The Thirty Meter Telescope: How California, Canada, China, India and Japan are Working Together to Build a Next Generation Extremely Large Telescope

Gary H Sanders
SLAC National Accelerator Laboratory
September 18, 2013
TMT on Mauna Kea
Sharper Vision with TMT: Distant Galaxies from Space and Hawaii Island

Hubble Deep Field

HST resolution

TMT

30m + adaptive optics resolution
Why build a 30 meter telescope?

- Light collection $\sim$ diameter$^2 = D^2$
  - Sets limit on sensitivity of “seeing-limited” observing
- TMT will have
  - 144 times the light collection and sharper optical resolution than the Hubble Space Telescope, and
  - 36 times the light collection of the Palomar telescope
  - 9 times the light collection of the Keck telescopes
"It is impossible to predict the dimensions that reflectors will ultimately attain. Atmospheric disturbances, rather than mechanical or optical difficulties, seem most likely to stand in the way. But perhaps even these, by some process now unknown, may at last be swept aside. If so, the astronomer will secure results far surpassing his present expectations."

- Hale, Study of Stellar Evolution, 1908 (p. 242) writing about the future of the 100 inch.

100 years later, TMT is being designed end-to-end to correct atmospheric disturbances to approach the **diffraction limited image quality** of a 30 meter aperture.
TMT Aperture Advantage

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

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

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

*Sensitivity* = 1/time required to reach a given s/n ratio

\( \eta = \) throughput, \( S = \) Strehl ratio. \( D = \) aperture diameter
Defining Capabilities in the TMT Discovery Space

Adaptive Optics needed
Defining Capabilities in the TMT Discovery Space
TMT Construction Proposal (PDF)

In May 2007, an initial TMT Construction Proposal was created by the project and reviewed by an external advisory panel (EAP). The EAP membership is nominated by the TMT Board. This Construction Proposal will be revised and updated as TMT design and development proceeds.

Editors: S. Dawson, S. Roberts
Last update: September, 2007

The Detailed Science Case (PDF)

The Detailed Science Case (DSC) is the highest level statement of the TMT science case. The DSC was created and is maintained by the TMT Science Advisory Committee (SAC). It provides examples of the kinds of exciting, groundbreaking science that will be enabled by a 30m telescope. Wherever possible, synergies with other major upcoming facilities (e.g. the James Webb Space Telescope and the Atacama Large Millimeter Array) are discussed. As appropriate, performance numbers (often conservative) are provided (e.g. sensitivities, integration times, spatial resolutions).

Editors: D. Silva, P. Hickson, G. Steidel, M. Bolte
Last update: October, 2007

The Science-based Requirements Document (PDF)

The Science-based Requirements Document (SRD) describes the science-driven requirements for the Thirty Meter Telescope (TMT) project. TMT will be the first of the next-generation giant optical/infrared ground-based telescopes and will be a flagship facility for addressing the most compelling areas in astrophysics: the nature of Dark Matter and Dark Energy, the assembly of galaxies, the growth of structure in the Universe, the physical processes involved in star and planet formation and the characterization of extra-solar planets.

Editors: J. Nelson
Last update: July, 2013

The Observatory Requirements Document (PDF)

The Observatory Requirements Document (ORD) contains the highest level system requirements for the observatory. Too low level requirements are defined for the telescope and instrumentation, summit and support facilities, environmental health and safety, and high level software. The ORD also defines site specific environmental parameters and constraints.

Editors: G. Angell, S. Roberts
Last update: June, 2012
Summary of TMT Science Objectives and Capabilities

