The photonic lantern wavefront sensor: on-sky and lab demonstration of photonic focal plane wavefront sensing, PSF reconstruction and single-mode fiber-injection with machine learning

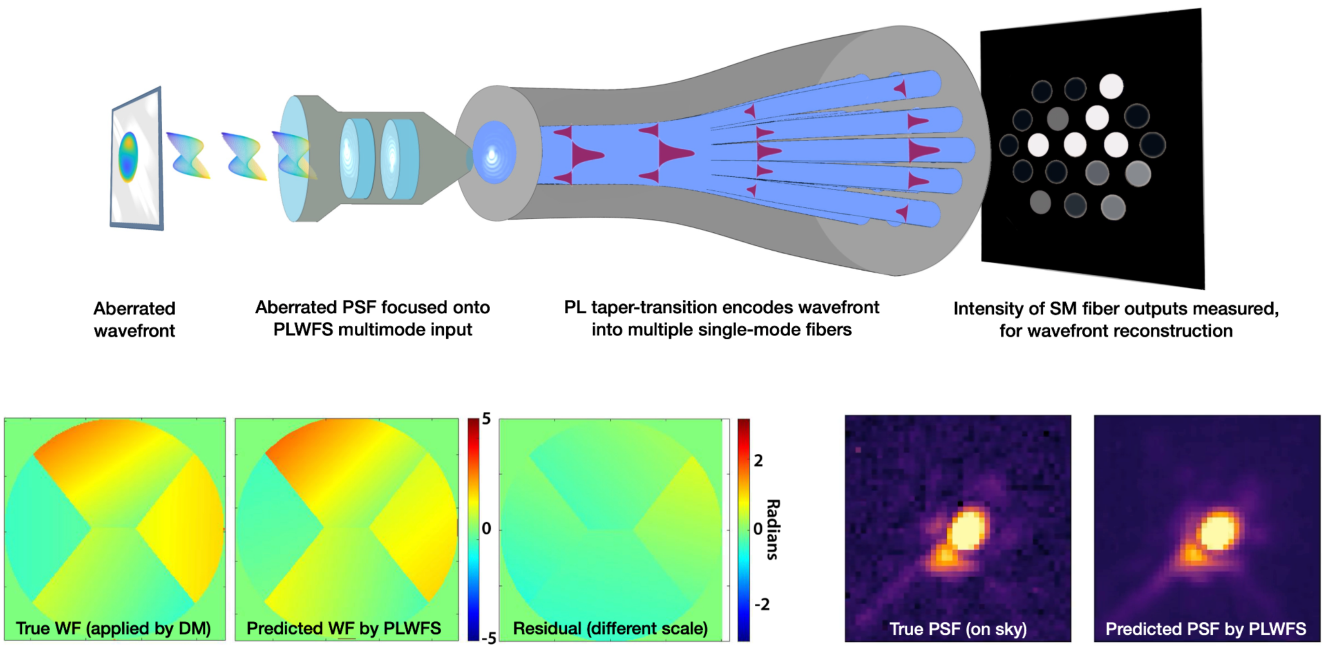
A focal plane wavefront sensor offers major advantages in AO, including removal of non-common-path aberrations and providing sensitivity to blind modes (especially low-wind-effect / petalling modes). This is especially important for ELTs, with petalling anticipated to be an important issue. But simply using the observed PSF is not sufficient for wavefront correction, as only the intensity, not phase, is measured.

Here we present the use of an all-photonic device, the photonic lantern wavefront sensor (PLWFS), to sample the PSF's phase and amplitude directly. The device encodes the PSF's complex wavefront information into the intensities of a single-mode fiber output array. Although the encoding function is very stable, it must be learned empirically. Linear control systems can perform this for smaller wavefront errors (*see abstract from Jonathan Lin*), but a different approach is required for larger wavefront errors as the encoding becomes non-linear.

We thus demonstrate the use of a neural network to reconstruct the wavefront using the PLWFS, both in-lab and on-sky with SCExAO at the Subaru Telescope. Accurate reconstruction of petalling and low-order modes, and closed-loop correction, is shown. The PLWFS also optimizes detector usage, needing only one pixel per mode, and output fibers can be easily spectrally dispersed to resolve degeneracies from phase wrapping/scintillation. It could be invaluable in phasing up ELT mirrors, and the PLWFS fits in a standard fiber connector, ideal for MOAO.

We also describe the use of the PLWFS to optimally inject starlight into a single-mode fiber, as desired for single-mode spectroscopy and long-baseline interferometry. A hybrid mode-selective photonic lantern injects starlight into the fundamental mode and uses higher order modes for wavefront sensing. The fundamental mode is then mapped over a wide bandwidth into a single output fiber fed to the science instrument. Wavefront-sensing fibers drive the AO loop to maintain maximum injection, forming a truly zero-non-common-path wavefront sensor.

We also demonstrate on-sky PSF reconstruction using the photonic lantern. Finally, we explore the next step - measurement of spatial coherence, phase, and amplitude for full image reconstruction. This disentangles wavefront error/speckle from true astronomical signals, enabling full diffraction-limited performance of an ELT.



Top: Conceptual diagram of the PLWFS. The multimode end of the device is placed at the focal plane, and PSF amplitude and phase information is encoded into the intensities of its single mode outputs. **Bottom-left:** Example wavefront reconstruction by the PLWFS in a lab-test, with low-wind-effect modes applied via the DM. **Bottom-right:** Example instantaneous PSF reconstruction by the PLWFS for an on-sky observation at Subaru Telescope.