The TMT Instrumentation Program*

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Abstract: An overview of the Thirty Meter Telescope (TMT) instrumentation program is presented, including descriptions of the requirements for instruments and adaptive optics systems that have been identified as high priority capabilities by the TMT Science Advisory Committee. In addition to powerful seeing-limited instruments, TMT will include instruments that provide full diffraction-limited performance at wavelengths $> 1\mu$m to meet the challenges presented by the science, and to enable full complementarity to JWST, ALMA, and comparable missions. An overview of the TMT project and its status as of mid 2005 is also included.

Keywords: telescopes, instrumentation, adaptive optic systems

1. INTRODUCTION

TMT will provide a 30m diffraction-limited ground-based facility as well a huge increase in raw light gathering power compared to the current 8-10m telescopes. Recent experience on Keck and Gemini with laser guide star adaptive optics demonstrates the huge potential offered by diffraction-limited science now that laser beacons provide the sky coverage needed for virtually all targets of interest. The 30m diffraction-limited capability will provide the angular resolution and D^4 gains required to fulfil the scientific aspirations of the TMT community, and to provide data that fully complements that expected from missions like ALMA and JWST.

Based on the science projects that are currently foreseen for TMT, the TMT Science Advisory Committee (SAC) has developed a Science Requirements Document for the observatory that includes a list of eight instruments and associated adaptive optics systems for the first decade of operation. During the initial phase of the project, an interim Instrument Working Group provided notional design concepts and requirements (IWG 2004) for these instruments and, similarly, an Adaptive Optics Working Group developed requirements for the adaptive optics (AO) systems. These groups also helped to develop a strategy for the development of the instruments and AO systems for TMT. The latter included recommendations for additional technology development as well as, e.g., laboratory and on-sky experiments with existing AO and Laser Guide Star (LGS) systems. All of this activity led to a series of feasibility and conceptual design studies that were initiated in the spring of 2005. These studies are proceeding simultaneously with the design of the TMT Observatory and so are providing detailed requirements and cost information for the telescope and observatory, as well as feedback on the the feasibility of the projected scientific capabilities.

A brief overview of the TMT project and its current status are given in section 2; the instrumentation development strategy is described in section 3; brief descriptions of the instruments follow in section 4; and the development of the AO systems are described in section 5.

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*The TMT project is a collaboration of Caltech, the University of California, the Association of Universities for Research in Astronomy(AURA), and the Association of Canadian Universities for Reasearch in Astronomy (ACURA). This is TMT document number TMT.INS.JOU.05.001.REL01

2. OVERVIEW OF THE TMT PROJECT

2.1. TMT Partnership and Goals

The TMT project follows the recommendation of the Decadal Survey (NAS 2001) of the US National Academy of Science that a public-private partnership is the best way to build and operate a US-led 30-m class telescope. In fact, such a telescope is their highest priority ground-based initiative for the decade ahead. Consequentially, a 50-50 public-private partnership is one of the goals of TMT. The current partners are the University of California(UC), Caltech, the Association of Canadian Universities for Research in Astronomy (ACURA) and the Association of Universities for Research in Astronomy(AURA). Although these four partners are notionally "equal", the ultimate shares (e.g., of observing time) will be based on contributions to capital and operation costs. Since funding has not yet been secured for the overall project, the partnership remains open to joining with others to build the intellectual, technological and financial base necessary for a project of this magnitude and promise.

2.2. TMT Project Schedule

The governance of the TMT project was established in June, 2003 through agreements among the partners and the formation of a Board of Directors and a Science Advisory Committee. The latter includes not only institutional representatives, but through AURA and ACURA, representatives of the broader US and Canadian communities. Gary Sanders was appointed Project Manager in April 2004 with Jerry Nelson as Project Scientist.

The project is currently in the midst of a vigorous Design and Development Phase (DDP) that is intended to end in late 2008. Assuming timely delivery of capital and operational resources, construction will end in 2014 and science operations will begin in 2015. Intermediate milestones in the DDP phase include a Conceptual Design Review for the whole observatory in May, 2006, followed by a Cost Review in September, 2006. Once the costs and design are firmly established, full funding for the entire project will be sought. In the meantime, the DDP activity is being funded by a grant to Caltech and UC from the Gordon and Betty Moore Foundation, and by contributions from ACURA and AURA.

