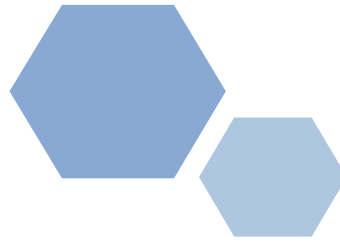
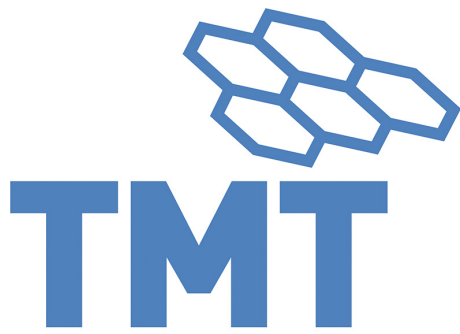


THE THIRTY METER TELESCOPE

Canadian Project Digest



Published August 2014



Contents

Overview	2
TMT Science	4
Observatory Design and Site	7
Project Status and Partnership	11
Canadian Involvement in Design and Construction	14
Contact Info	17

Overview

When completed in 2024, the Thirty Meter Telescope (TMT) will be one of the world's most advanced and powerful telescopes. Driven by frontier science, TMT will offer 10 times the light-gathering power of today's largest optical telescopes and will produce images 10 times sharper than the Hubble Space Telescope. This 100-fold increase in power will allow TMT to open the door to new discoveries and a deeper understanding of the universe, from our own Solar System to the dawn of cosmic time.



Figure 1 – An artist rendition of the TMT Observatory, showcasing the iconic Canadian-designed enclosure. Started in 2003, the project is now moving into the construction phase: the groundbreaking ceremony at the Maunakea, Hawaii, site is currently scheduled for October 7, 2014.

The TMT project started in 2003 as a collaboration between the California Institute of Technology (Caltech), the University of California (UC), and the Association of Canadian Universities for Research in Astronomy (ACURA). By the late 2000s, the high level of maturity to which Canadian and US efforts had brought the project led three major partners – China, India and Japan – to join the collaboration. Canada is responsible for two critical TMT components: the enclosure, an innovative design by Canadian Industries, and the Adaptive Optics (AO) system that will allow TMT to suppress atmospheric distortions and produce images as sharp as those of a similar size telescope in space. Canada has already invested over \$30M in the development of these systems.

Today, Canada's participation in the project is at a critical juncture. In 2014 TMT entered the construction phase and a new partnership, the TMT International Observatory (TIO), was formed by Caltech, UC, China and Japan, all of whom have committed construction funds. India has joined the TIO as an Associate Member with the expectation to become a full member this fall, once the government commits construction funds. Through ACURA, Canada has also joined as an Associate Member. To become a full member and maintain its place in the partnership, Canada needs to secure its share of the construction funds -- \$300M over nine years, in 2015.

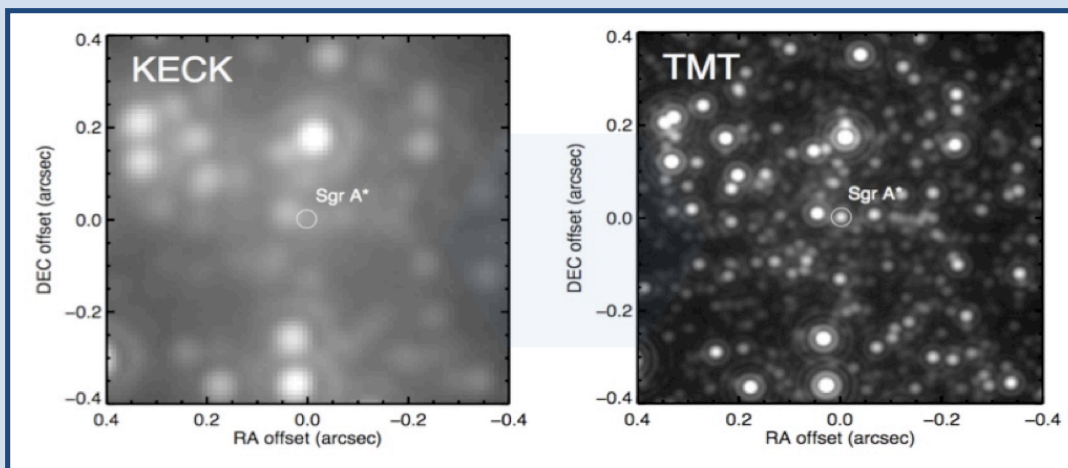


Figure 2: (left) an image showing the center of the Milky Way, taken with the 10-metre Keck telescope, currently the largest telescope in the world. Sgr A marks the location of a million solar mass black hole. (Right) a simulated TMT image of the same field. Thanks to its superior angular resolution and depth, TMT will vastly improve our ability of trace orbits of individual stars as they revolve around the central black hole. This will lead to a deeper understanding of black holes and will enable new and unique tests of Einstein's theory of General Relativity.*

