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OBSERVATIONAL FACILITIES

India-TMT project—science instrumentation program

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Abstract. The future of astronomy in the coming decades will be shaped by the upcoming three extremely large optical telescopes, the Thirty Meter Telescope (TMT), the Giant Magellan Telescope (GMT) and the European Large Telescope (ELT). The USA astronomy and astrophysics 2020 decadal survey and the Canadian long-range plan for astronomy have recently recommended these large observatories as a top priority for ground-based astronomy for the upcoming decade. India is a 10% partner in one of these large observatories, the TMT, which is jointly funded by the Department of Science and Technology (DST) and Department of Atomic Energy (DAE). Here, we highlight India's contributions to the development of the telescope and science instruments. The size of back-end science instruments scale with telescope aperture, hence, science instruments for TMT will be the biggest ever built for any telescope. Designing and building them requires broad collaboration within India, across TMT partnership and industries. India contributes >30% of the work share towards the development of wide field optical spectrometer (WFOS). India is part of the development of other first-light instruments, the infrared imaging spectrograph (IRIS) and multi-object diffraction-limited high-resolution infrared spectrograph (MODHIS). Infrared guide star catalog is an important contribution from India to these adaptive optics (AO)-assisted instruments. India leads the development of high-resolution optical spectrograph (HROS), a major workhorse among the first decade instruments of TMT. India is also part of the instrument development team of other first-decade instruments. Concerted efforts have been made to contribute to some of the TMT precursor instruments that will help us to maximize the scientific productivity when TMT is operational, especially in the area of exoplanet science and observations that require AO. India-TMT is part of the science team for the Keck high-resolution infrared spectrograph for exoplanet characterization (HISPEC), a precursor instrument to TMT-MODHIS. In addition, Indian Institute of Astrophysics (IIA) is participating in the science and development of Santa Cruz array of lenslets for exoplanet spectroscopy (SCALES) project for Keck, which is a direct imaging spectrograph for exoplanet studies and a precursor to the TMT planetary system imager.

Keywords. Astronomy–extreme large telescope—Thirty Meter Telescope—instrumentation—spectrograph.

1. Introduction

During 2030s, the three large telescopes of 30-m class will be operational and is expected to change the

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landscape of astronomy. The Giant Magellan Telescope (GMT, https://www.gmto.org/, Fanson *et al.* 2020) of 25-m diameter and the European Large Telescope (ELT, https://elt.eso.org/) of 39-m diameter are both under construction in Chile to access the southern skies. The Thirty Meter Telescope (TMT, https://www.tmt.org/, Sanders 2013), (30-m diameter), will be the only large telescope that will have access to the northern celestial hemisphere. The 30-m aperture of the TMT primary mirror is chosen to be the largest diameter that will support fully seeing-limited science instruments within the current technology limits. TMT will also have the most advanced adaptive optics (AO) system at first light. TMT telescope optics is a three-mirror Richey–Chrétian optical layout (Figure 1), that has 30 m hyperbolic ($F/1$) primary mirror (M1) (made out of 492 hexagonal segments, each measuring 1.44 m diameter and 45 mm thickness), a 3.1 m convex hyperbolic secondary (M2) and a flat 2.5 × 3.5 m tertiary mirror (M3). The $F/15$ beam at the Nasmyth focus provides a plate scale of 2.18 mm/$''$. The overall 30 m aperture will have a hyperboloid shape with a conic constant of -1.000953 and a radius of curvature of 60 m. The primary mirror is divided into six identical sectors, resulting in six-fold symmetry each of 82 unique segment types. The final aplanatic focal plane will have a field-of-view $\approx 20'$ diameter (2.56 m), and an unvignetted field-of-view of $15'$. Indian Institute of Astrophysics (IIA) has a dedicated segment polishing facility at the CREST campus for polishing the M1 segments and the integration of the M1 segments with segment support assemblies (SSAs) (Figure 2). Initially, each of the roundels are polished to a shape described by its unique Zernike terms, to a level that the optical surface figure errors relative to the theoretical surface is <1.73 μm peak-to-valley (P–V). Stress mirror polishing, a novel technology is used to polish these aspherical M1 segments. The polished roundels are hex-cut into hexagons $\sim$1.44 m as measured across corners. However, the segments are not regular hexagons and they are also not identical. After hex-cutting, the segments go through ion beam figuring (IBF). At this stage, the required surface roughness of both front and back surfaces need to be 20 Å RMS that includes all features with a spatial period between 20 and 800 μm. India TMT Co-ordinating Center (ITCC) has already successfully completed polishing a segment at the training site in USA. The hex-cutting process is also sucessfully demonstrated by vendors in India. Each of the mirror segment is supported by a SSA that will hold the segment in position with minimal gravity distortion. The primary mirror control system (M1CS) maintains the overall shape of the segmented primary mirror despite structural deformations caused by temperature, gravity and disturbances from wind and other vibrations. Each of segments are actively controlled by the M1CS via three high-precision actuators per segment through nanometer-level feedback that is provided by two sensors per inter-segment edge. In total, the M1CS contains 1476 actuators and 2772 sensors. The entire fabrication of SSA and the M1CS (Figure 3), which is the heart

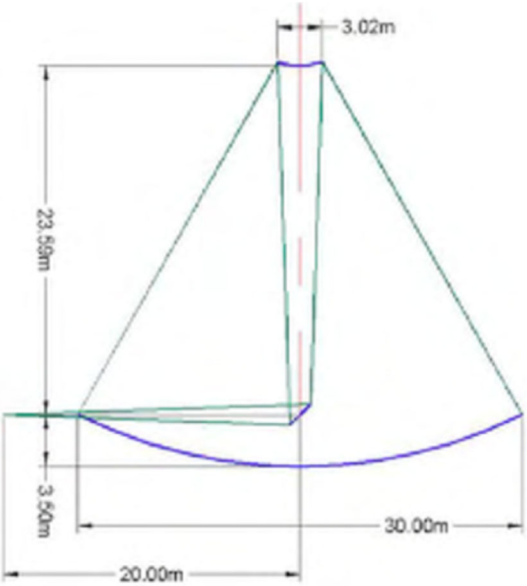


Figure 1. Optical layout of TMT Richey–Chrétian design. Primary is $F/1$ and at the tertiary, it provides $F/15$ beam at a plate scale of 2.18 mm/$''$.

