

Introduction and motivation

Imaging exoplanets is challenging because they orbit stars which are vastly brighter. A coronagraph instrument can be used to block off starlight while still letting through planet light. The goal of the Habitable Worlds Observatory (HWO) is to image Earth-like exoplanets orbiting Sun-like stars. These kind of planets are usually around 10^{-10} fainter than their host stars, so in order to detect them the coronagraph needs to achieve a comparable level of instrumental contrast.

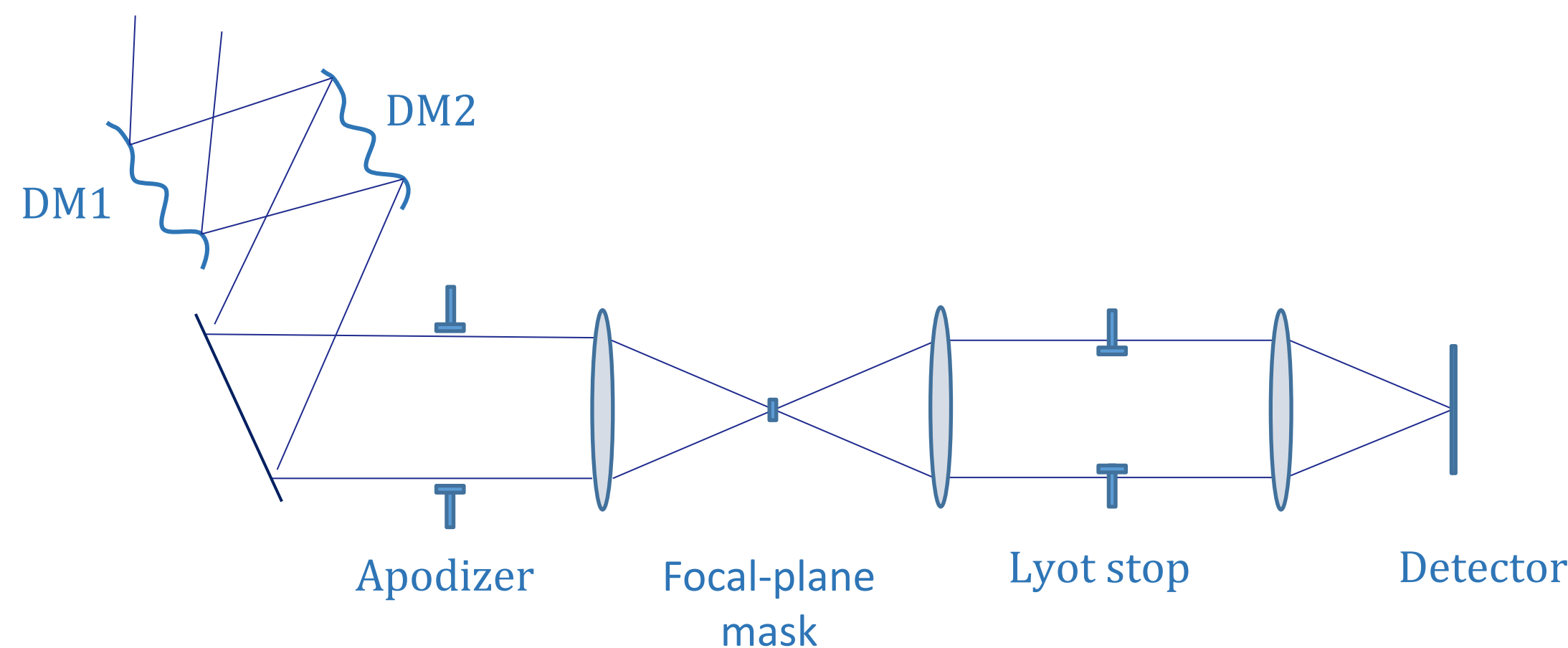


Figure 1. Schematic representation of a Lyot-type coronagraph. The telescope exit pupil is imaged onto the in-pupil deformable mirror (DM1), which, together with the out-of-pupil deformable mirror (DM2), corrects for optical aberrations that generate speckle noise at the detector.