In 2000, the Long Range Plan (LRP) for Canadian astronomy¹ – the roadmap that lays out the field's priorities for the next decade – identified TMT as an emerging priority. By the time of the 2010 LRP, TMT had firmly risen to the top of the priority list. The LRP argues that TMT is vital to maintain the forefront status and worldwide reputation of the Canadian astronomical community. But equally important are TMT's contributions to engineering and technology innovations, education, workforce development, and international relations. TMT-specific technologies (such as advanced control algorithms, software and hardware for adaptive optics, real-time control systems and image post-processing techniques) reach far beyond the scientific community, and have led to breakthroughs in areas such as medical imaging and the fabrication of large complex structures such as sports stadiums, bridges, and even amusement park attractions.

¹ The 2000 LRP was commissioned by the National Research Council (NRC) and the Natural Sciences and Engineering Research Council (NSERC) with the collaboration of the Canadian Astronomical Society (CASCA). The 2010 LRP was commissioned by CASCA with the support and collaboration of NRC, NSERC, ACURA, the Canadian Space Agency (CSA), and the Canadian Foundation for Innovation (CFI).

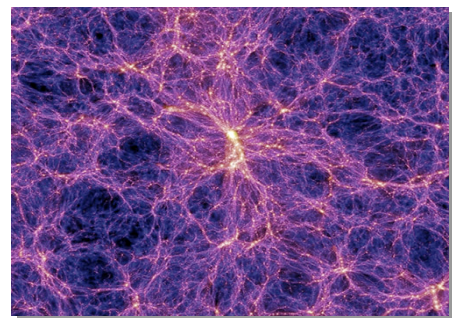
TMT Science

TMT will provide breakthroughs in essentially every field of astronomy. Its 30-metre mirror collects more light than smaller telescopes, allowing us to detect and study farther and fainter objects. Additionally, TMT is designed to incorporate Adaptive Optics (AO) technologies. AO – a critical Canadian contribution – will allow TMT to correct for atmospheric distortions and achieve diffraction-limited performance, i.e. the sharpest images that can physically be produced by the telescope optics. For many applications, diffraction-limited observations yield gains in sensitivity that scale like the diameter of the mirror to the fourth power, allowing TMT to reach farther and see more clearly than previous telescopes by a factor of 10 to 100, depending on the observation. Compared to the Hubble Space Telescope, for instance, TMT will produce images 10 times sharper, and will be capable of detecting objects 150 times fainter than HST can see.

Working from optical to mid-infrared wavelengths, TMT will rank firmly as one of the world's premiere observing facilities for decades to come. By providing complementary and follow-up imaging and spectroscopic data at higher spatial resolution than currently possible, TMT will leverage and enhance the return of other existing and proposed facilities, including the James Webb Space Telescope, the Atacama Large Millimeter Array (ALMA) and the Large Synoptic Survey Telescope (LSST). 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 of the U.S. National Academies, and addresses all four key thematic questions outlined in the 2010 Canadian LRP. Examples of the pressing questions TMT will allow us to address are listed below.

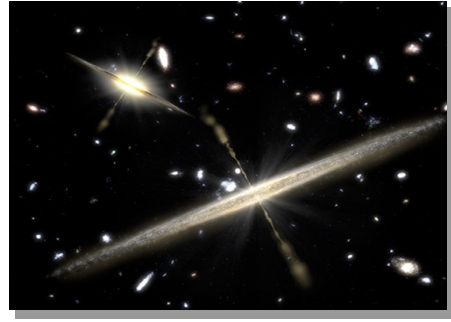
What is the nature of dark energy and dark matter?

Dark matter and dark energy are the main ingredients of the universe, yet their nature remains a complete mystery. Einstein's General Relativity predicts that mass distorts the light from far away galaxies into beautiful arcs of light, known as "gravitational lenses". Tiny anomalies in the arcs' structure might be the key to solve the dark matter mystery. Only TMT can detect such anomalies: by doing so TMT will allow us to hunt dark matter particles with masses at least one order of magnitude lower than currently possible. TMT will also be capable of observing massive stellar explosions – or supernovae – in the very early Universe. Supernovae will reveal how the signature of dark energy changes over cosmological times, thus furthering our understanding of the mysterious force that drives the accelerated expansion of our universe.



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 merge with each other to form bigger and bigger galaxies over billions of years. Thanks to its unprecedented sensitivity, TMT will produce detailed maps of the morphology, chemistry, and kinematics of galaxies as they assemble and evolve over cosmic time: from the very first galaxies that formed in the universe, to our own Milky Way, which TMT will explore to unprecedented depths to reveal the varied nature of galaxy assembly.



