Adaptive Optics for the Thirty Meter Telescope

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Presentation Outline

- TMT adaptive optics (AO) requirements
- The first light TMT AO system design
  - Narrow Field Infra-Red AO System (NFIRAOS)
  - Laser Guide Star Facility (LGSF)
- AO component development
- Summary
The Thirty Meter Telescope (TMT) Project

- Intends to build a Thirty Meter Telescope for ground based, visible and near infra-red astronomy
- Is a collaboration of:
  - The Association of Canadian Universities for Research in Astronomy (ACURA)
  - The University of California
  - The California Institute of Technology
  - NAOJ (participant), NAOC (participant), and India (observer)
- Is now concluding a Design and Development Phase (DDP) to
  - Establish the system design
  - Determine the cost and schedule
  - Select a site (Mauna Kea 13N)

- Construction scheduled to begin in 2012-13
- First light to follow after a 7-year construction schedule
The TMT Design

- Ritchey-Chretien optical design form
- D = 30 m, f/1 primary
- 492 1.42m segments
- 3.05 m convex secondary
- f/15 output focal ratio
- 15 arc min unvignetted FOV
- Articulated tertiary
- Nasmyth-mounted instrumentation
Many TMT Observations Require High Angular Resolution

- Studying the spatial structure and star formation regions of distant galaxies
- Precision astrometry and photometry of crowded star fields
  - Has been used to determine star orbital dynamics and “weigh” the black hole at the center of our galaxy
- Direct detection and characterization of extra-solar planets
  - Expected star-to-planet contrast ratios from $10^6$ to $10^9$
- Real-time atmospheric turbulence compensation via adaptive optics (AO) enables high resolution observations such as these from the ground
Sample AO Results on Large Telescopes

Galactic Center Astrometry (Keck LGS AO)

Multi-Conjugate AO on a 2’ FoV (VLT)

LGS AO Science Papers vs. Year (All)

Classical AO

Imaging of Extra-Solar Planets (Keck/Gemini)

M Liu, 2008

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Numerous LGS AO Systems Are Now Operational

- Keck II, Gemini-North, VLT, Palomar, Lick, William Herschel Telescope, SOAR
- Others to come: Gemini-South, Keck I, Subaru

Propagation of 3 laser guide stars at Mauna Kea (Keck I, Keck II, Subaru)

Propagation of the Gemini-South 50W laser and 5-LGS asterism
Can Adaptive Optics Be Scaled to Future Extremely Large Telescopes?

From Page 7-25 of the Astro2010 Report of the Panel on Optical and Infrared Astronomy from the Ground:

- AO for GSMT-scale telescopes [Giant Segmented Mirror Telescopes] is practical given current technology.
- Deformable mirrors, wavefront sensors, tomographic reconstruction algorithms, and lasers all exist in prototype forms that will be straightforward to scale to the requirements for a GSMT.
- The TMT project has completed a preliminary design for their first-light AO system, NFIRAOS, which could be constructed today using existing technologies.
TMT AO Requirements at Early Light (1/2)

- **Diffraction-limited** near IR image quality over a “narrow” field-of-view of 10-30 arc seconds
  - Order 60x60 wavefront compensation
  - Multi-conjugate AO (MCAO) with 6 guide stars and 2 deformable mirrors (DMs)

- **50% sky coverage** at the galactic pole
  - Laser guide star (LGS) wavefront sensing
  - Low order (tip/tilt/focus) natural guide star (NGS) wavefront sensing in the near IR with a 2 arc min patrol field

- **High throughput** in J, H, K, and I bands, with low emission
  - Minimize optical surface count
  - Cooled (-30C) optical system
TMT AO Requirements at Early Light (2/2)

- **Excellent photometric and astrometric accuracy**
  - Well characterized and stable point spread function
  - Telemetry for PSF reconstruction
  - Three low-order NGS WFS for tilt anisoplanatism compensation
  - Well characterized and stable focal plane plate scale and distortion

- **High observing efficiency**
  - Automated, reliable system
  - Minimal downtime and night time calibration

- **Available at first light with low risk and acceptable cost**
  - Utilizing existing/near-term AO technologies
  - Design AO into TMT from the start
**Derived TMT AO System Architecture**

- **Narrow Field IR AO System (NFIRAOS)**
  - Mounted on Nasmyth Platform
  - Interfaces for 3 instruments
  - 4-OAP, distortion free design

- **Laser Guide Star Facility (LGSF)**
  - Laser launch telescope mounted behind M2
  - Lasers mounted on TMT elevation journal
  - All-sky and bore-sighted cameras for aircraft safety (not shown)

- **AO Executive Software**
NFIRAOS Optical Layout
Recent Design Improvements to NFIRAOS

- New low-distortion, 4 off-axis parabola (OAP) design
- Larger volume (~2x) permits simplifications/savings
  - Space frame design for optical support
  - Simplified turbulence simulator
  - Simplified laser guidestar wavefront sensor
- Other subsystem simplifications and savings
  - Thermal enclosure
  - Instrument selection fold mirror
  - Acquisition camera
  - Optical source simulators
Field Distortion and NFIRAOS

- Original NFIRAOS design was a off-axis parabola (OAP) relay
  - Good image quality
  - High distortion; 0.4 arc sec at edge of field
- New design is based upon 4 OAPs, and eliminates the distortion
Space Frame Optics ‘Table’
Laser System within telescope azimuth structure
- For large lasers requiring a fixed gravity vector, frequent alignment and maintenance

