Phasing of Large Optical Segmented Ground-Based Telescopes

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Definition of Phasing

- Phasing is the adjustment of segments in piston degree of freedom only.
- After segment re-installation at Keck the following alignments are routinely performed with a Shack-Hartman camera:
  - Segment ID
  - Coarse segment tip/tilt
  - Secondary mirror rigid body
  - Measurement of segment figures
  - Phasing of segments: adjustment of piston degree of freedom only
- This talk will concentrate on the most difficult of the above items: Phasing.
Outline

- Review of current telescopes and techniques
- Basic description of “Shack-Hartmann” phasing
- Narrow band phasing – capture range $\pm \lambda/4$
  - How it works
  - On-sky Keck results
  - Testbed results
- Coherence phasing – capture range $>\pm \lambda/4$
  - How it works
  - On-sky Keck results
Ground-Based Optical Segmented Telescopes-Phasing Techniques

- Keck: “Shack-Hartmann” Phasing (used >1000 times)
  - Phase Discontinuity Sensing as an “optional” method
- GTC: “Shack-Hartmann” Phasing
- ESO Alignment and Phasing Experiment
  - SHAPS: “Shack-Hartmann” Phasing
  - ZEUS: “Zernike Unit for Segment Phasing”
  - PYPS: “Pyramid Phase Sensor”
  - DIPSI: “Diffraction Image Phase Sensing Instrument”
- Planned telescopes
  - Thirty Meter Telescope (TMT): “Shack-Hartmann” Phasing
  - European-ELT: “Shack-Hartmann” Phasing
Shack Hartmann Test
Keck Phasing (and Alignment) Camera
Phasing subaperture size selected to be smaller than $r_0$. 
Multiple Choices for Forming Sub-Images

Lenslets, Prisms, Masks

- **Lenslets**
  - Need to worry about quality
  - Commercially available
  - Expensive

- **Prisms**
  - Good image quality
  - Hard to make large arrays

- **Masks (Fresnel diffraction)**
  - Good image quality
  - Inexpensive
  - System parameters define if this approach will work
Piston Error = 0

Piston Error = \frac{\lambda}{4}
Phasing Template Sequence
(891 nm filter, 10 nm FWHM)

Step Size = \( \frac{\lambda}{22} \) = 40 nm
Phasing Keck Telescope

- 78 edge-sampled spots used in phasing
- 120 mm diameter
Narrowband Phasing – Keck Data (852 nm filter)
Phasing: 852 nm vs 651 nm

RSS of differences: 12 nm
Narrowband Phasing Limitation

- When edge step approaches $\lambda/4$ (220 nm), measurement becomes uncertain by $\lambda/2$
- “Effective” capture range reduced to: 220 nm – max edge residual
Phasing with Perfect Segments
(use Segment Tip/Tilt to align edges)

- Piston RMS = 2 nm
- RMS edge residual = 9 nm
Fresnel Phasing

- Fresnel number of a lens: \( F = \frac{a^2}{f \lambda} \)
  - \( a \) = radius of lens
  - \( f \) = focal length of lens
  - \( \lambda \) = wavelength of observation

- For \( F < 1 \), Fresnel and Fraunhofer diffraction patterns are very similar.

- This means that to a first approximation one can replace the lenslet array with a mask consisting of clear apertures.

- For the nominal design of the TMT Alignment and Phasing System, the Fresnel number of the lenslets is \( F = 0.6 \). [The Keck system has \( F = 1.3 \).]
The ESO Active Phasing Experiment (APE), originally conducted at the VLT, has been set up in the ESO optical labs.

APE, with its 61 segment actively controlled mirror, provides an ideal testbed for Fresnel phasing.

We conducted a series of experiments at ESO using APE to confirm Fresnel phasing (with generous support from ESO).
APE phasing image: all edge steps have 0 (circular subimages) or $\lambda/4$ (split subimages) phase errors.
Sample Phasing Image II

APE phasing image: one segment pistonned by 100 nm.
Measured vs. Theoretical Edge Steps – Fresnel Phasing

RMS Piston Error: 18 nm
Measuring Piston Error of a Single Segment

- Error in segment piston from first measurement = 7.0 nm
- Error in segment piston after 2 iterations = 2.0 nm
Measuring A Random Mirror Configuration

**Applied Mirror State**

(RMS = 29 nm)

**Measured Mirror State**

(RMS = 24 nm)

- RMS piston error of first measurement = 9.0 nm
- RMS piston error after sending 2 iterations times = 3.6 nm
Coherence Phasing

