30 M DIAMETER FOR 7 MILLI-ARCSEC RESOLUTION

The Thirty Meter Telescope has been designed to meet the demands of the scientific community for a next-generation observatory. TMT will have approximately three times the resolution and nine times the collecting area of the current 10m-class telescopes. Advanced adaptive optics capabilities will allow highly sensitive, diffraction-limited observations from a wavelength shortward of 1 μm to the mid-infrared over most of the sky. A 20arcmin-diameter field of view facilitates the deployment of wide-field, multi-object spectrographs. These capabilities will enable groundbreaking advances in a wide range of scientific areas, from the most distant reaches of the Universe to our own Solar System.

FRED KAMPHUES

AUTHOR'S NOTE

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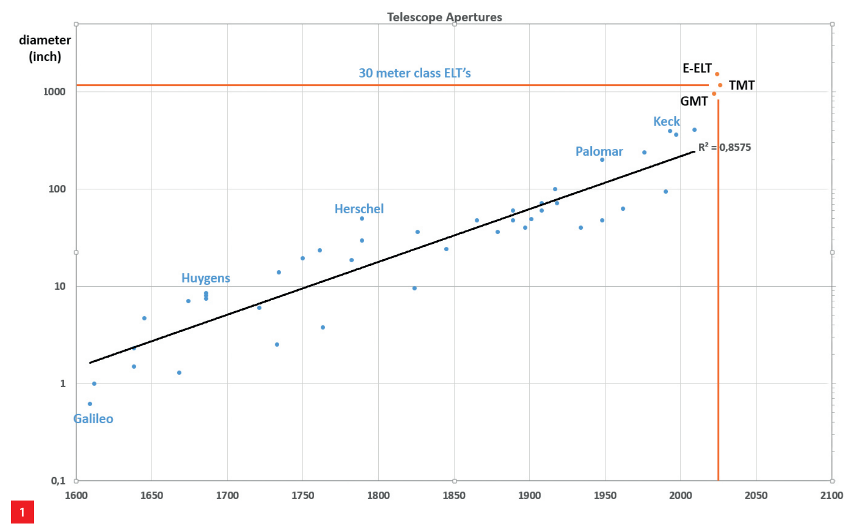
History

Optical astronomical telescopes have been around for a little over 400 years. Galileo's first refractor had a tiny 1.5cm aperture. Isaac Newton achieved a big improvement in optical quality in 1668 by building the first practical reflecting telescope. This type of telescope quickly became the norm in astronomy and primary mirror apertures grew gradually from 20 cm in the late 17th century (Christiaan Huygens) to the current 10m-class telescopes (Keck, VLT, Gemini, Subaru, GTC, etc.). Apertures doubled in size approximately every fifty years.

The new class of extremely large telescopes – European Extremely Large Telescope (E-ELT), TMT, and the Giant Magellan Telescope (GMT) – break away from this four centuries old trend (Figure 1). History teaches us that breaking a trend, brings high technical and financial risks to a project. The 1.2m Herschel in 1789 and the 6m Russian BTA-6 in 1976 are examples of telescopes with limited success.



1 *Telescope progression. (Data source: Wikipedia)*

In 1977 a team of astronomers from the University of California (UC) and the California Institute of Technology (Caltech) came up with a plan for a successor of the 5m Hale Telescope in Palomar. Initially, the idea was to design a scaled-up version of the Hale Telescope. However, a primary mirror with a 10m diameter would require a heavy structural support system and a very thick piece of glass to maintain a good optical surface. Cost estimates for a 10m telescope, using a monolithic primary mirror, were in excess of one billion dollars.

Jerry Nelson, a young and innovative astronomer and physicist, proposed a different approach. Instead of using a monolithic mirror, he advocated a segmented primary. But this presented another challenge: co-phasing all segments to form a continuous reflective surface. This approach required advanced sensor technology, control algorithms and computer power. But if the technology could be mastered, there would, theoretically, be no limit to the size of a reflecting surface. Nelson said in an interview at the time, "The Hale Telescope was very innovative for its day, but in terms of advancing the state of the art – or at least pushing the available technology to its limits – it's been downhill ever since for optical telescopes. It is time for a forward step, not just making improvements in an old design."

