ExEP Technology Colloquium – March 31, 2020

Exoplanet Detection with the LUVOIR Coronagraph Instrument

Performance evaluation and aberration sensitivity requirements

Roser Juanola-Parramon[a]

Neil Zimmerman[a], Laurent Pueyo[b], Matthew Bolcar[a], Garreth Ruane[c], John Krist[c], Tyler Groff[a]

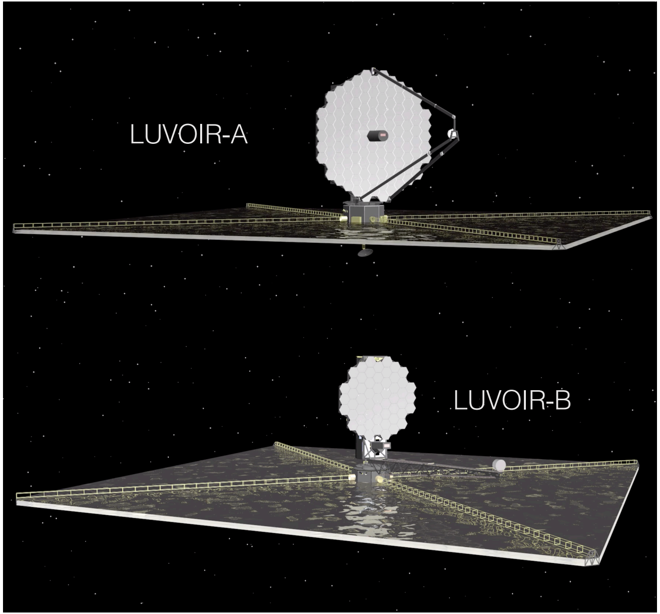
[a] NASA Goddard Space Flight Center, USA

[b] Space Telescope Science Institute, USA

[c] Jet Propulsion Lab., USA

Outline

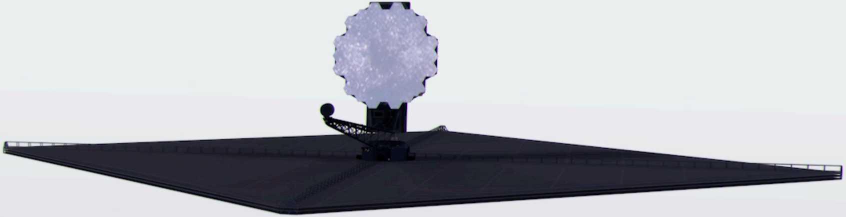
- LUVOIR Architectures
  - Coronagraph designs for ECLIPS
  - Evaluation of coronagraph designs
- Coronagraph sensitivity to telescope aberrations
  - Coronagraph sensitivity to static aberrations
    - Global aberrations and segment phasing errors
    - LUVOIR-A APLC / LUVOIR-B VVC +WS&C
  - Coronagraph sensitivity to dynamic aberrations
    - Line of sight pointing errors
    - Segment phasing errors - Jitter
    - Segment phasing errors - Drift
- Simulated observations
  - Assumptions
  - Simulation of exoplanet detection

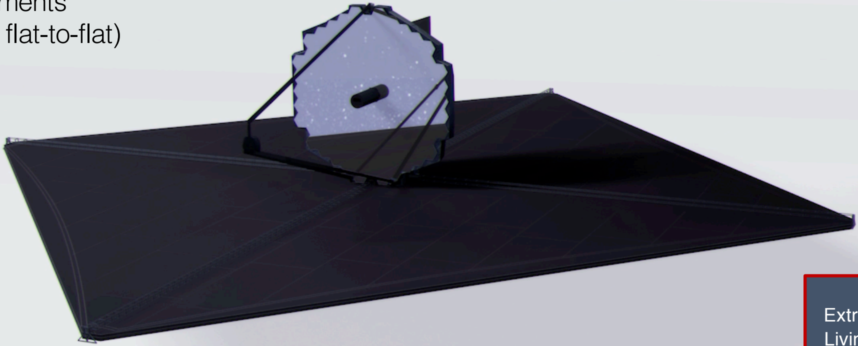


LUVOIR. The Large UV-Optical-Infrared Surveyor

Architectures

LUVOIR A
On-axis telescope
15 m aperture
120 segments
(1.223m flat-to-flat)





LUVOIR B
Off-axis telescope
8 m aperture
55 segments
(0.955m flat-to-flat)

ECLIPS
Extreme Coronagraph for Living Planetary Systems

HDI
High Definition Imager

LUMOS
LUVOIR Ultraviolet Multi Object Spectrograph

POLLUX
UV spectro-polarimeter
(LUVOIR A only)

More information at:
https://asd.gsfc.nasa.gov/luvoir/

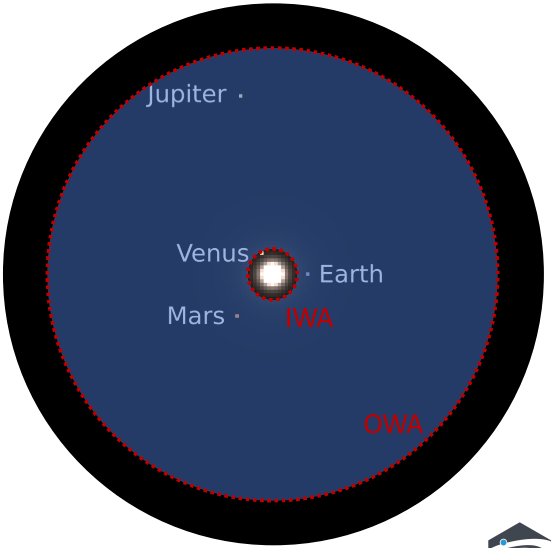
LUVOIR ECLIPS
Extreme Coronagraph for Living Planetary Systems

- **Wavelength range**: 200nm to 2.0µm (3 channels)
- Simultaneous operation in all channels via **dichroics**
- **2 Deformable Mirrors** (DM) per channel, to correct remaining phase and amplitude errors to null speckles in the focal plane and achieve desired contrast.

Goal: raw contrast 10^{-10}

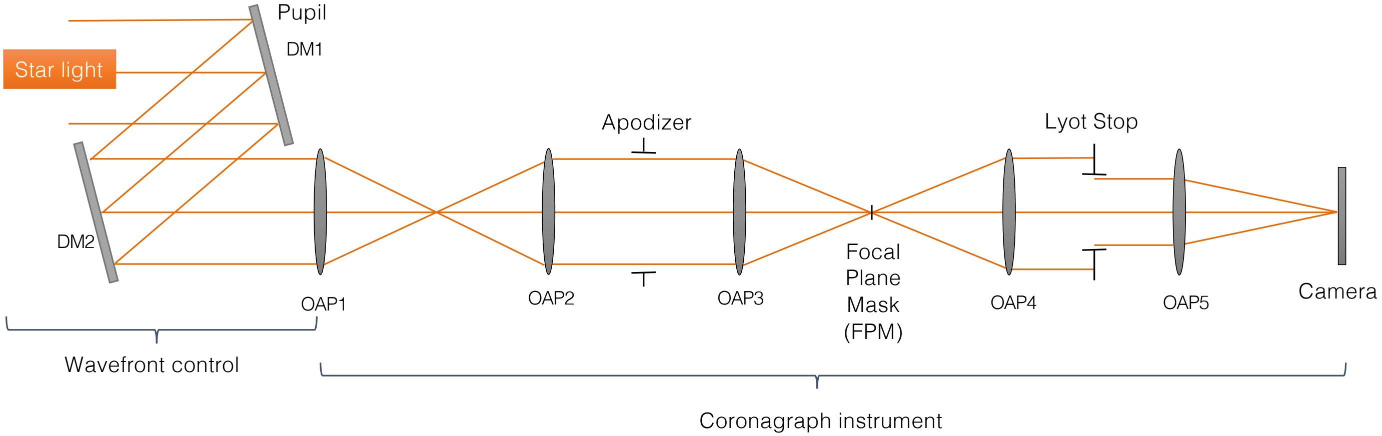
Dark zone (IWA to OWA) ~3 to 64 λ/D

Instantaneous Bandpass 10-20%



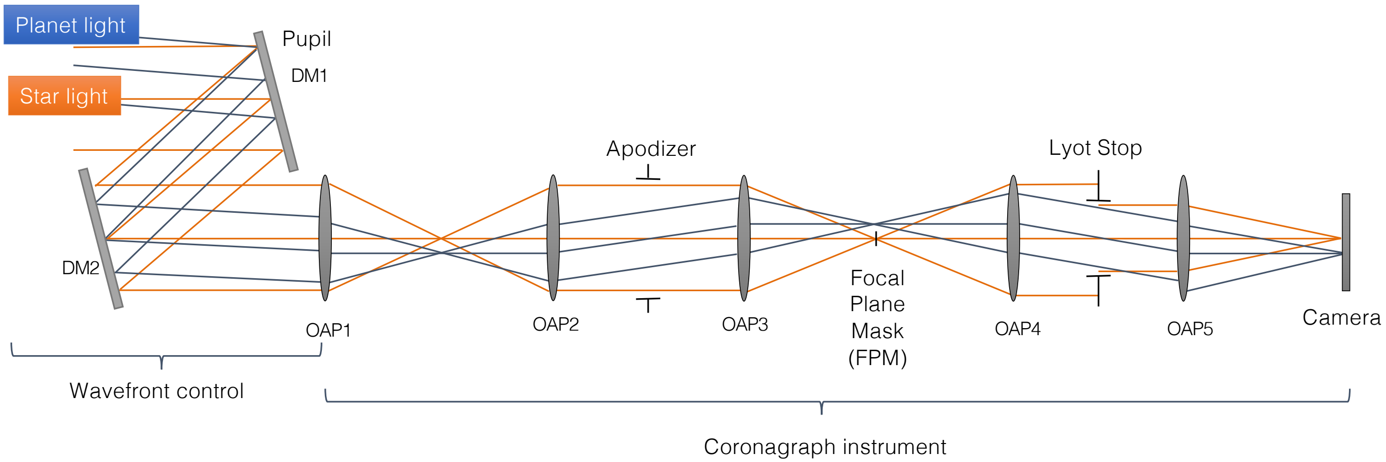
ECLIPS model developed with John Krist's PROPER Optical Propagation Library (Python)
Based on the LUVOIR ZEMAX model – visible channel
All simulations are broadband (10%)

