The LUVOIR Extreme Coronagraph for Living Planetary Systems (ECLIPS)

II. Performance evaluation, aberration sensitivity analysis and exoplanet detection simulations

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ABSTRACT

Future space missions such as the Large UV-Optical-Infrared Surveyor (LUVOIR) and the Habitable Exoplanet Observatory (HabEx) require coronagraphs with active wavefront control to suppress starlight to discover and characterize habitable exoplanets.

The Extreme Coronagraph for Living Planetary Systems (ECLIPS) is the coronagraph instrument on the LUVOIR Surveyor mission concept, an 8–15m segmented telescope. ECLIPS is split into three channels: UV (200 to 400 nm), optical (400 nm to 850 nm), and NIR (850 nm to 2.0 microns), with each channel equipped with two deformable mirrors for wavefront control, a suite of coronagraph masks, a low-order/out-of-band wavefront sensor, and separate science imagers and spectrographs.

The Apodized Pupil Lyot Coronagraph (APLC) and the Vector Vortex Coronagraph (VVC) are the baselined mask technologies for ECLIPS to enable the required $10^{-10}$ contrast for observations in the habitable zones of nearby stars. Their performance depends on active wavefront sensing and control, as well as metrology subsystems to compensate for aberrations induced by segment errors (piston and tip/tilt, among others), secondary mirror misalignment, and global low-order wavefront errors. Here we present the latest results of the simulation of these effects for the two technologies and discuss the achieved contrast for exoplanet detection and characterization after closed-loop wavefront estimation and control algorithms have been applied. Finally, we show simulated observations using high-fidelity spatial and spectral input models of complete planetary systems generated with the Haystacks code framework.

Keywords: high-contrast imaging, direct detection, coronagraphs, exoplanets, modeling, LUVOIR

1. INTRODUCTION

The complexity of imaging exoplanets resides in the extreme ratio in flux with respect to their parent star, in addition to their sub-arcsecond angular proximity. For this reason, not only large telescope apertures with extreme sensitivity are required, we also need coronagraph instruments for starlight suppression. The Large UV-Optical-InfraRed (LUVOIR) surveyor\textsuperscript{\textsuperscript{1}} is a concept for large aperture, serviceable, multi-wavelength space observatory with science goals that would enable transformative advances across a broad range of astrophysics\textsuperscript{\textsuperscript{2}}. To this date, two mission architectures are under study: LUVOIR-A, a 15-meter on-axis segmented aperture, and LUVOIR-B, an 8-meter off-axis segmented aperture.

Optically, both LUVOIR-A and LUVOIR-B are designed as a three-mirror anastigmat system with a fourth fine steering mirror located at the real exit pupil of the optical telescope element, which enables a wide field-of-view that can be accessed by its instruments, and ultra-fine pointing stability. The LUVOIR-A architecture

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\textsuperscript{1}https://asd.gsfc.nasa.gov/luvoir/
will have four instruments: the High Definition Imager (HDI), the LUVOIR Ultraviolet Multi Object Spectrograph (LUMOS),\(^2\) the UV spectro-polarimeter POLLUX\(^3\) and ECLIPS,\(^4\) the Extreme Coronagraph for Living Planetary Systems, while LUVOIR-B will have three instruments: HDI, LUMOS, and ECLIPS.

ECLIPS is split into three channels: UV (200 to 400 nm), optical (400 nm to 850 nm), and NIR (850 nm to 2.0 microns), with each channel equipped with two deformable mirrors for wavefront control, a suite of coronagraph masks, a low-order/out-of-band wavefront sensor, and separate science imagers and spectrographs. The Segmented Coronagraph Design & Analysis (SCDA) study\(^1\), led by NASA’s Exoplanet Exploration Program, has shown that several coronagraph mask technologies are compatible with segmented primary mirrors\(^5\). However, the mask types with the most mature designs for consideration in the LUVOIR study were the vector vortex coronagraph (VVC) and the apodized pupil Lyot coronagraph (APLC).

In the presence of even a modest central obscuration, as is the case for the LUVOIR-A telescope (~10% of the diameter), the APLC provides the best overall performance.\(^6\)–\(^8\) Therefore, most LUVOIR-A ECLIPS observing modes rely on a suite of APLC masks optimized for various ranges of angular separation. The LUVOIR-B ECLIPS concept, on the other hand, makes use of the VVC’s superior performance on unobscured segmented pupils\(^9\),\(^10\) (in terms of inner working angle and throughput). Both the A and B ECLIPS concepts carry slots for alternative mask types in order to reduce risk, since different mask technologies tend to have complementary performance sensitivities. The Phased-Induced Amplitude Apodization (PIAA) coronagraph\(^11\)–\(^13\) is another promising coronagraph architecture for LUVOIR-B, though we do not analyze the LUVOIR-B PIAA performance in this paper.

