Scientific Requirements for Extremely Large Telescopes
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Design and development of TMT†

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Abstract. The scientific goals for the TMT (Thirty Meter Telescope) are consistent with all the objectives outlined by the top level astronomy review committees in both Canada and the United States. In addition to powerful seeing-limited instruments, TMT will include instruments that will take advantage of the full diffraction-limited performance of a 30m telescope at wavelengths $>1\mu$m. This will enable TMT to meet the challenges presented by the scientific requirements and will provide full complementarity with future project like JWST and ALMA. This paper presents a brief review of the status of TMT and an overview of the instruments and their adaptive optic systems.

Keywords. telescopes — instrumentation: adaptive optics, miscellaneous

1. Introduction

TMT will provide a 30m ground-based facility capable of delivering diffraction limited images as well an order of magnitude increase in raw light gathering power compared to the current 8-10m telescopes. Laser beacons developed for Keck and Gemini adaptive optics systems have demonstrated the enormous potential of diffraction-limited observations and, as a consequence, the TMT community has determined that most, if not all, of the instruments should utilize adaptive optics. This, in turn, means that the telescope and all of its subsystems are being designed for diffraction-limited performance at wavelengths $>1\mu$m.

Based on analysis of the science projects that are currently foreseen for TMT, the TMT Science Advisory Committee (SAC) 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. A series of feasibility and conceptual design studies 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. The 30m diffraction-limited capability will provide the angular resolution and D^4 gains required to fulfil the scientific aspirations, and to provide data that fully complements that expected from missions like ALMA and JWST.

A brief overview of the TMT project and its current status are given in section 2; the telescope 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.

† 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 Research in Astronomy (ACURA). This is TMT document number TMT.IAO.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 30m 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.

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.

2.2. *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 2003b) and the Canadian VLOT science committee. More details on the science objectives for the individual instruments are included below.

2.3. *The TMT reference design*

Three independently conceived "ELT" (Extremely Large Telescope) design studies corresponding to a total effort worth approximately US$6M serve as the foundation for the TMT reference design. These three studies are the CELT design (CELT 2002) produced jointly by Caltech and UC, the VLOT design (VLOT 2003) carried out in Canada and the GSMT design (GSMT 2003a) 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.

transparency and emissivity, manpower availability, geotechnical, environmental issues, etc., will delivery of capital and operational resources, construction will followed by a Cost Review in September, 2006. Once the costs and and by contributions from ACURA and AURA. (ACURA, AURA, UC and Caltech) giving a total staff effort of nearly

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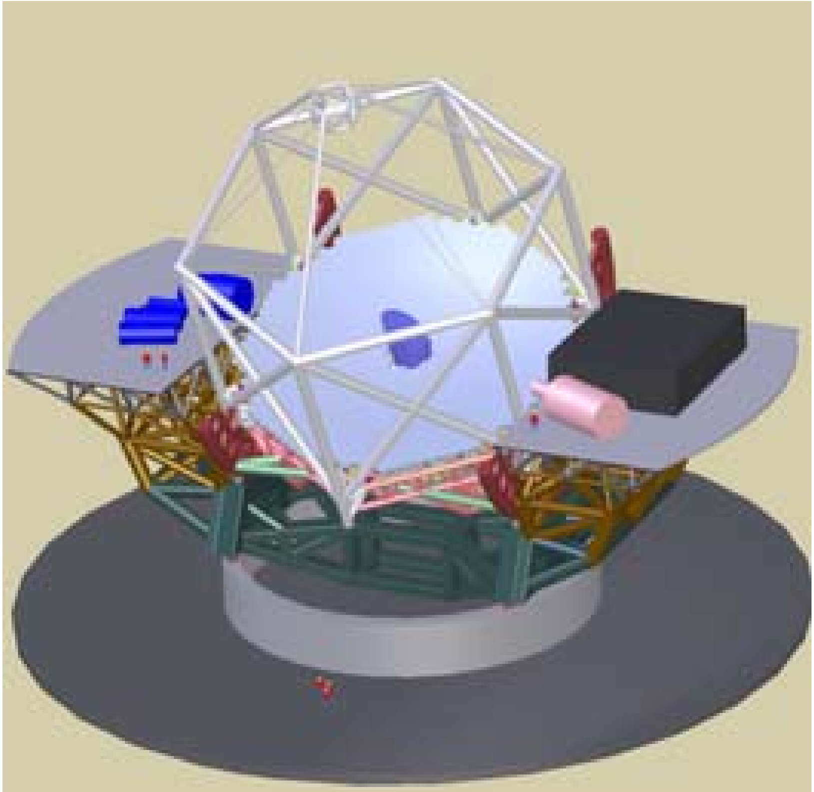