LUVOIR
Coronagraph designs for ECLIPS



The optical layouts for ECLIPS-A and ECLIPS-B are identical

LUVOIR
Coronagraph designs for ECLIPS



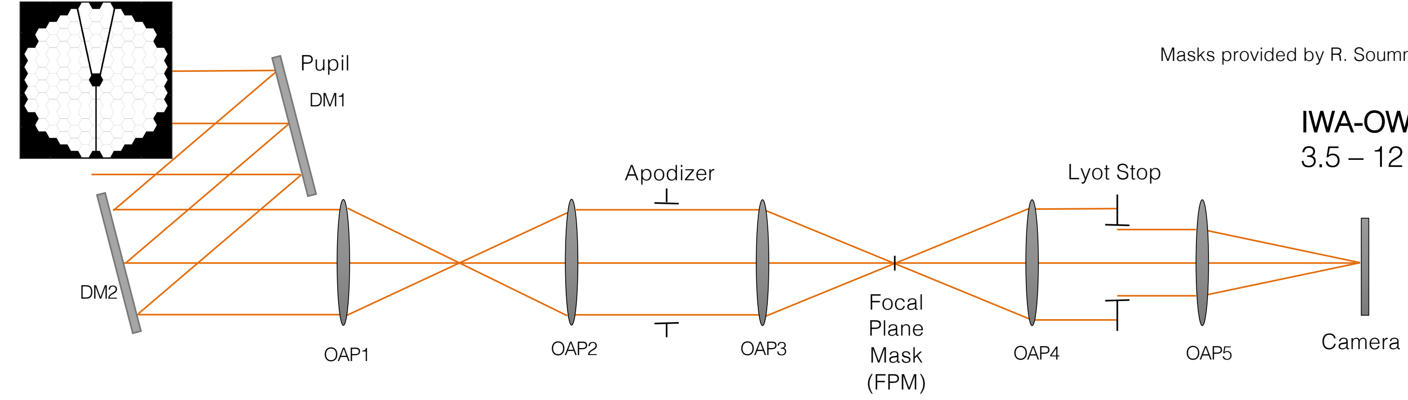
Coronagraph primary design for ECLIPS-A: APLC

Coronagraph primary design for ECLIPS-B: VVC

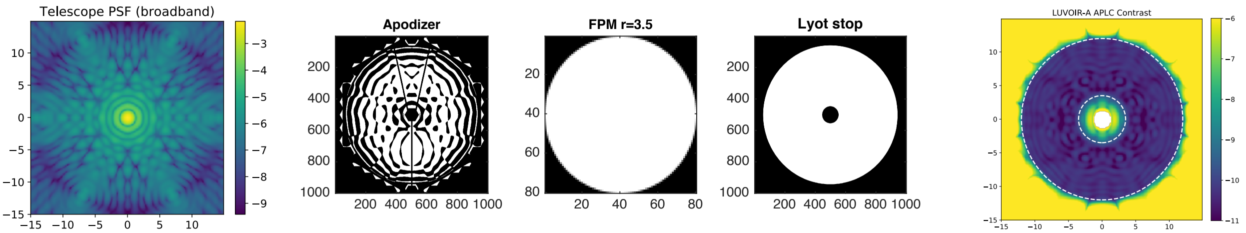
Coronagraph design for ECLIPS-A

APLC - Apodized Pupil Lyot Coronagraph

Masks provided by R. Soummer (STScI)

