University of California
Santa Cruz, CA, 95064
USA
jnelson@ucolick.org

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Jerry Nelson

University of California at Santa Cruz

TMT: the next generation of segmented mirror telescopes

1. Introduction

The Thirty Meter Telescope (TMT) is a project to build and operate a ground-based thirty-meter telescope for optical and infrared astronomy. The primary mirror is segmented (492 segments) and follows the general design approach of the Keck Observatory. The telescope is compact (f/1 primary) and can accommodate multiple science instruments on either of two Nasmyth platforms.

1.1. Organization

The partnership that forms the TMT consists of the University of California, Caltech, Canada (HIA), Japan (NAOJ) and possibly other international partners. It is our desire that the National Science Foundation join the Project in order to provide a significant share of the telescope for use by the broad USA community of astronomers.

The headquarters of the project are in Pasadena, CA, but work is carried out as well by partner institutions at other locations. A number of industrial firms are involved in the design of the observatory.

The project began officially in 2004 with the hiring of its Project Manager, Gary Sanders. Jerry Nelson is the Project Scientist.

1.2. Site Selection

Finding the best site for such a large telescope is essential, and an extensive study of potential sites all over the world was initiated. Satellite studies of cloud cover and water vapor were used to reduce the candidates to five (Armazones, Tolar, Tolanchar in Chile, San Pedro Martir in Baja, and Mauna Kea in Hawaii). At these sites extensive testing equipment was installed to measure various weather and atmospheric conditions. Of greatest importance was the measurement of the seeing, and the vertical profile of atmospheric turbulence. Based on over two years of data at the five sites, two were judged highly meritorious on the basis of their science potential and were our final candidate sites (Armazones, Mauna Kea). After carefully reviewing the science potential, likely construction and operating costs, staffing issues, and other partner interests, we have recently selected Mauna Kea as the site for TMT. The actual site on Mauna Kea is a region known as 13N, somewhat lower than the summit ridge, at an altitude of 4000 m. This high site has particular potential for infrared astronomy due to its low precipitable water vapor and low temperature.

1.3. Schedule

The preliminary design phase has run from 2004 to 2009. We are now in the pre-construction phase, and expect that construction will start in the fall of 2011. The construction project includes the telescope as well as a very capable adaptive optics

(AO) system and three first-light science instruments. These will be discussed later. First light is expected in late 2018, with all the above systems operational and science operations underway, including AO.

1.4. Cost

The cost of the Observatory in FY2009$ is estimated at $970M which includes a 30% contingency. Cost is based on a detailed work break down structure, often going 7 layers deep and each WBS element costed bottoms-up. A formal risk analysis is employed for each of these elements. These risks are then rolled up to form the final percentage contingency for the Project. Of course the Project cost depends on what year $ it is calculated in, and will ultimately be sensitive to when actual construction starts.

2. Telescope Overview

Telescopes have grown gradually over time, from the 5 m Hale telescope completed in 1948 to the 10 m Keck telescope, put into operation in 1993. The Keck telescope uses a radical technical departure to achieve this size. The primary mirror is not a monolithic mirror, but is composed of 36 hexagonal segments whose positions are actively controlled. This allows the primary to behave optically as though it is a monolithic mirror.

Figure 1: The TMT shown with its enclosure and support facilities as it will appear on Mauna Kea

The TMT is built on the principles established by the Keck Observatory. The TMT primary mirror is segmented, with 492 hexagonal segments. The primary focal length is 30 m, allowing for a very compact enclosure. The optical configuration is a Ritchey-Cretien (RC) design, providing a 20 arcminute field of view with images < 0.5 arcsec. The telescope with its enclosure is shown in Figure 1. The optical layout is shown in Figure 2.

The primary mirror with its 492 hexagonal mirror segments is shown in Figure 3.

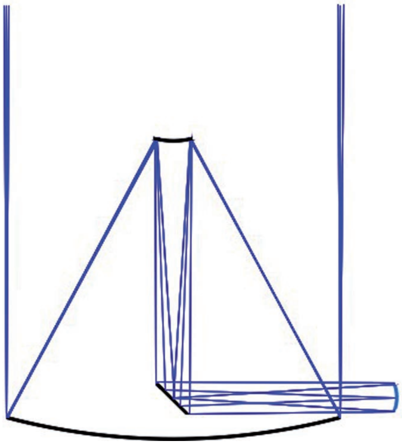

Figure 2: The Ritchey-Cretien design of the TMT with an f/1 primary and an f/15 final focal ratio. All instruments will be on the Nasmyth platforms, fed by the articulated tertiary.