The goal of ECLIPS is to perform direct imaging and characterization of potentially habitable extrasolar planets. The detectability of exoplanets in long coronagraph exposures depends on both the level of contrast achieved in the high-contrast region or dark zone of the focal plane, and on the throughput of the coronagraph at the apparent separation of the planets located between the inner working angle (IWA) and outer working angle (OWA). Given that the flux ratio between an Earth-like exoplanet and its parent star will be of order of \(10^{-10}\) in visible light, ECLIPS must produce a dark search zone where the starlight is nulled by a similar factor in intensity. Even after achieving such a deep contrast, the number of detectable exoplanets depends strongly on the IWA of this dark search zone.\(^14\) For this reason, the ECLIPS concepts for LUVOIR-A and -B are designed to access angular separations as low as, respectively, \(3.5 \lambda/D\) and \(2 \lambda/D\) from the star, equivalent to 34 and 36 milliarcsec on the sky at a wavelength of \(\lambda = 700\) nm.

Here we present the numerical model of the ECLIPS instrument for both LUVOIR-A and LUVOIR-B, which we use to evaluate the performance of the instrument as well as to simulate the effects of wavefront aberrations and their impact on coronagraph performance. First, in Section 2 we provide an overview of the coronagraph designs for ECLIPS. In Section 3 we evaluate the general performance of these designs under the assumption of a perfect telescope. In subsequent Section 4, we evaluate the sensitivity to telescope aberrations by simulating static and dynamic aberrations, as well as the wavefront sensing and control required to mitigate their effects. Finally, in Section 5 we present the first simulated observation of a planetary system with the LUVOIR-A ECLIPS instrument.

2. CORONAGRAPH DESIGNS FOR ECLIPS

The two main coronagraph designs envisioned for ECLIPS are an Apodized Pupil Lyot Coronagraph (APLC) for LUVOIR-A, and a Vector Vortex Coronagraph (VVC) for LUVOIR-B. The optical design for both cases is identical, and is shown unfolded in Fig.1. Further information can be found in Pueyo et al., in these proceedings.

We can divide the optical layout in two main parts: the wavefront control optics and the coronagraph optics. The wavefront control optics are comprised of two deformable mirrors (DMs) required to optimize the coronagraph performance in terms of wavefront sensing and control, as well as for apodization for the VVC design. The DM1 is in the pupil plane, while DM2 is at a distance \(z_{DM}\). For LUVOIR, the current design requires 128 x 128 actuators per DM in order to perform active wavefront control up to an OWA of \(64 \lambda/D\). However, for practical reasons (computational resources and maximum OWA of the masks used) the simulations

\(^1\)https://exoplanets.nasa.gov/exep/technology/SCDA/
Figure 1. Optical layout and principle of operation of the ECLIPS instrument. Starlight (orange) and planet light (blue) enter the optical system on-axis and off-axis, respectively. The wavefront control optics will apodize the incoming light and/or correct for telescope aberrations. The apodizer will further modulate the incoming light, before an OAP focuses it on the Focal Plane Mask. The stellar PSF is highly suppressed in a dark zone prescribed by the apodizer and/or DMs, while off-axis planet light propagates through the system, attenuated only by the apodizer and Lyot stop.

Presented here assume 64x64 actuators per DM. The coronagraph optics include the off-axis parabolic mirrors (in the figure represented as lenses) and the coronagraph masks: an apodizer, a focal plane mask (FPM) and a Lyot stop. Although the masks are different, the principle of operation is the same for APLC and VVC: the starlight (orange) enters the system on-axis. The combination of DMs and apodizer modulate the on-axis complex field such that the diffracted starlight in the FPM plane is concentrated outside the coronagraph dark zone (IWA-OWA region). The focal plane mask blocks the on-axis light, while off-axis planet light propagates through the system. The Lyot stop further suppresses residual starlight.

