TMT: the next generation of segmented mirror telescopes

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SSL 50th
2009 August 30
Topics

- Brief history of telescopes
- Motivation for segmented mirror telescopes
- Keck Observatory and its technology
- Other segmented mirror telescopes
- Adaptive Optics
- The future of segmented mirror telescopes: TMT
Science Potential

- Solar system detailed studies
- Direct imaging planets around nearby stars
- Stars and stellar evolution
- Black holes and galaxies
- Nearby galaxies
- Distant galaxies and first light
Herschel’s 1.26m telescope

- 1789 Herschel’s largest telescope
- Discovered physical binary stars (gravity works outside solar system)
- 1800 Herschel discovered infrared radiation
Rosse’s 1.83m telescope

- 1845 Rosse metal mirror telescope
- Discovered spiral nebulae (galaxies)
Giant telescopes

**Optical Telescopes**
- Mt Wilson 1918 2.5m
- Palomar 1948 5m
- Lick 1965 3m
- Keck 1,2 1993, 1996 10m
- Gemini 1999 8m
- VLT 1999-01 4 x 8m
- GTC 2009 10m
Largest Aperture Optical Telescopes

-5.00  -4.00  -3.00  -2.00  -1.00  0.00  1.00  2.00  3.00  4.00

1500  1550  1600  1650  1700  1750  1800  1850  1900  1950  2000  2050  2100

year

log10 collecting area (meters^2)

TMT

Galileo
Lippershey
Newton
Herschel
Keck
Soviet
Hale

refractors
reflector - speculum
reflector - silver on glass

human eye
Giant astronomical optics issues

- Optical goals are typically invariant with size, errors must be \( \sim \lambda/10 \)

- How do telescope issues scale with size? If we scale all dimensions by \( s \):
  - Mass grows as \( s^3 \) (volume)
  - Wind loads grow as \( s^2 \) (cross sectional area)
  - Stiffness increases as \( s \) (as in \( k = dF/dx \), \( k \) is stiffness)
  - Deflections grow as \( s^2 \) (gravity)
  - Natural frequencies grow as \( s^{-1} \) (as in \( \omega = (k/m)^{1/2} \))
  - Stresses increase as \( s \) (gravity loads)
Why are large telescopes hard

Monolithic mirrors
  - Mirrors get thick and heavy
  - Hard to cast blank
  - Equipment for polishing big
  - Handling systems large
  - Mirror support gets very delicate
  - defl $\sim$ diameter$^4$/thickness$^2$
  - Mirror transportation difficult
  - Mirror coating chamber large
Segmented Mirrors

- Smaller mirrors thinner and lighter
- Eases all the difficulties listed above
- Lowers overall mass and cost

- Added difficulties
  - Polishing mirror segments
    - Not axisymmetric
  - Segment positions require active position control
    - Gravity deformations of telescope ~ 1mm
    - Thermal deformations ~ 1mm
    - Need surface alignment to ~ 20 nm
The Keck Telescopes
• Keck Telescopes on Mauna Kea
Keck active control geometry

- 36 hexagonal segments
- 3\times36=108 actuators
- 2 edge sensors/edge
  - 168 edge sensors
Principle of active control with edge sensors

- Actuator (piston)
- Sensor (measures height difference)

Sensor signal depends only on motion of two neighbor segments

\[ s = a_1 P_1 + a_2 P_2 + a_3 P_3 + a_4 P_4 + a_5 P_5 + a_6 P_6 \]

\( a \) are constant coefficients that depend only on geometry

For Keck final step is to solve 168 equations in 108 “unknowns” This is easy
Keck Sensor Geometry

R = 35 m

Mirror Segment

7.5 cm

Conducting Surfaces

Sensor Mount

Sensor Body

Sensor Paddle

2 mm

L
Sensor Overview

- Sensors are used to measure relative positions of segments.
- Sensors mount to segment edges with electronics mounted remotely.

Each sensor consists of a send and receive head facing each other across the segment gap.