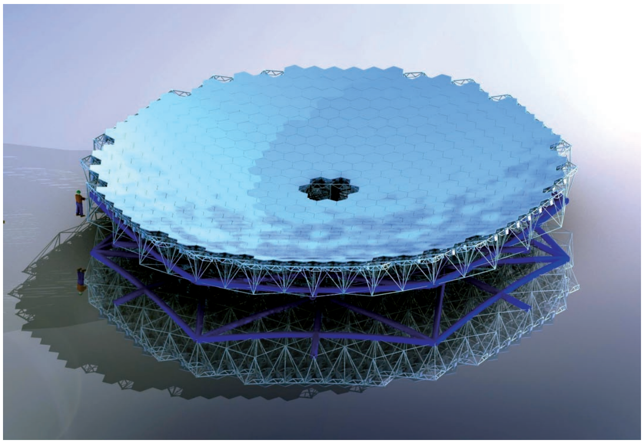

Figure 3: The TMT primary mirror with 492 1.45m diameter hexagonal segments, 45mm thick. Each is supported axially by a 27-point whiffletree system, and laterally by a diaphragm imbedded in the center of the segment.

The telescope as a whole is shown in Figure 4. The major components are labeled in the figure. The telescope can be moved to the horizon but science observations are limited to zenith angles above 65°.

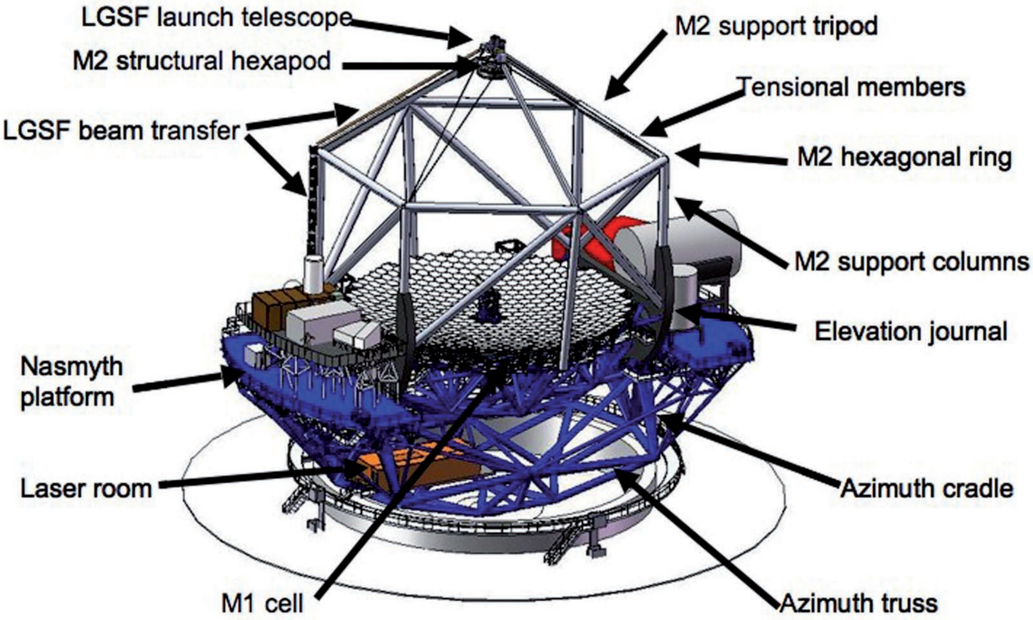

Figure 4: The telescope, showing its main structural features and the instrument facilities

The enclosure is a calotte design, with a fixed 31.25 m opening and an inclined rotation axis on top of a vertical rotation axis. This affords excellent protection of the telescope from wind and at the same time the enclosure system is balanced, so tracking the telescope does not require performing any work against gravity.

3. Key Features of TMT

The RC design provides excellent image quality over a 20 arcmin field of view. The optics are sized to provide an unvignetted 15 arcmin field of view and with <10% vignetting over the full 20 arcmin.

