Performance and sensitivity of PIAA coronagraphs for future segmented space telescopes

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INTRODUCTION

The Large UV/Optical/IR Surveyor (LUVOIR) [1] is a next-generation segmented telescope with an aperture ranging in circumscribed diameter from 8-15 m. LUVOIR is planned to survey star systems within 30 parsecs through direct imaging to detect and characterize habitable exoplanets.

Due to its large size, LUVOIR presents technical challenges for the direct imaging of exoplanets. First, LUVOIR will be a segmented telescope which introduces additional diffraction challenges that must be accurately controlled. Additionally, the LUVOIR-A design is on-axis with a significant obstruction due to its secondary that must be controlled using a coronagraph. LUVOIR-B will be an off-axis telescope with segmentation. Finally, LUVOIR's large diameter increases its sensitivity to nearby stars – thus coronagraph designs must be robust to tip/tilt sensitivity to efficiently survey nearby stars.

Here, we present a range of high-efficiency coronagraph designs based on the Phase-Induced Amplitude Apodization (PIAA) coronagraph [2]. First we present hybrid a PIAA-Vortex design that uses a focal plane mask with an achromatic-vortex charge 6 that in combination with the wavefront-control-system control both the on-axis obstruction and the segmentation of the LUVOIR-A pupil. We also present classical PIAA designs with an opaque focal plane mask for the off-axis LUVOIR-B architecture optimized for robustness to tip/tilt sensitivity. These designs are optimized for robustness to tip/tilt sensitivity.

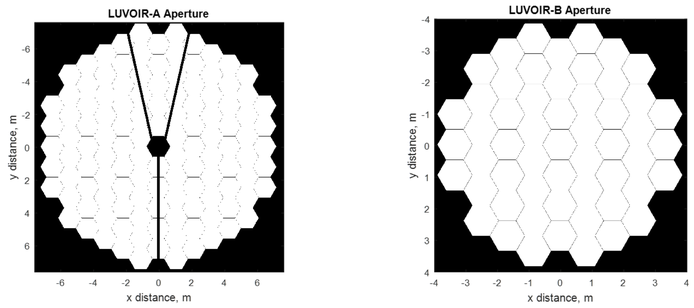
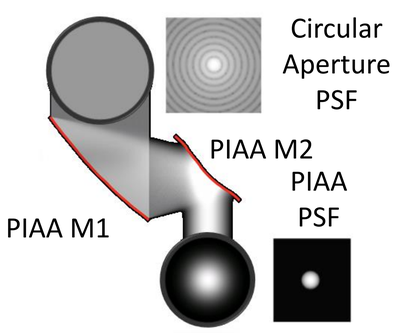
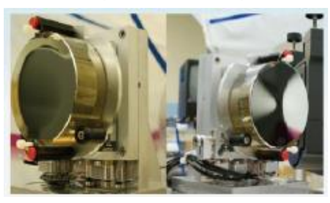


Figure 1. (Left) LUVOIR-A features a 15.2-m circumscribed diameter with an on-axis obstruction, supporting spiders, and segmentation. (Right) LUVOIR-B is a fully off-axis design with a 8-m circumscribed diameter aperture and segmentation

PIAA Coronagraph

The PIAA Coronagraph uses a set of two aspheric mirrors to reshape the evenly illuminated telescope aperture and generate a smooth apodization that concentrates light in the center and tapers off towards the edges. This principle is illustrated in Figure 2 where a circular telescope's PSF's Airy pattern is removed by the PIAA apodization. PIAA features two main advantages: the apodization is lossless and can be used for aggressive inner-working angle (IWA) designs. PIAA mirrors have been successfully manufactured by Axsys, Tinsley, and NuTek with very small residual aberrations (<5 nm RMS). Finally, our approach is to use circularly symmetric PIAA mirrors and the DMs to eliminate diffraction due to telescope segmentation and spiders. The central obstruction of LUVOIR-A requires a focal plane mask with a complex focal plane.