<table>
<thead>
<tr>
<th>Theme</th>
<th>Science Objectives</th>
<th>Observations</th>
<th>Requirements</th>
<th>Capabilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cosmology and Fundamental Physics</td>
<td>Mapping distribution of dark matter on large and small scales (CFP-1,2,3,4), GAN-3,4, GCT-1&lt;sup&gt;*&lt;/sup&gt;</td>
<td>Proper motions in dwarf galaxies</td>
<td>( \lambda = 0.31-0.62 \mu m, 2.2-2.4 \mu m )</td>
<td>SL/WFOS</td>
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<tr>
<td></td>
<td>General Relativity in new mass regime&lt;sup&gt;*&lt;/sup&gt; (GAN-4, D), SSE-4</td>
<td>Wide-field optical spectroscopy of ( R = 245 ) galaxies</td>
<td>( R = 1000 - 50000 )</td>
<td>SL/HROS</td>
</tr>
<tr>
<td></td>
<td>Very precise expansion rate of Universe (CFP-2)</td>
<td>Microarcsecond astrometry</td>
<td>Very efficient acquisition</td>
<td>MCAO/IRIS/WIRC</td>
</tr>
<tr>
<td></td>
<td>Mapping variations in constants over cosmological timescales</td>
<td>Transient events lasting &gt; 30 days</td>
<td>0.05 mas astrometry stable over 10 years</td>
<td>MCAO/NIRES</td>
</tr>
<tr>
<td>Physics (Dark energy, dark matter, physics of extreme objects, fundamental constants; DSC Section 3)</td>
<td>Physics of extreme objects&lt;sup&gt;*&lt;/sup&gt; (SSE-2,3,4)</td>
<td>High spectral resolution observations of quasars and GRBs</td>
<td>Field of view &gt; 10&lt;sup&gt;°&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>The Early Universe (First objects, IGM at ( z &gt; 7 ); DSC Section 4)</td>
<td>Detection of metal-free star formation in First Light objects&lt;sup&gt;*&lt;/sup&gt; (GAN-2, GCT-4)</td>
<td>Multiplexed, spatially-resolved spectroscopy of faint objects</td>
<td>( \lambda = 0.8 - 2.5 \mu m )</td>
<td>MCAO/IRIS/WIRC</td>
</tr>
<tr>
<td></td>
<td>Mapping topology of re-ionization (GCT-4)</td>
<td>High spectral resolution, near-IR spectroscopy</td>
<td>( R = 3000 - 30000 )</td>
<td>MCAO/IRIS/WIRC</td>
</tr>
<tr>
<td></td>
<td>Structure and neutral fraction of IGM at ( z &gt; 7 ) (CFP-1, GCT-4)</td>
<td>Optical/near-IR multiplexed diagnostic spectroscopy of distant galaxies &amp; AGNs</td>
<td>Very efficient acquisition</td>
<td>MOAO/IRMO</td>
</tr>
<tr>
<td>Galaxy formation and IGM (DSC Section 5)</td>
<td>Detection of peak galaxy formation&lt;sup&gt;*&lt;/sup&gt; (CFP-1, GAN-1, GCT-1,2,3)</td>
<td>Optical/near-IR multiplexed identification spectroscopy of extremely faint high redshift objects (to ( R = 27 ))</td>
<td>Multiplexing factor &gt; 100</td>
<td>MOAO/IRMO</td>
</tr>
<tr>
<td></td>
<td>2D Velocity, SFR, extinction &amp; metallicity maps of galaxies at ( z = 5-6 ) (CFP-3, GAN-1, GCT-1,2)</td>
<td>Spatially-resolved spectroscopy of galaxy cores</td>
<td>( \lambda = 0.8 - 2.5 \mu m )</td>
<td>MCAO/IRIS</td>
</tr>
<tr>
<td></td>
<td>IGM properties on physical scales &lt; 300 kpc&lt;sup&gt;*&lt;/sup&gt; (GAN-1, GCT-2)</td>
<td>Spatially-resolved spectroscopy of galaxy cores</td>
<td>( R = 3000-5000 )</td>
<td>MOAO/IRMO</td>
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<td>Precise positioning</td>
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<tr>
<td>Extragalactic supermassive black holes (DSC Section 6)</td>
<td>Demographics of black holes over new ranges in mass and redshift&lt;sup&gt;*&lt;/sup&gt; (GAN-4, GCT-3)</td>
<td></td>
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<td>Dynamical measurements out to ( z = 0.4 )&lt;sup&gt;*&lt;/sup&gt; (GAN-4, GCT-1,3)</td>
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<tr>
<td></td>
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<td>Scaling relations out to ( z = 2.5 ) and masses at ( z &gt; 6 )&lt;sup&gt;*&lt;/sup&gt; (GAN-4, GCT-1,3)</td>
<td></td>
<td></td>
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<tr>
<td>Galactic Neighborhood (DSC Section 7)</td>
<td>Abundance of oldest stars in Milky Way (CFP-4, GAN-2,3, SSE-2)</td>
<td>High spectral resolution optical and near-IR spectroscopy</td>
<td></td>
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<tr>
<td></td>
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<td>Chemical evolution in Local Group galaxies&lt;sup&gt;*&lt;/sup&gt; (GAN-2)</td>
<td>High-precision photometry in crowded fields</td>
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<td></td>
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<td>Diffusion and mass loss in stars (GAN-1, SSE-1)</td>
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<td></td>
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<td>Resolved stellar populations out to Virgo cluster&lt;sup&gt;*&lt;/sup&gt; (GAN-2,3)</td>
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<tr>
<td>Planetary Systems and Star Formation (physics of star formation, proto-planetary disks, exoplanets; DSC Section 8, Section 9)</td>
<td>Origin of mass in stars (GAN-1,2,2,3,4, SSE-1, SSE-2)</td>
<td>High-resolution, crowded field photometry</td>
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<td>Architecture of planetary systems (PSF-2,3,4, SSE-2)</td>
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<td></td>
<td>Deposition of pre-biotic molecules onto protoplanetary surfaces (PSF-2)</td>
<td>Diffraction-limited, high spectral resolution mid-IR spectroscopy</td>
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<td>First direct detection of reflected-light Jovians (PSF-2)</td>
<td>Very high Strehl AO-assisted imaging: precise wavefront control</td>
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<td>Characterization of exo-atmospheres (e.g., oxygen) (PSF-3,4,4, D)</td>
<td>High spectral resolution optical and near-IR spectroscopy</td>
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<tr>
<td>Our Solar System (outer parts, surface physics and atmospheres; DSC Section 10)</td>
<td>Composition of Kuiper Belt Objects and comets (PSF-2)</td>
<td>Spatially resolved spectroscopy of objects in solar system</td>
<td>( \lambda = 1 - 25 \mu m )</td>
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<td></td>
<td>Monitoring, (cryo-) vulcanism and tectonic activity&lt;sup&gt;*&lt;/sup&gt;</td>
<td>( R = 4000, 30000-100000 )</td>
<td>MCAO/IRIS</td>
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<td></td>
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<td>Low telescope emissivity</td>
<td>MIRA/NIRES</td>
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<td>Dry site (PWV &lt; 5 mm)</td>
<td>MIRA/NIRES</td>
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<td>Fixed gravity vector and thermal control</td>
<td>MIRA/NIRES</td>
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<td>Very efficient acquisition</td>
<td>MIRA/NIRES</td>
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<td></td>
<td>Contrast ratio of ( 10^{-4}-10^{-9} )</td>
<td>MIRA/NIRES</td>
</tr>
</tbody>
</table>

