CATAC Report

May 17, 2017

1 Introduction

1.1 Committee Members

Michael Balogh (Chair, Waterloo), **Sarah Gallagher** (Vice-Chair, CASCA representative, Western), **Ray Carlberg** (CASCA representative, U Toronto, resigned April 19, 2017), **David Lafrenière** (CASCA representative, U Montréal), **Stefi Baum** (ACURA representative, U. Manitoba), **Harvey Richer** (ACURA representative, UBC), **Christine Wilson** (ACURA representative, McMaster University), **Luc Simard** (NRC, observer), **Tim Davidge** (NRC, Observer), **Greg Fahlman** (NRC, observer), **Roberto Abraham** (CASCA President, Observer), **Don Brooks** (ACURA Executive Director, Observer), **Stan Metchev** (TMT SAC, Western, Observer), **Doug Welch** (TIO Board, Observer)

1.2 Background

In April 2015, Canada committed funds to construct the Thirty Metre Telescope (TMT) on Mauna Kea (MK), Hawai'i. The $243.5M contribution included industrial contracts to build the enclosure and the adaptive optics system, NFIRAOS. This represented the realization of a long-held aspiration of the Canadian community, as expressed in the Long Range Plans of 2000 and 2010, to be major players on the international scene of optical/infrared astronomy during the era of 30m-class telescopes.

The tremendous excitement that accompanied this announcement was almost immediately tempered by protests in Hawai'i that led to a halt of construction and eventually a revocation of the construction permit. Since then the project has been delayed while we await the decision of the courts. The delay has been costly for the project, and with a need to move forward the TMT International Observatory (TIO) Board in 2016 began considering alternative sites for TMT, should MK no longer be possible. In advance of the October 2016 Board meeting, 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 site scientifically. At the Board meeting, 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.

That recommendation, together with a clear need for a better community advisory structure for the TMT, led to the formation of the CASCA-ACURA TMT Advisory Committee (CATAC), in January 2017. While CATAC has a broad mandate, at this critical time our efforts are focused on evaluating the scientific capability of TMT sited on ORM, and in particular assessing how competitive it will be compared with the European Extremely Large Telescope (ELT) being built on Armazones, Chile and the Giant Magellan Telescope (GMT) being built at Las Campanas, Chile. A TIO Board decision on whether or not to move to ORM is expected sometime before the construction start date of April 2018, and our purpose is to make sure the implications of this choice are as well understood as possible, and communicated with the Canadian community.

1.3 Scope and Modus Operandi

The purpose of this report is to inform the community of professional Canadian astronomers (CASCA members and the Long Range Planning Implementation Committee [LRPIC]) and their university representatives (Association of Canadian Universities for Research in Astronomy [ACURA]) about the current status and future prospects of the TMT project. It represents the synthesis of independent review by all the committee members and observers, of existing reports and documents, consultation with experts currently working on TMT or potential future TMT instruments, and feedback from the community. The objective is to provide some guidance based on what we know at this point, and inform the community of the committee's findings and opinions given this information. The committee will remain in place and will continue to follow developments and incorporate new information.

CATAC has met approximately weekly by telecon since we formed. Between meetings there was also much discussion via email and Slack. In addition we opened four meetings to CASCA members, via Webex. These included presentations by Luc Simard (Instruments Group Leader, TMT), Matthias Schöck (TMT site testing team) and Chris Packham (PI for the MICHI instrument). Valuable unsolicited contributions from members of the community have also been received and discussed at length by the committee.

The body of this report presents a summary of what we have learned about the expected performance of TMT at ORM, how this compares with our competitors, and how it compares with the expectations and needs of the Canadian community. From these facts and data we then present some preliminary findings and recommendations. These are restricted to describing how competitive TMT will be relative to other planned 30-m class telescopes, how to make the most of the opportunities TMT presents, and how to maximize the benefit to Canada. We focus on the long-term competitiveness that results from the telescope design and site selection. This report does not attempt to address the question of Canada's future in the partnership or how involvement in TMT compares with other possible futures for Canadian astronomy. These broader questions are more appropriately discussed within LRPIC, and we hope this report is informative to those discussions.

2 The Canadian Context of a Very Large Optical Telescope (VLOT)

2.1 Scientific Capabilities

Engagement and leadership in a VLOT has consistently been a top priority for the Canadian community, as expressed in the Long Range Planning process, for more than 15 years. The main reason for this is the scientific capability such a facility would bring, allowing Canadians to remain at the forefront of astronomical discovery. An aperture of 30m provides an increase of a factor 10 in light collecting power and a factor of 3 in spatial resolution over the largest telescopes available today. For adaptive-optics imaging of point sources the two effects combine for an increase in sensitivity that scales as D^4, or a factor ~100 relative to 10-m class telescopes. This 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); ELT and GMT also have detailed science cases available[1]. 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 in nearby galaxies
- Discovery and mapping of the oldest stars in the Milky Way
- Direct detection and characterization of exoplanets
- Characterization of exoplanet atmospheres and a search for biomarkers
- Detection and spectral characterization of Kuiper Belt objects

Canadians have interest and expertise in these and many other topics for which 30-m telescopes will have an enormous impact. It is worth pointing out that science cases flow down to technical capabilities; different aspects of VLOT technology will impact these cases differently. For our purposes it is useful to consider the following broad capabilities:

- High spatial resolution imaging. The AO capabilities of 30-m class telescopes open up fundamentally new capabilities, with 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 in multi-object spectroscopy. It is noteworthy that, despite the AO capabilities of Gemini, GMOS remains consistently the most popular

[1] https://www.eso.org/sci/facilities/eelt/science/doc/eelt_sciencecase.pdf and http://www.gmto.org/Resources/GMT-SCI-REF-00482_2_GMT_Science_Book.pdf

instrument. Even in natural seeing mode, a 30m aperture provides the additional sensitivity needed to explore stellar populations of distant and ultra-diffuse 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, at a sensitivity that is competitive with JWST. The most important wavelength region to cover here is the red/NIR, where the main markers (CH4, O2, H2, CO2) are.
- A VLOT will also allow the study of extremely rapid variability in the optical spectrum, which been previously inaccessible. 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 I1a 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 2018 launch, there is a shrinking window of opportunity to overlap contemporaneously, though of course 30-m follow up of JWST discoveries will remain important for many years later. On the longer timeline, many Canadians are involved in Euclid and LSST, and access to a VLOT 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 WFIRST, SKA, MSE and CASTOR.

2.2 Share and governance

While Canadians have proven to be excellent collaborators, obtaining access to all telescopes around the world through exchange of data and intellectual or technical expertise, leadership in the field requires not only access to a significant amount of time on large telescopes, but also a role in their development, operation and governance. The goal for a long time has been to ensure Canadians are “second-to-none” in terms of partnership, and this has led to the present 15% share of TMT. With increasing costs, unless additional funds can be found, our share will drop. Based on existing demand for the Gemini telescopes, where Canada is a ~15% partner on two telescopes, with moderate proposal pressure of 2-3, a 15% share in a VLOT seems appropriate. Gemini, however, is not perfectly suited to the needs of many Canadian astronomers, who carry out their observations on VLT, Keck, Magellan or Subaru through collaborations. A VLOT with excellent instruments and a good operations model is likely to be very attractive. Unlike with the 8-m class telescopes, there will be at most three for the foreseeable future, and thus Canadians will rely on their VLOT access more than they need to for Gemini. For these reasons we expect that proposal pressure will be very high at a 15% share, and a larger share would certainly be welcomed.

During our open meeting with the community on March 7, 2017, it was clear that among the most important requirements is that we have a strong enough voice to influence the scientific direction of the observatory. This is only partly influenced by share. With an appropriately open governance model, even small partners can have a strong influence.

In our community consultations it became apparent that flexibility is the one of the most attractive elements of good observatory operations. This means strong support for a fully adaptive queue system, an evolving balance of “small” and large programs, ease of coordinating with other 30m or smaller telescopes when beneficial, with a wide range of competitive instrumentation including workhorse and experiment-driven instruments.

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 the scientific needs of the community.

3 Site Characteristics

In this section we compile and compare some basic site characteristics: image quality, clear sky fraction, extinction, precipitable water vapour, temperature and atmospheric pressure. Specifically we are interested in the sites at MK13N and ORM (potential sites for TMT), as well as Armazones and LCO which are the sites for the ELT and GMT, respectively. Locations and altitudes are given in Table 1.

Site	Latitude	Longitude	Altitude (m)
ORM, La Palma	28.753° N	17.9017° W	2250
MK13N, Hawai'i	19.833° N	155.481° W	4050
Armazones, Chile	24.589° S	70.1917° W	3114
LCO, Chile	29.018° S	70.6915° W	2500

Table 1: Location and altitude of sites considered in this report

Figure 1: Candidate TMT locations on ORM, with locations of site testing equipment indicated. TMT3 is the selected alternate site for TMT.

The alternative site selected for TMT on ORM is indicated as TMT3 on Figure 1. It is on the downslope about 150 m below the ridge, as is the other large telescope on the mountain, GTC. Coloured points indicate locations of site testing equipment considered by the TMT site selection team.

Unless otherwise noted, measurements in this section come from site testing documents from GMT (Thomas-Osip et al. 2011), ELT (Vernin et al. 2011) and TMT (Skidmore et al. 2009; Schöck et al. 2009).

3.1 Image Quality

3.1.1 Background Information

We start by providing some definitions of atmospheric turbulence measurement techniques used in this section:

DIMM – Differential Image Motion Monitor
: Differential image motion measurement of a single star in two apertures of ~35-cm telescope. Measures integrated seeing only.

MASS – Multi-Aperture Scintillation Sensor
: Scintillation measurements in 4 concentric apertures. Can be mounted on same telescope as DIMM, but is separate instrument. Low resolution (6 layers) profile of turbulence excluding the ground layer yields mesurements of the seeing and isoplanatic angle. Scintillation measurement also measures coherence time.

SODAR – Sound Detection and Ranging
: Acoustic sounders. High-resolution profiles of ground layer turbulence strength and wind velocity. 10 – 800 m elevation, 5 – 20 m resolution

SCIDAR – Scintillation Detection and Ranging
: Scintillation measurement along crossed paths toward a binary star. Yields full turbulence profiles with resolution of a few hundreds of meters, from which is derived the seeing and isoplanatic angle. In principle, SCIDARs can also measure wind profiles (which gives the coherence time), but the ORM SCIDAR is not yet set up to do so. Requires a 1 – 2 m telescope.

It should be appreciated that DIMM seeing and the FWHM of a stellar image on a detector are not the same thing. The DIMM seeing refers to the FWHM of a stellar image with a perfect large telescope at a wavelength of 500 nm at zenith for a Kolmogorov spectrum of turbulence of infinite outer scale. The captured FWHM on a detector includes, of course, all the mirror imperfections, dome and atmospheric degradations and telescope and detector problems. Tokovinin (2002, equation 19) shows that telescope optics-corrected IQ values (FWHM) are about 20% smaller than corresponding DIMM values for a typical 30m outer scale of turbulence. Since for some sites (MK13N and ELT on Armazones) we only have DIMM values, we will convert all measurements into appropriate DIMM values for comparison.

3.1.2 Turbulence Profiles

The seeing at the telescope aperture depends on the relevant atmospheric seeing, plus contribution and modification of the turbulence profile due to the dome and the telescope itself.