- Each sensor half has its own right-handed coordinate system. The origin, and x and y axes, lie in the optic.
TMT P1 Capacitive Edge Sensor

- Has two separate outputs: $V_g = dy$ (gap) and $V_z = dz + dQ_x$ (piston+dihedral)
- $dz$ (piston) signal is proportional to
  (sense-to-drive1 overlap area) - (sense-to-drive2 overlap area)

- $dQ_x$ (dihedral) signal is proportional to
  $1/(sense-to-drive1 \ gap) - 1/(sense-to-drive2 \ gap)$.

- $dy$ (gap) signal is proportional to the sum (vs. difference) of the currents induced by drive1 and drive2, goes as $1/gap$.

- $\text{Leff}\ (dVz/dQ_x$ goes as $1/gap$
Gran Telescopio Canarias (GTC)

- 10-m telescope
- GTC completed in 2009
- Closely follows design of Keck
- On La Palma, Canary Islands
Hobby-Eberly Telescope (HET)

- Segmented mirror telescope
- 91 segments
- Spherical primary
- Segments not phased
- Very inexpensive
- Started science 1999
SALT Telescope

- Similar in design to HET
- Completed in 2005
- Unphased segments
- No infrared capability
- Fixed elevation angle
Other future giant telescopes: GMT

- Giant Magellan Telescope
- Seven 8m mirrors
- ~22m effective diameter
- Consortium of ~8 institutions and countries
- Completion 2018
- Cost?
Other future giant telescopes: EELT

- ESO is planning a 42m segmented mirror telescope
- 900 segments, 1.4m
- 6 mirrors to instruments
- One mirror is adaptive
- Completion date 2018
- Cost ~1.5$B
Adaptive Optics
Adaptive Optics

- Adaptive optics seriously introduces the concept of high speed, high bandwidth control
  - Primary aim is to remove rapidly varying atmospheric turbulence that causes image blur
  - Secondary bi-product is ability to remove static, slowly varying and rapidly varying wavefront errors that are in the telescope
- As currently envisioned and used, adaptive optics is only practical in the near infrared, not the visible.
- Adaptive optics is technologically challenging!
- Result is diffraction-limited performance
  - AO is revolutionary
  - For TMT resolution of 0.005 arcsec 100x better than atmosphere
Basic Elements of Adaptive Optics

- Atmospheric turbulence...
- Introduces wavefront and image quality degradations...
- Which can in principal be compensated by a wavefront corrector...
- Provided that they can be measured with a wavefront sensor...
- Observing a suitable reference star
Feedback loop: next cycle corrects the (small) errors of the last cycle

Adaptive Optics
Na Laser Tomography and MCAO

Na laser beams (6 total)

Na layer (~10 km)

35 arcsec

Turbulent atmosphere (~15 km)

30 m

Light from 1 arcmin off axis

“Meta-pupil” for a +/-1 arc min FoV

DM conjugate to h = 0 km

DM conjugate to h ~ 10-12 km

Na Laser Tomography and MCAO

90 km

starlight
Distant Galaxies – TMT+AO

Credit: M. Bolte

- TMT with AO angular resolution
  100x better than seeing limited

30m + adaptive optics resolution
NFIRAOS has two deformable mirrors- MCAO
- 64x64
- 73x73

NFIRAOS laser will produce 6 laser spots
- Illuminates Na layer, 90km up in the atmosphere
- 150 Watts Na power
- One central spot, 5 perimeter spots

Two arc minute field of view

Atmosphere is tomographically reconstructed, then projected out in the direction of interest

Computationally intensive
- Solve 38000x7000 control problem at 800 Hz
Why build a 30-m telescope: huge aperture advantage

- Seeing-limited observations and observations of resolved sources
  \[ \text{Sensitivity} \propto \eta D^2 \ (\sim 14 \times 8\text{m}) \]

- Background-limited AO observations of unresolved sources
  \[ \text{Sensitivity} \propto \eta S^2 D^4 \ (\sim 200 \times 8\text{m}) \]

- High-contrast AO observations of unresolved sources
  \[ \text{Sensitivity} \propto \eta \frac{S^2}{1-S} D^4 \ (\sim 200 \times 8\text{m}) \]