<sup>*</sup> Note: This indicates an additional focus or emphasis on specific aspects.
TMT instrument capabilities (in red) compared to JWST and ALMA

NELF is the Noise-Equivalent Line Flux in ergs s\(^{-1}\) cm\(^{-2}\)
Science → Technical Requirements
Science → Technical Requirements

Science Cases

Define instrument capabilities
Parameters: \( \lambda, \Delta \lambda, R, \omega, \theta \)

“Pack” capabilities into design and instrument suite

Science Requirements Document

Feasibility (~200 scientists+ from 46 institutions)

TMT Foundation Documents

Observatory Requirements Document (ORD)
Observatory Architecture Document (OAD)
Operations Requirements Document (OPSRD)

Revised SRD

TMT Detailed Science Case

More Detailed Science Cases

Innovative Technical Concepts

Operational Concepts (calibrations, etc.)
Science → Technical Requirements
<table>
<thead>
<tr>
<th>Domain</th>
<th>Parameter Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Configuration</td>
<td>Observing Mode</td>
</tr>
<tr>
<td></td>
<td>Wavelength range</td>
</tr>
<tr>
<td></td>
<td>Spectral Resolution</td>
</tr>
<tr>
<td>Spectral Parameters</td>
<td>Flux/radial velocity</td>
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<td></td>
<td>Relative / absolute Precision</td>
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<tr>
<td></td>
<td>Stability timescale</td>
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<tr>
<td>Spatial Parameters</td>
<td>Image quality</td>
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<tr>
<td></td>
<td>Resolution</td>
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<tr>
<td></td>
<td>Strehl ratio / contrast ratio</td>
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<tr>
<td></td>
<td>Geometry</td>
</tr>
<tr>
<td></td>
<td>Total areal coverage</td>
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<tr>
<td></td>
<td>Field of view per observation</td>
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<td>Field overlap</td>
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<td></td>
<td>Astrometry</td>
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<tr>
<td></td>
<td>Relative / absolute Precision</td>
</tr>
<tr>
<td></td>
<td>Stability timescale</td>
</tr>
<tr>
<td>Multiplexing</td>
<td>Sample size</td>
</tr>
<tr>
<td></td>
<td>Number of observations</td>
</tr>
<tr>
<td>Tracking</td>
<td>Rate</td>
</tr>
<tr>
<td>Synoptic Signature</td>
<td>Baseline</td>
</tr>
<tr>
<td></td>
<td>Cadence</td>
</tr>
</tbody>
</table>
### Science Flowdown Matrix - A small subsection

