CATAC Report to the Long Range Plan 2020 Panel

Background

Participation in a 30-m class telescope has been a Canadian priority for two full decades, since LRP2000 first recommended that

> *a team be established to develop designs for a Very Large Optical Telescope (VLOT). This study should be one of the highest priorities among moderate size projects. Canada should join a world team in this effort. Canada should also position itself to be involved with a possible ground-based Very Large Optical Telescope (VLOT) that may be 25 metres in diameter or even more.*

LRP2010 specifically identified participation in the next generation of very large optical/near infrared telescopes (VLOTs) as the top priority for ground-based optical-infrared astronomy through the following recommendation:

> *Timely access to a VLOT remains Canada's number one priority for large projects in ground-based optical-infrared astronomy over the next decade. Canadian participation in a VLOT needs to be at a significant level, such that it will not be treated as a "lesser partner" in scientific, technical, and managerial decisions.*

Continued support from the midterm review was unwavering, despite some of the challenges the project was facing at that time:

> *With access to a VLOT being the number one priority for ground-based optical-infrared astronomy, the MTRP reaffirms the importance of maintaining a "second-to-none" share in TMT. Since partner shares will also factor in future contributions to the observatory, the MTRP therefore strongly endorses ongoing development of second-generation instrument concepts and encourages the various teams to pursue funding.*

The project was in fact poised to be an enormous success of the LRP2010 (and LRP2000) planning exercises, with a construction start in 2014. However, as is well known and described further below, issues related to both funding and site access have delayed the project by five years.

Despite this, as one of only three VLOTs under consideration in the world, and the only one planned for a Northern site, TMT remains an enormously important and powerful facility that will be the cornerstone of Canadian optical and infrared astronomy for decades to come. The scientific capability of this facility will allow Canadians to remain at the forefront of astronomical discovery. The following summary of the capabilities is taken almost directly (with light modification) from our May 2016 report.

An aperture of 30m enables new fields of research and promises transformative changes to our understanding of a wide range of astrophysics. The science capabilities of TMT are well described in the detailed science case (Skidmore et al. 2015). Some examples of core science goals include:

- New tests of General Relativity and cosmology
- Discovery and characterization of the first galaxies
- Proper motion measurements around supermassive black holes (SMBH) in nearby galaxies
- Discovery and mapping of the oldest stars in the Milky Way
- Measurement of low-mass end of the dark matter halo mass distribution through astrometric anomalies in gravitational lenses
- Direct detection and characterization of exoplanets
- Characterization of exoplanet atmospheres and a search for biomarkers
- Detection and spectral characterization of Kuiper Belt objects

This new science is enabled through key technologies and capabilities, including:

- High spatial resolution imaging. Adaptive optics on 30-m class telescopes open up fundamentally new capabilities, including sensitivity that is a factor >200 better than on current 8-m class telescopes. This will provide transformative observations of gravitational lenses, spatial/kinematic maps of galaxies, AGN fueling and feedback mechanisms, exoplanets, protoplanetary disks, and many more. Precision astrometry of both galactic and extragalactic objects (e.g. SMBH) is an especially exciting capability that will likely give rise to a large community engaged in this largely unexploited technique.

- Canadians have a strong community experienced with multi-object spectroscopy. It is noteworthy that, despite the AO capabilities of Gemini, GMOS remains consistently the most popular instrument. Even in natural seeing mode, a 30m aperture provides the additional sensitivity needed to explore stellar populations of faint and/or low surface brightness galaxies; quasar and galaxy outflows; low mass satellite dynamics; the initial-final mass relation in stars; low mass halo stars and white dwarfs; supernovae; and many other topics. While highly-multiplexed instruments on ~10m telescopes will dominate for wide field work, large samples of very faint objects require the collecting area of a VLOT. A high resolution spectrograph would also serve to open up completely uncharted territory with a 30m diameter mirror.
- While undertaking deep observations in the mid-infrared wavelength region is challenging from the ground even at the best sites, the high spatial and spectral resolution that can be achieved with a VLOT enables some very exciting exoplanet science that Canadians are eager to tackle. For example, a modest AO system at 3-5 μm will enable observations of sub-Saturn mass planets at a separation of ~10AU, well within the separations that JWST will ever probe. This wavelength region is the "sweet spot" for exoplanet science, and it is likely that such a system would outperform even an extreme-AO system at JHK.
- At very high spectral resolutions, R~100k, it becomes possible to resolve individual molecular lines. Through transit spectroscopy it will be possible to detect biosignatures in earth-like planets with confidence for the first time; there can hardly be a more compelling goal for the coming decades. A VLOT with high resolution spectroscopic capability also allows measurements of the position-velocity distribution of complex, life-related molecules in protoplanetary disks on scales of 1AU, at a sensitivity that is competitive with JWST. The most important wavelength region to cover for these studies is the red/NIR, where the main markers (CH4, O2, H2, CO2) are.
- Rapid response for follow-up of time variable phenomena is important for many science cases. TMT has a requirement 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. Measurement of radial velocities in objects with very short orbital periods enables, for example, the measurements of high-mass neutron stars, X-ray binaries, exoplanet

