
TMT
Canadian Project Digest
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तीस मीटर दूरबीन
Thirty Meter Telescope
Télescope de Trente Mètres

Contents

Overview

The Thirty Meter Telescope (TMT) represents the next generation of ground-based astronomical observatories. Driven by the frontier science issues of this decade, the TMT design offers 10 times the light-gathering power of the largest existing ground-based facilities and will produce images 10 times more detailed than the Hubble Space Telescope. With this tremendous increase in power, TMT will deliver as yet unforeseen, ground-breaking discoveries about the universe. In short, TMT will be the leader of a new generation of telescopes and will serve its partner communities as a flagship research facility.

Figure 1 - The TMT Observatory, planned for construction on Mauna Kea in Hawaii

The TMT project is an international partnership involving the Canada, the USA, Japan, China, and India. It represents a unique combination of technical, industrial, and scientific collaboration that benefits all partners. Sited near existing, complementary facilities on Mauna Kea in Hawaii, TMT will unite the Pacific Rim astronomical community about its vantage point, and will exclusively provide extremely-large telescope (ELT) access to the northern sky.

TMT offers immense scientific advantages over existing facilities (See TMT Science). The unprecedented light-gathering capability and angular resolution of TMT will revolutionize our understanding of many fundamental questions in science. These capabilities will open the door to new discoveries and a deeper understanding of the universe all the way from our own Solar System to the first stars. As an example of enhanced capability, Figure 2 compares an image from the 10-metre Keck telescope, currently the largest telescope in the world, with a simulated TMT image of the same field. It shows TMT's ability to trace orbits of stars in order to investigate the supermassive black hole at the centre of our galaxy and test Einstein's theory of General Relativity in new, unique ways.

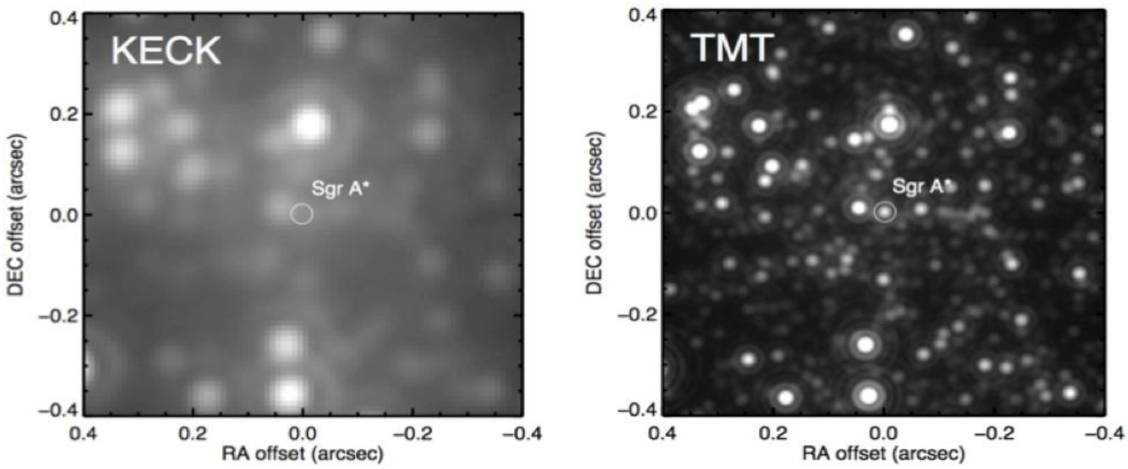

Figure 2 - Detecting and mapping the orbits of stars at the Galactic centre with the current Keck 10m telescope, and simulated first-light TMT adaptive optics systems (Courtesy: A. Ghez, UCLA)

TMT's science mission has been developed in collaboration with other existing and proposed facilities. TMT astronomers contributed to an important study[1] that emphasized synergy with the James Webb Space Telescope and provided key input into the National Science Foundation's Astro2010 process, which described synergies with the Atacama Large Millimeter Array (ALMA) and the Large Synoptic Survey Telescope (LSST), both sited in Chile. As evidence of this complementarity and its wide science capability, TMT's Detailed Science Case addresses 22 of the 24 science areas and 43 of the 68 basic science questions listed in the Astro2010 Decadal Survey report, and addresses all four key thematic questions that were outlined in the Canadian Long Range Plan for Astronomy.

The TMT design has been under development since 2003 and is now technically mature. With the completion of the Design Development Phase in March 2009, the project entered the Preconstruction Phase, and is ready to enter the Construction Phase at the Mauna Kea site in April 2014.

The TMT partnership represents a powerful, forward-looking research community that will secure an important place for Canada in the next generation of astronomy. In the past decade, Canadian astronomers have been ranked amongst the top researchers in the world, enrolment in astronomy at Canadian universities has been thriving, and Canada has been a partner in leading international astronomy projects. Partnerships in projects like TMT will maintain the forefront status of Canadian astronomy. Without such partnerships, the reputation of Canadian research will be placed at risk, and Canada stands to lose its best scientists and engineers to countries where they can flourish. The TMT project is the top-ranked priority in the current decadal Canadian Long Range Plan for astronomy research.

[1] R. P. Kudritzki. *A Giant Segmented Telescope: Synergy with the James Webb Space Telescope.* GMST Science Working Group, 2005.

Project History and Partners

In the early 2000s, Canada and the United States independently developed designs for the next generation of optical telescopes. The Canadian Very Large Optical Telescope (VLOT) working group studied designs for a next-generation, extremely large optical telescope in response to the first Canadian Long Range Plan for Astronomy. In 2003, the VLOT team published a project book describing the science case and observatory[2]. The U.S. effort involved the Association of Universities for Research in Astronomy (AURA), the University of California (UC), and the California Institute of Technology (Caltech). AURA developed designs for a Giant Segmented Mirror Telescope (GSMT), while UC and Caltech developed a design for the California Extremely Large Telescope (CELT).

Later in 2003, these groups merged their efforts to collaborate on a Thirty Meter Telescope concept incorporating aspects of all three designs. The same year, UC and Caltech founded the TMT Observatory Corporation with the aim of developing a preliminary design. AURA and the Association of Canadian Universities for Research in Astronomy (ACURA) joined immediately as partners. In the following years, other partners joined the project: in 2008, the National Astronomical Observatory of Japan (NAOJ); in 2009, the National Astronomical Observatories, Chinese Academy of Sciences (NAOC); and in 2010, the Department of Science and Technology of India (DSTI). India has recently made a commitment of more than $100 million to TMT, as announced by Indian Minister of External Affairs Shri S. M. Krishna and U.S. Secretary of State Hillary Clinton in June 2012.