The tertiary mirror is articulated to allow it to direct starlight to any of the instruments placed on the Nasmyth platforms. Instruments along the elevation axis itself do not require motion of the tertiary, but instruments off the elevation axis require modest rotations of the tertiary as a function of zenith angle.

This feature allows all instruments to be stationary on the platforms and instruments will be live and ready for observations at all times. Each instrument will point towards the tertiary. This will allow the astronomer to switch between any instruments, and be ready to begin integration on a new target in under 10 minutes. This interchangeability is shown schematically in Figure 5.

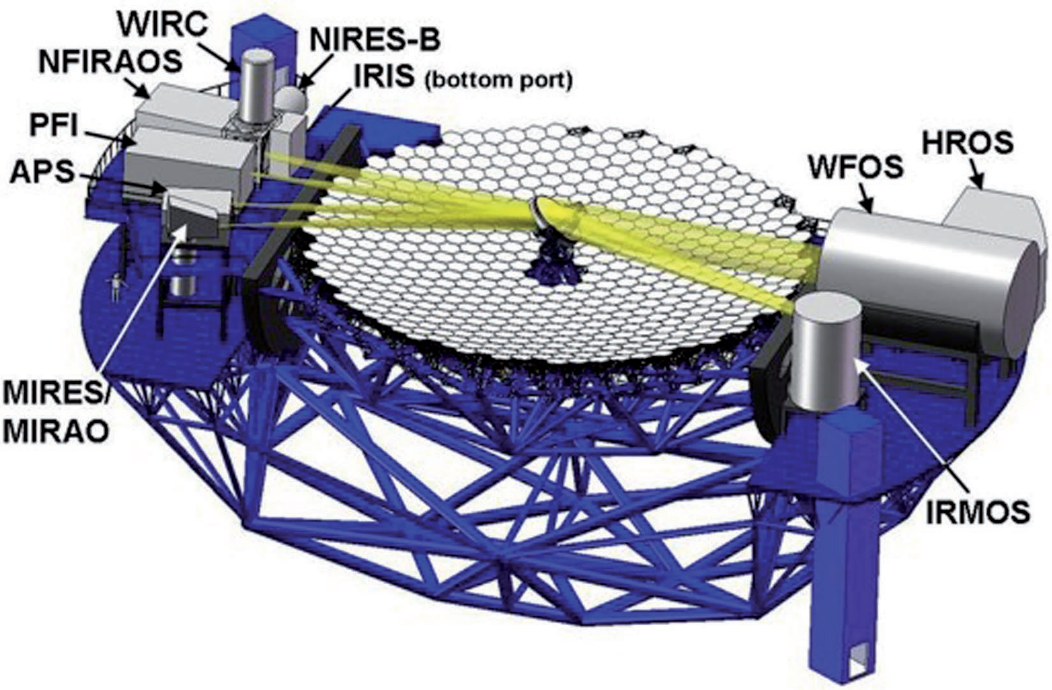

Figure 5: All science instruments and the AO system are located on the Nasmyth platforms and will be available at all times. Starlight can be directed to each instrument by rotation of the tertiary mirror.

The AO system for TMT includes a sodium beacon system with six laser beams launched from a telescope located behind the secondary mirror. This will form an asterism of six spots that is used to measure the turbulence of the atmosphere.

4. Major Science Goals

4.1. *Scaling laws*

A thirty-meter telescope obviously offers great gains over smaller telescopes, particularly when diffraction-limited. It is useful to consider the science metric of 1/time needed to make an observation. For seeing limited observations of background limited point sources the metric is sensitivity~ ηD^2 where η is the throughput of the system.

For background-limited observations of point sources in the infrared, AO is available to greatly improve the image quality. Here this metric is sensitivity~$\eta S^2 D^4$ where S=Strehl =$1/\exp(\sigma^2)$ and σ is the rms wavefront error in radians. With perfect optics S=1, so it is generally < 1. The D^4 gain is remarkable and is a major motivation for the science where TMT will excel. By this metric, reducing the wavefront error for AO is clearly very beneficial as well, and it will be limited by available technology. This narrow metric ignores the obvious benefit of improving image quality itself, so one can better understand the morphology of the targets of interest.