In general the atmospheric seeing is a strong function of altitude, with the ground layer turbulence providing a large contribution to the total seeing. Expected performance is then quite sensitive to the height of the mirror above the ground, and the role of the dome. There has been much discussion both at CATAC and in the literature around this issue. The TMT site-testing group (Schöck et al. 2009) provided data at various heights above the ground using a combination of simultaneous MASS, SODAR and DIMM turbulence data. Measurements were made at four sites (Armazones, Tolonchar, San Pedro Martir, Mauna Kea – they did not survey ORM). All exhibit a decline in seeing as the height increases from 7m above ground up to 200 m as shown in their Figure 3, reproduced here as Figure 2:

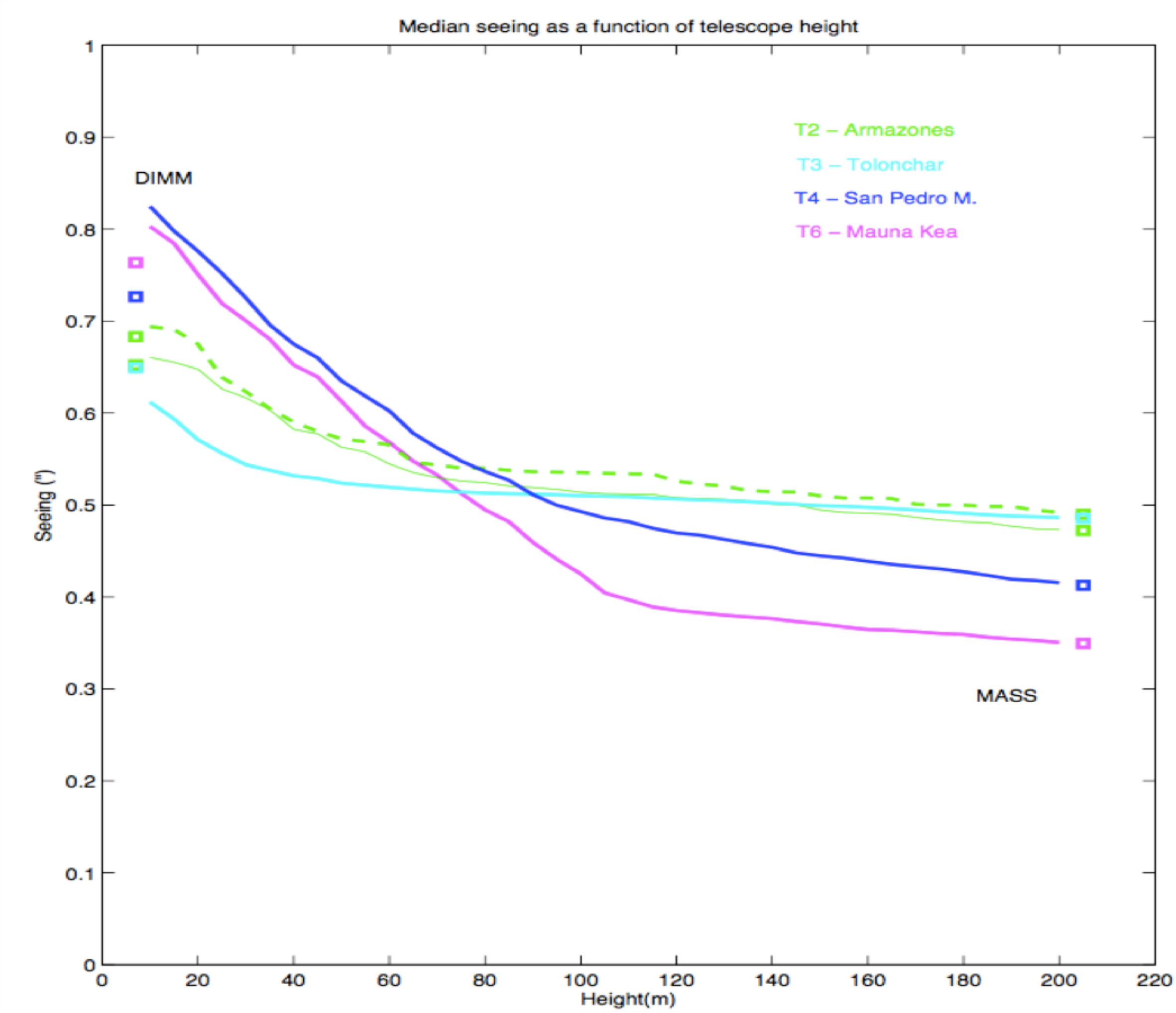


Figure 2: Turbulence profiles for four of the original sites tested for TMT. The lines are SODAR measurements, with a normalization determined based on the DIMM and MASS measurements at ~7m and ~200m altitudes as shown. From Schöck et al. (2009)

The SODAR profiles in this Figure have a calibration (normalization) uncertainty of 10-20%, but the shape is precise. The MASS measurements give a precise seeing measurement at ~200m, and the DIMM give a precise measurement at 7m. The profiles are therefore scaled to match the difference between the MASS and the DIMM, and the resulting turbulence is then added to the MASS measurement at 200m to give the curves shown. This results in an uncertainty on the seeing at 60m of about 5-10%, smaller than the SODAR calibration uncertainty because it is pinned to the MASS and DIMM measurements.

Figure 2 indicates that at about 60m all four sites produce about the same seeing (~0.55”). ORM is on a site with strong low-level turbulence, like MK13N and SPM in the figure, and the turbulence profile is expected to be similar to those sites. MASS-like[2] measurements at ORM are available, and indicating a seeing at 200m of about 0.31”-0.36”, comparable to that at MK13N. It is therefore expected that the turbulence profile at ORM will be very similar to the T4 or T6 curves in Figure 2. This is supported by CFD modelling of the ORM site by the TMT Project Office.

The top of the TMT enclosure is 56m above the ground, and the mirror itself is 16m off the ground, as shown in Figure 3. The TMT project has made detailed CFD modelling of the air flow around and in the TMT enclosure. The framework for their modelling was validated against measurements inside the Keck, Gemini and CFHT domes. Their results indicate that the turbulence inside the TMT enclosure is significantly different from the turbulence outside of it, both in characteristic length scale and in strength, the former being dominated by the temperature gradients of the enclosure and telescope structures and the interaction of the flow with these structures. That is, under the regime modelled, the turbulence inside the enclosure primarily originates from the observatory structure itself and should be roughly the same at any site with, only differences in the turbulence above the dome (>60 m) at different sites leading to differences in image quality. Thus, for site comparison purposes, the TMT project adopted the 60-m seeing parameters, calculated from the measured turbulence profile at the different sites. Most of the relative performance-related metrics provided neglect any contribution from the ground layer.

There are two important places where CATAC is concerned this assumption produces overly optimistic predictions. Most of the CFD studies and empirical testing done by the TMT project office have been restricted to sites with very good DIMM seeing, and a small contribution of ground layer turbulence. As we will see in Section 3.1.3.2, ORM has a larger median DIMM (7m) seeing than these sites. The assumption that the internal turbulence from the dome dominates any turbulence brought in from the outside may no longer be valid. Thus, for comparison purposes, some consideration should be given to the relative seeing between sites at a height of ~20m, corresponding to that of the primary mirror.

The other point of concern is for observations at large zenith angle, where the telescope will be looking through layers of the atmosphere below 60m. Again external turbulence generated by air flow around the dome is significant, but may not be dominant when the ground layer seeing is large. Thus, predictions for large zenith-angle observations at ORM, which did not account explicitly for the ground layer turbulence, are likely to be overoptimistic.

[2] These are resolution-degraded SCIDAR measurements, in fact more reliable than MASS. There is an actual MASS measurement from the TMT-2 site with a median of 0.31”.

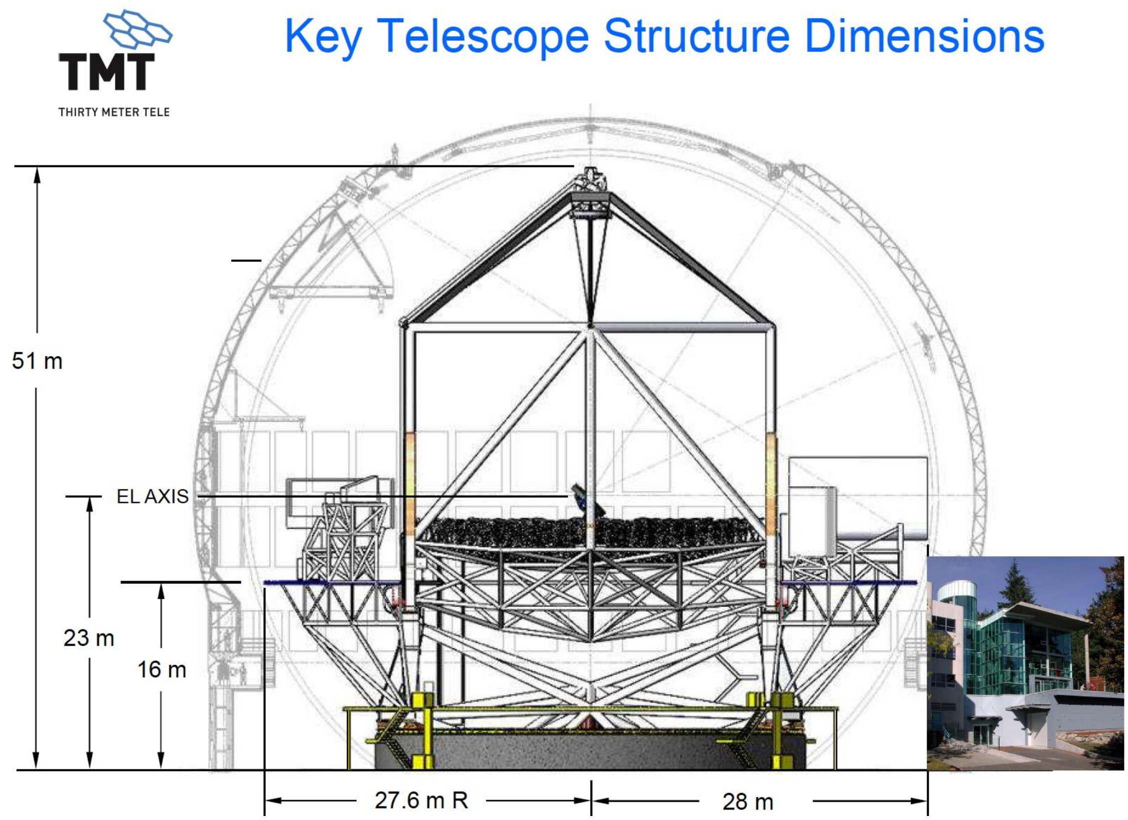


Figure 3: Key dimensions for the TMT telescope and enclosure. The inset shows the HAA building, for scale.

3.1.3 Ground-level seeing measurements

The seeing at 7m can be measured directly from DIMM, when available. Below we compile available measurements at the sites under consideration.

