The low-order wavefront control system for the PICTURE-C mission: Preliminary testbed results from the Shack-Hartmann sensor

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INTRODUCTION

PICTURE-C: Planetary Imaging Concept Testbed Using a Recoverable Experiment – Coronagraph

Mission Overview: Directly image debris disks and interplanetary dust in three nearby star systems at visible wavelengths (600 nm with 20% bandwidth)

Deployment Vehicle: High-altitude balloon (~40km)

Two Flights: June 2018, September 2019

Flight Duration: <12 Hours

Raw Contrast Goal Flight 1: 10^{-4}
Raw Contrast Goal Flight 2: 10^{-7}

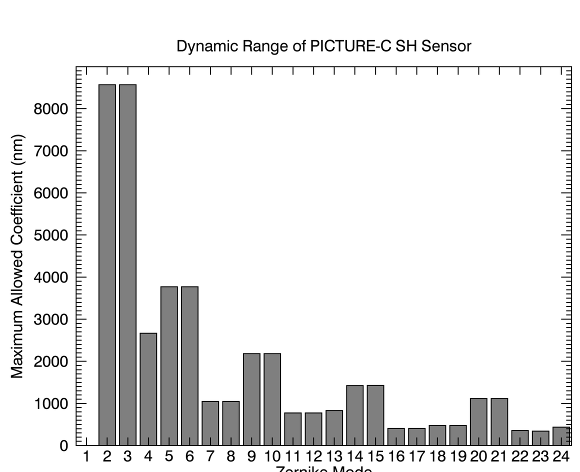
Inner Working Angle (IWA): 1.7 λ/D

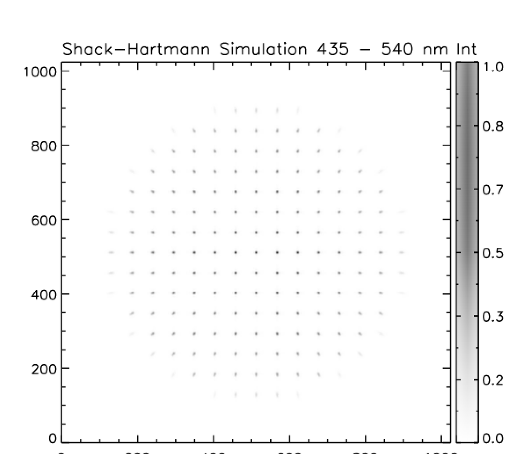
Wavefront Control and Coronagraph (FL1):
6-axis stage for M1-M2 alignment (Hexapod)
76-actuator DM with tip/tilt control (IWC)
Charge 4 vector vortex coronagraph[1]
Low-order Shack-Hartmann (SH) wavefront sensor
Low-order reflective Lyot wavefront sensor[2,3]

Dynamic Range of SH Sensor: ~30 µm
Dynamic Range of Lyot Sensor: ~20 nm

BACKGROUND

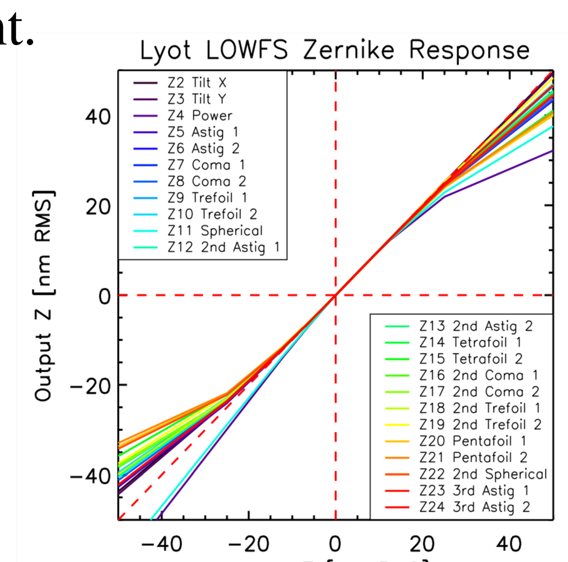
SH Requirement:
Control wavefront error to ±20 nm RMS





