CATAC Report on TMT Instrumentation after first light

Draft for comment, April 15, 2019

Authors: CATAC (Michael Balogh, Laura Ferrarese, Stefi Baum, Kristine Spekkens, David Lafrenière, Harvey Richer, Bob Abraham, Luc Simard, Don Brooks, Rob Thacker, Kim Venn, Stan Metchev, Tim Davidge, Greg Fahlman)

Purpose

Instrumentation for large telescopes takes a long time to develop, with the typical time between start of conceptual design to first light being 7-10 years. Work must start now if TMT is to realize its goal of introducing a new capability every two years after first light, and to remain competitive with ELT. The US community has begun to organize around this, and is preparing an NSF proposal to help fund design studies for several compelling capabilities. It is important that we in Canada give careful consideration to our own priorities so these can be clearly communicated to the SAC. US planning, for example, is being done in the context of possible access to both TMT and GMT. Canadians and other partners will not have GMT access, except through collaboration.

In this document we present a summary of the different capabilities that have been considered for TMT. These are discussed within the context of Canadian science interests and instrument building capabilities as they are today. Based on this information and the premise that early light capabilities should have an emphasis on workhorse instruments that increase the parameter space TMT can explore, we suggest a prioritization and phasing of these capabilities, as a starting point for broader discussion within the Canadian community. As well as considering these priorities we welcome ideas for innovative capabilities that are perhaps not reflected in these instrument concepts, most of which have been around for more than a decade already.

Following community consultation we will deliver our recommended prioritization to CASCA and ACURA.

Background

Instrumentation planning for the TMT

The Science Requirements Document (SRD) for the Thirty Meter Telescope (TMT) describes proposed capabilities (instruments and facility systems) divided into “Early Light” and “First Decade”. Beyond first light (expected in 2028), a new capability should be deployed every two years. Thus, there are no instrument “generations” as such, but rather a constantly evolving instrumentation suite, and the observatory design has been developed accordingly. The instrumentation budget is expected to enable funding of early concept studies, to help teams compete for construction funding from sources outside the TMT. Table 1 maps concepts in the SRD to the current status and instrument name, with first light instruments in bold.

Table 1: A summary of instrument capabilities considered for TMT, matched with the instrument concept name from the Science Requirements Document and any changes as of today. Instruments in boldface are first light capabilities.

Instrument Concept	**SRD**	**2018**
Near-IR Multi-conjugate AO system	NFIRAOS	NFIRAOS
Diffraction-limited IR imager and R=4000 integral field spectroscopy	**IRIS**	**IRIS** Final design stage
Seeing-limited multiplexed 1000<R<6000 optical spectroscopy over a wide (40 sq. arcmin field)	**WFOS**	**WFOS** - Xchange 25 sq. arcmin
NIR AO-assisted imaging slit spectrometer, 3000<R<5000	**IRMS**	IRMS No longer a first light capability
Multiple NIR IFU operating near the diffraction limit	IRMOS	IRMOS
Diffraction limited, high resolution mid-infrared imaging and spectroscopy	MIRES	bMICHI
Very high contrast imaging and low resolution spectroscopy	PFI	PSI
Diffraction-limited, high resolution NIR spectroscopy	NIRES	NIRES-B (1-2.5μm) MODHIS
High-resolution optical spectroscopy	HROS	HROS
Diffraction limited NIR imaging over a >30arcsec contiguous field	WIRC	

As this table shows, TMT is currently planning to have two instruments commissioned at first light in 2028 (highlighted in **boldface**). One is IRIS, a near-infrared, AO-assisted imager with an integral field spectrograph. IRIS passed its Preliminary Design Review in late 2017 and is now in the Final Design stage. The other instrument is the Wide-Field Optical Spectrograph (WFOS), about which CATAC has previously commented. The approved Xchange design has a smaller field of view than originally planned, but maintains the sensitivity and flexibility in resolution and multiplexing that has proven to be successful for similar instruments on other telescopes (e.g. GMOS). Capabilities of WIRC as described in the SRD are largely met by the current IRIS design.

Prioritizing and phasing instrumentation after first light

The TMT Science Advisory Committee (SAC) last presented a preferred phasing of capabilities in March 2011. At that time, the infrared multiobject spectrometer (IRMS) was expected to be a first light instrument, along with IRIS and WFOS. Its status was re-evaluated because it did not exploit the telescope diffraction limit, and was based on decade-old technology and design that require updating. High-resolution optical (HROS) and near-infrared (NIRES-B) spectroscopic capabilities were to follow as the fourth and fifth instruments, respectively.

In early 2018 the SAC solicited, reviewed and ranked white papers from the TMT community. These rankings have not been made public, but the concepts under consideration are available at https://www.tmt.org/page/second-generation-instruments. This list represents a mild evolution of the original descriptions in the SRD.

Both the TMT and GMT are short of funds, and this affects the abilities of the projects to start work on the capabilities that must be developed to realise their science potential. To address this, a proposal is being prepared within the US community to request $USD 50 million from the NSF. These funds would be administered by NOAO, and directed to US universities to develop instrumentation and facility components for both the TMT and GMT.

Expanding parameter space to enable discovery science

The first decade of a new facility operation is ripe for making new discoveries. Science cases being developed now are necessary to guide the design, but many of the most exciting results are likely to be entirely unanticipated. To maximize this discovery potential, it is important to develop an instrument suite that probes a wide range of new parameter space. A diverse suite of flexible, workhorse instruments is best suited to achieve this. At the same time, there must be an opportunity for niche instruments that have the potential for exceptionally high scientific impact.

