Capabilities of the Thirty-Meter Telescope (TMT) for Solar System Astronomy

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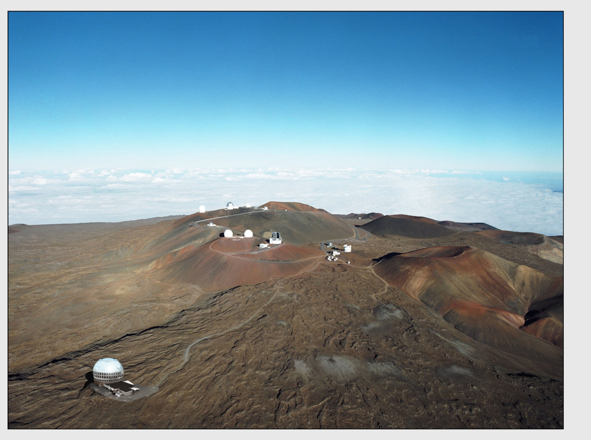
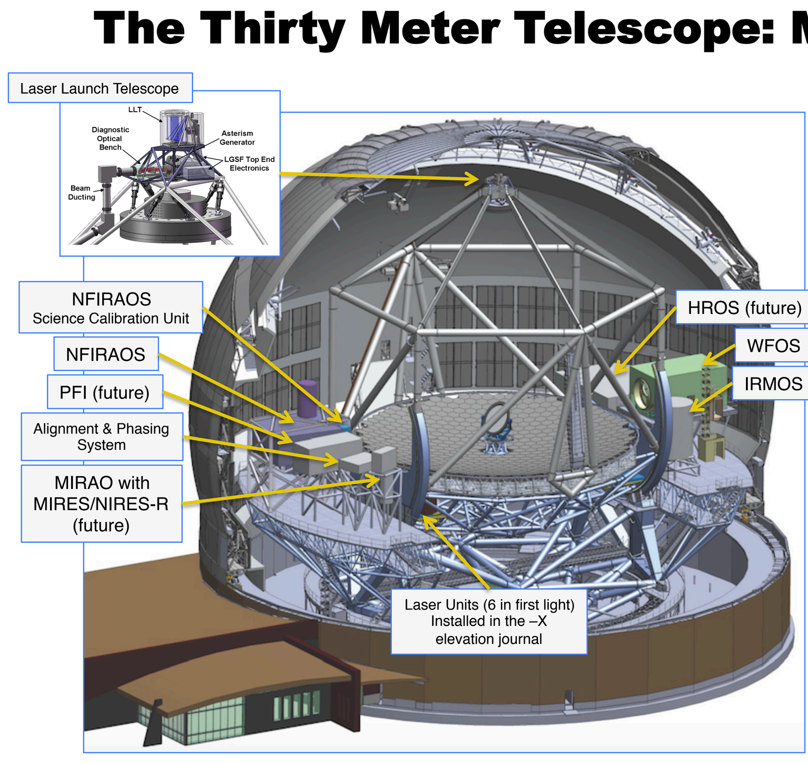


Abstract

The TMT will consist of a 30-m filled-aperture segmented primary mirror and will include non-sidereal rate tracking capabilities for observing Solar System objects. Its sensitivity will be 14 times larger than that of 8-m class telescopes for seeing-limited observations -up to 200 times larger for background limited adaptive optics (AO) observations- and will allow high angular/spatial resolution with diffraction-limited capability in the near infrared. AO guiding will accommodate faint, small angular size solar system objects to serve as natural guide stars for non-sidereal observations. For Kuiper belt objects (KBOs), on-instrument wavefront sensors can crawl the field-of-view to look for background natural stars that can be used for tip/tilt correction. Here, we describe the main characteristics of the Thirty Meter Telescope, its first light instrumentation suite, and the most relevant science-driven requirements for its design, emphasizing the strengths of the TMT for Solar System astronomical research. Some real-case scenarios of sensitivities for solar system, for the first-light instruments, are presented.

The Thirty Meter Telescope: Main Parameters



Main Parameters
Ritchey-Chrétien optical design
M1: 30 m hyperboloidal f/1
M1 made of 492 hexagonal segments
M2: 3.1 m hyperboloidal
M3: Flat 2.5m x 3.5m
Field Of View 20 arcmin
Final Focal Ratio f/15
Masmyth platforms for science instruments
First Light Instrumentation Wavelength Coverage
Visible (0.4 mm – 0.8 mm) NIR (1.0 mm– 2.5 mm)
Location
Maunakea ϕ=19°49'58.8" N λ=155°28'51.6" W 4050 m.a.s.l.