Before joining the TMT collaboration, each partner conducted careful, long-range planning studies with their astronomy communities, weighing alternative directions in astronomy research and evaluating other giant-telescope projects. TMT is now a powerful collaboration representing the astronomy aspirations of a large portion of the world's population, uniting established astronomy communities with large, rapidly developing ones. By the end of 2011, the collaboration had invested a total of $150.1 million (U.S.) in design, development, and preconstruction. To date more than $30 million (CAD) has been invested in TMT within Canada. Caltech/UC have invested $104.4 million, including $95 million from the Gordon and Betty Moore Foundation. Additional private funding has already been pledged for the Construction Phase from the Gordon and Betty Moore Foundation and from Caltech and UC. The partners are developing a more formal Memorandum of Understanding (MOU) stating their intentions as participants in the project during the current Preconstruction Phase. The MOU describes the governance of project during the Preconstruction Phase; the anticipated governance during the Construction phase; and an implementation plan, including the expected contributions of each partner.

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[2] VLOT Project Book. A Large Optical Telescope for the 21th Century, Canadian VLOT Working Group. Herzberg Institute of Astrophysics, National Research Council of Canada, Victoria, BC, Canada, 2003.

In 2012, the TMT project submitted a funding proposal to the U.S. National Science Foundation (NSF) to plan a potential partnership between the two organizations. If approved, this proposal will enable TMT to benefit from engagement with the full U.S. astronomy community in the years ahead.

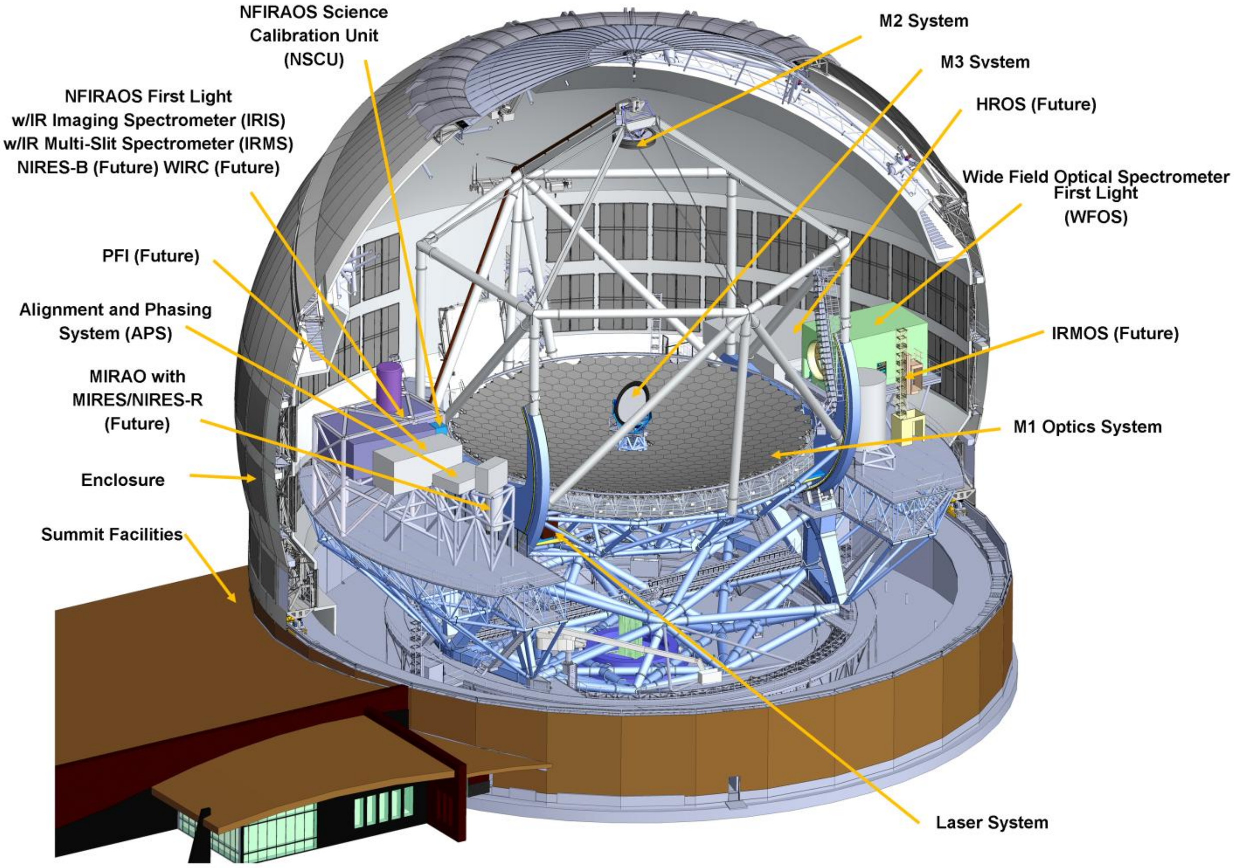


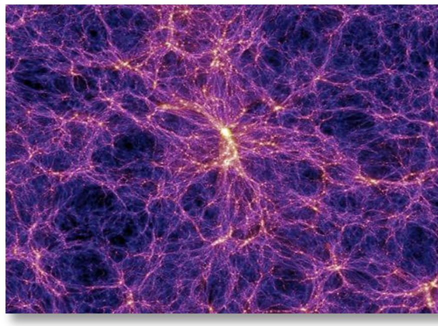
Figure 3 - TMT Observatory design showing the facilities, and telescope systems and instrumentation within the Canadian designed Enclosure

TMT Science

With its large collecting area, wide field of view, and powerful adaptive optics systems, TMT will produce images of unmatched reach and sharpness. It will be able to distinguish features as small as 25 km in size at the distance of Jupiter (at 5 AU). TMT's powerful science instruments will facilitate precise measurements of the motion of celestial objects on the sky, including other galaxies, and will be able to detect planets around other stars that are a billion times fainter than their parent star.

TMT will be sensitive from the ultraviolet to mid-infrared wavelengths and provide new capabilities to address astronomy's "Big Questions", ranging from the nature of the Universe to the formation of our own Solar System.

What is the composition of the Universe?