Figure 1 provides an overview of how the various instrument concepts under consideration now compare, in the parameter space of spectral resolution, wavelength and spatial resolution. In particular it illustrates the extent to which new capabilities complement the first light instruments IRIS and WFOS. We note that the parameter space of high spectral and spatial resolution best exploits the advantages of a 30-m class telescope.

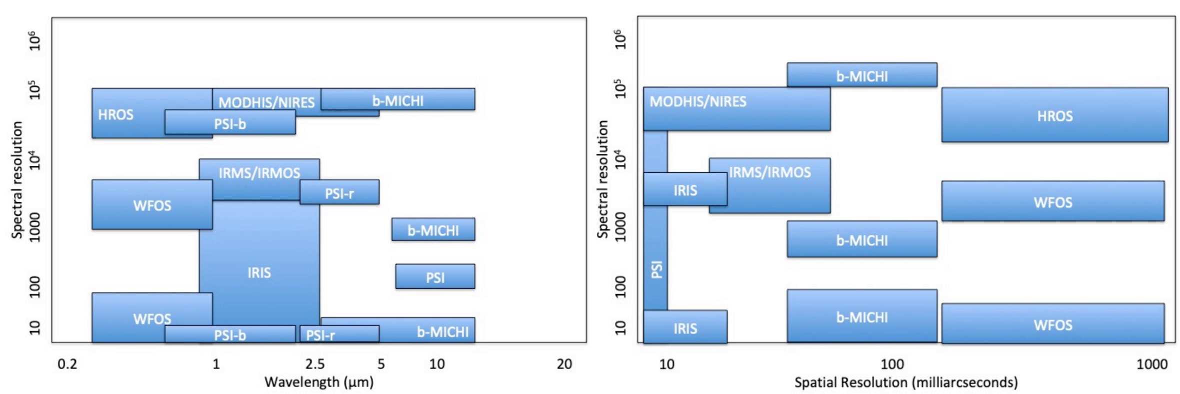


Figure 1: First light (WFOS and IRIS) and subsequent capabilities as a function of wavelength coverage, spectral resolution and spatial resolution.

Rapid response for follow-up of time variable phenomena is important for many science cases. TMT has a requirement (REQ-0-SRD-0315) to be able to begin observing with any instrument, at night, in less than ten minutes. Acquisition time without an instrument change is required to be less than 5 minutes. This makes TMT the only agile extremely large telescope, well-suited for rapid response, targets of opportunity, and time-variable science. Instruments that can take advantage of this are poised to have a big impact in the largely unexplored field of transient phenomena that vary on timescales of less than a day, in a way that cannot be matched by GMT or ELT.

Instrumentation on ELT and GMT

It is necessary to also consider the instrumentation planning of the other large telescopes: the Giant Magellan Telescope (GMT) and the European Extremely Large Telescope (ELT). The ELT instrumentation roadmap is summarized in Figure 2. From this Table it is clear that ELT is already close to starting construction of its post-first light capabilities.

Year	ELT- IFU HARMONI +LTAO	ELT-CAM MAORY+ MICADO	ELT-MIR METIS	ELT-MOS MOSAIC	ELT-HIRES HIRES	ELT-6	ELT-PCS
2014	Decide science requirements, AO architecture.		VISIR start on-sky	Develop science requirements for MOS/HIRES			Start ETD
2015				Call for Proposals			
2016				Start Phase A			
2017						Call for proposals	
2018				Phase A reviews Finalise agreements			
2019				Start Construction Phase			
2020						Selection	Start Phase A
2021							
2022							
2023							
2024							

(grey)	Pre-studies taking the form of phase A or delta-phase A work and/or ESO-funded Enabling Technology Development (ETD)
(orange)	Decision point
(green)	Development of Technical Specifications, Statement of Work, Agreement, Instrument Start.

Figure 2: The ELT instrumentation roadmap, from Ramsay et al. (2018)

The GMT is currently planning two first light instruments - a wide field, optical MOS (GMACS) and a high resolution optical spectrometer (G-CLEF). This will be followed shortly by a near-IR AO-assisted imager and IFU (GMTIFS) and echelle spectrometer (GMTNIRS). Table 2 matches capabilities to the relevant instrument design on each telescope.

Table 2: Instrument comparisons across the three extremely large telescopes. First light instruments are in boldface.

<table>
<tr><th>Type of Instrument</th><th>GMT</th><th>TMT</th><th>E-ELT</th></tr>
<tr><td>Near-IR, AO-assisted Imager + IFU</td><td>GMTIFS</td><td>IRIS</td><td>HARMONI</td></tr>
<tr><td>Wide-Field, Optical Multi-Object Spectrometer</td><td>GMACS</td><td>WFOS</td><td rowspan="2">MOSAIC</td></tr>
<tr><td>Deployable, Multi-IFU Imaging Spectrometer</td><td></td><td>IRMOS</td></tr>
<tr><td>Near-IR Multislit Spectrometer</td><td>NIRMOS</td><td>IRMS</td><td></td></tr>
<tr><td>Mid-IR, AO-assisted Echelle Spectrometer</td><td></td><td>bMICHI</td><td>METIS</td></tr>
<tr><td>High-contrast exoplanet imager</td><td>TIGER</td><td>PSI</td><td>EPICS</td></tr>
<tr><td>Near-IR, AO-assisted Echelle Spectrometer</td><td>GMTNIRS</td><td>NIRES-B
MODHIS</td><td rowspan="2">HIRES</td></tr>
<tr><td>High-resolution Optical Spectrometer</td><td>G-CLEF</td><td>HROS</td></tr>
<tr><td>Wide-field AO Imager</td><td></td><td>WIRC</td><td>MICADO</td></tr>
</table>

Summary of TMT Instrument Concepts

High resolution optical spectroscopy

High-resolution spectroscopy at optical wavelengths is an essential capability for a very large telescope. The overarching science motivation is clear: photon starvation limits the sample of stars that can be observed on smaller aperture telescopes, and it is only by placing high-resolution spectrographs on larger telescopes that sample sizes can grow.

