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
• 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)
• Dynamic range (FR-141) = +/-1.77” @ 700 nm.
• Static non-calibratable aberrations in the NGSWFS = 25 nm (FR-138)
• 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

NGAO WFS

Sci. Int. 1

Sci. Int. 2

IF

LGS WFS

3D LAYOUT

NGAO RELAY, VERSION 9, FOLDED LGS, TWO INSTRUMENT PORTS
FRI MAR 26 2010

NGAO WFS design, Caltech Optical Observatories

V. VELUR
CALTECH OPTICAL OBSERVATORIES
M/C 11-17

NGAO_100MM_PUPIL_120BFOSEXRAY_XML
CONFIGURATION: ALL 9
Context diagram of the NGS WFS

- 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>GRID DISTORTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>TUE MAR 23 2010</td>
</tr>
<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 on high order NGS wavefront sensing

Max. dispersion introduced by the atmosphere between 500-900 nm = 189 mas at 45 degree zenith angle – *results spot blurring of 0.2” [as opposed to 10 mas (RMS) ‘nominal’ spot blurring with an ADC]*

NGAO WFS design, Caltech Optical Observatories
Static aberrations

- Geometric spot size at the relay (RMS) = Error budget alloc. (asec, FWHM)/2.355 (FWHM/RMS) * 21 (um/pixel)/(1asec/pixel)

⇒ We know from the relay design that the spot size is 3 um (RMS), **hence error budget allocation must be 0.33 asec instead of 0.25 asec.** This leads to a 6% change in apparent spot size at the detector.

⇒ Since we will use the NGS WFS with bright stars (Mv>=8), atmospheric fitting error and not measurement error is the dominating error term in the error budget (Fitting error/Measurement error ~2)

⇒ We do have a alternate relay design with a extra (field flattening) optic that delivers performance within specs. - it is not clear if this is useful given the sensitivity analysis.

<table>
<thead>
<tr>
<th>Seeing</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural seeing FWHM at GS wavelength</td>
<td>0.43 arcsec</td>
</tr>
<tr>
<td>Subaperture Tip/Tilt corrected FWHM</td>
<td>0.20 arcsec</td>
</tr>
<tr>
<td>AO-compensated FWHM</td>
<td>0.06 arcsec</td>
</tr>
<tr>
<td>Contribution due to seeing</td>
<td>0.20 arcsec</td>
</tr>
<tr>
<td>System Aberrations</td>
<td></td>
</tr>
<tr>
<td>Aberrations in AO thru to WFS</td>
<td>0.25 arcsec</td>
</tr>
<tr>
<td>Atmospheric Dispersion</td>
<td></td>
</tr>
<tr>
<td>ADC in HOWFS? (NO)</td>
<td></td>
</tr>
<tr>
<td>RMS blurring due to atmospheric dispersion</td>
<td>0.109 arcsec</td>
</tr>
<tr>
<td>Total size of detected return beam:</td>
<td>0.34 arcsec</td>
</tr>
<tr>
<td>Charge Diffusion</td>
<td></td>
</tr>
<tr>
<td>Charge Diffusion</td>
<td>0.25 pixels</td>
</tr>
<tr>
<td>Contribution due to Charge Diffusion</td>
<td>0.40 arcsec</td>
</tr>
<tr>
<td>Subaperture Diffraction</td>
<td></td>
</tr>
<tr>
<td>Lambda/d (for sensing)</td>
<td>0.83 arcsec</td>
</tr>
<tr>
<td>Spot size used for centroiding</td>
<td>0.99 arcsec</td>
</tr>
</tbody>
</table>

NGAO WFS design, Caltech Optical Observatories
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 \( y = ar^2 \rightarrow 0.69 \times 10^{-6} = 25 \times a \rightarrow a = 0.276 \times 10^{-7} \); \( \frac{dy}{dr} = 2 \times a \times r \rightarrow \frac{dy}{dr} = 0.2 \times 10^{-6} \) [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 sub-aperture spot size.
  – Acceptable centroid offsets (~0.1 pixel worst case)
  – Small amount of distortion (0.13%) will be calibrated using stimulus and acquisition camera.
  – Chromatic aberrations acceptable
• The dynamic range of the sensor is +/- 2 asec (within spec.)
• Atmospheric dispersion introduces 0.19 asec of spot blurring.
• The WFS relay is slightly out of spec., but sensitivity analysis reveal that this is not the bottleneck for performance with bright guide stars (request for change of specs).
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. This give us a p-value (ratio of pixel size to spot size) = 1

For sanity check, we also calculate the apparent spot size at the detector.

