India's participation in the Thirty Meter Telescope International Observatory project

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The Thirty Meter Telescope International Observatory (TIO) is being built by an international consortium of institutes and universities in Canada, China, India, Japan and USA. The estimated cost is about US$ 1.47 billion (2012 base year). At present, it is planned to be built on Mauna Kea, Hawaii, at an altitude of about 4000 m. The mountain is already home to many of the world's largest telescopes. The Union Cabinet chaired by the Prime Minister, at its meeting held on 24 September 2014, approved India's participation in the TIO project at a total cost of Rs 1299.80 crores. Only about 30% of India's contribution to the project will be made in cash to be utilized for building common facilities and infrastructure. The rest will be made through design, development and manufacturing of a number of hardware, software and optical components. India's participation in the TIO is an extramural national project jointly funded by the Department of Science and Technology (DST) and the Department of Atomic Energy (DAE). To successfully deliver India's in-kind contributions, the two funding agencies have jointly set up the India TMT Coordination Centre (ITCC) which is located at the Indian Institute of Astrophysics (IIA), Bengaluru. IIA along with the Aryabhatta Research Institute of Observational Sciences, Nainital and the Inter-University Centre for Astronomy and Astrophysics, Pune are the key institutes which manage the India TMT project through ITCC. Being a major extra-mural national effort, several other institutes as well as universities participate in the technological, developmental and scientific aspects of the initiative.

Keywords: Actuators, coating chambers, edge sensors, International Observatory project, segment support assembly.

Introduction

THE Thirty Meter Telescope or TMT will be one of the world's most advanced ground-based observatories that will operate in the optical and mid-infrared wavelengths. It will be equipped with the latest innovations in precision control, phased array of mirror segments and laser guide star-assisted adaptive optics system. At the heart of the telescope is the segmented mirror, made up of a total 492 individual hexagonal segments, each 1.44 m in size made up of ultra-low expansion ceramic glass. Each segment is separated from the adjacent one by 2.5 mm to prevent contact between them. Precisely aligned, these segments will work as a single reflective surface of 30 m diameter, a hyperboloid primary mirror (M1) with a radius of curvature of 60 m and a conic constant of –1.00095. The telescope will have a 3 m diameter convex hyperboloid secondary mirror (M2) which reflects light from the *f*/1 primary and converts into an *f*/15 beam. An optically flat oval shaped (2.5 m × 3.5 m) tertiary (M3) mirror at the centre of the primary mirror directs the M2 beam to one of a suite of instruments sitting on Nasmyth platforms of the TMT. An elevation view of the TMT is shown in Figure 1.

The TMT is designed with an integrated adaptive optics (AO) system. AO is a technology-driven solution to counteract the image quality degrading effect caused by turbulence in the atmosphere. The fundamental goal of any AO system is to improve telescope performance from seeing-limited, i.e. the image quality is limited by the atmosphere above the telescope, towards diffraction-limited, i.e. images as sharp as those that could be obtained with a telescope of the same diameter but located in space. Even in the seeing-limited mode, the large light-gathering capacity of the TMT will yield an order of magnitude improvement over existing observations. This unprecedented light-gathering capability and angular resolution of the TMT will shed new light on many challenging problems in astronomy and astrophysics. The TMT will be a leading next-generation telescope posited to serve the worldwide astronomy community as a flagship research facility.

India's role in the project

Till recently, the largest optical telescopes in India were of 2 m class, including the 2.3 m Vainu Bappu Telescope (VBT) which was indigenously built in the late 1980s. In 2016, after almost three decades since the VBT, the Aryabhatta Research Institute for Observational Sciences (ARIES), Nainital, established a 3.6 m telescope known as Devasthal Optical Telescope (DOT). On the other hand

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Box 1.

The formal ground-breaking ceremony of TMT was held on Mauna Kea on 7 October 2014. Since then, construction of the observatory on the mountain has been stopped due to protests by a section of native Hawaiian groups who consider the mountain to be sacred according to their cultural beliefs. They are joined by other groups concerned about the environmental impact of locating the observatory on the mountain. Following a lengthy court process, the Supreme Court of Hawaii on 2 December 2015 cancelled the construction permit of TMT after it determined that the procedure that was followed for issuing the permit by the State of Hawaii was incorrect. The State of Hawaii is now pursuing the due process to reissue the permit. TIO is hopeful of getting the permit by mid-2017. Full access to the site may happen only by the end of 2017 or later. Given the uncertainties in Hawaii, the TIO board of governors examined a number of alternate sites suitable for the project, including Hanle, Ladakh, India. The TIO and its science advisory committee chose La Palma in Canary Islands, Spain, an island in the Atlantic Ocean, as the best alternate site in case the TIO board decides that construction of TMT on Mauna Kea is unviable due to continuing protests and legal processes.