PIAA Aspheric Mirrors

Figure 2. (Left) PIAA mirrors reshape the optical beam to a favourable apodization which removes Airy rings. (Top) Manufactured PIAA mirrors

LUVOIR-A PIAA-Vortex Design

The hybrid PIAA-Vortex design for LUVOIR-A uses an optimized, complex focal plane mask to deal with the enhanced diffraction rings from the secondary obstruction. The focal plane mask is a vortex charge 6 achromatic mask that provides robustness to tip/tilt and other low-order aberrations, with a design enabled by the PIAA-Vortex.

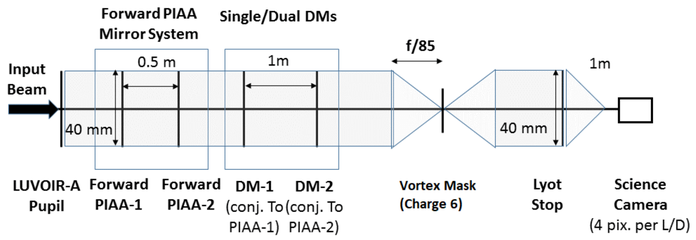


Figure 3. Schematic of Hybrid PIAA-Vortex Design for LUVOIR-A

Numerically-Optimized PIAA-induced apodization (Fogarty et al 2017, 2019)

Vortex Charge 6 Mask robust to low-order aberrations (Ruane et al 2018)

DM Solutions generated with FALCO (Riggs et al 2017)

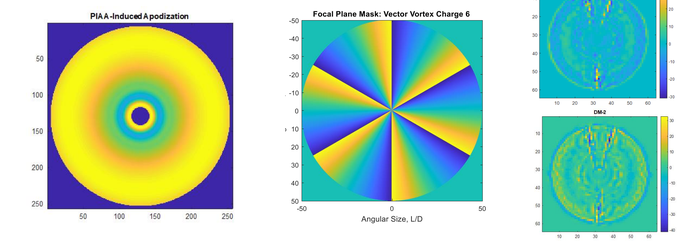


Figure 4. (Top) LUVOIR-A PIAA-Vortex design (apodization, FPM, and DM solutions)

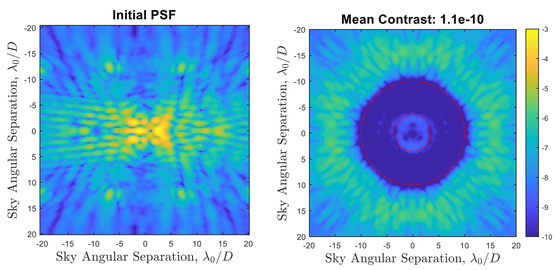


Figure 5. (Left) Initial PIAA-Vortex PSF. (Right) Dark hole after WFC using DMs in 10% band.

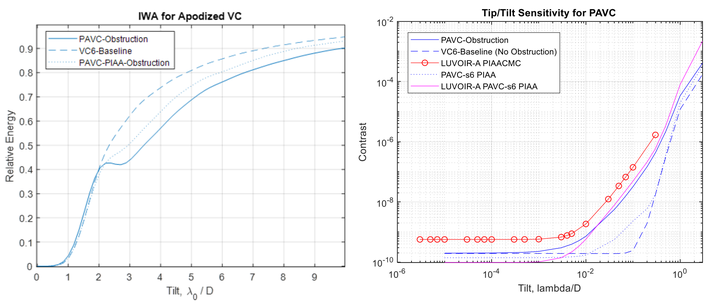


Figure 6 PIAA-Vortex IWA and tip/tilt sensitivities and comparison to VC-6 baseline and existing LUVOIR-A PIAACMC design (Belikov et al 2020).

ACKNOWLEDGEMENTS

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REFERENCES

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4. K. Fogarty et al, AJ 2017

LUVOIR-B Classical PIAA Design

The LUVOIR-B features only segmentation so a classical PIAA design with an opaque focal plane mask can be used. The focal plane mask can be swapped with larger diameters to decrease the sensitivity to tip/tilt as well as other low-order modes [5].