2.1 Apodized Pupil Lyot Coronagraph

An APLC suppresses starlight by propagating the optical beam through an apodizer, a focal plane occulting mask, and a Lyot stop.\textsuperscript{15} Following Fig. 1, at the relayed telescope pupil (apodizer plane), the field corresponding to the collimated on-axis starlight is modulated in amplitude by the apodizer, in this case a binary-valued transmission pattern. The light is then focused onto the focal plane mask (FPM) which occults the core of the stellar PSF. The diameter of the FPM determines determines the IWA of the coronagraph: an off-axis source situated outside the angular scale of the FPM propagates onward with minimal distortion. The beam is then re-collimated and modulated by the Lyot stop, before the final focus onto the detector. The apodizer transmission pattern is numerically optimized - with knowledge of the downstream FPM and Lyot stop - to produce a specified dark zone (contrast and spatial extent) while maximizing the transmission of the off-axis planet.\textsuperscript{16}

Fig. 2 shows the APLC masks for LUVOIR-A. Two sets of mask are shown: LUVOIR-A APLC Narrow and Wide, which cover a dark zone from 3.5 to 12 $\lambda/D$, and 7 to 27 $\lambda/D$ respectively. The narrow angle set of masks used here are designed for a 10% bandpass, while the wide angle masks are designed for an 18% bandpass.

One of the main advantages of APLC is its adaptability to arbitrary telescope aperture shapes.\textsuperscript{8} In our case, the primary mirror segment gaps and struts are taken into account by the apodizer profile. This relaxes the demands placed on the deformable mirror components in the wavefront control system, which can instead be dedicated to the compensation of aberrations and maintenance of the dark zone. In the current LUVOIR-A optical design, the separation between DMs is set to $z_{DM} = 0.8m$.

2.2 Vector Vortex Coronagraph

For the VVC, we assume a DM-only apodized design,\textsuperscript{17} that is, the DMs are actively used to create the desired apodization pattern. Following Fig. 1, the field corresponding to the collimated on-axis starlight is modulated in phase with the DMs, and in amplitude by the apodizer, in this case a circular aperture. The light is then focused onto the focal plane phase mask, which suppresses the diffraction from the central obscuration. The focal plane mask has a complex transmittance given by $\exp(il\theta)$, where $\theta$ is the azimuthal angle and $l$ is the charge. The DM shapes and masks for this design are shown in Fig. 3.
3. EVALUATION OF CORONAGRAPH DESIGNS

In order to study the performance of the LUVOIR-A APLC and its sensitivity to telescope aberrations we developed a model using a combination of the Python version of the PROPER Optical Propagation Library and FFTs/MFTs (Matrix Fourier Transforms). Our prescription is based on the ECLIPS Zemax optical design, but some simplifications have been made in order to fold the optical information into PROPER. Because PROPER does not model off-axis parabolic mirrors (OAPs), all the OAPs have been replaced by ideal lenses and their focal length modified accordingly as $f_{\text{lens}} = f_{\text{OAP}}/2$, where $f_{\text{OAP}}$ is the parent focal length of the OAP. Also, the model assumes the primary mirror is unpowered, and we artificially compress the input beam to match the size of the optics from the pupil plane (DM1) as $D_{\text{pupil}} = D_{\text{telescope}}/300$ for LUVOIR-A, and $D_{\text{pupil}} = D_{\text{telescope}}/160$ for LUVOIR-B. For the DMs, each actuator is represented by the default influence function distributed with the PROPER software package.

Given that the region of interest for coronagraph instruments for exo-Earth detection and characterization is near the IWA, we concentrate our analysis on the LUVOIR-A APLC narrow angle masks and VVC masks. Hence, unless otherwise specified, we will be referring to the APLC narrow angle masks as APLC masks.
The nominal contrast for the LUVOIR-A and LUVOIR-B coronagraph designs is shown in Fig. 4, as a function of angular separation in units of $\lambda/D$. For this simulation we have assumed 9 wavelengths per 10% bandpass, the effect of which can be clearly seen in the speckle pattern of the VVC design, outside the OWA. For LUVOIR-A, the contrast is more uniform within the dark zone, due to the fact that the apodizer accounts for the segment gaps and struts. For LUVOIR-B, one can notice the presence of speckles within the dark zone, located at the harmonic spatial frequencies associated to the segmentation pattern of the aperture. These speckles are due to the fact that the DM apodization is intrinsically chromatic. As a consequence, the nulling of the on-axis plane wave degrades towards the ends of the bandpass.