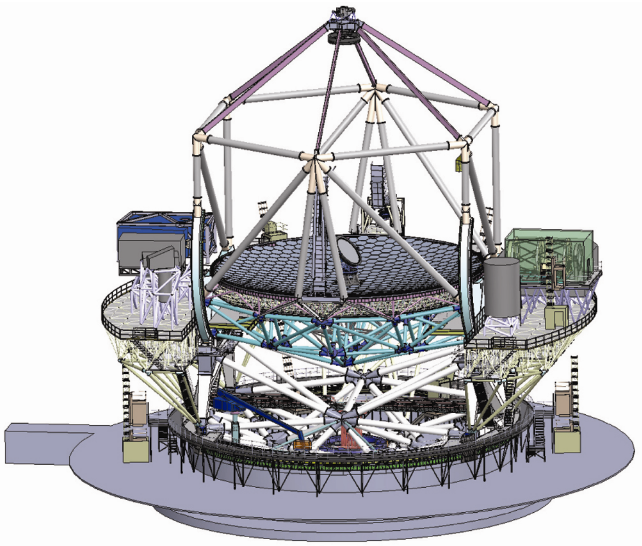

Figure 1. A 3D model of elevated view of the Thirty Meter Telescope.

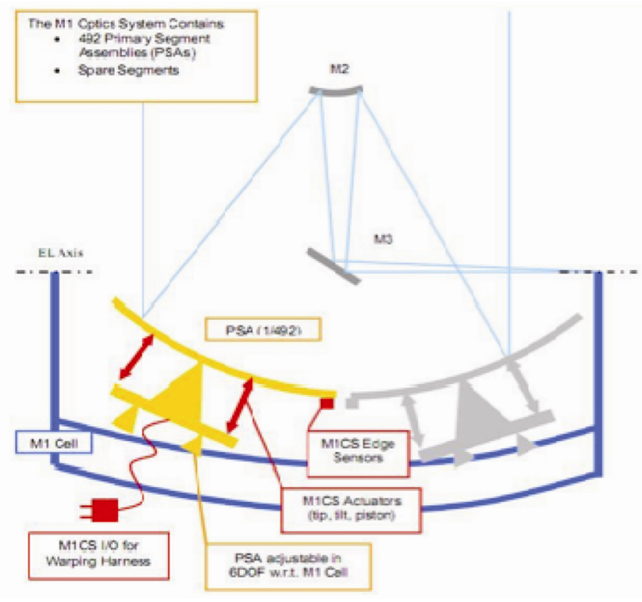

Figure 2. A schematic optical layout of TMT with key components of M1CS shown. (Courtesy: TMT Project Office.)

many countries, including TIO partners, built 4 m class and subsequently 8–10 m class telescopes and have been carrying out frontier scientific research for the last 2–3 decades. Technological complexity in building telescopes grows many fold even with a modest increase in the size of the primary optics aperture. For India to move from the limited experience of building and using telescopes of 2–3 m aperture size to participating in the building of a 30 m class telescope is indeed a whole new challenge as well as an opportunity in terms of developing and/or acquiring the relevant technologies and carrying out path-breaking scientific discoveries.

Almost all of the hardware development that is undertaken by India TMT is associated with one of most important subsystem of the telescope – the primary mirror. This involves the production of some of the key hardware required for precisely positioning the 492 primary mirror segments so that the entire array of mirrors acts as a single surface of 30 m diameter aperture. The Segment Support Assembly (SSA) and the M1 Control System (M1CS), which includes edge sensors and actuators are designed to achieve a mirror surface figure across the 30 m diameter, within 20 nm peak to valley deviation from the nominal design specification. In addition to the M1CS and SSA, India TMT is also responsible for the design and development of mirror-coating chambers, fabricating about 90 of the segments, and a significant fraction of the software, including the Telescope Control System (TCS) as well as the Observatory Software (OSW). An optical layout of the telescope is given in Figure 2, which shows its key components.