Figure 2. India-TMT optics fabrication facility (ITOFF) at the IIA, CREST campus shown above is a dedicated facility for India-TMT M1 polishing. The glass blanks from Ohara, Japan, are stored for polishing at ITOFF can be seen.

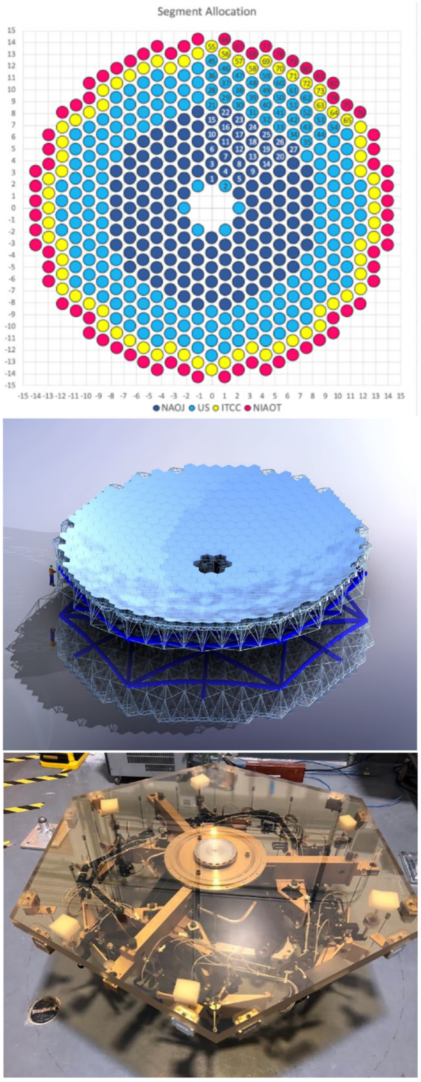


Figure 3. The top panel shows individual TMT partners share in the fabrication of the M1 segments. The middle panel shows the 30 m segmented primary and the bottom panel shows one of the fabricated SSA and a polished M1 segment.

of the telescope and is being carried out by the ITCC, through Indian Industrial contracts (Reddy 2013). The main challenge for M1CS is to have a large dynamic range, i.e., the M1 segments require corrections of few nanometer precision over an operation range of several millimeters. The final surface figure error, which is <2 nm after IBF and SSA corrections need to be achieved. First, SSA is successfully integrated at the Indian vendor facility and meets the stringent requirements.

All the science instruments are permanently mounted on the Nasmyth platform (Figure 4) and M3 can feed the light to any of the instruments. One of the Nasmyth platform is dedicated for seeing-limited instruments, such as the wide field optical spectrometer (WFOS) and high-resolution optical spectrometer (HROS) and the other Nasmyth platform supports the AO-assisted instruments. TMT will provide diffraction limited wavefront quality in J, H and K bands using a narrow field infrared adaptive optics system (NFIRAOS) (Ellerbroek 2013), a facility AO system that has three output ports of F/15, 2-arc-min field of view to feed three AO-assisted science instruments. NFIRAOS supports multi-conjugate AO (MCAO) system, which provides uniform, diffraction-limited performance in the J, H and K bands over 34 × 34 arc-sec field. NFIRAOS operates up to 800 Hz and includes two deformable mirrors conjugated at 0 km (63 × 63) and 11.8 km (76 × 76). The laser guide star facility (LGSF) generates the needed multiple laser guide stars and asterism geometry. However, much fainter natural reference stars are still required for image position (tip/tilt correction) information. A catalog of suitable guide stars will be a critical resource for TMT operations that enables efficient planning and observing. The TMT infra-red guide star catalog (TMT-IRGSC) should be a star catalog consisting of point sources with JHKs magnitudes as faint as 22 mag in J band (Vega system), covering the entire TMT-observable sky. India-TMT is leading the activity of generating suitable Infrared guide star catalog that reaches faint magnitudes (Jvega = 22 mag) and covers the entire TMT accessible sky (Subramanian *et al.* 2013, 2016; Shah *et al.* in preparation).

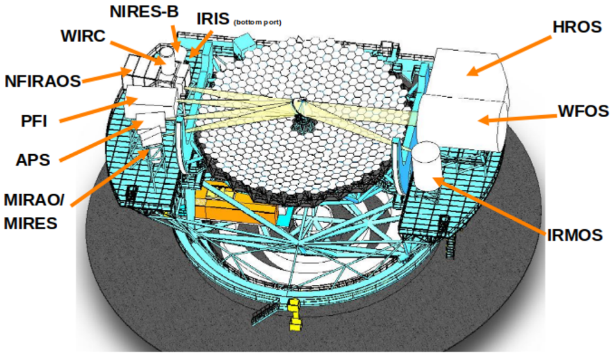


Figure 4. An illustration of TMT science instruments mounted on the two Nasmyth platforms. M3 rotates to feed light to the instruments. Instruments on the left are AO-assisted and right are seeing-limited.