The contrast level that can be achieved with a coronagraph instrument, such as the one depicted in Fig. 1, is limited by optical aberrations. These errors are corrected via a combination of active control using deformable mirrors (DMs) and subtraction of residual starlight with image postprocessing techniques. The objective of this project is to explore and compare the robustness of two classical postprocessing techniques, Reference Star Differential Imaging (RDI) and Angular Differential Imaging (ADI), to temporal wavefront error instabilities.

System parameters and assumptions

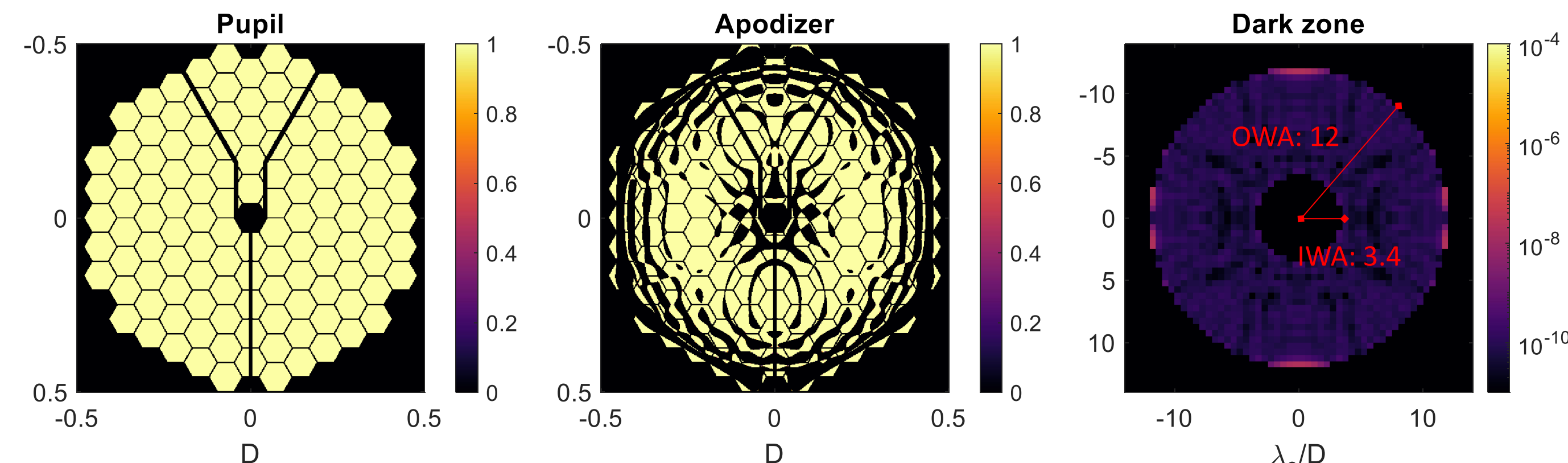


Figure 2. LUVOR-A apodized-pupil Lyot coronagraph (APLC) coronagraph (left and center) and output image (right) with inner working angle (IWA) of $3.4 \lambda_0/D$ and outer working angle (OWA) of $12 \lambda_0/D$

- Two identical DMs with 48x48 actuators each
- Electron-multiplying CCD (EMCCD) detector model
- Flat spectrum with $\lambda_0 = 500$ nm and 10% bandwidth
- Telescope diameter: 6 m (assumed for photometry)
- Target star: Kappa Ceti ($m = 4.84$, $T = 5708K$)

Aberrations

We simulated time varying phase-only aberrations placed in the pupil plane. We simulated Zernike aberrations of radial orders 2-4 (Z4 - Z15), which excludes piston, tip and tilt. The aberrations vary with time according to a Gaussian random process with tunable drift rate.