TMT First Light Instruments

The TMT has been designed to include seeing limited and diffraction limited instruments. Astronomical observations in the J, H, K and I band will be assisted by a Multiconjugate Adaptive Optics System (MAOS) dubbed the Narrow Field Infra-Red Adaptive Optics System (**NFIRAOS**). At first light, NFIRAOS will feed two instruments: The **Infra-Red Imaging Spectrograph** (**IRIS**) and the **Infra-Red Multi-object Spectrograph** (**IRMS**).

NFIRAOS Specifications

For minimizing noise, arising from warm optical surfaces, NFIRAOS has been designed to operate at -30 °C. Includes a 60x60 sub-apertures wavefront compensation, assisted by 6 laser guide stars and 2 deformable mirrors conjugated to the surface level turbulence and to the 11.8 km altitude turbulence, respectively.

Technical Requirements

Deformable Mirrors	**63x63** and **76x76** actuators at 5 mm spacing, 10 mm stroke and 5% hysteresis at -30 °C
Tip/Tilt stage	500 μrad stroke with 0.05 μrad noise, 20 Hz bandwidth
NGS WFS detectors	240x240 pixels ~0.8 QE, 3 e^- noise at 10-800 Hz
LGS WFS detectors	60x60 sub-apertures with 6x6 to 6x15 pixels each ~0.9 QE, 3 e^- noise at 10-200 Hz
Low order IR NGS WFS detectors	1024x1024 pixels ~0.8 QE, 3 e^- noise at 10-200 Hz
Real time controller	Sove 35x x 7k reconstruction problem at 800 Hz
Sodium guidestar lasers	25W, M^2=1.17, coupling efficiency of 130 ph/s/W/sr/(atom/m^2)

85% throughput in J, H, K and I bands
Thermal emission < 15% of sky + telescope
Maximum wavefront errors 187 nm at bore-sight 191 nm over a 10 arcsecs FOV 208 nm over a 30 arcsecs FOV
High sky coverage with 50% at the galactic pole
2% photometry accuracy over a 30 arcsecs FOV at l=1 um for a 10 min observation
50 mas astrometry accuracy over a 30 arcsecs FOV in H band for a 100 s observation

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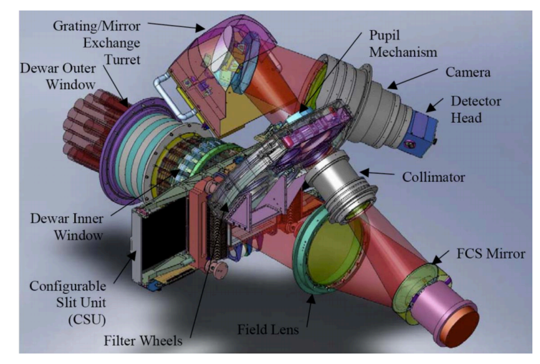
IRMS



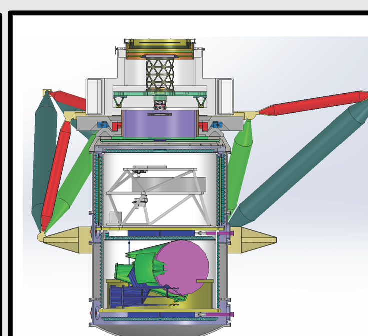
Filters	Y, J, H, K
Field of View	2.27' x 2.27' (imaging) 2.00' x 0.60' (spectroscopy)
Spatial Scale	60 mas/pix (18 μm/pix)
Spectral Resolution	R ~ 3000 - 4000
Slit Width / Length	0.16" (minimum) / 2.5"
Wavelength Coverage	**0.9 – 2.5 μm**
Detector	2048x2048 H2RH and ASIC
Multi-Object capability	Cryogenic configurable slit unit, 0.16" up to 46 slits
5 hr exposure, S/N limiting magnitudes	24.25 (J band) 25.35 (K Band)

The IRMS design is closely based on the MOSFIRE instrument used at Keck Observatory. This instrument is fed by NFIRAOS and therefore exploits the diffraction limited capabilities of TMT.