3.1.3.1 MK13N and Armazones

The site chosen for the TMT on Mauna Kea is on the plateau, 200 m below the summit ridge. There has been extensive testing of the site by the TMT group (Skidmore et al. 2009; Els et al. 2009; Schöck 2009) with a DIMM and the median value at an altitude of 7m is 0.75" (using both the Skidmore data and Schöck results). The DIMM seeing for MK on the summit (near CFHT) consistently yields a value of 0.62", so the 7m DIMM seeing on the slope is about 0.13" worse than it is on the summit. For Armazones we adopt the DIMM measurements of 0.64" from Els et al. (2009) .

3.1.3.2 ORM

Though no DIMM measurements are available at the selected TMT site (TMT-3 on Figure 1), we do have measurements from nearby sites. Testing was carried out by the ELT group at the site TMT-2, in a short campaign in 2008 (Vazquez Ramio et al. 2012). They found a median value of 0.80". An earlier survey was carried out at the GTC site over a nine month period (Nov 1994 – Aug 1995, Munoz-Tunon et al. 1997), from which a value of 0.76" was obtained after applying corrections to zero exposure time and 500nm. As the result of site testing for the ELT, 5m DIMM seeing measurements near JKT, on the summit ridge, are reported to be 0.80" (Vernin et al. 2011).

We have also considered data from the 2.5m Nordic Optical Telescope (NOT), which is well engineered, located near the ridge and has a vented dome. The IQ numbers for this telescope are in Table 2 and are based on observations of standard star fields from three runs in the 1990s, kindly provided by Peter Stetson.

best	10%	25%	50%	75%	90%	worst
0.38"	0.60"	0.71"	0.85"	1.05"	1.46"	3.51"

Table 2: Image Quality percentiles from the 2.5 NOT (Stetson, private communication).

The director of NOT, Dr. Thomas Augusteijn, informed CATAC that the 50% IQ in V-band for an air mass < 1.74 was 0.86". He also stated that the NOT optics contribute about 0.25" to the IQ, so that the NOT dome plus atmosphere contribution to the IQ is 0.79".If we use the best seeing estimate of 0.38" as a measure of the optics plus dome for the NOT and 0.85" as the 50% IQ (corresponding to 1" median seeing) we would then predict a DIMM seeing of 0.85", close to the value measured in Vernin et al. (2011). Computational fluid dynamics (CFD) simulations show that the seeing on the downslope may be ~0.1" worse than at the NOT site (near the ridge), consistent with experience at MK (see above).

Finally, we have obtained DIMM measurements from the director of the TNG, Emilio Molinari. René Racine has also kindly provided an analysis of data from the TNG DIMM spanning 2013-2016. The TNG is sited close to the proposed TMT site (see Figure 1), and is equipped with a DIMM that has been in continuous use for about six years. The location of their DIMM is about 15m below the TNG (thus ~85m above the TMT site), and about 5m above the ground. The year-to-year median, average and standard deviation over the past five years is given in Table 3. From these data, we conclude that the median seeing is about 0.85 +/- 0.1", consistent with the other numbers quoted above.

Year	Median Seeing (arcseconds)	Average Seeing (arcseconds)	σ Seeing (arcseconds)
2012	0.78	1.21	0.78
2013	0.97	1.24	0.81
2014	0.90	1.16	0.79
2015	0.79	1.00	0.59
2016	0.77	0.95	0.57

Table 3: Average DIMM seeing at the TNG over a six year period.

The difference between the average and median is notable, and indicative of a long tail to high seeing values. To further demonstrate this, the cumulative distribution of 2012 seeing values is shown in Figure 4. For this year, the seeing was measured to be greater than 2” just over 8% of the time. For comparison, the 90%-ile DIMM seeing at MK13N is 1.43", and the 90%-ile DIMM seeing at Armazones is 1.14". Excursions of the seeing to very large values are thus much more frequent at ORM relative to other sites, as shown in Table 4, kindly provided by Racine. This feature of the site is not captured in most of the performance metrics considered, but effectively leads to a decrease in the fraction of usable time (Section 3.2).

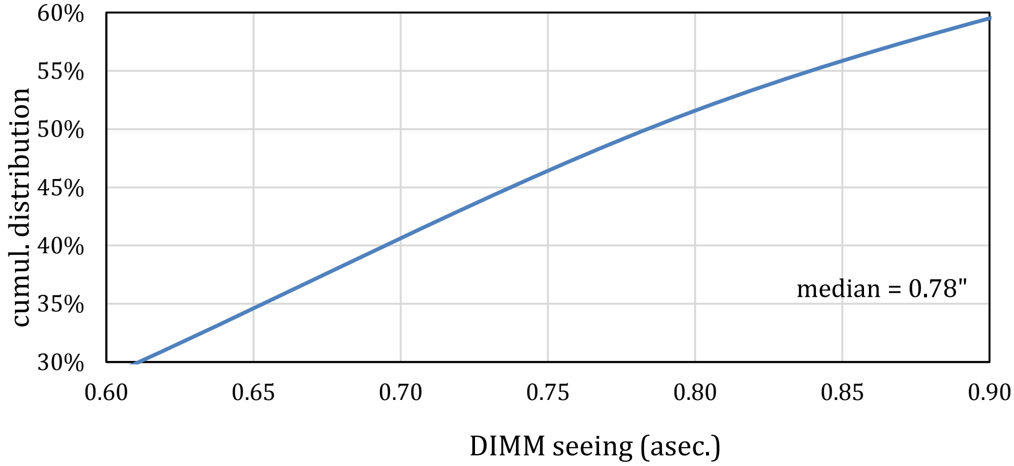


Figure 4: Cumulative distribution of seeing in 2012 from the TNG, at a site near the proposed TMT site on ORM.

Site	Median (“)	Average (“)	% > 2”
ORM TNG	0.85	1.05	7.8%
ORM ING	0.82	0.97	4.9%
MK13N	0.75	0.87	3.2%
LCO	0.65	0.70	0.2%
Armazones	0.64	0.73	0.5%

Table 4: Median and average seeing at ORM (two sites) compared with MK13N, LCO, and Armazones, kindly provided by René Racine. We also show the fraction of DIMM measurements greater than 2”, in the final column.

Finally we point out that there is a strong seasonal variation in the seeing, with conditions considerably worse during the winter months. This is shown, using the TNG data, in Figure 5.

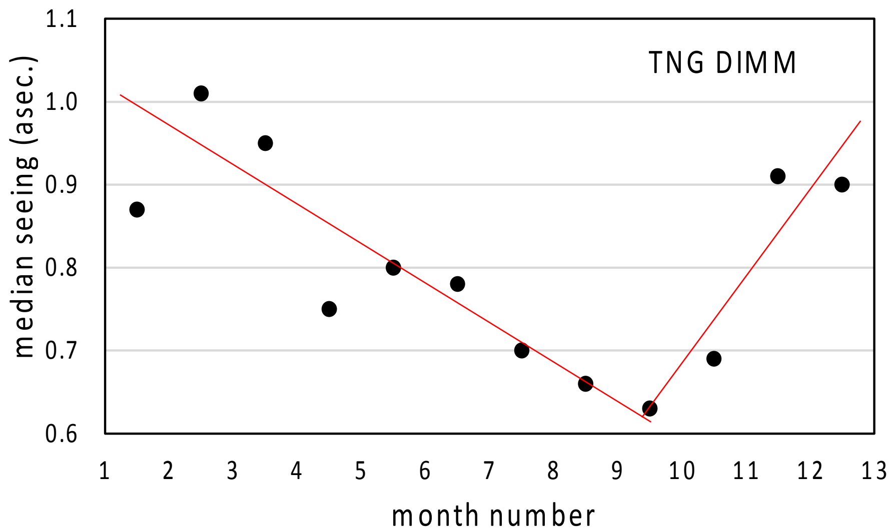


Figure 5: The seasonal variation in the median seeing as measured from the TNG DIMM.

Table 5 below summarizes the various estimates we have described for median DIMM seeing at ORM.

Estimated from	**Reference/notes**	**Median seeing**
ELT site testing (TMT-2)	Vazquez Ramio et al. (2012)	0.80”
ELT site testing (near JKT)	Vernin et al. (2011)	0.80”
GTC site	Munoz-Tunon et al. (1997); 9 month period	0.76”
NOT	Augusteijn/Stetson	0.85”
TNG	Molinari	0.80”
TNG	Racine	0.85”
ING	Racine	0.82”

Table 5: A summary of median seeing estimates near the proposed TMT site, as described in the text.

Based on these measurements, and weighting more heavily the measurements from TNG, TMT-2 and GTC, that are physically closest to the selected TMT alternative site, we adopt 0.80” as the best estimate of the median seeing at that site. There is at least a 0.05” uncertainty in this number, as well as strong seasonal variation.

3.1.4 Summary

We present a summary of two relevant seeing measures - at 7m and 60m - for the four relevant sites, in Table 6.

Site	Median DIMM Measurements at 7m	Median seeing at 60m
Armazones	0.64"	0.50"
MK13N	0.75"	0.50"
ORM	0.80"	0.55"
LCO	0.63"	0.50"

Table 6: Median DIMM (~7m) and 60m seeing for each of the four sites.

Although there have been no direct DIMM measurements at the proposed TMT site on ORM, a careful comparison with neighbouring sites shows that it is likely to be close to 0.80" in the median, with a large seasonal variation (0.60" – 1.0") and a significant tail to large values, with >8% of the time spent with seeing >2.0". The median DIMM seeing is comparable to, but worse than, the preferred site at MK13N. It is significantly worse than the seeing at Armazones or LCO. Sensitivity in observations where this seeing is relevant will suffer by ~50% compared with those sites. However, both CFD simulations and comparison with other downslope sites indicate that the ground layer is more important at ORM than at Armazones, and thus the seeing becomes more comparable as altitude increases.

In most of the performance metrics and comparisons provided by the Project Office, and used in this report, contribution from the ground layer at <60m is neglected. This is probably reasonable for good seeing sites that do not vary too much, and for zenith observations. But it is likely optimistic for a site like ORM where the ground layer is strong and the median seeing at 7m is large.

3.2 Clear Sky Fraction

To establish the fraction of clear sky on ORM and other sites for comparison, we mainly refer to the work of the ELT site characterization group (Vernin et al. 2011) who provide extensive statistics for four sites including ORM and Paranal (where the VLTs are located). We supplement their results with those from the TMT Alternate Site Team (Schöck – CATAC presentation). The values we adopt are given in Table 7. The clear fraction on ORM is consistent with that measured by Della Valle et al. (2010) from satellite data, and lower than the 84% reported by Vernin et al. (2011). We note there is strong seasonal variation in this fraction at ORM, as shown in Figure 6.

There is some controversy over the definition of “useable time” that affects the absolute values in the table at the ~10% level. We follow the TMT project office in adopting consistent measurements, based on satellite data, for the fraction of clear nights at each site. This is not the same as the fraction of clear hours, or the fraction of usable nights/hours, and measurements from satellites can both over- and underestimate what is measured from the ground (della Valle et al. 2010). Furthermore, the large fraction of time with seeing >2” (Section 3.1.3.2) leads to an additional ~5% loss of usable time at ORM relative to the other sites.

Site	**% Nights Clear**	**Source**
Armazones	86%	Vernin et al. 2011
LCO	75%	Schöck
ORM	72%	Della Valle et al. (2010)
MK13N	72%	Schöck

Table 7: Fraction of clear nights, and source of the information, for each of the four sites.