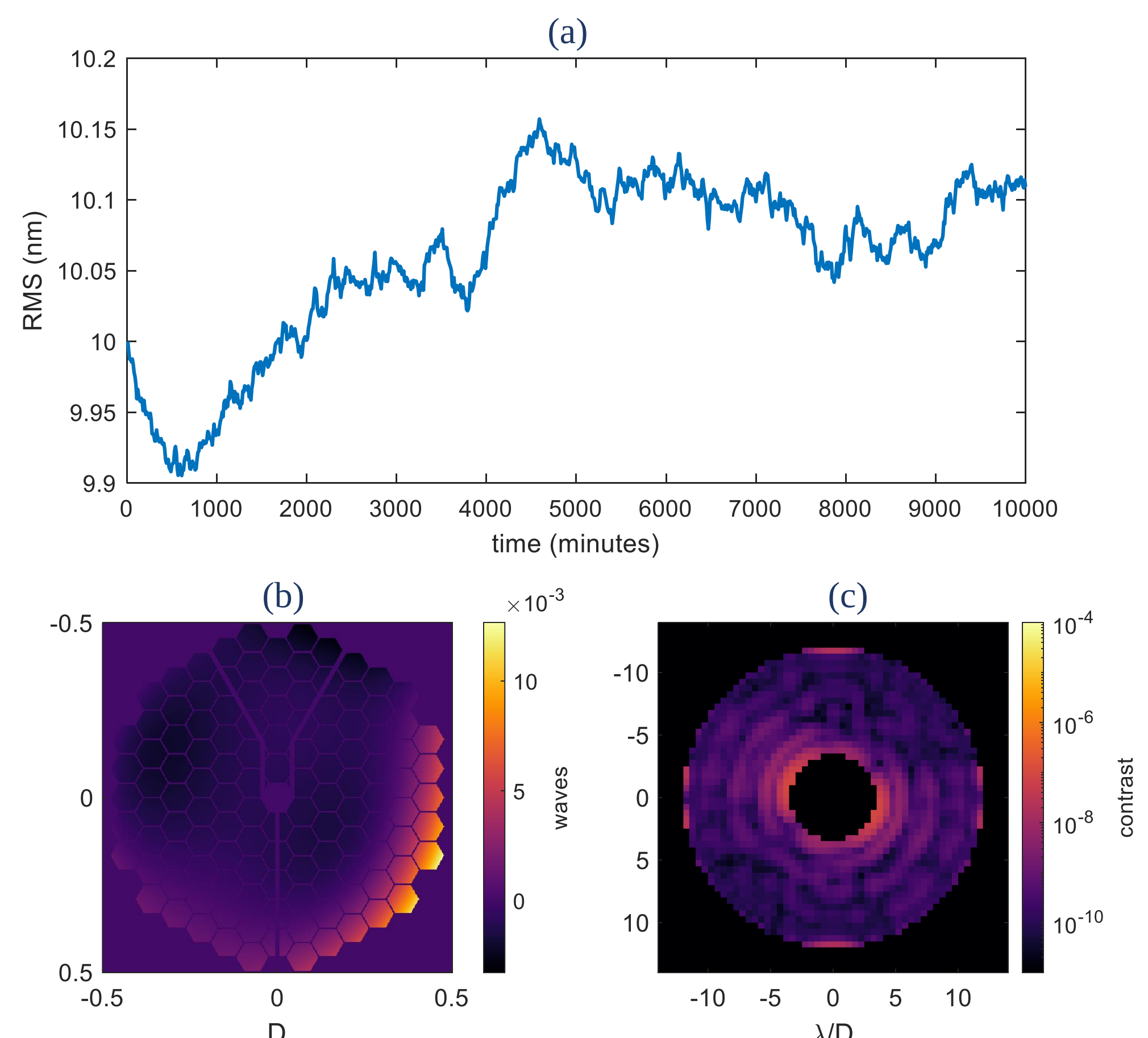


Figure 3. (a) Simulated time evolution of pupil-plane wavefront error using a Gaussian random process model. The starting wavefront error is fixed to 10 nm RMS over the open part of the telescope exit pupil, and changes by 10 pm RMS per 10 minutes. (b) Zernike aberrations at time zero in the pupil plane and, (c) resulting noiseless coronagraph image.