There is a wide range of broad science applications for HROS, which place it in the category of `workhorse instrument'. A high-level (but by no means exhaustive) list of science applications includes:

- the origin of the elements (e.g. measuring the chemical contents of extremely metal-poor stars)
- the chemical evolution of the Galaxy and members of the Local Group (e.g. surveys of the chemical contents of stars in the Milky-Way and nearby galaxies that span a range of metallicities, ages, and environments; radionuclide dating of stars).

- exoplanet detection and characterization (e.g. radial velocity surveys of stars and circumstellar disks; possible searches for biosignatures)
- the composition and evolution of the IGM and ISM (e.g. QSO absorption line studies)

There is also a pragmatic operational consideration: high-resolution spectrographs can be used efficiently during suboptimal observing conditions, such as in mediocre seeing and during episodes of light cloud cover.

Science Specifications

Key science specifications from the Science Requirements Document are listed in the Table below:

Wavelength range	0.31μm-1.1μm (goal 0.31μm-1.3μm)
Field of view	>10" (acquisition/slit viewing camera)
Spectral resolution	R=50,000 (1" slit) R≥90,000 (image slicer)
Throughput	Must maintain 30m aperture advantage. >20% from telescope focal plane to detected photons.

The instrument concept proposed for further study in the recent call for white papers additionally has multiplex capability (≤ 100), and extends the spectral resolution range from R=25,000 to R=100,000. In addition, the TMT SAC has specified that the instrument should have long-term stability sufficient to achieve radial velocity measurement repeatability and accuracy of 1 m/sec over time spans of 10 years.

Early design work suggests that with a 6 hour exposure it should be possible to achieve a S/N = 100 at a resolution of 100000 for a source with V=19.

While the specifications listed above make reference to slits, it is understood that there is a strong case for a fibre feed. In addition to the benefits of fibres for single-object spectroscopy, a fibre feed has the potential to enable multi-object work. It was suggested in one early design study that HROS could serve as a facility fibre feed for other TMT capabilities. For work at short wavelengths it might prove desirable to use a naked slit, or an optimized slicer, but this will require further investigation.

Other considerations

- The GMT is planning a first light instrument of comparable capability, G-CLEF. US planning is naturally considering complementarity of GMT and TMT instrumentation, and this could lead to some difference in priorities compared with partners, like Canada, that do not have access to GMT.
- India and China are currently working together on HROS design (see https://www.tmt.org/news/370). In addition to our scientific interest in high-resolution spectroscopy, Canadians may be well placed to contribute to the instrument development given our work on the Gemini GHOST instrument and GRACES fibre facility (Chene et al. 2014).
- Polarimetry may prove challenging to implement on TMT HROS, given the Nasmyth platform feed optics (Atwood et al. 2014; Anche et al. 2018). Still, there are options that are being (or have been) deployed on other Nasmyth-based spectrographs (e.g. on the VLT), such as the use of a retarding plate to compensate for rotation of optics in the light feed.

Multiobject NIR spectroscopy

A near-IR AO-fed multiobject spectrograph is another workhorse instrument that can address a wide range of science cases including topics in galaxy formation, AGN evolution, early universe and stellar populations. In particular, the high spatial resolution, combined with moderate spectral resolution, is ideal for finding and characterizing distant galaxies and AGN. In this way it addresses much of the same science as IRIS spectroscopy, but with a multiplex advantage that is ideal for IGM tomography, galaxies and AGN in protoclusters and other dense environments, and surveys of high redshift galaxies, among many other things.

The TMT SRD describes two concepts:

- IRMS, a multi-slit imaging spectrometer operating behind NFIRAOS at 3000<R<5000 over a contiguous field of view of 2' with >40 slits. It uses a cryogenic slit unit that allows slits to be configured "on-the-fly", over the full field of view.
- IRMOS, a near-diffraction limited IFU-based spectrometer, operating at 2000<R<10000. It would deploy multiple IFUs and have its own MOAO system. It combines the multiobject capability of IRMS with the diagnostic power of IRIS.

Both designs address similar science cases and more study is needed to establish if one is more scientifically compelling than the other.

Science Specifications

The IRMS concept is envisioned as a MOSFIRE clone, and takes advantage of NFIRAOS to provide substantial AO correction over the full 2' field. Initially considered a first light capability, it was seen as a relatively quick and easy way to achieve MOS in the NIR, with a generally more capable multi-IFU design to follow later. However, it turned out to be more complicated and expensive than expected.