transits, and close white dwarf binaries (SN 1a progenitors and potential gravitational wave sources).

Canada also has a large investment in JWST, and there is a great scientific synergy between that observatory and 30-m class telescopes on the ground. With at most a 10-year lifetime, and a 2021 launch, there is a shrinking window of opportunity to overlap, though of course 30-m follow up of JWST discoveries will remain important for many years after JWST stops operations. On the longer timeline, several Canadians are involved in Euclid and LSST, and access to TMT to follow up these very deep imaging surveys with spectroscopy is of critical importance. There are also important synergies with current observatories such as ALMA, and future Canadian ambitions, including SKA, MSE and CASTOR. In particular, TMT will have the same spatial resolution as ALMA, but probing very different wavelengths.

MTR2015 noted that the nature of Canada's participation in Gemini needs to be considered "within the context of a coordinated plan for funding the operation of our ground-based facilities", reaffirming a sentiment expressed in LRP2010. The operations costs associated with TMT will clearly be a big part of that plan. It is not our place to comment on the future of Gemini, but we note that the 2016 Strategic Vision for the Gemini Observatory emphasizes synergy with other facilities:

> *There is broad support in the community for enhancing scientific impact in post-2021 Gemini by operating in a mode that is closely synergistic with other observatories.*

Indeed, the scientific and operational direction Gemini has been taking in recent years promises a bright future. The support of GIRMOS, as a pathfinder for a future TMT multi-IFU capability, is a good example of how Canadians are already using Gemini to support TMT activity.

Construction Delay

Construction of the TMT began in October 2014 with a ground-breaking ceremony. However, Canada's share of the funding did not come through as hoped that year, so construction could not actually begin until the following year (India was also six months late in obtaining their required funding). In April 2015, almost immediately following the announcement of Canada's funding (at about 80% of the requested amount), protests on Maunakea halted on-site work. On December 3, 2015, the Hawai'i Supreme Court revoked the construction permit on the grounds that due process had not been followed. A lengthy contested case hearing was launched. In July 2017, the hearing officer issued her decision, that the permit should be granted under a number of conditions. After receiving written and oral responses to these recommendations, the Board of Land and Natural Resources issued a decision to approve the permit in October 2017. As expected, the decision was appealed directly to the Hawaii Supreme Court (HSC).

This joined an appeal to the HSC by the TMT International Observatory (TIO), related to the vacating of consent for the UH-TIO sublease. The issue at stake here was a possible requirement to conduct another contested case hearing, this time for the granting of the sublease. In August 2018, the Hawai’i Supreme Court ruled unanimously in favour of TMT, that a contested case hearing is not required for the sublease.

Finally, at the end of October 2018, the Court delivered a 4-1 decision to uphold the Conservation District Use Permit issued to TMT by the Land Board. This gave TMT the legal right to restart construction.

The result of this legal process in Hawai’i was an additional four year delay to the start of construction, representing a total of five years delay from the anticipated 2014 start. While polls at this time show a majority of support for TMT among Hawaiians, there is still a highly visible minority that are strongly opposed. The Board and Project Office have decided to proceed carefully, with consultation among key stakeholders. As of May 31, 2019, construction has not yet restarted, though due to various partner considerations it must start before September 2019.