Wavefront control with EFC

Electric field conjugation (EFC) [1] can be used to iteratively change the deformable mirror (DM) surface shape to conjugate aberrations and obtain a higher contrast. We simulated wavefront (WF) control with EFC and pairwise probing [2]. We assumed that the star is an unresolved point source without a planet companion. These simulations include aberrations with an initial magnitude of 10 nm RMS and varying through time with a tunable drift rate.

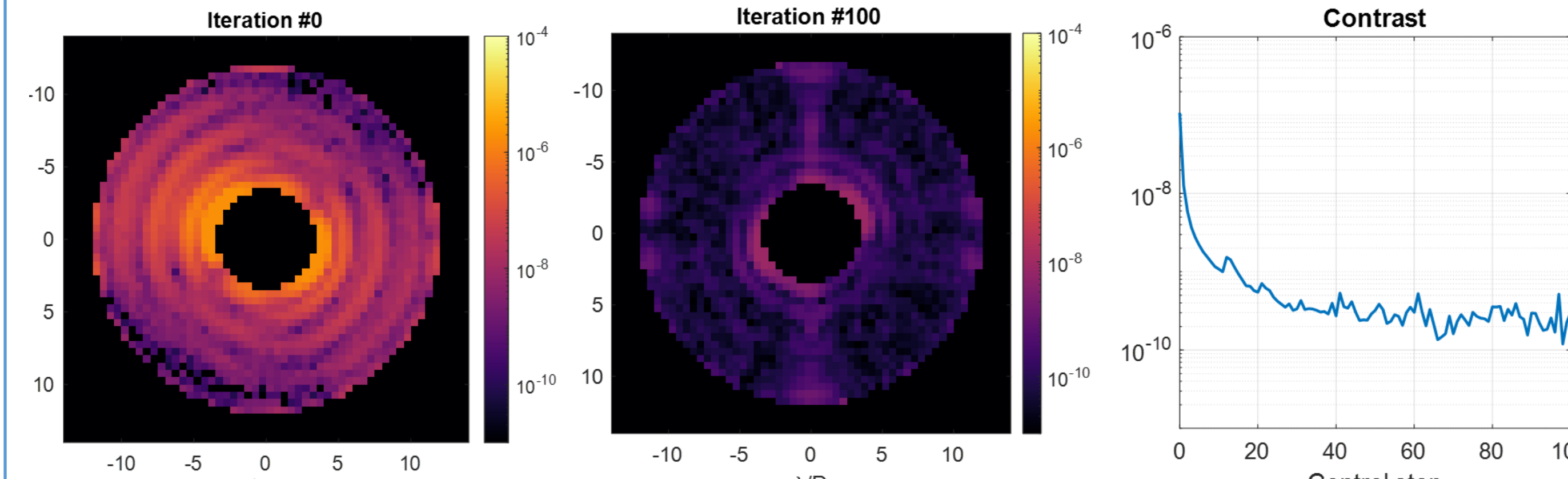


Figure 4. Coronagraph images before (left) and after (center) 100 time steps of closed-loop wavefront control using EFC and pairwise probing, with 10 pm RMS wavefront drift per 10 minutes, along with plot of mean contrast vs. control time step (right).

The final contrast level achievable by wavefront control is affected by wavefront drift. As the control loop reaches deeper contrast levels, the exposure times required to achieve adequate SNR in pairwise probing images increase, leading to greater impact of wavefront drift on sensing performance.

