Focal-plane wavefront sensors for direct exoplanet imaging: theory, simulations and on-sky demonstrations

Bos, S.P.

8 | Outlook

The current generation of HCI instruments will continue to target young giant gas planets after their upgrade programs (Beuzit et al., 2018; Chilcote et al., 2018). One of the key upgrades are focal-plane wavefront sensors to address non-common path aberrations. Several focal-plane wavefront sensors have been successfully tested on-sky (Chapter 2, 4, and 6; Bottom et al. 2017; Galicher et al. 2019; Huby et al. 2017; Martinache et al. 2016, 2014; Wilby et al. 2017). However, they have not been used during science observations, except for QACITS (Huby et al., 2017), making it difficult to assess the impact of focal-plane wavefront sensing on the post-processed contrast. Therefore, to assess the impact of focal-plane wavefront sensing on the end-to-end system performance (including post-processing), on-sky testing during science observations should be a prime test for the immediate future.
Current ground-based HCI instruments have been unsuccessful in detecting exoplanet variability due to speckle noise. The VSG concept, presented in Chapter 7, is a new concept to dramatically increase the signal-to-noise ratio of exoplanet variability measurements with HCI instruments. Combining the VSG concept with alternating the position of the artificial speckles, as presented in Sahoo et al. (2020), by rotating the optic's mount between images is a promising solution to reach the required photometric precision. When this is implemented at HCI instruments, it will open up an exciting new avenue to study the variability of already directly-imaged exoplanets.

The long term goal of high-contrast imaging is the detection and characterization of rocky exoplanets in the habitable zone of nearby stars, and look for signs of life. An important part of this future are the next generation of Giant Segmented Mirror Telescopes (GSMTs), such as the Extremely Large Telescope (ELT; Gilmozzi & Spyromilio 2007), the Thirty Meter Telescope (TMT; Nelson & Sanders 2008), and the Giant Magellan Telescope (GMT; Johns et al. 2012). These telescopes have primary mirrors with diameters between 25 and 39 meter, resulting in a tremendous increase in light-gathering power and angular resolution compared to current telescopes. Therefore it is expected that GMSTs will acquire the first spectra of rocky habitable exoplanets around M-type main sequence stars by means of direct imaging (Guyon et al., 2012).
Due to the massive support structures required to support the secondary mirrors of GSMTs, which can be the size of a current 4-meter class telescope, it is expected that the low-wind effect will play a dominant role in their wavefront error budget (Holzlöhner & Brinkmann, 2020). Furthermore, these telescopes have segmented primary mirrors, and the segments have to be carefully co-phased to reach their ultimate performance (Quirós-Pacheco et al., 2018). The island effect will limit the most common pupil-plane based wavefront sensors in dealing with these problems. Focal-plane wavefront sensors do not have this limitation as they do not sense in the pupil plane and are therefore among the prime solutions for these issues. Especially for the Fast&Furious focal-plane wavefront sensing algorithm (F&F; Chapter 6) there is a big opportunity to step in and provide the wavefront sensing solution. We have proven on sky that F&F is able to deal with the LWE, and are currently testing it on sky at the segmented Keck telescope, as shown in Figure 8.1.

GSMTs will host high-contrast imaging instruments that are expected to image and char-

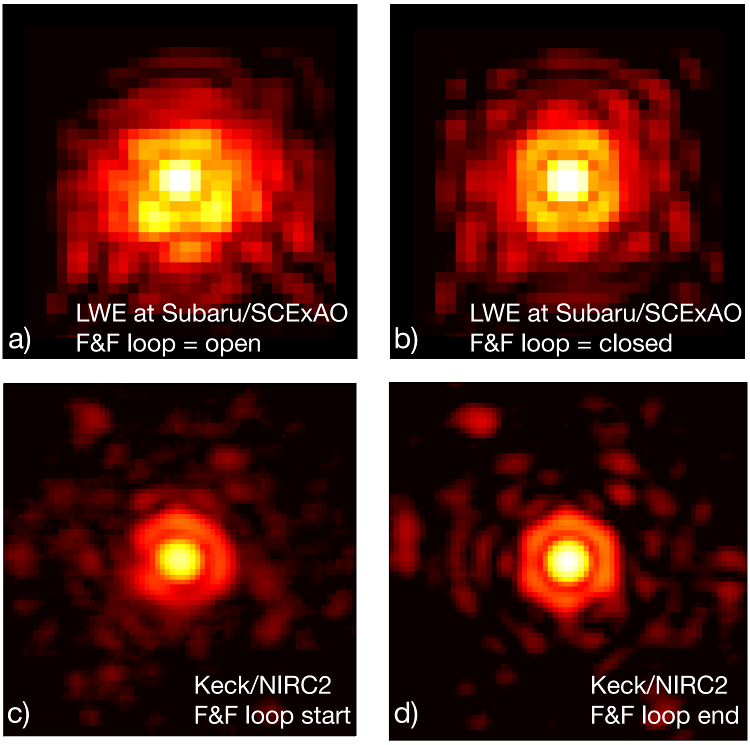

Figure 8.1: On-sky F&F tests at Subaru/SCExAO and Keck/NIRC2. The average PSF during a LWE event at Subaru/SCExAO when the F&F loop was a) open and b) closed. Tests at Keck/NIRC2 for low-order aberration correction with F&F, c) start and d) end of the correction loop. Collaborators of the Keck/NIRC2 tests are M. Bottom, J. Delorme, S. Ragland, S. Cetre, and L. Pueyo. The images are shown in log scale.

acterize rocky exoplanets in the habitable zone of nearby stars. Instruments under consideration are the Exo-Planet Imaging Camera and Spectrograph (EPICS; Kasper et al. 2010) for the ELT and the Planetary Systems Imager (PSI; Fitzgerald et al. 2019) for the TMT. The Mid-Infrared ELT Imager and Spectrograph instrument (METIS; Carlomagno et al. 2020) is already under construction for the ELT, and will try to image the closest exoplanet Proxima b. To reach the extreme contrasts at small angular separations required to image a rocky exoplanet, it is of the utmost importance that the entire HCI instrument is optimized as a whole, and not per individual subsystem. The work presented in this thesis provides such integrated solutions. We have shown that the vAPP coronagraph can be integrated with focal-plane wavefront sensing in Chapters 2, 3 and 4. Furthermore, it has been shown that the vAPP is suitable for broadband coronagraphic imaging (Otten et al., 2014), and can be combined with polarimetry (Bos et al., 2018; Snik et al., 2014). It is possible to combine all these functionalities, and a first design for such a vAPP is presented in Bos et al. (2020). In Chapter 5 we have presented the PESCC – a combination of focal-plane coronagraphy with focal-plane wavefront sensing. As detailed in Chapter 5, the PESCC encodes wavefront information into one of the polarization states, and therefore many of the necessary components for polarimetry are already in place. This presents a unique opportunity to combine coronagraphy, focal-plane wavefront sensing and control, coherent differential imaging and polarimetry, which will enable the direct imaging and characterization of rocky exoplanets in the habitable zone.

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