Astro2020 APC Whitepaper

Relaxing Stability Requirements on Future Exoplanet Coronagraphic Imaging Missions

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Abstract:

Several future observatory proposals incorporate coronagraphs for exoplanet imaging and spectroscopy. This addresses one of the top priorities of NASA astrophysics. In particular, a key science goal of both HabEx and LUVOIR is the discovery and characterization of Earthlike planets in the habitable zone of nearby, sunlike stars. The baseline operational approach in these missions to using a coronagraph with wavefront control is to generate the dark hole by pointing to a bright reference star, slew to the target star, and perform a long science integration with occasional slews back to the reference star to obtain reference PSFs. Post-processing is then performed using a library of PSFs to separate out the planet. The fundamental effectiveness of this approach is limited by instabilities in the optical system. The result has been tight requirements on wavefront stability, in the 10s of picometers, with an accompanying increase in cost and development. In this white paper we present an alternative, algorithmic approach that involves dithering the deformable mirrors to separate planet light from speckles. We show that using this approach allows for a significant relaxation of requirements, of up to 2 orders of magnitude or more, on observatory stability. This brings the stability requirements into the range of the current JWST segment drift requirements, suggesting that no new engineering development may be necessary for these future missions. We hope that this will be considered in evaluating these future mission concepts.

Introduction

The last decade has seen enormous progress in the design and testing of coronagraphic techniques for achieving the high contrast needed to detect and characterize exoplanets down to Earth size (where a contrast of 1e-10 is needed). This progress has relied on advances in coronagraph design and manufacturing, in algorithms and approaches to wavefront sensing and control, and in post-processing techniques for extracting the planet signal from the residual speckle halo (Mazoyer et al. 2019, Pueyo et al. 2019). Two of the large mission studies chartered by NASA, HabEx and LUVOIR, employ coronagraphs to achieve the needed high contrast along with advanced post-processing for identifying the planet and taking spectra (Gaudi et al. 2019, Roberge et al. 2019). The WFIRST mission Coronagraph Instrument (CGI) will demonstrate in-space high-contrast imaging using two different types of coronagraphs along with high-format deformable mirrors to correct the residual aberrations, proving the capability before the decade is out.

Each of these mission concepts and instruments share a common operational approach. The telescope is pointed at a bright reference star to enable fast wavefront control to establish the "dark hole" where planets can be seen and then slewed to a target star for a long science observation during which no control is performed. Intermittently during the observation the telescope is slewed back to the reference star to obtain reference point spread functions (PSFs). This set of PSFs is then used in a post-processing algorithm (known as Reference Differential Imaging) that decomposes the images using a principle component analysis to enable the most effective PSF subtraction over the observation (Soummer et al. 2012). Assuming very low speckle drift and long integrations, this subtraction can reveal planets from factors of 2 to 10 below the residual halo. (Another approach, Angular Differential Imaging, is commonly used on the ground and is planned for CGI. This involves rotating the spacecraft to differentiate speckles from planets; however, it is much less effective for close-in planets such as exo-Earths.)

Because no control is performed during the observation, strict requirements are placed on the stability of the telescope optical system. While the KLIP process can track small changes in the aberrations, large and rapid instabilities quickly outpace the ability to perform PSF subtraction. As a result, robust coronagraphs are needed that are maximally insensitive to changes in the wavefront and extremely stable telescopes are required. Coronagraphs cannot reject the dynamic, mid-spatial-frequency aberrations from segment drift without also rejecting planet light at the same location. Current plans call for segment-to-segment stabilities in the 10's of picometers (Gaudi et al. 2019, Roberge et al. 2019, Shaklan et al. 2019). In particular, simulations and studies have found that for large, segmented primaries, segment drift of more than 100 pm in 10 hours renders PSF subtraction ineffective, even with KLIP (Shaklan et al. 2019).