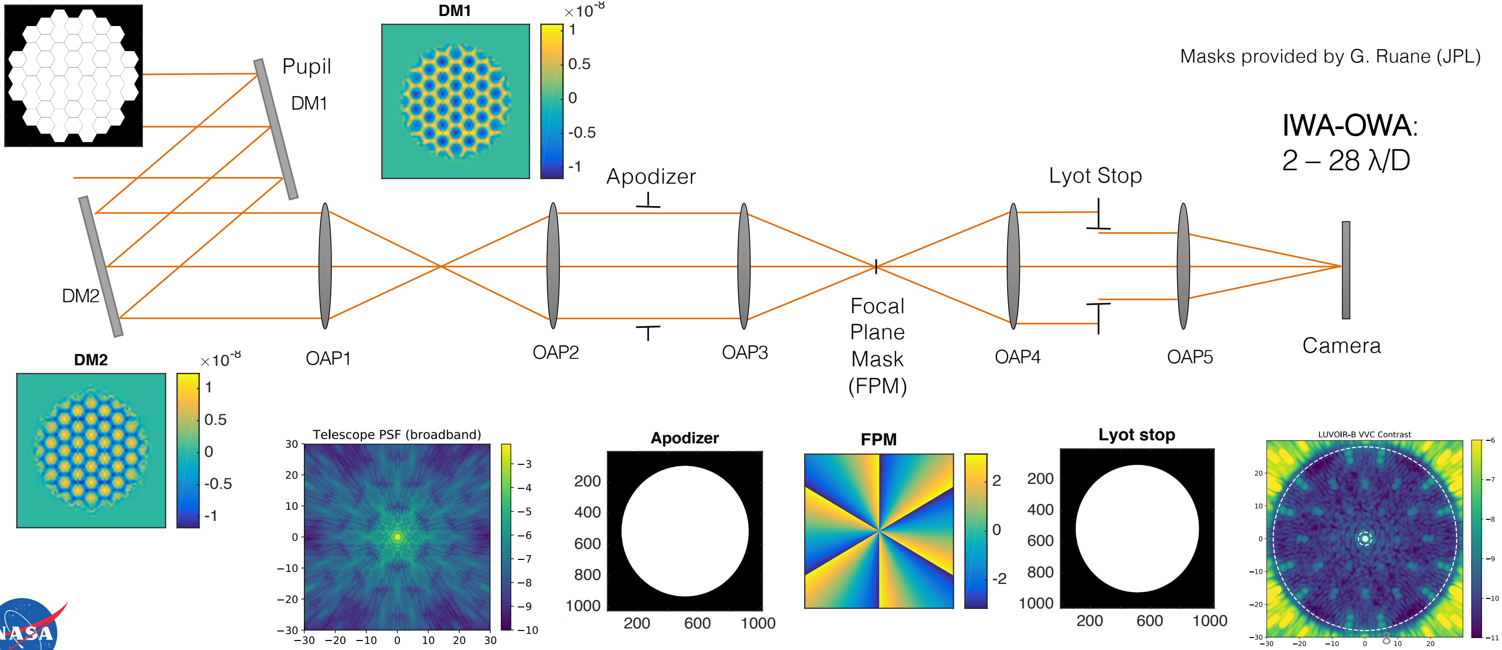


IWA-OWA:
3.5 – 12 λ/D



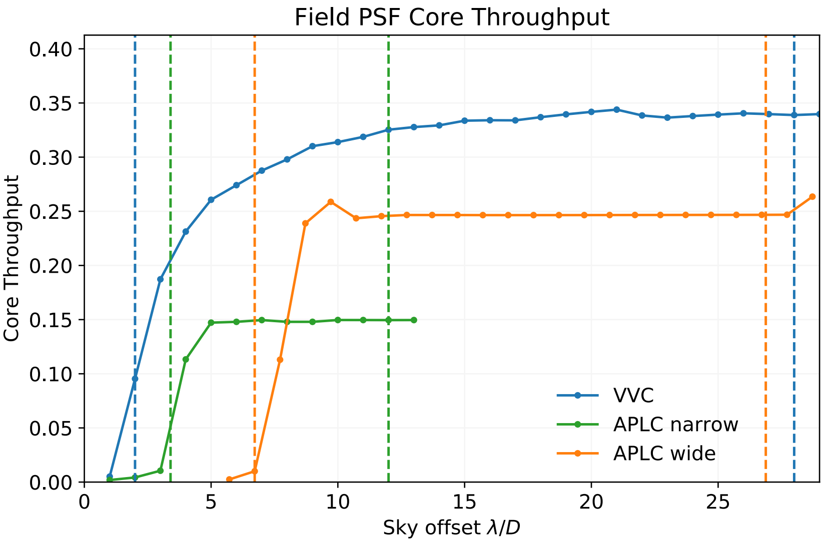
Coronagraph design for ECLIPS-B

VVC - Vector Vortex Coronagraph

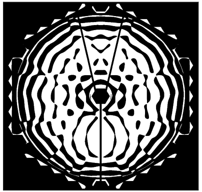


Evaluation of coronagraph designs

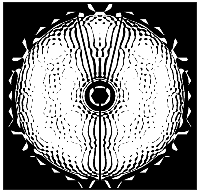
Throughput



APLC narrow

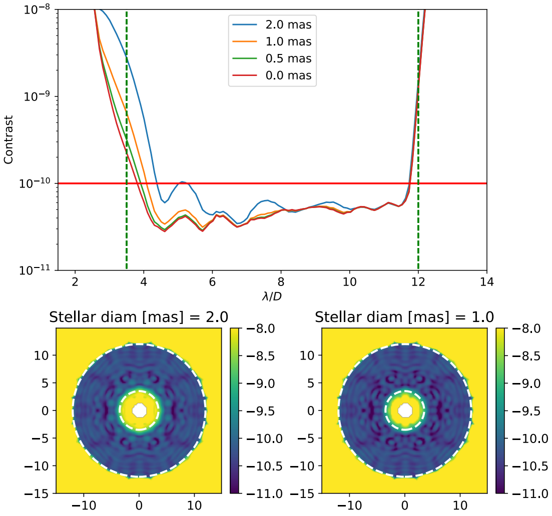


APLC wide

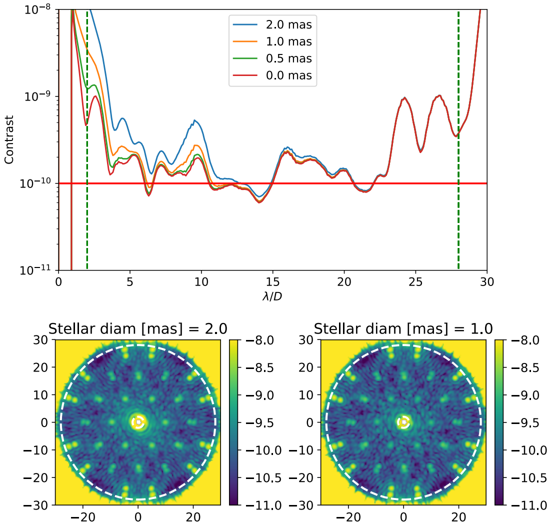


Evaluation of coronagraph designs
Sensitivity to stellar diameter

LUVOIR-A APLC



LUVOIR-B VVC



Coronagraph sensitivity to telescope aberrations

Wavefront sensing and control

- Both **APLC** and **VVC** designs are sensitive to global aberrations and segment phasing errors
- We can increase the tolerance to telescope aberrations with **wavefront sensing and control** (WS&C)

	(Quasi) Static aberrations	Dynamic aberrations
Segment	PW+EFC	Payload metrology (edge sensors)
Global	Phase retrieval	LOWFS

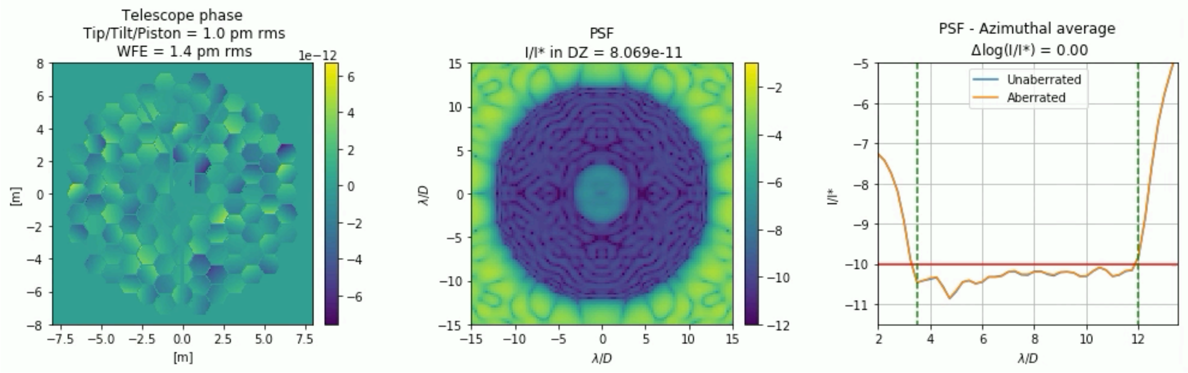
Segment jitter
Segment drift

LoS pointing error

PW+EFC: Pair-wise electric field estimation + Electric Field Conjugation

LOWFS: Low Order Wavefront Sensing

Coronagraph sensitivity to telescope aberrations
Segment phasing errors



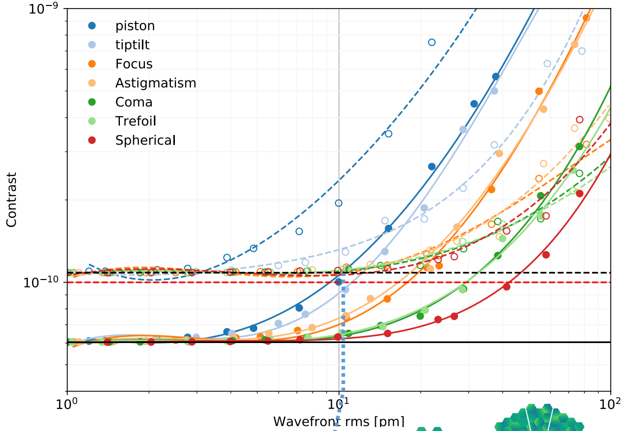
Piston and tip/tilt induced phase errors added to each segment independently (random normal distribution).

Coronagraph sensitivity to static aberrations

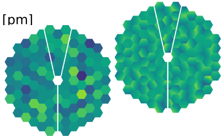
Segment phasing errors

Most sensitive to
Piston and Tip/Tilt

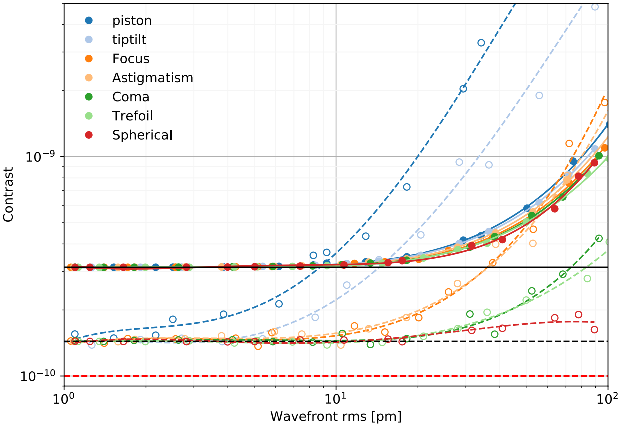
LUVOIR-A APLC



Piston: 9.24 pm
Tip/tilt: 11.16 pm



LUVOIR-B VVC

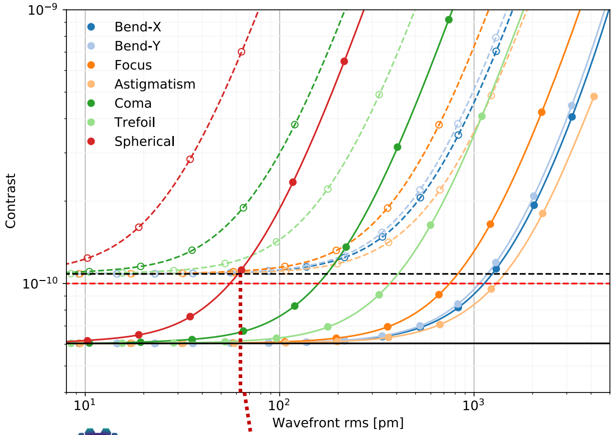


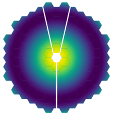
Solid line - average contrast in the DZ
Dashed line - average contrast at 4 ± 0.5 λ/D