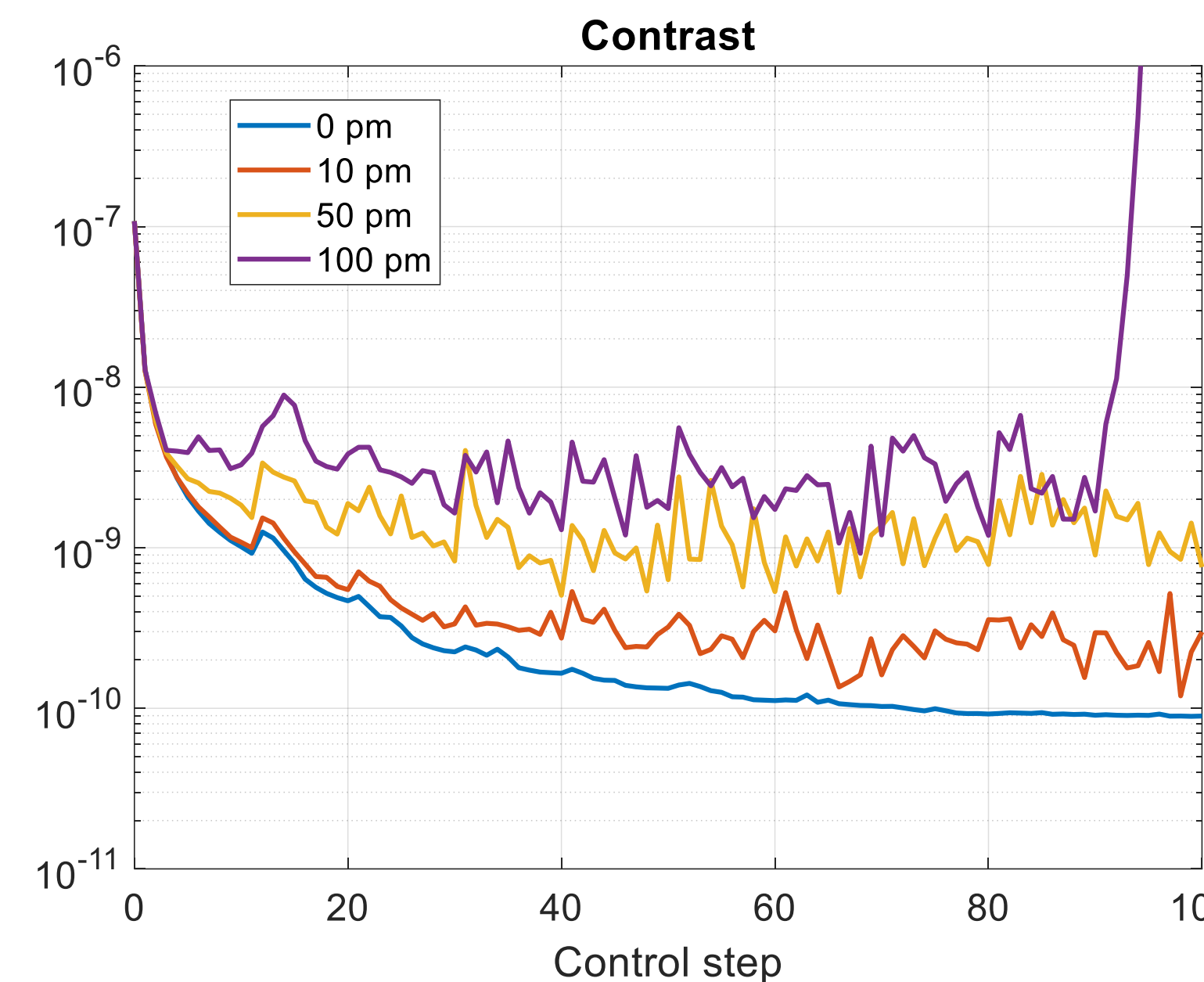


Figure 5. Mean contrast over 100 iterations of EFC with different amounts of wavefront drift per 10 minutes.

Reference star differential imaging (RDI) [3]

This PSF subtraction technique consists of obtaining a PSF estimate by observing a reference star without a companion. The estimate is then subtracted from the image of a target star, containing a combination of planet light and residual starlight. Ideally, the difference of the two images consists solely of the desired planet signal and photon noise. However, due to wavefront drifts over time, the reference star (left) and target star images (center) differ slightly, leading to degraded subtraction performance (right).