TMT science instruments' priorities are developed from key science cases (Simard 2013). TMT detailed science case document (Skidmore *et al.* 2015) provides the requirements for the science instruments and observatory to reach the key science goals. Some of the key areas included are: studies of the first sources that light up the Universe for the first time (Pandey 2013) and make chemical elements beyond Hydrogen and Helium, dispersal of these heavy elements and assembly of large-scale structures and galaxies similar to milky way, and formation and evolution of super massive black holes through cosmic time. Planet formation processes and the characterization of extra-solar planets and detection of bio-markers around habitable worlds (Sengupta 2013) are some of the thrust areas that will be possible only with 30-m size telescope aperture. TMT will provide follow-up spectroscopy of James Webb space telescope (JWST) exoplanet targets, at higher spectral and spatial resolution. Both self-luminous giant planets and reflected light terrestrial planets can be directly imaged with TMT. TMT will spatially resolve the accretion disks of active black holes in the centers of galaxies up to the distance of Virgo cluster and resolves individual stars of the galaxy and their chemical composition can be studied. The TMT science advisory committee and the international science development team (ISDT), provide road map and recommendations for the scientific capability of the TMT observatory. Science instruments are planned based on these broad science goals. By design, TMT can provide new science opportunities and maximize the science output in every field of astrophysics. As shown in Figure 5, India has good representation across all the key science areas that TMT will address. TMT can cater to almost every area of astronomy and has a large synergy with other large multiwavelength facilities (e.g., the square kilometer array, SKA), leading to biggest scientific impact (e.g., Iswara-Chandra 2013). Detailed characterization of the telescope mirror polarization was carried out at ITCC as a part of student PhD thesis (Anche *et al.* 2018, 'http://prints.iiap.res.in/bitstream/handle/2248/7526). Characterization of TMT telescope polarization at various wavelengths has been derived using Gemini coating (Anche *et al.* 2015). The expected telescope polarization at NFIRAOS port (Anche *et al.* 2018) and at mid-infrared wavelengths for MICHI instrument has been estimated analytically (Anche *et al.* 2018a).

TMT is also way ahead in the development of an operational model of the observatory and the observatory software development for its operations. India-TMT is a major developer of this subsystem through the Indian software industry. The common software that provides the backbone for the entire software framework of the observatory was successfully developed and delivered the phase I of executive software and the prototype for data management system. The telescope control software and some of the instrument control software are also been developed in the country. TMT uses adaptive scheduling to maximize the observing efficiency. This allows crucial science observations that require best sky and environment conditions during changing weather conditions. Similar strategies are being explored in Gemini and European Southern Observatories (ESO), but not implemented in any observatories.

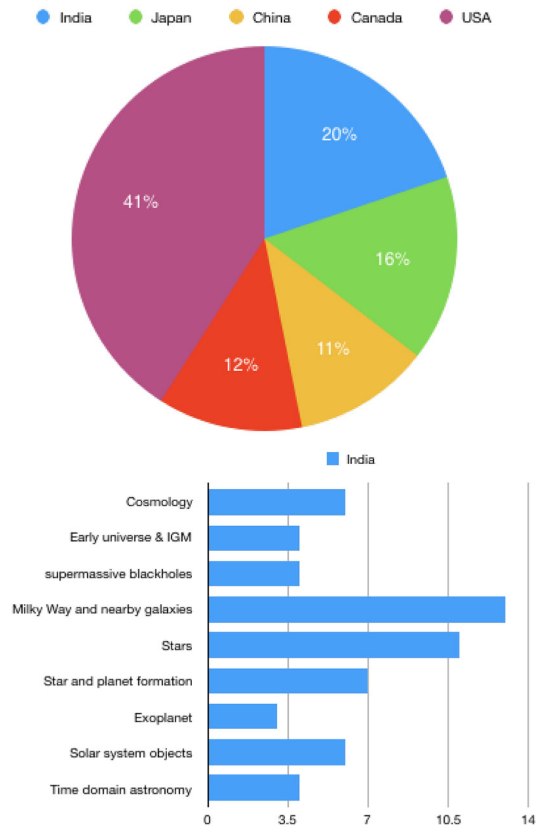
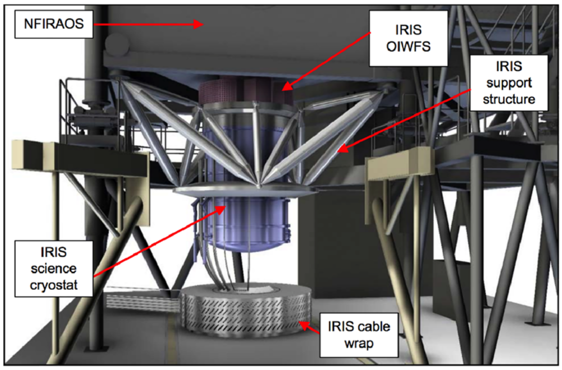


Figure 5. A PI chart of the distribution of members in the International science development team for TMT among the partners and also the histogram of members from India across different science areas are shown. The x-axis shows the number count.