The nature of dark matter and dark energy, the main ingredients of the universe, remains a complete mystery. The dark matter particle is to cosmology what the long-sought Higgs boson is to particle physics. Einstein's General Relativity predicted that large masses in the Universe should produce beautiful arcs of light through gravitational lensing effects. These arcs have now been observed throughout the Universe, and tiny anomalies in their structure that only TMT will be able to detect should allow us to hunt the dark matter particle down to mass scales at least 10 times lower than is possible with current instruments. Dark energy, which is believed to come from the quantum structure of space itself, drives the expansion rate of the Universe. TMT observations, in the far away Universe, of massive stellar explosions known as supernovae will allow us to measure changes in the signature of dark energy over cosmological times for the first time.

When did galaxies form, and how did they evolve?

How does one go from tiny quantum fluctuations in the Big Bang to gigantic galaxies like our own Milky Way? The answer is believed to be a process of hierarchical mass assembly in which small galaxies collide with each other to form bigger and bigger galaxies over billions of years. The traces of this "Construction Derby" should remain imprinted on galaxies at the present time, and TMT will study galaxy formation near and far. TMT will tag stars in the Milky Way according to their chemistry, age and motions over volumes 100 times larger than currently possible to provide the first-ever "archeological" sample large enough to reveal the varied nature of galaxy assembly. It will also detect the spectroscopic signatures of stars in the first galaxies formed very early after the Big Bang. The sensitivity of TMT will produce detailed maps of the morphology, chemistry, and kinematics of galaxies as they assemble and evolve over cosmic time.

What is the relationship between black holes and galaxies?

Black holes with masses as high as a billion times the mass of the Sun are now known to occupy the centres of galaxies. Their formation process is unknown, but must be intimately linked to the formation and history of galaxies. The spatial resolution and sensitivity of TMT will make it possible to measure the masses of black holes ten times smaller, and map kinematics in 8000 times more galaxies, than currently possible. TMT will expand by a factor of a thousand the number of galaxies on which direct measurements of black-hole masses can be performed.

How do stars and planets form?

The mass of a star dictates how it will live and how it will die. Direct stellar mass measurements provide a fundamental test of theories of stellar formation and evolution. Currently, these mass measurements are only possible for a small number of double stars with specific orbital configurations. The angular resolution of TMT removes this obstacle and allows us to weigh stars in an entirely new way through gravitational lensing. As a star passes in front of a background star field, its gravity will slightly bend the light rays from these background stars, and the amount of bending will be proportional to its mass.

New planetary systems form out of disks of gas and dust coalescing around new stars. By mapping these proto-planetary disks with a spatial resolution five times greater than currently possible, TMT will unveil the regions in which *terrestrial* planets are forming.

What is the nature of extrasolar planets?

The first planet around another star was discovered in 1995. Since then, so-called exoplanets have been observed in ever increasing numbers thanks to massive observing efforts from the ground and space. Exploring them requires the high-contrast imaging and high-resolution spectroscopy provided by TMT. We will be able to distinguish rocky worlds like Earth from “micro-Neptunes” and search for brightness fluctuations caused by weather on giant exoplanets. TMT will directly image the reflected stellar light from mature, cold planets as small as Neptune in orbits the size of the inner Solar System. These observations will advance our understanding of planetary systems beyond our own and answer an age-old question: how many Solar Systems are out there?

Is there life elsewhere in the Universe?

Determining how and in what quantity complex, pre-biotic molecules come to exist on the surface of emergent exoplanets is key to understanding the origin of life. With its high angular resolution and high spectral resolution in the mid-infrared, TMT will probe areas of planet-forming disks where Earth-like planets are expected to form. Analyzing the spectra of parent starlight through exoplanet atmospheres during transits (analogous to the recent transit of Venus across our Sun) will reveal the chemical composition of exoplanetary atmospheres, including bio-markers such as oxygen. The detection of life is within the reach of TMT.

Science Synergies

Synergy with other ground and space based facilities is an important strength of the TMT project. The U.S. Astro2010 Program Priority Panel identified TMT's spectroscopic capabilities as crucial to detailed follow-up studies of objects discovered by smaller facilities. TMT will complement the existing facilities at Mauna Kea through its ability to work on fainter objects and at higher resolution. Members of the TMT partnership operate the Keck, Subaru, and Canada France Hawaii Telescope observatories at Mauna Kea, so there is great potential to share the complementary strengths of these facilities.

TMT will be a powerful complement to the future James Webb Space Telescope (JWST), just as the Hubble Space Telescope has complemented current 8- to 10-metre ground-based telescopes. TMT will take optical and UV spectra of objects observed by JWST. At wavelengths over 1 micron, TMT will provide higher-resolution spectra and five-times-higher resolution images than JWST.

The coming decades will be an era of time-domain astronomy, and the planned Large Synoptic Survey Telescope (LSST) will be a flagship in this area. TMT's sky coverage will overlap LSST's by about 75 percent. It will be able to take spectra on targets identified by LSST that are too faint for 8- to 10-metre telescopes.

TMT's sky coverage will also overlap that of the Atacama Large Millimeter Array (ALMA) by about 75 percent, providing complementary imaging and spectroscopic data at shorter wavelengths and higher spatial resolution than currently possible.

Finally, TMT's ability to access the northern hemisphere sky above 30 degrees declination will complement the capabilities of the planned European ELT 38.5-metre telescope, to be sited in Chile.

Potential for Interdisciplinary Research

Astronomy is an intrinsically interdisciplinary field within the traditional sciences. The names of its subfields tell this story well: astrophysics, astrochemistry, astrobiology. The science case for TMT describes many experiments that TMT will make possible, ranging from investigating fundamental physics to the search for life beyond our planet. The Universe provides the most diverse environment for the study of chemistry and chemical reactions in conditions not found on Earth.

TMT will also benefit technical research areas far removed from astronomy. These include advanced control algorithms, software, and processing hardware for adaptive optics; real-time control systems; and image post-processing techniques. These methods can be applied to areas such as medical imaging; and the design and construction of large complex structures such as sports stadiums, bridges, and entertainment rides. Another directly impacted research area is atmospheric physics, providing a better understanding of the Earth's atmosphere below 100 km.

Broader Impacts

TMT is a unique opportunity for advancing science and technology. Cutting-edge technology development is required to build and operate this next-generation telescope. Its frontier scientific discoveries, and a diverse, strong international partnership, will make TMT a unique, rich resource to inspire, inform, educate the young, and attract and retain the best scientists.