- High-contrast ExAO observations of unresolved sources
  \[ \text{Contrast} \propto D^2 \ (\sim 14 \times 8\text{m}) \]
  \[ \text{Sensitivity} \propto \eta D^6 \ (\sim 3000 \times 8\text{m}) \]

\[ \text{Sensitivity} = \frac{1}{\text{time required to reach a given s/n ratio}} \]
\[ \eta = \text{throughput}, \ S = \text{Strehl ratio}, \ D = \text{aperture diameter} \]
Project Introduction

- **Time line**
  - 2004: project start, design development
  - 2009: preconstruction phase
  - 2011: start construction
  - 2018: complete, first light, start AO science

- **Partnership**
  - UC
  - Caltech
  - Canada
  - Japan
  - NSF?
  - Other nations?

- **Cost**
  - 970M$ (2009$)
TMT Mauna Kea

- Best high-altitude seeing
- 4200 m
5 Meter
Hale 200-inch Mirror

10 Meter
Keck Mirror

30 Meter
TMT Mirror
What is TMT?

- Thirty-meter aperture
- Filled, segmented primary
- Elevation axis in front of primary
- Active and adaptive optics
- UV to thermal IR
- Broad range of instruments
TMT features

- 14 - 200 times the sensitivity of 8 m telescopes ($D^2 - D^4$ gain)
- 3 - 5 times the resolution of 8 m telescopes and JWST
- 20 arcmin field of view
- 5 AO modes
- Pointing in < 3 min
- Instrument change in < 10 min
- Calotte enclosure
Nasmyth Configuration: First Decade Instrument Suite
TMT AO Early Light Architecture

- **Narrow Field IR AO System (NFIRAOS)**
  - MCAO LGS AO System
  - Mounted on Nasmyth Platform
  - Feeds 3 science instruments

- **Laser Guide Star Facility (LGSF)**
  - Laser enclosure located within telescope azimuth structure
  - Conventional optics for beam transport
  - Laser launch telescope behind M2

- **AO Executive Software (AOESW)**

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**NFIRAOS:**
- 190nm RMS WFS
- 60x60 order system
- 2 DMs, 6 LGS, 3 TTF WFS
- 800Hz
Primary Mirror Segments

- TMT segmented mirror is an evolution of the Keck mirror
- 36 segments, 1.8m, in each Keck telescope
- 492 segments, 1.45m, in TMT
- Polishing and segment module fabrication must be “mass produced” to cost and quality
- TMT is working with industrial partners to compete production design, testing and cost
Segment Support Assembly (SSA) Design

- Seven Segment Assembly – Top View
Segment Support Assembly (SSA) Design

- Seven Segment Assembly – Bottom View
<table>
<thead>
<tr>
<th>Instrument</th>
<th>Spectral Resolution</th>
<th>Science Case</th>
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<tbody>
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<td>Near-IR DL Spectrometer &amp; Imager (IRIS)</td>
<td>~4000</td>
<td>● Assembly of galaxies at large redshift&lt;br&gt;● Black holes/AGN/Galactic Center&lt;br&gt;● Resolved stellar populations in crowded fields&lt;br&gt;● Astrometry</td>
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<td>● Stellar abundance studies throughout the Local Group&lt;br&gt;● ISM abundances/kinematics, IGM characterization to z~6&lt;br&gt;● Extra-solar planets!</td>
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## TMT Early Light Instrument Suite

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The spatial resolution of the TMT will allow a dramatic advance in the work in the Galactic Center.

Will be able to probe the “strong regime” of General Relativity near the surface of the Black Hole.
Summary

- TMT will be a 30-m telescope with AO capabilities from the start
  - ~190 nm rms wavefront error over 10 arcsec
  - First light 2018

- Very large and exciting science case

- 8 instruments planned for the first decade

- 3 instruments planned for first light
  - IRIS (an AO NIR integral field spectrograph and imager)
  - IRMS (an AO NIR multi object spectrometer (46 slits)
  - WFOS (a seeing-limited multiobject spectrometer with R<8000, and ~50 arcmin²coverage)
www.tmt.org/foundation-docs/index.html

- Detailed Science Case 2007
- Observatory Requirements Document
- Observatory Architecture Document
- Operations Concept Document
- TMT Construction Proposal
  - Currently in use for funding proposals