The current requirements for IRMOS includes at least ten deployable IFUs (SRD-1325), with a 2' addressable FoV (goal of 5', SRD-1305). The GIRMOS instrument being built for Gemini (PI Sivanandam) provides a clear and natural path to a NFIRAOS-fed IRMOS. The multiplexing ability of this design is limited at this point by its cost. The Detailed Science Case for TMT (Skidmore et al. 2015) is developed around a 20-unit design, but more study is needed to determine the source target density and, hence, the most cost-effective multiplex.

	IRMS	**IRMOS**
Wavelength range	0.95μm-2.45	0.8μm-2.5
Field of view	2.05'x2.05' square	IFU heads deployable over >2' (5' goal) diameter field, with each IFU head covering 3"x3".
Spectral resolution	R=3270 with 3 pixel slit (0.24")	2000<R<10000
Wavelength coverage	All of Y, J, H or K for slits placed at the centre of the field	Complete atmospheric band covered in single exposure at R=4000
Multiplex	46 adjustable cryogenic slits with total slit length of up to 120"	At least ten IFU units
Spatial sampling	0.060 arcsec/pixel (spatial) 0.08 arcsec/pixel (dispersion)	0.05x0.05"
Imaging	Entire NFIRAOS 2' FOV with 0.06" sampling	N/A
Throughput	>40% (imaging); >30% (on order blaze)	>30%

Other considerations

- The development of GIRMOS now possibly makes the IRMOS design less risky than IRMS, eliminating one of the main advantages of the slit-based design. More study is needed to determine if there are science drivers for a multi-slit instrument that cannot be achieved with an IFU.
- The higher resolution modes improve detection limits for narrow emission and absorption lines relative to JWST, which is limited to R=2700 (NIRSPEC).
- As IRMOS/IRMS largely extends the capability of IRIS by increasing the multiplex ability, it may be less urgent than other instruments that open up truly new parameter space shortly after first light.

Planetary Systems Imager

The Planetary Systems Imager (PSI) is a platform that would endow TMT with the key capabilities of high accuracy wave front control (advanced adaptive optics – AO) and efficient starlight suppression, enabling the direct analysis of light from very faint sources in the close vicinity of a much brighter one, i.e., high-contrast imaging and spectroscopy. This is a core capability for a 30-m class telescope, and has driven many of the requirements and designs for TMT including the top-end, the coating of the primary mirror segments, the cleaning of these segments, the choice of segment actuators, the primary mirror segment surface accuracy and quality, and many others.

PSI is expected to achieve contrasts of ~10^8 at separations as small as 1-2 λ/D. This gives it an enormous advantage over JWST, as it enables sensitive measurements at separations that are well within the JWST resolution limit (e.g. 0.06" at 2μm for NIRCAM), and where observations are limited by host star brightness and not the sky background. Various instruments, tailored to the desired measurements, can be installed behind this core AO/starlight suppression capability. The PSI architecture is entirely modular, for flexibility and versatility, and any subsystems can be replaced or upgraded easily. Accordingly, the instrument could be implemented sequentially, starting with only a few subsystems and adding new ones as funding or technology permits.

As currently planned, the PSI front-end would feature two channels, a blue (0.6-1.8 μm) and a red (2-5 μm), each one having its own wave front sensor and deformable mirror for AO, and its own coronagraph module for starlight suppression. There may also be a port for a 10 μm channel. The science back-end of the blue channel would have an imager with integral field spectroscopy functionalities (R~50) and a polarimetry module, as well as a separate fibber-fed high-resolution spectrograph (R~10^5). The red channel would have an imager with integral field spectroscopy functionalities (R~50-5000), as well as a separate fibber-fed high-resolution spectrograph (R~10^5). The science back-end instruments can deliver further contrast gains beyond what is achieved by the extreme AO+coronagraph front-end, for example using correlation techniques with high dispersion spectroscopy or high frequency temporal modulation matched with wave front evolution.

The main science case of PSI is to find and study exoplanets. In this area, among other things, PSI can do the following:

- Discover and characterize the atmosphere of sub-Neptunes to Jupiter-like planets at 0.5-5 AU separations, where we know that they are abundant from radial velocity surveys;
- Measure the composition and other properties of the atmosphere of planets that are cooler/ smaller and/or around earlier-type hosts than those accessible through transit spectroscopy;
- Measure planet rotation periods and, through Doppler imaging, measure the distribution of their surface features;

- Directly detect mature, RV-detected planets in *reflected light* in the innermost regions of nearby M-dwarfs, as well as in thermal emission around earlier-type stars;
- Detect biosignatures in the atmosphere of habitable rocky planets around nearby M dwarfs;
- Image the inner regions of disks in planetary systems at scales of ≤1 AU, from the proto-planetary to the debris stages.

By providing diffraction-limited imaging with high contrast, spectroscopy with a wide range of resolutions, and high sensitivity in the near- and mid-infrared, PSI can pursue a lot of other science as well, including:

- Solar system: volcanism on Io, organics in comets, asteroid multiplicity, atmosphere of solar system planets;
- Galactic: stellar multiplicity, close circumstellar environment of evolved stars, chemistry of protoplanetary disks; image flows in interacting binaries, precise astrometric monitoring of compact objects in binaries;
- Extra-galactic: inner regions of quasar-host galaxies, spatially resolved spectroscopy of nearby galaxies.

Science Specifications

Many of the specifications for PSI remain to be firmly established. The purpose of early NSF funding would be to do an end-to-end optical design of all variants to establish these. The table below shows nominal specifications for PSI-red and –blue as they stand today. There is also a possibility for a 10μm arm, not listed here.