LLT behind TMT M2
- Minimizes LGS elongation; was also thought to minimize wavefront error due to noise

Mirror-based beam transport between the lasers and the LLT
Recent Design Improvements to the LGSF

- Lasers now mounted on the telescope elevation structure
  - Feasible with new laser system designs
  - Reduces beam transport path length
  - Eliminates “deployable duct” to transfer beams from azimuth to elevation structure

- Beam transfer optical path changed to match modifications to the telescope structural design

- LGSF top end repackaged to reduce height and wind cross section

- New laser launch telescope (LLT) design with improved performance and enlarged field-of-view

- Laser guide star acquisition sensor added
New LGSF Architecture and Laser Location on the Telescope Elevation Journal
**AO Component Technology Choices**

- **Laser Guide Star Facility (LGSF)**
  - Solid state Nd:YAG sum frequency laser or Raman fiber laser
  - Conventional optics (not fiber-based) beam transport

- **Narrow Field IR AO System (NFIRAOS)**
  - Piezostack actuator deformable mirrors and tip/tilt stage
    - Sufficient stroke and small hysteresis at -30C
  - “Polar coordinate” CCD array for the LGS WFS
    - Reduces impact of laser guide star elongation
  - HgCdTe CMOS array for the IR low order NGS WFS
    - Performance enables 50% sky coverage
  - Computationally efficient real-time control algorithms implemented on DSP and FPGA hardware
    - Reduced cost and improved flexibility compared with conventional processing architectures
### AO Component Requirements Summary

<table>
<thead>
<tr>
<th>Component</th>
<th>Key Requirements</th>
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<tr>
<td>Deformable mirrors</td>
<td>63x63 and 76x76 actuators at 5 mm spacing</td>
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<tr>
<td></td>
<td>10 μm stroke and 5% hysteresis at -30°C</td>
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<tr>
<td>Tip/tilt stage</td>
<td>500 mrad stroke with 0.05 mrad noise</td>
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<td></td>
<td>20 Hz bandwidth</td>
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<td>NGS WFS detector</td>
<td>240x240 pixels</td>
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<td>~0.8 quantum efficiency, ~1 electron at 10-800 Hz</td>
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<tr>
<td>LGS WFS detectors</td>
<td>60x60 subapertures with 6x6 to 6x15 pixels each</td>
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<tr>
<td></td>
<td>~0.9 quantum efficiency, 3 electrons at 800 Hz</td>
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<tr>
<td>Low-order IR NGS WFS</td>
<td>1024x1024 pixels (subarray readout on ~12x12 windows)</td>
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<tr>
<td>detectors</td>
<td>0.6-0.8 quantum efficiency, 3 electrons at 10-200 Hz</td>
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<tr>
<td>Real time controller</td>
<td>Solve 35k x 7k reconstruction problem at 800 Hz</td>
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<td>Sodium guidestar lasers</td>
<td>20-25W, near diffraction-limited beam quality</td>
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<td>Coupling efficiency of 130 photons-m²/s/W/atom</td>
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Wavefront Correctors: Prototyping Results

Subscale DM with 9x9 actuators and 5 mm spacing demonstrated 10 μm stroke, 5-6% hysteresis at -30C (2006)

Prototype Tip-Tilt Stage (2009)

Simulated DM Wiring included in bandwidth demonstration

-3dB TTS bandwidth of 107 Hz at -35C

60x6 actuator breadboard will qualify new piezo material source and validate FEA models for thermal distortion (2012)
“Polar Coordinate” CCD Array Concept for Wavefront Sensing with Elongated Laser Guidestars

- D = 30m
- Elongation ∼ 3-4” at 15m separation
- H=100km
- sodium layer ΔH =10km

Fewer illuminated pixels reduces pixel read rates and readout noise

MIT/LL CCD Design

TMT.AOS.PRE.11.085.REL01
NFIRAOS Visible Wavefront Sensor Detector Prototyping

- Prototype wafer fabrication completed at MIT/LL
  - Single quadrant prototype of polar coordinate LGS WFS CCD
  - 256² and 160² NGS WFS CCDs
- Good results obtained in initial probing of 160² CCDs and polar coordinate devices.
- Devices have now been diced, and packaged
  - Tests in progress
  - Results expected end of October

Image of the front side of a finished wafer
Other AO Component Development Activities

- Sodium guidestar lasers
  - TIPC design studies, prototyping, and on-sky tests at Yunan and UBC
  - Also monitoring laser development for ESO and Keck (TOPTICA)
- Real Time Controller (RTC) electronics, software, and algorithms
  - Conceptual design studies completed (tOSC and DRAO)
- Hawaii 2RG HgCdTe detectors for low order NGS wavefront sensing
  - Recent tests demonstrate that required detector readout noise is achieved at specified pixel read rates (Caltech)
- Deformable mirror drive electronics
  - Prototyping underway (HIA)
- WFS detector readout electronics
  - Proposed conceptual design reviewed in July (Keck)
Summary

- TMT has been designed from the start to exploit AO
  - Facility AO is a major science requirement for the observatory
- The overall AO architecture and subsystem requirements have been derived from the AO science requirements
  - Builds on demonstrated concepts and technologies, with low risk and acceptable cost
- AO subsystem designs have been developed
- Component prototyping and lab/field tests are underway
- Analysis/simulation confirm the designs meet requirements
- Construction phase schedule leads to AO first light in 2019-2020 time frame
- Upgrade paths are defined for improved performance and new capabilities during the first decade of TMT