Figure 1. An illustration of the reference design. The telescope is an aplanatic Gregorian design with an f/1 primary and an f/15 final focus. It has a 20′ field of view. The instruments and their AO systems are located on large Nasmyth platforms, addressed by an articulated tertiary mirror.

70. important to TMT success, three companies (Zygo, Sagem, ITT/Tinsley) have been contracted to study how best to produce them. Similarly, studies are underway of the segment support assembly, actuators and edge sensors, and a sophisticated alignment and phasing system.

Two interchangeable 3.6m secondary mirrors are planned: a conventional one that will be used for first light and as a spare, and an adaptive mirror that may not be available at first light but will eventually become a component of the solutions for adaptive optic systems. Sagem is under contract to provide performance and cost estimates for the adaptive secondary.

As illustrated in Fig 1., the elevation axis of the telescope is above the primary mirror and the secondary is supported by spiders on top of a truncated tube. Since one of the science requirements is to rapidly (10 min) switch between instruments, the instruments and their AO systems are located on two large Nasmyth platforms, fed by an articulated tertiary mirror.

Two options are being seriously considered for the telescope enclosure: a carousel design and a calotte design. Since large carousel-type enclosures have been constructed previously they are presumably a lower risk option, but the calotte offers substantial savings in mass and cost. AMEC Dynamic Systems are studying telescope structure and enclosure designs.

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3. Instruments and AO systems

The TMT SAC identified the following instruments and AO systems as high priority for the first decade of operation.

AO systems:

- NFIRAOS, a narrow field facility AO system for first light
- MOAO (Multi-Object Adaptive Optics): ∼20 positionable, 5″ compensated patches in a 5′ field
- MIRAO (Mid-IR AO)
- MCAO (Multi-Conjugate AO): wider field AO, optimized for photometry and astrometry

Instruments:

- 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 imager and 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.* 2006) demonstrate that Ground-Layer AO (GLAO) may provide substantial benefits to seeing-limited instruments like WFOS and HROS and so it now also being considered as an option.

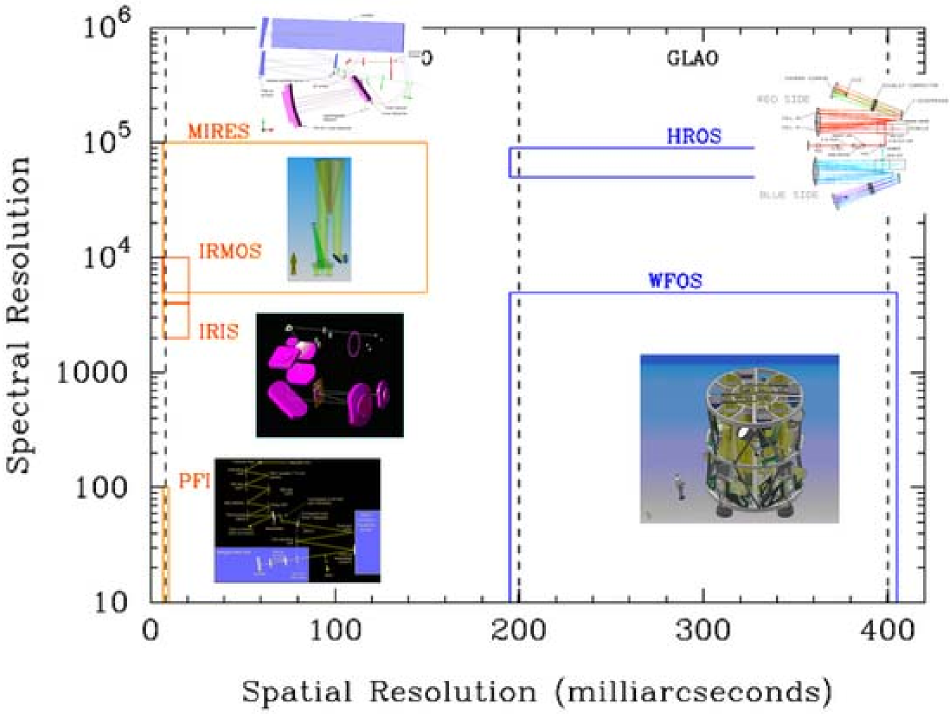

Figure 2. A diagram showing how the scientific requirements and capabilities for the instruments span spectral and spatial resolution space.