2. Infrared imaging spectrograph

Infrared imaging spectrograph (IRIS) is one of the first-light instruments for the TMT fed through the AO facility NFIRAOS. IRIS has an IR imager and an integral field spectrograph (IFS) and provides simultaneous wavelength coverage over the 0.84–2.4 μm range. IRIS offers diffraction limited performance for wavelengths longer than 1 μm (Wright *et al.* 2014, 2016; Larkin *et al.* 2020). The IRIS imager provides a 30 × 30 arcsec FOV with pixel sampling of 4 mas. Figure 6 shows IRIS image simulation of M31, and a comparison of HST ACS image. The on-axis portion of the imager field is relayed to the IFS. IFS has four spatial scales achieved through image slicers and lenslet arrays listed



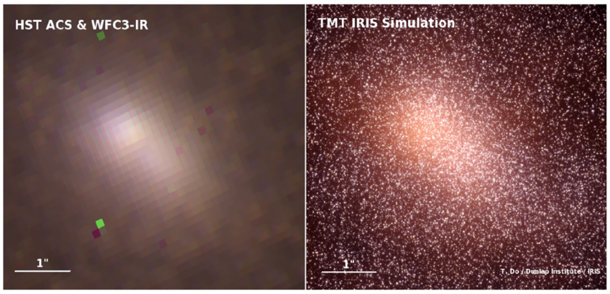


Figure 6. A simulation M31 galaxy with IRIS imaging mode at 1 μm and a comparison of HST ACS image is shown. Individual stars can be well resolved with IRIS. Image credit: IRIS team.

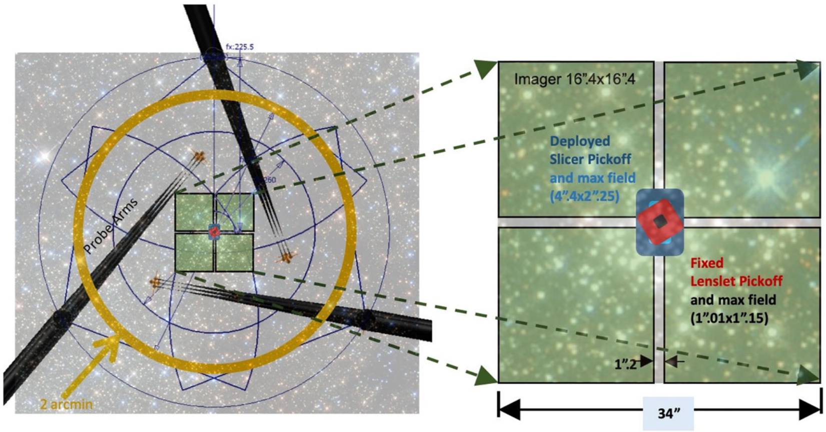
in the table in Figure 7. Innovative IRIS sequential layout allows common suite for filters and detectors. IRIS has three on-instrument wavefront sensors (OIWFS) for natural guide star (NGS) tip/tilt/focus (TTF) measurements, which access the entire NFIRAOS field of view. The top panel in Figure 7 shows the mechanical layout of IRIS, attached to NFIRAOS bottom port and supported at the Nasmyth platform on the telescope. The large cable wrap at the bottom allows required instrument rotation to correct the field rotation during observations. Table in Figure 7 lists the capability of IRIS. IRIS has very large number of filters to cater various science cases and observing modes. The spatial resolution of IRIS allows to resolve few kilometers of the solar system objects and 1-parsec for objects at the distances of Virgo clusters. One of the main contribution for IRIS from India is the IR guide star catalog. Though the contribution is limited, there are postdoctorals from India, who are deeply involved in IRIS which is quite valuable (e.g., Surya *et al.* 2020).

3. Multiobject diffraction limited high dispersion spectrograph

Multiobject diffraction limited high dispersion spectrograph (MODHIS) is a diffraction-limited high-resolution infrared facility for TMT-NFIRAOS. MODHIS will be an exoplanet focused science instrument which will be available at first light, which is apt as per the astronomy road map for the upcoming decade. MODHIS is capable of performing transit and direct high resolution spectroscopy ($R = 100000$), along with precision radial velocity capability in the wavelength range of 0.95–2.5 μm. It is a compact, single mode fiber fed and stable spectrograph (shown in Figure 8) that will provide doppler velocity precision of 30 cm s^{-1}. MODHIS is also capable of catering to other science areas, such as solar system studies, galactic and extra-galactic IR spectroscopies. High resolution spectroscopy of the galactic center and probing the variations of fundamental constants in extreme gravity environments are some of the other key science areas. Laser frequence comb will be used for calibration. MODHIS can take spectra of up to four objects in a narrow field-of-view $4''$. The instrument parameters are listed in Table 1. The instrument has a two-spectrograph layout, each of the spectrograph has a R4 grating with TMA design for the collimator and the camera. Both spectrographs will have an H4RG detector. The MODHIS team is also building a cost-effective precursor spectrograph called HISPEC for the 10-m Keck telescope. This will give early access for the TMT science community to a precursor instrument that will enable training and collaboration between research groups across the partnership. MODHIS started its development late compared to other first-light instruments. IR guide stars catalog developed by ITCC will remain valuable for MODHIS as well. Currently, there is an active science team from ITCC that is part of MODHIS and HISPEC and the team is part of the NSF proposal.