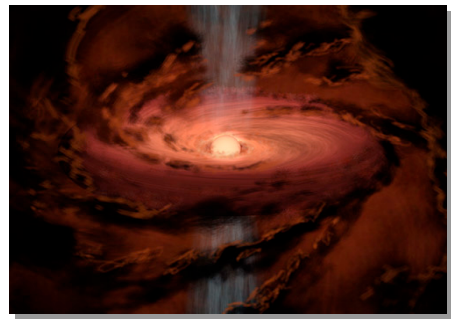
What is the relationship between black holes and galaxies?

Black holes with masses as large as a billion times the mass of the Sun are known to lurk at the centres of galaxies. Their formation process is unknown, but it is believed to be intimately linked to, perhaps even control the growth of galaxies themselves. Two decades of studies, mostly with the Hubble Space Telescope, have produced barely a few dozen detections of such “supermassive” black holes. In contrast, TMT will be capable of directly probing black holes in thousands of galaxies, thus breaking the field open. The question of how black holes influence the growth of structure in the universe will be answered once and for all.



How do stars and planets form?

The mass of a star dictates how long it will live and when it will die. Direct mass measurements provide a fundamental test of theories of stellar formation and evolution; however such measurements are extremely difficult, and have been performed only for very few stars. TMT will allow us to ‘weigh’ thousands of stars using an entirely new technique: as a star moves in front of a background stellar field, its gravity will slightly bend the light rays from these background stars by an amount that is proportional to the star’s mass. TMT will also be capable of studying in unprecedented details the disks of dust and



gas that surround stars, unveiling the processes by which planets like our own Earth form.

What is the nature of extrasolar planets?

The first planet around another star was discovered in 1995. Since then, “exoplanets” have been observed in ever increasing numbers thanks to massive observing campaigns on the ground and in space. Moving from “detection” to “exploration” requires the high-contrast imaging and high-resolution spectroscopy of which only TMT is capable. TMT will distinguish rocky worlds like Earth from “micro-Neptunes”. It will detect tiny changes in brightness caused by weather on giant exoplanets. It will 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 a 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. Analysing the spectra of parent starlight through exoplanet atmospheres during transits (analogous to the 2012 transit of Venus across our Sun) will reveal the chemical composition of exoplanetary atmospheres, including bio-markers such as oxygen. The detection of extraterrestrial life is within the reach of TMT.



Observatory Design and Site

TMT is a robust, broadly capable, and scientifically efficient system that will address some of the most compelling science questions of our time. Many of the discoveries that will be made by TMT will be possible thanks to adaptive optics (AO), a technology integral to the TMT observatory and one of two critical Canadian contributions to the project. 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. Using AO technology, TMT's vision will be 10 times sharper than that of the Hubble Space Telescope (HST), and 5 times sharper than that of NASA's planned successor to HST's, the James Webb Space Telescope (JWST).