Besides astronomy, the TMT project involves the broader physical sciences, and contributes to engineering and technology innovation, education, workforce development, and international relations. The Pacific Rim nature of the partnership enables exciting scientific, technical and community collaborations, in all of these areas. TMT will be a model for future co-operation in major scientific facilities between the Canada and the United States and India, China, and Japan.

TMT's education, outreach, and public communications plan proposes activities and programs at the local, national, and international levels. In accordance with TMT's commitment to public engagement, a robust education and public outreach (EPO) program has already begun. This program currently focuses on establishing a wide-reaching, prominent public communications effort to convey project news and raise awareness about astronomy in general and the specific science that TMT will enable.

TMT will provide extensive educational opportunities for the general public at all levels of formal education, as well as opportunities for citizen science and informal learning. The data obtained using TMT will be the basis for many graduate-student dissertations.

Project Status and Partnership

The TMT project is in Pre-construction Phase. Major subsystems crucial for starting construction are either in Final Design Phase or are being readied for construction by developing detailed fabrication and construction documentation.

The design of the summit facilities, including the enclosure fixed base and the telescope pier, has been finalized. The design development documents were reviewed and accepted by TMT in January, 2012. The process of preparing construction documents with additional detailed design, and preparation of construction packages ready for bidding, is now underway. The design fully complies with the Final Environmental Impact Statement approved by the State of Hawaii. The Final Design Review for the enclosure was completed in December, 2010. The detailed fabrication and construction documentation has been progressing since.

Mission-critical subsystems, in particular those with long lead-time items are in Final Design. An example is the design for the primary mirror segments. Mirror blanks produced by two different manufacturers (Sagem and Tinsley) are currently being tested for glass quality and thermal properties. Blanks have also been used in successful polishing experiments: in cooperation with E-ELT, both firms generated the challenging high-asphericity segment surfaces with good fidelity. Canon demonstrated finishing capability very close to our specification. The segment support assembly is also close to final design. The optical test set for segment production is in Preliminary Design.

Other major subsystems and key components are in Preliminary Design: the telescope structure, including the mount-control system, the secondary and tertiary mirror systems, segment actuators and edge sensors, the alignment and phasing system, and the primary-mirror control system. We have evaluated prototypes for actuators, sensors, and the phasing camera and selected final technologies.

TMT's adaptive optics system, NFIRAOS, developed in Canada, passed the Preliminary Design Review in December 2011 with high marks. We have developed prototypes for deformable mirrors and polar-coordinate wavefront sensors, which are currently being tested. Likewise in December 2011, a review of the conceptual design for the major near-diffraction-limited instrument, IRIS, was conducted. The first-light seeing-limited spectrograph, WFOS, is in Conceptual Design.

The entire project is subject to regular and comprehensive technical and program reviews, including reviews conducted by expert international technical and cost review panels. These panels have concluded that the technical progress and implementation planning are both appropriate and suitably mature for the expected construction schedule. Besides technical readiness, other key elements of the construction project are in place. These include the project-management control system and the systems-engineering, quality-assurance, and safety processes. In January 2011, the non-advocate cost-review panel evaluated the baseline budget and schedule for construction.

In 2009, AURA, through the US National Optical Astronomy Observatory (NOAO), established the GSMT Community Assessment Review (GCAR) to obtain an independent assessment of the U.S.-led Giant Segmented Mirror Telescope (GMST) projects. This assessment process focused on technical progress towards achieving the science-driven technical requirements and construction readiness, as well as cost and schedule issues that would affect National Science Foundation (NSF) investment and scientific return to the community at large. The independent panel concluded "that the design presented for the TMT is sound in almost all areas and that the team has completed its design and development stage successfully, essentially placing it at a PDR level consistent with the NSF MFREC process."

Partner Shares

The implementation plan for TMT development and construction is well developed and provides a consistent basis for partner proposals to respective sponsors, including the proposal to NSF. TMT partners have defined a matrix of work packages for delivery during the Construction Phase. These define the project deliverables to be provided as in-kind contributions as well as cash contributions to a Common Fund and a centralized Infrastructure Fund.

The Common Fund provides for costs that benefit all partners and that are partnership responsibilities. These include costs for centralized TMT project management, system engineering, business, and project-management control systems, legal and regulatory costs, taxes, subsystem management, and Hawaii expenses including fees and community benefits. Infrastructure Fund costs include all civil construction, roads, facilities, utility improvements, and basic technical infrastructure not specifically assigned as an in-kind work share item. This spreads the cost of all shared infrastructure in a pro rata manner according to the share contribution of each partner.

The implementation plan defines deliverables, the base-year and then-year estimated Total Costs (Budgeted Cost plus Contingency) for each delivered work package and the cash contribution schedule by fund. It specifies the annual funding profile that is the basis for project planning. The baseline plan for TMT assumes NSF participation in the project. Three alternate plans have also been developed, including an option for earlier NSF participation, and two plans that do not include NSF funding.

In the baseline TMT implementation plan, First Light is planned for late 2022, and NSF funding occurs in years 2020 through 2022. The major contributions by partner in the baseline plan (in addition to infrastructure and common project funds), are shown below, along with the summary construction share percentage contribution.

	UC/Caltech 15.4%	NSF 17.4%	Canada 19.9%	Japan 23.7%	China 12.4%	India 11.4%
Enclosure			X			
Telescope Structure and Mount Control				X		
Optics support, cleaning and handling equipment, metrology system, and spares	X	X		X	X	X
M1 System	X	X		X	X	X
M1 Control System	X	X				X
M2 System				X	X	
M3 System					X	
Alignment and Phasing System	X	X				
NFIRAOS Adaptive Optics System, including real time controller and AO components			X			
NFIRAOS Science Calibration Unit			X			
IRIS Instrument	X	X		X		
IRMS Instrument	X	X				X
WFOS Instrument	X	X			X	
Lasers and Laser Guide Star Facility					X	
Instrument lab and cooling systems					X	
Operations Software						X

Table 1 - Construction Contributions by Partner

Managing the Collaboration

The TMT Project is managed by the TMT Observatory Corporation under the direction of the TMT Board. The project organization functions within and under the TMT Observatory Corporation, though it is staffed by both Corporation employees and by partner-institution staff. The organization is structured to deliver the entire TMT observatory and each of the subsystems composing it, as described in a formal Work Breakdown Structure. There is a designated manager responsible for each subsystem and component. The TMT Project Manager reports to the governing Board and is responsible for all elements of the TMT design, development, and construction, as well the early operations activities of the project.