4. Wide field optical spectrometer

Wide field optical spectrometer (WFOS) will be one of the first-light instruments that will operate under natural seeing condition. WFOS is an imaging spectrograph that operates in the near-ultraviolet to optical spectral range (0.31–1.0 μm) over $8.3' \times 3'$ field-of-view. Using precision cut focal plane masks, WFOS will enable short-multi-slit observations of $\sim$50–80 objects simultaneously (as shown in Figure 9). The full wavelength range can be captured in a single exposure at $R = 1500$ with a 0.75 arc-sec slit. WFOS opto-mechanical layout has a gravity invariant vertical rotation axis (Figure 10) to minimize instrument flexure and will incorporate a robust structure to support various components of the instrument. In addition, it will incorporate an



Capability mode	*Spatial sampling (mas)*	*Field of View (arcsec)*	*Resolution (λ/dλ)*	*Min/Max wavelength (μm)*	*Bandpass*
Imager	4 mas	34 x 34	Set by filter	0.81-2.4	37 filters Variety of bandpasses
Slicer IFS *88x45 Spaxels*	50 mas 25 mas	4.4 x 2.25 2.2 x 1.125	4,000, 8,000	0.81-2.4 0.81-2.4	20%,10% 20%,10%
Slicer IFS *44x45 Spaxels*	50 mas 25 mas	4.2 x 2.25 1.1 x 1.125	4,000-10,000	0.81-2.4 0.81-2.4	20%,10%, H+K 20%,10%, H+K
Lenslet IFS *112x128 Spaxels*	9 mas 4 mas	1.01 x 1.15 0.45 x 0.51	4,000	0.81-2.4 0.81-2.4	5% 5%
Lenslet IFS *16x128 Spaxels*	9 mas 4 mas	0.144 x 1.15 0.064 x 0.51	4,000-10,000	0.81-2.4 0.81-2.4	20%, H+K 20%, H+K

Figure 7. The panel on the top left shows IRIS field view, including the guiding probe patrol field. The panel on the top right is the zoomed view of the science field. The clever optical design of IRIS allows simultaneous spectroscopy and imaging mode as shown here. The table lists the wide range of capability with IRIS, allowing range of spatial and spectral resolutions.

enclosure to protect its components and provide a light tight environment for the optical elements. The optical design has two-channel layout, the blue channel covers 310–550 nm and the red channel covers 550–1000 nm (Table 2).

Possible upgrades and additional functionality include an integral field-unit, image-slicing spectroscopy and options for gratings, if funding allows. The instrument front end incorporates a linear ADC and controlled fold mirror (M4) that directs the beam to the slit mask and guidance system. The optical design (Figure 10) includes an on-axis two-mirror collimator, and nearly identical blue and red channel mechanisms for camera rotation, and grating and filter exchange. The novel two mirror aspheric collimator provides on-axis access and a good image quality and reduce the requirement of additional mirror similar to three-mirror-anastigmat (TMA). The gratings proposed for WFOS provide the highest diffraction efficiencies. Both volume phase holographic (VPH) and volume binary grating (VBG) gratings are being explored. The camera and grating system can move independently to maximize the efficiency. For calibration, the output of an integrating sphere (shown in Figure 10, bottom right panel) directed into the instrument by tilting M4, is designed. WFOS will have highest throughput among the other seeing-limited WFOSs of ELTs. One of the key science goal is to provide tomography of intergalactic medium (IGM) to probe the baryonic distribution at redshifts up to $z = 2$–3 (as shown in Figure 9). Overall WFOS will have 32 independent configurations to optimize the science goals. The salient features of WFOS are the high throughput and large flexibility in the observing modes to maximize discovery space. The high throughput is achieved by VBG or VPH gratings along with grating and camera articulation to follow the grating blaze function. Several choice of gratings, its articulation and flexible slit width and orientation and slit-less modes provide flexibility to achieve range of science goals with WFOS. Some of the key contributions from ITCC are the mechanical design and development of the blue and red camera rotation system, the grating and filter exchange system (Figure 10). All the designing is done in-house within ITCC. The key challenge in the design is size and weight of the camera rotation system that holds the camera optics, filter system and the detector assembly, and cryostat. The camera-grating system is needed to provide a repeatability of the daytime wavelength calibration to a level of one pixel at the detector. The calibration system is being developed entirely at ITCC. The calibration

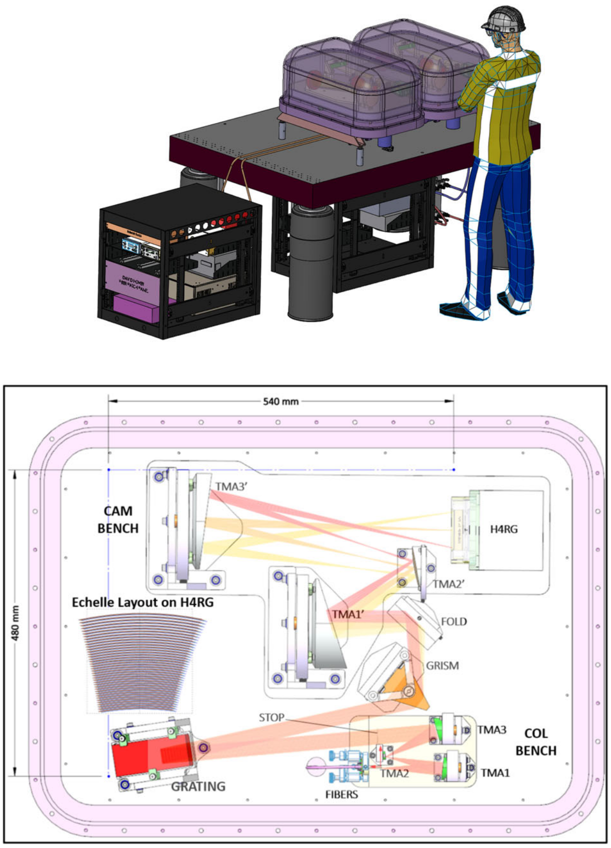


Figure 8. The top panel shows two spectrograph channels of MODHIS. It is very compact under vacuum and cryogenic temperature and will be highly stable. The bottom panel shows the optical design of red spectrograph.