Development, manufacturing, assembly and testing of each of the subsystems mentioned above and delivering them according to an aggressive construction schedule demanded resource mobilization at a scale which is unprecedented in the history of astronomy in the country. Clearly none of the academic/research institutions in the country has adequate in-house facilities and human resources already available for this effort. Thus, the effort requires substantial industrial participation. With an initial seed funding provided by the Department of Science and Technology (DST), Government of India, and support from the PI institutes, India TMT approached a number of industries to take up the work of manufacturing prototypes of each of the key systems to demonstrate manufacturing technology capability. This exercise began in 2012 with an aim of qualifying at least two industry partners for each of the systems by the expected start of TMT construction in 2015. Each of these efforts is discussed in more detail in the following sections.

Segment support assembly

Each segment will be mounted on a SSA that provides passive support to the mirror through a 27 point whiffle tree. A central diaphragm made of Invar 36 provides rigid lateral and flexible axial support to the segment.

The SSA passively controls the three in-plane degrees of freedom of the segment, while the overall shape of the M1 mirror is actively controlled by the Primary Mirror Control System (M1CS). Figure 3 shows a 3D drawing of a mounted segment support assembly along with the edge sensors and actuators.

Three prototype SSAs each were manufactured at Avasarala Technologies Ltd, Bengaluru, and Godrej & Boyce Ltd, Mumbai. These were subjected to extensive functional and performance tests both in India and at the TMT project office in Pasadena, CA, USA. A number of issues were identified both in the manufacturing exercise as well as the design of the SSAs through this effort. An extensive root cause analysis of the issues was carried out. India TMT will carry out another round of SSA prototyping effort in which these design and manufacturing issues will be addressed. Efforts will also be made to qualify a set of manufacturers who could successfully build SSAs in India.

M1 Control System

Disturbances induced by varying environmental conditions like temperature, gravity, wind, etc. will lead to changes in the overall shape of the primary mirror surface due to relative motions of the segments. The M1CS has the job of maintaining the mirror surface shape within an extremely tight tolerance. The M1CS consists of 1476 actuators and 2772 edge sensors and a whole lot of electronics. The M1CS is intergrated into the SSA to provide a closed loop control of the surface figure of the entire primary mirror. India TMT is responsible for developing all the SSAs and the M1CS components for TMT.

Edge sensors

The edge sensors are precisely machined, ultra-low expansion glass blocks which are coated with chromium and gold. Each sensor is made of two parts which form a drive and sense pair. Accurately etched patterns are drawn on the gold coatings which differentiate the drive block from the sense block as shown in Figure 4. The edge sensor blocks are mounted below the edges of the primary mirror segments in a way that a drive block of one segment pairs up with a sense block of an adjacent segment. On each edge of a segment there are two such edge sensors, thus adding up to 12 per segment. Given that there are 492 segments, there are altogether 3284 sensor pairs.

Drive and sense pair across two adjacent segments forms an air-gap capacitor system, which allows high-precision contact-less measurement over a large operational range. A change in the capacitance and thereby charge in a capacitor measures a linear combination of a change in the relative height and a change in the dihedral angle between the two respective adjacent segments. The drive block is fed with time-varying, coherent as well as

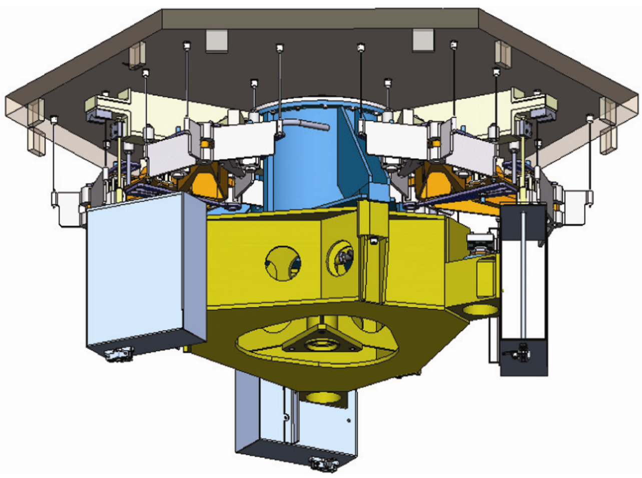

Figure 3. Primary mirror segment support assembly showing edge sensors and actuators. (Courtesy: TMT Project Office.)

