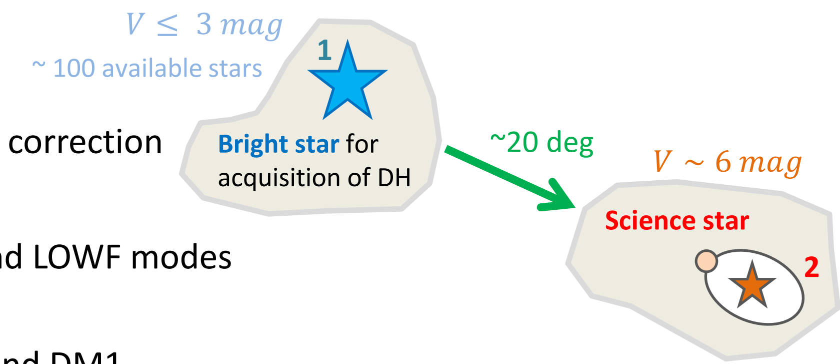


Summary

- 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



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

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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.