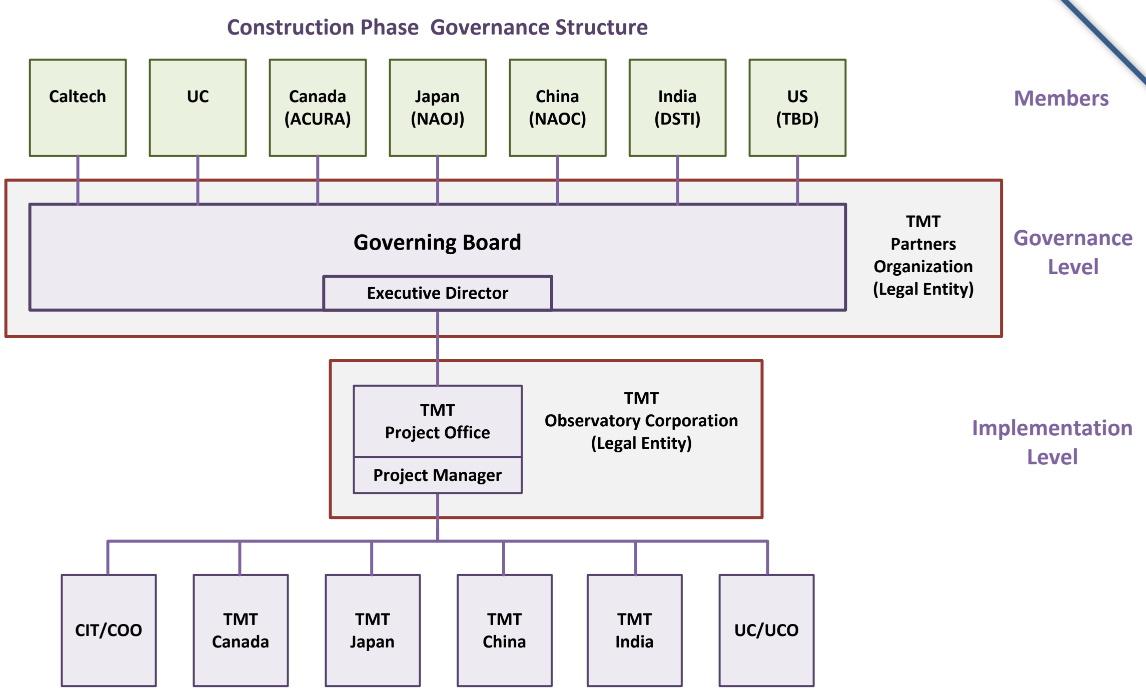


Figure 4 - Construction Phase Governance Structure

The project implementation plan defines deliverables, base-year and then-year estimated total costs (i.e., budgeted cost plus contingency) for each delivered work package, and the cash contribution schedule by fund. The implementation plan also specifies the annual funding profile as the basis for project planning. The plan is fully time-phased within the TMT Integrated Project Schedule (IPS).

Timeline and Budget

The planning basis for the TMT is a technically paced schedule and cost estimate, i.e., one that assumes that construction funds are available when indicated by the technically paced schedule. Assuming an April 2014 start date for on-site civil construction, first light will be achieved in December 2021. Additional key project milestones have been identified and categorized at varying levels of the work breakdown structure.

The most important critical path in the schedule starts with the on-site work (on-site civil construction activities, the erection of the enclosure and the telescope structure at the summit) and concludes with the assembly, integration, and verification (AIV) of all remaining systems at the observatory.

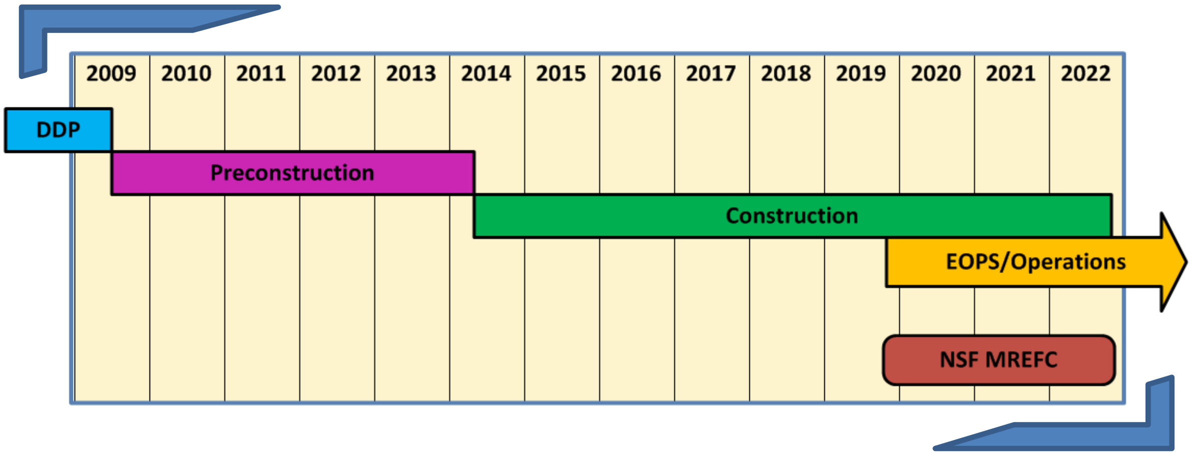


Figure 5 - TMT Project Timeline showing Design and Development (DDP), Preconstruction, Construction, Early Operations and the proposed National Science Foundation funding timeline

TMT has established a state-of-the-art project management control system: an integrated set of tools that supports effective management of the project's cost, schedule, and risk. The integrated project schedule, cost estimate, earned-value management system, and enterprise reporting components are used to measure the project's cost and schedule performance as part of the TMT project management plan. In addition to a schedule contingency methodology and estimates of contingency funds (needed to respond to cost, schedule, and technical risks), the project utilizes a risk-management process that assesses and tracks resolution of the major project risks.

Using a comprehensive, bottom-up cost-estimating process, with nearly 100,000 items estimated, the total cost to construct TMT in base-year 2011 U.S. dollars is $1,187 million including $244 million in contingency costs. In January 2011, an external non-advocate committee, consisting of experts in all aspects of observatory construction, carefully reviewed and accepted the TMT cost estimate. A matching comprehensive integrated scheduling process indicates that if TMT construction begins in April 2014 it will achieve first light in December 2021. TMT has planned an additional year of schedule contingency beyond this technically paced schedule.

Taking the detailed schedule into account, and using U.S. Office of Management and Budget escalators, the base-year construction cost quoted above inflates to a then-year cost of $1,499 million. This is in addition to an estimated cost of $232 million (then-year dollars) for Design Development and Preconstruction prior to April 2014.