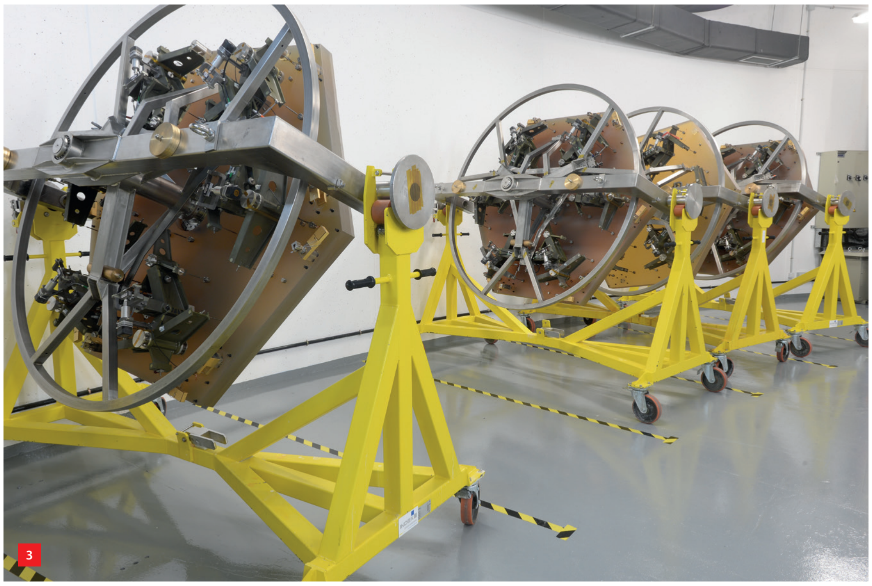

2

The UC/Caltech committee invited Nelson and his team to develop his idea. In 1979 they presented their segmented mirror approach to the committee, which was subsequently chosen over several other concepts. The new telescope would become the twin telescope W.M. Keck Observatory (Figure 2).

The twin Keck telescopes are located on the summit of Maunakea in Hawaii. Both identical telescopes have a 10m primary mirror, composed of 36 hexagonal segments. The segments are aligned by 160 electronic sensors and 108 position actuators. Since first light in 1993, the W.M. Keck telescopes have been the most productive observatory in the world.

2 *The twin Keck telescopes. (Photo: Fred Kamphues)*

3 *Primary mirror segments of the Gran Telescopio Canarias (GTC) in La Palma. (Photo: Fred Kamphues)*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Although the elevation of 4,145 meter reduces a significant part of the atmosphere's turbulence, long exposures still cause image blurring. Both Keck telescopes are therefore equipped with an advanced Adaptive Optics (AO) system, including Laser Guide Stars and Deformable Mirrors. The combination of excellent seeing and Adaptive Optics, enables Keck to produce images that rival the resolution of the Hubble Space Telescope.

Due to the success of Keck, the concept of segmented primary mirrors has been adapted by many other observatories around the world, including the Gran Telescopio Canarias, currently the largest optical telescope in the world (Figure 3). It is also the baseline design for the future Thirty Meter Telescope (TMT) and the European Extremely Large Telescope (E-ELT).

TMT International Observatory

The TMT project was born out of the merging of three earlier large-telescope projects: CELT, the California Extremely Large Telescope; VLOT, the Very Large Optical Telescope; and GSMT, the Giant Segmented Mirror Telescope. In 2003, TMT convened a Science Advisory Committee to help match the technical capabilities of the TMT with the demands of the scientific community for a next-generation observatory. Their efforts were instrumental in forging the Detailed Science Case for TMT, which continues to guide the design of the project.

TMT will have a 30m primary mirror, composed of 492 hexagonal segments. TMT's dramatic increases in collecting aperture and spatial resolution, will revolutionise studies of early star formation in the Universe, the evolution of galaxies, the characterisation of extra solar planets and the understanding of the fundamental physics of dark matter and dark energy.

TMT Systems Engineering.

The TMT International Observatory has its headquarters in Pasadena, California and includes five partner countries with participation from multiple organisations and industrial partners in the design and implementation of the observatory subsystems. TMT is comprised of 32 individual subsystems which include optical systems, instruments, AO systems, controls, mechanical systems, supporting software and hardware and the infrastructure required to support their operation.

In a project with so many time zones, the work never stops. A significant challenge for TMT Systems Engineering is to enable multiple international partners and suppliers to work on these self-contained subsystems, whilst having confidence that when they are integrated as a system they will meet the system level performance requirements.