4.2 *Broad Science Areas*

TMT has generated detailed science cases for a diverse range of science opportunities and we will not review them in any detail here. The interested reader can find documentation on the TMT web page. Excellent opportunities include solar system studies, direct imaging of planets around nearby stars, detailed study of stars and stellar evolution, black holes and galaxies, nearby galaxies, distant galaxies and first light, and many more.

5. Science Instruments

5.1. Adaptive Optics

Because of the enormous science potential, diffraction-limited image quality (7mas at 1µm) will be available at first light of TMT. The adaptive optics system for initial science is NFIRAOS and will deliver wavefront errors ~ 190 nm rms over a 10 arcsec field of view, and only modest degradation over a 2 arcmin field of view. This will be achieved by having a dual conjugate AO system, with one deformable mirror (DM) conjugate to the ground, and a second DM conjugate to 11km height. This greatly increases the corrected field of view. The operating range of NFIRAOS will be from 0.8 to 2.6µm.

Light is needed to sense the ever-changing atmospheric wavefront errors. Generally, sufficiently bright stars for this are rare, thus sky coverage using natural stars to measure the wavefront errors is very limited. As a result we will have 6 sodium lasers that make bright spots in the sodium layer in our atmosphere. These artificial beacons will be used to tomographically reconstruct the three-dimensional turbulence structure of the atmosphere. From this three dimensional knowledge one can determine the optimal correction to be applied to each of the two deformable mirrors. Future systems may take further advantage of this knowledge by correcting the atmosphere in specific directions (using a deformable mirror for each direction) suited to the locations of the science targets. A schematic showing the principles of the tomographic measurement and correction is shown in Figure 6. To generate enough return light to measure the atmosphere at speeds of ~ 800 Hz we will have six 25W lasers generating Na light. The lasers will be mounted on the base of the telescope and with beam transfer optics the light will be shipped up to the launch telescope that is behind the secondary mirror.

Given the six measured wavefronts, actually reconstructing the atmosphere and generating commands to the deformable mirrors is extremely computationally intensive. We have studied various efficient iterative algorithms to solve the equations, and reviewed the use of specialized computational hardware (digital signal processors or DSP's). We have established that this computation can be done with existing hardware.

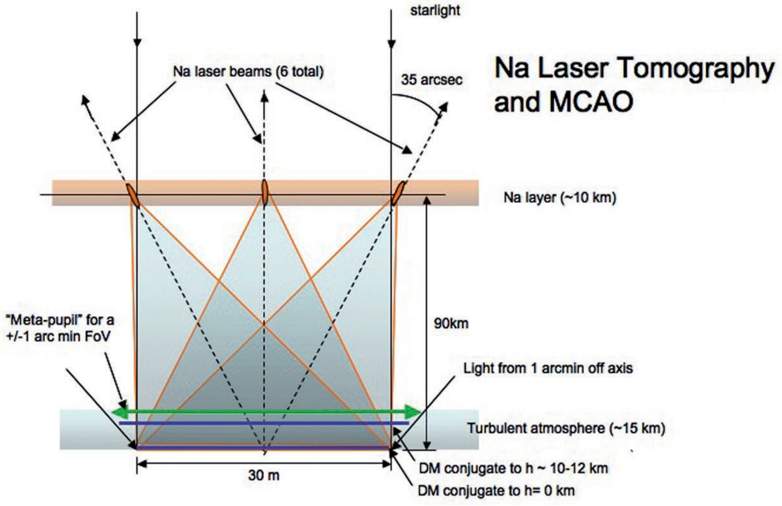

***Figure 6** This schematic shows the Na spots ~90km up and the illumination path of each spot through the atmosphere. The turbulent atmosphere of interest is only the lowest ~ 15km of atmosphere. The two DM's are conjugate to 0km and 11km for NFIRAOS.*

Laser beacons to measure the atmospheric distortions will measure the high order wavefront errors but cannot measure the tip, tilt, or focus errors. These must also be measured and stabilized. This will generally be done by measuring the locations and defocus of three natural guide stars that are within the 2 arcmin field of view. These will be measured in the near infrared to take advantage of the AO correction on these images. They will have a diffraction-limited core that will allow accurate centroiding. Because of this core, very faint guide stars can be used, and the resulting sky coverage at the galactic poles will be > 50%.