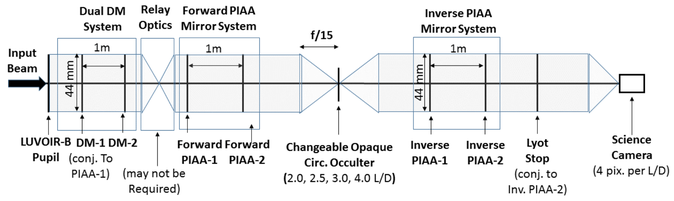


Figure 6. Schematic of Classical PIAA Design for LUVOIR-B

An inverse PIAA mirror set is provisioned to increase the OWA and core throughput of the design and a dual-DM configuration is used for a 360-degree dark zone.

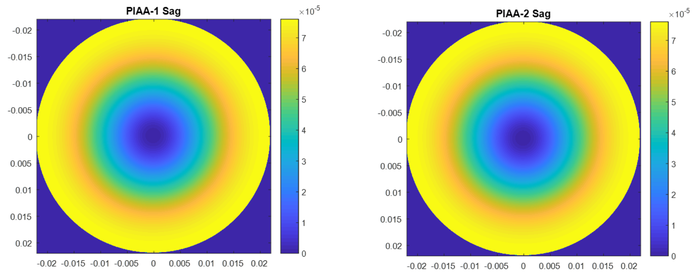


Figure 7. PIAA-1 and PIAA-2 mirrors are circularly symmetric with a mild apodization (corresponding to IWA ~ 1.6 L/D). Inverse PIAA mirrors are identical to forward PIAA mirrors in reverse order.

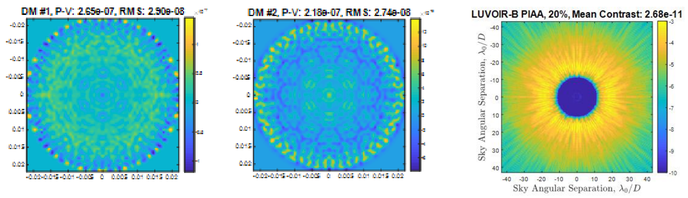


Figure 8. The DM is used to control diffraction from the LUVOIR-B segmentation: (Left) DM-1 surface, (Top) DM-2 surface, (Right) Dark Hole in 20% band

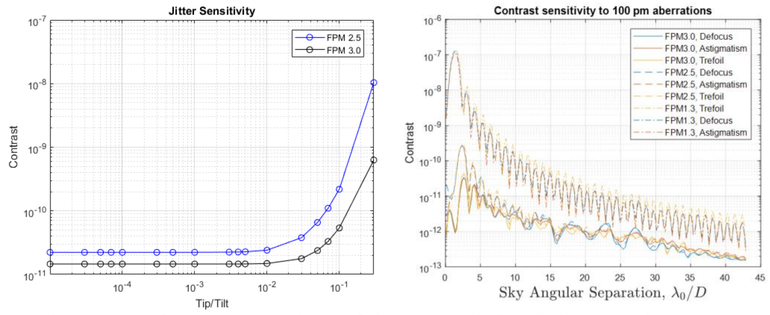


Figure 9. (Left) Jitter sensitivity of designs with focal plane mask radius of 2.5 and 3.0 L/D. (Right) Sensitivity to 100 pm of low-order aberrations for decreasing FPM radii.

CONCLUSION

We have presented high-efficiency PIAA designs for both the LUVOIR-A obstructed, segmented aperture and for the LUVOIR-B segmented aperture. Both of these designs are being implemented in the SCDA end-to-end simulator to demonstrate sensitivity to realistic thermal-induced and line-of-sight segmentation errors.

5. K. Fogarty, Spirit of Lyot 2019
6. A. J. Riggs et al., Proc. SPIE 2017
7. G. Ruane et al., JATIS 2018
8. R. Belikov et al., Proc. SPIE 2020