**Throughput**  We calculate the coronagraph throughput as the fraction of light from a planet within the core of its off-axis PSF, which is defined as the region circumscribed by its half-max contour. This metric ignores losses from filters, reflections, dichroics, etc., but accounts for coronagraphic mask losses (apodizer, Lyot stop and focal plane mask) as well as distortion to the off-axis PSF caused by those masks and the DMs.

Fig. 5 (left) shows the throughput for LUVOIR-A APLC Narrow angle and Wide angle masks, and LUVOIR-B VVC. Since the LUVOIR-B VVC does not use an apodizer mask and has a transmissive focal plane mask, its PSF throughput is significantly higher, more noticeably at small angular separations. For LUVOIR-A, although the throughput for the narrow angle set of masks reaches 15%, we can see a steep increase when switching to the wide angle masks. This effect is due to the APLC apodizer: the narrow angle apodizer is more opaque, which can be observed in Fig. 2.

**Distortion near the IWA**  Close to the IWA, not only does the throughput decrease, but the focal plane mask introduces a distortion in the centroid of the off-axis (planet) PSF. Fig. 5 shows the effect of the coronagraph around the IWA. For an APLC (center) the position distortion effect is more prominent due to the sharp edges of
the opaque occulting spot FPM, while for a VVC (right) the distortion is barely noticeable. We have computed this distortion by finding the center of mass of a planet PSF at a given sky offset.

**Sensitivity to Stellar Diameter** Any telescope as large as LUVOIR will partially resolve the nearby stars that it targets during exoplanet surveys. The finite angular extent of an occulted star tends to degrade the dark zone around the IWA of a coronagraph. Thus, the impact of stellar diameter on the performance of a given coronagraph is an important design consideration for ECLIPS. For this reason, we systematically evaluated the sensitivity of each coronagraph type to stellar diameter, computing the intensity leakage into the dark zone of the coronagraph instrument.

To simulate stars as extended sources, we approximate them as a uniform grid of plane waves filling a disk, and incoherently average their contribution in the final image plane. The sampling of the extended source is set to seven plane waves spanning the diameter of the star. We evaluate the sensitivity at four apparent angular diameters: 0 mas (for reference), 0.5 mas, 1.0 mas and 2.0 mas. For LUVOIR’s exo-Earth survey, we expect the angular sizes of most targeted stars to fall in the range of 0.5 to 1 mas. Fig. 6 summarizes the results of these trials. For both LUVOIR-A and LUVOIR-B we observe the effect of the star angular size causing starlight leakage in the dark zone near the IWA: the contrast degradation for the APLC design is of around $10\times$ for a 2.0 mas star, and around $3\times$ for a 1.0 mas star. For VVC we obtain similar results in terms of contrast degradation near the IWA. However, it must be noticed that the VVC IWA is $2\lambda/D$, which is more restrictive.

Figure 6. Coronagraph sensitivity to stellar diameter for LUVOIR-A APLC (left) and LUVOIR-B VVC (right). We assume diameters of 0.5, 1 and 2 mas, and 0 mas (nominal contrast) is shown for reference. The contrast degradation due to stellar leakage near the IWA is similar for both mask types.
4. CORONAGRAPH SENSITIVITY TO TELESCOPE ABERRATIONS

Up to this point, we have assumed the LUVOIR optics to be perfect. However, given the size and segmentation of the primary mirror, and the distance between the primary and secondary mirror, we expect to have wavefront aberrations induced by movement of these two mirrors as well as misalignments at a segment level. The effects of aberrations are wavelength-dependent, hence for the rest of this section we have locked the central wavelength at 575 nm. All the APLC results in this section refer to the APLC narrow angle masks.

Figure 7. Coronagraph sensitivity to global aberrations (left) and segment phasing errors (right) for the LUVOIR-A APLC design (top) and for the LUVOIR-B VVC design (bottom). Solid lines represent the average contrast in the full design dark zone, while dashed lines represent the average contrast of an annulus of 1λ/D width centered at 4λ/D. The LUVOIR designs are most sensitive to piton and tip/tilt segment phasing errors. For global aberrations, LUVOIR-A is most sensitive to spherical aberrations, while LUVOIR-B is most sensitive to trefoil, followed by spherical aberrations.