Coronagraph sensitivity to static aberrations

Global aberrations

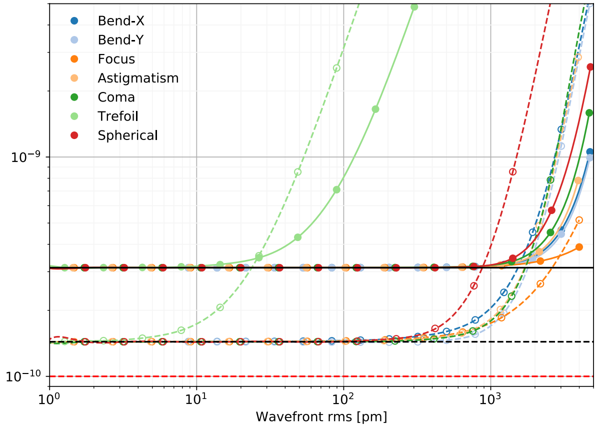
LUVOIR-A APLC





Spherical: 55.53 pm

LUVOIR-B VVC



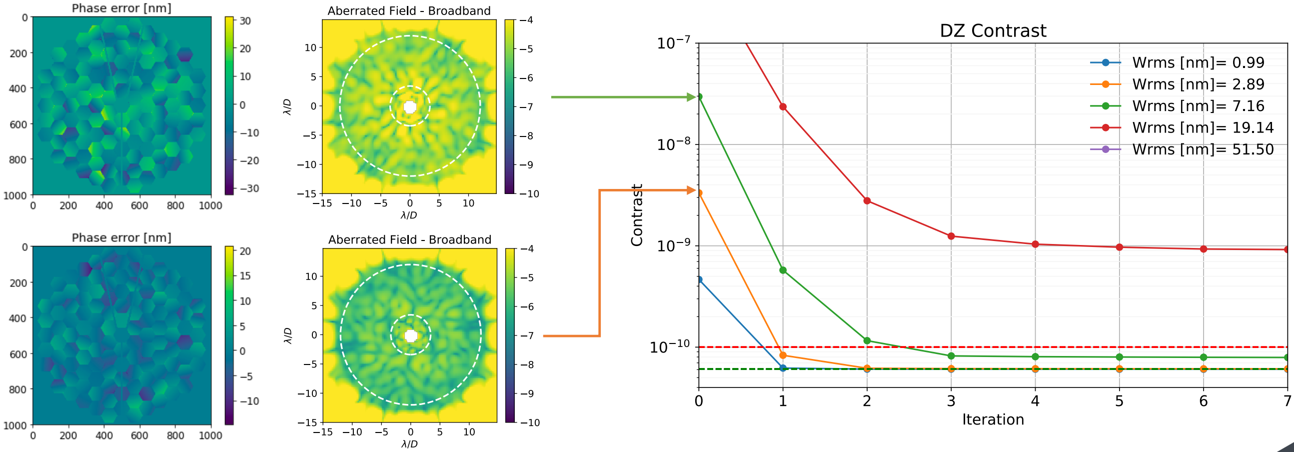
Solid line - average contrast in the DZ
Dashed line - average contrast at 4 ± 0.5 λ/D

Coronagraph sensitivity to static aberrations
LUVOIR-A APLC + WS&C

Broadband EFC (10%) with 2 deformable mirrors (DM) (64 x 64 actuators per DM)

P/T/T rms
7.07 nm

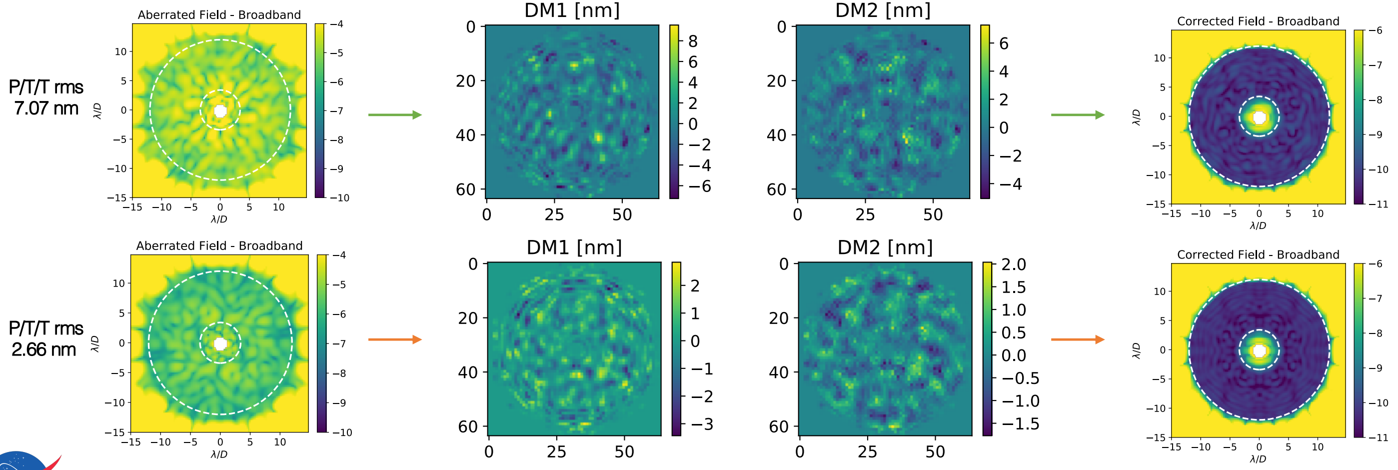
P/T/T rms
2.66 nm



Coronagraph sensitivity to static aberrations

LUVOIR-A APLC + WS&C

Broadband EFC with 2 deformable mirrors (DM) (64 x 64 actuators per DM)

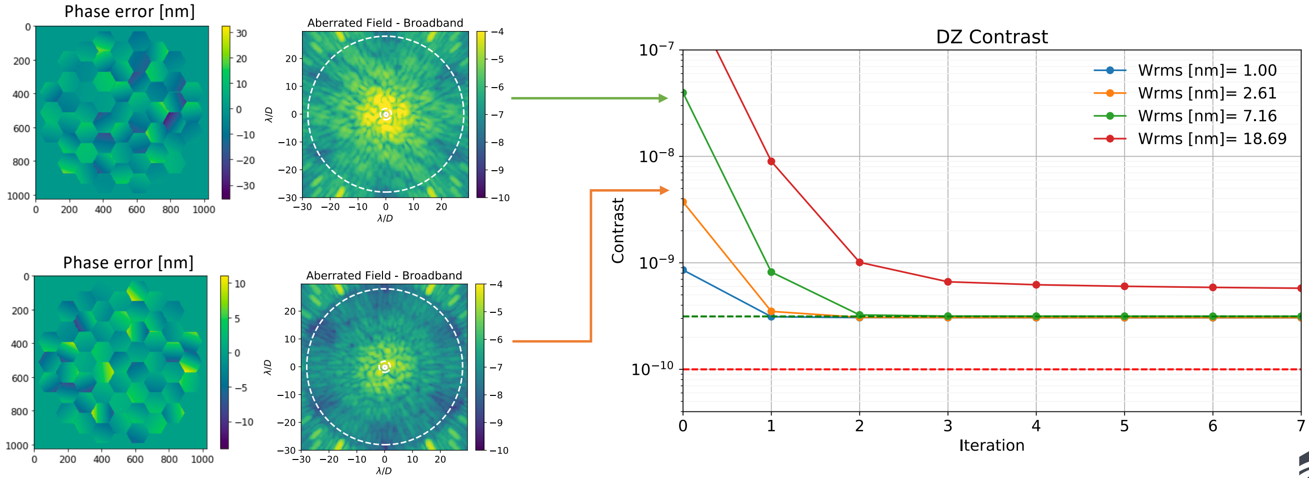


Coronagraph sensitivity to static aberrations
LUVOIR-B VVC + WS&C

Broadband EFC (10%) with 2 deformable mirrors (DM) (64 x 64 actuators per DM)

P/T/T rms
7.07 nm

P/T/T rms
2.66 nm



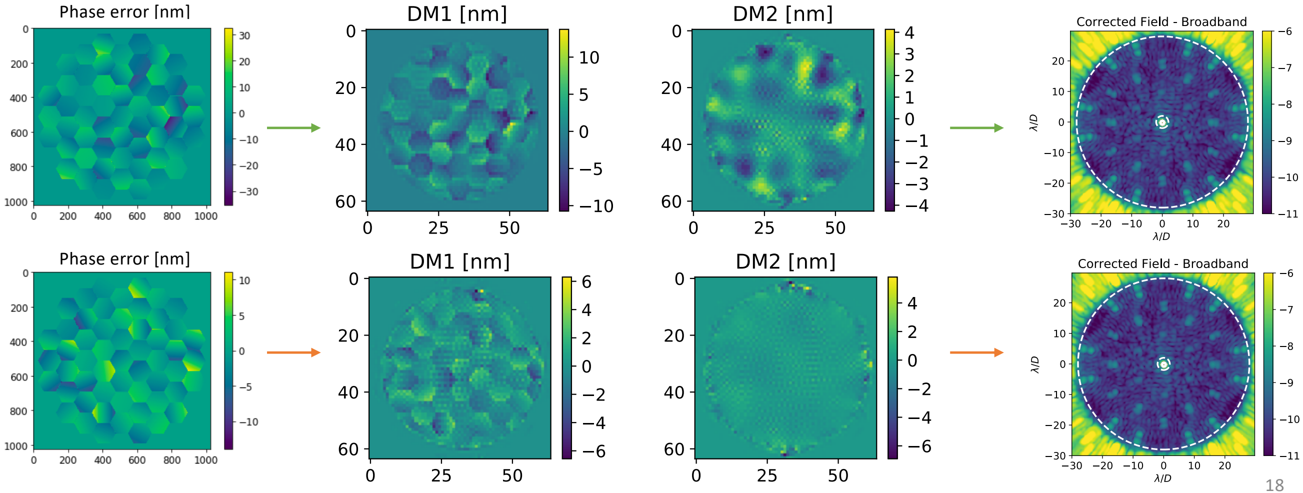
Coronagraph sensitivity to static aberrations