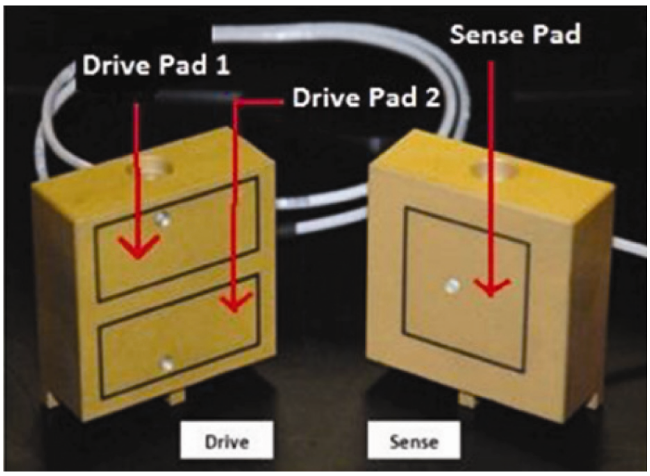

Figure 4. TMT edge sensors. (Courtesy: TMT Project Office.)

phase-shifted signals at the same frequency. This induces a corresponding signal in the sense block. When the capacitance changes either due to variation in separation between capacitor plates or due to a change in overlapping area, the accumulated charge between the plates also changes. Based on the nominal conditions we can then detect and apply corrective actions for gap, height and dihedral angle between the primary mirror segments.

A set of edge sensors was successfully prototyped at General Optics Asia Ltd, Puducherry and subjected to various functional and performance tests. India TMT will be soon undertaking a second-round prototyping effort in which the design improvements which resulted from the first round will be incorporated.

Actuators

The tip, tilt and piston of each of the TMT segments (1.44 m across corners) are controlled by three position actuators which help maintain the overall shape of M1. A total of 1476 (492×3) position actuators, each with 5 mm travel and positioning accuracy better than 4.4 nm are required for the purpose. The actuators receive correction commands from the Global Loop Controller (GLC) – another part of the M1CS – which are derived primarily from the edge sensor signals.

The actuators should have high quasi-static stiffness for wind-induced disturbance rejection, high mid-frequency damping to minimize vibration transmission, small tracking jitter, high reliability, low power dissipation, limited instantaneous travel for the protection of segments from earthquakes and low cost.

The TMT M1CS actuator (Figure 5) is a soft actuator controlled by a voice coil. The voice coil coupled to the output shaft of the actuator provides the output force. A spring connected in parallel with the voice coil cancels the weight of the mirror. The spring is compressed or expanded using an auxiliary linear stepper motor in such a way as to compensate for the slow changing gravity force which depends on the zenith angle at which the telescope is pointing. An important feature of the design is that it is friction free because all the motions are obtained through flexural elements. Also, a snubber mechanism is incorporated to limit instantaneous travel to protect the actuator against earthquake loads.

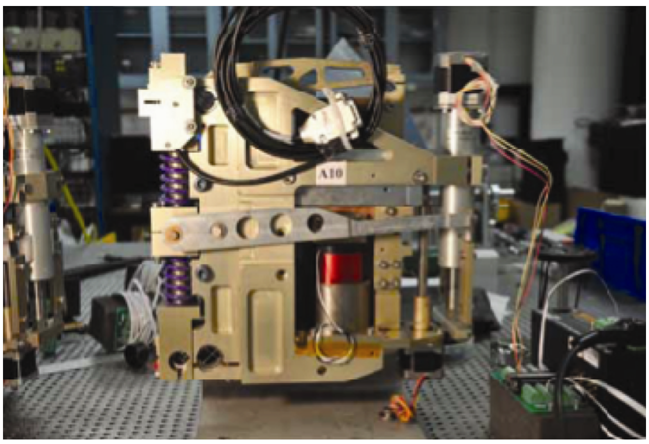

Figure 5. Assembled TMT actuator at India TMT Lab, IIA.

A set of prototype actuators has been fabricated at Avasarala Technologies Ltd, Bengaluru. End-to-end system performance modelling of the actuators has been conducted and the performance predictions are compliant with TMT requirements. The actuator performance has been verified by tests, both standalone and integrated with the Primary Segment Assembly (PSA). The tests confirm the lifetime and reliability predictions. The high-load experiments to test earthquake survivability were also conducted and the design found to be suitable. Another round of prototype manufacturing with additional vendors will be undertaken soon. For technical parameter requirements and design detail, refer to references 3 to 6.