For a segmented primary mirror, we expect the most stringent wavefront requirements to originate in the alignment of the segments, particularly in piston and tip/tilt. We represent additional per-segment phase aberrations as Zernike modes. To quantify their impact, we generated a set of random per-segment Zernike aberrations from 1 picometer to 100 picometer total RMS wavefront error (random normal distribution), up to and including the spherical aberration mode. We then evaluated the mean contrast degradation in the final detector image for the two coronagraph designs. Fig. 7 (right) shows the resulting contrast degradation as a function of the root-mean-square (RMS) wavefront error.

We have studied two regimes: full dark zone (solid lines) and an annulus of 1λ/D width centered at 4λ/D to capture the effects of the aberrations near the IWA. For APLC, if we consider the full dark zone, the target contrast of 10^{-10} is maintained for piston and tip/tilt levels below approximately 10 picometers RMS, while we can tolerate higher levels or RMS for subsequent Zernike modes. For the VVC design, because the nominal contrast is above 10^{-10} due to the speckles in the nominal PSF, we study the RMS level at which the contrast starts degrading. As for the APLC, the tip/tilt and piston values are around 10 picometers RMS. To disentangle the effects of the different Zernike modes, it is easier to study the contrast degradation at the 4 λ/D annulus: in both cases we confirm that the coronagraph instrument is most sensitive to segment-to-segment piston and
tip-tilt errors. For APLC the contrast degradation at the 4 λ/D annulus is more prominent than for VVC with respect to their nominal values, which is due to the fact that this annulus is closer to the design IWA for APLC than for VVC.

Global aberrations can be present at the pupil plane due to the primary mirror itself or due to misalignments of the secondary mirror, as these translate to wavefront aberrations in the form of Zernike modes at the pupil plane. Fig. 7 (left) shows the contrast degradation as a function of the wavefront error for different types of global aberrations, in this case from 1 pm to 5 nm RMS wavefront error. For LUVOIR-A, the coronagraph is most sensitive to spherical aberrations: the contrast remains below $10^{-10}$ for a wavefront error below 55 picometers RMS. For LUVOIR-B, the contrast starts degrading first due to trefoil (around 10 pm wavefront RMS), followed by spherical aberrations (around 1 nm wavefront RMS). However, trefoil is not expected to be a significant global aberration for LUVOIR-B. The trefoil mode tends to occur when a three point connecting system is used, which is common for a conventional on-axis telescope, but not how an off-axis telescope like LUVOIR-B would be implemented.

### 4.1 Sensitivity to Static Aberrations

Even with state-of-the-art telescope design assumptions, the LUVOIR concept will not rely entirely on mechanisms built into the primary mirror to align the segments to within the 10-picometer tolerances suggested above. Instead, the ECLIPS instrument design – similar to the WFIRST Coronagraph Instrument – relies on a wavefront control system that includes a series of two deformable mirrors (DMs) to compensate for static aberrations originating in the primary mirror. In order to examine the capability of sensing static wavefront aberrations and correcting them with a 2-DM system, we expanded the LUVOIR model to include wavefront control based on the Electric Field Conjugation (EFC) method. Although this model\textsuperscript{20} can perform wavefront estimation via pair-wise sensing,\textsuperscript{21} in this section we have assumed perfect knowledge of the electric field at the detector plane to increase computational speed.

As described above, the segment-to-segment errors that dominate the contrast degradation are piston and tip/tilt rather than higher-order modes. To study the effectiveness of our wavefront control system we generated a set of wavefront error maps with equal levels of piston and tip/tilt contributions. It should be noted that in terms of total RMS wavefront error, the segment tip and tilt contributions add in quadrature.

![Figure 8. Evolution of the contrast per iteration of EFC, for different levels of wavefront RMS, for LUVOIR-A (left) and LUVOIR-B (right). EFC can correct nanometer levels of segment phasing errors.](image)

These wavefront error maps are fed into our model, and EFC is activated. The results obtained are shown in Fig. 8 as the evolution of the contrast, averaged in the dark zone, per iteration of the optimization algorithm. It can be observed that for wavefront errors of at least up to 7 nm RMS, our wavefront control system can correct the wavefront error and drive the dark zone to values below the $10^{-10}$ target for APLC, and to the nominal contrast for VVC, after 3 control iterations.

Fig. 9 shows the input wavefront error maps for LUVOIR-A (top-left) and LUVOIR-B (bottom-left), and the corresponding resulting aberrated PSFs before wavefront control has been applied. The initial aberrated...
Figure 9. Wavefront error correction with EFC. Example input phase error maps for LUVOIR-A (top-left) and LUVOIR-B (bottom-left). The aberrated field shows the contrast degradation due to the wavefront errors, around 5 orders of magnitude for LUVOIR-A and 4 orders of magnitude for LUVOIR-B. Applying the EFC solutions for the DMs (DM1 and DM2), the nominal contrast is recovered (right) for both coronagraph designs.