LUVOIR-B VVC + WS&C

Broadband EFC with 2 deformable mirrors (DM) (64 x 64 actuators per DM)

P/T/T rms
7.07 nm

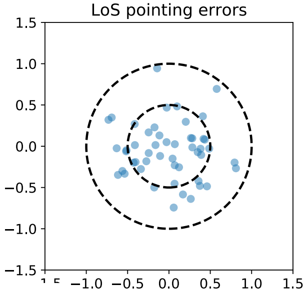
P/T/T rms
2.66 nm

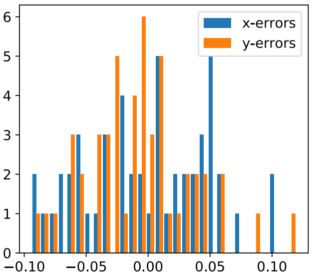


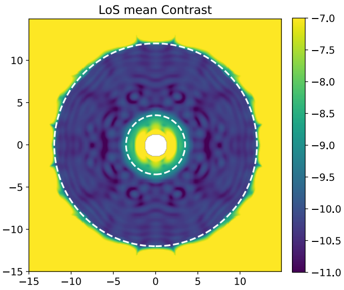
Coronagraph sensitivity to dynamic aberrations
Line of Sight (LoS) pointing errors

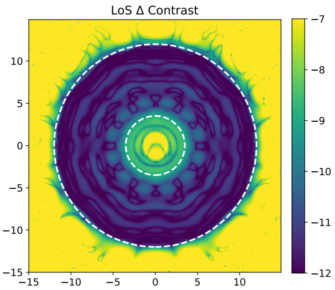
LUVOIR-A
APLC

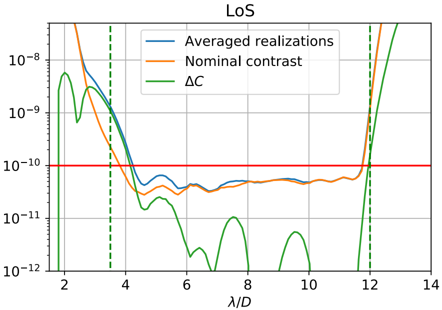
σ_{LoS} = 0.5 mas
Normal distribution
50 realizations averaged











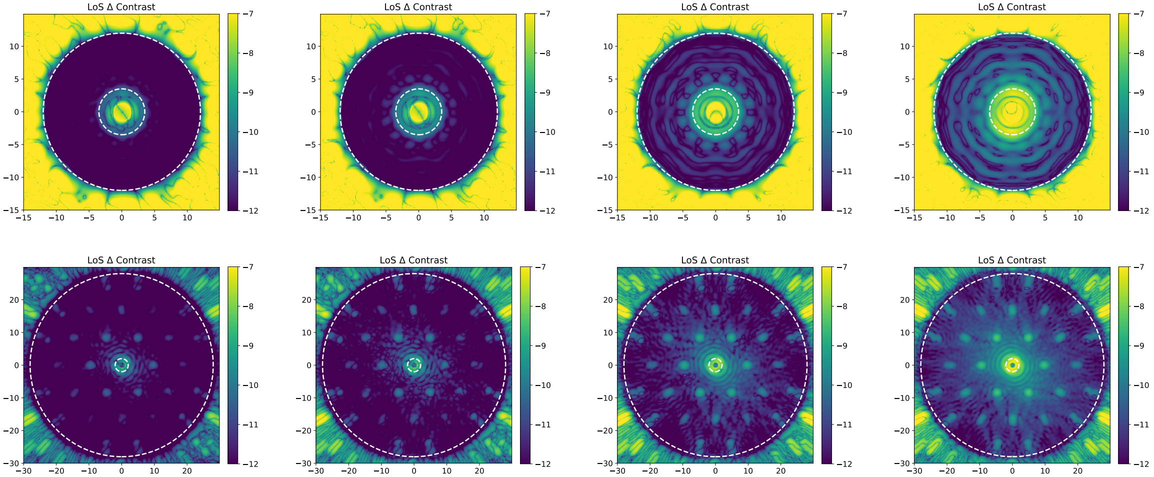
Coronagraph sensitivity to dynamic aberrations

Line of Sight (LoS) pointing errors

σ_{LoS} = 0.1 mas | σ_{LoS} = 0.2 mas | σ_{LoS} = 0.5 mas | σ_{LoS} = 1.0 mas

LUVOIR-A APLC

LUVOIR-B VVC



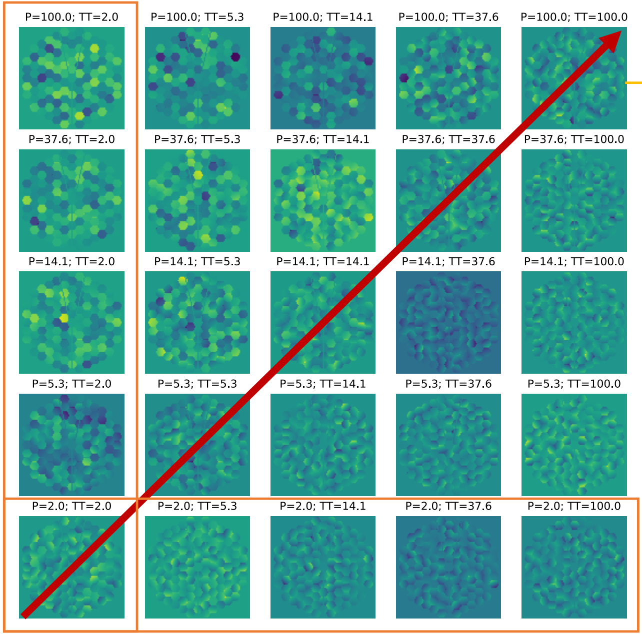
Coronagraph sensitivity to dynamic aberrations