2.3. The TMT Reference Design

Three independently-conceived (and independently-reviewed) "ELT" (Extremely Large Telescope) design studies corresponding to a total effort worth approximately \$6M serve as the foundation for the TMT reference design. These three studies are the CELT design[†] produced jointly by Caltech and UC, the VLOT design[‡] carried out in Canada and the GSMT design[§] developed by NOAO and the New Initiatives Office. All three of these studies were reviewed by international panels and received very positive reviews; taken together they represent a very broad exploration of the technical options. The best aspects of these designs were extracted and consolidated into a single reference design for a 30m highly-segmented Gregorian telescope in October 2004. The main features of this design are shown in Figure 1. Note that the AO systems and instruments are located on two very large Nasmyth platforms, and are addressed by an articulated tertiary mirror.

[†] `celt.ucolick.org/greenbook`

[‡] `www.hia-iha.nrc-cnrc.gc.ca/VLOT`

[§] `www.aura-nio.noao.edu`

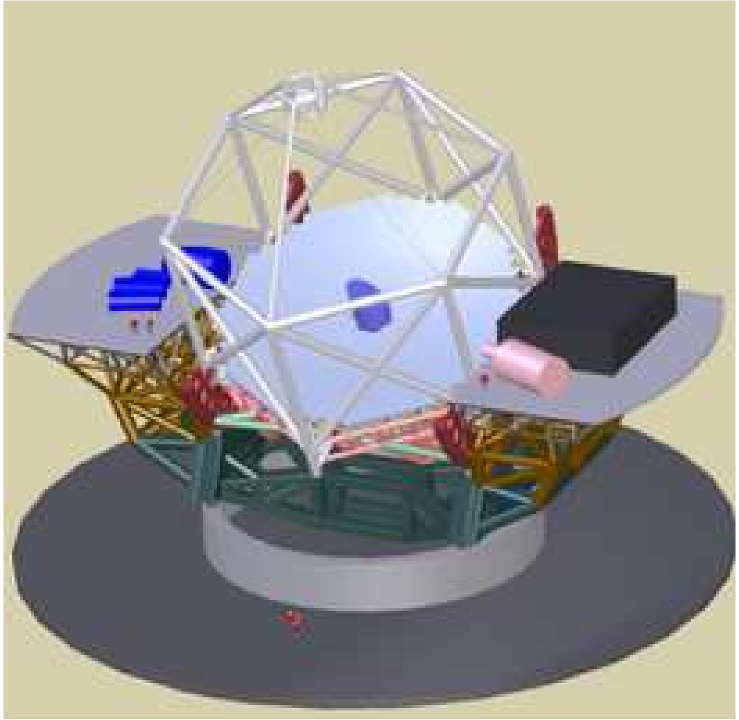

Figure 1. An illustration of the reference design. The telescope is an aplanatic Gregorian design with an f/1 primary and an f/15 final focus. It has a 20′ field of view. The instruments and their AO systems are located on large Nasmyth platforms, addressed by an articulated tertiary mirror.

2.4. Potential Sites

Four sites are currently being tested in Chile as well as sites on San Pedro Martir in Baja Mexico and Mauna Kea in Hawaii. In addition to cloud cover, seeing, transparency and emissivity, the potential of these sites to deliver diffraction limited images with feasible AO systems is being investigated. Many other programmatic factors such as operational and construction costs, manpower availability, geotechnical, environmental issues, etc., will be factors in the eventual selection, scheduled to be made in 2008.

3. SCIENCE INSTRUMENTS

3.1. TMT Science Case

The high level science objectives established by the TMT SAC include understanding the origin of large scale structure of the Universe, understanding how galaxies assembled in the early universe, detection and characterization of extra-solar planets, and investigating the processes involved in the formation of stars and planets. A detailed science case that will help guide the technical and operational requirements for the instruments and AO systems is in final draft form. The overall science goals are consistent with those detailed by the GSMT Science Working Group (GSMT 2003) and the Canadian VLOT science committee. More details on the science objectives for the individual instruments are included below.

