Exoplanet Detection with the LUVOIR Coronagraph Instrument

Performance evaluation and aberration sensitivity requirements

Roser Juanola-Parramon

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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 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)

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 $\lambda/D$
  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%)
The optical layouts for **ECLIPS-A** and **ECLIPS-B** are identical.
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

Masks provided by G. Ruane (JPL)

IWA-OWA: 2 – 28 \( \lambda / D \)
Evaluation of coronagraph designs

Throughput

Field PSF Core Throughput

Sky offset $\lambda/D$

Core Throughput

VVC
APLC narrow
APLC wide

APLC narrow

APLC wide

NASA
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)**.

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**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

LUVOIR-A APLC
LUVOIR-B VVC

Most sensitive to Piston and Tip/Tilt

Solid line - average contrast in the DZ
Dashed line - average contrast at 4 ± 0.5 \( \lambda / D \)

Piston: 9.24 pm
Tip/tilt: 11.16 pm
Coronagraph sensitivity to static aberrations

Global aberrations

LUVOIR-A APLC

LUVOIR-B VVC

Solid line - average contrast in the DZ
Dashed line - average contrast at $4 \pm 0.5 \lambda/D$
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

DZ Contrast

Contrast

Iteration

10^{-7}

10^{-9}

10^{-10}

Wrms [nm] = 0.99

Wrms [nm] = 2.89

Wrms [nm] = 7.16

Wrms [nm] = 19.14

Wrms [nm] = 51.50
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)

Phase error [nm]  
P/T/T rms 7.07 nm

Phase error [nm]  
P/T/T rms 2.66 nm

Aberrated Field - Broadband

DZ Contrast

Contrast

Wrms [nm] = 1.00
Wrms [nm] = 2.61
Wrms [nm] = 7.16
Wrms [nm] = 18.69

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

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

Phase error [nm]

P/T/T rms 7.07 nm

Phase error [nm]

P/T/T rms 2.66 nm

DM1 [nm]

DM2 [nm]

Corrected Field - Broadband

Corrected Field - Broadband
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

\[ \sigma_{\text{LoS}} = 0.1 \text{ mas} \]
\[ \sigma_{\text{LoS}} = 0.2 \text{ mas} \]
\[ \sigma_{\text{LoS}} = 0.5 \text{ mas} \]
\[ \sigma_{\text{LoS}} = 1.0 \text{ mas} \]
Coronagraph sensitivity to dynamic aberrations
Segment phasing errors - Jitter

LUVOIR APLC

- Piston
- Tip/tilt

+ Piston

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

5 Piston vals x 5 Tip/tilt vals x 20 realizations
Coronagraph sensitivity to dynamic aberrations

Segment phasing errors - Jitter

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

LUVOIR-A APLC

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

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
Segment drift

Radial profile - std

W_{rms} end = 14.1 pm
W_{rms} end = 160.6 pm
Coronagraph sensitivity to dynamic aberrations

LUVOIR-A APLC

Coronagraph sensitivity to dynamic aberrations
Coronagraph sensitivity to dynamic aberrations

Segment piston/tip/tilt JITTER

Segment piston/tip/tilt DRIFT

1-σ
3-σ

~20 pm
~32 pm
~5 pm
~14 pm

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: $3.5-12 \lambda/D + 6.72-26.88 \lambda/D$

• 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)

Roll subtraction
Simulation of exoplanet detection
LUVOIR-A APLC

LUVOIR-A APLC narrow angle mask (3.5-12 \(\lambda/D\)): 3 bands, 10%, \(\lambda= \) (600 nm, 700nm, 800nm)
LUVOIR-A APLC wide angle mask (6.72-26.88 \(\lambda/D\)): 3 bands, 18%, \(\lambda= \) (600 nm, 700nm, 800nm)
Simulation of exoplanet detection
LUVOIR-A APLC

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

- 600 nm: $T_{\text{int}} = 17$ hr, $\text{SNR} = 14$
- 700 nm: $T_{\text{int}} = 19$ hr, $\text{SNR} = 12$
- 800 nm: $T_{\text{int}} = 24$ hr, $\text{SNR} = 9$
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.

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


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