Segment fabrication

Figure 6 shows the top view of the primary mirror (M1) segmentation pattern. The segment arrangement pattern has a sixfold symmetry about the vertical axis. Thus the entire M1 is divided into six identical sectors (A–F). There are 82 hexagonal segments in each sector. Since an array of identical regular hexagonal segments cannot uniformly fill a curved hyperboloid surface, the shape and asphericity for each of the 82 segment types are uniquely defined. For example, the outermost segment (type-82) has the greatest aspheric departure ~226 μm PV, while the innermost (type-2) has only ~6 μm peak-to-valley.

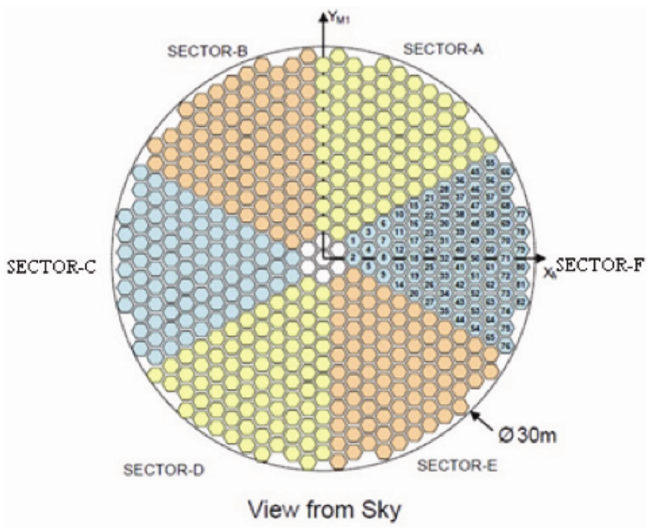

Figure 6. TMT primary mirror segment arrangement pattern showing the six-fold symmetry. (Courtesy: TMT Project Office.)

The TMT requires a total of 574 segments comprising 7 sets of the 82 unique segments. Also, 492 of these segments will form M1 and remaining 82 extra segments are used to facilitate re-coating of the primary mirror and for use as spares. The segments are closely placed with a nominal gap of 2.5 mm to maximize the fill factor.

All the primary mirror segments are polished in two stages. The first stage is to polish down to 2 μm PV with a stressed mirror polishing (SMP) technique, and the second stage is to reach 2 nm rms using ion beam figuring (IBF). India TMT is to deliver 86 of the segments (15% of total segments) polished down to 2 μm PV-first stage finish.

SMP, as a technique for producing non-axisymmetric mirrors was developed by J. E. Nelson in 1980 (refs 1 and 2). This technique was successfully employed in manufacturing the mirror segments for the 10 m Keck telescopes. SMP is a fast and cost-effective method to fabricate large, aspheric, off-axis thin mirrors. In this approach a mirror blank of circular section is warped by application of a set of moments and shear forces around the periphery with uniform back support system. Under warped condition, the top surface of the mirror blank is polished into a sphere using large polishing tools. Upon releasing the moment/shear loads, the blank springs back to the desired shape as long as the stresses are within the elastic limit of glass.

SMP technique is favoured for the TMT segments as this technology has been demonstrated to provide excellent accuracy in the fabrication of thin, aspheric, non-axisymmetric mirror segments with a fast converging rate of polishing. As this technique uses large tool for polishing, it directly limits mid and high spatial frequency errors and hence reduces the processing time for IBF to reach the final surface requirement.

India TMT is building an optics fabrication facility at the Hosakote campus of the Indian Institute of Astrophysics. This facility will be equipped with a set of SMP equipment and metrology-related tools. Once the blanks are polished and 2 μm PV is achieved, the roundel will be cropped into hexagonal shape under CNC machine operation. After shaping, the segments will undergo machining at the back surface to include pockets for the edge sensors and the central diaphragm.