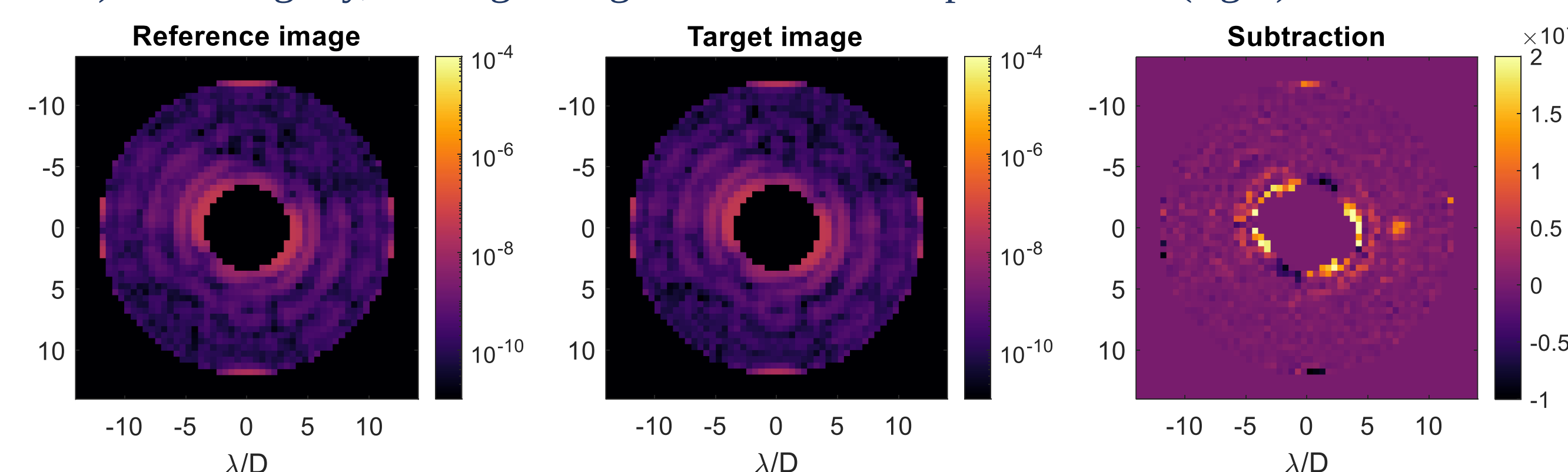


Figure 6. Example simulation of RDI with WF drift. For case with 10 pm WF drift per 10 minutes. Note that subtraction results here and in the following figures are shown on a linear scale. The planet has a contrast of 10^{-9} and is located at $7.5 \lambda/D$ to the right of the origin.

We simulated reference and target images assuming both stars are unresolved point sources with identical spectra. The target image contains a planet of contrast 10^{-9} . Each image was acquired with an exposure time of 7.5 hours (total time: 15 hours). The simulations below assume time-varying Zernike aberrations starting at an RMS of 1 nm, and with different amounts of wavefront drift.