3.2. Instruments and AO systems

The TMT SAC identified the following instruments and AO systems:
NFIRAOS, a narrow field facility AO system for first light
MOAO(Multi-Object Adaptive Optics): 20 positionable, $5''$compensated patches in $5'$
MIRAO(MidIR AO)
MCAO(Multi-Conjugate AO): wider field AO, optimized for photometric and astrometric goals
IRIS, a Near IR(NIR) imager and integral field spectrograph, fed by NFIRAOS
WFOS, a wide field, seeing-limited optical spectrograph
IRMOS, a NIR multi-object integral field spectrograph fed by MOAO
MIRES, a mid-IR echelle spectrograph fed by MIRAO
PFI(Planet formation instrument): a high contrast AO system and an imaging spectrograph.
NIRES, a NIR echelle spectrograph, fed by NFIRAOS
HROS, a high spectral resolution optical echelle spectrograph
WIRC, a wide field NIR camera fed by multi-conjugate AO

Recent studies (Andersen et al. 2005) demonstrate that Ground-Layer AO (GLAO) may provide substantial benefits to seeing-limited instruments like WFOS and HROS and so it was added to the above list. Preliminary concepts and estimates of the probable performance of instruments and associated AO systems were initially developed by the two working groups on AO and the instruments. These groups helped to identify challenging aspects of the designs and developed basic technical requirements. The Instrument Working Group report (IWG 2004) includes references and links to presentations and reports. Although these groups continue to provide guidance, management of the adaptive optics and instrumentation programs is now led by Brent Ellerbroek and David Crampton respectively.

3.3. TMT instrumentation development strategy

A top-level goal for TMT is to use world-class teams to develop the best possible instrument concepts to meet the scientific requirements. An attempt is being made to engage the whole astronomical community, including international partnerships, although the realities of funding constrain this goal. During the conceptual design phase it was decided to fund competitive studies to develop state-of-the-art but feasible and realistic concepts. In addition, it is expected that these studies will provide more reliable cost and schedule estimates, as well as identifying and retiring risks. After the project Conceptual Design Review in May 2006, it is hoped that designs for the very first light instruments will be initiated that will result in full conceptual designs, including firm price quotations, in preparation for the start of the construction phase in 2009.

3.4. Timeline

First light for TMT is scheduled to be early in 2014. In order for NFIRAOS and the very first instruments (here assumed to be WFOS, IRIS and MIRES) to be ready in time it is obvious that they must be started now. Call for proposals for feasibility studies for 8 instruments and conceptual design study for NFIRAOS were issued in early Jan, 2005. 40 letters of interest were expressed that led to receipt of 16 proposals: 3 each for HROS, IRMOS, WFOS; 2 each for MIRES and NFIRAOS; 1 each for IRIS, NIRES and PFI; and 0 for WIRC. The submitted proposals demonstrate that several major collaborations came together in response to the call for studies. Altogether, some ~ 200 scientists and engineers were involved; at 34 US institutions, 10 Canadian, and 2 French institutions. The proposals were reviewed by panels mostly composed of external referees plus SAC and working group members, and 12 feasibility studies are now underway.

4. INSTRUMENT SUITE

The instruments, in rough order of priority, are as follows.

4.1. IRIS: Infrared Imaging Spectrograph

IRIS, an integral field (IFU) spectrograph and imager, is a very high priority first light instrument, partly since it takes advantage of the full diffraction limit of TMT. It will operate in the 0.8 - 2.5 micron range and provide fields of up to $2''$ with the IFU, and up to $10''$ for imaging. Other top level requirements are:

- Spatial sampling up to Nyquist sampling at 1 micron, i.e., $0.004''$per pixel, with fields of up to $2''$ with the IFU (with adjustable plate scale); at least $10x10''$ for imaging.
- Spectral Resolution: R = 4000 over entire J, H, K bands, one band at a time. R = 2 - 50 for imaging mode.

Some of the top science cases for IRIS include:

- Physics of galaxy formation - spatially resolved ($\sim$ 100pc scales) studies of kinematics, chemistry and physical conditions for objects at the epoch of peak star formation
- AGN and Black Hole demographics and growth throughout cosmic history
- Stellar populations in galaxies from the Local Group to the Virgo Cluster

A team led by J. Larkin(UCLA) and K. Taylor(Caltech) are conducting a feasibility study for IRIS that includes consideration of both a lenslet-based IFU and an image slicer option.