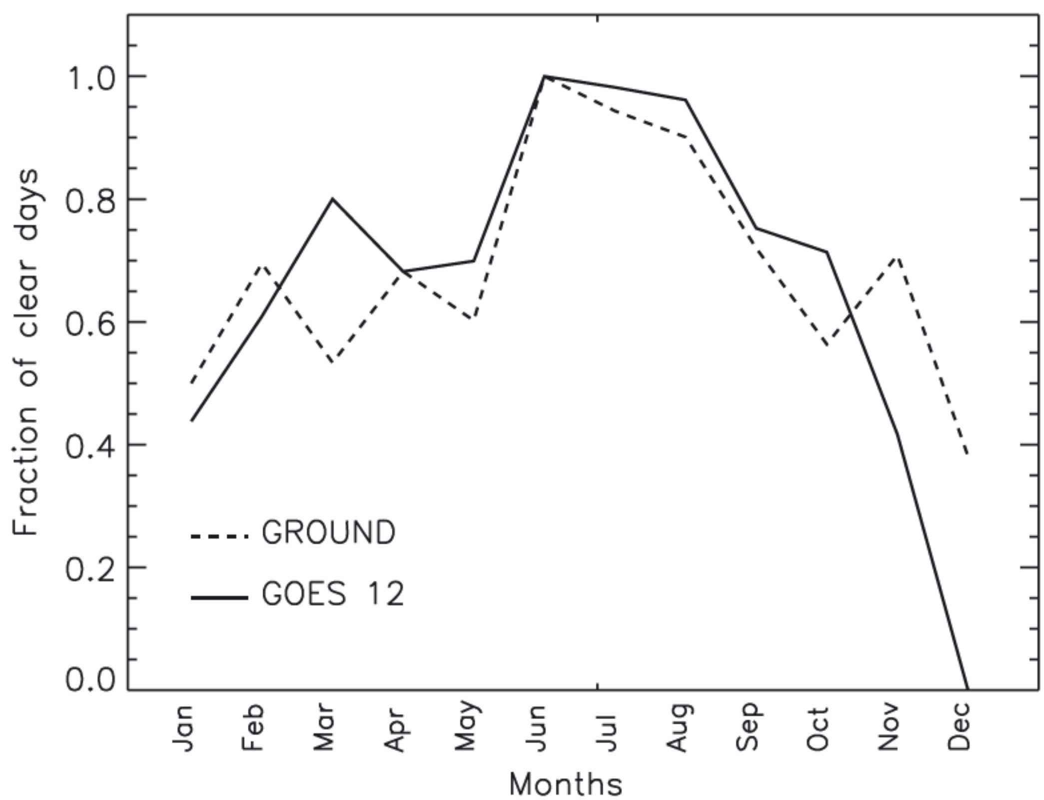


Figure 6: Fraction of clear nights (despite the y-axis label) at ORM, taken from Fig 16 in della Valle et al. (2010). The dashed line shows data from the TNG and CMT logbooks, while the solid line shows GOES 12 satellite data.

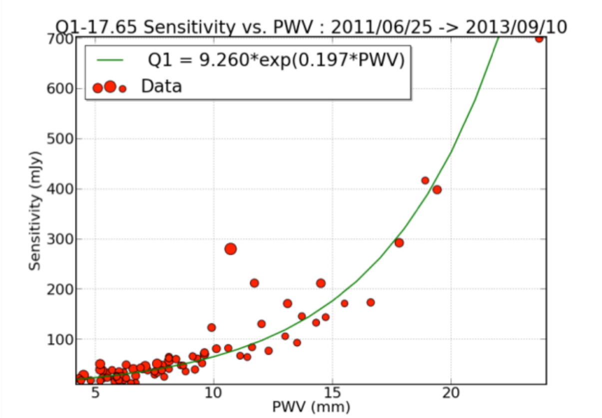
3.3 Extinction

The figure of merit for the effect of dust in the atmospheres at the various sites is the extinction in magnitudes per airmass. At wavelengths shorter than about 400 nm there is a sizeable difference between ORM, MK (at the Gemini site) and the best Chilean site (at 400 nm the values are 0.4, 0.3 and 0.25). However at wavelengths longer than 550 nm there is very little to choose between the sites under normal circumstances. The formal values at 550 nm are 0.14, 0.11 and 0.13 respectively.

There has been much discussion on the effect that the dust can have on the extinction – dust at ORM that gets blown up from the Sahara. As shown by Lombardi et al. (2011), the presence of the dust is by no means seasonal – it can show up at any time of the year but is generally higher during February to April and July to August each year. Their most important finding is that the dust contribution to the total sky background in the near infrared is negligible compared to the airglow even during dusty conditions, contributing only about 9% to the total background at K band.

3.4 Precipitable Water Vapour, Temperature and Pressure

The amount of water vapour in the atmosphere will strongly affect the efficacy of infrared observations. This will be particularly important in the K band (out to 2.4 μm) where a number of first light instruments on TMT are planned and later in the L and M bands (3-5 μm) and possibly out to 14 μm where it is expected that high resolution imagers and spectrographs will search exoplanetary atmospheres for evidence of life. The metric adopted by the TMT SAC to evaluate the water vapor content of the atmosphere is the fraction of time where the precipitable water vapor (PWV) of the atmosphere is less than 2 mm. The PWV in the atmosphere is the depth of a column of water if all the atmospheric water precipitated out as rain. Sensitivity in the MIR is a strong function of PWV, as illustrated in Figure 7, from Chris Packham's presentation:



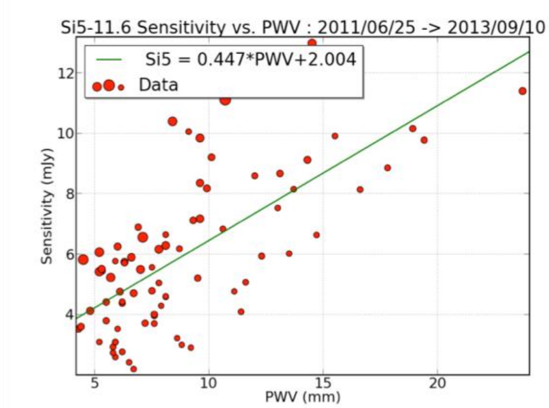


Figure 7: Sensitivity in mJy as a function of PWV, for the Q1 band (17.65μm, left) and the Si5 band (11.6μm, right)

Table 8 provides PWV estimates for the relevant sites. These data were selected from Schöck's the presentation to CATAC. We also show measurements of the mean night temperatures, and the atmospheric pressure estimated directly from the site altitude. The pressure is relevant because pressure broadening of telluric lines affects the useful windows for high resolution spectroscopy; lower pressure means narrower lines and a larger useful wavelength range.

Site	**Percentage of time with PWV < 2 mm**	**Mean night Temperature (C)**	**Pressure (hPA)**
MK13N	54%	2.3	612
Armazones	50%	7.5	691
LCO	23%	13.0	750
ORM	20%	7.6	771

Table 8: Site characteristics most relevant to MIR observations: PWV, temperature and pressure, for each of the four sites.

3.5 Adaptive Optics Performance

3.5.1 Background

As AO may be unfamiliar to some people and involves more technical considerations, we begin this section with a preamble introducing some basic definitions and explanations.

Put simply, AO is used to correct the blurring effects of atmospheric turbulence and concentrate the light at wavelength λ of an imaged point source within a sharp diffraction core of diameter λ/D. The image quality delivered by an AO system is usually measured by the Strehl ratio, S, which roughly corresponds to the fraction of the total flux that lies in the diffraction core of an imaged point source. Strehl has a significant bearing on the efficiency and sensitivity of the observations, as in the background limited regime, the time needed to reach a given signal to noise scales as $1/S^2$.

The value of the Strehl ratio depends on the total residual wavefront error (WFE) after AO correction, which is the RMS departure of the wave front from a perfect plane wave over the full aperture of the primary mirror. In turn, the residual WFE depends on the details of implementation of the AO instrument and on the atmospheric turbulence characteristics of the site and telescope enclosure. Here we are concerned mainly with the atmospheric characteristics of the site, of which the most relevant are the turbulence profile, the isoplanatic angle, and the atmospheric coherence time.

The turbulence profile is simply the strength of atmospheric turbulence as a function of height in the atmosphere. By integrating the turbulence profile from some height above the ground up to infinity, one can obtain the seeing parameter r_0 corresponding to that height, which corresponds to the typical sub-aperture diameter over which the perturbed wave front is reasonably coherent, or flat. The value of r_0 is related to the FWHM of an imaged point source, known as the seeing width, through $w=\lambda/r_0$. Thus, the value of either r_0 or the seeing width, for some height, specifies the total error imparted on the wave front by the atmosphere turbulence above that height; larger values of r_0 or lower seeing widths are better, corresponding to smaller WFE. The values of r_0/seeing width for a height well above the top of the telescope enclosure are referred to as the “free atmosphere” seeing parameter/width. Turbulence occurring only near the ground is referred to as the ground layer turbulence. The AO system attempts to correct the total WFE introduced by the free atmosphere and ground layer turbulence (and any boundary layer in between, as well as the dome), but it cannot do so perfectly and leaves a residual WFE that is proportional to $r_0^{-5/6}$, which is referred to as the fitting error. The fitting error accounts for about half of the total residual WFE budget and, for NFIRAOS on-axis observations, its contribution dominates over those from anisoplanatism or coherence time.

For single conjugate adaptive optics (SCAO), the isoplanatic angle corresponds to the angular scale within which the wave fronts between two lines of sight through the atmosphere remain reasonably well correlated. The correction applied by the AO system will be most effective for sources within that angular separation from the optical axis, as the mirror deformation will match more closely their actual wave front than it would for a source further off axis. In multiconjugate adaptive optics (MCAO) systems like NFIRAOS, the isoplanatic angle corresponding to two deformable mirrors (2-DM) is more appropriate. It has a different dependence on the turbulence profile, and also depends on the conjugate altitudes of the DMs. For a given off-axis angular separation, image quality degrades faster for smaller values of the isoplanatic angle. Of the atmosphere contributions, this anisoplanatism error is one of the major contributors to the total residual WFE for NFIRAOS off-axis observations; it is irrelevant for on-axis observations.

The atmospheric coherence time is the timescale over which the wave front remains well correlated with itself. In any AO instrument, there is a finite time delay between the measurement of the WFE and the correction applied to the deformable mirror, typically about 1 ms with current AO systems. If the time lag between the sensing and correction is short compared to the atmospheric coherence time, then the correction will be most effective; on the other hand, if the delay is long, then the mirror deformation applied will poorly match the wave front hitting it and the correction will be ineffective, leading to a loss of Strehl. The residual WFE associated with this delay is referred to as the bandwidth error. For NFIRAOS, calculations indicate that the bandwidth error is never a dominant factor for the delivered Strehl. However, it could become an important factor In the extreme AO regime.

3.5.2 Site characteristics relevant to AO operation

TMT has made extensive measurements and analysis of the atmospheric turbulence characteristics of ORM and other sites, and the NFIRAOS team has made full simulations of the instrument operation to predict the delivered Strehl. As noted in Section 3.1.2, no turbulence profile measurements were made at the precise planned TMT location at ORM, which is on a slope below the ridge; instead, turbulence profile measurements at other ORM ridge locations were used to estimate the profile above the TMT site. Moreover, the turbulence profile at heights <60m were not included in the simulations. Thus there remains some uncertainty in both the magnitude of the ground layer contribution and its impact on AO observations. The free atmosphere profile is very close to the same for sites in close proximity.

