Pyramid wavefront sensor with laser guide star: Photon noise and convolutional model

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Abstract

The new generation of Extremely Large Telescopes (ELTs) will be dependent on artificial laser guide stars (LGS)
for their adaptive optics correction systems, given the lack of enough natural guide stars (NGS) to have a good sky
coverage. Due to their large mirror diameter, and the cilinder-like structure of the artificial sodium laser stars, instead
of having a point source as reference, the image of the artificial star is a 3D object more than three hundred times wider
than a diffraction limited spot and over five thousand times larger. On an 80x80 Shack-Hartmann wavefront sensor
(SH) for a 40 meter telescope, the laser spot is four times wider and as much as sixty times larger than a diffraction
limited spot. This extension means that the SH's detector needs to have a large amount of pixels (e.g. 1600x1600),
making it slow and noisy.
Given the difficulties of the SH, the Pyramid wavefront sensor (PWFS) has been proposed as an alternative, given
its higher sensitivity and lower demand on pixels, as an equivalent 80x80 PWFS would need a detector no bigger than
240x240 pixels, making it possible to use fast, low noise detectors. One of the problems with the PWFS is the depth of
focus of the telescope. As the sodium layer where the LGS is generated is about 20 km thick, and the laser beam has
a width of 1 arc-second, different portions of the LGS reach the pyramid with different tip, tilt and focus coefficients,
hindering the measurements of the atmospheric disturbances.
In this work, a study of closed loop operations was made to compare the performance of the PWFS for different
sources: NGS, LGS FWHM spot on sky (1 arcsec spot with no thickness)(LGS-SOS) and LGS, and different telescope
sizes: 8, 16, 24 and 40 m. The main focus of this research was to test the influence of photon noise in closed loop

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operation and to compare the end to end (E2E) results with predictions using linear models. To do this, a new method of simulating Fourier filtering wavefront sensors (FFWFS) with LGS was developed, which speeds up the computation over sixty times when compared to traditional methods. Also, a convolutional model (CMod) was validated and then implemented to further speed up the simulations.

We found that using the CMod we could compute the interaction matrix (iMat) for every source up to one thousand times faster than compared to the E2E method, allowing us to estimate the photon noise sensitivity and optimize the reconstructor matrix for each case. Then, comparing the E2E closed loop simulations to the sensitivity analysis we found a good agreement, meaning that it is possible to estimate the performance of the AO system by only computing the iMat using the CMod and not having to do all the E2E simulations. Finally, we found that the limiting magnitude for a LGS does not increase as the telescope gets bigger, and the main contributor to the lost sensitivity is the width of the laser, rather than the thickness of the sodium layer.

Keywords: AO, Pyramid, LGS, Convolutional