In the remainder of this short white paper we summarize new results that allow for significant relaxation of these tight stability requirements (Pogorelyuk et al. 2019, 2019a). Rather than perform long science observations with no control, we perform control continuously during the science observation, what we call "dark hole maintenance". We accomplish this by "dithering" the deformable mirrors (DMs) to modulate the signal and make the electric field observable. This DM motion also causes speckles to move while having no impact on the planet PSF. By incorporating an Extended Kalman Filter for estimation we can separate the stellar electric field from the planet signal. The resulting sequence of control signals and electric field estimates are then post-processed using a maximum likelihood estimator to determine the planet intensity (Pogorelyuk et al. 2019). To improve efficiency we use a variation of the principle component analysis that expands the estimated electric field rather than the intensity to reduce the order of the estimator (Pogorelyuk et al. 2019a). Altogether, these techniques outperform KLIP in identifying the planets even with wavefront drifts relaxed by more than 20 times current requirements. While it is the case that performing dark hole maintenance during observations is common on the ground, it so far has not been planned for space observatories due to the very low photon count when operating at such high contrast. Other concepts for overcoming this to do continuous control have been proposed (such as Linear Dark Field Control) but they suffer from non-common path errors. Here, dithering the DM enables control with no additional hardware or observatory overhead and it simultaneously performs the processing needed to estimate the planet signal.

While certainly more research is needed and lab demonstrations are currently underway at Princeton, these simulated results show that the tight stability requirements–and thus the cost– of future planned missions can likely be relaxed using only new algorithms. No changes would be needed to the coronagraph or observatory designs.

Simulation results

For brevity the details of the algorithms will not be presented here (see Pogorelyuk et al. 2019, 2019a). In this section, we show the results of recent simulations using the open source software package FALCO to model wavefront drift and control for the LUVOIR mission concept (Riggs et al. 2018). We use the same software and models to simulate the segment drift of the primary LUVOIR mirror as in the LUVOIR and SCDA studies. We wrap our estimation and control algorithm using DM dither commands around FALCO for the closed loop simulation. We then use the history of electric field estimates and DM commands to perform a maximum likelihood fit to each pixel, revealing the planet PSF.

To simplify the simulation, we only performed control at two wavelengths simultaneously (522 nm and 577 nm). For the post-processing step we only used the data from the 522 nm wavelength (all results below are images at the single 522 nm wavelength). Image frames were taken every 100 sec. We assumed a photon counting camera with a dark current of 0.25 photons/pixel/frame. A typical target star magnitude was chosen such that for the off-axis LUVOIR observatory we could expect an average of 1 photon per pixel per frame. Two planets were injected, one at 20 \lambda/D with a flux ratio to the star of 2e-10 and one at 9 \lambda/D with a flux ratio of 2.4e-10. Figure 1 shows the perfect PSF of the target star, which has chromatic satellite spots remaining from the primary mirror segmentation. Figure 2 shows the two injected planets without the stellar PSF (units are in photons per 100 sec frame).

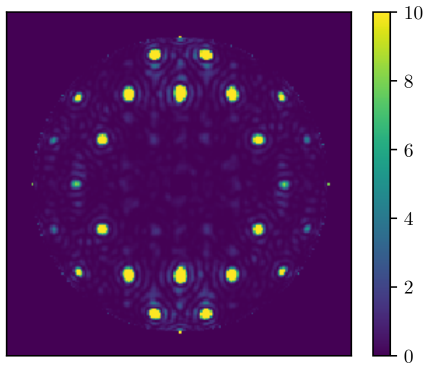

Figure 1: Ideal LUVOIR PSF. (Units are photons per 100 sec frame.)

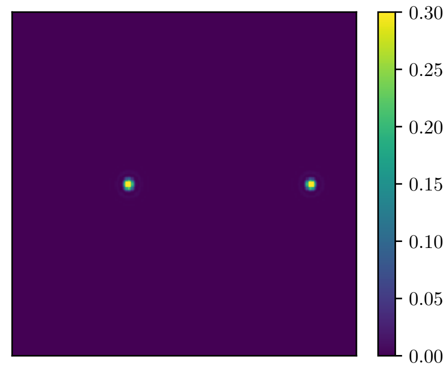

Figure 2: Injected planets at 9 and 20 lambda/D. (Units are photons per 100 sec frame.)