Site

In the face of the delay and uncertainty regarding the Hawaiian site, the TIO Board began considering alternative sites for TMT in 2016. CASCA and ACURA struck a Tiger Team to consult the community and advise on what the different site choices meant for Canada’s aspirations. This committee had two weeks to come up with their recommendation. Of the sites under consideration, the committee unanimously identified Cerro Honar, in Chile, as the superior alternative site, scientifically. In October of that year, the TIO selected ORM, La Palma as the alternative site. The Tiger team released a public summary of their report in which they identified a split in the community opinion regarding ORM, and strongly recommended further study to assess the degree to which this choice would satisfy Canadian expectations. CATAC was formed partly in response to this, and also to fill a needed link between the TMT Board and SAC and the broader community. CATAC’s report in May 2017 concluded in part:

> *...the site at MK13N is strongly preferred to ORM. However, TMT@ORM still offers many opportunities for transformational science, and for Canadians to take an international leadership role. Realizing its potential will require appropriate instrumentation, an efficient and effective governance model, and a path to first light that does not engender a large delay relative to the competition.*

CATAC formally reviewed these recommendations in 2018, and on Sept 27 issued a statement reaffirming our support for the Maunakea (MK13N) site. This statement was not released publicly, and is therefore worth restating here in full:

> *CATAC has reviewed our findings and recommendations from May, 2017, in light of progress made since that time. We have concluded that nothing material has happened to alter the findings or recommendations we made at that time. To add some clarity and specificity:*
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> - *Maunakea remains the strongly preferred site, over ORM.*

    - *The quantified site characteristics at Maunakea are superior, and they enable science in the MIR and UV that is unique among ELTs, and much more difficult to achieve at ORM.*
    - *Many important ORM characteristics remain uncertain, lacking the specific site testing data we have for other sites. This is particularly true for the predicted AO performance.*
    - *Finally, success of TMT is going to require continued broad, strong support from the Canadian community. This support is modest, at best, for a relocation at ORM prior to MK being ruled out. There remains a risk of community disengagement if such a move is made.*
- *The preference is so strong that any additional delay, even of several years duration, does not change it. TMT is being built for future generations, and will have a productive lifetime of many decades. We should not be shortsighted about the impact of a few years' delay, but must build the best telescope we can, on the best site we can: of the options available, this site is Maunakea.*
- *ORM is an acceptable site and TMT will be able to do transformational science at that location. If it becomes impossible to build on Maunakea, or if a decision to pursue Maunakea jeopardizes the future of the project, we then recommend a move to ORM.*

It turned out that pursuing the permit for construction on ORM was also a slow process, and faced unanticipated bureaucratic hurdles. As of May 17, 2019, a building permit at ORM has still not been secured, although there do not appear to be any fundamental impediments. With the favourable decisions of the HSC, the Project is focused on construction on Maunakea, while ORM remains a viable backup.

The European ELT project

The delay to TMT construction has led to it being overtaken, in terms of anticipated first light, by the European ELT project. In 2014 the ESO Council approved the construction of the ELT in two phases, and authorized spending on the first phase. Since that time ESO has found the money for full construction, by shifting the cost of second generation instrumentation to the successful bidders, in return for guaranteed time. One of the consequences of this change is that it it has opened up the possibility for Canadian teams to participate in ELT instrumentation, if funding can be secured.

The ELT first stone ceremony was held in March 2017 and construction is expected to be complete by 2024, with first light in 2025. Construction of three first light instruments (HARMONI, MICADO and METIS) is underway. The AO system (MAORY) will not be ready by 2025; MICADO will have its own single conjugate AO system, limiting it to a smaller field of view until MAORY is ready. A second generation instrument, MOSAIC, is in Phase B of design, and a submission to ESO for construction is expected in summer of 2019. The Phase A Design study for HIRES was completed in August 2018.

As it stands today, first light on TMT is likely to be 3-5 years after that on the ELT. While it is certainly disappointing to have missed out on the opportunity to be first on sky, the potential lag should not be of great concern. The first light dates of both telescopes are somewhat uncertain and, in particular, the ELT instrumentation schedule may be optimistic. Moreover, the anticipated lag represents only a few percent of the expected useful scientific lifetime of TMT. While the opportunity to grab some of the low-hanging fruit will undoubtedly fall to the ELT, there is certainly enough transformational science to keep TMT relevant for multiple generations of future astronomers. Making good choices about the phasing of future instrumentation, relative to the ELT plans, will be important. This is something CATAC has been working to address (see more on this, below).

While ELT will have a larger primary mirror than TMT, there are several key differences that TMT is able to exploit. One obviously is the sky access; as the only VLOT in the northern hemisphere, TMT will have exclusive access to many important targets. Another is the higher altitude of the TMT site, which benefits observations at both the bluest and mid-infrared wavelengths. In particular, the requirement to retain good sensitivity down to the atmospheric cutoff drives many of the design requirements of the telescope, and opens up a range of science that will be difficult or impossible for ELT to address. Both telescopes are designed to take advantage of adaptive optics technology, but it is critical to the operation of ELT (and partly drives the 5-mirror design, which somewhat compromises the aperture advantage for throughput). TMT will have seeing-limited instrumentation at first light (WFOS), and possibly soon after (HROS), allowing it to exploit conditions when it is difficult or impossible for ELT to operate.