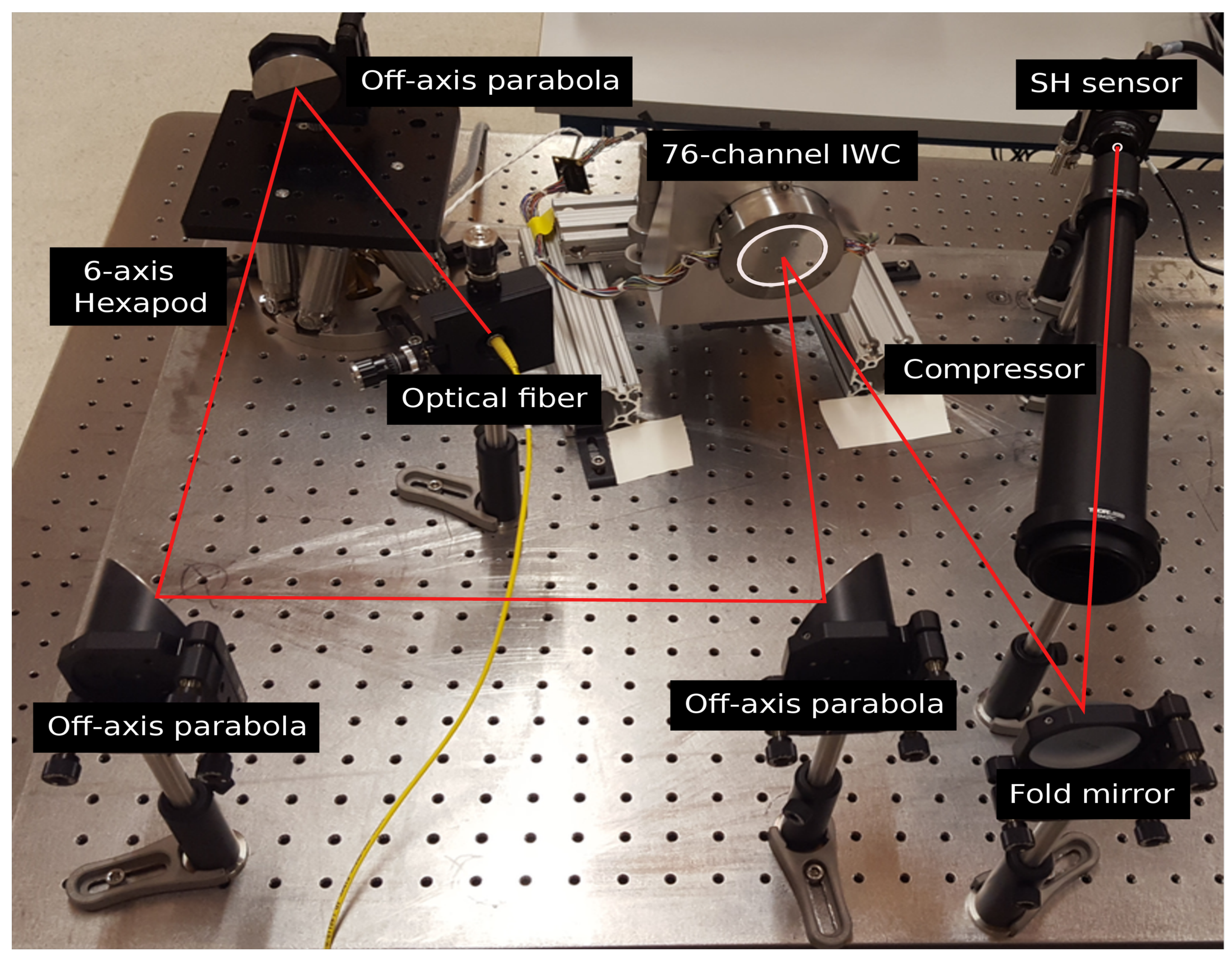
Above Left: Independent dynamic range of Zernike modes for the PICTURE-C SH sensor. **Above Right:** A simulated image of the PICTURE-C spotfield pattern produced by the SH sensor. 154 spots are used to measure the wavefront.

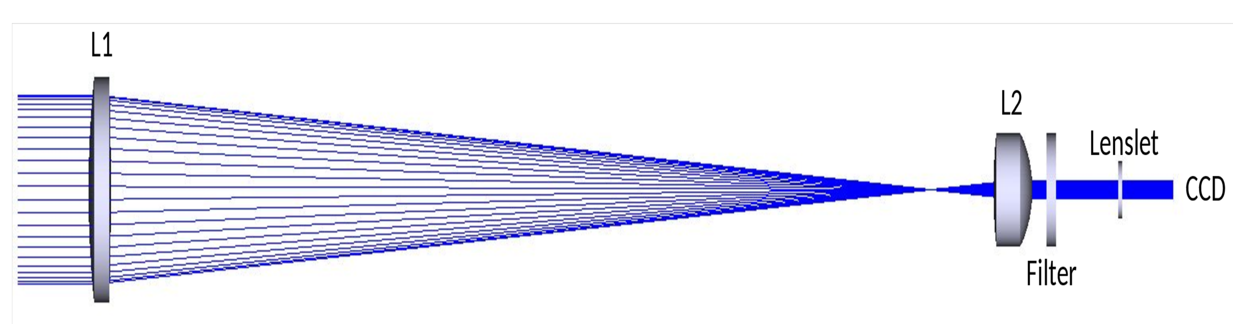
Right: The dynamic range of the high-precision Lyot wavefront sensor (±20 nm linear region) sets the control requirement for the SH sensor. Figure from (Mendillo, 2015).[3]