Table 1. MODHIS design parameters.

Parameter	Value
Wavelength coverage	0.95–2.4 μm
Temperature stability	1 mK
Spectral resolution	$\sim$100,000
Doppler velocity precision	30 cm s^{-1}
Throughput	$\sim$10% (including Strehl ratio)
Spatial sampling	Diffraction limit (6 mas in y-band, 15 mas in K-band), sampled by single mode fibers
Field-of-view (patrol) for MOS	$4''$

unit will have a 1.5 m integrating sphere. A largest integrating sphere used for astronomy. This will provide spatially uniform light source and the relay optics is designed to mimic the telescope pupil. We also explore novel light sources for flat fielding and wavelength calibration. White light LEDs, laser-driven light sources are considered for flat fielding, PtCrNe and ThAr, and combination of Penray lamps will be used for wavelength calibrations. The mechanical and the baffle designs are underway. The entire instrument control software development is being carried out within the country. The overall electronics control layout will also be designed in the country. The entire WFOS mechanical structure analysis is also done at ITCC.

5. High-resolution optical spectrometer

High-resolution optical spectrometer (HROS) is selected as one of the top priority workhorse among the first decade instruments (that comes online after the first-light instruments) for TMT, by the TMT science advisory committee. HROS is expected to be installed within 2–3 years after the first-light instruments. HROS design and development is led by ITCC. High-resolution spectrographs, in general, are photon-starved for most science cases and hence, HROS is designed to collect the entire seeing disk to provide full aperture advantage of TMT, even under poor-seeing conditions. HROS is designed as a general purpose instrument with several observing modes and spectral resolutions ($>$25,000), which will complement the first-light instrument WFOS. It offers large flexibility in stability and throughput using slit, fibers and image-slicers and covers entire optical wavelengths between 310 and 1000 nm. Different spectral resolutions ($R = 25{,}000$, 50,000 and 100,000) are achieved by using different input fiber sizes of the fiber bundle. In all the modes, the fiber bundle covers the full seeing disk. HROS also offer limited multiobject capability, up to 6-objects can be observed at $R = 25{,}000$, that will cover the entire wavelength range by accommodating the different object fibers within the inter-order gap. However, a larger number of objects (up to 40) can be observed with limited wavelength coverage by blocking the nearby echelle orders. HROS also allows direct slit feeding of the spectrograph that will significantly improve the blue throughput, which makes HROS unique among the GMT/ELT high-resolution spectrographs, as all the other ELTs have only a fiber mode and operates at $>$350 nm or 400 nm. Wavelength bluer than 400 nm are quite important to probe rare neutron-capture elements and cosmic-ray nucleosynthesis using beryillum, deutrium and nitrogen isotopic ratios, all possible only at wavelengths below 350 nm.

Though, HROS is designed as a general purpose instrument, it can still provide high stability and precision calibration required for exoplanet transit spectroscopy (about 1 m s^{-1} or better) and to radial

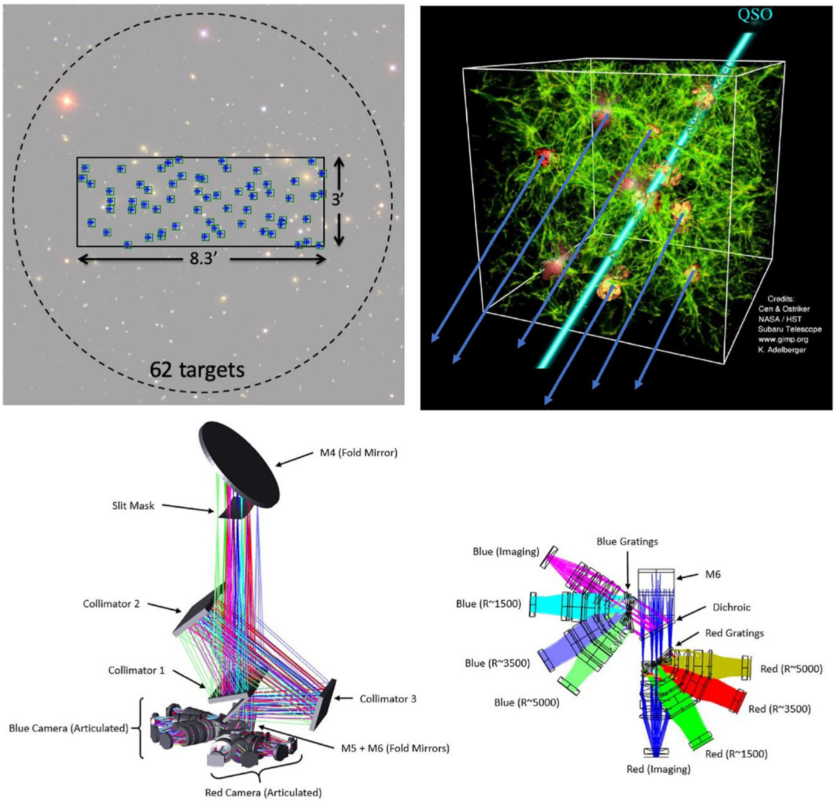


Figure 9. The top-left panel shows WFOS field-of-view, that is on axis at the TMT Nasmyth focus. Using a custom predesigned slit mask, spectra of chosen objects of interest can be taken. The top-right panel shows an illustration of IGM tomography with WFOS. The bottom panel shows the optical layouts. The optical design has two channel layout, the blue channel covers 310–550 nm and the red channel covers 550–1000 nm.