<table>
<thead>
<tr>
<th>Science Program</th>
<th>Image Quality</th>
<th>Spatial Parameters</th>
<th>Astrometry</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Resolution (mas)</td>
<td>Strehl(R) / Contrast(C) ratio</td>
<td>SRD/ORU Requirement(s)</td>
</tr>
<tr>
<td>-----------------</td>
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<td>------------------------</td>
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</tr>
<tr>
<td>Multiplexed spectroscopy of distant galaxies: rest-frame optical DSC 5.4</td>
<td>200</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Spatial dissect of forming galaxies DSC 5.5</td>
<td>8</td>
<td>S = 0.5 ( \mu )</td>
<td>275 ( \mu )</td>
</tr>
<tr>
<td>IGM: Core samples during galaxy formation epoch DSC 5.6</td>
<td>800 ( \mu )</td>
<td>SRD-0070, 0110, 0120, 0145, [0455-0470], [0565-0580], 0920, 0930, 0935, 1015, 1025, 1030, 1035, 1310, 1315, 1320, 1330</td>
<td>4 ( \times ) 4032</td>
</tr>
<tr>
<td>Epoch of galaxy formation in 3D DSC 5.7</td>
<td>800 ( \mu )</td>
<td>SRD-0070, 0110, 0120, 0145, [0455-0470], [0565-0580], 1220, 1225, 1230, 1235, 1275, 1276, 1279, 1280</td>
<td>4 ( \times ) 4032</td>
</tr>
<tr>
<td>SMBHs in nearby galactic nuclei DSC 6.1</td>
<td>10 ( \mu )</td>
<td>S = 0.5 ( \mu )</td>
<td></td>
</tr>
</tbody>
</table>

**TMT**  
THIRTY METER TELESCOPE
Science Flowdown ➔ Technical Requirements

Level 0 - Customer
- Science Verification
- System Verification Plan

Level 1 - System
- DOORS object-oriented requirements management
- Observatory Architecture Document
- Observatory Requirements Document

Level 2 - Subsystem
- Design Requirements Document
- Interface Control Document
- Integration & Verification Plan

Science-Based Requirements Document
- System Budgets
Key Telescope Dimensions

EL AXIS

Stay-in Radius

28.5 m R

51 m

56 m

23 m

27.6 m R

28 m

16 m
TMT as an Agile Telescope: Catching The “Unknown Unknowns”

TMT target acquisition time requirement is 5 minutes (i.e., 0.0034 day)

TMT is the only agile extremely large telescope and only system with plans to go to 310nm.

Source: Figure 8.6, LSST Science Book
From Science to Subsystems

Transients - GRBs/ supernovae/tidal flares/?
Fast system response time

NFIRAOS fast switching science fold mirror
-X Nasmyth structure

Articulated M3 for fast instrument switching
+X Nasmyth structure

Fast slewing and acquisition

TMT.PMO.PRE.13.023.REL01
From Science to Subsystems (NFIRAOS + IRIS Imager)

Galactic Center
High Strehl w/ stable PSF over 15” ≥ MCAO

LGSF asterism generator + launch telescope
LGSF beam transfer
NFIRAOS + IRIS

GR Tests
Precession of Periapse
Relativistic Redshift

Observing Io with AO on TMT

Simulations of Io Jupiter-facing hemisphere in H band (Courtesy of Franck Marchis)

*TMT resolution at 1μm is 7 mas = 25 km at 5 AU (Jupiter) (0.035 AU at 5 pc, nearby stars)*
Galactic Center with the IRIS Imager

K-band

$\tau = 30s$

$K_{\text{lim}} = 25.5$

Over 100,000 stars

Courtesy: L. Meyer (UCLA)
TMT on Mauna Kea
TMT on Mauna Kea
The TMT Calotte Enclosure
Aero-Thermal Effects Modeled

- Wind through opening
- Dome seeing
- M1 seeing
- M2 buffeting
- Wind through vents
- M1 buffeting
Z65°-A180°

Wind speed contours with 100% vents open
(flow along x, $U_o \sim 5$ m/s)
Keck 10-m (400") Telescope (1992)

The technical heritage for TMT
Keck Observatory, Mauna Kea, Hawaii
Keck 10m Segmented Mirror Telescope – 36 segments
The Keck Breakthrough: Segmented Mirrors
Full Scale Segment on Segment Support Assembly

Prototype of one of the 492 TMT segments
492 off-axis hyperboloidal segments
Most aspheric TMT M1 Segment before hexing polished by Tinsley
E-ELT Blank Polished at Tinsley With TMT Stressed Mirror Polishing Process

Most aspheric E-ELT M1 Segment before hexing polished by Tinsley 1/27/2012
And Another High-Asphericity Segment!
Canon Type-82 Segment Prototype

Most aspheric TMT M1 Segment polished as hexagon by Canon 1/18/2012
Segment Support Assembly Integration
Completed by Canon and TMTJ

TMT.PMO.PRE.13.023.REL01
Nanjing: NIAOT Exercising Stressed Mirror Polishing (SMP)
M1 System – Integrated Testing at JPL
Telescope Controls Prototyping: Actuators, Edge Sensors, Mirror Supports
Uncoated Edge Sensor Prototypes at GOAL (Pondicherry, India)
Prototype sensors at GOAL

Photolithography mask for sensor coating at GOAL

Test coupon for Indium soldering process at GOAL
M1 Segment Support Assembly
Leaf Spring Prototypes

