Sodium Laser Guide Star Issues: Modeling and Mitigation

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Presentation Outline

- TMT AO program
- Sodium Layer Fundamentals
- Overview of Issues Arising from LGS Elongation and range distance
  - Focus tracking
  - Signal to noise ratio
  - Biases and gains
- Algorithm developments
  - Undersampled images in subapertures
  - Noise-optimal gradient estimation: with real-time updates from:
    - dithering algorithm...
    - …and the TWFSs “Truth Wavefront Sensors”
- Planned sodium layer measurement campaigns: UBC LZT Lidar, UH-88, Lick
- Experiments in UVic lab
- AODP polar coordinate CCD development
- Summary
Narrow Field IR AO System (NFIRAOS)
- Mounted on Nasmyth Platform
- Feeds 3 science instruments
- Cooled to approx. -35°C

Laser Guide Star Facility (LGSF)
- Laser enclosure mounted on telescope elevation journal
- Launch telescope behind M2
- Conventional optics for beam transport

Science instrument AO functions
- IR tip/tilt wavefront sensors
- Field derotation at NFIRAOS interface
**NFIRAOS purposes**

- **Observatory Requirement Document specifications:**
  - Facility Laser Guide star AO system feeding three near infrared instruments 1.0 – 2.5 µm (goal 0.8 – 2.5 µm)
  - 50% sky coverage at galactic pole …with RMS tip/tilt jitter < 0.002”
  - Wavefront error: 191 nm RMS over 10” Field of View (FoV)
  - 85% throughput (goal 90%)
  - NFIRAOS must not increase inter-OH background by more than 15% of sky + telescope background
  - 2 arcminute beam fed to instruments
  - High encircled energy within 160 mas slits on a 2’ FoV for IRMS
  - High observing efficiency, fast instrument switching < 10 min., with a minimum of downtime and night-time calibration

- **Ready for commissioning at first light with low risk, reasonable cost**
Implications for NFIRAOS

Design Concept

- Excellent sky coverage
  - Multi-conjugate AO (multiple Deformable mirrors)
  - Sensing in the infra-red with “sharpened” tip/tilt/focus natural guidestars

- Excellent image quality on a moderate science FoV
  - Very high order system 60x60

- Very good throughput and background
  - Minimum surface count
  - Systems cooled to approximately -30 Celsius

- Commission system shortly following telescope first light
  - Use existing and near-term components/concepts when possible
  - Utilize Piezostack DM technology
    - Interactuator spacing of at least 5 mm
      - mechanically large system
  - Utilize CW laser guidestar technology
    - Guidestar elongation ➔ bright beacons, advanced algorithms
NFIRAOS Milestones

- Preliminary Design Phase July 07 to 4Q08
- Detailed design 2Q09 to 1Q11
- Subsystem Fabrication & Subsystem Test 2Q11 to 2Q13
- IRIS integrated with NFIRAOS 4Q13
- Start Packing & shipping to TMT 1Q15
- Ready to go on sky 4Q15
- First light 2Q16
NFIRAOS
Latest Optomechanics

- 2 Truth NGS WFSs
- 1 60x60 NGS WFS
- IR acquisition camera
- Input from telescope
- OAP
- 75x75 DM at h=12 km
- 63x63 DM at h=0 km
- Output to science instruments and IR T/T/F WFSs
- 6 60x60 LGS WFSs

IR
Visible
Laser
Sodium Beacon Issues for ELTs

- Well known laser beacon problems:
  - Cone effect..
    - Mitigated by multiple beacons probing atmosphere
  - Position uncertainty..
    - Need natural stars for Tip-Tilt measurement

- This presentation is about TMT efforts to understand, and develop solutions for, additional related error sources
  - arising from properties of the sodium layer,
  - which are significant for Extremely Large Telescopes.

- The edge of the TMT pupil is much further from the laser launch telescope than for any existing AO system
- Thus, the thickness of the sodium layer and its variability have a larger potential impact
Sodium Layer Properties

- Sodium layer is at finite altitude ~ 90 km
- Sodium layer has thickness ≥10 km
- Sodium layer has internal structure
- All these parameters are uncertain and vary with time
Lidar measurements of Sodium Layer

Purple Crow Lidar, University of Western Ontario
Three LGS AO error terms increase significantly with telescope aperture diameter $D$:

1. **Focus measurement errors** due to uncertainties in range ($\alpha D^2$)

2. LGS WFS **measurement error due to noise** -- varies with layer thickness ($\alpha D$ for fixed laser power)

3. LGS WFS **gain and offset errors** due to uncertainties in the vertical distribution of sodium (no simple scaling law)
   - Range and profile variations also induce (small) errors in tomographic wavefront reconstruction

Existing sodium LIDAR data provides temporal sampling at $\sim 0.01$ Hz

- **10-100 Hz rates** are needed to quantify these effects and optimize LGS AO system designs
Extracts from NFIRAOS Error budget

TMT work to confirm and/or mitigate these terms described next.