METHODS

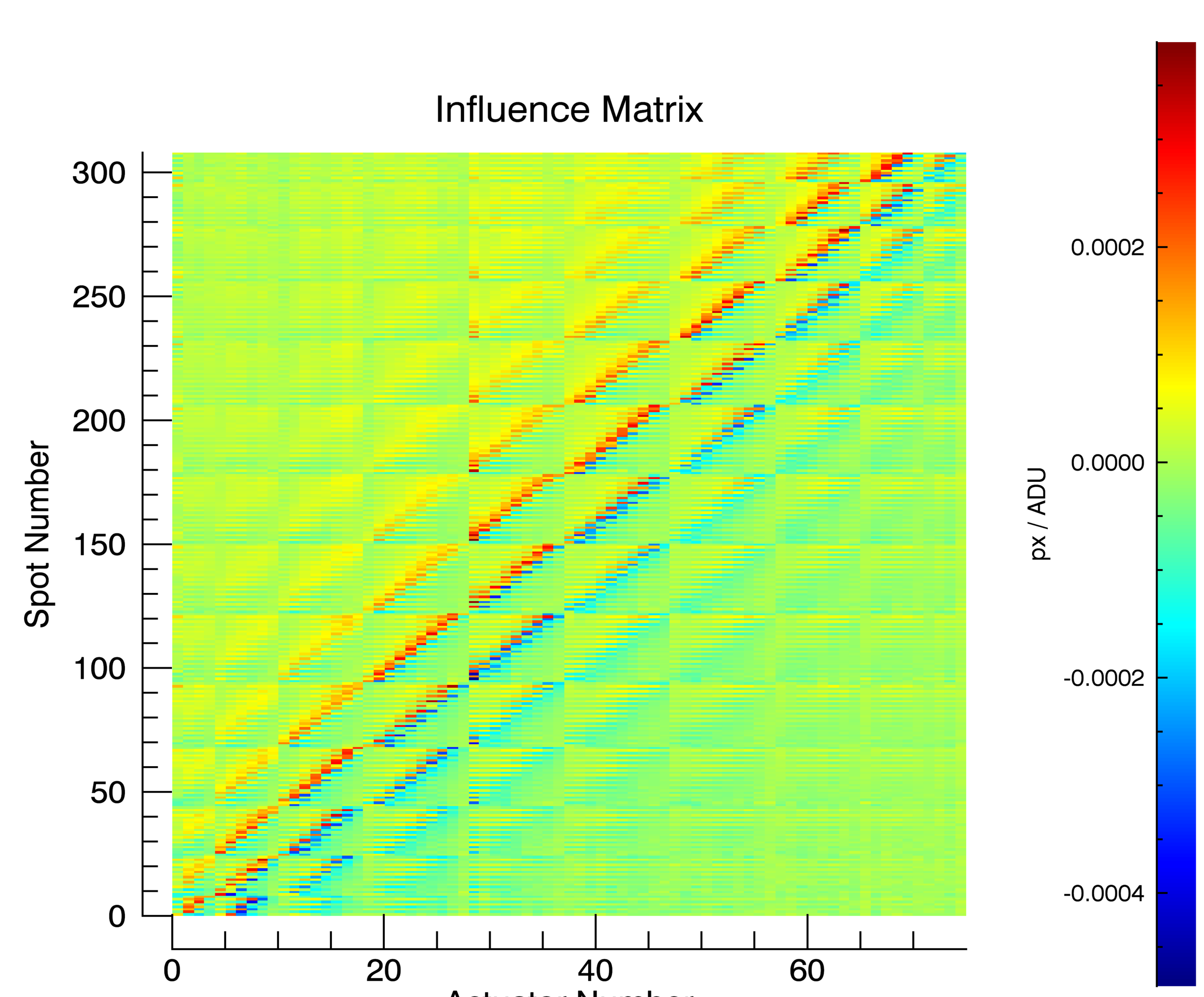
The PICTURE-C testbed is shown in the figure below. The spotfield pattern measured at the SH sensor is used to command the combination fast steering mirror and 76-actuator deformable mirror known as the integrated wavefront controller (IWC) in a closed PID (proportional + integral + differential) loop running at 20-40 Hz.