We have commented on the great improvements in angular resolution (factor of 100) that can be achieved with AO. One way to visualize the potential impact of such improvements is shown in Figure 7. A typical galaxy is shown at the resolution of the Hubble Space Telescope and then at the resolution of TMT with AO. This shows the gains by improving the angular resolution. The other measure we previously discussed was the gain in point source sensitivity.

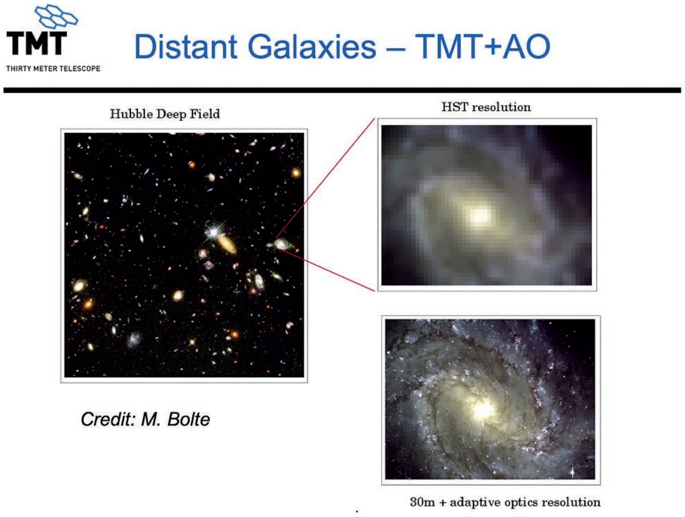

***Figure 7** To show the power of the improved angular resolution that AO brings, we have taken the Hubble Deep Field and picked a typical galaxy from it, and shown it at the resolution of Hubble and at the resolution of TMT with AO.*

NFIRAOS resides on one of the Nasmyth platforms. It can send corrected light to any of three science instruments that can mounted on NFIRAOS itself. The general layout is shown in Figure 8. NFIRAOS feeds any of the three instruments by rotating a fold flat inside of NFIRAOS. The main enclosure is cooled to -30°C to reduce thermal emission from NFIRAOS. This is important for the wavelength region 2.0-2.6μm.

A better view of the actual optical system inside of NFIRAOS can be seen in Figure 9. There are two off–axis paraboloids that image the atmospheric layers onto the deformable mirrors. The DM at 0km is mounted on a fast tip-tilt stage that will remove rapid image motion as sensed by the three natural tip tilt stars. More details of the optics are available in a number of published papers.

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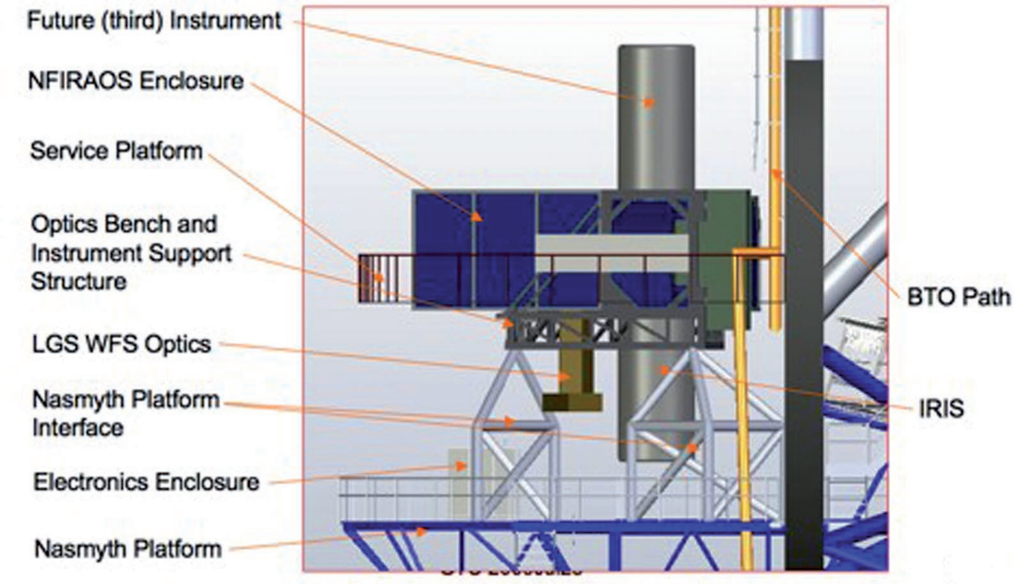


Figure 8 NFIRAOS is shown on the Nasmyth platform. Three science instruments can be fed by NFIRAOS. Two are shown (grey cylinders) and the third instrument is on the far side. Any of these instruments are fed by rotating a fold flat mirror that is inside of NFIRAOS.

