PYRAMID WAVEFRONT SENSING UPDATE FOR MAGAO-X

LAUREN H SCHATZ¹, JARED MALES², MICHAEL HART¹, LAIRD CLOSE², KATIE MORZINSKI², OLIVIER GUYON¹,²,³,⁴, MADISON JEAN¹, CHRIS BOHLMAN², KYLE VAN GORKOM¹, ALEXANDER HEDGLEN¹, MAGGIE KAUTZ¹, JUSTIN KNIGHT¹, JOSEPH D. LONG², JENNIFER LUMBRES¹, KELSEY MILLER¹, ALEXANDER RODACK¹

¹College of Optical Sciences, University of Arizona. ²Steward Observatory, University of Arizona. ³National Astronomical Observatory of Japan, Subaru Telescope, National Institutes of Natural Sciences, Hilo, Hawaii. ⁴Astrobiology Center, National Institutes of Natural Sciences, Tokyo, Japan.
- MagAO-X Pyramid Wavefront Sensor Design
  - Optical design of system
  - Lens Results
  - Lab Results
- PYRITE
  - GMagAO-X motivation
  - 3 PWFS vs 4 PWFS
  - PYRITE simulator
MOTIVATION

High airmass and 11th mag GS demand high performance.

Image of LkCa 15b taken by Kate Follette (Sallum et al., Nature, 2015)
MagAO-X: Magellan Extreme Adaptive Optics System

- P.I. Dr. Jared Males, Steward Observatory
- First light planned: Early 2019
- 2,000 actuator Boston Micromachines Deformable Mirror
- 3.6 kHz correction speed
- Pyramid Wavefront Sensor
- Coronagraph
- Imagers and Spectrographs
MAGAO-X

BMC 2K Tweeter DM

Custom locking kinematic optical mounts

Laird Close
MAGAO-X

SDI: 2x Princeton Inst. 1024 EMCCDs

OCAM2K

Pyramid
PYRAMID WAVEFRONT SENSING

\[ S_x = \frac{I_1 + I_2 - I_3 - I_4}{I_1 + I_2 + I_3 + I_4} \]

\[ S_y = \frac{I_1 - I_2 - I_3 + I_4}{I_1 + I_2 + I_3 + I_4} \]
Purple: 0.5 arcsec modulation
Blue: Real modulation 60mili arcsec
Green: No modulation

Guyon 2005
Fold Mirror

Pyramid

Triplet

OCAM2K

Designed and Manufactured by Arcetri

Schatz et. al. in prep
SYSTEM DESIGN

MagAO-X bandpass same as MagAO

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength Range</td>
<td>600-1000 nm</td>
</tr>
<tr>
<td>Pupil Size</td>
<td>56 pixels; 2.688 mm</td>
</tr>
<tr>
<td>Pupil Separation</td>
<td>60 pixels; 2.880 mm</td>
</tr>
<tr>
<td>Pupil Tolerances</td>
<td>$\Delta &lt; 1/10^{th}$ pixel; 4.8 \mu m</td>
</tr>
<tr>
<td>Lens Diameter</td>
<td>10 mm &lt; D &lt; 20 mm</td>
</tr>
</tbody>
</table>

Schatz et. al. in prep
## Lens Design

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Requirement</th>
<th>As Built</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength Range</td>
<td>600-1000 nm</td>
<td>600- 1000 nm</td>
</tr>
<tr>
<td>Pupil Size</td>
<td>56 pixels; 2.688 mm</td>
<td>2.696 mm</td>
</tr>
<tr>
<td>Pupil Separation</td>
<td>60 pixels; 2.880 mm</td>
<td>2.857 mm</td>
</tr>
<tr>
<td>Pupil Tolerances</td>
<td>$\Delta &lt; 1/10\text{th pixel}; 4.8 \mu m$</td>
<td>$\Delta_{\text{size}} = 8 \mu m, \Delta_{\text{sep}} = -23 \mu m$,</td>
</tr>
<tr>
<td>Lens Diameter</td>
<td>10 mm $&lt; D &lt;$ 20 mm</td>
<td>D=10.1 mm</td>
</tr>
</tbody>
</table>