The contrast is 1.9e-5 for LUVOIR-A, and 6.4e-6 for LUVOIR-B. The difference in contrast resides in the OWA for both designs: for LUVOIR-A the averaged dark zone is narrower than for LUVOIR-B, capturing mainly the aberration contribution. Next, the DMs solutions are shown. For LUVOIR-B, it can be seen how the DM1 is attempting to conjugate the phase of the segments, and the DM1 stroke is larger than the DM2 stroke. This is because the aberrations present here are purely in phase, and DM2 is intended to correct mainly amplitude aberrations. For LUVOIR-A the DM stroke is more evenly distributed because the distance between the two DMs is shorter. It must be noticed that the DM solutions for LUVOIR-B do not include here the initial apodizing DM shapes, which must be added to obtain the corrected field (right).

4.2 Sensitivity to Dynamic Aberrations

Once the static aberrations have been mitigated with wavefront sensing and control techniques, we are left with the uncorrectable aberrations, these are, the dynamic aberrations that are too fast to correct for. For LUVOIR, edge sensors and laser metrology systems can be used to measure segment motions with picometer precision, providing a closed loop control system to maintain segment alignment stability. In a global scale, the main expected errors are in line-of-sight pointing. Within ECLIPS, pointing errors are sensed with the low-order or out-of-band wavefront sensor. Telescope pointing errors are also sensed by the High Definition Imager’s fine guidance mode. Fast pointing errors are corrected by the fast steering mirror, while slower pointing errors are corrected by the Vibration Isolation and Precision Pointing System (VIPPS).

In this section we analyze three forms of residual errors: the line of sight pointing errors and dynamic segment phasing errors, this is segment jitter and segment drift.

4.2.1 Line-of-Sight (LoS) Pointing errors

In order to model the line-of-sight (LoS) pointing errors we generate a random normal distribution of stellar offsets in the $x$ and $y$ direction with a given standard deviation $\sigma_{\text{LoS}}$. We have evaluated four values of $\sigma_{\text{LoS}}$: 0.1, 0.2, 0.5 and 1 mas. For LUVOIR, system requirements define a $\sigma_{\text{LoS}}$ of 0.3 mas.

Fig. 10 shows the results obtained after averaging 50 realizations per each $\sigma_{\text{LoS}}$ distribution. The $\Delta$Contrast shown is defined as the averaged PSF minus the nominal PSF. At $\sigma_{\text{LoS}}=0.2$ mas we can observe the effects of the pointing as starlight leakage in the dark zone. The effects are similar for LUVOIR-A (top row) and LUVOIR-B (bottom row), but are visually more noticeable for LUVOIR-A due to the narrower OWA.
4.2.2 Segment phasing errors – Jitter

To evaluate and quantify the system tolerance to dynamical segment phasing errors, specifically piston and tip/tilt, we have conducted a survey in which we assume 5 different levels of piston and tip/tilt from 2 pm to 100 pm (logarithmically scaled), and we combine them. We note that the resulting sensitivities depend strongly on the telescope design and the coronagraph architecture, the number of averaged wavefront realizations, as well as the dark zone IWA.

Figure 11. Contrast degradation due to different levels of piston and tip/tilt segment phasing errors for LUVOIR-A (top row) and LUVOIR-B (bottom row): piston only (left), tip/tilt only (center-left), and equal levels of piston and tip/tilt (center-right). The combination of piston and tip-tilt is evaluated in an $1/D$ annulus centered at $4/D$ from the star (right).
Fig. 11 illustrates the results of these trials. The phase error maps are simulated assuming a normal distribution of pistons and tip/tilts across the segments with a total global RMS wavefront error ranging from 2 pm to 100 pm. Per each combination of piston and tip/tilt level, the contrast degradation is calculated by averaging 20 intensity maps corresponding to 20 independent realizations of piston and tip/tilt error after subtracting the nominal intensity map (error free).

For piston-dominated phase error maps (first column of plots), we observe that in order to remain below the raw contrast target, the wavefront RMS should not exceed a few 10s of picometers (around 30 pm for LUVOIR-A, and around 15 pm for LUVOIR-B).