Funding and the US ELTP

In 2014, the original cost estimate for the TMT project was about $1.6B (2012 US dollars), including $212M in contingency. The Board goal had been to initiate construction once 81% of the funds were in place. In April 2015, Canada committed $243.5M (CAD) to the TMT project. These funds are to be spent primarily in Canada, to enhance our industrial capability and competitive edge for future contracts. Canada’s largest contribution will be the enclosure, a precision steel structure to be built by Dynamic Structures Ltd. (Port Coquitlam, BC). Approximately $70M, which included funds already within NRC Herzberg, was earmarked for Canadian instrumentation work, including the sophisticated adaptive optics system (NFIRAOS) under development at the NRC. The remaining funds were for centralized project management and infrastructure costs. This funding commitment, with the early investments of nearly $30M and fundamental contributions to the design of the TMT facility and instruments, meant that Canada would secure a “second to none” share at approximately 15% of this project.

While very welcome, this commitment was about $75M short of what was needed to secure the requested 20% contribution, leaving the project with only 76% of the funding in place. The Board agreed to proceed with construction, nonetheless. It was acknowledged that additional partners would be needed to complete the project, and in particular it was hoped the US would join, through the National Science Foundation (NSF).

In May 2018, the NSF expressed a willingness to support a network of 30-m class telescopes at a level of at least 25%, provided this emerged as the top-ranked priority in the 2020 Decadal survey. Though this is certainly not a funding commitment, it has provided the much-needed impetus for AURA, TMT and GMT to begin working together to build a strong case for the 2020 Decadal survey. The access to full sky, a broader instrumentation suite, and more time for US astronomers, are being highlighted as the benefits of participation in both TMT and GMT. Joining these telescopes represents an important leadership opportunity for the US, and the response from that community has been strong and positive. A report from the US National Academies of Sciences, Engineering and Medicine made an important recommendation, that the NSF "should invest in both the GMT and TMT and their exoplanet instrumentation to provide all-sky access to the US community".

A central element of the anticipated proposal to NSF is the development of "Key Science Projects" (KSP), which is currently coordinated by NOAO, and will become a focus of the National Center for Optical and Infrared Astronomy (NCOA). While at the moment this is strictly limited to the US community, it does build on work done by the International Science Development Teams and the expectation is that KSPs would not exclude other partners from competing (or, hopefully, collaborating) on the science. In any case, these are "exemplar" cases that are necessary for the NSF MREFC construction proposal; it is expected that any actual KSP would be subject to peer review and possible international collaboration.

Even if this comes to pass, a couple of difficulties remain. One is that any NSF money would not flow before 2023, and there is a need for additional contribution prior to that date. Secondly, engagement of the NSF is likely to trigger the need for a federal Environmental Impact Statement, which could take two years or longer to complete. Finally, since the aborted construction start in 2014, the project has increased significantly in cost, largely (but not entirely) driven by the five year delay. Both Canada and Japan are providing major pieces of infrastructure, and the cost of those have increased significantly over the past five years. More money will be needed to keep these contracts, and the share of the project that they represent. The other issue related to Canadian funding is that the money allocated in 2015 was to be spent over nine years, coming to an end by 2024. With the construction delay, the money has been carried forward to later years. There will almost certainly be a need to request extending the spending profile beyond 2024.

Share and governance

The 2017 CATAC report made comments about the share and governance of TMT that remain relevant today. This report recognized that, in addition to collaborative access to telescopes around the world, true leadership "not only access to a significant amount of time on large telescopes, but also a role in their development, operation and governance".

The current partner shares in TMT are still being negotiated, as the project works to re-estimate the value of the work-share being provided by Canada, Japan, India and China. Many of the associated in-kind costs have increased, often by more than expected due to standard inflation rates. This is complicating the determination of cost to completion, and hence partner share. However it is fairly clear that Canada will not be able to secure the "second-to-none" share in TMT that was initially planned, and that was strongly endorsed by the LRP process. At the moment we anticipate a share of roughly 15%, just behind Japan. Assuming a single new partner (hopefully the NSF) joins for the remaining 25%, our share will also be smaller than theirs. It is important to note that, unlike the situation with Gemini, no single partner will have a dominant share in the telescope. Even if the three anticipated US partners (NSF, UC and Caltech) were to coordinate, they would only represent about 50% of the partnership. Thus, even though Canada will have a smaller share than some, the power balance between the partners is fairly equitable.