	PSI-red	**PSI-blue**
Wavelength range	2.0μm-5.3 μm	0.6μm-1.8 μm
Field of view	TBD	
Spectral resolution	50<R<5000 IFS R=100k fibre fed spectrograph	R=50 IFS R=100k fibre-fed spectrograph
Wavelength coverage	All of K, L and M	VRIYJH
Spatial sampling	<0.0065” (better than critically sampled at 2μm)	<0.002” (better than critically sampled at 0.6μm)
Contrast (with coronagraph)	10^5 raw and 10^9 processed at inner working angle (1-2 λ/D)	
Polarization	Yes	Yes

Other considerations

- A report issued by the (US) National Academic of Science Engineering and Medicine (2018) made an important recommendation that exoplanet instrumentation should be a priority.
- A proposal was submitted to NSF earlier this year by members of the US community. If successful, design work on PSI could start this year.
- Canadians have relevant experience with the successful GPI instrument on Gemini (e.g. Marois et al. 2008, 2014, Thibault et al. 2011, Pazder et al. 2012, Draper et al. 2014), and could make important contributions to the development of PSI.

High resolution, diffraction limited NIR spectroscopy

This capability is provided by two concepts: the “original” NIRES concept found in the Science Requirements Document, and a more recent design called MODHIS. The latter is designed specifically around obtaining precise radial velocity measurements for exoplanets. However, both instruments have science cases that extend well beyond exoplanets. For example, with TMT's rapid response capability they are ideal for following up high redshift transients. This is an important advantage over similar instruments on other ELTs.

MODHIS and the blue arm of NIRES, called NIRES-B, are designed to work behind NFIRAOS, giving them a compact and comparatively economical design. NIRES-B is a scientific descendent of Keck/NIRSPEC, VLT/CRIRES and now NIRPS, being built for the ESO 3.6m (PI René Doyon, UdeM). Interest has been expressed in extending the wavelength coverage of MODHIS to sample 2.5 – 5um, matching the full coverage of NIRES. For both instruments, this would require a different system than NFIRAOS, as the NFIRAOS optics limit it to wavelengths shortward of 2.5um.

The main distinction between the two designs is that MODHIS is fibre fed with a multiplex capability of 25, while NIRES is single-slit. MODHIS has a requirement to achieve a 30cm/s velocimetry precision, which makes it ideal for studying exoplanets.

Key science cases for this capability include:

- velocimetry of exoplanets
- masses, orbital alignment and atmospheric composition and structure of transiting planets
- velocimetry of circumstellar gas disks, and spatial mapping of their kinematic structures
- surface mapping of exoplanets and brown dwarfs
- surface chemistry of solar system objects
- stellar astrophysics of dense stellar environments: Galactic Centre, globular clusters, AGB stars and nuclear star clusters in nearby galaxies
- characterization of ultra-luminous IR transients in nearby galaxies
- spectro-astrometry of gas disks for the detection of supermassive black holes in AGN
- the history and process of reionization, through high S/N spectra of faint GRBs at z>7;
- together with HROS, determine the chemical evolution of dwarf galaxies, through detailed abundance analysis of stars below the tip of the red giant branch
- kinematic evolution of star clusters

Some of these cases will see science-enabling capabilities in MODHIS. In particular, high-dispersion, high-contrast characterization of directly imaged planets, or of planet-forming clumps in circumstellar disks would be uniquely enabled by MODHIS. In other cases—solar system body surface features, galactic and extragalactic (sub)stellar populations—the scientific gain comes primarily from the improvement in angular resolution and collecting area.

Science Specifications

	MODHIS	**NIRES**
Wavelength range	0.95μm-2.5 μm	1μm-5 μm
Wavelength coverage	All of Y, J, H or K for slits placed at the centre of the field	Simultaneous coverage 1.0μm-2.4μm or 3.5μm-5.0μm at R>20,000
Field of view	Patrol radius of 2" (goal 5") with mini-IFU FOV 0.1"x0.1"	10", acquisition camera sampled at 0.0035 arcsec/pixel
Spectral Resolution	R=100,000	R=50,000 (1.0μm-2.5μm); R=100,000 (3μm-5μm)
Spatial sampling	0.02" spatial sampling	0.004"

Multiplex	25	1 slit
Doppler velocimetry precision	30 cm/s	
Throughput	>10% end-to-end, including Strehl ratio considerations (expected >50% at JHK from NFIRAOS)	>20%

MODHIS will use a Fibre Injection Unit (FIU) that will be installed at the third port of NFIRAOS. To achieve maximum coupling efficiency, the spatial sampling has to match the diffraction limit exactly. The positioning of the fiber however has to be maintained to within 0.1 λ/D. A similar setup is being tested on Keck and Subaru. MODHIS will have integral field (IFU) and multi-objects (MOS) units. The integral field and multi-object capabilities will be provided by a fibre-connected micro-lens array and multi-mirror array, respectively. Due to the fundamental trade-off between resolution and number of science channels/fibers, MODHIS will be limited to a few objects at discrete locations in the focal plane.

Other considerations

- Since they operate at the diffraction limit, the physical size of these instruments is comparable to that of an instrument on a 10-m class telescope. Thus they are relatively inexpensive.
- MODHIS has a strongly motivated team, which is pushing to be ready at or shortly after first light. It is proceeding on a development track that is somewhat parallel to other TMT instrumentation, and it may become available for modest cost to the TMT project.
- The high spectral resolution of either instrument will complement IRIS spectroscopic capabilities (4,000 < R < 10,000).
- NIRES-B has significant (but not total) overlap in capability with MODHIS. Further study is needed to identify key science cases that can be done with one design but not the other.
- MODHIS is a precursor to the Planetary Systems Imager (PSI), and could in fact serve as the high-dispersion spectrograph in the blue arm of PSI.
- Canadian experience with NIRPS (e.g. Bouchy & Doyon 2018) makes us well positioned to contribute to the design and construction of either NIRES or MODHIS.