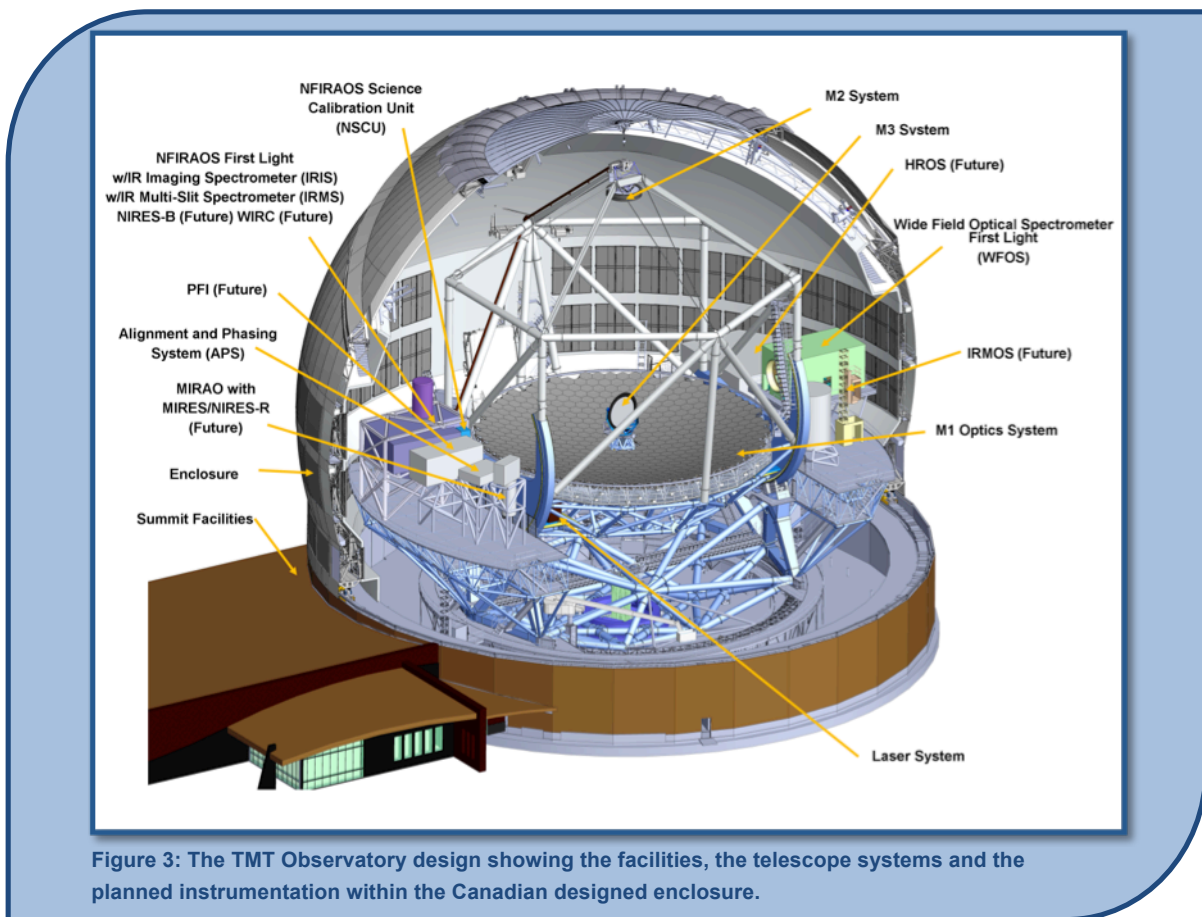


Figure 3: The TMT Observatory design showing the facilities, the telescope systems and the planned instrumentation within the Canadian designed enclosure.

Key Design Features.

- TMT's primary mirror is 30 metres in diameter. Detailed studies concluded that a 30-metre telescope provides the optimal balance of science benefits, cost, technology readiness and schedule.
- The primary mirror consists of 492 hexagonal segments, each 1.44 metre across, individually controlled to maintain exceptional image quality.
- TMT has two additional mirrors: a convex secondary mirror, 3.1 metres in diameter, and a 2.5x3.5 metres articulated tertiary mirror.
- Adaptive Optics is an integral part of TMT's design. The light gathering power of the primary mirror, combined with the ability of AO to provide sharp and stable images over a large field, contribute equally to making TMT almost 100 times more powerful than the 10-metre Keck telescopes, the largest optical telescopes currently in operation. This two orders of magnitude gain opens windows in the nearby and distant universe inaccessible by any other observatory, on the ground or in space.
- TMT's optical design and telescope support structure provides high efficiency, wide field of view, low thermal emission, and minimal obscuration of the primary mirror. This results in superior image quality, sky coverage, wavelength coverage, astrometry, and photometry that will allow us to definitely answer the key science questions of our time.
- The iconic TMT enclosure, another critical Canadian contribution, is designed to strict aero-thermal standards, and realizes the full potential of Maunakea's exceptional image quality and of the telescope's optical quality.
- The articulated tertiary mirror allows for quick switches between science instruments. This greatly increases the efficiency of the telescope by allowing astronomers to match the programs being executed to the observing conditions. Additionally, it facilitates fast follow-up of transient phenomena, such as supernovae and gamma-ray bursts.

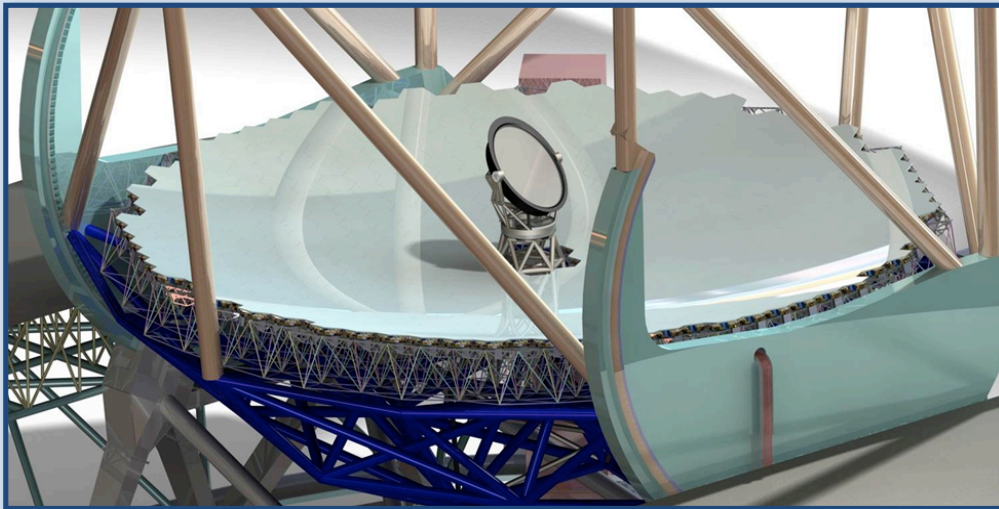


Figure 4 – A rendering showing TMT primary and tertiary mirrors integrated into the telescope structure.

