NGAO NGS WFS design review

Caltech Optical Observatories

1st April 2010
Presentation outline

• Requirements (including modes of operation and motion control)
• Introduction –
• NGSWFS input feed (performance of the triplet and effect of atmospheric dispersion)
• Modes of operation and pupil mapping demystified
• NGS WFS design (sensor design in all three modes, post-lenslet relay design and performance
• Summary
• Outstanding issues
• Brief outline of CCID74 performance specs.
NGS WFS Requirements

- **Modes of operation (FR-130 and FR-3247)**
  - 63 x 63 sub-apertures
  - 5 x 5 sub-apertures
  - Pupil imaging mode
- **Transmission & Operating wavelengths (FR-203 and FR-3444)**
  - 500 to 900 nm with transmission of (500nm: 78%, 550nm: 80%, 633nm: 77%, 700nm: 74%, 880nm: 78%).
- **Patrol Field of Regard (FR-127)**
  - 40 x 60 arcsec rectangle (limited by narrow field relay)
  - NGS WFS Field Steering Mirror Ass’ly based pick-off design
- **WFS FoV**
  - 4 arcseconds in 60 x 60 mode (FR-131)
- **NGS WFS operates with no ADC (B2C decision)**
Motion control requirements

- Field steering mirrors – need to be able to pick any star in a 60x40 arcsecond Field of Regard
- Whole WFS motion – the WFS must work with and without the IF dichoric
- Lenslet XY motion & post-lenslet relay and camera focus – the WFS needs to operate in 63x63, 5x5 and pupil imaging modes.
NGAO optical relay – the packaging problem
The AO (supervisory) control can configure (FSM motion, lenslets, read-out mode etc.) and access status signals from the NGSWFS sub-system.

• NGS WFS needs to interface mechanically and optically to the AO relay/ optical bench.
• NGSWFS needs to send pixel data to the RTC.
• Note that the RTC has no control path to the sensor (unlike the LGSWFS where there is a TT mirror control).
Input to the NGS sensor

Design characteristics:
- NGS light is picked off in collimated space and focused using a (BASF2-N15-BASF2) triplet
  - F/# = 20.012
  - Plate scale = 1.063 mm/"

NGAO WFS design, Caltech Optical Observatories
Input to the NGS sensor – spot diagram at the NGS sensor pick-off focal plane

NGAO WFS design, Caltech Optical Observatories
Ray fans at the NGS sensor pick-off focal plane

NGAO WFS design, Caltech Optical Observatories
Grid distortion at the NGS WFS input

<table>
<thead>
<tr>
<th>TUE MAR 23 2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>FIELD: 0.0118 W 0.0118 H DEGREES</td>
</tr>
<tr>
<td>IMAGE: 45.03 W 45.03 H MILLIMETERS</td>
</tr>
<tr>
<td>MAXIMUM DISTORTION: -0.1217%</td>
</tr>
<tr>
<td>SCALE: 10.000X, WAVELENGTH: 0.6000 μm</td>
</tr>
</tbody>
</table>

NGAO WFS design, Caltech Optical Observatories
Effect of atmospheric dispersion

Residual atm. Dispersion (P-P, mas) in each HOWFS sub-ap.

Max. dispersion introduced by the atmosphere between 500-900 nm = 29 mas at 45 degree zenith angle – results in negligible change in sub-aperture spot size
What’s the implication for the NGS WFS?

• Wavefront error on input beam is 1.15 waves RMS (6 waves P-V) @ 600 nm at the extreme (and worst case) field points. This is mostly astigmatism.

• As per KAON 685 we know that this corresponds to \( y = ar^2 \rightarrow 0.69 \times 10^{(-6)} = 25 \times a \rightarrow a = 0.276 \times 10^{(-7)}; \)
  \( dy/dr = 2*a*r \rightarrow dy/dr = 0.2 \times 10^{(-6)} \) [c.f. Figure 13 in the KAON]

• KAON 692 Figures 9 and 10 along with corresponding analysis also indicate that for a large # of sub-apertures (60 in our case) the sub-ap spot size due to input aberration is going to be of the order of 2 um (RMS).
Analysis result

• Impact of input aberrations
  – Negligible impact on NGS WFS subaperture spot size
  – Acceptable centroid offsets (~0.1 pixel worst case)
  – Small amount of distortion (0.13%) will be calibrated using ACQ system
  – Chromatic aberrations acceptable (TBC?)

• Atmospheric dispersion introduces ~30 mas of spot blurring.
NGS WFS parameters

• Following Keck Drawing Drawing #1410-CM0010 Rev. 1, we have 59 (+1/2+1/2) WFS sub-apertures across the a circle that inscribes the Keck primary mirror. We also support another calibration mode with 5x5 pupil samples across the Keck primary mirror.