velocity characterization of interesting exoplanet systems. Current state-of-the-art spectrographs are able to achieve radial velocity stability of 20–25 cm s^{-1} (e.g., EXPRESSO, EXPRES, NEID). Considering the fact that RV follow-up of exoplanets requires significant observing time and hence, it can be done better with 4–10m telescopes with dedicated instruments, and hence, HROS is not catered as a RV machine, but a general purpose high throughput spectrograph to maximize the science return. HROS will be used to study the sites of the first metals that were produced in the early Universe by the Pop-III stars and can trace its evolution all the way to the present day exoplanet atmospheres. Some of the key science drivers of high-resolution optical spectroscopy with TMT are galactic archaeology, Inter and circum-galactic medium studies and exoplanet transit spectroscopy. The stability and precision calibration (1 m s^{-1}) of HROS will facilitate studies of characterising Earth like planets around nearby stars and possible variations in fundamental constants at different redshifts.

Multiple layouts of HROS is shown in Figure 11, to optimize the space envelope of the instrument in the Nasmyth platform. The instrument has two main observing configurations, a single-object mode that accesses a small central field ($20''$ diameter) and a medium-resolution multi-object mode that covers the full available TMT focal plane (about 2 m diameter). The details of the multi-object mode will be decided based on HROS location on the TMT Nasmyth plateform. However, the spectrograph design allows multi-object capability, which will allow 5–6 objects for a full wavelength coverage and up to 40 objects for a very narrow wavelength coverage (just one echelle order). The central field uses a K-mirror or an equivalent optical derotator to correct the field rotation during observations. This facilitates long exposures without the need for fiber reconfiguration. The field is corrected for the atmospheric dispersion. A dichroic beam splitter (with a cut-off at 450 nm) separates the beam into a blue and a red channel. The blue spectrograph is located closer to the focal plane to allow the possibility of short fibers and a slit mode to enhance the blue throughput. The red fibers are long and the spectrograph is housed in an environmentally controlled vacuum enclosure. The blue spectrograph is not placed

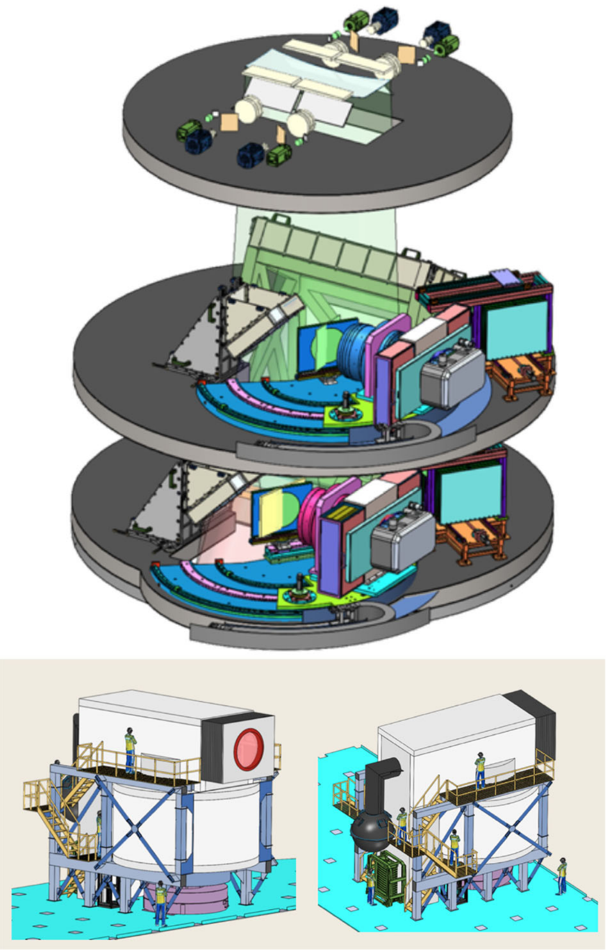


Figure 10. The top panel shows the three-level mechanical layout for WFOS structure. The instrument is quite stable and all the optical components are rigidly mounted on three optical benches. The top optical bench hosts the guiding and IFU units, the lower two benches hosts the blue and red cameras and the collimator, fold mirror and dichroic beam splitter. The bottom panels show the closed WFOS structure on the Nasmyth platform. The bottom-right panel shows the large integrating sphere, which will be used for WFOS calibration.

inside a vacuum enclosure. The combined red and blue spectrographs cover the entire wavelength range between 310 and 1100 nm. The overall design achieves a peak throughput of 29%. Light from the TMT tertiary mirror (M3, F/15 beam) is fed to an off-axis, F/15 collimator of the spectrograph. Choice of an F/15 collimator is to provide possible slit mode. The dispersed beam forms a white pupil after the second pass of the collimator. An R4 echelle grating is used. The possible observing configurations with HROS are listed below.

Standard observing mode (STD-mode): STD-mode has a spectral resolution of R=50, 000, and most science cases will likely use this mode. In the STD-mode a sky coverage of 1.2$''$ is sampled by a fiber bundle with seven individual fibers (0.4$''$ diameter) to achieve $R = 50{,}000$. STD-mode allows simultaneous observations of two objects (object and sky simultaneous) and a calibration.

Table 2. WFOS design parameters.