TMT Instruments

The TMT design is driven by a set of science-based requirements developed by a committee of scientists representing all of TMT's partners. Central to these requirements are a suite of instruments conceived to attack the key science problems of the first decade of TMT operations. Detailed conceptual design studies were commissioned from international instrument development teams; these conceptual designs were reviewed by non-advocate review teams. Following these reviews, three instruments emerged as being the most critical and capable of exploring the widest astronomical terrain, from the first stars in the Universe to planets orbiting nearby stars. These instruments, referred to as "first light" instruments, will be mounted on the telescope in 2024 as TMT begins operations:

- The *Multi-Object Broadband Imaging Echellette (MOBIE, also referred to as WFOS)* will provide near-ultraviolet and optical (0.3 – 1.1 μm wavelength) imaging and spectroscopy over a more than 40 square arcminute field-of-view. Using precision cut focal plane masks, MOBIE/WFOS will be capable of obtaining simultaneous spectra for 200 objects.
- The *Infrared Imaging Spectrometer (IRIS)* will be fed by TMT's AO system, NFIRAOS, and be capable of diffraction-limited imaging and integral-field spectroscopy at near-infrared wavelengths (0.8 – 2.4 μm).
- The *Infrared Multi-object Spectrometer (IRMS)*, also fed by NFIRAOS, will allow close to diffraction-limited imaging and slit spectroscopy over a 2 arcminute diameter field-of-view at near-infrared wavelengths (0.9 – 2.5 μm).

To achieve their required performance, IRIS and IRMS must be fed by the facility AO system, NFIRAOS. A Canadian contribution, NFIRAOS is therefore essential to the operations of the telescope. NFIRAOS is already in a very advanced state of development: it successfully completed its preliminary design phase in December 2011, and started the Final Design Phase in April 2014 with industry involvement.

During the first decade of TMT's operations, additional instruments will be developed and built to complement the first light instruments; amongst those that are planned are a Planet Formation Instrument (PFI), high resolution optical, near- and mid-infrared spectrographs (HROS, NIRES and MIRES), and a wide-field near-infrared AO Imager (WIRC). These instruments will be deployed on a schedule paced by a combination of technological readiness and available financial resources.

Site

TMT will be located just below the summit of Maunakea on the island of Hawaii at an elevation of 4050 metres (13,300 feet). This site was selected after a decade-long survey that began with global satellite studies and concluded with five years of on-site data collected with robotic observatories at five locations: three in Chile, one in Mexico, and one on Maunakea. This was the most comprehensive study of excellent observing sites for astronomy ever conducted.

The summit is 69 km by road from Hilo and 74 km from Waimea, with a driving time of about one hour; several other telescopes, including the Canada France Hawaii Telescope (CFHT) and the Gemini-North Telescope (both of which are operated jointly by Canada) share the summit and the infrastructure costs. The TMT headquarters will be located in Hilo, co-located with the headquarters for eight other Maunakea observatories in a science and technology park adjoining the University of Hawaii campus.

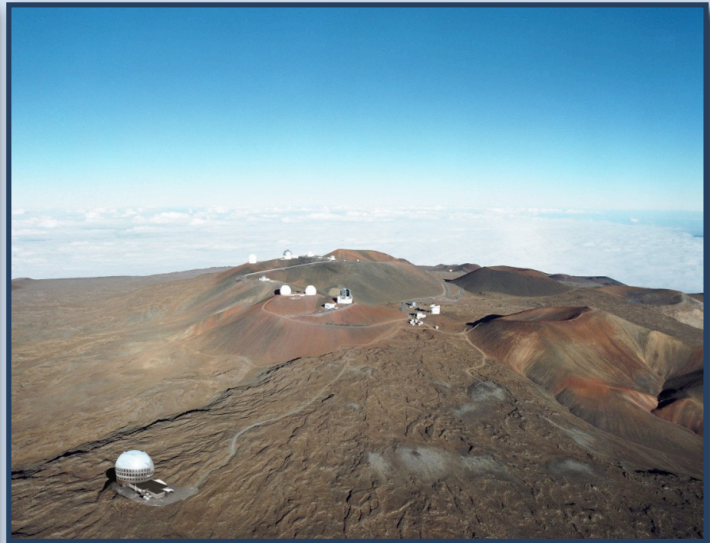
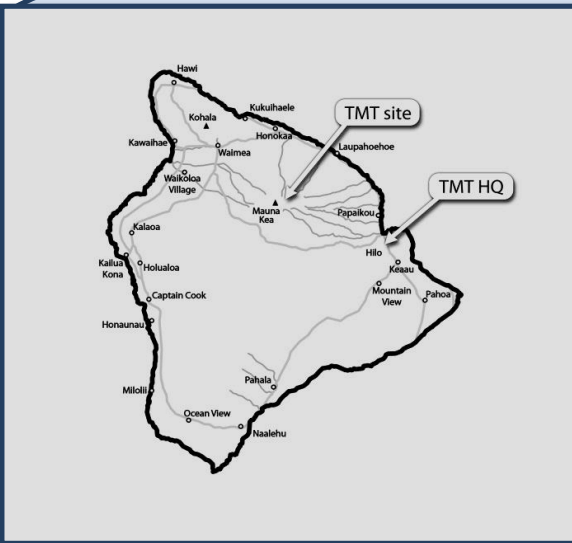


Figure 5 – Left: Map of the Island of Hawaii, showing the location of the TMT Observatory and Headquarters. Right: an artist conception showing TMT (in the foreground) against the current set of Telescopes on Maunakea .

