Focal Plane Wavefront Sensing and Control Strategies for High-Contrast Imaging on the MagAO-X Instrument

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14 JUNE 2018
AUSTIN, TEXAS
• Wavefront sensing on MagAO-X
• Focal plane wavefront sensing with a vAPP
  • Low-order wavefront sensing (LOWFS)
  • Linear dark field control (LDFC)
• Future on MagAO-X
• Conclusions and ongoing work
Wavefront sensing on MagAO-X
Primary wavefront sensor:

- Pyramid wavefront sensor (PyWFS)
- Operating at up to 3.63 kHz

MagAO-X on the Nasmyth mount @ the Magellan Clay Telescope
MagAO-X on the Nasmyth mount @ the Magellan Clay Telescope

Primary wavefront sensor:
- Pyramid wavefront sensor (PyWFS)
- Operating at up to 3.63 kHz

Schatz [10703-74] 4:50 – 5:10 pm
Why focal plane wavefront sensing?
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- Enable continuous high-contrast imaging performance at the raw contrast level delivered by the coronagraph
Why focal plane wavefront sensing?

- Enable continuous high-contrast imaging performance at the raw contrast level delivered by the coronagraph

- Mitigate the impact of quasi-static and non-common path (NCP) aberrations
Why focal plane wavefront sensing?

- Enable continuous high-contrast imaging performance at the raw contrast level delivered by the coronagraph
- Mitigate the impact of quasi-static and non-common path (NCP) aberrations
- Low-order aberrations
Why focal plane wavefront sensing?

• Enable continuous high-contrast imaging performance at the raw contrast level delivered by the coronagraph
  • Mitigate the impact of quasi-static and non-common path (NCP) aberrations
    • Low-order aberrations
    • Mid-spatial frequencies
FPWFS w/ a vAPP

Focal plane wavefront sensing of low and mid-spatial frequencies with a vAPP coronagraph

vAPP coronagraph
(vector Apodizing Phase Plate)
vAPP coronagraph (courtesy of D. Doelman, F. Snik, et. al.)

Figure 1: Schematic diagram of the double-grating. Unpolarized light (yellow) enters the grating-vAPP. The grating-vAPP consists of two patterns added together: a polarization grating and a vAPP that generates a 360-degree dark zone. The combined pattern splits the two circular polarization states and applies the phase that generates the dark zone (green). The second polarization grating reverses the tilt from the first polarization grating pattern and the apodized light continues without tilt. A leakage term (red) goes through the grating-vAPP without acquiring any phase. This leakage term is apodized by the second grating and is diffracted. Any offset from half-wave retardance for the second polarization grating generates three leakage terms. The first is a double leakage term, that only contains 0.01% of the light and the other two are diffracted beams of the grating-vAPP. Note that the latter leakage terms have been apodized by the first grating-vAPP and have a dark zone.

“Patterned liquid-crystal optics for broadband coronagraphy and wavefront sensing”, Doelman et. al 2017
Figure 1: Schematic diagram of vAPP coronagraph. vAPP consists of a 360-degree dark zone. The polarization grating pattern generates the dark zone when the vAPP is offset from half-wave retardation.
vAPP coronagraph

- Polarization grating + vAPP
- Polarization grating

High-contrast dark holes

Planet-hunting regions of interest that must be kept dark

Figure 1: Schematic diagram. vAPP coronagraph consists of a 360-degree dark zone. The polarization grating pattern and the apparent offset from half-wave retardation is a double leakage term, vAPP without acquiring an additional polarization grating. Note that the dark zone.
Figure 1: Schematic diagram of a partially coherent vAPP coronagraph. The diagram consists of a 360-degree dark zone. The vAPP pattern is generated by a polarization grating and the aperture is defined by the vAPP without acquiring an axis offset from half-wave retard. This is a double leakage term, typical for vAPP. Note that the dark zone.

Modal wavefront sensor (MWFS) spots

LOWFS
Control of low-order aberrations
Figure 1: Schematic diagram of the vAPP coronagraph. The vAPP coronagraph consists of a 360-degree dark zone. The light that generates the dark zone is the moiré pattern formed by the orthogonally oriented vAPP without acquiring an offset from half-wave retardation, which is a double leakage term, to the vAPP without the grating-vAPP. Note that the dark zone.

vAPP coronagraph

a) Polarization grating + vAPP

b) Polarization grating

Bright field speckles

LDFC
Control of mid-spatial frequencies

Patterned liquid-crystal optics for broadband coronagraphy and wavefront sensing, Doelman et al., 2017
Low-order wavefront sensing (LOWFS)

Low-order wavefront sensing (LOWFS) using modal wavefront sensor (MWFS) spots created in the image plane by the vAPP coronagraph.
LOWFS w/ a MWFS

Applied Zernike modes
LOWFS w/ a MWFS
LOWFS w/ a MWFS

Zernike Mode 1

Zernike Mode 2

Zernike Mode 3

Zernike Mode 4

Zernike Mode 5

Zernike Mode 6

Zernike Mode 7

Zernike Mode 8

Zernike Mode 9

Zernike Mode 10

Zernike Mode 11

Zernike Mode 12
LOWFS w/ a MWFS

Zernike Mode 1

Zernike Mode 2

Zernike Mode 3

Zernike Mode 4

Zernike Mode 5

Zernike Mode 6

Zernike Mode 7

Zernike Mode 8

Zernike Mode 9

Zernike Mode 10

Zernike Mode 11

Zernike Mode 12

Applied Zernike modes
Applied Zernike modes
Applied Zernike modes

LOWFS w/ a MWFS

Upper MWFS spots

Lower MWFS spots

LOWFS signal

Upper MWFS spots  Lower MWFS spots
Simulated data: Linear response curves for the Zernike MWFS
Lab data: Linear response curves for the Zernike MWFS
Simulated closed-loop MWFS LOWFS