The 2017 CATAC report stated that we expect Canadian proposal pressure on TMT to be very high with a 15% share, and that "a larger share would certainly be welcomed". Certainly, a share of much less than 15% would compromise Canada's ability to participate in forefront science and to direct the future of the Observatory. The CATAC report also noted that, beyond share, it is important that "we have a strong enough voice to influence the scientific direction of the observatory… Canadians clearly want to be engaged with their observatory, and there is a stark contrast between how engaged they feel with CFHT compared with Gemini. While an aspect of this engagement comes down to role in governance (which is large and complicated in the case of Gemini), many feel that it is through instrumentation development that the community nurtures its partnership with the Observatory. In particular it is the best way to ensure alignment between the available instrumentation and scientific needs of the community".

Building on that, in recent years CATAC has shown leadership on addressing issues that are critical to the TMT, including our reports on the site selection (2017), first light instrumentation (2018) and future instrumentation (2018).

Instrumentation

Since the midterm review, the picture of TMT's first light instrumentation suite has changed. IRMS is no longer planned to be a first light capability, leaving WFOS and IRIS as the two instruments, with the AO facility NFIRAOS. At the present time there is also a push to try to get an exoplanet capability available for as close to first light as possible (MODHIS). IRIS, a near-infrared, AO-assisted imager with an integral field spectrograph, passed its Preliminary Design Review in late 2017 and is now in the Final Design stage. Canada is heavily involved in the IRIS instrument. WFOS, as a seeing-limited instrument, has proven very challenging to design to specifications given its size and complexity. It has had a history of changing requirements and designs, as described in the CATAC report of April 4, 2018. A decision has been made to proceed with the Xchange design, which 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). We were pleased to learn of this decision, which is the one recommended by CATAC.

The TMT project is now revisiting planning of instrumentation phasing beyond first light. This began in 2018 with the solicitation of white papers from the community. The US community has been quite active, 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. To this end, CATAC has prepared a draft report and begun open communication with the Canadian community, toward producing a set of recommended priorities for future instrumentation. Importantly, Canada is well-positioned to make contributions to several different instrument concepts, including:

- India and China are currently working together on the High Resolution Optical Spectrograph (HROS) design. 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.
- The development of the multi-IFU NIR instrument GIRMOS for Gemini puts Canada in a strong position to lead a similar (IRMOS) instrument for TMT, and further leverages our investment in NFIRAOS.
- 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 the Planetary Systems Imager (PSI).
- Canadian experience with the high-resolution NIR spectrograph NIRPS (e.g. Bouchy & Doyon 2018) makes us well positioned to contribute to the design and construction of either NIRES or MODHIS.

CATAC will lead a lunch session at CASCA 2019 to discuss these and other instrumentation concepts.

Canadian Engagement

CATAC was formed in 2016, in part to improve the communication between TMT activity (especially the SAC and Board) and the broader Canadian community. The construction delay, and the challenges presented by the protests on Maunakea, were making it difficult for

Canadians to fully engage with the project. Meanwhile, the relatively steady progress of ELT and the fact that the need to keep government focus on TMT was perceived to be impeding other LRP-supported projects led to a growing sense of frustration. This disengagement was beginning to threaten Canada's position in TMT.

CATAC has therefore played an active role in keeping the Canadian community informed about TIO activity, and also in providing thoughtful, researched advice to our SAC and Board members to ensure that Canada's position is well represented within the Project. CATAC has provided specific advice about the site selection, the WFOS instrument design, and the phasing of subsequent instrumentation.

The International Science Development Teams (ISDTs) have played an important role within the Project, helping to define science requirements for instrumentation and keeping the Detailed Science Case up to date. Canadian participation prior to 2016 had been limited to a handful of people. CATAC actively encouraged more engagement in these teams, and ultimately 28 new applications were generated. We now have 39 ISDT positions filled by Canadians, much more representative of our role in the project.

Finally, CATAC recommended that ACURA provide some travel support for Canadians to attend the annual TMT Science Forum. These events have been very important for developing the science and instrumentation for TMT, but have typically been poorly attended by Canadians. ACURA recognized this as an important investment to ensure the success of our TMT partnership, and has been supporting travel to these meetings at the level of about $10,000 per year since 2017. This has enabled several people to attend who would otherwise not have been able.

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