TMT Systems Engineering has developed processes to support this distributed development, while maintaining the ability to respond and trade cost and schedule with requirements, budgets and performance at the system level. The key approaches that have been adopted include the following:

- Maintain a clear flow-down from science cases to system and subsystem requirements, enabling a clear understanding of trade-offs, and an ability to make changes as needed in an efficient manner.
- Maintain a logical system decomposition that can describe each subsystem in terms of requirements that are consistent with system performance and interfaces that clearly define responsibilities, functions and designs.
- Provide an efficient change process that supports appropriate review and efficient approval cycles at the needed project level.
- Document and agree the configuration of the system and subsystems in a manner that is clear and enables efficient change when required.
- Organise the Project and Systems Engineering (SE) team such that there is direct interaction between SE and partner organisations, while maintaining the appropriate reporting relationships between the TMT and partner work package managers.
- Maintain requirements and interfaces in a common DOORS (dynamic object-oriented requirements system) database, providing all project stakeholders access to the database and its products.
- Maintain a common observatory geometry database that accepts models from subsystem teams and incorporates them into a common digital mock-up (DMU) of the observatory. Make this database available to stakeholders within the project.
- Provide a verification and acceptance test process that emphasises the importance of verification and pre-shipment acceptance of subsystems before shipment to the observatory.

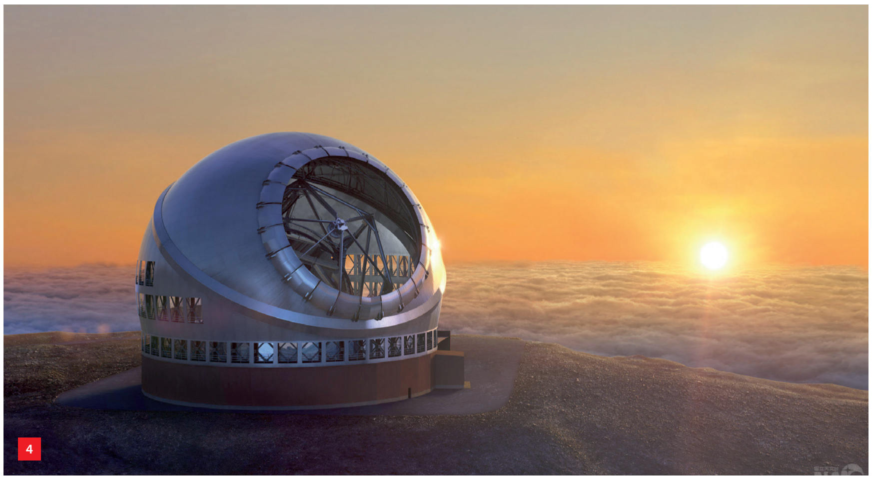
TMT Design

TMT's enclosure (Figure 4) features an innovative calotte design. Its circular aperture and spherical shape preserve the exceptional image quality of the telescope while minimising costs. The compact calotte design, with its smooth exterior, even while open for observing, is significantly less affected by unbalanced wind forces. This will lower the induced vibrations to the structure and optics.

The selected optical configuration for TMT is a 3-mirror Ritchey-Chretien design (Figure 5), providing a 20arcmin field of view. The science instruments are located on the two Nasmyth platforms. Figure 5 shows the TMT digital mock-up.

The telescope structure is designed as an altitude-over-azimuth (alt-az) mount. This allows the telescope to be very compact (relatively speaking) and provides direct load paths from the telescope down through the structure to the pier and foundations. TMT's primary mirror will be composed of 492 closely spaced hexagonal segments. A total of 1,476 actuators and 2,772 sensors will control the overall shape of the primary mirror to just a few nanometers.