The relevant site characteristics findings are summarized in Table 9. The Strehl merit function used in the table is simply a metric proportional to the square of the Strehl ratio, S^2, normalized to its value at MK13N. It should be stressed that this metric is strictly about AO, and assumes no contribution from atmospheric turbulence below 60m. To compare the overall sensitivities between sites other factors such as atmosphere transparency, cloud cover and sky coverage due to guide star availability should also be taken into account, as we do in Section 4.1. For reference, at MK13N the NFIRAOS team predicts a delivered Strehl of 75% at K, 60% at H and 40% at J, under median seeing, on-axis, and at zenith. Such high values have been reached with existing AO systems at Keck and the LBT.

From a strict AO perspective, the values in Table 9 indicate that all four sites are good for AO observations, with MK being the best on all accounts, followed closely by both ORM and Armazones, which are on par with each other. ORM has the largest 60-m seeing width, and thus would offer the poorest performance for on-axis observations, but the degradation of the Strehl merit function is only a few percent. On the other hand, ORM has a larger isoplanatic angle, which compensates and brings it on par with Armazones for off-axis observations. Another difference to note is that for ORM the Strehl decreases less rapidly when moving away from the zenith compared to Armazones, but again the differences are small, and moreover the predictions neglect any contribution from the <60m ground layer turbulence, which could have a stronger impact for off-zenith observations. ORM also has a marginally longer coherence time than Armazones, which could be an advantage for future generations of extreme AO instruments. Although not quantified in the table above, the TMT team mentioned that the seasonal and short-timescales variations of seeing and availability of conditions appropriate for AO are comparable between the three sites. Overall, from the above consideration, ORM is a good AO site and should be competitive with Armazones for AO performance.

Parameter	ORM	MK13N	LCO	Armazones
60-m median seeing width	0.55”	0.5”	0.5”	0.5”
Isoplanatic angle	2.33”	2.55”	2.05”	2.05”
Isoplanatic angle, 2 DMs	8.27”	9.45”	7.78”	7.78”
Atm. coherence time	6 ms	7.3 ms	5.0 ms	5.0 ms
Strehl merit function for median seeing				
On-axis, at zenith, JHK	0.95	1.0	N/A	0.98
On-axis, at 45° from zenith, JHK	0.94	1.0	N/A	0.92
Full field, at zenith, JHK	0.92	1.0	N/A	0.93
Full field, at 45° from zenith, JHK	0.93	1.0	N/A	0.84
Average of above	**0.93**	**1.0**	**N/A**	**0.92**
J-band, full field, zenith	0.84	1.0	N/A	0.81
H-band, full field, zenith	0.94	1.0	N/A	0.88
K-band, full field, zenith	0.98	1.0	N/A	0.93

Table 9 : Summary of site characteristics relevant for AO and Strehl merit function as determined by the TMT project and NFIRAOS team. The first 4 lines of the Strehl merit function are based on the full NFIRAOS simulation, while the last three lines are based on a simple proportionality of the square of the Strehl ratio, S^2. The isoplanatic angle with 2 DMs represents an effective isoplanatic angle when using a two-stage wave front correction as in NFIRAOS. The entries for LCO are as used by the TMT site testing team, but assume the same atmospheric turbulence parameters as Armazones; the GMT site-testing by Thomas-Osip et al. (2011) suggests this is reasonable within the uncertainties. Source: TMT.SIT.PRE.16.008.REL04 (SMF_160718_v0722.pptx)

The above conclusions rely in part on the assumption that the turbulence below 60-m would be the same at all sites for TMT. However, it is likely that the actual dome seeing will be affected to some degree by ground layer turbulence outside the dome. It is thus worthwhile to consider the lower level turbulence at the different sites. As described in Section 3.1.3.2, the median 7-m seeing at the TMT site on ORM is likely near 0.8”, only slightly larger than the value at MK13N (0.75”), but considerably larger than that at Armazones or LCO. If the turbulence outside the dome were to influence the seeing inside the dome, the Strehl degradation would be more important at ORM than at MK13N. A simple scaling of the delivered Strehl with estimated 25-m seeing values (0.68” at MK13N, 0.76 at ORM), assuming that the seeing accounts for only half of the total residual WFE, leads to a Strehl merit function of 0.73, 0.84 and 0.9 at ORM for respectively J, H and K, normalized to MK13N. For observations at large zenith angles, where the ground layer could affect more the effective turbulence at <60m, the impact could be worse. However, the real impact is not as straightforward to determine. Another consideration to keep in mind, as explained in the NFIRAOS error budget document, is that the CFD modelling used a coarse spatial sampling of 0.2 m and may have missed higher spatial frequency components, which are harder for the AO system to correct. It is not known if including these higher frequency components could reveal an increased dependence on the outside ground layer turbulence.   For reference, the NFIRAOS team assumed a dome seeing WFE of 400 nm for all their work, independent of site. Again for reference, the ground layer at MK13N was measured to be 0.54”, corresponding to about 6500 nm of WFE at H band.

4 Science prospects and Competitiveness

4.1 Point source sensitivity in the optical and NIR

Hickson and Carlberg produced a report on TMT sensitivity in UV through NIR bands, at various sites and compared with ELT. This was characterised as the point source sensitivity (PSS), proportional to the inverse of the actual time required to reach any given S/N ratio on a faint, unresolved target. It uses the definition of Seo et al. (2009), modified to include the fraction of usable nights available. It accounts for collecting area, atmospheric transmission, background emission and seeing or Strehl ratio, as appropriate. However, these calculations assume no contribution from atmospheric turbulence below 60m; the justification being that turbulence below 60m is dominated by the dome and approximately site independent. As we pointed out in Section 33.1, this assumption is likely optimistic for predicted performance at ORM, particularly for non-zenith observations.   On the other hand, the ELT predictions are based on an older, 5 mirror design, while the current design has six reflections, reducing throughput. The ELT AO predictions also do not include the extra reflections in MAORY that are yet to be added to mitigate image distortion. In Table 10 we summarize the PSS at zenith for TMT@ORM and ELT, where the values are normalized to 1 for TMT@MK:

	TMT@ORM +NFIRAOS	ELT +MAORY	TMT/ELT Ratio	ELT at same Strehl as TMT	TMT/ELT Ratio Assuming same Strehls
UV	0.65	1.8	0.36	1.8	0.36
V	0.75	1.95	0.38	1.95	0.38
J (AO)	0.85	0.5	1.7	3.05	0.28
H (AO)	0.85	0.85	1.0	3.30	0.25
K (AO)	0.75	0.6	1.25	2.16	0.35

Table 10: Expected PSS values for TMT@ORM and ELT at zenith are shown in 5 different bands. The first two columns show the expected first-light performance, when TMT will have the NFIRAOS AO system, and ELT will have the MAORY system. The ratio of PSS is given in column 4. It is conceivable that a second-generation AO system on ELT will have comparable Strehl to TMT; with this assumption we obtain the PSS in column 5, and the ratio of TMT to ELT under this assumption is given in the final column. Note that these values are based on an older, 5 mirror design for the ELT (the current design has six), and do not include the anticipated extra reflections in MAORY.

Despite the aperture disadvantage, TMT is expected to outperform ELT for AO applications in the NIR, due to the better Strehl ratios predicted. This advantage is mitigated somewhat (15%) by the lower clear fraction on ORM compared with Armazones. There is also significant controversy about the actual Strehl ratio that will be achieved, by either telescope. Improvements to adaptive optics technology may mean that both telescopes achieve comparable Strehl results at some point in the future. In this case, shown in the final column, the larger aperture of ELT would lead to better performance (D^2) at all wavelengths, by a factor 2.5 (V) - 4 (H). In this case ELT would significantly outperform TMT, even if TMT were sited at MK13N.

4.2 Thermal Infrared

In the thermal IR, the small fraction of time with PWV<2mm (20%), coupled with the warm average temperature and higher atmospheric pressure makes for a challenging environment. We use the site merit functions computed by the TMT project office (Skidmore) to reflect the combination of these parameters. They are reproduced in Table 11, normalized to 1.0 for MK13N, and are based on detailed transmission calculations, including all relevant atmospheric parameters. The first entry is a combined metric of low and high spectral resolution capabilities over the 3-14 μm window, while the second is just for low-resolution at 3-5μm.

	ORM	LCO	Armazones	ORM/Armazones
MIR metric (3-14μm, low+high res)	0.16	0.21	0.78	0.20
MIR metric (3-5μm, low res)	0.25	N/A	0.81	0.31

Table 11: Site merit functions in the MIR for the four sites under consideration.

The adopted SMF demonstrate that Armazones outperforms ORM by a factor 3-5. Most of this is due to the lower fraction of time with clear, dry skies at ORM. When conditions are appropriate for MIR observations, the performance disadvantage of ORM is ~50%. Note that this is strictly a site comparison metric, and does not include thermal background from the telescope structure, which can dominate the sensitivity. A better illustration of the relative performance of TMT@ORM and ELT@Armazones is shown in Figure 8, taken from the MICHI team's July 2016 submission to the TMT project, and as shown in Chris Packham's presentation to CATAC. The figure compares the time required for TMT@ORM to reach the same S/N as ELT@Armazones, as a function of wavelength, and includes thermal emissivity from the telescopes (but no instrument contribution, and based on an older ELT design with five reflections instead of six). The disadvantage of TMT is a factor two at best.