Parameter	Value
Field-of-view	25.5 (8.3 × 3) arc-min^2
Wavelength range	0.31–1.0 μm (full spectral range at $R = 1500$ in a single exposure)
Spatial resolution	Seeing limited
Spatial sampling	0.05 arc-sec per pixel
Spectral resolution	$R = 1500$–3500 at 0.75$''$ slits, higher resolution possible with narrower slits
Throughput	$>$25% from 0.31 to 1.0 μm, $>$30% from 0.35 to 0.9 μm, not including the telescope
Sensitivity	S/N = 150 per element, $R = 3500$ and $V = 20.5$ for an exposure 5×900 s

High-resolution mode (HR-mode): HR-mode ($R = 100{,}000$), is achieved by sampling the 1$''$ seeing disk with 19 smaller fibers (0.2$''$ diameter). Fibers form a pseudo-slit of 0.2$''$ width, which is sampled by 3.5 pixels (15 μm pixel size) at the spectrograph detector for accurate centroiding of spectral lines required by precise radial velocity (RV) observations. HR-mode also allows simultaneous observations of two objects and a calibration is possible in HR-mode. An additional fiber scrambling for uniform illumination at the near and far field is provided for precise RV-mode along with calibration fibers.

Medium-resolution multi-object mode (MOS mode): $R = 25{,}000$ is achieved by a single fiber of 1.2$''$ diameter. At medium resolution, a wide-field multi-object medium-resolution mode (MOS-mode) is designed, using several pickoff arms over the full TMT field of 200 diameter to choose the targets (similar to VLT-KMOS). The pickoff arms carry a beam-splitter to feed the separate red and blue fibers (as in ELT-HIRES). Fibers are routed through a cable wrap to the blue and red spectrograph pseudoslits. The spectrograph design allows full wavelength coverage of six objects with $R = 25{,}000$ and nine objects in the ground layer adaptive optics (GLAO) mode with 0.5$''$ fibers. Using order blocking filters and tunable etalons, a larger number of objects can be observed, trading off for narrower wavelength coverage.

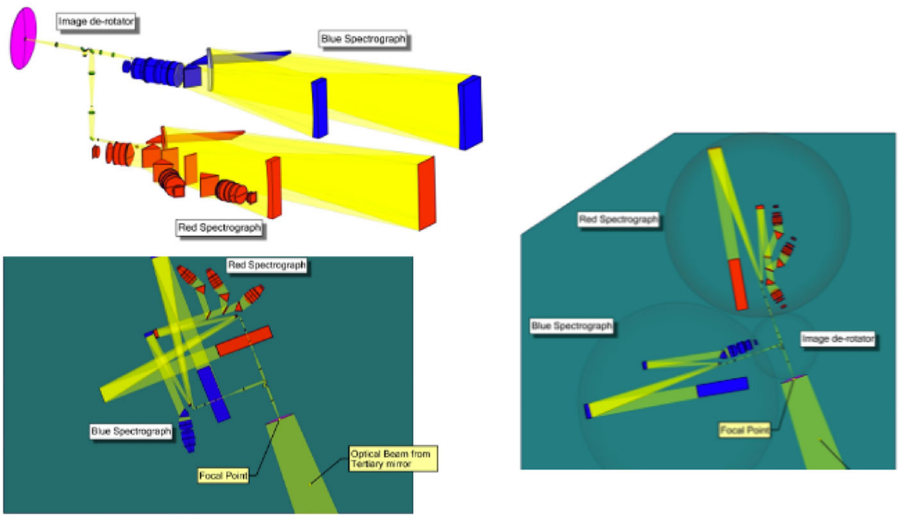


Figure 11. Various possible layouts of HROS on the TMT Nasmyth platform are shown.

Table 3. HROS design parameters.

Specification	Requirements
Wavelength coverage	310–1000 nm
Spectral resolution	$R > 100{,}000$, $R = 50{,}000$, $R \sim 20{,}000$
Image quality	0.2 arc-sec FWHM at detector
Sensitivity	Maintain 30 m aperture advantage
Stability	1 m s^{-1}

Slit mode: This is possible for the single-object mode. A slit width of 0.5″ and 0.75″ provide $R = 39{,}500$ and $R = 26{,}300$ spectral resolutions, respectively, and a throughput of 75% and 95% for 0.5″ seeing.

Polarimetric mode: TMT-HROS will be located on the Nasmyth platform that is fed by the 45° M3 mirror. This is not optimal for polarimetry, since the reflected light will cause considerable instrument polarization and cross-talk. A crossed twin mirror will not work for the HROS port, since the M3 will be rotated to feed light to HROS at different elevations. A mitigation similar to that used for VLT-SPHERE is foreseen, where a retarder is used to compensate for the M3 rotation and the cross-twin mirror for the 45° compensation.

6. Summary

Participation in TMT is a major leap forward for the Indian astronomy community from having access to 2–3 m class telescopes to 30 m size aperture size telescope. So far, several software subsystems for the observatory and telescope control have been successfully completed the final design phase, the common software was completed and recently ITCC successfully delivered the phase I of executive software as well. Major contracts for M1 SSA and training for M1 polishing is going on successfully. The first light instrument WFOS will be completing the final conceptual design phase after several major changes to the original design that was proposed in 2005. India-TMT played a major role in the trade studies and the evolution of WFOS design. Currently India-TMT is contributing to the opto-mechanical design of several subsystems of WFOS, the control electronics and instrument control software. The IRGSC catalog and parts of IRIS data pipeline is also India's contribution. The TMT precursor instrument SCALES, which is a direct imaging and spectroscopy facility for Keck 10-m telescope has successfully completed the preliminary design review (in November 2021) and moved to subsystem final design and fabrication phase and expected to see first light in 2025. Another TMT precursor instrument HISPEC for Keck telescope is also in the advance stage of development. These significant efforts have leveraged both science and technology development in the country.

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