4.2. WFOS: Wide Field Optical spectrograph

The basic goal for this instrument is multi-object spectroscopy over as much of the $20'$ TMT field as possible. It is to operate over the wavelength range from 0.31 - 1.1μm(1.6μm goal). Other top level requirements include:

- Field of view: 75 arcmin^2; goal 300 arcmin^2, with a total slit length $\geq 500''$
- Spectral resolution: R = 500-5000 for $0.75''$ slit; goal: R = 150 - 6000

Principal WFOS science cases include:

- Tomography of the IGM and exploring the epoch of galaxy formation, especially between $1 < z < 7$
- Spectroscopy of high redshift supernovae, gamma ray bursts, and other faint transient phenomena
- Spectroscopy of very faint sources (e.g., white dwarfs, stars and globular clusters out to galaxies in the Virgo cluster) in the local Universe

A team at NRC-HIA Victoria led by R. Abraham (U of Toronto), P. Cote and S. Roberts are studying a four-barrel concept that was initially pioneered by J.B. Oke.

4.3. MIRES: Mid-IR Echelle Spectrometer

The required wavelength range for this diffraction-limited instrument is 8 - 18μm; the goal is 5 - 28μm. The required field of view is $10''$ and the spatial sampling is 17mas per pixel. The required spectral resolution is $5000 < R < 100000$ with a diffraction limited slit width.

Some of the main science goals include:

- Dissipation timescales for gas in terrestrial and giant planet regions of star-forming disks
- Identification of forming planets during the disk accretion phase
- The structure and kinematics of infalling envelopes of protostars

In theory, an instrument working at the diffraction limit of an 8-10m telescope, such as TEXES, could be directly transferred to work at the diffraction limit of a 30m telescope, albeit with smaller field. Thus the fundamental concept for MIRES is relatively straightforward. The team carrying out the feasibility study for this instrument is being led by J. Elias(NOAO) and A. Tokunaga(UH) with significant involvement from M. Richter(UC Davis) and J. Carr(NRL).

4.4. IRMOS: Infrared Multi-Object Spectrograph

IRMOS is basically a deployable IFU spectrometer that uses MOAO to provide near-diffraction limited image quality in at least 10 positions spread over a $5'$ diameter field. It must deliver spectral resolutions between $2000 < R < 10000$ over entire J, H, K bands at once. The IFU field size is specified to be $2''$ with 50mas pixel spatial sampling.

Main science goals include:

- Detailed physical properties of galaxies during the era of peak star formation
- Properties of extremely high redshift galaxies
- Resolved stellar populations in Local Group and Virgo cluster galaxies

Two studies that rely on very different concepts for IRMOS target selection are underway: a group at U Florida led by S. Eikenberry, together with D. Andersen(NRC-HIA), is studying a pickoff arm concept, whereas a team at Caltech led by R. Ellis and K. Taylor is studying a concept that involves a tiled array of mirrors.

4.5. PFI: Planet Formation Imager

As its name suggests, the basic goal of this instrument is to utilize high contrast imaging to detect and characterize planets. PFI will employ very sophisticated high order adaptive optic and coronagraphic techniques to null the glare of the parent star, allowing relatively dim planets to be studied. Basic requirements are:

- To provide a contrast of 10^6 (goal: 10^7) in a field of view with radius 0.3 - $1''$ from the parent star
- Wavelength range: 1 - 2.5μm; goal 1 - 5μm
- Spectral resolutions ≤ 100

Obviously the smaller diffraction-limited images of a 30m telescope will allow searches for planets much closer to the parent star than will be possible with the 8-10m instruments currently under development. A collaboration led by B. Macintosh(LLNL), M. Troy(JPL) and R. Doyon(UMontreal) are studying PFI concepts.

4.6. NIRES: Near IR Echelle Spectrometer

NIRES will be fed diffraction-limited images by NFIRAOS and consequentially offers a D^4 sensitivity gain for point source targets.

- Wavelength range: 1 5μm; simultaneous 1 - 2.4μm and 3 - 5μm
- Spectral Resolution: $20,000 < R < 100,000$

Science highlights include:

- Detailed abundance studies of stars in Local Group galaxies.
- Studies of the intergalactic medium beyond z = 7
- Doppler-based planet studies - especially for planets around lower mass stars
- Abundances, chemistry and kinematics in star- and planet-forming disks

Like MIRES, a NIRES-like instrument designed to work at the diffraction limit of an 8m telescope can, in principle, be used on a 30m telescope and so the basic instrument concept is fairly well understood.

4.7. HROS: High Resolution Optical Spectrometer

HROS is a seeing-limited optical spectrometer intended for use in the wavelength range 0.31 - 1μm(goal 1.3μm) and produce a spectral resolution of R = 50,000 for $1''$ slit.