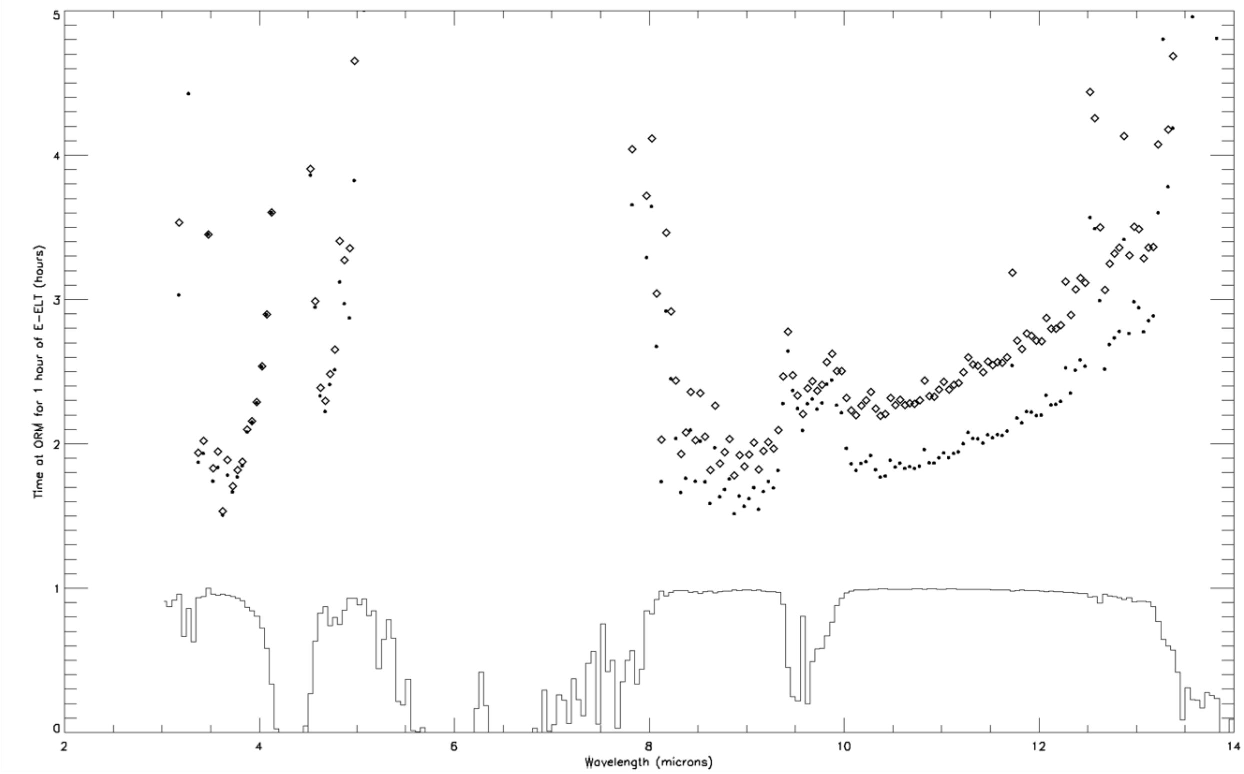


Figure 8: The expected time for TMT@ORM to reach the same S/N achieved at ELT in 1hour, as a function of wavelength, is shown as the points. The diamonds are the median, and the small dots show results under 20th percentile conditions.

4.3 Predicted scientific performance with AO: The Example of Nearby Galaxies

IRIS is a first light instrument on the TMT. It will be used with NFIRAOS, and the IRIS+NFIRAOS combination will provide a basic means of exploiting the D^4 advantage that is inherent to VLOTs. Given the role that NFIRAOS+IRIS provides in exploiting the diffraction-limited performance of the TMT, and that IRIS is one of only three first light instruments, then it is likely that NFIRAOS+IRIS will see extensive use during the first few years of TMT operations.

The scientific performance of any AO system depends on the quality of the site. As we have shown, ORM is expected to have comparable AO performance to MK, assuming that the turbulence profile below 60m is dominated by telescope and dome effects, and thus approximately site independent. Under this assumption, the science examples below that used NFIRAOS simulations generated for MK should still be relevant at ORM, although one should keep in mind that sensitivity-wise the PSS metric would be 15-25% lower than at MK.

The TMT on ORM will be able to access to numerous Local Group galaxies that are considered to be benchmarks for understanding galaxy evolution. These include M31 and its companions, M33, and NGC 6822 among many others. It will not be able to access the LMC and SMC from ORM – these are exclusive southern hemisphere targets. There are also numerous nearby galaxy groups that will be accessible from ORM, and these include the M81 group (e.g. M81, NGC 2403, and M82 – a nearby starburst galaxy), the northern part of the Sculptor group (including NGC 247 and NGC 253 – another starburst galaxy), the Maffei/IC 342 group, and the Leo group (including NGC 3379, which is one of the closest classical – from a morphological perspective - elliptical galaxies). A nearby galaxy group that cannot be observed from ORM is that centered on CenA and M83.

NFIRAOS+IRIS on ORM will deliver transformational science when used to observe nearby resolved systems. When observing at a given wavelength, the angular resolution of the TMT is just under one fifth that delivered by JWST, and more than one-tenth that delivered by the HST. The results of such an improvement in angular resolution are illustrated in Figure 9, from Stephens et al. (2003), where a field in the bulge of M31 observed with 1 arcsec angular resolution from the ground in H is compared with an HST NIC2 image with 0.2 arcsec FWHM resolution. Objects that appear to be single stars in the ground-based image are clearly resolved into asterisms. This has profound implications for understanding the properties of stars in galaxies. A gain in resolution that is comparable to that shown in the figure will be realized for studies of galaxies at distances of 8 Mpc when comparing observations with 8 meter telescopes with those achieved with the TMT.

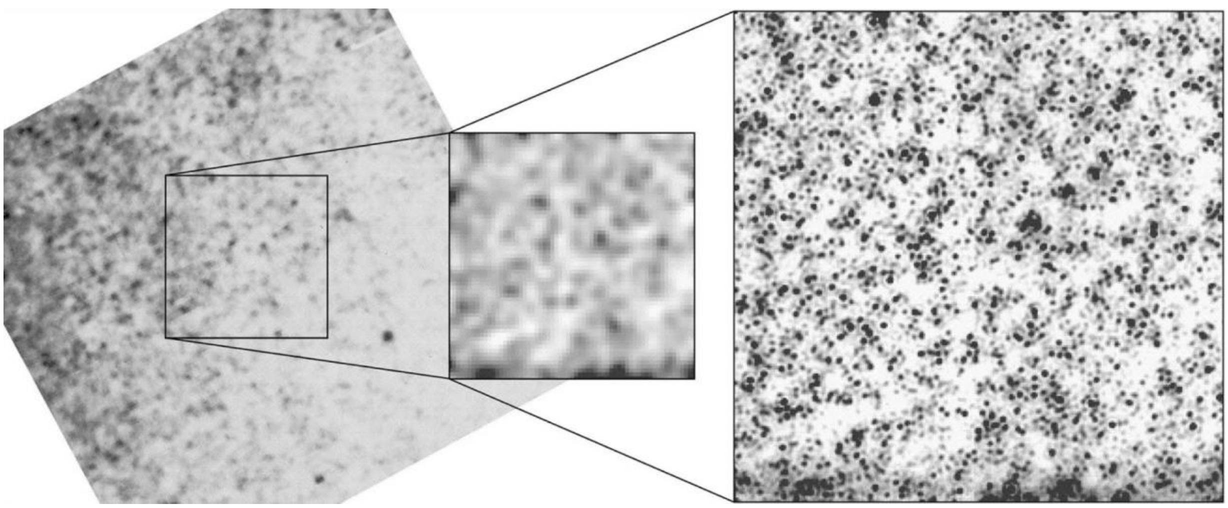


Figure 9: Figure 15 from Stephens et al. (2003). The left hand panel shows a field in the bulge of M31 observed in H with an angular resolution of 1 arcsec. The right hand figure shows a part of this field observed with NIC2, with an angular resolution of 0.2 arcsec FWHM. This comparison demonstrates using real observations how our understanding of stars in nearby galaxies can be revolutionized with gains in angular resolution.

The angular resolution of the TMT will allow stars to be resolved in areas of M31 where this has been heretofore impossible. Figure 10 compares the central few arcsec of M31 as observed with the HST with a NFIRAOS+IRIS simulation. The use of a 30 meter telescope results in an order of magnitude improvement in angular resolution. Whereas the central sources P1 and P2 are not resolved with the HST, they will be resolved into myriad stars with the TMT, most of which are evolving on the upper asymptotic giant branch (AGB).

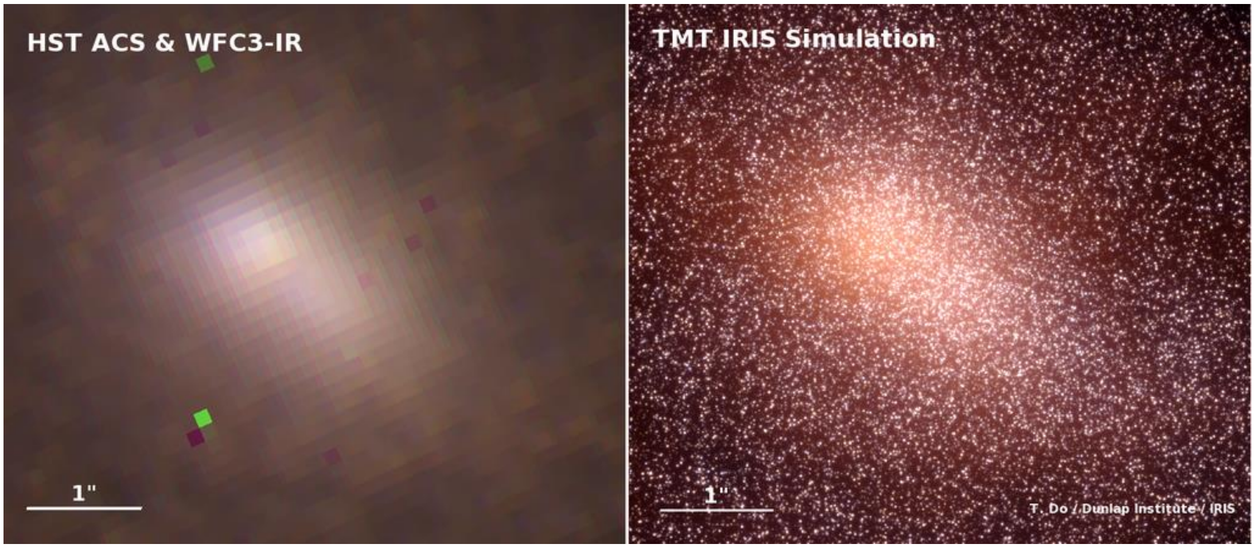


Figure 10: A three color (F814W, F110W, and F160W) image of the central regions of M31 observed from the HST (left hand image) and a simulated three color (Z, J, and K) image of the same field as observed with IRIS+NFIRAOS (right hand image). Stars that are unresolved with the HST can be resolved with the TMT.

The Virgo and Coma galaxy clusters pass close to the zenith on ORM, and with IRIS+NFIRAOS it will be possible to resolve galaxies in the Virgo cluster into stars that are well below the AGB-tip. This is demonstrated in Figure 11, which compares a field with a surface brightness of 22 mag/arcsec^2 in V in a Virgo spheroid as observed for three hours in K with Keck (left hand panel) and NFIRAOS+IRIS (right hand panel). With Keck it is only possible to resolve and detect the brightest AGB stars. However, with NFIRAOS+IRIS it will be possible to resolve stars below the tip of the red giant branch. This will enable – for example – the direct measurement of mean metallicities and metallicity dispersions in these systems. We further note that with NFIRAOS+IRIS galaxies in the Coma cluster will be observed with roughly the same performance as Virgo cluster galaxies observed with Keck – i.e. while it will not be possible to reach the RGB-tip in Coma cluster galaxies the brightest stars can still be resolved.