Observatory Design and Site

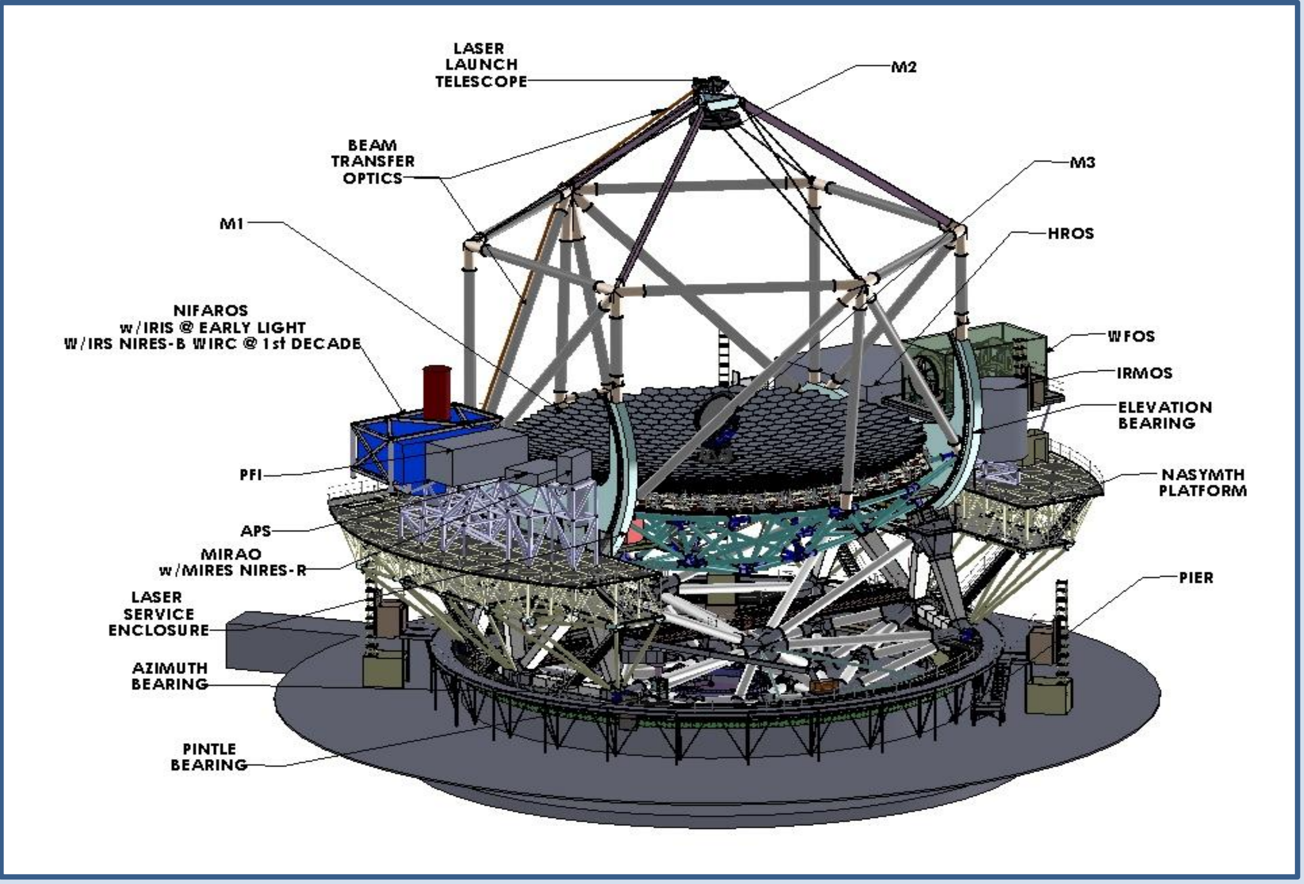


Figure 6 – The TMT telescope system and instruments

TMT is a robust, broadly capable, and scientifically efficient system that will address the most compelling astrophysical science questions of our time. Many of the advances of TMT are made possible by adaptive optics (AO), a technology integral to the TMT observatory. AO systems correct the degradations in image quality that result from viewing objects through the Earth's turbulent atmosphere and from aero-thermal and optical imperfections within the observatory itself. AO is capable of producing "diffraction-limited" images that are as sharp as those that could be obtained with the same diameter telescope located in space. Certain types of observations are still performed in "seeing-limited" mode, meaning AO is not used and that the image quality is limited by the atmosphere above the telescope. Even in seeing-limited mode, TMT offers an order of magnitude improvement over existing observatories, mostly due to its light-gathering capacity.

Key Design Features of TMT include:

- A primary mirror 30 metres in diameter providing greatly increased light-gathering power for detecting faint objects and, in combination with AO systems, observing objects in much finer detail.
- A primary mirror shape and fill-factor with little obscuration from the telescope structure, which results in AO-corrected light being concentrated to a sharply imaged core, enhancing TMT's ability to detect and measure individual objects in detail.
- Exceptional seeing-limited image quality even without AO, taking advantage of the Mauna Kea site, the telescope's optical quality , and the enclosure's aero-thermal performance.
- Telescope, instrument, and AO designs that provide superior image quality, sky coverage, wavelength coverage, field of view, throughput, emissivity, astrometry, and photometry to effectively investigate the science cases.
- The ability to provide observations on multiple instruments (with and without adaptive optics) that are co-located on the telescope.
- The ability to switch quickly between science instruments to provide efficient observations matched to observing conditions and to facilitate fast follow-up of transient phenomena.