• The WFS FoV is 4” because the sensor needs to track extended objects that are 4” in diameter. One could also work out the spot size.

<table>
<thead>
<tr>
<th>Seeing</th>
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<tbody>
<tr>
<td>Natural seeing FWHM at GS wavelength</td>
<td>0.46 arcsec</td>
</tr>
<tr>
<td>Subaperture Tip/Tilt corrected FWHM</td>
<td>0.36 arcsec</td>
</tr>
<tr>
<td>AO-compensated FWHM</td>
<td>0.06 arcsec</td>
</tr>
<tr>
<td>Contribution due to seeing</td>
<td>0.36 arcsec</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>System Aberrations</th>
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<tbody>
<tr>
<td>Aberrations in AO thru to WFS</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Atmospheric Dispersion</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADC in HOWFS?</td>
</tr>
<tr>
<td>RMS blurring due to atmospheric dispersion</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total size of detected return beam:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge Diffusion</td>
</tr>
<tr>
<td>Charge Diffusion</td>
</tr>
<tr>
<td>Contribution due to Charge Diffusion</td>
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</tbody>
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<table>
<thead>
<tr>
<th>Subaperture Diffraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lambda/d (for sensing)</td>
</tr>
<tr>
<td>Spot size used for centroiding</td>
</tr>
</tbody>
</table>
Modes of operation

• 63x63 sub-ap. mode of operation
  – We use 4 physical pixels per sub-ap. Which can be binned on chip and read as 2x2 pixels/sub-aperture with almost zero read noise penalty. This gives us the flexibility of 2 modes, one with high linearity and another with lower read noise.
  – Only 59x59 sub-apertures are lit by NGS star light at any time. The pupil imaged by the WFS nutates around the 63x63 sub-apertures.

• 5x5 mode of operation
  – to simply the size of moving parts while facilitating the two pupil sampling modes, we use the same collimator and post-lenslet relay for both the 63 and 5 sub-ap mode of operation.
  – We choose 48 pixels/sub-aperture (instead of 50 pixels/sub-ap) to enable 4x4 binned pixel/sub-aperture operation with standard centroiding algorithms.
  – A small fraction of light will be lost from the outer-most sub-apertures due to pupil nutation.

• Pupil imaging mode – The NGS WFS can image the pupil using the WFS camera.
Keck primary projected on the 64x64 actuator BMM HODM

Envelope over which the pupil wobbles (nutates)
Motion control

Post-lenslet relay and camera focus

Lenslet X & Y motion

Whole WFS translation
Modes of operation cont’d

Modes (Clockwise from top): 5x5, 63x63 and pupil imaging modes
Modes of operation cont’d

Modes (Clockwise from top): 5x5, 63x63 and pupil imaging modes
Pupil mapping between NGSWFS-DM and primary mirror

As per [Drawing #1410-CM0010 Rev. 1](#), :

- The whole DM would be mapped by using a pupil that is 25.2 mm/24 mm * 10.949 = 11.49645 m and has the same focal length (149.583 m). This corresponds to an F/# = 13.01123.

- Plate scale = 13.01123*11.49645/(180/pi*3600) = 725.1979 um/" at the telescope focal plane

- The apparent plate scale at the NGS pick off focal plane is 19.06163 (instead of 20.012). The plate scale is 1.0623 mm/".
## WFS design parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>60x60 mode</th>
<th>5x5 mode</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>f_collimator</td>
<td>60</td>
<td>60</td>
<td>mm</td>
</tr>
<tr>
<td>Input plate scale</td>
<td>1.0623</td>
<td>1.0623</td>
<td>mm/&quot;</td>
</tr>
<tr>
<td>Binned pixel size (# of pixels)</td>
<td>1</td>
<td>12</td>
<td>pixels</td>
</tr>
<tr>
<td>Detector plate scale (mm/&quot;&quot;)</td>
<td>0.0210</td>
<td>0.2520</td>
<td>mm/&quot;</td>
</tr>
<tr>
<td>Plate scale ratio (IPS/DPS)</td>
<td>50.58</td>
<td>4.22</td>
<td></td>
</tr>
<tr>
<td>input f/#</td>
<td>19.06</td>
<td>19.06</td>
<td></td>
</tr>
<tr>
<td>pupil sampling</td>
<td>63</td>
<td></td>
<td>5 sub-aps across pupil</td>
</tr>
<tr>
<td>d_lenslet</td>
<td>0.05</td>
<td>0.60</td>
<td>mm</td>
</tr>
<tr>
<td>de-magnification (m)</td>
<td>1.68</td>
<td>1.68</td>
<td></td>
</tr>
<tr>
<td>f_lenslet</td>
<td>0.71</td>
<td>8.47</td>
<td>mm</td>
</tr>
<tr>
<td>f# lenslet</td>
<td>14.12</td>
<td>14.12</td>
<td></td>
</tr>
<tr>
<td>wavelength (for worst case FN calc.)</td>
<td>0.90</td>
<td>0.90</td>
<td>um</td>
</tr>
<tr>
<td>fresnel #</td>
<td>0.98</td>
<td>11.80</td>
<td></td>
</tr>
<tr>
<td>radius of curvature of lenslet</td>
<td>0.36</td>
<td>4.38</td>
<td>mm</td>
</tr>
</tbody>
</table>
63x63 NGS WFS layout