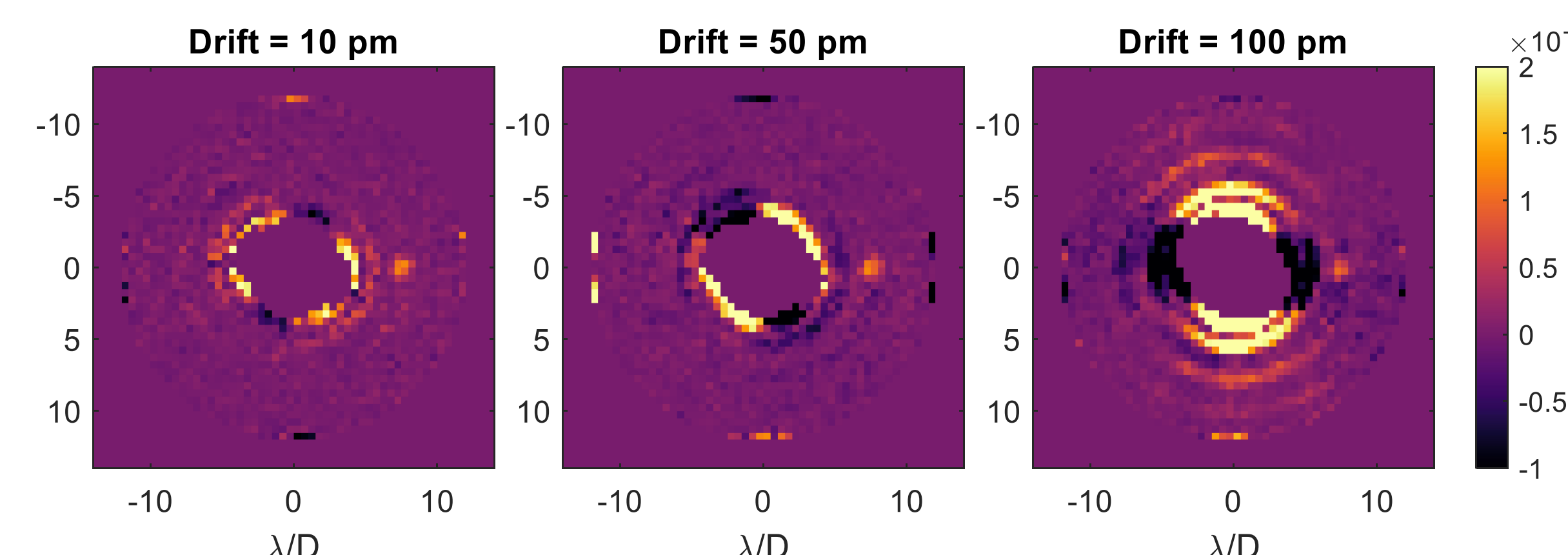


Figure 7. Final image after RDI for different amounts of wavefront drift per 10 minutes. The subtraction performance gets worse with a higher wavefront drift rate since there are larger differences between the target and reference images.

It is important to note that these simulations assume a single reference and target image. If one had a collection of images, as might be the case if a reference star was used to dig the dark zone, then the results that could be obtained should be better. Another important consideration is that these simulations assume identical stars. This might not be true in reality, and that might introduce additional errors.

Angular differential imaging (ADI)

ADI [4] consists of rotating the telescope and taking short exposure images at different angles. A reference PSF is constructed from this collection of images and subtracted from each image. Then the images are aligned with respect to the planet and recombined by taking the median, resulting in the final reduced image.

Marois et al. [4] devised two methods to obtain the reference PSF from the collection of images, as well as a third one that combined both methods. We simulated the original two methods as well as a modified combined method; these are as follows:

- Method 1: Calculate the median of all images
- Method 2: Calculate the median of the four images closest in time where the planet has moved at least 1.5 FWHM
- Method 3: First subtract the median of all images, then use the Locally Optimized Combination of Images (LOCI) algorithm [5] with the four images closest in time

We simulated 90 images containing a planet of contrast 10^{-9} with different FOV angles. Each image was acquired with an exposure time of 10 minutes (total time: 15 hours). These simulations include the same time-varying Zernike aberrations used in the RDI simulation.