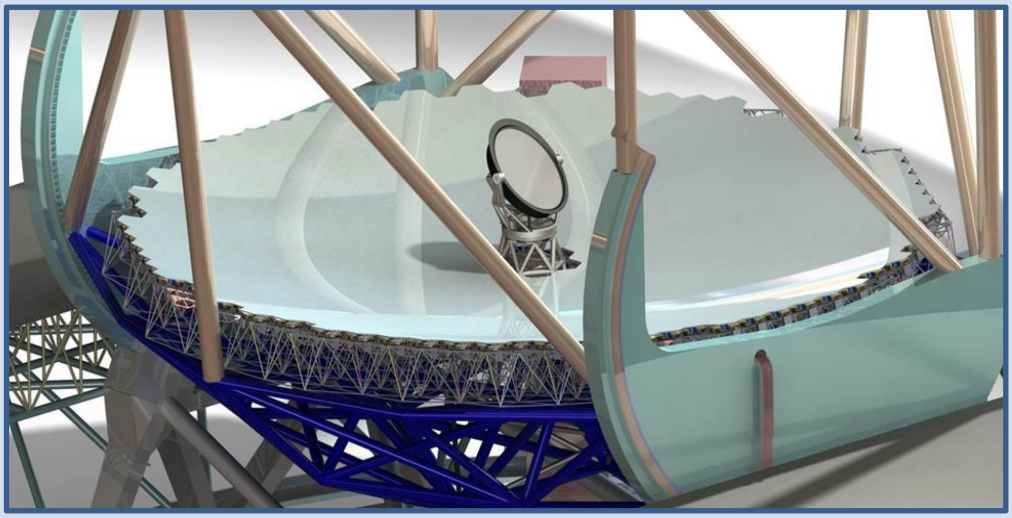


Figure 7 - TMT primary and tertiary mirrors integrated into the telescope structure

The TMT f/1 primary mirror consists of four hundred and ninety-two 1.44-metre hexagonal segments, each individually controlled to maintain exceptional image quality. Our studies have shown that 30 metres offers a "sweet spot" between science benefit, cost, technological readiness, and schedule. TMT provides the sensitivity required to achieve the science objectives efficiently, within an implementation timeframe that is scientifically competitive with other ELT projects, at a manageable cost and risk.

The telescope design makes the focal surface readily accessible at several instrument stations on the large platforms located at each side of the telescope. This configuration offers a number of key advantages:

- A gravity-invariant, highly stable, and low-vibration environment.
- Accommodation of the full planned suite instrumentation with low overhead.
- Ability to pursue targets of opportunity and transient objects.
- Minimal throughput losses and low thermal background for infrared observations.
- Ability to install and maintain instruments in different stations independently.

The excellent atmospheric characteristics at the Mauna Kea site are fully utilized through an innovative Calotte enclosure design developed in Canada. This design includes vents and a daytime thermal-management system offering a highly favorable thermal environment that preserves TMT's excellent image quality. The enclosure's small aperture and aerodynamic features provide excellent protection from wind buffeting at the top end of the telescope. In addition the secondary mirror support structure has a very small wind cross-section to further reduce wind-buffeting effects.

At first light TMT will be fully capable of supporting all observing modes needed for the TMT science cases. Observing modes will include seeing-limited observations over a wide field, and stable diffraction-limited AO imaging.

In summary, the key features of the TMT design that optimize its science capability are:

- Excellent diffraction-limited sensitivity provided by the primary-mirror collecting area, filled-aperture geometry, and minimal obscuration by the telescope structure.
- An optical design that provides high throughput and low thermal emission.
- High observing efficiency with the ability to quickly switch instrument modes for targets of opportunity.
- Adaptive optics providing sharp and stable images over a large field, essential for precision photometry and micro-arcsecond level astrometry.

The TMT architecture is based on technologies either currently used in 8-metre to 10-metre class observatories or set to be deployed in other projects before TMT subsystem fabrication commences. In the baseline project, we have, where possible, avoided new technologies that we perceive to be high-risk. Instead, TMT uses a modular design that includes upgrade paths that can be implemented after first light, as technologies mature.

Priority has been given to developing the critical subsystems with the most challenging technical requirements, the highest estimated costs, and the longest lead times. Examples include primary mirror system development, and prototypes of enclosure ventilation modules. This development work is prioritized towards rapidly reducing technical, cost and performance risks.

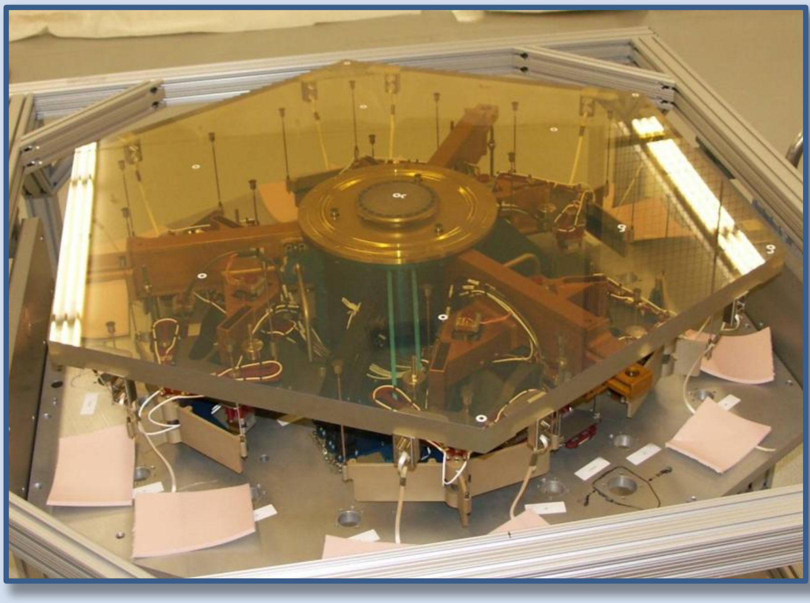
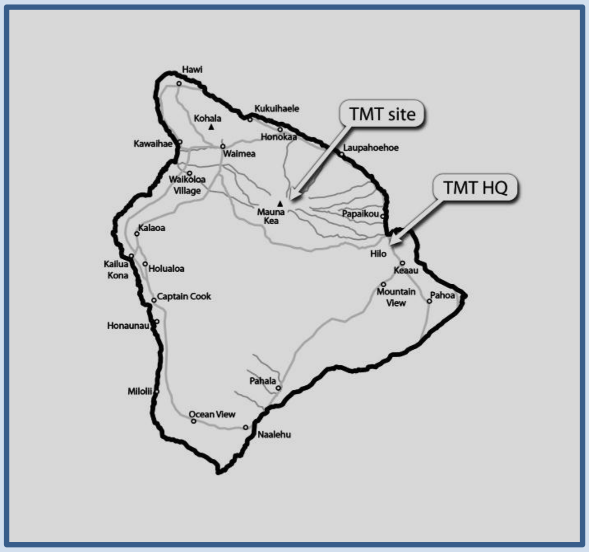


Figure 8 - A 1.44 m, 45 mm thick primary mirror segment integrated with supporting structure and actuators. A total of 492 segments form the TMT primary mirror.

Figure 9 - The full-scale TMT enclosure ventilation module prototype, built by Dynamic Structures Ltd in Port Coquitlam, BC.