IPA India leaf spring left – US leaf spring Right
M3 System Progress at CIOMP, Changchun

Conceptual Design Review (CoDR) for the M3 Cell Assembly successfully completed 2013/04/26
TMT Global Participants - Adaptive Optics

- TOPTICA, Munich (Laser Systems)
- CILAS, Orleans (Wavefront Correctors)
- TIPC, Beijing (Laser Systems)
- IOE, Chengdu (Laser Guide Star Facility)
- Keck Observatory, Waimea (WFS readout electronics)
- HIA, Victoria (NFIRAOS)
- DRAO, Penticton (RTC)
- MIT/LL, Lexington (WFS CCDs)
- AOA/Xinetics, Devens (Wavefront Correctors)
- TMT, Pasadena (Management and SE)

Also Rochester Scientific (Berkeley, Sodium Atomic Physics)
TMT Global Participants – First Light Science Instruments
First Light Science Instruments and Adaptive Optics Systems

- **Science instruments**
  - IRIS
  - IRMS
  - WFOS

- **Laser Guide Star Facility (LGSF)**

- **Narrow Field IR AO System (NFIRAOS)**
589 nm Laser Light Produces Artificial Guide Stars

sodium layer
ΔH =10km
D = 30m
⇒ Elongation ≈ 3-4”
at 15m separation
NFIRAOS Design at HIA (Canada)

- **Dual Conjugate Laser Guide Star (LGS) AO System**
  - Feed 3 IR Instruments
  - 60x60 order system operating at 800Hz
  - 4 OAP relay to eliminate distortion
  - Operation at -30°C to reduce thermal emission

- Completed preliminary design phase in December 2011
  - Very successful review led by panel of external reviewers
NFIRAOS Opto-Mechanical Overview

- Input from Telescope
- Source simulators
- Turbulence Simulator Phase Screen
- OAP
- Output to science instruments
- Beam-splitters
- 76x76 DM at h=11.2 km
- 63x63 DM at h=0 km on tip/tilt stage
- 6 60x60 LGS WFSs
- 1 Truth NGS WFS
- 1 60x60 NGS-mode WFS
- LGS Trombone
CILAS (France) Deformable Mirrors

- Hard piezostack technology with high stroke, low hysteresis, operating at -30°C
- Sub-scales prototypes on-going

6x60 DM initial test results:
- 19 μm stroke (10 μm requirement)
- Hysteresis ≤ 5% (10% requirement)
AO: Deformable Mirror
6x60 Test at CILAS

6x60 DM before polishing

Interferometer measurement on half the DM Breadboard showing TMT shape
CILAS Tip-Tilt Stage

Full scale prototype demonstrated at -30°C
Closed loop bandwidth of ~100Hz (>> 20Hz Requirement)
Gemini South Guide Star Laser 5-Star Artificial Constellation – January 2011
Refereed Keck AO Science Papers by Year

![Chart showing the number of refereed Keck AO science papers by year, categorized into extra-galactic, galactic, and solar system types.]

Year: 2000 to 2012

Number of Papers:
- Extra-galactic
- Galactic
- Solar System
Laser Guide Star AO Astronomy
Refereed Papers by Year

![Graph showing the number of papers published by year and telescope.](image-url)
Chengdu LGSF: BTO/LLT/E&SW update
LGSF Design Elements

- 6 (eventually 9) laser systems mounted on telescope elevation journal
  - Possible with current generation of compact, efficient, low(er)-maintenance designs
- Reflective launch telescope and diagnostics located behind TMT M2
- Mirror-based beam transport due to path length and beam power
- Safety systems (personnel, equipment, aircraft, satellites)
Laser Development at TIPC (China) and Toptica/MPB (Germany/Canada)

TIPC 20W field test TIPC prototype
- Nd:Yag sum frequency generation

Toptica/MPB 20W Prototype
- Raman fiber doubled second harmonic generation
- Pre-Production Unit Tested for ESO

On sky tests of the TIPC prototype in China: 8.7 mag. LGS

TMT.PMO.PRE.13.023.REL01
Yunnan Laser Test
Sodium Laser and 1.8m Telescope
First Light with the TIPC Guide Star Laser

- The exposure time was 1s

Wavelength near the Na D2 Line

Wavelength far away from the Na D2 Line
“Polar Coordinate” CCD Array for Wavefront Sensing with Elongated Laser Guidestars

- D = 30m
- Elongation ≈ 3-4” at 15m separation
- Fewer illuminated pixels reduces pixel read rates and readout noise

- H = 100km
- Sodium layer ΔH = 10km

MIT/LL CCD Design

TMT PMO PRE.13.023.REL01
High-Order LGS and NGS Shack Hartmann Wavefront Sensor CCDs

- MIT/LL prototype detectors:
  - Quadrant of polar coordinate LGS WFS detector
  - 256^2 visible NGS WFS CCD