### Lens Radius, Thickness, and Material

<table>
<thead>
<tr>
<th>Radius</th>
<th>Thickness</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.76800</td>
<td>4.40900</td>
<td>S-NPH2</td>
</tr>
<tr>
<td>9.18400</td>
<td>4.24900</td>
<td>S-BSM4</td>
</tr>
<tr>
<td>11.24350</td>
<td>2.82400</td>
<td>S-LAH64</td>
</tr>
<tr>
<td>11.75473</td>
<td>0.00000</td>
<td></td>
</tr>
</tbody>
</table>

Manufactured by Rainbow Optics

Schatz et al. in prep
ALIGNMENT

Pyramid

Triplet

OCAM2K

Madison Jean
Optical Science Undergrad

Schatz et al. in prep
INITIAL RESULTS

HeNe Laser Full Pupils

White Light, Stopped Down

Schatz et. al. in prep
THE GIANT MAGELLAN TELESCOPE EXTREME ADAPTIVE OPTICS SYSTEM: GMAGAO-X

- 7x 3,000 actuator deformable mirrors
- 3 OCAM2K detectors
- 240 x 240 mode 2kHz on OCAM2k

Look out for Jared’s Poster tonight!
10702-341
3PWFS VS 4PWFS

Benefits of Three Sided PWFS:
• Easier to manufacture
• Less pixels = less read noise

Benefits of Reflective vs Refractive:
• Multiple detectors
• Faster, less read noise

Oli Durney

Schatz et. al. in prep

4 sided

$$S_x = \frac{I_1+I_2-I_3-I_4}{I_1+I_2+I_3+I_4}$$

$$S_y = \frac{I_1-I_2-I_3+I_4}{I_1+I_2+I_3+I_4}$$

3 sided

$$S_x = \frac{I_2\left(\frac{3}{2}\right)-I_3\left(\frac{3}{2}\right)}{I_1+I_2+I_3}$$

$$S_y = \frac{I_1-I_2\left(\frac{1}{2}\right)-I_3\left(\frac{1}{2}\right)}{I_1+I_2+I_3}$$

Schatz et. al. in prep
**Pyramid Residual Wavefront Experiment**

Robust Simulation Tool:

- Simulates atmospheric turbulence.
- Different Pyramid architectures.
- Reflective vs Refractive
- Manufacturing errors.
- Uses residual wavefront error as a metric.

Schatz et. al. in prep
Run through a console script. Can select:

- Number of photons
- Read noise
- # Pixels across pupil
  - 16, 32, 64
• Kolmogorov Turbulence Model
  • Random phase screens generated
  • Piston, tip/tilt removed.

• Plate Scale: \( \frac{1}{10} \left( \frac{\lambda}{D} \right) \)
1 Pyramid Console
   - Select simulation parameters

2 Pupil Plane
   - Generate phase screens
   - Define aperture

3 Focal Plane
   - Apply Pyramid phase mask

4 Pupil Plane
   - Simulate detection
   - Scale for photon counts
   - Apply noise

5 Open Loop Correction
   - Calculate wavefront slopes
   - Reconstruct wavefront phase
   - Subtract reconstruction from original phase to get residual

6 Data Analysis
   - Fit Fourier Modes to residual wavefront
   - Take variance of the Fourier Mode amplitudes
   - Plot the variance versus spatial frequency
5) RESIDUAL WAVEFRONT

Fit with Fourier Modes to analyze power spectrum
TRADE STUDY

- 3PWFS vs 4PWFS
- Reflective vs Refractive Pyramid
- Manufacturing Errors vs No Errors
- Read Noise
- Guide Star Magnitudes
PYRAMID WAVEFRONT SENSING UPDATE FOR MAGAO-X

LAUREN H SCHATZ¹, JARED MALES², MICHAEL HART¹, LAIRD CLOSE², KATIE MORZINSKI², OLIVIER GUYON¹,²,³,⁴, MADISON JEAN¹, CHRIS BOHLMAN², KYLE VAN GORKOM¹, ALEXANDER HEDGLEN¹, MAGGIE KAUTZ¹, JUSTIN KNIGHT¹, JOSEPH D. LONG², JENNIFER LUMBRES¹, KELSEY MILLER¹, ALEXANDER RODACK¹

¹College of Optical Sciences, University of Arizona. ²Steward Observatory, University of Arizona. ³National Astronomical Observatory of Japan, Subaru Telescope, National Institutes of Natural Sciences, Hilo, Hawaii. ⁴Astrobiology Center, National Institutes of Natural Sciences, Tokyo, Japan.
Figure 5. The roofing of a four sided pyramid tip.