Subaru Next Generation Wide Field AO: Ground Layer AO Simulation

Shin Oya (Subaru Telescope)
Subaru Next Generation AO Working Group
2013/5/9 @ Victoria
Subaru Next Generation Wide-Field AO

**Schedule**
- 2013: CoDR
- 2014: PDR
- 2016: FDR
- 2017: Integration / test
- 2019: First Light
- 2020: Science Observation

Diagram showing multi-laser, ASM, and multi-WFS components of the instrument.
What is GLAO?

• Corrects only turbulence close to the ground
• Improves seeing over wide-filed of view

Multiple guide stars are required to determine the ground layer strength
Early Results before 2013
Subaru GLAO configuration

\[ r = 5 \text{ arcmin} \]
\[ 7.5 \text{ arcmin} \]
\[ 10 \text{ arcmin} \]

DM: 32 act. Across @ -80m

RAVEN seeing:
- good: 0.52"
- moderate: 0.65"
- bad: 0.84"

\[ \star: \text{HoGS} \quad \oplus: \text{TTF-GS (50" inside of LGS)} \]
\[ \blacksquare: \text{PSF eval.(toward GS)} \quad \blacktriangle: \text{(between GS)} \]
\[ \star: \text{DM fitting} \]
Seeing dependence of WFE

Wavefront error

difference by FoV size (color) is small

seeing

bad (0.84")

moderate (0.65")

good (0.52")

tip/tilt ~ higher order (half & half contribution)

FOV: blue: $\phi = 10$ arcmin, green: $\phi = 15$ arcmin, red: $\phi = 20$ arcmin
WFE order: $\bigcirc$: all order, $\bigstar$: tip/tilt removed = higher order
Seeing: $\times$
Seeing dependence of FWHM

FOV: blue: $\phi = 10\text{arcmin}$, green: $\phi = 15\text{arcmin}$, red: $\phi = 20\text{arcmin}$
GLAO: ○, Seeing: ×
Dependence on the system order

- **Dependence on the system order**

**FoV:** 15' φ moderate seeing

**NGS simulation**

At shorter wavelength, lower order system performance is worse.

The system order will be determined by LGS brightness and WFS noise.

**Graph:**
- **Red line:** 32 act. across DM (& WFS)
- **Blue line:** 10 act. across DM (& WFS)

Note that the result for the combination of high-order DM (32 act. across) and low-order WFS (10 act. across) is the same as 10 act. across DM (&WFS).
The early results says

• Expected performance is 0.2" in the K-band under moderate seeing condition.

• The performance little changes by FoV between 10 arcmin and 20 arcmin; i.e., hardware (telescope of instrument) limits the available FoV.

• The system order as low as 10x10 results same performance at NIR wavelengths. The number of ASM actuator is determined by possible mechanical spacing range. S/N in a sub-aperture determines the number of WFS sub-aperture.

• No slide here, but see Oya+12, SPIE, 8447, 3V TTFGS < R=18, Frame rate of LGS WFS > 100Hz.
Recent Results
Seeing Model

Raven Model (Andersen+12, PASP124, 469) has been used
• free atmosphere: TMT site test (13N) (Els+09, PASP, 121, 527)
• ground layer: difference between Subaru IQ and 13N

Subaru Model

<table>
<thead>
<tr>
<th>percentile seeing</th>
<th>25%-ile (good)</th>
<th>50%-ile (moderate)</th>
<th>75%-ile (bad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>height</td>
<td>fractional contribution</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 km</td>
<td>0.4777</td>
<td>0.5507</td>
<td>0.5000</td>
</tr>
<tr>
<td>0.06 km</td>
<td>0.2055</td>
<td>0.1957</td>
<td>0.1872</td>
</tr>
<tr>
<td>0.5 km</td>
<td>0.0394</td>
<td>0.0605</td>
<td>0.0860</td>
</tr>
<tr>
<td>1 km</td>
<td>0.0137</td>
<td>0.0204</td>
<td>0.0359</td>
</tr>
<tr>
<td>2 km</td>
<td>0.1107</td>
<td>0.0234</td>
<td>0.0400</td>
</tr>
<tr>
<td>4 km</td>
<td>0.0488</td>
<td>0.0546</td>
<td>0.0518</td>
</tr>
<tr>
<td>8 km</td>
<td>0.0313</td>
<td>0.0429</td>
<td>0.0556</td>
</tr>
<tr>
<td>16 km</td>
<td>0.0731</td>
<td>0.0518</td>
<td>0.0435</td>
</tr>
</tbody>
</table>

$\int C_N^2 \times 10^{-13} \text{m}^{1/3}$

<table>
<thead>
<tr>
<th>$r_0(0.5\mu\text{m})$</th>
<th>14.9 cm</th>
<th>11.8 cm</th>
<th>9.1 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>fwhm(0.5\mu\text{m})</td>
<td>0.56”</td>
<td>0.73”</td>
<td>0.97”</td>
</tr>
<tr>
<td>fwhm(AG)</td>
<td>0.49”</td>
<td>0.64”</td>
<td>0.84”</td>
</tr>
</tbody>
</table>