Wafer run funded by TMT, Keck and USAF

3.5 electrons read noise initial results
# TMT First Light Instrument Suite

<table>
<thead>
<tr>
<th>Instrument</th>
<th>$\lambda$ (µm)</th>
<th>Field of view/Slit length</th>
<th>Spectral resolution</th>
<th>Science Cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>InfraRed Imager and Spectrometer (IRIS)</td>
<td>0.8 – 2.5</td>
<td>&lt;3” IFU</td>
<td>&gt; 3500</td>
<td>• Assembly of galaxies at high z</td>
</tr>
<tr>
<td></td>
<td>0.6 – 5</td>
<td>&gt;15”imaging</td>
<td>5-100 (imaging)</td>
<td>• Black holes/AGNs/Galactic Center</td>
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<td>(goal)</td>
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<td>• Resolved stellar populations in crowded fields</td>
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<td>Wide-field Optical spectrometer and imager (WFOS)</td>
<td>0.31 – 1.0</td>
<td>&gt;40 arcmin$^2$</td>
<td>1000-5000@0.75” slit</td>
<td>• IGM structure and composition at $2 &lt; z &lt; 6$</td>
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<td>&gt;100 arcmin$^2$ (goal)</td>
<td>&gt;7500 @0.75”</td>
<td>• Stellar populations, chemistry and energetics of $z &gt; 1.5$ galaxies</td>
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<td>Slit length&gt;500”</td>
<td>(goal)</td>
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<tr>
<td>InfraRed Multislit Spectrometer (IRMS)</td>
<td>0.95 – 2.45</td>
<td>2 arcmin field, up to 120’ total slit length with 46 deployable slits</td>
<td>R=4660 @ 0.16 arcsec slit</td>
<td>• Early Light</td>
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<td>• Epoch of peak galaxy building</td>
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<td>• JWST follow-ups</td>
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<tr>
<td>Deployable, multi-IFU, near-IR spectrometer (IRMOS)</td>
<td>0.0 – 2.5</td>
<td>3” IFUs over &gt;5’ diameter field</td>
<td>2000-10000</td>
<td>• Early Light</td>
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<td>• Epoch of peak galaxy building</td>
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<td></td>
<td>• JWST follow-ups</td>
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<tr>
<td>Mid-IR AO-fed Echelle spectrometer (MIRES)</td>
<td>8 – 18</td>
<td>3” slit length</td>
<td>5000-100000</td>
<td>• Origin of stellar masses</td>
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<td>4.5 – 26</td>
<td>10” imaging</td>
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<td>• Accretion and outflows around protostars</td>
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<td>(goal)</td>
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<td>• Evolution of gas in protoplanetary disks</td>
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<tr>
<td>Planet Formation Instrument (PFI)</td>
<td>1 – 2.5</td>
<td>1” outer working angle, 0’.05 inner working angle</td>
<td>R≤100</td>
<td>• 10$^8$ contrast ratio (10$^9$ goal)</td>
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<td>1 – 5</td>
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<td>• Direct detection and spectroscopic characterization of exoplanets</td>
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<tr>
<td>Near-IR AO-fed echelle spectrometer (NIRES)</td>
<td>1 - 5</td>
<td>2” slit length</td>
<td>20000-100000</td>
<td>• IGM at z &gt; 7, gamma-ray bursts</td>
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<td>• Local Group abundances</td>
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<td>• Abundances, chemistry and kinematics of stars and planet-forming disks</td>
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<td>• Doppler detection of terrestrial planets around low-mass stars</td>
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<td>High-Resolution Optical Spectrometer (HROS)</td>
<td>0.31 – 1.1</td>
<td>5” slit length</td>
<td>50000</td>
<td>• Doppler searches for exoplanets</td>
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<td>• Stellar abundance studies in Local Group</td>
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<td>• ISM abundance/kinematics</td>
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<td>• IGM characteristics to z=6</td>
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<td>&quot;Wide&quot;-field AO Imager (WIRC)</td>
<td>0.8 – 5.0</td>
<td>30” imaging field</td>
<td>5-100</td>
<td>• Precision astrometry (e.g., Galactic Center)</td>
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<td>• Resolved stellar populations out to 10 Mpc</td>
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MOBIE Schematic View
Inter-Galactic Medium Tomography: Now

(Simulation: M. Norman, UCSD)
Inter-Galactic Medium Tomography: TMT

(Simulation: M. Norman, UCSD)
The IRIS Focal Plane:
Imager + 2 IFUs + 3 Guide Stars

- **Imager**
  16″.4 × 16″.4 field (on-axis)
  w/ 0″.004 pixels
  (JHK + Narrow-bands)

- **Three Probe Arms**
  4″ FoV w/
  0″.004 pixels
  (control plate scale
  and astrometry)

- **Concentric integral field
  spectrographs**
  18″ off-axis
  Wavelength range =
  0.84 - 2.4μm
  Spectral Resolution = 4000

  - 2 Coarse Scales (Slicer)
    45 ″ 90 ″ ~2000 elements
    1″.125 ″ 2″.25@0″.025
    2″.25 ″ 4″.5@0″.050

TMT.PMO.PRE.13.023.REL01
InfraRed Multi-slit Spectrometer (IRMS)

TMT/IRMS = Keck/MOSFIRE clone!