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The instruments are listed above in approximate order of SAC priority, and the two of the instruments, WFOS and HROS, are thought of as primarily seeing-limited instruments. Figure 2 shows how these instruments fill the spatial and spectral resolution "discovery space." Since it is recognized that it is impossible to predict what the actual scientific priorities will be 10+ years in the future, it is reassuring that the full complement of instruments will cover much of this discovery space. Budgetary limitations and practical considerations will likely make it impossible to provide more than a few of the instruments for actual first light.

3.1. *TMT instrumentation development plan*

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 expected 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. 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.

The following brief overviews of the instruments demonstrate that they will be capable of tackling most of the high priority scientific projects that are discussed elsewhere in these proceedings.

3.2. *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 in the 0.8 – 2.5 micron range. Other top level requirements include: 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 $10 \times 10''$ 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) is conducting a feasibility study for IRIS that includes consideration of both a lenslet-based IFU and an image slicer option.

3.3. *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 $\geqslant 500''$; spectral resolution, R = 500 – 5000 for $0.75''$ slit; goal: R = 150 – 6000.

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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 based at NRC-HIA Victoria led by R. Abraham (University of Toronto), P. Côté and S. Roberts is studying a four-barrel concept that was initially pioneered by J.B. Oke.

3.4. *MIRES: Mid-IR Echelle Spectrometer*

The required wavelength range for this diffraction-limited instrument is $8 - 18\mu$m; the goal is $5 - 28\mu$m. The required field of view is $10''$ and the spatial sampling is 17mas per pixel. The required spectral resolution is $5\,000 < \mathrm{R} < 100\,000$ 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 (University of Hawaii) with significant involvement from M. Richter (UC Davis) and J. Carr (NRL).

3.5. *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 $2000 < \mathrm{R} < 10000$ 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 for target selection.

3.6. *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: $1 - 2.5\mu$m; goal $1 - 5\mu$m

• Spectral resolutions $\leqslant$100

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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 (University of Montreal) is studying PFI concepts.

3.7. *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. It should operate over a wavelength range: 1 – 5μm (simultaneous 1 – 2.4μm and 3 – 5μm) with a 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.

3.8. *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 UC 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 beam splitters by a team at the University of Colorado led by C. Froning.

3.9. *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.

4. Adaptive optics

At least half of the scientific 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 include a laser guide star facility (LGSF), a conventional active secondary mirror and the narrow field AO system NFIRAOS. The completed AO architecture will be much more ambitious, as demonstrated in Fig 3.