Figure 3 shows the results of a perfect system where the PSF is exactly known and subtracted after 360 frames (no segment drifts). The two planets are clearly visible. In contrast, Figure 4 shows the same simulation with PSF subtraction but the segments are allowed to drift (as a random walk) at a rate of 100 pm per 360 frames RMS. This is the upper limit of stability requirements on LUVOIR. The planets are still visible though the residual speckle is much brighter.

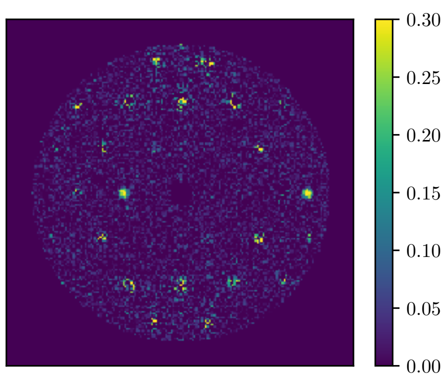

Figure 3: PSF subtracted image assuming perfect PSF. Planets are visible at 9 and 20 lambda/D. (Units are photons per 100 sec frame.)

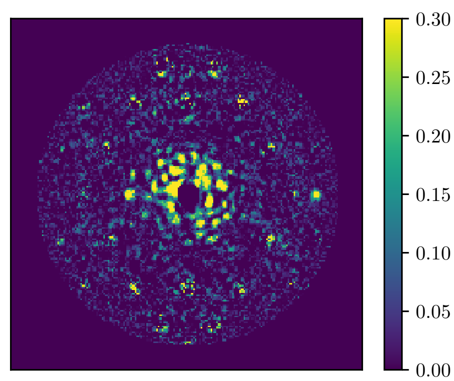

Figure 4: PSF subtracted image assuming 100 pm per 10 hour wavefront drift. (Units are photons per 100 sec frame.)

For the remaining simulations we substantially increase the segment drift to 600 pm per 360 frames and 2 nm per 360 frames as representative examples of looser requirements. Figure 5 shows a segment phase map from FALCO for the 600 pm drift case (units in nm). Figure 6 shows the resulting PSF after 10 hours with 600 pm RMS segment drift. Figure 7 shows the resulting contrast drift due to the drift of the stellar speckles without control (red) and with control (blue) using our DM dithering approach (dark hole paper). By using dithering and continuous dark hole maintenance, the algorithm maintains the contrast slightly below the initial level even with large segment drifts. It is also noteworthy that the chosen planet contrast is over a factor of 4 below the residual speckle halo.

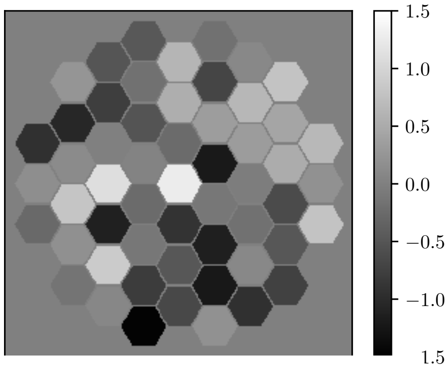

Figure 5: LUVOIR segment phase map after 600 pm drift in 10 hours (in nm).

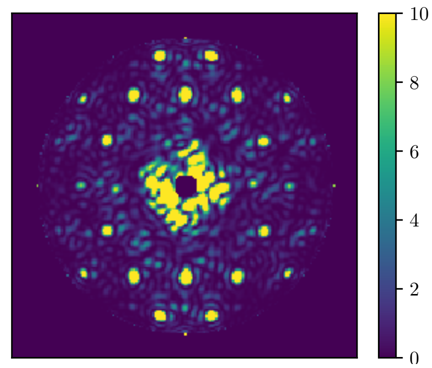

Figure 6: LUVOIR PSF after 10 hours with 600 pm drift. (Units are photons per 100 sec frame.)