IRMS Predicted Sensitivities

Passband μm	Spec. Sky Brightness (mag arcsec^{-2}) Vega (AB)	Vega (AB) mag for SNR = 10 in 1000 s R=3270 with 0.23" slit	Line Flux for SNR=10 (unresolved line) in 1000 , R=3270 ergs s^{-1} cm^{-2}
Y (0.97–1.13)	17.3 (17.9)	23.4 (24.0)	7.0x10^{-19}
J (1.15–1.35)	16.8 (17.7)	23.0 (23.9)	7.4x10^{-19}
H (1.48–1.80)	16.6 (18.0)	22.7 (24.1)	4.7x10^{-19}
K (1.95–2.40)	14.4 (16.3)	21.2 (23.1)	8.5x10^{-19}

IRIS



This is a diffraction limited integral field spectrograph and imager fed by the adaptive optics system NFIRAOS. coverage from **0.84 μm to 2.4 μm** in wavelength.

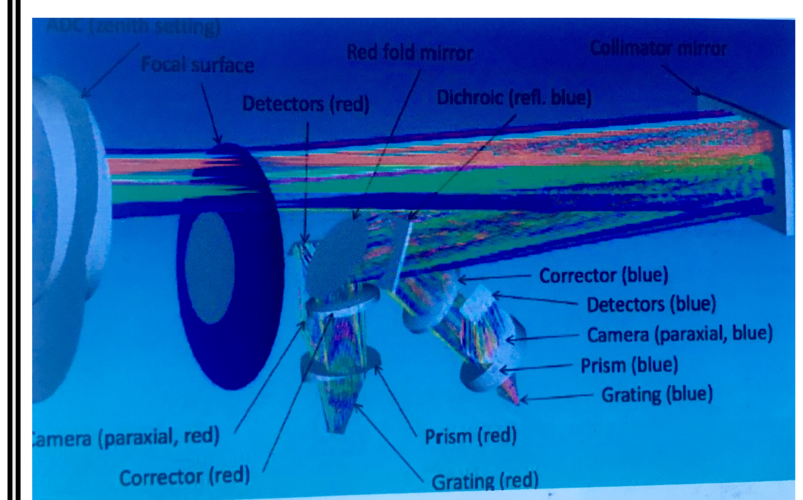
Mode	Spatial Sampling (mas)	FoV arcsec	Res. ($\lambda/\delta\lambda$)	Bandpass
Imager	4	16.4x16.4		37 filters Various bandpass
Slicer IFS 88x45 Spaxels	50 25	4.4x2.25 2.2x1.125	4000-8000 4000-8000	20%,10% 20%,10%
Lenslet IFS 112x128 Spaxels	9 4	1.01x1.15 0.45x0.51	4000 4000	5% 5%
Lenslet IFS 16x128 Spaxels	9 4	0.144x1.15 0.064x0.51	8000-10000 8000-10000	20%20%

Performance Category	Value	Comment
Expected Strehl ration for greater than 50% of sky	J band → 0.41 H band → 0.60 K band → 0.75	For on-axis object.
Astrometry accuracy	Relative precision 10 μas, relative accuracy 30 μas, absolute accuracy: 2-4 mas.	Relies on multiple visits to a particular field and a variety of reference fields.
Limiting magnitude (imager) *AB Magnitudes*	J band → 27.8 H band → 27.3 K band → 26.9	Point source sensitivity, S/N=100 2λ/D aperture.
Limiting magnitude (spectrograph) *AB Magnitudes*	J band → 25.8 H band → 26.9 K band → 25.2	For 4 mas pixel scale, 5hr integration, S/N=10, 2λ/D aperture.

WFOS

This is a seeing-limited instrument that covers the spectral range from **0.31 μm to 1.1 μm** using separate red and blue color channels. Provides three spectral resolution modes (R=1000, R=5000 and R=8000) with multiplexing factors up to 200 objects over a 25 arcmin^2 field.

Description	Requirement
Wavelength	0. 31 μm to 1.0 μm
Image quality (imaging)	≤ 0.2 arcsec FWHM in each band
Image quality (spectroscopy)	≤ 0.2 arcsec FWHM at all wavelengths
Field of view	≥ 500 arcsec total
Spatial sampling	< 0.15 "/pixel, goal < 0.10 "/pixel
Spectral resolution	R=500-5000 w 0.75" slit, R=150-7500 (goal)
Throughput	≥ 30% from 0. 31 μm to 1.0 μm
Sensitivity	Shot noise limited for > 60 s
Wavelength stability	Flexure < 0.15 arcsec at detector

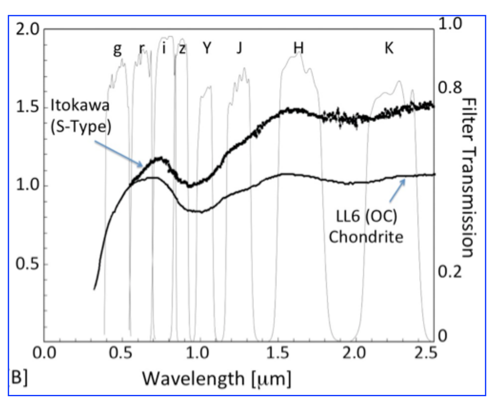


An Exposure Time Calculator (in development), for the Early Science TMT instruments is available at:

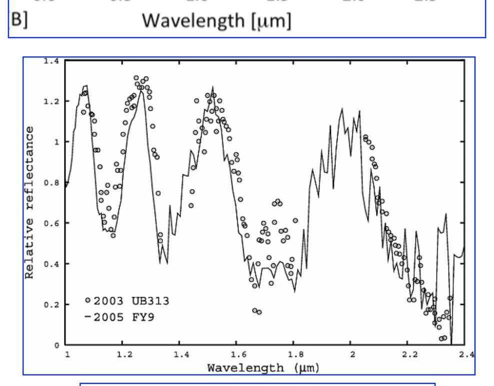
http://tmt.mtk.nao.ac.jp/ETC-e.html

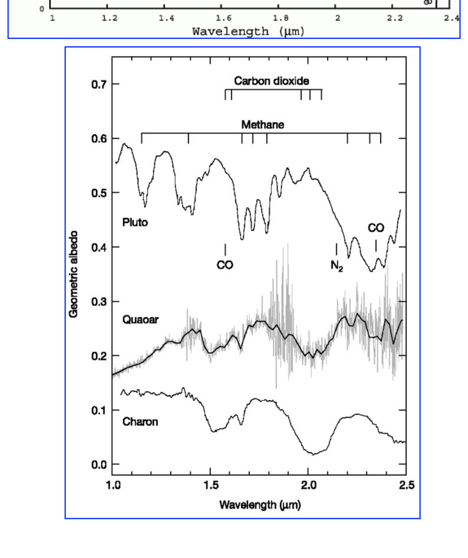
Examples of Solar System Science Cases

- ***Observation of long-period orbit comets, study of their composition to help constrain dynamic models of planet migration***: Some models predict no planet migration, consequently the spectral type of comets in the Oort cloud shall exhibit no S-type spectral characteristics, while other models predict from 0.1% to 4% S-type material. The characterization of the surface composition of a large enough statistical sample would be required to provide support information to distinguish between dynamical models of planet formation and migration. Specifically, it will be required to tell apart between C, D and S type of surfaces, where C is characterized by a flat spectrum with a UV downturn, D is a flat and very red, while S has a steep drop in the UV range with a broad 0.9 μm absorption feature that can be between 5% to 20% deep (*see example for the Itokawa comet*). For statistical confidence, it will be ideally required to achieve a S/N of 50 for photometry in the various visible (g, r, i, z, Y) and near infrared (J, H, K) bands to fully characterized the population of long orbital period comets. The magnitude of for most of this objects are within 21-24. ***Assuming a flat spectrum, in order to achieve a S/N of 50 in a 8-m class telescope it would be required about 14 observing nights, this can be done with a mere 2 observing nights in a facility like TMT combining observations of WFOS and IRIS for observation of 100 targets down to magnitude 24***.