Mid infrared imaging and spectroscopy

bMICHI (Packham et al. 2018) is a mid-IR, AO-fed imager and integral field spectrometer operating at 3-14 μm. The instrument will be useful for studies of protoplanetary disks and AGN astrophysics, but likely the most compelling application is for the detailed characterization of exoplanets. Specifically, the high-resolution spectroscopy will enable detailed characterization of exoplanetary atmospheres, measuring strong water and methane absorption features, as well as CO, CO_2, and higher order hydrocarbons. Examples of some of the key science breakthroughs expected using this mode include (from Packham et al. 2018):

- Detection of the atmospheres of the nearest rocky exoplanets
- Detection of giant storms on the surfaces of widely-separated giant planets
- Atmospheric chemistry of exoplanets ranging in size from super-Earths to hot Jupiters.
- Measurements of the true masses of non-transiting super-Earths around nearby bright stars.

In imaging mode, the increase in angular resolution and sensitivity compared with existing telescopes will allow bMICHI to detect cool, Gyr-old Jovian planets orbiting nearby (d<10pc) stars. This represents a dramatic increase in the number of planets that can be detected and will overlap substantially with planets found using the radial velocity technique. In this respect it is complementary to PSI, which will mostly enable detection of rocky exoplanets in reflected (visible and NIR) light, around low-mass stars.

Science specifications

Wavelength range	3μm-14 μm
Field of view	24.4” (L&M) 28.8” (N)
Spectral Resolution	R=600 and 100,000 (long slit) R=1000 IFS in N-band (7.3μm-13.8 μm)
Spatial sampling	11.9 mas per pixel (L&M imaging) 27.4 mas per pixel (N-band imaging) 35.0 mas per spaxel (N-band IFS)
Polarimetry	R=600 (imaging and long slit)

Other considerations

- The high spatial and spectral resolution of bMICHI gives it a significant advantage over JWST for direct imaging and characterization of exoplanets.
- It is likely that some bMICHI observations can be conducted during the day.

Adaptive Secondary Mirror

An Adaptive Secondary Mirror (AM2) consists of a thin glass meniscus whose shape can be rapidly changed by a grid of actuators in order to compensate atmospheric turbulence. Smaller adaptive secondary mirrors are already employed at the MMT, VLT and LBT. The ELT will have a large adaptive mirror (AM4 not AM2) that will serve the same purpose. AM2 corrects low-order, high amplitude perturbations, which has an impact on all instruments (design and/or performance).

Among other things, AM2 enables ground-layer adaptive optics (GLAO). GLAO is a technology that compensates only turbulence close to the ground, ignoring high-altitude turbulence. This allows correction over a much larger field of view. The images are still blurred by the high-altitude turbulence, but there is nevertheless substantial improvement compared to natural seeing: at 1 micron, the FWHM of an image (50th percentile conditions) is reduced to 0.24” from 0.38”. A better metric to characterize the improvement is the normalized point source sensitivity (PSSN, Angeli et al. 2011). This is related to the PSF of a telescope, and is unity when there are no telescope errors and zero when the error is infinitely large. The aim at TMT is to make PSSN larger than 0.80. Employing a GLAO plus AM2 system at MK and using the 50th percentile conditions, we expect a ~30% gain in PSSN over seeing limited observations at 600 nm and 40% at 1 micron. Similar numbers for ORM are 20% and 30%. For a smaller field of view on MK (e.g. 4’ x 4’), the gain is improved by almost 80%. The expected 30% gain at 600 nm translates into a decrease in exposure time to reach a given signal to noise ratio of about 40% for direct imaging. At longer wavelengths of 2 microns, the improvement is about a factor of two.

AM2 may simplify other AO systems by providing them with a beam that is already partially corrected. This, in turn, may lead to significant cost savings in the design and construction of these systems. In this case AM2 will normally provide compensation for both the low and high altitude turbulence, but over a smaller field of view. In the mid infrared, AM2 may be all that is needed to achieve diffraction-limited images (e.g. with MICHI and PSI).

Unlike the highly-corrected images produced with NFIRAOS, that provide AO correction over no more than a 30” field, AM2 together with GLAO will yield AO-corrected images over a large field up to 8’ x 3’, but with lower correction. This will be a potentially important capability for optical (0.3 - 1 micron) wide field imaging and spectroscopy with WFOS.

There is a trade-off between the level of correction and the FOV. The science FOV for WFOS is 8’ x 3’, but simulations suggest that 6’ x 4’ is optimal for GLAO correction. Nevertheless, fields of this size can be corrected with AM2 plus a ground layer system.