MOSFIRE on-sky commission very successful

Keck, February 2012
Focal Plane Visualization and Asterism Selection Project (FOVAST) from TMT-India.
Focal Plane Visualization and Asterism Selection Project (FOVAST) from TMT-India
Public Participation in Permitting TMT in Hawaii
Democracy is hard work!

TMT CDUP Contested Case hearings August 2011
VIDEO: MKMB OK on TMT

May 20, 2010 | Hilo, Mauna Kea | 1 Comment

Plan for $1 billion Thirty Meter Telescope on Mauna Kea summit now goes to chancellor
Press Release

TMT Takes Step Towards Construction after Approval by the Board of Land and Natural Resources

04.13.2013

Friday marked another important step forward for the future of astronomical discovery and economic opportunity on Hawaii Island. The Hawaiian Board of Land and Natural Resources (BLNR) announced that it has granted a permit to the Thirty Meter Telescope (TMT) project to build and operate the next-generation observatory near the summit of Mauna Kea.

With this approval, the BLNR has recognized TMT’s goal of responsible development and environmental stewardship of Mauna Kea in close partnership with local interests. The carefully considered conditions in the permit help ensure the protection of sensitive environments in Hawaii.

"Over the last several years, the TMT project has welcomed the support it has received from all sectors of the Hawaiian community, from education to cultural to business to labor," said Sandra Dawson, TMT’s Manager of Hawaii Community Affairs. "We look forward to beginning construction and becoming a neighbor of the outstanding observatories on Mauna Kea."

In February 2011, the BLNR issued a preliminary decision conditioned on the successful conclusion of a contested case. The contested hearings began later that year. The final approval followed a hearing held February 12, 2013 in Hilo, HI. At this time, the BLNR reviewed a report by the hearing officer regarding the contested case.

“We are delighted that the TMT project has now been granted a Conservation District Use Permit” said Edward Stone, the Monroe Professor of Physics at the California Institute of
Southwest View
Summit Facility Section
Enclosure Section
Construction Sequence
Access Road
Construction Sequence
Rough Grading
Construction Sequence
Enclosure Excavation & Utilities
Construction Sequence
Pier and Tunnel Concrete
Construction Sequence
Fixed Enclosure Foundation & Slab

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TMT.PMO.PRE.13.023.REL01
Construction Sequence
Fixed Enclosure Structural Steel

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[Image of a 3D model of a telescope enclosure]

TMT.PMO.PRE.13.023.REL01 97
Rotating “Calotte” Enclosure

- Shutter Structure
- Cap Structure
- Base Structure
- Fixed Structure

TMT.PMO.PRE.13.023.REL01 98
Enclosure Construction Sequence
Construction Sequence
Rotating Enclosure Erection
Construction Sequence
Fixed Enclosure Wall Panels
## Construction Sequence Facility Excavation

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TMT.PMO.PRE.13.023.REL01 107
Construction Sequence
Facility Foundation
Construction Sequence
Facility Concrete Slab & Backfill

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Construction Sequence
Facility Steel
Construction Sequence
Facility Shell & Finishes

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Construction Sequence Completion
Facilities complete 1\(^{st}\) Quarter 2020 → First Light and Science 4\(^{th}\) Quarter 2022
Construction cost $1.45 billion “then-year” dollars
First TMT Geotechnical Studies on Mauna Kea
First TMT Geotechnical Studies on Mauna Kea (Last Week)
TMT Collaboration
TMT Collaboration

[TMT Collaboration Diagram]
Planning a U.S. Partnership in the Thirty Meter Telescope Project

30 m 望遠鏡
三十米望远镜
तीस मीटर दूरबीन
Thirty Meter Telescope
Télescope de Trente Mètres
These include the new initiatives between India’s Department of Science and Technology and U.S. National Science Foundation on a Virtual Institute on Mathematics and Statistical Sciences and DST-NSF Summer Internship; the recent initiative (PC3) of the Department of Electronics and Information Technology and U.S. NSF to jointly fund collaborations between universities and institutions in the two countries on the application of electronics and IT for societal challenges, which has already resulted in five collaborations in the areas of wildlife management, air quality, water sustainability, healthcare and smart electric grids; India’s recent commitment of more than $100 million to the California Institute of Technology’s Thirty-Meter Telescope Project; the exchange of weather and monsoon forecasting, climate change information and global precipitation under the Civil Space Working Group; and the collaborative project of the U.S. National Science Foundation and the Indian Department of Atomic Energy and Department of Science & Technology to develop a Laser Interferometer Gravitational Wave Observatory, with a likely contribution of $100 million from India.
Japanese parliament allocates money for Thirty Meter Telescope in new budget

THE ASSOCIATED PRESS
June 06, 2013 - 9:04 am EDT

HONOLULU — A group building what will be the world's largest and most advanced optical telescope atop Mauna Kea says the Japanese government has allocated key funding for the construction of the project.