TMT will be able to support instruments that are sensitive through the atmospheric windows from 0.31 to 28 μm. The atmosphere limits the angular resolution ('seeing-limited image quality') to about 0.5 arcsec. However, using adaptive optics (AO) a diffraction-limited angular resolution of 7 milliarcsec can be achieved at a wavelength of 1 μm. TMT's Adaptive Optics Instrument will produce images ten times sharper than those of the Hubble Space Telescope.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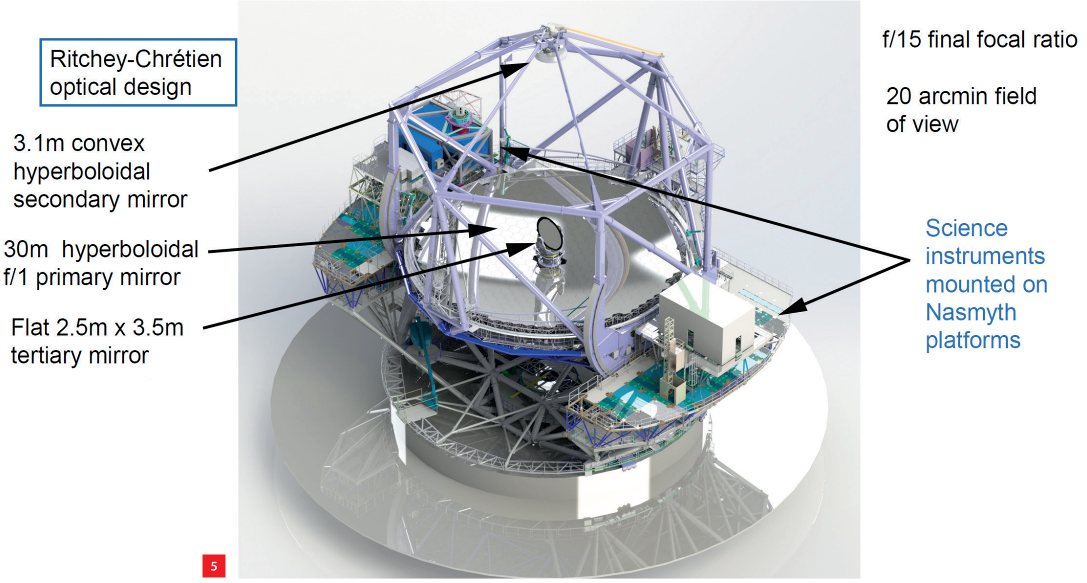
4 *TMT calotte enclosure. (Image: TMT/NAOJ)*



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5 *TMT digital mock-up (DMU). (Image: TMT/ Eric Wilde)*

6 *Primary Mirror blanks at Ohara in Japan. (Photo: TMT/NAOJ/Ohara)*

7 *M1 segment assembly at Harris, Rochester NY. (Photos: TMT/Harris/Fred Kamphues)*

Optics

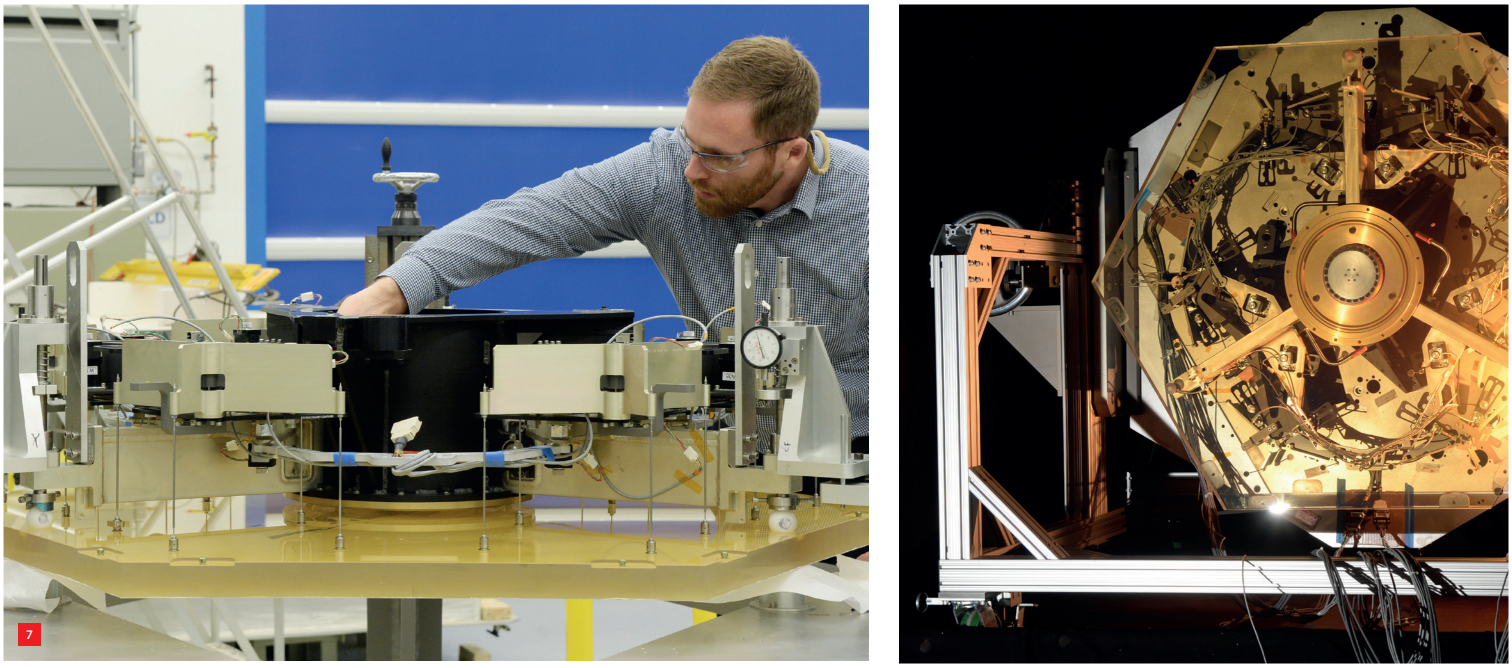
TMT is particularly drawing on Keck experience in the design of the primary mirror. The segmented TMT Primary Mirror (M1) is a 30m diameter concave hyperboloid. The focal ratio of the TMT M1 is faster than Keck (*f*/1 vs. *f*/1.75). This leads to segments that are more aspheric for a given size. It was the main reason to make the TMT segments 20% smaller than the Keck segments. The smaller segments can also be thinner. The segments are made from zero-expansion Clearceram-Z, with a thickness of 45 mm (Figure 6).