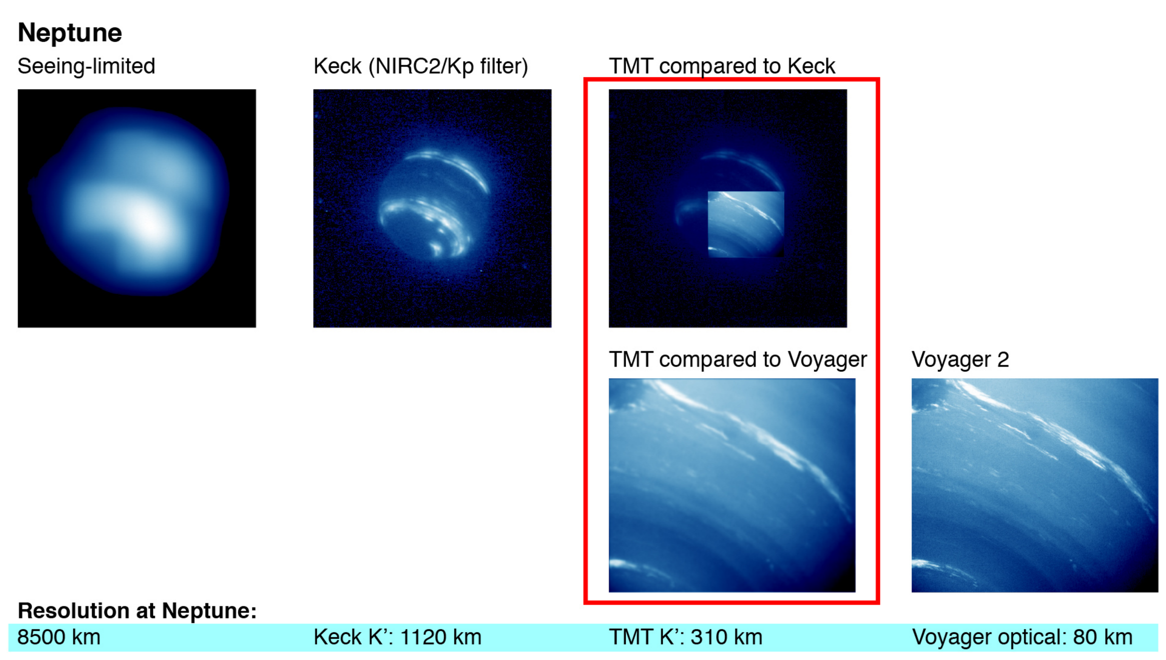


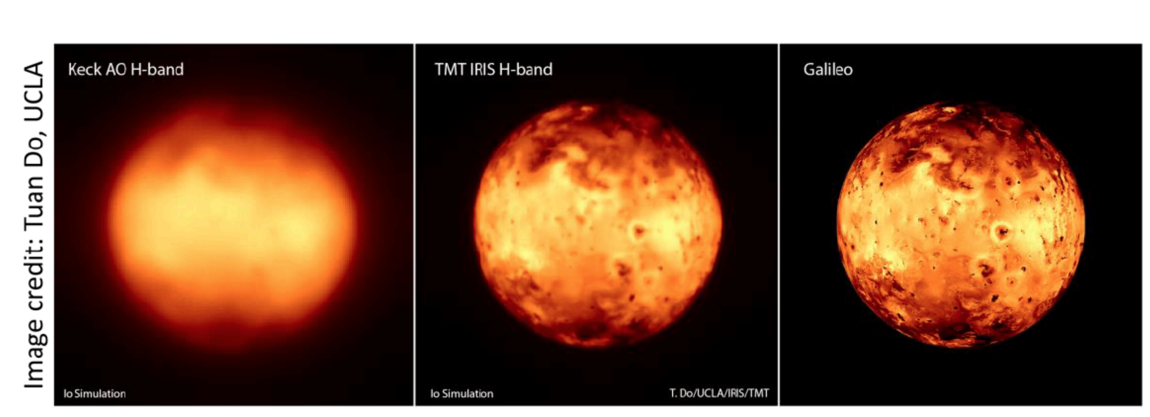
- ***Characterization of Trans-Neptunian Objects (TNOs)***: Out of over ~1500 TNOs known only 100 have been characterized – because they get too faint for 8-10 m class telescopes. Getting visible plus NIR spectra, particularly NIR to look for ice signatures, will allow these data set better constraints for solar system formation models. See the examples of the very brightest TNOs – Quaoar (*Jewitt & Luu, 2004, Nature*), and for comparison the spectra for 2003-UB313 and 2005-FY9 (*Licandro et al., 2006 A&A*).





- ***Diffraction limited observation of Solar System objects***: (**Neptune**) TMT's AO-assisted, diffraction-limited resolution will approach spacecraft-quality imaging for our most distant planet. Voyager optical data, blurred to match the resolution of TMT at K' (outlined in red), is overlaid on the Keck image for comparison. Cloud bands do not align because viewing geometries of the Keck and Voyager images are different. Keck data are from Fitzpatrick et al. (2014); Voyager data are from Smith et al. (1989). (**Jupiter and its natural satellites**) Similarly, spatial resolutions of 18 km (H band, at 1 μm) can be achieve at the distance of Jupiter allowing better characterization of atmospheric circulation and other processes. See example of TMT simulation of Io compared to image obtained by Galileo spacecraft in 1996.





Comparison of simulated H-band adaptive-optics (AO) corrected images of Io (raw-image equivalent, no deconvolution applied) for the 10m-Keck (left) and 30m-TMT (center). The original image (right) was obtained in September of 1996 by the Galileo spacecraft while it was at a distance of ~500,000km from Jupiter's satellite. The exposure time for the TMT (IRIS instrument + AO) simulated image (4 milli-arcsecond/pixel) is equivalent to 1 second. The finest spatial details in the TMT image are about 30km in size, to be compared to 10km for Galileo's.