Phase-Shifting Zernike Wavefront Sensor

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Why?

Is the world ready for another wavefront sensor?

Exoplanet imaging with coronagraphs needs some sort of adaptive optics.

ZWS gives you the best PSF contrast limit from by residual OPD aberrations after closed-loop adaptive optics.

Also, it’s useful for phasing large segmented telescopes like CCAT and TMT.

Phase Contrast

Frits Zernike, ca. 1935
Phase-contrast microscope
Robert Dicke, 1975

Fig. 1.—Simplified optical system showing the principle of the phase-contrast detection system. (See text.)
Phase Delay Techniques

Static phase-shift
- Zernike

Liquid crystal point-diffraction
- Mercer and Creath

Polarization phase-shifting
- Kadono, Takai, and Asakura
Phase-Shifting Zernike Wavefront Sensor

Focus beam on a reflective surface
Phase-shift the center of the spot
Re-image the pupil

\[ \Phi = \lambda \frac{f}{\#} \]

"Carrier" \times e^{i\theta} + "Signal"
Phase-Shifting Zernike Wavefront Sensor

**Common-path**
- Insensitive to vibration, thermal drift

**All-reflective**
- Works with broadband white light
- Polarization insensitive

**Phase shift is dynamic**
- Allows synchronous demodulation

**Math is easy**
- Measure absolute phase
- Phase reconstruction is pixel-by-pixel

Polished glass capillary tube
Fiber slides inside the capillary
Capillary and fiber are Ag-coated
Phase-shift center of PSF
Phase-Shifting Zernike Wavefront Sensor

- Capillary
- PZT
- Ag-coated capillary & fiber
- Fiber
- Clamp
ZWS Testbed at JPL

- Parabolic Mirror
- Tip/Tilt steering mirror
- White light
- Collimating mirror (off-axis parabola)
- Single Mode Fiber Source
- Phase-shifting mirror at focal plane
- Phase-shift actuator
- Aberration
- Camera at pupil relay
Dynamic Zernike Testbed

Microscope slide

Focal plane assembly
- Capillary and fiber
- PZT phase-shifter

Output pupil
CCD measures intensity proportional to phase delay in microscope slide
Performance

Fourier and Zernike modes

Misalignment
Fourier Mode Sensitivity

Input Phase

Image Plane Intensity

Phase Reconstruction

Residual Phase Error

Blobs
Fourier Mode Sensitivity

High-spatial-frequency aberrations are well sensed
Low-order aberrations (like tilt) are not

Estimate / Input Amplitude

\[
\text{Input Phase} \rightarrow \text{Phase Estimate}
\]

Input Phase

\begin{align*}
\text{Input Phase Amp} &= 0.01\lambda \\
\text{RMS} &= 0.002\lambda \\
\text{PV} &= 0.003\lambda
\end{align*}

Converges to 1
Zernike Mode Sensitivity

<table>
<thead>
<tr>
<th></th>
<th>Focus $Z_4$</th>
<th>Astigmatism $Z_5$</th>
<th>Coma $Z_7$</th>
<th>Spherical $Z_9$</th>
<th>Trefoil $Z_{10}$</th>
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<tbody>
<tr>
<td>Input Phase</td>
<td>![Image]</td>
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<td>Phase Reconstruction</td>
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</table>
Zernike Mode Sensitivity

Low-order modes introduce measurement error

![Graph showing Zernike Mode Sensitivity]

- Input Phase
- Phase Estimate
- Input Phase – Phase Estimate

Converges to 1
What about tilt?

Keep the spot mostly on the fiber

Tilt is overestimated by ~ 2

Cross-section through the pupil

Estimated tilt Zernike components (normalized)
Misalignment Challenges

Misaligned capillary and fiber surfaces
Reduces S/N
Summary

Phase-shifting Zernike Wavefront Sensor
- Converts input pupil phase to output pupil intensity

What’s it good for
- Exoplanet imaging at Mt. Palomar
- Phasing large segmented telescopes
- FTIR with long phase shifts

When can I get one?
- Ongoing work to improve manufacturing
- Caltech/JPL NTR-47975

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