Added to meet Subaru IQ

TMT site test

AG wavelength (0.73um) & outer scale corrected
Nea as a performance measure

Noise Equivalent Area \( = \frac{1}{\int \text{PSF}^2} \)

King+83, PASP, 95, 163

No need to assume profile, FWHM

- Limiting flux \( \propto \sqrt{\text{NEA}} \)
- Astrometry \( \propto \text{NEA} \)

In the case of Subaru GLAO
FWHM \( \sim 0.54\sqrt{\text{NEA}} \)
Relation between NEW and FWHM

$$\text{NEW} \equiv \sqrt{\text{NEA}}$$

NEW is roughly twice of FWHM

$$\text{FWHM} = 0.54\text{NEW} - 0.07$$

band: R, I, z, J, H, K

seeing: good: ○, moderate: △, bad: ×
Seeing model dependency

**RAVEN**
- Blue

**Subaru**
- Red

GLAO
- ○ & solid

Seeing
- × & dotted

NGS
- \( \varphi = 15 \text{arcmin} \)

Subaru model results
- -10% ~ +30% NEA compared with RAVEN model
Difference by ground layer

Subaru Model
- GL height of TMT site test (13N) is set to 60m
- The difference of Subaru IQ is set to 0m

if any change by some tweaks:
- raising the height of 60m to 100m
- combining 60m strength to 0m
- dividing 0m strength and put the half at 30m

The difference of results in
WFE < ~10%, NEA < ~20% (not so large),
GL turbulence evaluation needed to be more precise
Tip/Tilt/Focus GS config dependency

A-conf: TTGS adjacent to LGS

B-conf: TTGS between LGSs

B-conf results worse (WFE: ~10%, NEA: ~5%) than A-conf.
Adopt B-conf for further simulation for worse case estimation.
Guide Stars Configuration Dependency

Configuration: black NGS, blue: LGS-A, red: LGS-B
GLAO: ○, Seeing: ×  (φ = 15 arcmin)
Zenith angle dependency

NEA: red (solid): GLAO, blue (dashed): seeing

Seeing changes as Kolmogorov

GLAO gain over seeing decreases by 10\% at 45°, 20\% at 60°

Subaru moderate seeing
FoV: 15' φ
Zenith angle dependency: GLAO / Seeing

R-band

J-band

H-band

K-band

Subaru moderate seeing
FoV: 15' φ

NEA

loss by 10% at 45° and by 20% at 60°
Seasonal Variance of Seeing

Subaru IQ

Seasonal variation of Subaru median Seeing size (R band) 1999 - 2008

13N site, profile
Els+09, PASP, 121, 527 (Fig. 5)

Simulation of characteristic months
May (good) & Dec (bad).

<table>
<thead>
<tr>
<th></th>
<th>25%-ile</th>
<th>May (50%-ile)</th>
<th>50%-ile</th>
<th>Dec (50%-ile)</th>
<th>75%-ile</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.49&quot;</td>
<td>0.56&quot;</td>
<td>0.64&quot;</td>
<td>0.75&quot;</td>
<td>0.84&quot;</td>
</tr>
</tbody>
</table>

Subaru AG
Seasonal variation / all year

Seasonal difference of NEA

Seeing is bad in Dec, but GLAO correction is not bad.

Probably, the bad seeing in Dec is dominated by GL turbulence.

Season: Blue: May, Red: Dec
Solid: GLAO, Dotted: Seeing

Subaru moderate
$\varphi = 15\text{arcmin}$
Updates by recent results

• Seeing model revised, taking into account
  – Subaru Auto Guider wavelength (0.73um)
  – outer scale (30m)

• Introducing NEA: Noise Equivalent Area as performance measure
  – GLAO improves seeing by 20% ~ 70% in NEA basis

• Evaluating dependency on observation conditions
  – zenith angle: gain decreases by 10 % at 45°
  – seasonal variation: influence is small, if GL causes bad seeing should be checked for all months?
Comparison
## Simulation Conditions

<table>
<thead>
<tr>
<th></th>
<th>instatn_GLAO</th>
<th>MAOS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telescope diameter</td>
<td>7.92m</td>
<td></td>
</tr>
<tr>
<td>Central obstruction</td>
<td>1.265m</td>
<td></td>
</tr>
<tr>
<td>GS extent</td>
<td>15' diameter</td>
<td></td>
</tr>
<tr>
<td>GS number</td>
<td>6 hexagon</td>
<td>4 square</td>
</tr>
<tr>
<td>WFS</td>
<td>30x30 SH</td>
<td>32x32 SH</td>
</tr>
<tr>
<td>DM</td>
<td>31x31 SAM</td>
<td>33x33 ASM</td>
</tr>
<tr>
<td>Conjugation</td>
<td>-80m</td>
<td></td>
</tr>
<tr>
<td>Seeing</td>
<td>0.65&quot;</td>
<td></td>
</tr>
<tr>
<td>L0</td>
<td>30m</td>
<td></td>
</tr>
<tr>
<td>Turbulence layer#</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Turbulence height</td>
<td>0 ~ 1500m</td>
<td>0 ~ 16000m</td>
</tr>
</tbody>
</table>