Project Status and Partnership

The TMT project is very mature. Major subsystems crucial for starting construction are either in Final Design Phase or are being readied for construction. The design of the summit facilities, including the enclosure fixed base and the telescope pier, has been finalized and has been ruled to be fully compliant with the Final Environmental Impact Statement approved by the State of Hawaii. The production of the segments for the primary mirrors has begun in Japan, with more than 60 cast already.

The Canadian contributions in particular are ready for construction. The Final Design Review for the enclosure was completed in December 2010 and detailed fabrication and construction documentation has been progressing since. TMT's adaptive optics system, NFIRAOS, passed the Preliminary Design Review in December 2011 with high marks. Prototypes for deformable mirrors and polar-coordinate wavefront sensors have been built and are currently being tested. Both the enclosure and NFIRAOS now await funding to move forward.

Cost, Partner Shares and Roles

Using a comprehensive, bottom-up cost-estimating process including nearly 100,000 items, 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. 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.

To-date, the collaboration has invested roughly \$150 million (U.S.) in design, development, and preconstruction. Over \$30 million has been invested in Canada, while Caltech/UC have invested over \$100 million, largely thanks to a donation from the Gordon and Betty Moore Foundation.

Table 1 – Partners Status and Shares

Partner	UC/Caltech	Canada	Japan	China	India	Additional Sources
Status	Confirmed	Proposed	Confirmed	Confirmed	In approval process	Being sought
Projected Share	25%	19%	19%	9%	9%	19%

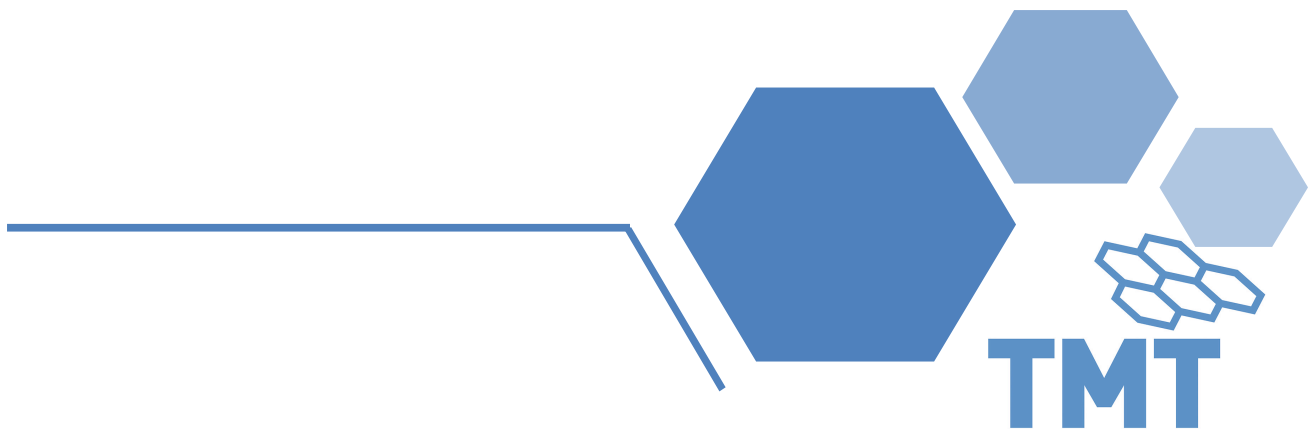
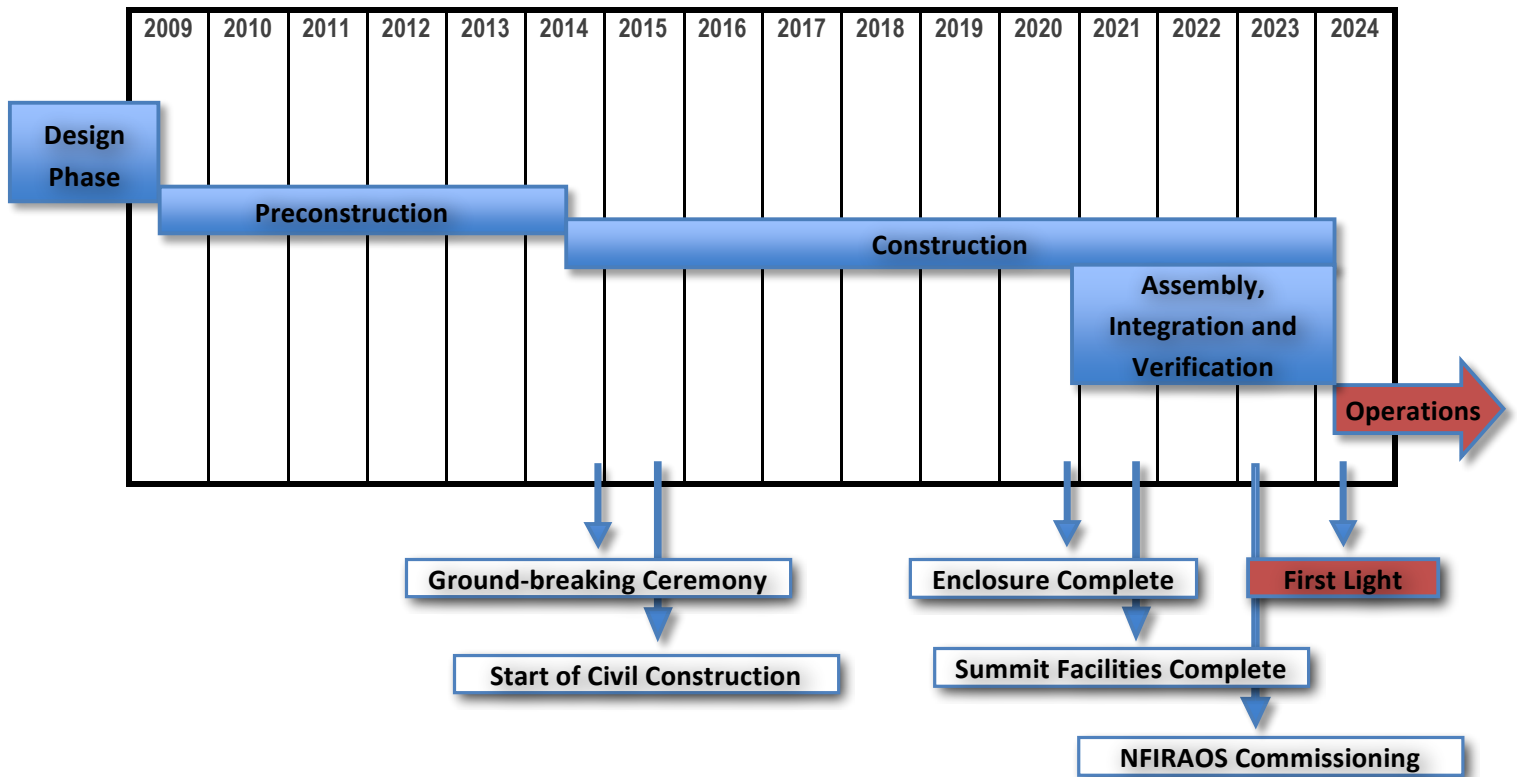
Timeline