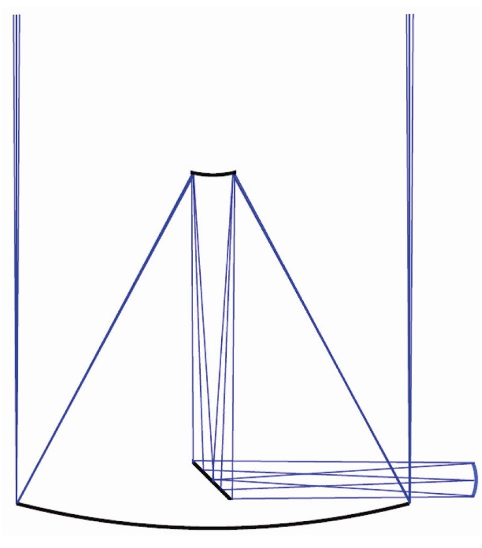

Figure 7. Three-mirror optical layout of TMT.

Since the SMP technology is not available in India, it has been proposed to obtain the necessary technology and the required grinding, polishing and metrology equipment from an international industry that has a well-demonstrated capability in producing large optics using this technology. This will give India TMT the necessary technology to jump-start the production of the 86 M1 segments. The India TMT optics group is also in discussion with industries in the country to develop the hex-cutting and pocketing process. The large optics facility being set-up for the TMT project will also serve future projects involving large optics.

Mirror coating chambers

As shown in Figure 7, the TMT optics consists of a three-mirror system – hyperboloid primary (M1) and secondary (M2) and flat tertiary (M3). The M1, M2 and M3 mirrors will have reflective coatings on them, primarily made of aluminium or silver. These coatings degrade due to continuous exposure to the environment and the reflectivity reduces over a period of time. Once every 1½–2 years, the degraded coating on the mirrors needs to be stripped-off and fresh coating deposited. Every time a segment is taken out for re-coating, it will be replaced by a spare one so that telescope operations are unimpeded. Since the primary mirror of the TMT is made of 492 segments, the mirror re-coating will be a continuous activity at the observatory round the year.

As mentioned before, the primary mirror segments of the TMT are to be polished down to 2 nm rms surface figure. The final polishing of each segment is carried out after mounting it on its segment support assembly so that even the support print-throughs are polished out. Once polished, the segment will never be separated from its support assembly. Therefore, while re-coating a segment, the entire assembly also will have to be accommodated along with the segment.

These and other requirements put stringent design constraints on the coating chambers for the TMT. India TMT is responsible for the design, development and commissioning of the coating chambers. At present, industry exploration is in progress to identify partners who could carry out this work in India. Once identified, preliminary design efforts will be initiated.

Software

In addition to the hardware development efforts, India TMT is also responsible for the design and development of a number of key software components for the TMT. These include the TCS as well as the OSW.

Telescope control system

TCS is a principal software system of the TMT. It is responsible for the coordination and control of various subsystems that make up the telescope, responding to commands received from the observatory control system and from expert user interfaces. It consists of the following: a sequencer and status/alarm monitor which provides high-level control of the mount, the primary, secondary and tertiary mirrors, and the enclosure; a pointing kernel which converts target positions (right ascension and declination) into pointing and tracking demands in the appropriate coordinate systems for the telescope mount, instrument rotators, atmospheric dispersion correctors, instrument and AO system wavefront sensor probes, and the enclosure cap and base and a correction module which is responsible for the creation and management of the look-up tables that control the position and shape of the primary, secondary and tertiary mirrors as a function of zenith angle and temperature. It will also process data from the telescope global metrology system and provide appropriate position information to the other control systems and several adaptors (Hardware Control Daemons) which provide an abstraction and interface point to the various TCS subsystems such as the mount and enclosure. HCDs are the way external systems and hardware are integrated into the TMT software system. Figure 8 shows the overall structure of the TMT TCS.

India TMT undertook an extensive effort to identify and qualify suitable software suppliers who could design and deliver the TCS. Three software industry partners (Honeywell, Persistent Systems and Thoughtworks) have qualified through this process. Currently, the preliminary design work of the TCS is underway through a partnership with Honeywell.

Observatory software

The TMT OSW provides the software architecture and infrastructure that integrate all the TMT software to form one cohesive system. It also provides the user-oriented software that supports the end-to-end observing process. The main components of the OSW are as follows:

Common Software (CSW) which provides the TMT software infrastructure needed to integrate all TMT control system software at the telescope; Data Management System (DMS) which provides the software and hardware mechanisms and infrastructure to capture, time-stamp, describe, store, transmit, and access all science and engineering data flowing through the TMT system; Executive Software System (ESW) which provides core functionality for synchronized operation of all TMT subsystems as well as the observing and monitoring user interfaces, and Science Operations Support Systems (SOSS) which provides software applications and infrastructure to enable high-level science operations from proposal preparation to observation execution. Figure 9 shows a block schematic of the TMT principal software subsystems.