Science highlights include:

- Detailed abundance measurements for stars as faint as V = 20 in globular clusters, our Milky Way galaxy, and Local Group galaxies
- Doppler-based searches for extra-solar planets - extending current searches with higher precision to enable searches for lower-mass planets
- Abundances, kinematics and physical conditions in the inter-galactic medium

Two feasibility studies are underway: a conventional, albeit huge, echelle spectrograph by a team at Santa Cruz led by S. Vogt and C.Rockosi, and another option consisting of a series of first-order spectrographs fed by a bank of dichroic beamsplitters by a team at the University of Colorado led by C. Froning.

4.8. WIRC: Wide-field Infrared Camera

Fed by a multi-conjugate adaptive optics system, possibly an upgrade of NFIRAOS, this instrument will deliver precise photometry and astrometry over a $30''$ field. The main science goals will be high precision, faint object astrometry in regions like the galactic center and studies of stellar populations and star formation histories in nearby galaxies. The IRIS imager may be able to provide much of the functionality required for this instrument, although with a smaller field.

5. ADAPTIVE OPTICS

At least half of the projects envisaged for TMT will require adaptive optics and most would benefit, even if it provides only modest compensation like GLAO. However, given both the cost and technological readiness of various components, it was judged prudent to limit the aspirations for first light and adopt a phased approach. The first light (2014) architecture is planned to only include a laser guide star facility(LGSF), an active secondary mirror and the narrow field AO system NFIRAOS. The completed AO architecture will be much more ambituous, as demonstrated in Fig 3.

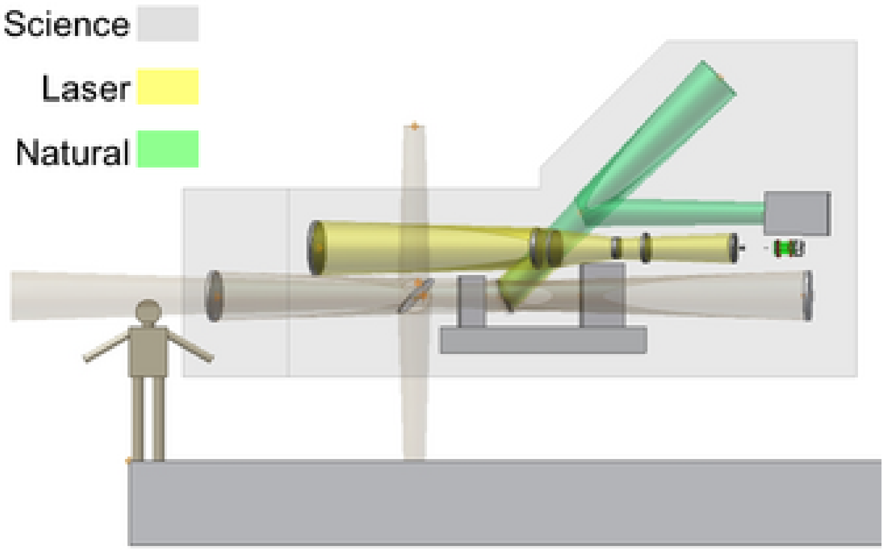

Figure 2. Side view of NFIRAOS sitting on the Nasmyth platform. Optical paths for the science light, NGS wavefront sensor and LGS wavefront sensor are shown. Instruments can be located at a lateral port, and above and below NFIRAOS.

5.1. First Light AO Capabilities

5.1.1. NFIRAOS

NFIRAOS will be the facility AO system, feeding IRIS at first light, and eventually feeding other instruments like NIRES and WIRC. It will deliver images with 150-200nm wavefront error with a 30″ field when initially implemented. A schematic diagram illustrating the current design is shown in Fig. 2. NFIRAOS is required to have 50% sky coverage at the galactic poles. To meet these requirements, the implied component and design parameters are:

- Order 60x60 wavefront sensing and correction
- 6 LGS wavefront sensors(WFS) with ∼25W of laser power per beacon
- MCAO system with 2 deformable mirrors conjugate to 0 and 12km
- NIR natural guide star(NGS) tip/tilt/focus sensing with a 2′ diameter guide field

5.1.2. MIRAO

This AO system is required to operate in the 7-20μm (goal 3-20μm) region with a 10$''$ field of view. This system requires 1-3 laser guide stars and one tip/tilt/focus NIR NGS wavefront sensor. Unless an adaptive secondary mirror becomes available for first light, it will also have to incorporate a deformable mirror of order 15x15 to 30x30. This will have considerable impact on the total emissivity of the system since a total of three extra surfaces are required to provide the light path for the internal deformable mirror.