The Thirty Meter Telescope said Wednesday the Japanese parliament last month approved a budget including more than $12 million for the telescope.

TMT says Japan is expected to manufacture the main telescope structure and the mirror blanks for the segmented primary mirror. In total, Japan is expected to fund one-fourth of the total cost of construction.

The telescope is being built by a group including the California Institute of Technology, the University of California and the
Chinese vice premier meets US university presidents

Chinese Vice Premier Liu Yandong (C) meets with Mark Yudof (2nd L), the President of the University of California (UC) and Henry Yang (2nd R), the Chancellor of UC Santa Barbara, in Beijing, capital of China, April 26, 2013 (Xinhua/Xie Huanchi)

BEIJING, April 26 (Xinhua) -- Chinese Vice Premier Liu Yandong met with Mark Yudof, the president of the University of California (UC) and Henry Yang, the chancellor of UC Santa Barbara on Friday.

During the meeting, Liu spoke highly of cooperations between the UC and Chinese universities, adding that China hopes the two sides will promote collaborations in education, technology and personnel exchanges.
India-China hold talks on science and tech after 11 years

University of Nicosia
MD from St. George's University UK 2014 Admissions Now Open - Enroll nicosia.sgu.ac.cy/Apply_Now

After a gap of 11 years, India and China held talks on Science and Technology and agreed to step up cooperation in earthquake prediction, disaster management, astronomy, traditional medicine and climate change.

An Indian delegation of top scientists headed by Dr Thirumalachari Ramasami, Secretary of the Department of Science and Technology, held the sixth dialogue on Science and Technology with their Chinese team led by Vice Minister for Science Technology Cao Jianlin here.

The talks, held during the last two days, were focussed on earthquake prediction and disaster management, astronomy, traditional medicine and climate change, officials told PTI.

The talks on earthquake predictions included exchange of notes on the movement of Indo-Tibetan plate which was stated to be the reason of a number of earthquakes in the Himalayan region, specially China's Sichuan province causing wide spread damage to life and property.

The two sides also discussed disaster management. The talks on Astronomy focussed on cooperation specially in Thirty Meter Telescope in Hawaii in which both the countries are taking part.

They discussed cooperation in areas of glaciology and climate change on which lot of work has been done by both sides.
TMT Board Meeting – Tokyo
October 9-10, 2012
TMT Board Agreement Development Team
– Kona – December 1, 2012
TMT Board Meeting – Delhi
January 21-22, 2013
Planning a U.S. Partnership in the Thirty Meter Telescope Project
Engaging the US astronomy community -- NSF awards partnership-planning grant to TMT

March 18th, 2013

This image depicts the Thirty Meter Telescope (TMT) near the summit of Mauna Kea, Hawaii. Construction of TMT is planned for 2014 with science operations beginning in 2021. Credit: TMT Observatory Corporation

Today the National Science Foundation (NSF) awarded a cooperative agreement to the Thirty Meter Telescope (TMT) Observatory Corporation to explore a potential partnership between the organizations.

The award is a milestone for the TMT project, initiating a broad dialog between TMT, the NSF and the United States' astronomical community. The partnership-planning award also paves the way for the NSF to confer with TMT's international partners.
1st one - July 22-23, 2013 at the Marriott Waikoloa, Hawaii

- Full partner meeting and introduction of TMT to the US community, 150+ people
- Project status, TMT science, Instruments
- Collaborative program – International Science Development Teams
- Also the Collaborative Board signed the Master Agreement
Acknowledgments

The TMT Project gratefully acknowledges the support of the TMT collaborating institutions. They are the Association of Canadian Universities for Research in Astronomy (ACURA), the California Institute of Technology, the University of California, the National Astronomical Observatory of Japan, the National Astronomical Observatories of China and their consortium partners, and the Department of Science and Technology of India and their supported institutes. This work was supported as well by the Gordon and Betty Moore Foundation, the Canada Foundation for Innovation, the Ontario Ministry of Research and Innovation, the National Research Council of Canada, the Natural Sciences and Engineering Research Council of Canada, the British Columbia Knowledge Development Fund, the Association of Universities for Research in Astronomy (AURA) and the U.S. National Science Foundation.