Other considerations

- Ideally, the adaptive mirror should be conjugated to the strong ground-layer turbulence. With TMT, conjugation is at -280 m; that is, below the ground level. This makes for a slightly less than optimal system but is an unavoidable consequence of the optical design of the telescope (Ritchey-Chretien rather than Gregorian). The AO correction is provided by a 30 x 30 set of actuators driving AM2. Simulations suggest that no improvement is obtained for a larger number of actuators when using WFOS. This may seem surprising at first as the AM4 on the ELT has about 8000 actuators. However 30 x 30 is sufficient for TMT because of the AM2 misconjugation and the fact that we are correcting for the ground layer over a large field of view. So our choice of a Ritchey-Chretien telescope has actually made GLAO (with AM2) a somewhat more modest and less expensive system.
- The estimated cost of AM2 alone on TMT is comparable to that of a facility instrument. It does deliver cost savings directly (by simplifying the design of other AO systems) and indirectly, through more efficient use of telescope time.
- If AM2 were the only secondary mirror available at first light, it would severely complicate the commissioning of the telescope, as it is difficult or impossible to use it during the day.
- The presence of AM2 does not obviate the need for a classical M2, which would be required for backup, as the possibility exists that an AM2 could be broken during use because of the constant changing pressure of the actuators. The glass faceplate on an AM2 is very thin (~2 mm), and is extremely fragile. More than one has broken during manufacture or installation.

Other capabilities

The SRD describes a Wide-field Infrared Camera (WIRC), that would image a >30” field of view behind NFIRAOS. This capability is currently achieved by IRIS, which reaches a 34”x34” field. However NFIRAOS covers a much larger (2’ diameter) field, and an imager capable of capturing that full area would take full advantage of TMT’s astrometric capability, among other things.

A white paper submitted to the SAC describes ARISE, an instrument capable of rapid readout (10Hz full frame, 100 Hz windowed). It is capable of imaging, polarimetry and R>15000 spectroscopy over the full wavelength range 0.31-4.8μm.

Consultation

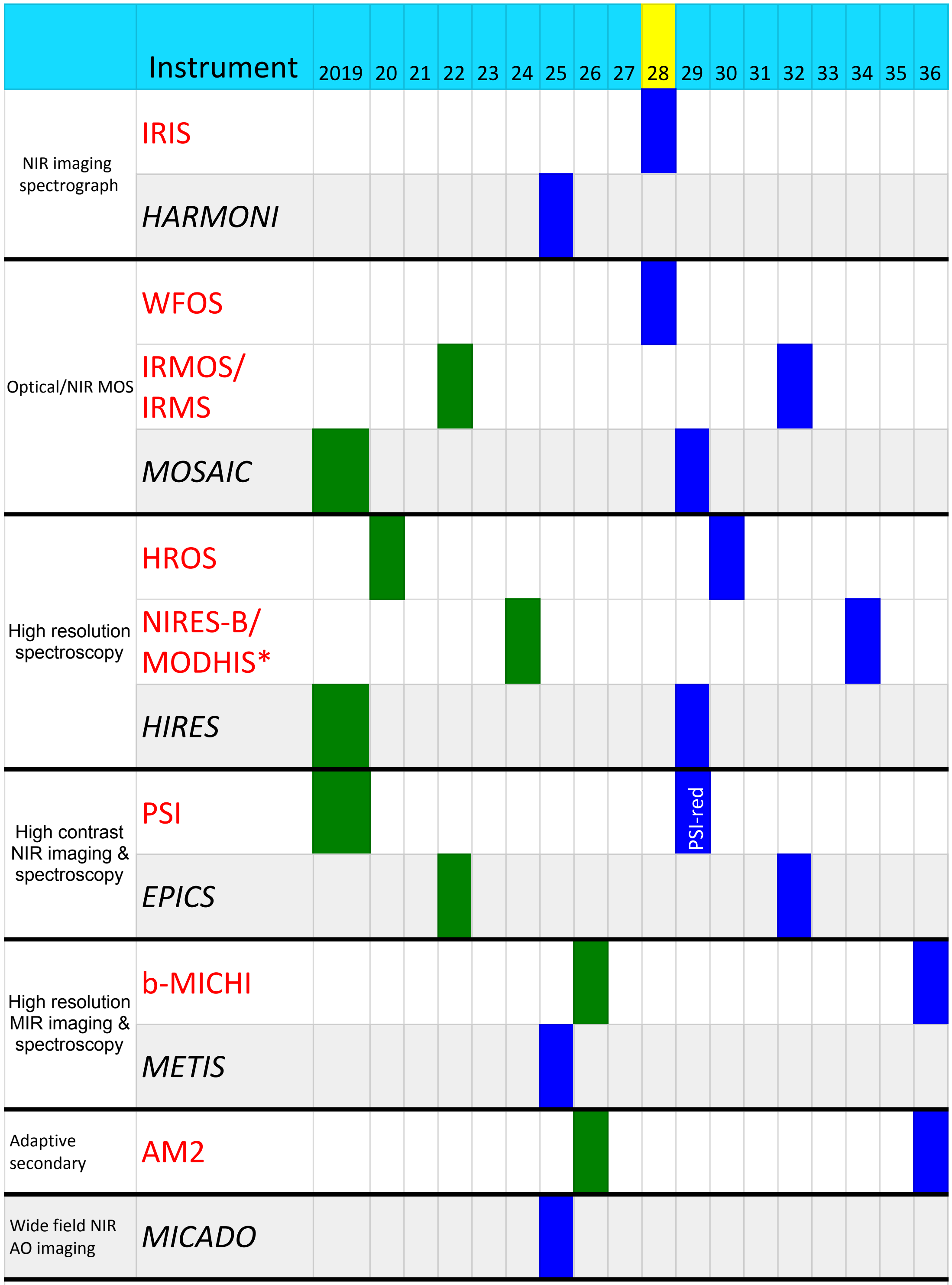
A draft of this document was provided to the community via the CASCA mailing list on March 14, 2019. Several people sent written feedback, and an open invitation was made for CASCA members to participate in a CATAC telecon on March 26. We acknowledge informative discussions with Glen Herriot (NRC) and Paul Hickson (UBC) regarding AM2. We thank Christian Marios (NRC), Dimitry Mawet (Caltech) and Mike Fitzgerald (UCLA) for updated information about PSI and MODHIS.