For tip/tilt dominated phase error maps (second column of plots), the tolerance is slightly higher. When we examine the PSFs obtained after equal levels of piston and tip/tilt errors (third column of plots) are combined, the morphology of the degraded PSF is dominated by the piston contribution. This suggests that segment piston errors are in general more critical in terms of contrast degradation.

Finally, in order to illustrate the effect of many different combinations of piston and tip/tilt level, we evaluated the ΔContrast for an annulus of 1 \( \lambda/D \) centered at 4 \( \lambda/D \) (right column of plots). The results are obtained after averaging 20 independent wavefront realizations. For LUVOIR-A, in order to achieve the raw contrast goal near the IWA, the maximum allowed wavefront RMS induced by piston and tip/tilt is around 20 pm and 50 pm, respectively. For LUVOIR-B, these values are around 15 pm for piston and 20 pm for tip/tilt.

Figure 12. ΔContrast due to different levels of piston and tip/tilt segment jitter for LUVOIR-A (left) and LUVOIR-B (right).

Fig. 12 shows examples of the final intensity maps as ΔContrast for different levels of piston and tip/tilt segment jitter, for LUVOIR-A (left) and LUVOIR-B (right). Segment jitter has caused the speckles introduced by each realization to be averaged, hence appearing as a halo at the final intensity maps. For LUVOIR-B, we can clearly see the effects of the segmentation of the primary mirror.

4.3 Segment phasing errors – Drift

To model the effects of segment drift, we assume the initial phase state of the primary mirror to be perfect, with zero phase errors. We then define the final phase state of the primary mirror as a normal random distribution of piston and tip/tilt values per segment. We simulate the drift by scaling the wavefront error RMS between the initial and final phase state (10 realizations), and average the resulting intensity maps. We do this for 8 combinations of piston and tip/tilt values, which result in final wavefront RMS from around 3 pm up to around 150 pm.
Fig. 13 shows the final intensity map in units of contrast for two examples of segment drift and the azimuthal standard deviation of the contrast variation \( \Delta \text{Contrast} \). Observing the azimuthal standard deviation of the \( \Delta \text{Contrast} \), we can see that in order to maintain the contrast degradation below 10\(^{-10}\) from 3.5 \( \lambda / D \) onwards the wavefront error RMS should not surpass 10–15 pm.

One of the effects of segment drift that can compromise observations is the fact that the speckles generated in the dark zone due to these aberrations are quasi-static, and more complex post-processing techniques will have to be used to correct for them. In contrast, we can see that this is not an issue in the case of segment jitter shown in Fig. 12, because different speckle patterns are averaged and appear as a halo at the final intensity map, shown there as \( \Delta \text{Contrast} \).

### 5. SIMULATED OBSERVATIONS

To simulate the observational capabilities of the LUVOIR-A APLC coronagraph, we use a Haystacks model of the “modern” Solar System as a test scene.\(^{22}\) Haystacks models encode time-dependent positions and orbital phases of a given planet system architecture, with wavelength-dependent albedos, scattered light from debris structures, and background stars and galaxies. These public Solar System scene models\(^1\) are stored in the form of FITS cubes containing high-resolution spatial and spectral data from 0.3 to 2.5 \( \mu \text{m} \).

For the simulation shown in this section, we combine two LUVOIR-A APLC masks, labeled respectively narrow- and wide-angle, with respective dark zones 3.5–12 \( \lambda / D \) and 6.7–26.9 \( \lambda / D \), and respective bandpasses of 10% and 18%. We place our twin Solar System at a distance of 12.5 parsecs, and image the system in three bandpasses centered at 600nm, 700nm and 800nm. At this distance, the LUVOIR-A APLC narrow angle mask has an inner working angle of 0.4 AU projected separation from the star at a wavelength of 600 nm. Therefore, this observing mode can easily detect the Venus analog, as shown in Fig. 14. The outer working angle of the wide-angle mask simulated here translates to 3.2 AU projected separation. With this Haystack scene’s combination of observing epoch and inclination angle (60 degrees), the Jupiter analog is situated near the edge of the wide-angle dark zone.

One of the essential intermediate steps in the construction of the coronagraph scene is to convolve the Haystacks irradiance distribution with the field-dependent coronagraph PSF. Fig. 14 (right) shows an example for the narrow-angle mask, where the star has been removed, so that all of the intensity is due to the planets and circumstellar debris. The PSF-convolved coronagraph image is represented here in units of photon count rate on the detector, and does not include any noise. The scattered light from the debris model appears as an extended, diffuse source concentrated near the edge of the APLC occulting spot.