- Applied aberration
- MWFS—sensed shape
- Residual wavefront error

RMS: 113 nm
RMS: 27 nm

Upper MWFS
Lower MWFS
MWFS LOWFS signal

Aberrated PSF
Corrected PSF
Aberrated PSF

Corrected PSF

Upper MWFS

Lower MWFS

Simulated closed-loop MWFS LOWFS

Aberrated PSF

Corrected PSF
vAPP testing on the UA
Wavefront Control Testbed
vAPP testing on the UA Wavefront Control Testbed

BMC Kilo-DM
- 1024 actuators
- 32 actuators across diameter
- 9.6 mm diameter pupil
- 300 µm pitch
- Stroke (PV): 1.5 µm
- Inter-actuator coupling: 15%
vAPP testing on the UA
Wavefront Control Testbed
vAPP testing on the UA Wavefront Control Testbed
vAPP testing on the UA Wavefront Control Testbed
vAPP coronagraphs @ UA Wavefront Control Lab

7 vAPP masks

7 PSFs & MWFS spots on the science camera

vAPP mask 1.1
vAPP mask 1.2
vAPP mask 2.1
vAPP mask 2.2
vAPP mask 2.3
vAPP mask 3.1
vAPP mask 3.2
vAPP coronagraphs @ UA Wavefront Control Lab

7 vAPP masks

7 PSFs & MWFS spots on the science camera
LOWFS w/ a MWFS

Upper MWFS spots

Lower MWFS spots
LOWFS w/ a MWFS

Upper MWFS spots

Lower MWFS spots

LOWFS signal

Upper MWFS spots

Lower MWFS spots
LOWFS w/ a MWFS

Lower MWFS spots

Upper MWFS spots

LOWFS signal
In-lab closed-loop MWFS LOWFS

Applied aberration
RMS: 88 nm

MWFS-sensed shape after 2 iterations

Residual wavefront error
RMS: 19 nm
Linear dark field control (LDFC)

Linear dark field control (LDFC) using the bright speckle field outside of the dark hole for suppression of mid-spatial frequency aberrations in the dark hole.
Linear Dark Field Control: Theory

- Stabilizes the dark hole
- Does not require field modulation; still fundamentally relies on coherent mixing of stellar speckles and aberration-induced speckles
- Uses the intensity variation in bright field speckles in the image plane
- Relies on the linear response of the bright field to wavefront perturbations that modify both the bright and dark field and decrease the contrast in the dark hole
Linear Dark Field Control: Theory

- Stabilizes the dark hole

"Spatial Linear Dark Field Control: Stabilizing Deep Contrast for Exoplanet Imaging Using Bright Speckles" (Miller et al 2017, JATIS)
LDFC with a vAPP coronagraph
LDFC with a vAPP coronagraph

Defocused image
LDFC with a vAPP coronagraph

- Applied aberration
  - RMS: 27 nm

- LDFC correction shape after 5 iterations

- Residual wavefront error
  - RMS: 21 nm
LDFC with a vAPP coronagraph

Residual wavefront error after 5 iterations:
RMS: 27 nm
RMS: 21 nm
LDFC with a vAPP coronagraph

Aberrated PSF

Corrected PSF

Dark hole contrast: $10^{-3.6}$

Dark hole contrast: $10^{-4.3}$

RMS: 27 nm

RMS: 21 nm
LDFC w/ a vAPP in the lab
LDFC w/ a vAPP in the lab

Bright field reference contrast: $10^{-2.4}$
LDFC w/ a vAPP in the lab

Initial dark hole contrast: $10^{-3.0}$
LDFC w/ a vAPP in the lab

Controlling 100 mid-spatial frequency mirror modes
LDFC w/ a vAPP in the lab

Aberrated dark hole (LDFC off)

Corrected dark hole (LDFC on)
LDFC on MagAO-X

Future plans for implementing LDFC on MagAO-X
LDFC on MagAO-X
vAPP mask

vAPP PSF

dark hole mask

bright field passed to WFS camera
vAPP mask

dark hole mask

vAPP PSF

bright field passed to WFS camera

defocused
dark holes passed to science camera

LDFC signal

defocused

bright field passed to WFS camera

dark hole mask

vAPP PSF

vAPP mask
Conclusions and ongoing work

- Further lab testing/demonstrations of LDFC
- Final selection of the MagAO-X vAPP coronagraph design
- Combining LOWFS with MWFS spots and LDFC into a single control loop for low and mid-spatial frequency control
Acknowledgements

Leiden University team:
Frans Snik
Christoph Keller
David Doelman
Emiel Por
Mike Wilby
Steven Bos
Matt Kenworthy

University of Arizona MagAO-X team:
Jared Males
Olivier Guyon
Chris Bohlman
Justin Knight
Alexander Rodack
Jhen Lumbres
Kyle van Gorkom
Laird Close
Maggie Kautz
Alexander Hedglen
Joseph Long
Katie Morzinski
Lauren Schatz

This work was supported [in part] by NSF MRI Award #1625441 (MagAO-X)
Thank you!
Backup slides
Primary wavefront sensor:

- Pyramid wavefront sensor (PyWFS)
- Operating at up to 3.63 kHz
In-lab closed-loop MWFS LOWFS

Aberration: random phase aberration

- Applied aberration
- MWFS-sensed shape after 1 iteration
- Residual wavefront error

RMS: 98 nm
RMS: 47 nm
Simulated beam footprint on the BMC Kilo-DM
### Table 6: Uncorrectable Common Path WFE (nm rms wavefront)

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### Table 7: Non-Common Path WFE (nm rms wavefront)

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