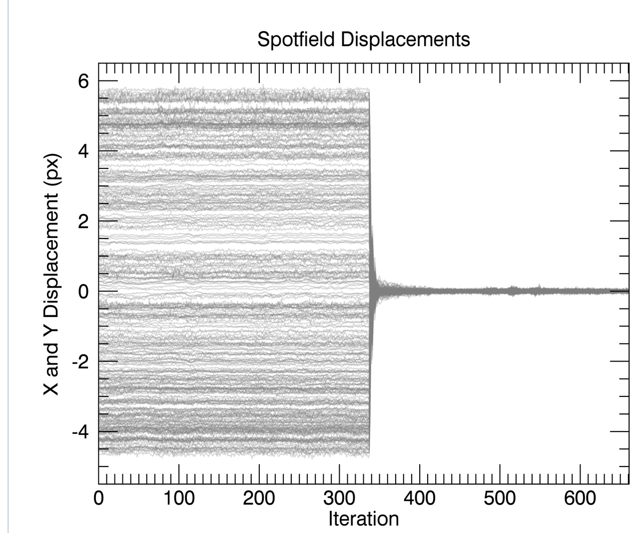


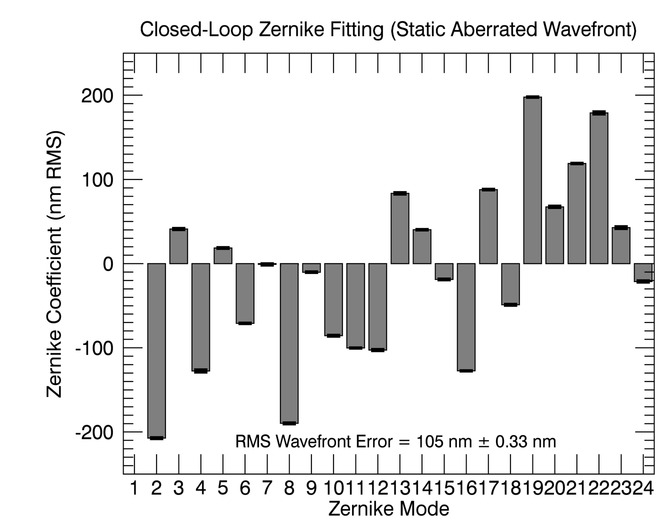
Above: Implementation of the PICTURE-C low-order wavefront sensor. Light reflected off the IWC is compressed and fed into the SH which measures spot displacements relative to a reference wavefront.

Below: Calibration of the instrument is carried out via construction of the influence matrix. Each column shows the x and y pixel deviation of each spot under the influence of a single actuator. This allows mapping between spotfield pattern (i.e. wavefront shape) and actuator commands.