Through an independent identification and qualification process, Honeywell, Persistent Systems and Thoughtworks have qualified for developing several of the OSW subcomponents which are the responsibility of India TMT to develop and deliver. At present, the development of CSW has been initiated through contract with Thoughtworks.

Science

In addition to the design and development work related to telescope subsystems and components, astronomers in India are actively participating in many of the scientific activities related to the TMT. Nine International Science Development Teams (ISDTs) have been formed, each dealing with a core science area which the TMT will address. The goals of ISDTs include helping to define the observatory capabilities and operations to maximize its scientific output, broadening the base of scientists actively engaged in the TMT project, including, for example, observers, theorists, high-energy physicists, building science-driven collaborations across the partnership, demonstrating the full potential of the TMT in key science areas cutting across instrumentation boundaries and increasing the visibility of the TMT science by producing white papers and organizing workshops.

The ISDTs are reconstituted annually through an open call for applications. At present, more than 35 astronomers working in institutes and universities across India are part of the ISDTs.

One of the important activities which the ISDTs had undertaken recently was a comprehensive revision of the TMT Detailed Science Case (DSC). This effort which lasted over a year culminated in the publication of the revised DSC for the TMT in 2015. The ISDTs are currently

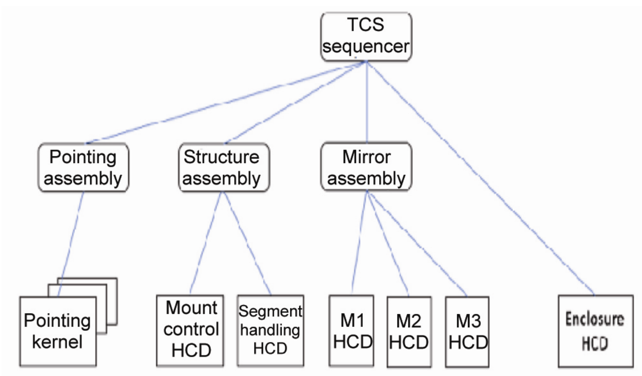

Figure 8. TMT TCS subcomponents.

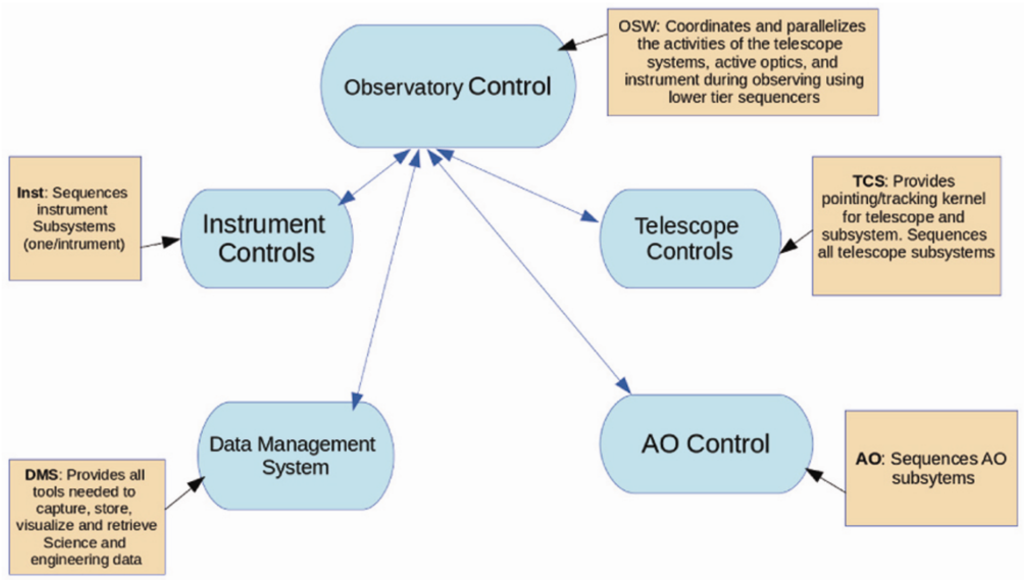

Figure 9. TMT software principal components.

involved in developing key science cases for the TMT which cut across partners and instrument capabilities.