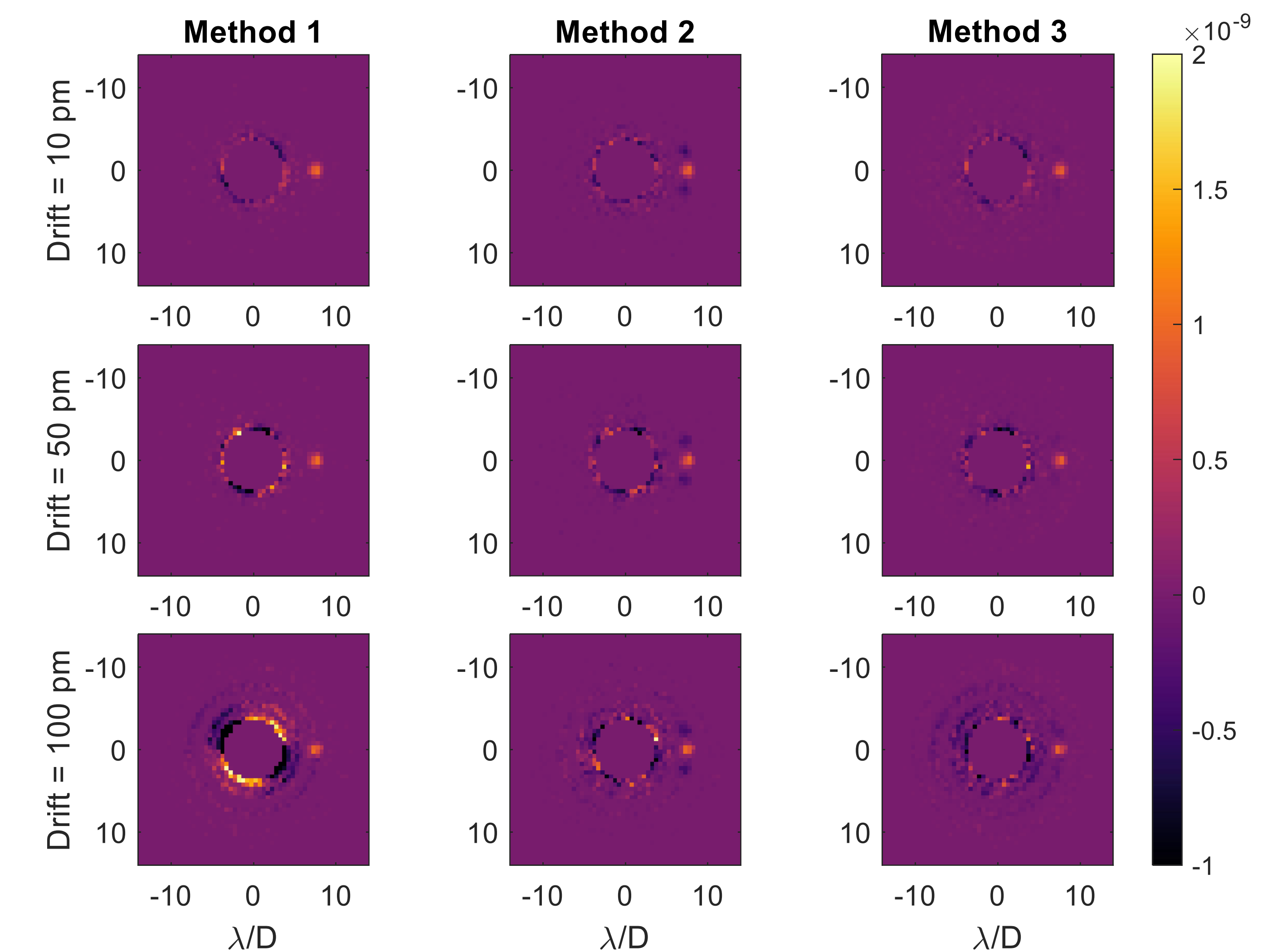


Figure 8. ADI results for all 3 methods, for different amounts of wavefront drift

Conclusion

For these simulations, ADI gave better results than RDI for the same total time. This may be due, in part, to the fact that for ADI every exposure has light from the planet whereas for RDI only half of the exposures have light from the planet. Wavefront drift limits the results that are achievable with both RDI and ADI; however, ADI seems to be less affected by it than RDI. Even with a high amount of drift, ADI is able to obtain reasonable results, especially for methods 2 and 3. These simulations help explore the limitations of these techniques, which is important to understand in order to determine what their performance would be like for an HWO-like observing scenario. Our next steps will be to perform a rigorous evaluation of performance through statistical measures, update the coronagraph design, and investigate PSF calibration approaches informed by forward modeling.

References

- [1] Give'on, Amir, et al. "Broadband wavefront correction algorithm for high-contrast imaging systems." *Astronomical Adaptive Optics Systems and Applications III*. Vol. 6691. SPIE, 2007.
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- [5] Lafreniere, David, et al. "A new algorithm for point-spread function subtraction in high-contrast imaging: a demonstration with angular differential imaging." *The Astrophysical Journal* 660.1 (2007): 770.

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