Segment phasing errors - Jitter

5 Piston vals x 5 Tip/tilt vals x 20 realizations
Piston(Tip/tilt) rms = 2..100pm

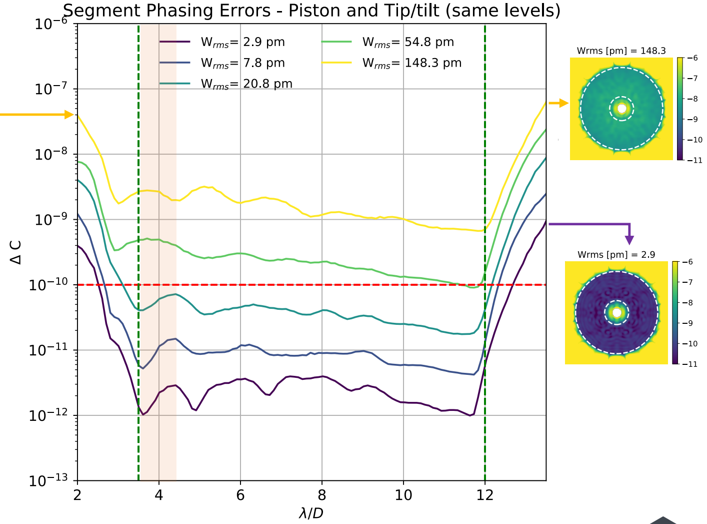
+ Piston

LUVOIR-A APLC



- Piston
- Tip/tilt

+Tip/tilt

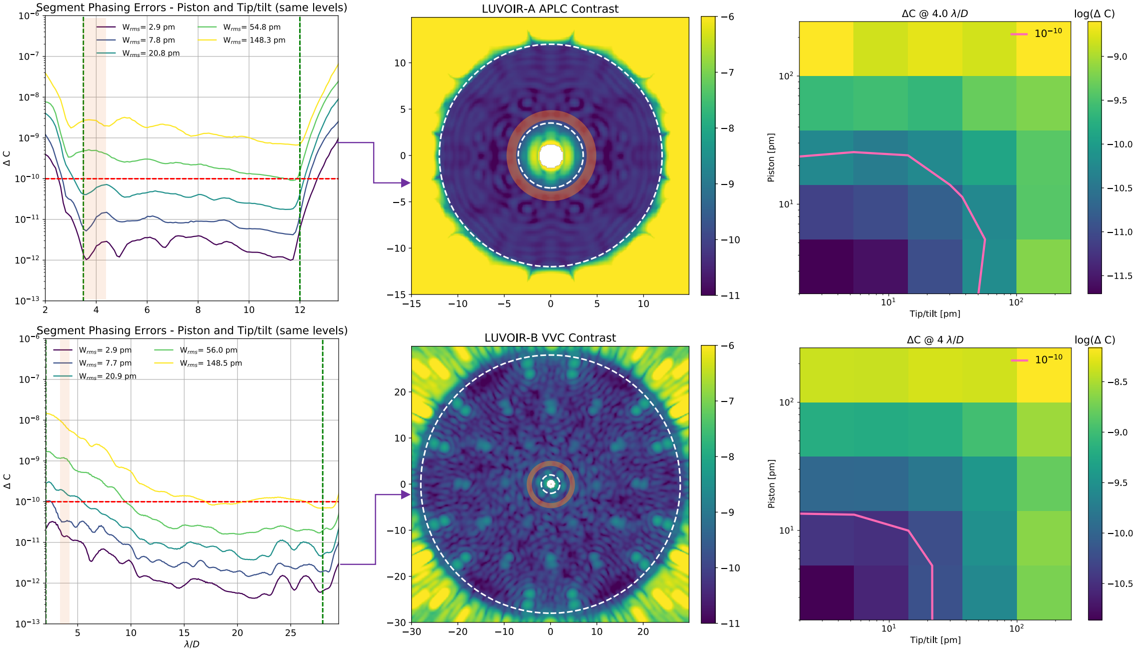


Coronagraph sensitivity to dynamic aberrations

Segment phasing errors - Jitter

LUVOIR-A APLC

LUVOIR-B VVC



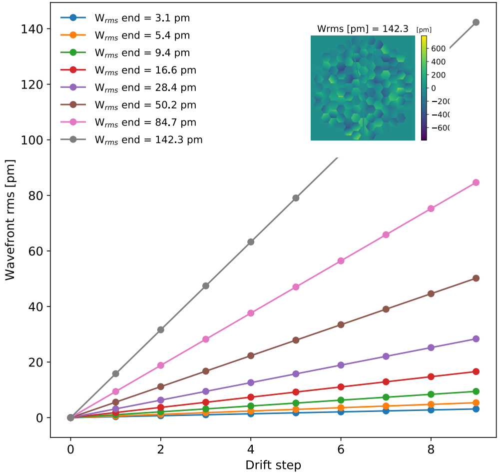
To remain below the 10^{-10} raw contrast target, the wavefront RMS should not exceed a few **10s of pm**

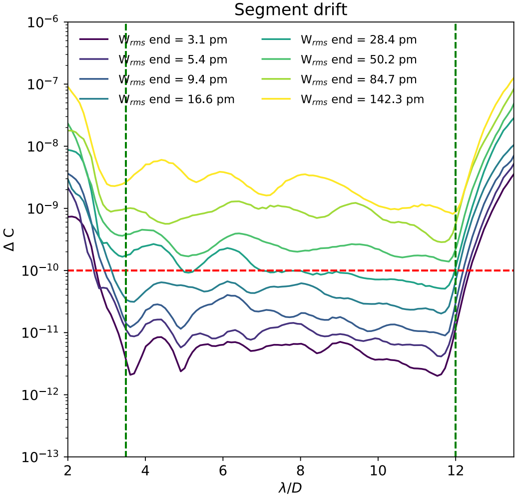
Coronagraph sensitivity to dynamic aberrations

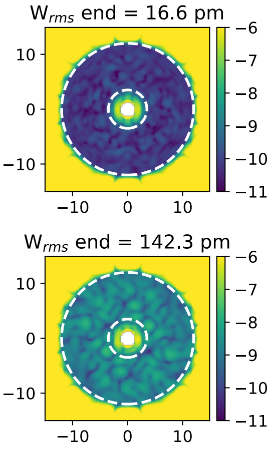
Segment phasing errors - Drift

8 x 10 realizations
Piston(Tip/tilt) rms = 2..100pm

LUVOIR-A APLC





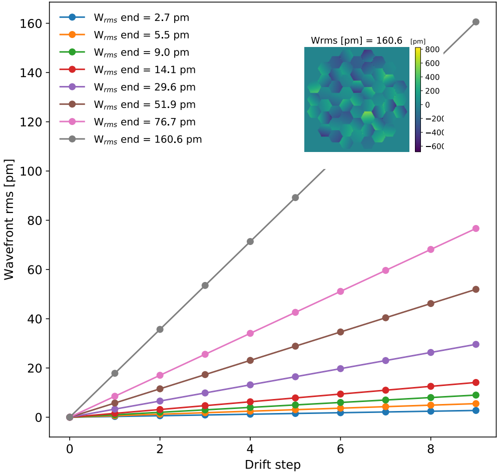


Radial profile - std

Coronagraph sensitivity to dynamic aberrations

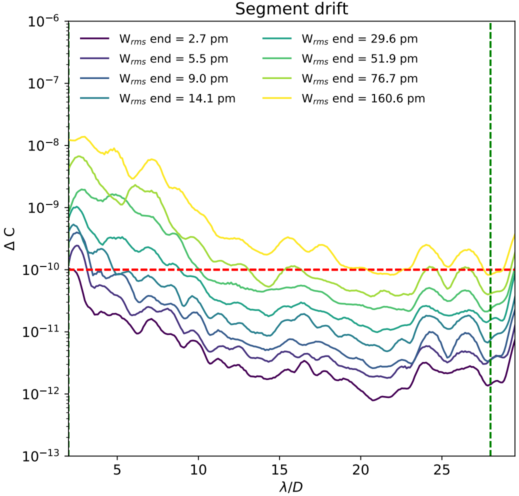
Segment phasing errors - Drift

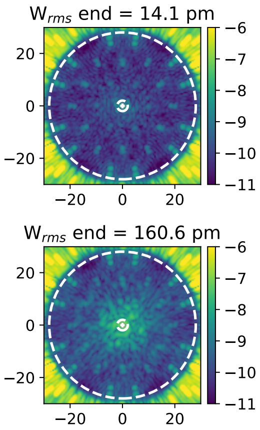
LUVOIR-B VVC



8 x 10 realizations

Piston(Tip/tilt) rms = 2..100pm

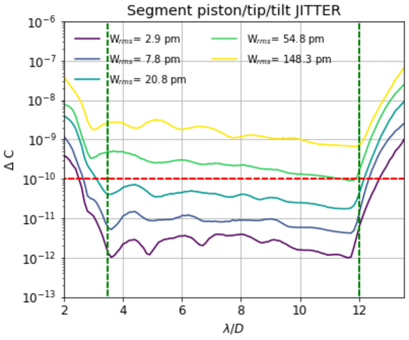


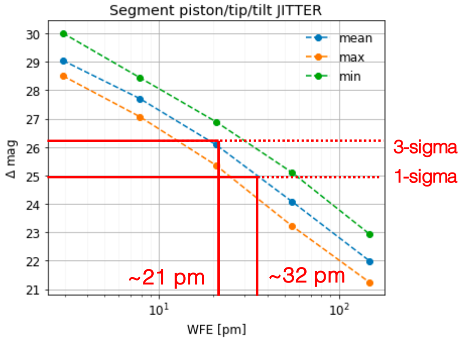


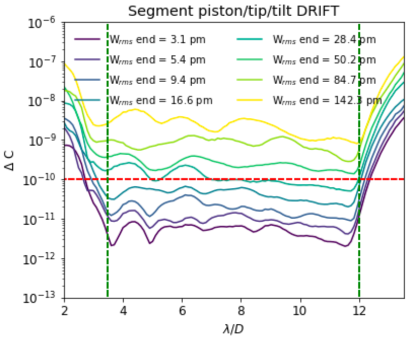
Radial profile - std

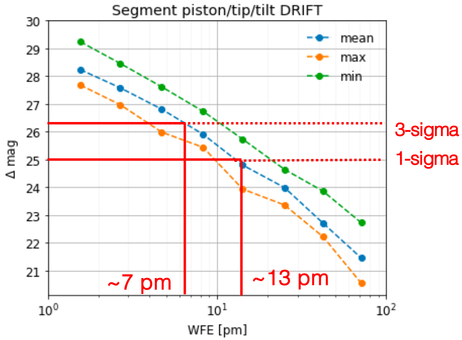
Coronagraph sensitivity to dynamic aberrations