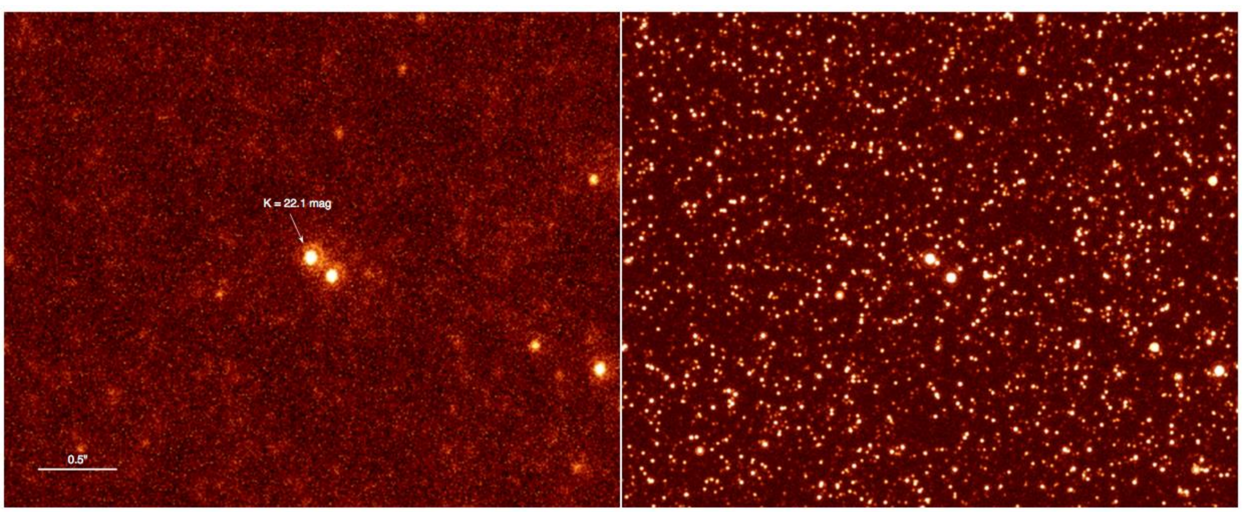


Figure 11: Simulations of a field in Virgo spheroid with a surface brightness of 22 mag/arcsec2 in V. The left hand panel shows the field as observed for 3 hours in K with Keck. The right hand

panel shows the same field observed through the same filter for the same exposure time, but with NFIRAOS+IRIS on the TMT.

4.3.1 Limitations of AO

While the simulations discussed above indicate that the TMT (at any site) will produce transformational science, there are important limitations of AO that should be noted. These are site independent.

1. Limited sky coverage. The ability to deliver good images depends on the availability of three guide stars in a suitable asterism. The system is designed to guide on objects that are as faint as J=21. While the density of objects with this brightness is very high, at this magnitude many possible guide objects may prove to be background galaxies or binary systems, and hence not suitable for wavefront sensing. NFIRAOS is designed to deliver `good' image correction with 50% sky coverage at the North Galactic Pole. While full performance will then not be delivered over the entire sky, it will still be possible to obtain images with a reduced level of correction using a partial asterism. While identifying suitable guide objects in extant surveys of nearby galaxies may prove to be a challenge given that many stars will break down into groupings of fainter objects when observed at higher angular resolutions, this will work to NFIRAOS's advantage. Indeed, NFIRAOS will have the ability to use signal from the IRIS imager to provide guiding information. It will then be possible to identify guide sources in regions that have not previously been resolved. Nearby galaxies might then prove to be an ideal environment for identifying good guide star asterisms.

2. Anisoplanicity. Multi-conjugate AO systems like NFIRAOS strive to deliver a uniform PSF over the corrected field. However, whereas PSF stability is vastly improved when compared with classical AO systems that use only a single reference beacon, PSF stability and subtle variations in the angular scale across the detector will still be sources of frustration. If there are numerous PSF stars available in the science field (which is the case in the dense regions of nearby galaxies) then a PSF and knowledge of its positional dependence across the field can be obtained empirically. However, a large number of suitable PSF stars will not be available in many cases e.g. observing fields near the Galactic Poles). The TMT is currently investigating methods to construct PSFs using telemetry from the AO system. This is still a work in progress and the finite information available from the AO system might limit the ability to construct accurate PSFs.

3. Time restrictions. AO can not be used all of the time. Not only will AO performance be limited during mediocre and poor seeing conditions, but the ability to propagate lasers will be hindered by aircraft, thin clouds, and transient properties of the Na layer.

4.4 Latitude and Site Synergies

Should TMT be sited on MK, the neighbouring telescopes will be familiar and possible synergies are fairly well known. The site at ORM will be less familiar to most Canadians, so in Table 12 we summarize the other operational telescopes with apertures larger than 2m. A number of smaller telescopes are also located on the site. As can be seen from this table, the majority of these facilities at present offer imaging and spectroscopic capabilities at visible and near-infrared wavelengths; the GTC also offers imaging and spectroscopy in the mid-infrared. With suitable co-ordination (through – say- the site owner Spain) these facilities could prove useful for the planning of TMT observations or for co-ordinated observing campaigns.

Telescope	Aperture (m)	Owners	Year Completed	Instruments
GTC	10.4	Spain, Mexico, USA	2008	VI, VS, Mi, MS
WHT	4.2	UK, Netherlands, Spain	1987	VI, VS, NI, NS
TNG	3.6	Italy	1998	VI, VS, NI, NS
NOT	2.6	Denmark, Sweden, Norway, Finland, Iceland	1988	VI, VS, NI, NS
INT	2.5	UK, Netherlands, Spain	1967 (moved to ORM 1984)	VI, VS

Table 12: The table above shows a list of telescopes located on ORM that have apertures larger than 2 meters. Instrument capabilities in the final column are VI (visible light imaging), VS (visible light spectroscopy), NI (near-infrared imaging), NS (near-infrared spectroscopy), MI (mid-infrared imaging), MS (mid-infrared spectroscopy).

In addition to the telescopes on ORM, the TMT partners operate major facilities at similar latitudes to that of ORM, and these are summarized in Table 13. These facilities span a large range of longitudes, effectively providing global coverage. With suitable coordination, the resulting multi-time zone coverage could enable the continuous monitoring of transient targets (e.g. gamma-ray bursts, supernovae, short period solar system phenomena, etc).

Telescope	Aperture (m)	Owners	Year completed	Latitude, Longitude	Instruments
China large telescope	12	China	2020+	+33,79E	?
Keck	10	US	1993	+20,155W	VI, VS, NI, NS
Subaru	8.3	Japan	1998	+20,155W	VI,VS,NI,NS
Gemini North	8.1	US, Canada, Argentina, Brazil	2000	+20,155W	VI,VS,NI,NS
LAMOST	4.9	China	2008	+40,117E	VS
Devasthal Optical Telescope	3.6	India	2016+	+29,80E	?

Table 13: Telescopes operated by TMT partners at sites similar to that of ORM (+29 degrees latitude, 18 degrees west longitude). The Chinese 12m and the Devasthal telescope are still under development. The instrument key is the same as for **Table 12**.

4.5 Timelines

- **TMT:** The stated plan is to start construction in April 2018, either at MK or ORM. The detailed plan for completion on MK is not fully funded at the present time. If the site is switched to ORM there will be a few months required for the governments of certain partners to assess and/or commit to the new site. Whether or not this amounts to a delay depends on how far in advance of the April 2018 date it becomes clear that MK is not a viable option. It is possible that the NSF Decadal survey will need to comment on GSMT (the generic US project) before the NSF will commit. A 2020 Decadal survey requires a white paper in early 2019, with a secure site in hand. The earliest that NSF would provide a response to the Decadal would be late 2020, with congressional funding in 2022, in an aggressive timeline. It is unclear whether or not construction can begin before NSF funds are in place, or if an agreement with NSF might be reached before the Decadal survey. The first light date therefore remains uncertain, with likely estimates falling in the range 2026-2030.
- **Mauna Kea:** The contested case hearings on the construction permit have concluded, and the hearing officer has set a mid-June date to receive proposed Findings and Conclusions of Law, along with comments on other party's submissions. Once her recommendations are made, they would go to the Board of Land and Natural Resources (BLNR) for a decision. The decision of BLNR could be appealed to the Hawaii Supreme Court, but the court may decide to not hear the appeal. There remains a possibility that a second contested case, for the site lease, will proceed. The timeline for being able to determine whether on not construction on MK will be possible therefore remains uncertain, but there are a handful of reasonably likely scenarios that would be consistent with a planned start date of April 2018.
- **GMT**: The 2017 update to AAS states telescope and enclosure contracts will be issued mid-2017, with engineering first light expected for 2023. However, like TMT, GMT does not have their funding in place and they are actively seeking new partners and philanthropists to enable construction. Their advertised time to first light is almost certainly optimistic, though a good estimate is lacking.
- **ESO:** ESO published a detailed overview along with financial information projected to 2040 in the ESO Messenger of Dec 2016. This plan envisions a 2024 first light for Phase 1, which is missing 20% of the mirror segments, largely negating the aperture advantage to TMT. There is no funding plan in place for Phase 2, though the recent announcement that Australia is entering into a strategic partnership with ESO may change that in the near future. Though Phase 1 is not funding-limited, the 2024 first light is likely optimistic technologically.

There is certainly a big scientific advantage to being first on the sky; to execute the first obvious observations that take advantage of new technology (the "low-hanging fruit") and to be first to stumble upon exciting new discoveries. Canadians are wary of the prospect of being on-sky much later than the competition, as the Keck/Gemini competition still stings. At this point it is still unclear which of the three VLOTs is most likely to be constructed first, even with the construction delays that TMT is facing. However, we can take action to minimize the impact of a delay, by ensuring that TMT has first-light capabilities that are unique, and scientifically exciting. A good example is that TMT is planning two MOS instruments, while ELT has none. The TMT AO system, NFIRAOS, is also an extraordinary capability and there are doubts that the ELT equivalent (MAORY) will be ready at first light. This would give TMT an advantage in MCAO operation. In the event that it becomes clear TMT will be significantly later than ELT or GMT, a push for accelerated development of unique instrumentation to be ready at first light would be a sensible, and possibly realistic, approach.

5 Communication with Canadian community

This section describes what has been done to improve communications with the Canadian community since the formation of the CATAC at the start of 2017, and includes website and contact information. It also describes an important initiative to increase Canadian participation in the International Science Development Teams.

Since its formation at the start of 2017, the CATAC has used several different methods to reach out to the community to provide information and to receive comments and feedback.

(1) Important and time-critical information and updates are sent to the CASCA email exploder. Information sent out via the exploder in 2017 included: the announcement of the formation of the CATAC and the committee members (January 27); an introduction to CATAC activities from the committee chair (Feb 13); circulation of the draft CATAC report to the community for feedback and comments (April 16); reminder of the schedule for TMT information and discussion sessions at CASCA (April 27); and an update of information from the recent TMT Board and SAC meetings as well as an invitation to join one or more of the International Science Development Teams (May 10). These email updates go only to CASCA members; astronomers who are not members of CASCA and who are interested in TMT information may wish to consider joining CASCA.

(2) In February and March 2017, the CATAC organized public information sessions approximately every other week. The sessions were organized using Webex and reminders and invitations to participate were sent out in advance of each public session. Typically between 25 and 35 people participated in each session. The topics covered in the 4 sessions were: First light instrumentation; what do Canadians expect from an ELT?; Adaptive Optics performance of TMT; and the proposed bMICHI instrument. The CATAC plans to hold occasional public information sessions in the future as topics and issues present themselves.

(3) A detailed update on CATAC activities was written for the spring equinox issue of Cassiopeia. The CATAC will continue to provide regular updates on its activities in this quarterly newsletter.

(4) The CATAC has a website which can be found at http://casca.ca/?page_id=8347; it functions primarily as a way to consolidate information for the committee and the community. It includes a recent news section, the CATAC Terms of Reference and draft report, and a schedule of the CATAC Webex meetings along with links to the presentation slides and minutes of the discussion. There are also occasional links to background material and external links e.g. to the TMT web site, the TMT Detailed Science Case, etc. This website will be maintained and new material added to it as required.

