Vector Zernike WFS Progress at JPL: Liquid Crystal and Metasurface Devices and Applications

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Development of Vector Zernike WFS

• ZWFS Operational Principle
• Origin and development
• Applications
• ZWFS Limitations and next generation devices
• Vector Zernike with Liquid Crystal Devices
• Vector Zernike with Metasurface Devices
  • Metasurface Devices and Status
• Impact of ZWFS
• The Future
Operational Principle

1. Put a phase-dimple in an intermediate focal plane
2. Look at the subsequent pupil plane

\[ E(\nu) = P(u,v) \cdot A(1 + \epsilon(u,v))e^{i\phi(u,v)} \]

\[ U^-(\xi) = \mathcal{F}(E_1(x)) \]
\[ U^+(\xi) = \mathcal{F}(E_1(x)) \cdot M\left(\frac{\rho}{\alpha}\right)e^{i\theta_0} + \mathcal{F}(E_1(x)) \cdot \left(1 - M\left(\frac{\rho}{\alpha}\right)\right) \]

\[ \phi(x) - \beta(x) = \frac{\pi}{4} + \text{ArcSin}\left[\frac{l_2(x) - l_1(x) - 2 I_{1,1f}(x)}{2 \sqrt{2 I_1(x) I_{1,1f}(x)}}\right] \]

\[ E_2(x_2) = L[E(x_1)]e^{i\theta_0} + (E(x_1) - L[E(x_1)]) \]
\[ L[E_1(x_1)] = \mathcal{F} \left[ \mathcal{F}(E_1(x)) \cdot M\left(\frac{\rho}{\alpha}\right) \right] = A_0 b(x_2)e^{i\beta(x_2)} \]

\[ l_2(x_2) = A_0^2 (p^2(x_2) + 2b^2(x_2) + 2b(x_2)P(x_2)(\sin(\phi(x) - \beta(x_2)) - \cos(\phi(x) - \beta(x_2))) \]

Steeves, J. et al., “Picometer Wavefront Sensing via the Phase-Contrast Technique”, in prep.


Workshop on Advanced Wavefront Sensing 4
Origin and Development


Applications

WFIRST-CGI Low-Order WFS


Phasing Segmented Apertures


Keck Planet Imager and Characterizer (KPIC)


Limitations and Next Generation Devices

• A single-dimple is limited in sensing by the phase-dimple depth (or height)

• It’s possible to increase the dynamic range by having a series of dimples of different depth, and scanning the white light fringe.

• However, a device with +/- $\pi/2$ diversity helps.

Limitations and Next Generation Devices

• Single Dimple has limited dynamic range.
• When the phase error gets too large, the brightness drops.
• Thus brightness can be associated with more than one phase error.
• Extra diversity can resolve this.
Liquid Crystal vZWFS testing at JPL

Segmented Deformable Mirror
Vector Zernike Focal plane mask (liquid crystal)
Focusing Off-axis Parabolic Mirror
Quarter waveplate plate + Wollaston Prism
CMOS Camera


Workshop on Advanced Wavefront Sensing
Vector Zernike with Metasurface Optics

Device operation requires phase shift over a $\phi$ 23.8 $\mu$m domain with $\varphi_x = \pi/2$ for x-polarized and $\varphi_y = 3\pi/2$ for y-polarized light with respect to the unpatterned substrate.

Mathematical expressions:

$$I_L = \frac{1}{2} (P^2 + 2b^2 - 2Pb\cos(\phi) + \sin(\phi))$$

$$I_R = \frac{1}{2} (P^2 + 2b^2 - 2Pb\cos(\phi) - \sin(\phi))$$
Metasurface Optics

Finite Difference Time Domain Simulations

- Software tool **Lumerical** to solve Maxwell’s equations of light propagation

\[ Re(E_x) \]
Application to KPIC

Optical Design

Edmund Optics 45-786
Dia: 6 mm

19.0 mm Dia. (mounted)

Karl Lambrecht MW2A-10-10
Dia: 10 mm

Edmund Optics 45-824
Dia: 9 mm

Mechanical Design

92.21 mm

300 mm

15.875 mm (mntd)

158.39 mm

24.87 mm
Impact of the ZWFS

• ZWFS has demonstrated itself to be a simple and robust method of measuring very small phase errors in optical systems.
  • It’s application to high-contrast imaging is a great match of both implementation and capability to need.

• Development of new devices will enhance its capabilities in both extending the dynamic range and increasing sensitivity.
The Future

• It’s time to take a different perspective, one that is more systems level.
• If we use a ZWFS to continuously monitor the wavefront in a high-contrast system, how might we use this capability to reduce requirements on the overall system?
• In particular, consider relaxing stringent requirements on DM’s and optical alignment.
• The Zernike WFS may not simply aide in establishing and maintaining high contrast, it may be essential for architecting these systems by enabling a new trade space.
Thank you for your time and attention.