<table>
<thead>
<tr>
<th>Item</th>
<th>nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>LGS WFS Noise</td>
<td>38.6</td>
</tr>
<tr>
<td>Focus Tracking</td>
<td>18.9</td>
</tr>
<tr>
<td>LGS spot position estimation error (linearity)</td>
<td>14</td>
</tr>
<tr>
<td>TWFS - Offset measurement and lag errors</td>
<td>10</td>
</tr>
<tr>
<td>Dithering - Gain measurement and lag errors</td>
<td>10</td>
</tr>
<tr>
<td>Anisoplanatism due to layer thickness</td>
<td>0</td>
</tr>
<tr>
<td>Perspective non-linear foreshortening</td>
<td>0</td>
</tr>
</tbody>
</table>
Design, development, and risk reduction activities include:

- High speed (electronic) focus offsets to LGS WFSs (HIA)
- Noise-optimal LGS WFS gradient estimation algorithms (CfAO and TMT)
- Update LGS WFS centroid gains and offsets in real time (HIA)
- Elongated LGS simulator (University of Victoria)
- “Polar Coordinate” LGS WFS CCD
- Sodium layer range and profile measurements (UBC LIDAR system)
- Sodium layer profile measurements (Lick and UH88+Gemini)
Focus Tracking

- Sodium altitude variation introduces defocus errors for LGS AO on TMT and other large aperture telescopes
- Sensitivity grows $\sim D^2$
- Focus sensing via natural guide stars, with good sky coverage, leaves residual servo errors
- Residual WFE = $f$(Natural Guide Star sky coverage)
Defocus Wavefront error $\sim D^2$

RMS wavefront focus error 187 nm from $\Delta h = 23$ m defocus is entire budget for TMT NFIRAOS

$$\sigma = \frac{1}{8\sqrt{3}} \frac{D^2}{h^2} \Delta h$$

Defocus peak-valley wavefront error $\sim D^2$

- $D = 10$ m pupil
- $D = $ TMT pupil

$h = 90$ km

$\Delta h$
Sample Sodium LIDAR Data (University of Western Ontario and Colorado State University)

Time History of 80 Profiles at ~0.01 Hz

\[ y = (1.79 \pm 0.02)x + 1.12 \pm 0.40 \]

Mean range vs. time

Range PSD (10^{-4} to 2 \times 10^{-3} Hz) from 34 nights of LIDAR data
Temporal frequencies overlap: turbulence focus and Na altitude defocus

Atmospheric Focus
PSD $\text{nm}^2/\text{Hz}$

Focus PSD $\text{nm}^2/\text{Hz}$ from Na altitude variations at 30-m telescope

$V = 15 \text{ km/h}$

$r_0 = 0.15 \text{ m @ 500 nm}$
LGS Zoom Optics

- 6 Separate zoom channels -- 1 for each guide star

- Stages move 1 m for Na ranging from 85 to 235 km

- (~0.1 Hz mechanical bandwidth)

- 6 stationary SH WFSs

- 3 stages per channel with small spherical optics
Sodium Layer Electronic Focus Offset for 30-m Telescope
Residual error after electronically refocusing via NGS measurements

Latest results from the CSU Lidar
56 time series, each >7 hours duration
90 Hz electronic focus offsets applied to LGS WFSs
50% sky coverage at galactic pole.
Guide stars appear elongated due to depth of sodium layer.

Elongation given to first order by:

$$\theta \approx \frac{hr}{H^2}$$

$$\approx 3 - 4 \text{ arc sec}$$

$$>> 1 \text{ arc sec (approx. LGS FWHM)}$$

Will significantly degrade LGS WFS accuracy for standard designs and algorithms.
Elongated Pattern on CCD

- Reduced signal to noise since photons spread across ~ 16 pixels.
- Shack-Hartmann Spots – CW laser
Sodium Layer Structure is helpful

- Sodium layer has internal structure
  - Can be used to assist centroiding of undersampled spots via a matched filter algorithm
  - Matched Filter and Undersampled images mean fewer pixels
    - enabling faster readout
    - and better signal to noise ratio,
    - or more affordable laser power

<table>
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<tr>
<th>Measurement Method</th>
<th>mas error</th>
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</thead>
<tbody>
<tr>
<td>NGS</td>
<td>14</td>
</tr>
<tr>
<td>Elongated LGS - Centroiding</td>
<td>87</td>
</tr>
<tr>
<td>Elongated LGS - Matched filter</td>
<td>58</td>
</tr>
</tbody>
</table>

For a subaperture at edge of pupil
Modeling LGS Spot Elongation

Convolution of 3 terms:

- Atmos. Turbulence
- Subaperture PSF
- Sodium layer profile

Undersampled Image (0.5” pixels)
Matched Filters for X & Y displacement measurement