LUVOIR-A APLC



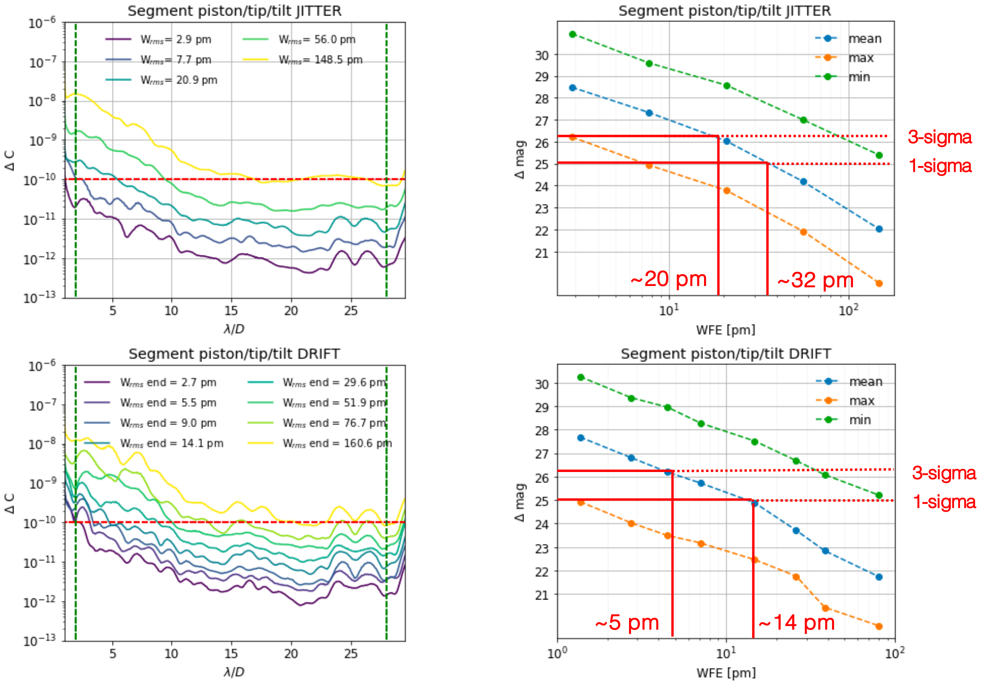






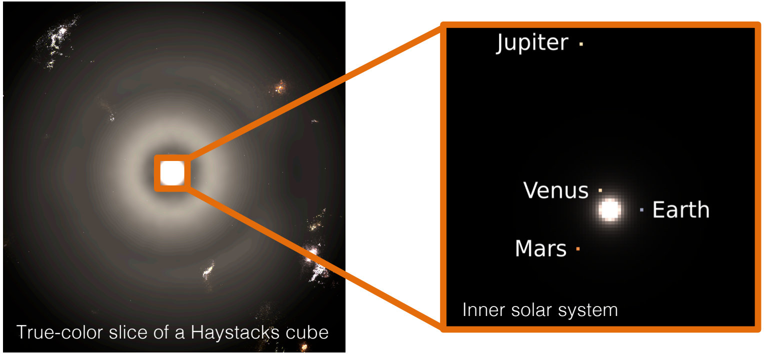
Coronagraph sensitivity to dynamic aberrations

LUVOIR-B VVC



Simulation of exoplanet detection
The Haystacks project

- We use **Haystacks** models of the Archean and Modern solar system as inputs to the LUVOIR coronagraph model.
- The models contain detailed information from the **planetary architecture**, the **dust structure**, the **background stars**, and the **background galaxies**.
- Spectral information from **0.3 to 2.5 um**, to cover the range of interest from future planet characterization flagship missions.



Anyone can download the models for various inclinations and wavelength bands at:
https://asd.gsfc.nasa.gov/projects/haystacks/

Simulation of exoplanet detection

LUVOIR-A APLC

Assumptions

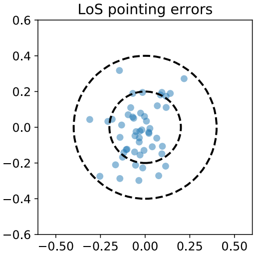
- About the **observatory**:

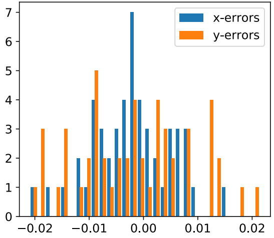
  LoS pointing error: 0.2 mas
  Segment jitter (tip/tilt/piston): 7pm (Wrms ~ 10pm)
  Num. averaged realizations: 50
  LUVOIR-A DZ masks: 3.5-12 λ/D + 6.72-26.88 λ/D

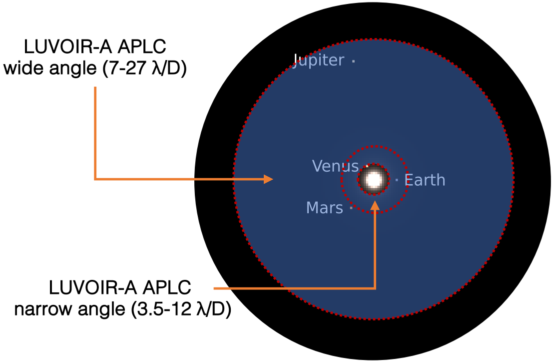
- About the **planetary system**

  Stellar diameter: 0.75 mas
  Distance: 12.5 pc
  Inclination: 60 degrees

  No background sources (stars / galaxies)
  Zodiacal debris disk

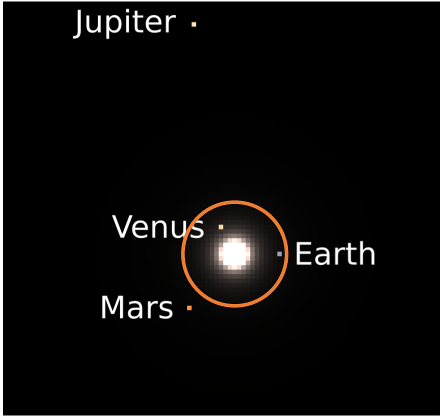




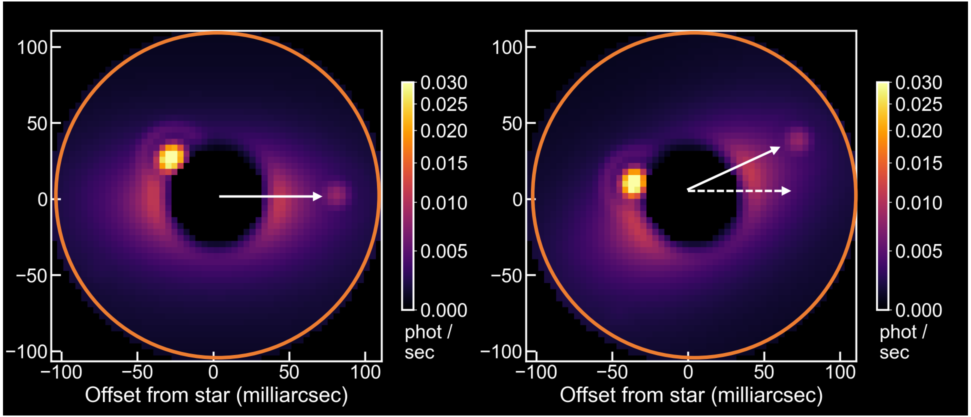


Simulation of exoplanet detection
LUVOIR-A APLC

Convolution of the Haystacks model with the field-dependent coronagraph PSF.



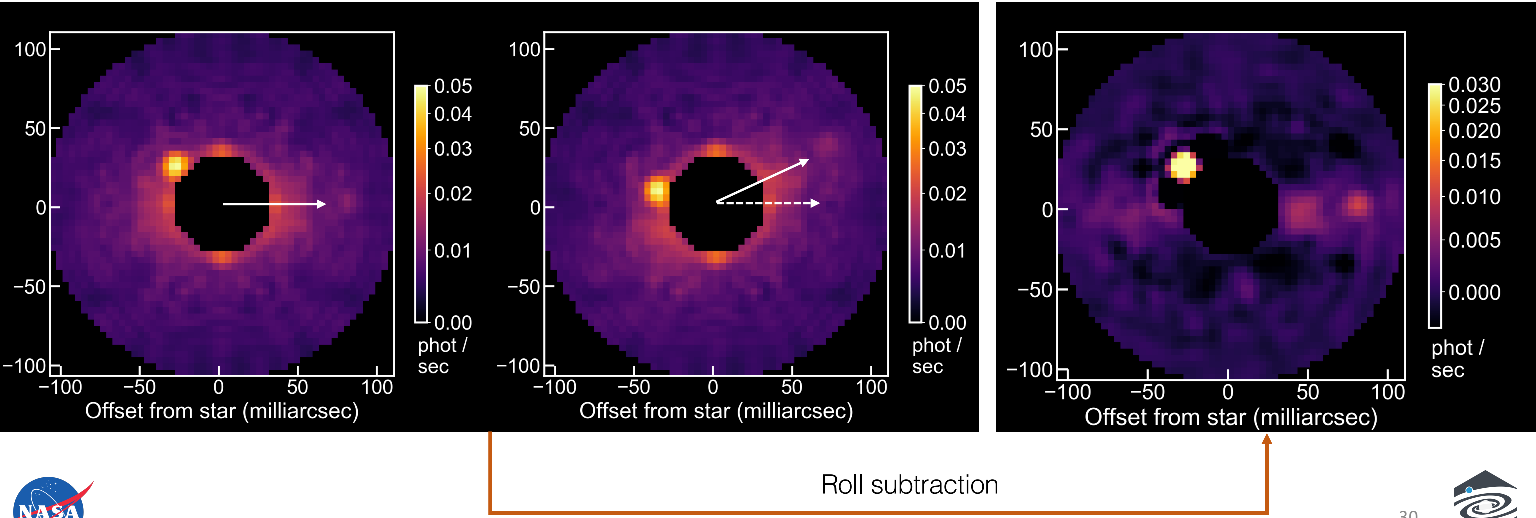
Haystacks scene



Narrow angle LUVOIR-A APLC masks
(without star, without noise)