\(^{1}\)https://asd.gsfc.nasa.gov/projects/haystacks
In order to add the effects of residual starlight to the coronagraph image, we must set the wavefront error assumptions. First, the star is assumed to have an apparent angular diameter of 0.75 mas, consistent with a G-dwarf at the 12.5 pc target distance. We assume the residual RMS line-of-sight pointing error is 0.2 mas, which is combined with a primary segment jitter (piston and tip/tilt) that introduces a total wavefront error RMS of approximately 10 pm per instantaneous realization. To simulate the time series, we average the intensity maps resulting from 50 independent realizations of segment phasing errors and line-of-sight pointing errors distributions.

In order to enable differential imaging to mitigate the residual starlight as well as scattered light from the debris disk, we simulate images acquired at two observatory roll angles spaced apart by 27 degrees. Later, we apply simple roll subtraction to the noisy co-added images.

Fig. 15 shows the images obtained in each wavelength channel, after detector noise has been included and roll-subtraction has been performed. We assumed values of QE, dark current, and read noise consistent with the
EMCCD design parameters baselined for ECLIPS. The total integration time is 60 hours split in 17 hours, 19 hours and 24 hours for the 600 nm, 700 nm and 800 nm channel, respectively. This total integration time, which includes the observation with the two APLC masks and the two observatory rolls per channel, also includes 25% overheads to account for cosmic ray data losses. The wavelength dependence in the IWA and OWA can be clearly seen: for the 600 nm channel, the wide angle masks can observe Jupiter only partially, while for the 800 nm channel Venus has been attenuated by the occulting mask. Earth is detected in each of the wavelength channels with an SNR of 14, 12, and 9 at 600, 700, and 800 nm, respectively.

Finally, we combined the reduced coronagraph images from the three bandpasses from Fig. 15 to generate the RGB composite shown in Fig. 16. The colors at the edge of the field of view illustrate the dependence of OWA on wavelength. While this data simulation is preliminary and not based on a fully integrated structural-thermal-optical performance (STOP) model, it gives us confidence that a mission like LUVOIR could detect exo-Earths around nearby stars with high enough SNR to perform spectroscopy and characterize their atmospheres.

![Simulated image of a twin Solar System at a distance of 12.5 pc observed through the LUVOIR-A ECLIPS instrument. This RGB image is a composite of data acquired in two APLC masks (with respective working angles 3.5–12 $\lambda/D$ and 7–27 $\lambda/D$) in three bandpasses (red – 800 nm; green – 700 nm; blue – 600 nm) at two observatory roll angles (27 degrees apart) over the course of 60 hours of total integration time. The coronagraph images were simulated with a diffraction model time series that includes 10 picometers of primary mirror segment jitter (random piston and tip-tilt errors applied to each mirror segment), 0.2 mas residual line-of-sight pointing jitter, and a stellar diameter of 0.75 mas. The input astrophysical scene is a model of a 'modern' Solar System inclined at 60 degrees, with an exozodiacal debris disk. In this scene, the Earth-like planet is observed at quadrature, appearing as a blue dot at 1 AU projected separation, to the right of the occulted star. Roll subtraction processing was used to remove starlight speckles from the 'raw' co-added images. The residual structure of the exozodiacal disk – distorted by the roll subtraction – appears as a horizontally-extended diffuse cloud.](image)

6. CONCLUSIONS

In this paper we have presented the coronagraph designs envisioned for the LUVOIR-A and LUVOIR-B ECLIPS instrument, an APLC and VVC, respectively, and evaluated their performance. Both designs offer similar performance in terms of sensitivity to stellar angular size and wavefront errors.

We performed a systematic aberration sensitivity analysis, evaluating both global and segment-level wavefront errors, for static and dynamic cases. By simulating the full high-order wavefront sensing and control loop, we conclude that ECLIPS can compensate for static wavefront aberrations up to several nanometers due to segment
level phasing errors. With respect to dynamic wavefront aberrations, both designs maintain their target contrast of $10^{-10}$ with segment jitter wavefront error levels in the range 15–20 pm.

Finally, 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. We will continue to investigate various levels and combinations of telescope wavefront errors and drifts, as well as instrument optical train aberrations. Future work will extend the simulations to include integral field spectroscopy data and retrieval of planet atmosphere properties.

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References