<table>
<thead>
<tr>
<th>Seeing</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural seeing FWHM at GS wavelength</td>
<td>0.43 arcsec</td>
</tr>
<tr>
<td>Subaperture Tip/Tilt corrected FWHM</td>
<td>0.20 arcsec</td>
</tr>
<tr>
<td>AO-compensated FWHM</td>
<td>0.06 arcsec</td>
</tr>
<tr>
<td>Contribution due to seeing</td>
<td>0.20 arcsec</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>System Aberrations</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Aberrations in AO thru to WFS</td>
<td>0.40 arcsec</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Atmospheric Dispersion</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>ADC in HOWFS? (NO)</td>
<td></td>
</tr>
<tr>
<td>RMS blurring due to atmospheric dispersion</td>
<td>0.109 arcsec</td>
</tr>
</tbody>
</table>

| Total size of detected return beam: | 0.34 arcsec |
| Charge Diffusion                |              |
| Charge Diffusion                | 0.25 pixels   |
| Contribution due to Charge Diffusion | 0.40 arcsec |

<table>
<thead>
<tr>
<th>Subaperture Diffraction</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Lambda/d (for sensing)</td>
<td>0.83 arcsec</td>
</tr>
</tbody>
</table>

| Spot size used for centroiding | 1.05 arcsec |

NGAO WFS design, Caltech Optical Observatories
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

Lenslet 1
Lenslet 2

Lenslet X & Y motion

Post-lenslet relay and camera focus

Whole WFS translation

NGAO WFS design, Caltech Optical Observatories
Modes of operation cont’d

Modes (Clockwise from top): 5x5, 63x63 and pupil imaging modes
Modes of operation cont’d
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)
21 um pixel detector with 63 spots with 4x4 pixels/sub-aperture.

63x63 sub-aperture NGS WFS spots
63x63 NGS WFS layout

NGAO WFS design, Caltech Optical Observatories
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
Post lenslet relay – grid distortion

The worst case sub-aperture spot motion due to distortion will be less than 0.1 of a pixel.
Pupil (HODM to Lenslet) mapping layout

HODM/tweeter
Triplet
Field stop (STOP)
Collimator
Lenslet plane
Grid distortion in pupil mapping

Extreme actuator-lenslet mapping is off by 2%
Chromatic effects in pupil mapping

Lenslet pitch is 50 um (same as scale)
Results of pupil mapping analysis

- Distortion in mapping of actuators to lenslets is >2% at the extreme sub-apertures.
- Point actuators are mapped onto >4 um RMS dia. Blobs [compare to influence function of an actuator].
- Chromatic effects make this blob as big as 12um (RMS) [compare to influence function of an actuator].
- Need to model chromatic effects all the way from the field points on the primary mirror with entrance window, LGS dichroic, w/ and w/o IF dichroic in the optical relay to the WFS lenslet and compare with the actuator influence function.
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]
5x5 NGS WFS layout

Reminder: The 5x5 and the 63x63 modes use the same post-lenslet relay
NGS WFS behind the NGAO optical relay

3D LAYOUT

NGAO WFS design, Caltech Optical Observatories

V. VELOUR
CALTECH OPTICAL OBSERVATORIES
M/C 11-17
CONFIGURATION: ALL 1
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.
NGS WFS operating in pupil imaging mode

- Total relay length = 260 mm
- Components from (left to right) – collimating doublet, field singlet, focusing doublet followed by the window and the detector.
- Wavelength of operation – 500-900 nm

This mode is for alignment only and doesn’t have any special requirement.

3D LAYOUT

TUE MAR 30 2010

V. VELUR
CALTECH OPTICAL OBSERVATORIES
M/C 11-17
NGS.WFS.63_W.RELAY_REVS_PI.ZMVX
CONFIGURATION: ALL 1
NGS WFS operating in pupil imaging mode
NGS WFS operating in pupil imaging mode
Preliminary tolerance analysis *(using built in tolerancing in Zemax)*

Since most of Zemax’s tools don’t work with a lenslet in the optical relay the simplest means to tolerance the WFS is to do it in 2 pieces, viz. post-lenslet relay and the collimator-to-lenslet part.
Preliminary tolerance analysis (using built in tolerancing in Zemax)

Nothing remarkable here!
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 and analyzed its performance
- Designed a compact WFS that works in 63x63, 5x5 and pupil imaging modes.
- Quantified the effects of color and distortion in mapping the HODM pupil to the lenslet.
- Did very preliminary tolerancing for the WFS.
- Made a list of outstanding issues and analysis for the DD phase.
- Built a compliance matrix and risk register.
Other issues

• 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)
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 \textit{[predicted and measured]}

\textbf{Read Noise vs. Frame Rate}

CCID-66 (actual, blue curve) and CCID-74 (predicted, orange curve) with 2 stage Planar JFET Readout

\textbf{Read Noise vs. Pixel Clock Rate}

CCID-66 (actual, blue curve) and CCID-74 (predicted, orange curve) with 2 stage Planar JFET Readout