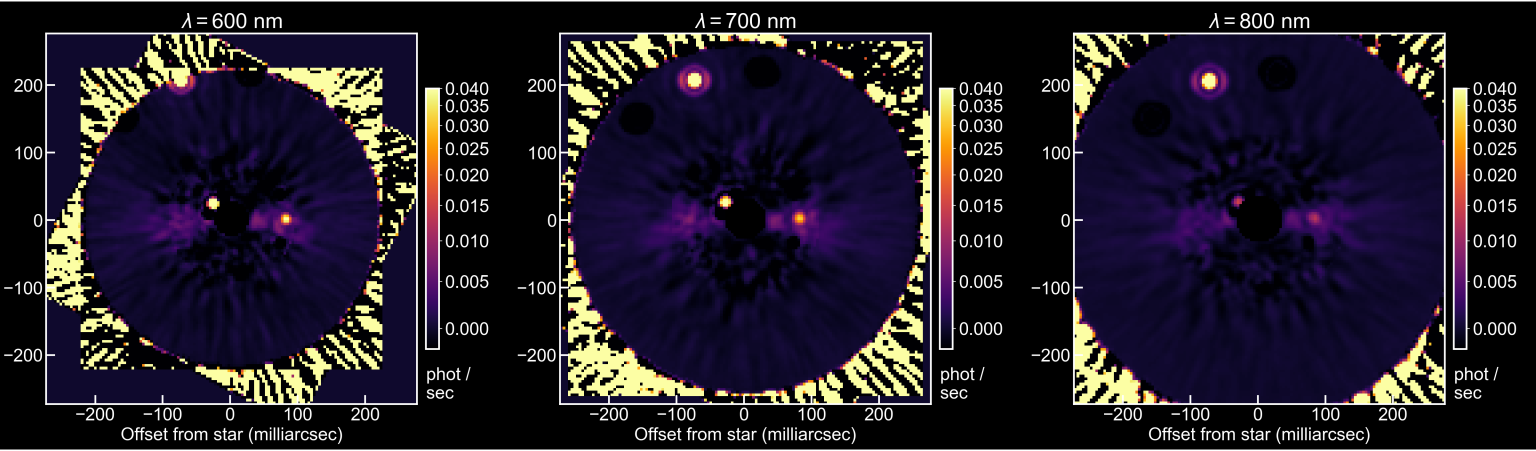
Simulation of exoplanet detection
LUVOIR-A APLC

Narrow angle LUVOIR-A APLC mask
(with star, without noise)



Simulation of exoplanet detection

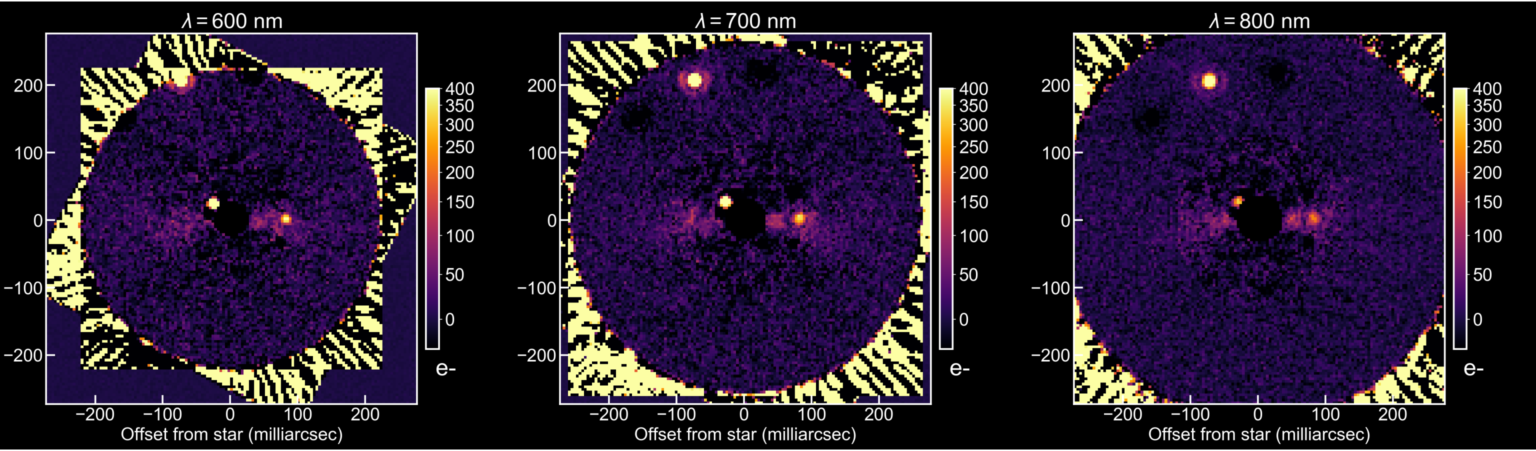
LUVOIR-A APLC



LUVOIR-A APLC **narrow** angle mask (3.5-12 λ/D): 3 bands, 10%, λ= (600 nm, 700nm, 800nm)
LUVOIR-A APLC **wide** angle mask (6.72-26.88 λ/D): 3 bands, 18%, λ= (600 nm, 700nm, 800nm)

Simulation of exoplanet detection

LUVOIR-A APLC



APLC Narrow: 5 hours
APLC Wide: 3 hours

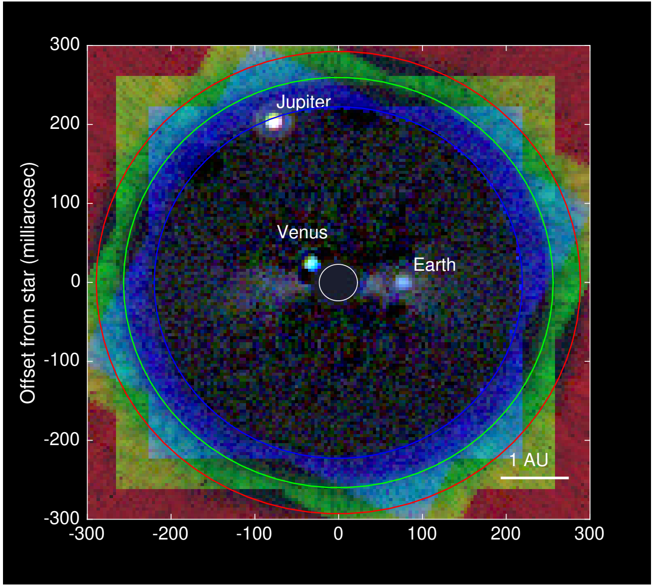
APLC Narrow: 6 hours
APLC Wide: 3 hours

APLC Narrow: 8 hours
APLC Wide: 4 hours

Including detector noise
Integration time: 60 hours (including 25% overheads)

600 nm: T_int = 17 hr, SNR = 14
700 nm: T_int = 19 hr, SNR = 12
800 nm: T_int = 24 hr, SNR = 9

Simulation of exoplanet detection
LUVOIR-A APLC



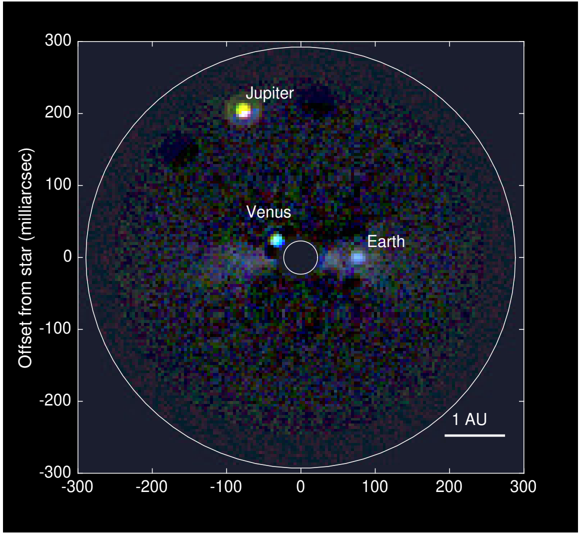
Conclusions

- We have presented the **first LUVOIR ECLIPS data simulations** incorporating error sources consistent with the engineering requirements defined in the LUVOIR study report

- Under our present assumptions for residual dynamical wavefront errors, simulations suggest that simple roll subtraction is an effective means to **recover exoplanet point sources at 10^{-10} contrast in the habitable zones of nearby stars.**

- Within SCDA, we will continue to investigate various levels and combinations of telescope **wavefront errors and drifts**, as well as instrument **optical train aberrations**

- Current telescope aberrations are purely random wavefront error representations. Future work will use integrated structural thermal models from industry partners.



Part of this work was supported by ExEP's Segmented Coronagraph Design and Analysis (SCDA) study.

LUVOIR website:
https://asd.gsfc.nasa.gov/luvoir/

LUVOIR Mission Concept Study Interim Report:
https://arxiv.org/abs/1809.09668

NASA ExEP's Segmented Coronagraph Design and Analysis (SCDA) study:
https://exoplanets.nasa.gov/exep/technology/SCDA/