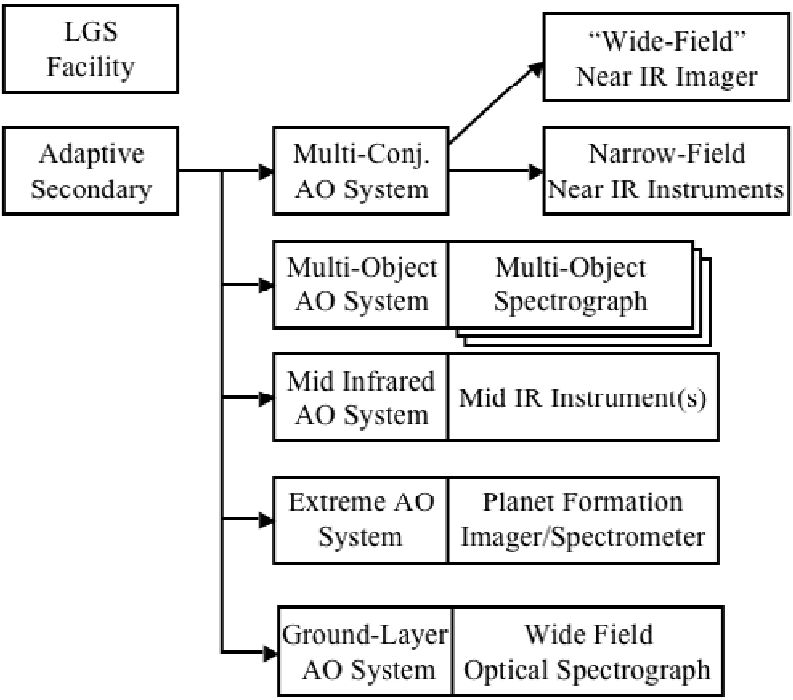

Figure 3. The complete AO system. Initially the facility AO system NFIRAOS + IRIS will be fed by the conventional (active) secondary but, as shown above, all instruments will eventually benefit from compensation by AO systems. An adaptive secondary will provide low order, high stroke "woofer" compensation. Upgrades to NFIRAOS will deliver high Strehl at wavelengths $>1\mu$m over a relatively large field.

4.1. *NFIRAOS: First light facility AO system*

NFIRAOS will be the facility AO system, feeding IRIS at first light, and eventually feeding other instruments like NIRES and WIRC. As initially implemented it will deliver images with 150 – 200nm wavefront error with a $30''$ field. A schematic diagram illustrating the current design is shown in Fig. 4. 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 $\sim$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

As high power pulsed lasers, higher-order deformable mirrors and the adaptive secondary become available, an upgraded NFIRAOS should deliver images with Strehl >0.5 at wavelengths down to 1μm.

5. Summary

So far, our studies indicate that the requisite instruments are feasible for a 30 m 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

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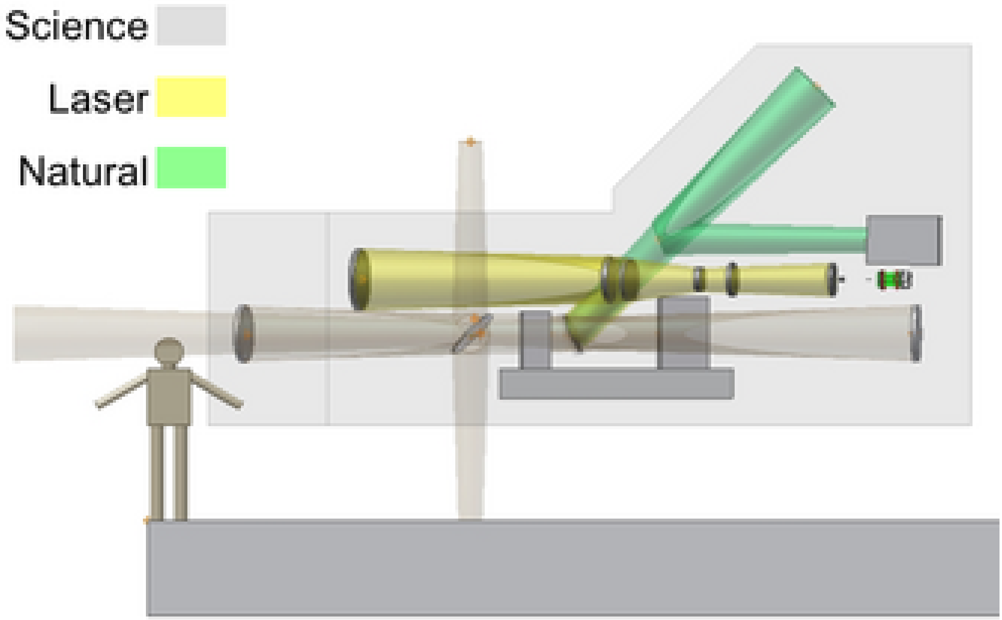

Figure 4. A schematic side view of the NFIRAOS AO system. Light enters from the left and two beam splitters are used to direct light upwards to the natural guide star and laser guide star paths. A fold mirror is used to direct the science light to instruments at three ports: upward, downward and side-looking.

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.

Acknowledgements

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Discussion

Cuby: You foresee 3 instruments out of 8 for first light. Any plan for the 5 other instruments?

Crampton: We plan to fund the other instruments out of operation funds. Of course we're also open to additional funding, particularly for specific scientific projects.