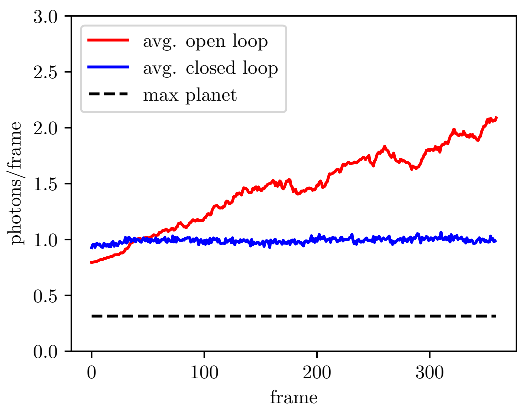

Figure 7: Contrast drift (averaged over all pixels) in units of photons per 100 sec frame with and without closed loop control. Planet intensity shown for reference.

We next apply the KLIP algorithm on the open loop data to attempt to extract the planet and compare to the maximum likelihood approach with dithering. Figure 8 shows the residual after PSF subtraction on the open loop data (600 pm drift over 360 frames) using KLIP. An additional 3 observations of 360 frames each were made on a reference star to build the PSF library of roughly 100 reference PSFs (the star was 16 times brighter than the target). The planet at 20 \lambda/D is just visible while the one at 9 \lambda/D is impossible to detect.

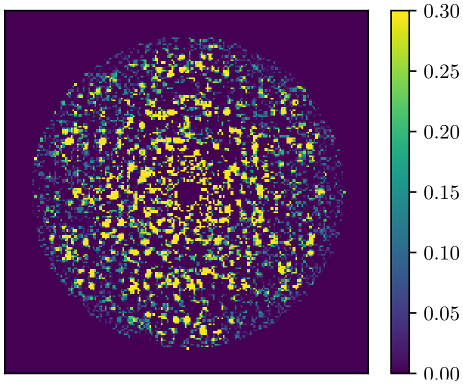

Figure 8: Residual speckle field after KLIP on open loop data with 600 pm per 10 hour drift. (Units are photons per 100 sec frame.)

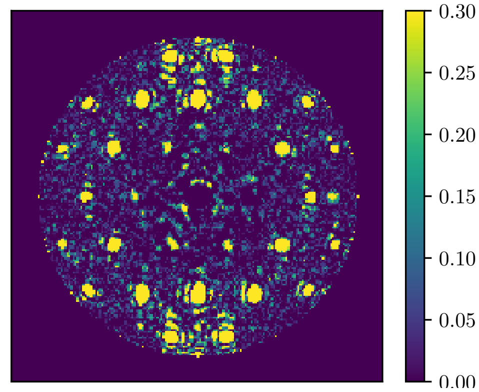

Figure 9: Estimated residual intensity using EFOR with 600 pm per 10 hour drift. Planets are visible at 9 and 20 lambda/D. (Units are photons per 100 sec frame.)

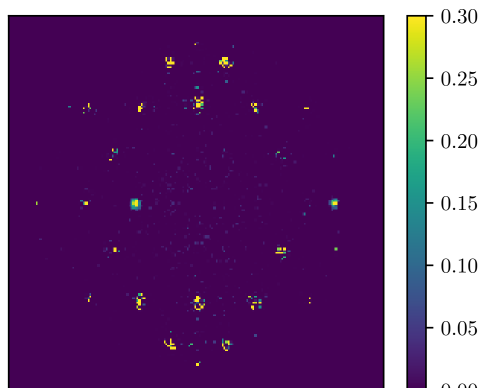

Figure 10: Residual intensity using EFOR without reference images. Planets are visible at 9 and 20 lambda/D. (Units are photons per 100 sec frame.)

In contrast, Figure 9 shows the result of using the dark hole maintenance algorithm with dither and Electric Field Order Reduction (EFOR) for post-processing the closed loop data, assuming the same 600 pm drift over 360 frames. Here, we also include 3 *closed-loop* reference observations of the bright star. (See Pogorelyuk et al. 2019 for how reference PSF images can be included in the post-processing.) Both planets are visible. Note that the satellite PSFs due to the segment gaps are also estimated as part of the processing. These reference spots can be used as astrometric references in a similar fashion as currently done on the ground.