Following this feedback it was decided that an extended period of consultation was needed, including a presentation and discussion at CASCA. Final recommendations will not be made until after that consultation has concluded.

Preliminary Findings and Prioritization

- The Canadian community has a wide range of scientific and technical strengths, and Canada should position itself to allow these to be utilized by the TMT.
- HROS, PSI, and some form of IRMOS are all scientifically compelling to Canadians and open up promising new regions of parameter space relative to the first light instruments. Many of these offer workhorse capabilities that will allow Canadians to exploit new programs that have not yet been identified. They also provide opportunities for Canadians to assert both scientific and technical leadership.
    - In particular, HROS is a must-have workhorse capability that is unique from the first light instrumentation. This should be a high priority and available as close to first light as possible. Interested Canadians are encouraged to explore the possibility of joining India and China on the development of this instrument.
    - PSI is a critical capability that exploits TMT advantages and has the potential for enormous science impact soon after first light. It operates in a highly competitive environment and it should be a priority to make the first phase of PSI (PSI-red) available as soon as possible after first light. More study is needed to understand how these phases can be integrated with the other capabilities (e.g. bMICHI, MODHIS and AM2).
    - IRMOS would also serve a broad community and is a workhorse instrument that significantly expands upon the science capability of the first light instrument IRIS.
- High resolution NIR spectroscopy (NIRES/MODHIS) is also an important capability that has broad application over parameter space that is not covered by other instruments. MODHIS may be available as a third first-light capability, at modest cost to the TMT project. We support a high priority for MODHIS, but only if it does not significantly impact the timely delivery of our top three priorities (HROS, PSI-red and IRMOS).
    - MODHIS and NIRES have similar, but not identical specifications. More study is required to identify important science cases that are enabled by one design but not the other.
- Following PSI-red and MODHIS/NIRES, b-MICHI would be the natural, next priority, extending TMT's reach into the mid-infrared. Arguably the greatest scientific drivers for bMICHI to the Canadian community will be in the context of exoplanet science.
- AM2 could provide a significant improvement in sensitivity for seeing-limited instruments, and potentially simplify future AO systems. If available at first light, AM2 would provide an effective, but expensive, upgrade for WFOS. With only two instruments available at first light, we consider it more important to have additional instrumentation that probes new parameter space.
    - Given the potential high cost of AM2, and the resulting impact on the funding of new instruments, we do not recommend an early deployment of this capability. The project should conduct a cost/performance trade-off study to better assess the priority of AM2 relative to future capabilities such as PSI.

Figure 3 shows a possible phasing of instrumentation that respects these priorities. We simply assume in all cases that there are ten years between start of conceptual design (green) and first light (blue). In reality there will be considerable variation in this timeline between instruments, and the actual phasing depends on funding profiles, which are unknown at this time. In particular, work on MODHIS is already underway and it could be developed on a schedule that is significantly accelerated compared with what is shown here. Instruments are paired with similar capabilities on the ELT, to better see how they might synchronize. However, this pairing is not perfect. For example, PSI-red also competes with some of the capability of METIS, which, according to current plans, could be deployed on ELT before TMT sees first light.



*Conceptual design work on MODHIS is starting now, which means it could be available at or shortly after first light. While this is desirable, it should not significantly impact the phasing of HROS, IRMOS or PSI-red.

Figure 3: Our recommended phasing for TMT instrumentation, with names in red letters, compared with similar capabilities for ELT (in italics and grey background) as taken from Ramsay et al. (2018). Green boxes represent start of conceptual design, with first light (blue boxes) assumed to take place ten years later. First light for TMT, in 2028, is indicated with yellow.

References

Anche, R., Sen,k A., Anupama, G., Sankarasubramanian, K., Skidmore, W. 2018, JATIS, 4, 8003
Angeli, G., Seo, B.-S., Nissly, C. & Troy, M. 2011, SPIE 8127, 09
Atwood, J., Skidmore, W., Anupama, G., Anche, R., Reddy, K. & Sen, A. 2014, SPIE 9150, 13
Bouchy & Doyon, 2018, EPSC, 12, 1147
Chene et al. 2014, SPIE 9151E
Draper et al. 2014, SPIE, 9147E
Hickson, private communication 2019
Marois et al., 2008, SPIE, 7015E
Marois et al. 2014, SPIE, 9148E
National Academies of Sciences, Engineering, and Medicine. 2018. Exoplanet Science Strategy. Washington, DC: The National Academies Press.
Packham, C. et al. 2018, SPIE 10702A0
Pazder et al. 2012, SPIE, 8450E
Ramsay, S. et al. 2018, SPIE 107021P
Seo, Nissly, Angeli, Ellerbroek, Nelson et al. 1 November 2009/ Vol. 48, No. 31 / Applied Optics
Skidmore, W. et al. 2015, arXiv 1505.01195
Thibault, 2011 SPIE, 8128E
Wang, 5 May 2017, internal TMT report on AO Performance with AM2