5.2. Planned or Potential Upgrades to the AO systems

As Figure 3 demonstrates, there are several components that will be added or upgraded to make it possible to achieve the full potential of a 30m telescope as desired by the TMT SAC.

- Adaptive secondary mirror (AM2). This enables low emissivity MIRAO, efficient GLAO operation, and could serve as a low order, high stroke "woofer" for other AO systems.
- NFIRAOS upgrade to 120nm RMS wavefront error. This implies a higher order (120x120) deformable mirror and improved lasers.
- MOAO system for IRMOS with about twenty MEMS deformable mirrors of order 100x100 for separate IFUs.
- Very high order "extreme" AO system for PFI. This implies very high order MEMS deformable mirrors.

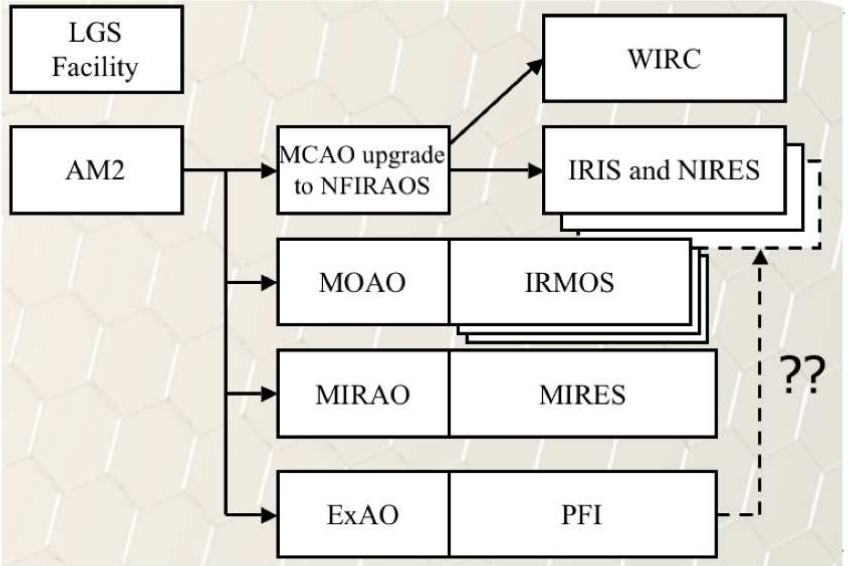

Figure 3. The completed AO architecture is envisaged to include an adaptive secondary mirror(AM2) that will provide high stroke, low order compensation to all subsequent AO systems (including GLAO; not shown) and instruments.

5.3. Component Development

In several areas there are clear needs for improvements in technology if TMT is to meet its science goals. Some of these are already being pursued by other programs, e.g., MEMS deformable mirrors, detectors for LGS wavefront sensors, improved lasers, etc., but studies for the following have been initiated by TMT:

- Piezostack deformable mirrors with adequate order of correction and stroke that can operate at cool (-35C) temperatures. A feasibility study and prototype demonstrator is underway at CILAS.
- Adaptive secondary mirrors. There are several options concerning material choices, details of segmentation, thickness vs. quilting vs. number of actuators and their force/power requirements, etc., that are being studied by SAGEM
- Real-time Controller Architecture. A feasibility study to investigate implementation of the requisite algorithms and computational requirements is underway by tOSC

6. SUMMARY

So far, our studies indicate that the requisite instruments are feasible for a 30m telescope. One of the challenges is to pace the design and development effort to take advantage of the latest technological advances yet ensure that there will be instruments ready for first light. Another challenge is to design effective, efficient instruments for the science currently envisaged while simultaneously maintaining discovery space, because experience shows that it is impossible to predict scientific priorities a decade in advance. Our philosophy is to adopt a relatively conservative, phased approach that relies on technology, e.g., of deformable mirrors, for first light that appears to be within grasp, and to map out upgrade paths that lead to utilization of the full power of a 30m telescope in a cost-effective manner.

More details on the TMT project can be found at www.tmt.org and lot.astro.utoronto.ca.

ACKNOWLEDGMENTS

The TMT project is generously supported by grants from the Gordon and Betty Moore Foundation, the Canadian Foundation for Innovation, the National Research Council of Canada, and the National Science Foundation.

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