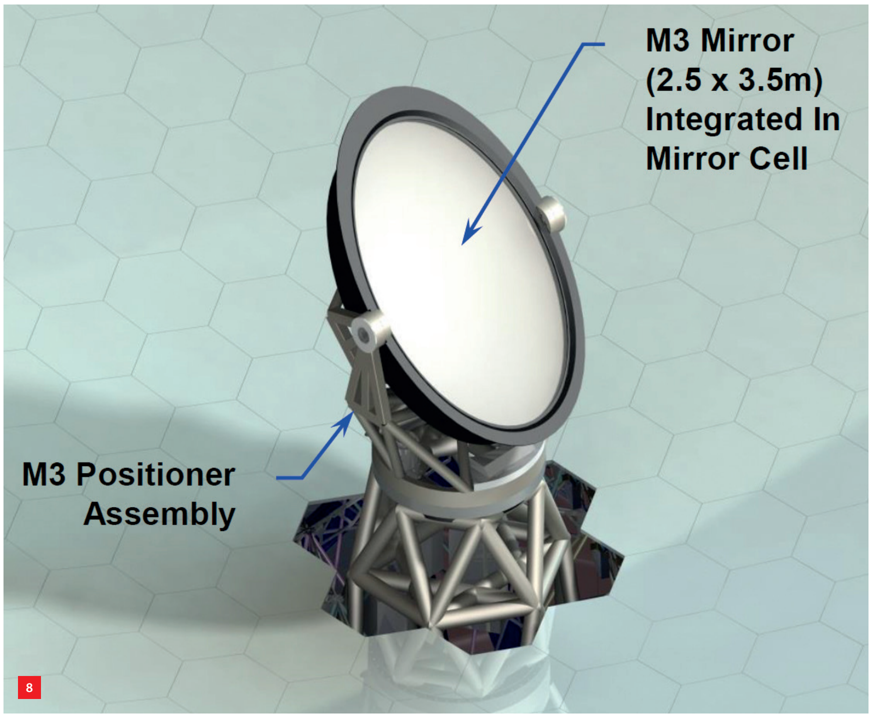
The Primary Mirror segments are already in production. Polishing of the aspheric segments is done with a technique called stress mirror polishing (derived from Keck). In this technique, forces and moments are selectively applied to the edges of a mirror blank in order to warp the blank to the desired degree of distortion. The segment is polished as a sphere. After removal of the forces and moments, the spherical surface will elastically deform into the desired aspherical shape.

After polishing, the round blanks are cut into a hexagonal shape (which may release some residual stresses and can deform the segment) and mounted on the Segment Support Assembly (SSA).
The SSA is a balanced whiffletree support, insensitive to gravity. 27 Thin flexures are attached to the back of the mirror to provide axial support. The lateral support (required when the telescope points towards the horizon) is provided by a central metallic diaphragm recessed into the glass. The segment with support system is shown in Figure 7. The segment size for TMT is almost identical to that for E-ELT and there is a good information exchange with ESO (European Southern Observatory) in Garching, Germany to benefit from each other's lessons learnt.