No telescope aberration; No dome seeing (included in 0m in MAOS)
Comparison of Results

FWHM

NEA

Comparison of the simulation by Olivier and Shin: FWHM

Comparison of the simulation by Olivier and Shin: NEA

Surprisingly, both results agree quite well even with different turbulence profiles typically ~0.2" @ K

Band: R, J, H, K
X: instant_GLAO, +: MAOS
Contribution from the high layer is different though the fraction is small.
Gray-Zone

Contribution from the gray-zone can be said similar?.
Seeing
Seeing at Mauna Kea

Suitable for GLAO

• Ground layer turbulence is stronger than that of free atmosphere
  – Els+09, PASP, 121, 527

• Concentrate < 100m

• However, no GL turbulence data at Subaru modify TMT(13N) site test data to match Subaru IQ
  – Andersen+12, PASP, 124, 469

Simulation results depend much on the seeing condition.

We are preparing seeing profilers
Local ground-layer at Subaru?

- 70m below and leeward of the ridge (laminar flow?)
- Fine resolution data for more detailed simulation
Seeing measurement plan at Subaru

Luna Shabar (PTP) by Univ.BC
optical: 1 ~ 1000m

SNODAR by Univ. NSW
acoustic: 10 ~ 100m
Two important parameters for GLAO

In addition to the ground-layer turbulence strength, there are two important parameters for performance estimation of GLAO.

- **Gray-zone**
  Even with the same total turbulence strength, performance changes if the height and strength of 'gray-zone' changes.

- **Outer Scale**
  The wavelength dependency of natural seeing size changes by 'outer scale'. To estimate the gain of GLAO, not only GLAO corrected image size but also seeing image size is required. (GLAO performance little changes by outer scale, but seeing size does.)
Gray-zone turbulence for GLAO

\[
\theta = \frac{d}{h}
\]

gray zone 500m ~ 1500m
- lower: well corrected
- higher: uncorrected
Gray-zone impact on the performance

A test case in "Gemini GLAO feasibility study report" (Apdx.F1)

- The same total seeing strength
  \[ r_0 = 17 \text{cm}(0.6") \] @ 0.5 \text{ um}, \( L_0 = 30 \text{m} \) and 8m aperture

- But 3 different gray-zone cases of height & relative strength

<table>
<thead>
<tr>
<th>Altitude [m]</th>
<th>low &amp; week</th>
<th>medium</th>
<th>high &amp; strong</th>
</tr>
</thead>
<tbody>
<tr>
<td>10000</td>
<td>0.33</td>
<td>0.33</td>
<td>0.33</td>
</tr>
<tr>
<td>2000</td>
<td>0.07</td>
<td>0.07</td>
<td>0.07</td>
</tr>
<tr>
<td>900</td>
<td>-----</td>
<td>-----</td>
<td>0.40</td>
</tr>
<tr>
<td>500</td>
<td>-----</td>
<td>0.30</td>
<td>-----</td>
</tr>
<tr>
<td>300</td>
<td>0.15</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>0</td>
<td>0.45</td>
<td>0.30</td>
<td>0.20</td>
</tr>
</tbody>
</table>

J-band FWHM | GLAO : | 0.230" | 0.250" | 0.330"

GLAO performance changes even with the same total strength of seeing!!
Wavelength dependency: Seeing $\propto \lambda^{-0.2}$; fitting: $-0.28 \sim -0.62$

Seeing is better at longer wavelength for smaller outer scale ($L_0$).
Comparison of outer scale correction

Tokovinin02, PASP, 114, 1156 vs MAOS

A little difference at longer wavelength, but overall agreement is good.
Observational evaluation of outer scale

- General method is to evaluate tip/tilt correlation between two points with different baseline (e.g., Ziad+04, Appl. Opt., 43, 2316)
- For GLAO, the ratio of image size between optical and infrared is important (even not caused by outer scale).

Simultaneous FWHM measurement in V (AO188 HoWFS) & K (IRCS)

Simultaneous seeing measurement in V- and K-band

FWHM ratio (V/K): simulated vs observed

Consistent w/ L0=30m
Seeing

- Mauna Kea is known to be a suitable site for GLAO, should be checked if Subaru site is the same as ridge or TMT site.

- Subaru is preparing two profilers:
  - Lunar SHABAR: 1 ~ 1000m (gray-zone), optical
  - SNODAR: 10 ~ 100m

- Two important parameters on GLAO:
  - gray-zone: height & strength
  - outer scale: uncorrected NIR image size under certain optical seeing
    quick results by simultaneous FWHM measurement at VIS and NIR.