- 2000: The Long Range Plan for Canadian Astronomy “*strongly recommends that a team be established to develop designs for a Very Large Optical Telescope (VLOT). This study should be one of the highest priorities among moderate size projects. Canada should join a world team in this effort.*”
- 2003: The VLOT team publishes a report describing the science case and observatory². Simultaneously, similar efforts in the U.S. culminate with the establishment of the TMT Observatory Corporation by the University of California (UC), and the California Institute of Technology (Caltech). Canada joins as a partner through the Association of Canadian Universities for Research in Astronomy (ACURA).
- 2008 The National Astronomical Observatories of Japan (NAOJ) joins the TMT Corporation.
- 2009: The project successfully completes the Design Development Phase and enters the Pre-construction Phase. Shortly after, the National Astronomical Observatories and the Chinese Academy of Sciences (NAOC) join the TMT Observatory Corporation.
- 2010: The Department of Science and Technology of India (DSTI) joins the Corporation.
- 2012: The U.S. National Science Foundation selects TMT as the preferred partner for the Giant Segmented Mirror Telescope project endorsed by the 2010 US Decadal survey, “New Worlds, New Horizons in Astronomy and Astrophysics”³.
- 2014: In April, UC, Caltech, Japan and China sign the contribution agreement – a commitment to provide funds for construction – and form the TMT International Observatory (TIO). India will become a full member of the TIO when committing funds later in the year. As of August 2014, Canada has not committed construction funds, and is a non-voting observer (“Associate Member”) within the TIO.
- 2014: The TMT groundbreaking ceremony is preliminarily scheduled on Maunakea on October 7.
- 2015: Canada must commit funds towards construction to secure its critical contributions to the telescope (the enclosure and the AO system) and become a full member of the TIO. Canada’s contributions amount to \$300M, distributed over 9 years.
- 2024: First light: according to the present schedule, TMT construction is completed and the telescope is operating.