After segment assembly, Polished Mirror Assemblies (PMAs) are finished with ion beam figuring (IBF). Residual errors from IBF and mounting in the Mirror Cell (a small clocking error of a few micrometers creates strong astigmatism) are removed with an active Warping Harness. 21 Actuators apply small moments to the whiffletrees and can correct low-order segment aberrations such as focus and astigmatism.

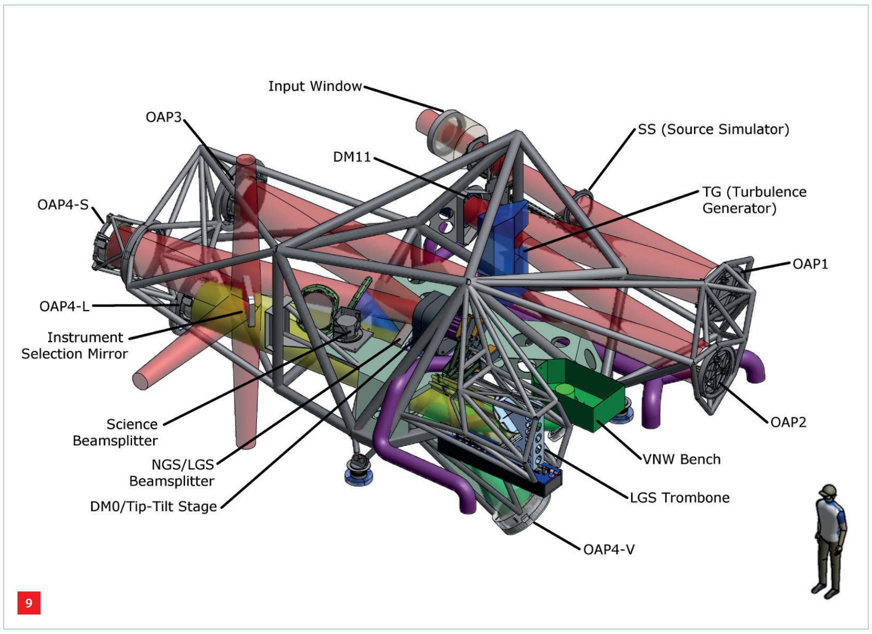
The Secondary Mirror (M2) is a 3.1m convex hyperboloid. It reflects the light from the *f*/1 primary mirror and converts it to an *f*/15 beam for the science instruments. It will have a passive whiffletree support and a hexapod for active alignment. The M2 detailed design phase has not started yet. Procurement of the M2 will start in early 2018.





8 *TMT Tertiary Mirror (M3). (Image: TMT/Eric Wilde)*

The Tertiary Mirror (M3) is articulated to allow it to direct starlight to any of the instruments placed on the Nasmyth platforms (Figure 8). 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 ten minutes.



9 *Narrow Field Infra-Red AO System (NFIRAOS). (Image: TMT)*

Adaptive Optics

The TMT first-light Adaptive Optics (AO) facility consists of the Narrow Field Infra-Red AO System (NFIRAOS) (Figure 9), the associated Laser Guide Star Facility (LGSF) and the AO Executive Software (AOESW).

NFIRAOS is located on the TMT Nasmyth platform and relays light from the telescope to three science instrument ports after sensing and correcting for wavefront aberrations introduced by atmospheric turbulence and the observatory itself. NFIRAOS is a multi-conjugate AO (MCAO) system, which provides uniform, diffraction-limited performance in the J, H, and K bands. NFIRAOS includes two deformable mirrors, six LGS Wave Front Sensors (WFSs), one high-order Pyramid WFS for natural guide star AO, and up to three low-order, IR, natural guide star on-instrument wavefront sensors (OIWFSs) and four on-detector guide windows (ODGWs) within each client instrument. The first-light LGSF system includes six sodium lasers to generate the NFIRAOS laser guide stars (Figure 10).