- Total relay length = 262 mm
- Components from (left to right) – collimating doublet, lenslet array, field singlet, focusing doublet followed by the window and the detector.
- Wavelength of operation – 500-900 nm (TBC)
63x63 sub-aperture NGS WFS spots

21 um pixel detector with 63 spots with 4x4 pixels/sub-aperture.
63x63 NGS WFS layout
63x63 NGS WFS layout
63x63 NGS WFS post lenslet relay

- Mag. = 1.681
- Total relay length = 139 mm
Post lenslet relay – spots delivered by the relay

(Huygen’s) PSF
Strehl = 97% at worst field point.

3 um RMS spot size corresponds to 0.33asec (FWHM) static error in the sensor @ 1asec/pixel plate scale
The worst case sub-aperture spot motion due to distortion will be less than 0.1 of a pixel.
5x5 NGS (calibration) WFS layout

- Total relay length = 269 mm
- Components from (left to right) – collimating doublet, lenslet array, field singlet, focusing doublet followed by the window and the detector.
- Wavelength of operation – 500-900 nm
5x5 NGS WFS layout

5040 um detector with 5 spots across the pupil with 4x4 (binned) pixels/sub-aperture [48x48 physical pixels/sub-aperture]
<table>
<thead>
<tr>
<th>Slide 30</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RD10</strong></td>
</tr>
<tr>
<td>This seems to show subimages separated by 2 x 2 pixels (ZMX artefact).</td>
</tr>
<tr>
<td>Would be better with actual detector pixels (or binned pixels)</td>
</tr>
<tr>
<td>Richard Dekany, 3/24/2010</td>
</tr>
<tr>
<td><strong>RD11</strong></td>
</tr>
<tr>
<td>So? ???</td>
</tr>
<tr>
<td>Richard Dekany, 3/24/2010</td>
</tr>
</tbody>
</table>
5x5 NGS WFS layout

Reminder: The 5x5 and the 63x63 modes use the same post-lenslet relay
NGS WFS behind the NGAO optical relay
NGS WFS spots showing 59 ‘lit’ sub-apertures
Post lenslet relay – magnified view

Magnified view of the WFS focal plane. 168 um correspond to 8 pixels.
Summary of work done by WFS team

• Contributed to systems engineering and requirements ratification process
• Designed a NGS feed using a refractive triplet to solve NGAO’s packaging problem while delivering a f/20 beam to the NGS sensor.
• Designed a compact WFS that works in 63x63, 5x5 and pupil imaging modes.
• Made a list of outstanding issues and analysis for the DD phase.
• Built a compliance matrix and risk register.
Other issues

• For B2C we ruled out an ADC in the NGS WFS
  – What is the implication of this?
• What about pupil imaging mode?
• What are the mechanical stage, etc. requirements?
• Alignment issues
  – Anything unusual? Fixtures, etc. Is this really the same as any other NGS WFS ever built?
  – Manufacturing / alignment tolerances
• Thermal issues
  – -15C operation (does this matter?)
• Stray light
  – Baffles / filters (unnecessary?)
  – Ghosts (usually not an issue of NGS WFS, but for PDR mention for completeness)
Not be top priority for mini-review

Richard Dekany, 3/24/2010
Detector choice and performance

• NGAO envisages the use of 256x256 pixel CCID74 detector with 21 um pixels that is under development at Lincoln Labs for wavefront sensing.
Predicted Quantum efficiency*
(based on 75 micron substrate, Bodacious Black AR coating^ on Pan-STARRS CCID-58)

^ - LL plans to use a different AR coating that will result in ~90% QE at 589 nm

Read noise \([\text{predicted and measured}]\)

**Read Noise vs. Frame Rate**
CCID-66 (actual, blue curve) and CCID-74 (predicted, orange curve) with 2 stage Planar JFET Readout

**Read Noise vs. Pixel Clock Rate**
CCID-66 (actual, blue curve) and CCID-74 (predicted, orange curve) with 2 stage Planar JFET Readout

NGAO WFS design, Caltech Optical Observatories