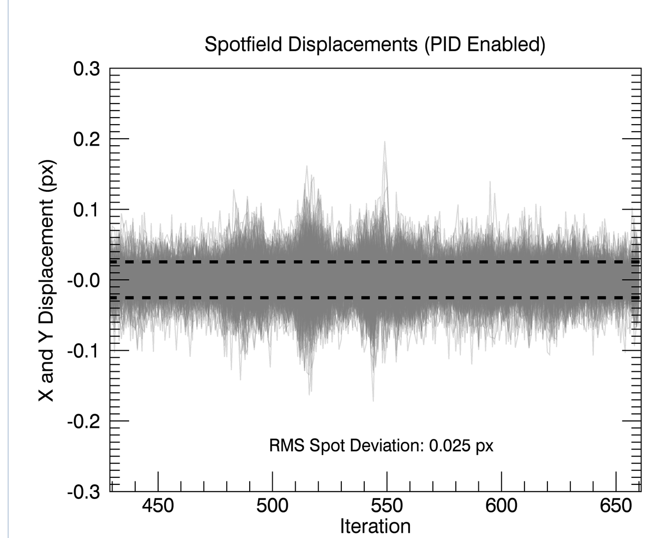


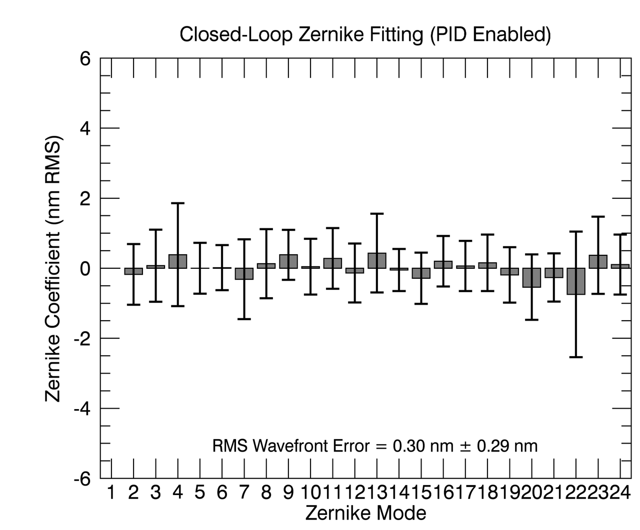
RESULTS





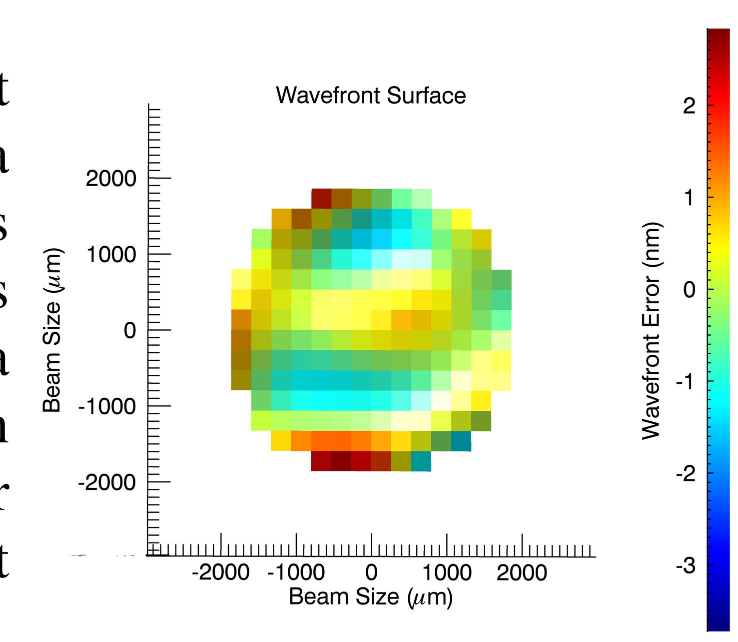
Above Left: Step response of the SH sensor.
Above Right: Zernike modes corresponding to the aberrated wavefront.





Above Left: Spotfield pixel deviations while the PID controller is enabled. **Above Right:** Zernike modes corresponding to the corrected wavefront.

Right: Wavefront error with respect to a reference while PID is enabled. The SH is able to stabilize a wavefront to within the ±20 nm linear region of the Lyot wavefront sensor.



CONCLUSIONS

The PICTURE-C low-order wavefront control system is able to correct a wavefront to within the ±20 nm linear region of the Lyot wavefront sensor. Next steps include measuring the stability with simulated flight disturbances. Further development of the PICTURE-C testbed and instrument will also see the implementation of the Lyot wavefront sensor and the vector vortex coronagraph, completing the wavefront control and coronagraphic optics for the first flight.

REFERENCES

[1] Mawet, D., Serabyn, E., Liewer, K., Burruss, R., Hickey, J., and Shemo, D., "The vector vortex coronagraph: Laboratory results and first light at Palomar observatory," *ApJ* **709(1)**, 53–57 (2010).
[2] Singh, G., Martinache, F., Baudoz, P., Guyon, O., Matsuo, T., Jovanovic, N., and Clergeon, C., "Lyot-based low order wavefront sensor for phase-mask coronagraphs: Principle, simulations and laboratory experiments," *Publications of the Astronomical Society of the Pacific* **126**, 586–594 (2014).
[3] Mendillo, C. B., Brown, J., Martel, J., Howe, G. A., Hewasawam, K., Finn, S. C., Cook, T. A., Chakrabarti, S., Douglas, E. S., Mawet, D., Guyon, O., Singh, G., Lozi, J., Cahoy, K. L., and Marinan, A. D., "The low-order wavefront sensor for the PICTURE-C mission," *Proc. SPIE* **9605** (2015).

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