First-light instruments

Infrared Imaging Spectrometer (IRIS)

IRIS (Figure 11) is a near-infrared (0.84 to 2.4 μm) integral field spectrograph and wide-field imager being developed for first light for TMT. It mounts to the advanced AO system NFIRAOS and has integrated On-Instrument Wave Front Sensors (OIWFSs) to achieve diffraction-limited spatial resolution at wavelengths longer than 1 μm. With moderate spectral resolution (R ~ 4,000-8,000) and large bandpass over a continuous field of view, IRIS will open new opportunities in virtually every area of astrophysical science. It will be able to resolve surface features tens of kilometers across Titan, while also mapping the most distant galaxies at the scale of an individual star-forming region.

Wide Field Optical Spectrometer (WFOS)

The Wide Field Optical Spectrometer (WFOS) will provide near-ultraviolet and optical (0.3-1.0 μm wavelength) imaging and spectroscopy over a more than 40 arcmin^2 field of view. Using precision-cut focal plane masks, WFOS will enable long-slit observations of single objects as well as short-slit observations of hundreds of objects simultaneously. WFOS will use natural (uncorrected) seeing images.

Acknowledgements

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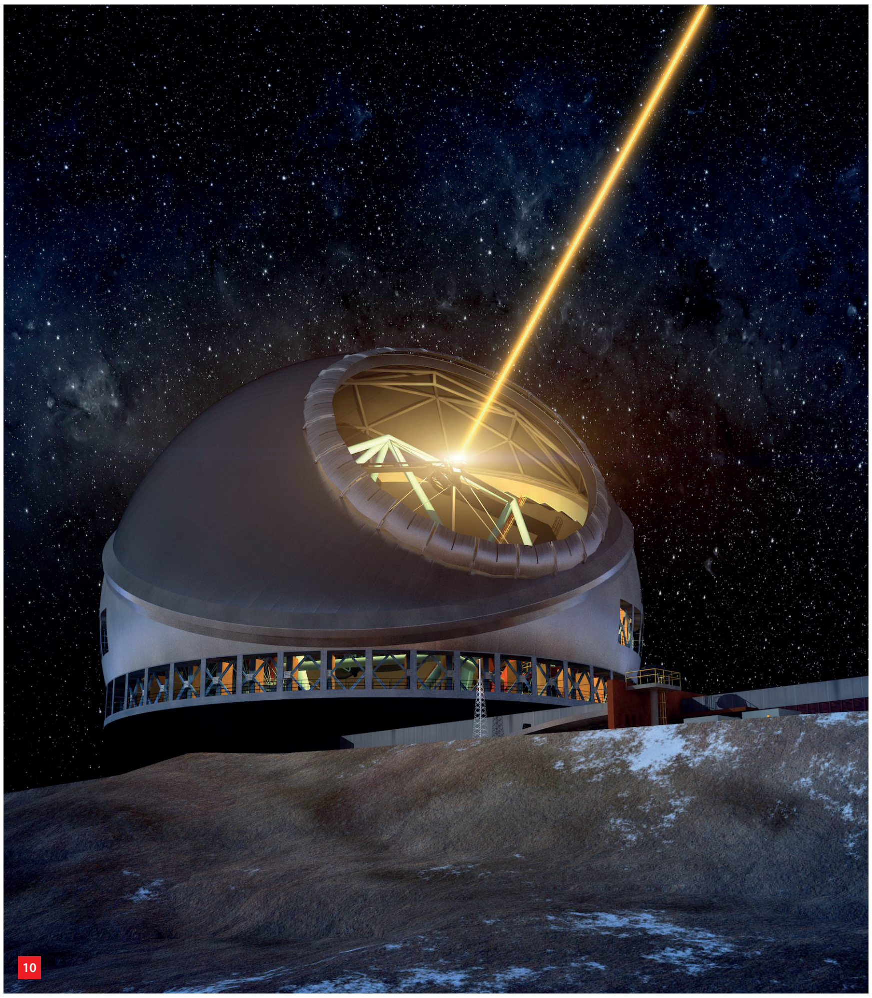

10 *TMT centre-launched Laser Guide Star Facility. (Image: TMT)*

11 *The IRIS instrument. (Image: TMT)*

of India and their supported institutes, and the National Research Council of Canada. 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 Natural Sciences and Engineering Research Council of Canada, the British Columbia Knowledge Development Fund, the Association of Canadian Universities for Research in Astronomy (ACURA), the Association of Universities for Research in Astronomy (AURA), the U.S. National Science Foundation, the National Institutes of Natural Sciences of Japan, and the Department of Atomic Energy of India. ■