Site

TMT will be located just below the summit of Mauna Kea on Hawaii Island at an elevation of 4050 metres (13,300 feet). The summit is 69 km by road from Hilo and 74 km from Waimea, with a driving time of about one hour. The headquarters will be located in Hilo, co-located with the headquarters for eight other Mauna Kea observatories in a science and technology park adjoining the University of Hawaii campus.



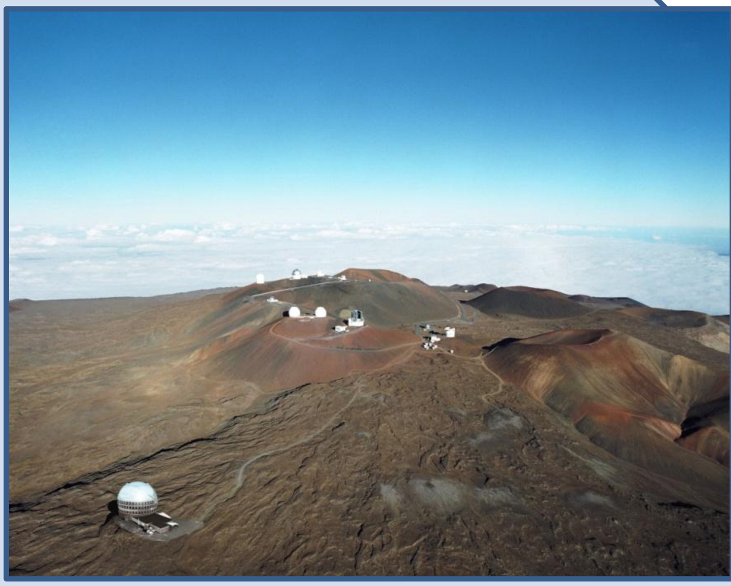


Figure 10 - Map of Hawaii Island showing TMT sites, and artist's depiction of TMT on Mauna Kea (lower left)

The site was selected after a decade-long survey that began with global satellite studies and concluded with five years of on-site data collected at three sites with robotic observatories: one in Chile, one in Mexico, and one on Mauna Kea. This was the most comprehensive study of excellent observing sites for astronomy ever conducted.

Canadian Involvement in Design and Construction

Canada aspires to a stake in TMT that is second to none. Within Canada, TMT is managed by ACURA in consultation with the National Research Council (NRC). Canadian contributions to TMT will include the Calotte dome enclosure, the NFIRAOS adaptive optics system, and the NFIRAOS science-calibration unit. Canadian industry, in partnership with the universities and the NRC, is well positioned to develop these TMT systems. .

Over the past decade, Canadian engineers and scientists have played a central role in the specification and design of the TMT, and have on-going major roles in the project including Science Advisory Committee membership and chair, Board membership, and senior technical management roles in Instrumentation, Systems Engineering, and Enclosure. The Canadian investment of about $30 million has been matched with more than $100 million, mainly from US sources, but also from Japan, China, and India. The project is ready to begin construction in 2014. To retain its place in the partnership and realize the project's scientific, technical and economic potential, Canada must have its construction funding assured by then. Canada's share approximates $300 million over eight years. This constitutes 19.9% of the total, and is second only to Japan, as shown in Table 1. Most of this dollar amount represents contracts to Canadian industry for construction.

The planned Canadian contributions are vital to the project, and fully developed within Canada. The enclosure is a major first item for construction, and is of unique Canadian design. The AO system is vital to the telescope performance and is of Canadian design. A proposal for construction funds is being prepared for the Canadian federal budget of 2014.

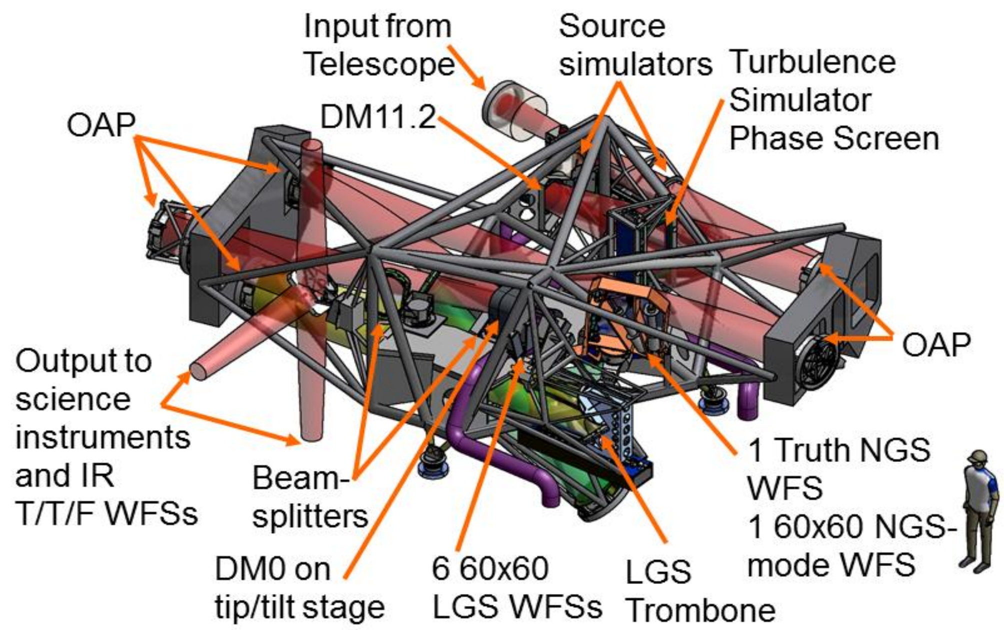


Figure 11 – The NFIRAOS Adaptive Optics System, a Canadian contribution to TMT. NFIRAOS enables TMT to achieve 10 times the image sharpness of the Hubble space telescope. This figure shows the opto-mechanical design of the system.

The Opportunity

With the development of TMT we are on the verge of a transformational voyage of exploration, both intellectual and technological. Provided we seize this once-in-a-generation opportunity, Canadians will have a front-row seat. Astronomy sparks the imagination of both young and old, with tangible benefits of engaging young people in the fields of science and engineering. The nature of the TMT partnership will provide stronger international linkages for Canada within the Pacific Rim trading group. The technical challenges of TMT will develop new globally competitive technical capabilities within Canadian industry. Finally, TMT will undoubtedly provide fundamental new insights into our universe, both past and future, and has the potential of discovering life on another planet.

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