An annual event called TMT Science Forum is held to foster international scientific collaboration and developing scientific policy guides for the TMT. The first TMT Forum outside USA was held in Japan in 2016. The TMT Forum 2017 is planned to be held in India towards the end of the year. The Forum will provide an opportunity for the wider Indian astronomy community to understand more about the TMT and its capabilities as well as to help nucleate new engagements.

The AO system of the TMT works in the near-infrared wavelength bands. The sodium laser guide star system of the TMT will be assisted by natural guide star system which provides measurements of the low order aberrations. The TMT will require to be able to use natural guide stars as faint as $J = 22$ mag to get adequate sky coverage. However, no all-sky catalogues exist which include stars as faint as $J = 22$. A team led by astronomers in India developed a new methodology for the prediction of near infrared magnitudes of faint stars from their optical magnitudes[7]. This will allow identification of potential near infrared guide stars for the TMT, from deep optical surveys like PANSTARRS.

Science instruments

The Indian astronomy community is also actively engaged in the design and development of science instruments for the TMT. As part of this effort several Indian teams participated in a set of mini-studies related to the Wide Field Optical Spectrograph (WFOS), which is one of the first light instruments planned for the TMT. Each mini-study team comprised of members across the TMT partnership and the entire activity was carried out over a span of about a year. At present India TMT is actively involved in the performance simulation and trade-off studies of various optical design options for WFOS.

Another team led by Indian astronomers carried out a detailed modelling and performance evaluation of polarimetric measurements capabilities of the current TMT design. Although at present no TMT instrument is planned to have polarimetric capabilities, this has been identified as a major deficiency in TMT's science plan. The modelling study clearly demonstrated that the current three-mirror design of the TMT will be capable of addressing a wide range of polarimetric science.

Astronomers in India are actively engaged with the TMT Science Advisory Committee to help define the future science instrumentation development plans for the TMT. Through a series of discussions and consultations within the Indian astronomy community, two science instruments capabilities have been identified as of priority – high-resolution optical spectroscopy and mid-infrared imaging and spectroscopy. Core teams have been identified among Indian astronomers who are tasked to crystallize these interests into specific science goals and instrument capabilities. They will also identify and forge collaborations with astronomy communities in other TMT partner countries which have similar scientific interests. These teams are already conducting regular telecon/videcon meetings as well as holding workshops either standalone or along the sidelines of other events like the meeting of the Astronomical Society of India, TMT Science Forum, etc.

Human resources development and public outreach

It is clear that the human resource capital of the astronomy community has to accelerate its growth over the next decade in order to be able to effectively utilize the capabilities of a mega-facility like the TMT. India TMT has initiated several steps to help with this process. A Workforce Development, Education and Public Outreach Committee (WEPOC) has been formed to coordinate these activities. This Committee also works in collaboration with similar efforts in other TMT partner countries through regular tele/video meetings, exchange visits, etc.

Several trainee engineers, and Masters' students work in India TMT institutes participating in several of the design and development work associated with India's in-kind contribution. India TMT has also established a laboratory where new technologies are developed which may be of use for large observatories. Schools and workshops are being organized which train young astronomers in analysing astronomical data from the existing large observatories in the world. Talks are given in institutions across the country to create awareness about the TMT among astronomers, students and the public in general. Six Indian young astronomers were sponsored by India TMT to participate in the TIO Leadership Workshop held in Hawaii in 2016. All of these need long-term efforts to bear results – indications show that they are helping in attracting talent to instrumentation and facility development as well as triggering the aspirations of a young educated population that is not afraid of turning difficult challenges into unique opportunities to excel.

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ACKNOWLEDGEMENTS. This is the summary of India TMT activities being executed by the respective work package managers: Mr P. K. Mahesh, Mr Varun Saraswath, Dr Neeraj Gupta, Dr Annapurni Subramaniam, Mr S. Sriram, Dr G. C. Anupama and Dr Padmakar Parihar along with their team members, India TMT Science Advisory Committee and WEPOC. We thank them for their contributions. This project is supported by the Department of Science and Technology, and the Department of Atomic Energy, Government of India.

doi: 10.18520/cs/v113/i04/631-638