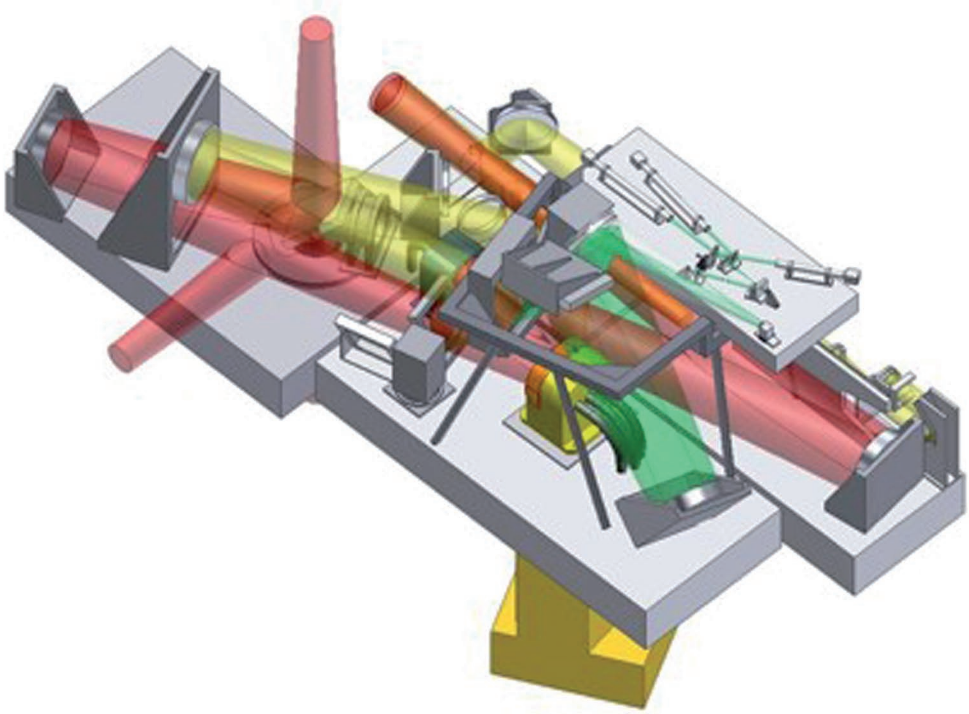


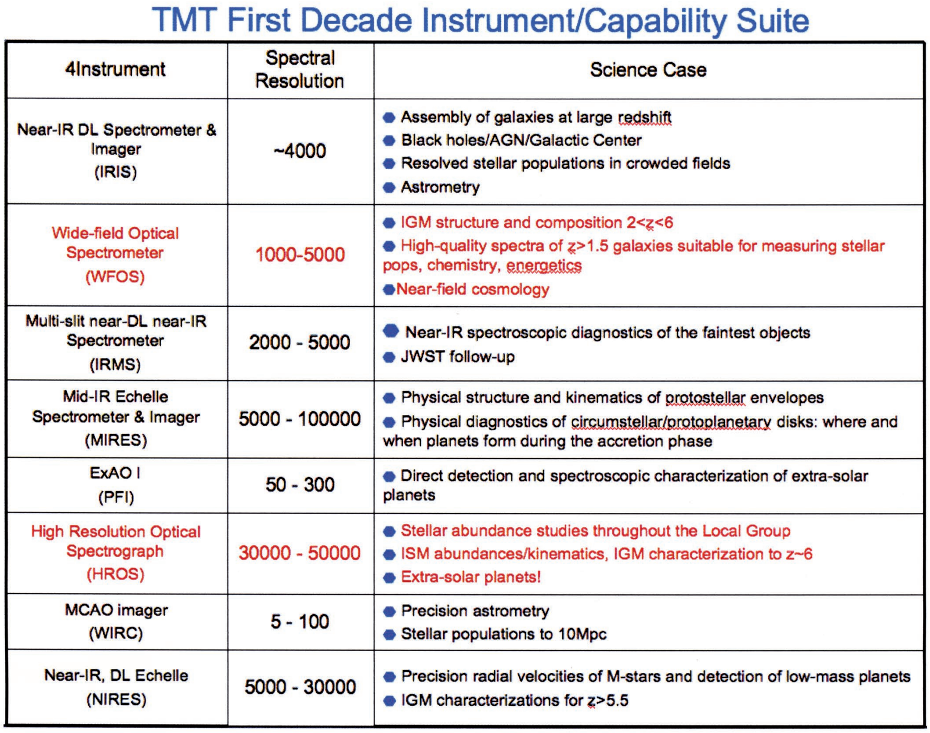
Figure 9 The optical bench of NFIRAOS shows the science beam (in red) and the laser light (in yellow). The three possible feeds to science instruments are shown. The yellow box directed downwards contains the wavefront sensing system for the laser light.