- Exploits the broadband nature of light
- When the phase step exceeds the coherence wavelength $\frac{\lambda^2}{2\Delta\lambda}$ the image becomes a superposition of multiple in-phase subimages resulting in an elongated sub-image
- We quantify this with the coherence parameter:
  - Maximum correlation – Minimum Correlation
- Each segment edge is stepped through 11 different phase steps and the coherence parameter calculated.
- The resulting coherence parameters are fit to a Gaussian and the edge step error calculated
Typical Broadband Sequence
(Actual Keck Data)

- Step Size = 6 µm
- Coherence Length = 40 µm
- (891/10 filter)
Coherence vs. Edge Step - Theory
(891/10 nm)
Coherence vs. Edge Step – Keck Data
(891/10 nm)
### Broadband Phasing Parameters

<table>
<thead>
<tr>
<th>Mode</th>
<th>Wavelength nm</th>
<th>Bandwidth nm</th>
<th>Coherence Length μm</th>
<th>Step Size μm</th>
<th>Accuracy nm</th>
<th>Capture Range μm</th>
<th>Star Magnitude V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phasing-1000</td>
<td>891</td>
<td>10</td>
<td>40</td>
<td>6</td>
<td>1000</td>
<td>±30</td>
<td>4</td>
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<tr>
<td>Phasing-300</td>
<td>852</td>
<td>30</td>
<td>12</td>
<td>2</td>
<td>300</td>
<td>±10</td>
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<td>Phasing-100</td>
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<td>100</td>
<td>3.8</td>
<td>0.6</td>
<td>100</td>
<td>±3</td>
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<td>Phasing-30</td>
<td>700 [eff]</td>
<td>200 [eff]</td>
<td>1.2</td>
<td>0.2</td>
<td>30</td>
<td>±1</td>
<td>7</td>
</tr>
</tbody>
</table>

Capture range and accuracy for a specific application can be optimized by changing the number of steps and the coherence length of the filters used.
Narrowband vs. Broadband

RSS of differences: 19 nm
Solving $2\pi$ Ambiguities: Coherence Length Is a Better Approach

**Synthetic Wavelength**
- Defined by $\frac{\lambda_1 \lambda_2}{\lambda_1 - \lambda_2}$
- 30 µm to $\frac{1}{4} \lambda$ in 4-6 exposures
- Highly sensitive to meas. Uncertainty
- Gives wrong answer if out of range (see Lofdahl & Erikson)
- Don’t need to move segment

**Coherence Length**
- Defined by $\frac{\lambda^2}{2\Delta\lambda}$
- 30 µm to $\frac{1}{4} \lambda$ in 22 exposures
- Moderately sensitive to meas. Uncertainty
- Gives no answer if edge step out of range
- Must move segments

Initial segment alignment errors and segment aberrations mean that edges are often out of range

APE Experiments confirmed problems with artificial wavelengths

Getting one edge wrong will “propagate” through the whole mirror

The coherence technique essentially guarantees you don’t get the wrong answer
Summary of Shack-Hartmann Phasing

- “Shack-Hartmann” phasing is routinely used for phasing of segmented telescopes
- Has a capture range that can exceed ±30 μm
- Has an accuracy to better than 6 nm RMS
- Can work with both atmospheric and lab turbulence
- Is not sensitive to global aberrations
- Can be combined with a “normal” Shack-Hartmann camera
- Can support coherence length or artificial wavelength phasing
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Backups
Phasing and Shack-Hartmann Cameras Have Somewhat Different Requirements

- Phasing requires a method to adjust the pupil location
  - Mask/Lenslet array should be on a stage
  - A piece of glass in the collimated beam that can be tilted
  - Accuracy is ~5% of a subaperture diameter

- The phasing camera re-imaged pupil must be of sufficient optical quality

- Focal plane plate scale:
  - Normal phasing: ~2 times Nyquist sampled images
  - Broadband phasing: ~4 times Nyquist sampled images
Keck Segment Phasing

- **Optic:** Array of micro-prisms
- **Wavelength:** 611 to 891 nm
- **Star Mag:** $V = 4$ to $8$

**Capture Range:**
- BB $\pm 30$ microns
- NB $\pm 200$ nm

**Accuracy:**
- BB $\pm 30$ nm
- NB $\pm 6$ nm
Fresnel vs. Fraunhofer: In-Phase Segments

Phasing: Fresnel No. = 0.625
Fresnel vs. Fraunhofer: Out-of-Phase Segments

Phasing: Fresnel No. = 0.625

Intensity

X (pix)

0.001

0.01

0.1

1
• Phasing Reference Beam
Primary Mirror Phase Error First Light (Keck II)

March 12, 1996
RMS Piston = 9.5 \mu m
• Primary Mirror After Broadband Phasing

• March 14, 1996
• RMS Piston = 0.14 μm
Primary Mirror Phase Error First Light (Keck II)

June 14, 1996
RMS Piston = 7.4 μm
Primary Mirror After Phasing

June 14, 1996
RMS Piston = 0.025 μm