One of the advantages of the dark hole maintenance with dither and EFOR is the ability to estimate the planet even without reference PSFs. The planet can be distinguished simply because it doesn't vary with dither. This removes the risk associated with of thermally-induced wavefront drift associated with slewing the telescope, but at the cost of longer integration times. Figure 10 shows the result of using EFOR with no reference images but a 40 hour integration (with the same 600 pm per 360 frames). Both planets are clearly visible.

As an extreme case, we repeated the simulations with a 2 nm drift per 360 frames. Figure 11 shows the open loop contrast drift compared to the closed loop. As before, the planet is a factor of 5 or so below the residual halo after initial correction. Figure 12 shows the results of using KLIP with three additional observations. The planet signals are buried well below the residual speckle floor. Figure 13 shows the results of EFOR with three reference observations. The planets are still clearly visible amid the satellite PSFs.

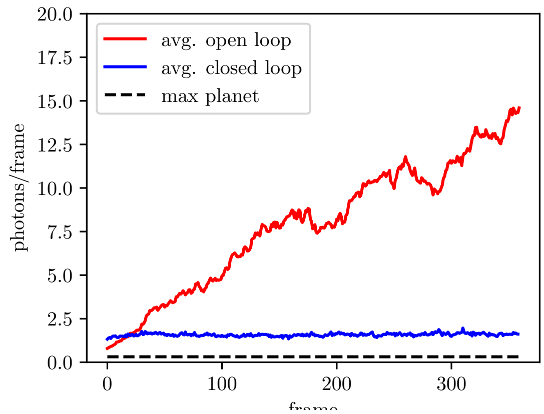

Figure 11: Open and closed loop contrast for 2 nm per 10 hours drift.

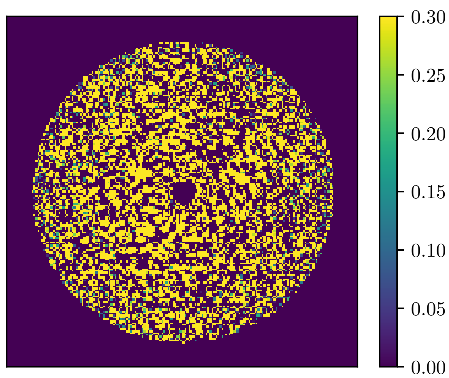

Figure 12: Residual speckle field after KLIP on open loop data with 600 pm per 10 hour drift. (Units are photons per 100 sec frame.)

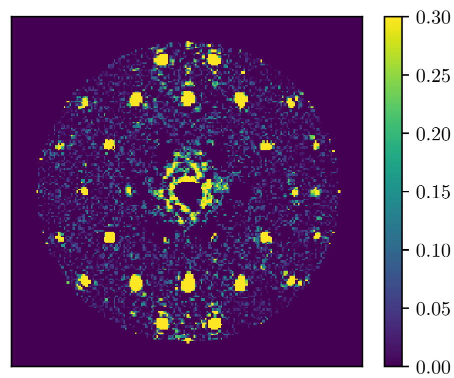

Figure 13: Estimated residual intensity using EFOR with 600 pm per 10 hour drift. Planets are visible at 9 and 20 lambda/D. (Units are photons per 100 sec frame.)

Summary

One of several factors driving the cost of future large exoplanet imaging missions is the tight stability requirement on the optical system. With the classical approach of long integrations and PSF subtraction, stability requirements on the order of 10s of picometers are needed. Using the same simulation tools and models that were used to predict performance for LUVOIR and HabEx, we presented here promising results that demonstrate it is possible to track a planet even with speckle changes due to drifts that are over an order of magnitude larger than current requirements (and 2 orders of magnitude more than the desired level). This would bring the stability requirements of future observatories within range of the current capability on JSWT (Perrin et al. 2018), suggesting that no new engineering development may be necessary. The result would be a significant reduction in cost. Lab experiments are currently underway at Princeton to verify the simulation results. We hope that in evaluating future mission concepts, the added robustness this approach potentially provides and the resulting reduction in cost will be considered.

References

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