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

³ http://www.nap.edu/catalog.php?record_id=12951

Figure 6 - TMT Project Timeline showing the most important phases and milestones



Canadian Involvement in Design and Construction

Within Canada, TMT is managed by ACURA in consultation with the National Research Council (NRC). Agreed major Canadian contributions to TMT include the Calotte dome enclosure, the NFIRAOS adaptive optics system, and the NFIRAOS science-calibration unit. Canadian industry, in partnership with universities and NRC, is well positioned to develop these TMT systems, and the technical innovations have wide applications outside of the TMT project.

The Calotte enclosure is an ingenious and unique Canadian design. By day, the enclosure must protect observatory systems, facilitate a broad range of maintenance activities, and keep the telescope temperature near the expected night time temperature. By night, it must shield the telescope from wind buffeting while allowing enough airflow to keep the interior iso-thermal and limit image degradation due to air turbulence in the enclosure. The Canadian design, by its spherical shape and circular “shutter” aperture, fulfills key functional requirements and preserves TMT’s excellent image quality with lower mass (and hence lower cost) than possible for previous enclosure designs.

The Narrow Field Infrared Adaptive Optics System (NFIRAOS) provides turbulence compensation over a large field of view in order to sharpen the images and increase the sky coverage. NFIRAOS will be able to work with three of TMT’s instruments, including two that will be available at ‘first light’. The entire TMT system is designed to exploit the extraordinary capabilities that adaptive optics will yield – a world first that will make TMT premier above all competition.

The Calotte enclosure and NFIRAOS represent an investment of \$300 million spread over nine years, starting in 2015, mostly in contracts to Canadian industry. This constitutes roughly 19% of the total cost of the telescope, giving Canadian scientists guaranteed access to a proportional amount of time at the telescope and allowing Canada to retain a significant role in defining the future operation and capabilities of the observatory.

Building Capabilities in Canadian Industries

Development of cutting-edge optical, mechanical, electrical and software systems is necessary for the successful construction of TMT and will advance Canadian industry capabilities. The industrial experience and expertise gained through this investment will be applicable to, and will increase Canadian innovation and competitiveness in the development of complex technical systems such as those found in the areas of manufacturing automation, military, medical, and aerospace. Below is a partial list of Canadian industries that have the capability to be involved in, and benefit from, Canadian participation in TMT:

- ABB Bomem: www.abb.ca
- Albina Pipe Bending: www.albinaco.com
- Altec Integrated Solutions: www.alteconline.com
- Applied Physics Specialties: www.wescam.com/index.php
- Arrow Machine Works
- B-con Engineering www.bconeng.com
- Canadian Electro Drives: www.baldorvancouver.ca
- Canam Tool & Engineering Ltd.: www.speeddryer.com
- Carmichael: www.carmichael-eng.ca
- ComDev: www.comdev.ca
- Commercial Solutions Inc.: www.csinet.ca
- Custom Plate & Profiles: www.customplate.net
- Dynamics Structures Limited: www.empireds.com
- Ebco Industries Ltd.: www.ebco.com
- Fastenal: www.fastenal.com
- Gordon Russell Limited: www.gordonrussell.com
- Heidenhain
- Immervision: www.immervision.com/en/home/index.php
- Institut national d'optique (IAO): www.ino.ca
- ITRES: www.itres.com/index.php
- KalTech Manufacturing Ltd.: www.kaltechmanufacturing.com
- KEO Scientific: keoscientific.com
- Neptec Design Group: www.neptec.com
- Optech: www.optech.ca
- Quantum Technology: quantum-technology.com
- Ramsay Machine Works Ltd.: www.ramsaygroup.com
- Russel Metals: www.russelmetals.com
- Sciencetech: www.sciencetech-inc.com
- SKF Canada: www.skf.com/ca
- StonCor Group: <http://www.stoncor.ca>
- Spectral Applied Research: www.spectral.ca
- Telops: www.telops.com
- Val Mart Door Sales: <http://www.valmartdoors.com>
- Wainbee: www.wainbee.com
- Wesco Industries Ltd.: www.wescovan.com



Concluding Remarks

With the development of TMT we are on the verge of a transformational voyage of exploration, both intellectual and technological. Provided we seize this unique opportunity, Canadians will be part of it. 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 strong international linkages between Canada and the partner communities. The technical challenges of TMT will develop new globally competitive technical capabilities within Canadian industry. Finally, TMT will provide fundamental new insights into our universe, both past and future. The detection of life on another planet could be a Canadian discovery.

Over the past decade, Canadian engineers and scientists have played a central role in the specification and design of TMT, and the Canadian investment of about \$30 million has been matched with more than \$100 million, mainly from U.S. sources, but also from Japan, China, and India. To retain its place in the partnership that it co-founded, and realize the project's scientific, technical and economic potential, Canada must have construction funds – \$300M to be spent over nine years – committed no later than 2015. The time to invest in the future is now.

Contact Info

TMT Project Web Pages:
www.tmt.org

Canadian Astronomical Society
Contact: Christine Wilson
Email: CASCA-President@casca.ca

ACURA and TMT Board
Contact: Ernie Seaquist
Email: seaquist@astro.utoronto.ca