- X matched filter
- Image
- Y matched filter

Dot Product

X motion

Dot product

Y motion
LGS WFS Transfer Curves with Ideal Gain and Offset Calibration

0.5 m LLT-to Subaperture offset

14.5 m LLT-to Subaperture offset
Caveat – Undersampled matched filter & Na structure

- But internal structure of sodium layer varies with time
  - aliasing varies on WFS detector
- Centroiding gain and null point must be updated in real time for matched filter algorithm
- We plan to use LGS dithering and Truth WFSs to separately update gains and offsets
  - Background task to create new matched filters at ~0.1 Hz described on later slides
WFE due to tilt estimate biases for an 0.01 Hz algorithm update rate yields an RMS OPD of ~18 nm after focus removal.
Update Processes

- LGS dithering process and Truth WFSs separately update gains and offsets
LGS dithering is a background process to update gains at ~0.1 Hz.

Background task at ~0.1 Hz

Real time task at 800 Hz

Dithering Gain Estimator → Update Matched Filter → Centroid WFS spots
“Centroid Gain” estimation

- Dither algorithm
  - Must determine both sign and magnitude of
    - Derivative of intensity vs tilt in subaperture
    - For each pixel, in both X and Y directions

- Robust in face of uncertainties in round trip delay to Na layer, and LGS pointing fast steering mirror transfer function

- Block diagram detail on next slide
Centroid Gain Dither Block Diagram

- **LGS WFS**
- **LGSF Pointing Mirror**
- **Gain Estimator**
- **Synchronous Detector**
- **Phase Locked Loop**
- **Tilts**
- **Gain**
- **Pixel Intensities**
- **Na Layer**
- **Dither Signal**

**Equation:**

\[ \approx \]
Top Level Simulink Model

Phase Locked Loop

Synchronous Detector
X & Y Derivatives (Pixel Gains)

- Produced by dithering algorithm

![Simulink gain X](image1)

![Simulink gain Y](image2)
Centroid offsets established by Truth WFSs

- Recall that matched filter is built around a nominal operating point.
- This offset (null point) depends on
  - non-common path errors and
  - apparent offsets due to aliasing sodium layer structure
- NFIRAOS monitors a Natural Guide Star via (High-order low-bandwidth) HOL Truth WFS, < 0.1 Hz, with oversampled...
  - Subapertures: 120x120 SH WFS
  - CCD spots: 8x8 pixels each SH spot
- Centroiding biases are mostly radially symmetric, low order, and rapid
  - Second, MOR Truth WFS (Moderate Order Radial) ~6x6SH, ~10 Hz
- Offsets calculated and fed to Real Time Computer

NGS WFS deployable to control DM without lasers
Architecture for LGS WFS Gain, Offset, and Focus Correction in Real Time

Tilt at 50-500 Hz

WFS

“Centroid”
Gain Estimation

Gains, TBD Hz

伐

TBD Hz

Elect. Focus 10-800 Hz

Offsets, TBD Hz

Wavefront Estimation

Visible higher-order WFS

Focus Lens

LGS WFS

Gradient Estimation

IR tip-tilt-focus WFS

Focus

Tip-tilt mirror

DM(s)

LGS

NGS
UH-88 & Lick: Na Profile Streak Camera Campaigns

- Drift Scan Photography of Gemini, Keck or Lick Laser streaks
- Viewing telescope at fixed coordinates (not tracking) while Laser is propagating near zenith
- Lick
  - 100 m vertical resolution
  - 1 second time resolution
- UH88"
  - length of plume = 29"
  - height resolution = 1" = 340 m
  - 0.1 second time resolution

Lick Na laser, from the 1-m Nickel telescope 600 m west

drift-scan image; time resolved in the direction orthogonal to the streak

--Don Gavel
Lidar Campaign
University of British Columbia

- 50 Hz sampling – 24 m resolution
- Long time records (all night) – improve accuracy of PSD

- Pulsed laser, launch telescope.
- 6 m Liquid Mirror telescope – high sensitivity
- Campaign to begin late 2007
Source plays movies of sodium profiles at 10 Hz as CCD integrates during each sweep of focus by DM

Used to test Centroid Gain and Truth WFS algorithms.
Polar coordinate CCD Pixel Geometry for Laser Guidestars

- Faster Readout
- Lower Readout Noise
- Higher SNR—with or without dynamic refocusing
Subaperture array size finalized in June
30x30 prototype layout completed in September
Wafer run (PanStarrs) in early November
Devices available for wafer probing around in February 2008
Testing and characterization of the device at LAO in April 2008
Initial report available in June 2008
Summary

- Sodium Layer mean altitude, thickness and structure varies on short time scales 0.1-100 Hz
  - causing focus errors and high-order measurement errors.
- Non-zero thickness of Na layer causes
  - Spot elongation
  - reduces signal to noise ratio
- Arsenal brought to bear on mitigating these problems
  - Electronic offsets
  - Matched filter
  - On-Instrument WFSs
  - Truth WFS
  - Dithering
  - Polar coordinate CCD
  - Na measurement campaigns
  - Lab experiments