5.2. The first decade Suite of Science Instruments

The TMT Science Advisory Committee (SAC) has selected 8 instruments for the first decade of observations. These were selected after conceptual studies for a variety of instruments were carried out. These studies generated conceptual designs, performance estimates, and cost and feasibility estimates.

We recognize that its impractical and perhaps inappropriate to have all these instruments available for first light. We may not have sufficient funds, and it may be that only after some experience with TMT and the science discoveries it makes can we properly design additional instruments.

As a result of this, the SAC has selected three of the eight science instruments to be available at the beginning of observing with TMT. These are broadly capable instruments that should have the highest possible initial science impact. The Table lists the names, spectral resolution, and some key science goals of each instrument. The instruments in red are seeing limited, visible light instruments. The others are infrared instruments that will use adaptive optics to produce diffraction-limited images. The first three instruments will be the initial suite.



TMT First Decade Instrument/Capability Suite

4Instrument	Spectral Resolution	Science Case
Near-IR DL Spectrometer & Imager (IRIS)	~4000	● Assembly of galaxies at large redshift ● Black holes/AGN/Galactic Center ● Resolved stellar populations in crowded fields ● Astrometry
Wide-field Optical Spectrometer (WFOS)	1000-5000	● IGM structure and composition 2<z<6 ● High-quality spectra of z>1.5 galaxies suitable for measuring stellar pops, chemistry, energetics ●Near-field cosmology
Multi-slit near-DL near-IR Spectrometer (IRMS)	2000 - 5000	● Near-IR spectroscopic diagnostics of the faintest objects ● JWST follow-up
Mid-IR Echelle Spectrometer & Imager (MIRES)	5000 - 100000	● Physical structure and kinematics of protostellar envelopes ● Physical diagnostics of circumstellar/protoplanetary disks: where and when planets form during the accretion phase
ExAO I (PFI)	50 - 300	● Direct detection and spectroscopic characterization of extra-solar planets
High Resolution Optical Spectrograph (HROS)	30000 - 50000	● Stellar abundance studies throughout the Local Group ● ISM abundances/kinematics, IGM characterization to z~6 ● Extra-solar planets!
MCAO imager (WIRC)	5 - 100	● Precision astrometry ● Stellar populations to 10Mpc
Near-IR, DL Echelle (NIRES)	5000 - 30000	● Precision radial velocities of M-stars and detection of low-mass planets ● IGM characterizations for z>5.5

Figure 10 The suite of science instruments planned for the first decade of TMT. The first three will be available for initial science. WFOS is a seeing-limited instrument and IRIS and IRMS are AO-fed diffraction limited instruments.

6. Conclusions

TMT is nearing the end of its preliminary design and the Observatory, the AO system, and the first three science instruments are far along in their designs, performance and cost estimates. We expect to begin construction on Mauna Kea in 2011, and begin science observations with the completed Observatory in 2018.

Foundation documents for TMT can be found at: www.tmt.org/foundation-docs/index.html. There one can find:

Detailed Science Case 2007

Observatory Requirements Document

Observatory Architecture Document

Operations Concept Document

TMT Construction Proposal

There are many reports about the TMT design that can be found in recent SPIE proceedings (Marseille, 2008).