In addition to these on-going efforts, CATAC is co-hosting two sessions at the CASCA 2017 AGM in Edmonton. The first is an NRC/CATAC lunch meeting on Wednesday May 31, which will provide the latest updates to the community. The second is a CATAC+LRPIC plenary session at the start of the morning on Thursday, June 1. This session will provide more of an opportunity for discussion of TMT/ELT related issues in the context of the full Long Range Plan. TMT information/discussion sessions are planned to be a regular feature at future CASCA AGMs.

5.1 International Science Development Teams

There are nine International Science Development Teams (ISDTs) that have contributed to the TMT science case and serve to provide guidance to the TMT project and instrument teams. Any member of a partner institution or country is eligible to apply to a current team or submit a proposal for a new team. Applications for new members are due in January of each year. The ISDTs are described in more detail at their website http://www.tmt.org/about-tmt/international-science-development-teams.

The ISDTs have a particularly important role to play in the current activity to define the next generation of new instruments, for which funding for feasibility studies may become available in 2018. The selection of ORM as the alternative site should MK prove impossible is also motivating a critical look at the impact of a change of site on the Detailed Science Case, another activity in which the ISDTs play an important role.

Two of the science teams have Canadian conveners: Alan McConnachie for Milky Way and Nearby Galaxies, and Christian Marois for Exoplanets. Of the nine teams, five have no Canadian members, and four have two or three. The lack of Canadian engagement on the science teams for the TMT project is not consistent with our published priorities in the Long Range Plan. Leadership and activity within the science teams can compensate to some extent for decreased partner share, and will contribute towards making sure Canadian priorities in terms of next generation instruments and operations are known. That said there are barriers to active participation, one being the lack of travel funding to participate in science team face-to-face meetings. Even a modest allocation of ~$2-8k per person would make a significant difference in facilitating science team membership. An allocation of $90k-$360k/yr would provide travel support for 1-2 yearly meetings for 45 Canadian ISDT participants.

The spring 2017 SAC meeting clarified that Canadian applications to join the ISDTs will be welcomed at any time (the normal call for new members is in January). This gives individuals from the broader Canadian community an opportunity to engage in detail with the TMT, our most ambitious astronomical observatory. The CATAC strongly encourages all interested Canadians to consider submitting applications to join one or two ISDTs. The CATAC will also be proactively reaching out to individual Canadians to encourage them to consider joining an ISDT as soon as possible.

The CATAC is actively pursuing options to find funding to assist Canadians astronomers in participating in ISDTs, particularly for the annual Science Forum (in 2017 to be held in Mysore, India). However, it is important to note that most of the work of the ISDTs is done remotely and so funding is not required to participate in an ISDT. Participating in the ISDTs is one of the ways for the Canadian community to work actively to help the TMT project succeed and the CATAC hopes that many people will rise to the challenge and become more involved in the TMT through participation in an ISDT.

5.2 Points of Contact

CATAC website http://casca.ca/?page_id=8347
CATAC chair: Michael Balogh: mbalogh@uwaterloo.ca

5.3 Information links

- **The Thirty Meter Telescope**
- TMT Detailed Science Case 2015
- TMT site testing page
- International Science Development Teams (ISDTs)
- ACURA
- CASCA (includes links to the Long Range Plan and the LRPIC)

6 Findings

Here we present our findings, regarding the competitiveness of TMT relative to other planned 30-m class telescopes. We consider a capability to be "competitive" if the expected performance is within a factor ~2. It is important to restate that we do not address here whether or not involvement in TMT is in the best interest of Canadian astronomy. Preferential access to an excellent telescope can be enormously advantageous, even if there are other facilities that may outperform in some ways. These findings are only meant to inform LRPIC, CASCA, ACURA and the community, about what we think TMT can and cannot do well.

1. TMT is marginally competitive with ELT for seeing-limited, visible wavelength observations. This is true at both MK13N and ORM, though MK13N is ~20% better and also enables UV observations that are not possible at ORM. If the ground layer turbulence proves a significant contribution to the seeing within the enclosure, performance at ORM will suffer by up to an additional 50% relative to ELT, making it non-competitive in this sense. However, ELT does not have a visible-wavelength instrument planned for first light. This makes the WFOS instrument on TMT unique, and presents an opportunity to have a huge impact in the first years of operation.
2. If NFIRAOS performs as well as expected, and the site turbulence profile and dome seeing also do not deviate far from expectations, TMT can expect to be very competitive for NIR AO observations, on both MK and ORM. This is a core capability of 30-m class telescopes. The advantage is not large, however, and should the ground layer turn out to play a significant role, it will be largely eroded. The lower fraction of usable nights on ORM, relative to Armazones, further degrades the advantage by about 20%. Second generation AO systems may reduce the Strehl advantage of TMT in the future, at which point the aperture difference will make TMT marginally competitive at best.
3. When conditions allow, MIR (2-10 μm) observations for TMT@ORM could be marginally competitive with ELT. However, the larger fraction of clear, dry nights at Armazones mean TMT would be non-competitive if ELT were to devote a substantial fraction of time to observations at this wavelength. If TMT could be built on MK13N, it would enjoy a 20% advantage over ELT at this important regime. ORM eliminates access to the >10μm wavelengths, and thus to several compelling science projects.
4. While ORM has comparable, or slightly better, AO characteristics compared with Armazones, in all other respects the site is less good and even eliminates observations in some regimes (<340 nm, >10 μm). The turbulence profile at the proposed TMT site has not been directly measured and predictions rely heavily on CFD simulations. History and experience suggest that incorrect assumptions and approximations are likely to push the realized image quality toward larger numbers rather than smaller. The ORM site thus comes with increased risk and uncertainty in achievable performance, relative to the other sites, that should be taken seriously.
5. Apart from access to the northern hemisphere, the ORM site offers no significant advantages relative to Armazones. Since TMT has a smaller aperture than ELT, any competitive edge must come from telescope and instrument design, operations, or targets exclusive to the northern hemisphere. All three VLOT projects are being led by

very capable teams, with a good exchange of information. If TMT could be built on MK13N, it would have a distinct performance advantage in the UV and MIR.

6. It remains the case that 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.
7. The in-progress construction of the ELT on Armazones within the expanded ESO observatory complex poses a very significant challenge to the TMT project. A detailed comparison of timelines and technical readiness of the two projects is beyond the mandate of CATAC as it requires comparable access to details of both observatories.
8. The biggest threat to the TMT is its financial position. With a large funding shortfall and no immediate prospect of closing the gap, the start date for construction and the future of the project remains uncertain. It is essential that the project position itself well for a strong showing in the US Decadal Survey, to allow it to compete for NSF funds. Even this may not be sufficient, and other avenues for funding beyond the NSF must be explored. These developments will be largely out of the control of the Canadian community.

7 Recommendations

1. Given that ELT will be located at an exceptional site, with a substantial aperture advantage, competitiveness now and in the future for TMT will require extracting the maximum from instrumentation and operations. Innovation will be of fundamental importance. A robust development budget with stable funding commitments is also essential. Operations must include an adaptive queue, and should allow observing flexibility. Canadian participation in a VLOT that fails to meet these basic national facility requirements should not be considered.
2. TMT@MK13N offers significant competitive advantages relative to ELT. In particular it is expected to outperform ELT in the UV and MIR, while remaining competitive for visible and NIR observations. Therefore the site on MK should not be given up prematurely. The decision to move to ORM should only be made once it is clear that construction on MK will delay the project significantly relative to ELT, or fail to attract the necessary funding. As both the realistic timeline for ELT and the funding opportunities for TMT remain uncertain, we should proceed with caution.
3. The broader Canadian community should be engaged in a project to which we are dedicating so many resources. We should aim to have ~5 Canadians on each science team. They should be representative in terms of geography, institution, gender, and career stage. While all Canadian researchers are encouraged to apply, CATAC (or LRPIC) should also develop a list of specific individuals to approach to apply for ISDT membership well before the next call (January 2018). LRPIC should investigate whether there exist mechanisms within the Canadian funding ecosystem to support ISDT activities, or whether a new allocation should be sought, perhaps by ACURA.

8 Acknowledgements

CATAC would like to thank the following people for their help in preparing this report. First we would like to thank Matthias Schöck from the TMT site testing team, for considerable help in providing data, reports and answering our questions via email and telephone. We also thank Lianqi Wang, Konstantinos Vogiatzis and Douglas MacMartin from the TMT project office for their help in understanding the CFD and other simulation work done by the project. From the community we are very grateful to René Racine and Paul Hickson for a great deal of data gathering, analysis, criticism and advice. Similarly we thank Peter Stetson for providing his data and analysis on seeing measurements at various telescopes, and the Directors of the NOT (Thomas Augusteijn) and TNG (Emilio Molinari) for sharing their DIMM data. We thank all who participated in our community consultations, and those who sent comments on our draft report. In particular we would like to thank Chris Pritchet and Glen Herriot for specific comments and questions that helped improve and clarify the final version of this report.

9 References

Della Valle, A. et al. 2010 MNRAS 401, 1904
Els et al. 2009 PASP 121 527
Lombardi et al. 2011 MNRAS 416, 1585
Munoz-Tunon, C., Vernin, J. & Varela, A.M. 1997 A&AS 125, 183
Schöck, M et al. 2009, PASP 121, 384
Schöck, M. et al. 2011, RMxAC 41, 32
Seo, B.-J. et al. 2009, ApOpt 48, 5997
Skidmore, W. et al. 2009, PASP 121, 1151
Skidmore, W. et al. 2015, RAA 15, 1945
Stephens et al. 2003, AJ, 125, 2473
Thomas-Osip, J. et al. 2011, arXiv1101.2340
Tokovinin 2002, PASP 114, 1156
Vazquez Ramio et al. 2012 PASP 124, 868
Vernin et al. 2011 PASP 123 1334

10 List of Acronyms

ACURA - Association of Canadian Universities for Research in Astronomy
AO - Adaptive Optics
CASCA - Canadian Astronomical Society/ Société Canadienne d’Astronomie
CASTOR - Cosmological Advanced Survey Telescope for Optical and UV Research
CATAC - CASCA/ACURA TMT Advisorty Committee
CFD - Computational Fluid Dynamics
CMT - Carlsberg Meridian Telescope
DIMM - Differential Image Motion Monitor
DM - Deformable Mirror

ELT - European Extremely Large Telescope
ESO - European Southern Observatory
GMT - Giant Magellan Telescope
GSMT - Giant Segmented Mirror Telescope (US generic term for 30-m class telescopes)
GTC - Gran Telescopio de Canarias (Grantecan)
HAA – Herzberg Astronomy and Astrophysics
IQ – Image Quality (not the same thing as seeing)
IRIS - Infrared Imaging Spectrometer (TMT first light instrument)
ISDT - International Science Development Team
LBT - Large Binocular Telescope
LCO - Las Campanas Observatory
LRPIC - Long Range Plan Implementation Committee
MAORY - ELT first light adaptive optics module
MASS - Multi-Aperture Scintillation Sensor
MCAO - Multiconjugate adpative optics
MIR - Mid-infrared (2-20μm)
MK - Maunakea / Mauna Kea
MK13N - the TMT site on MK
MSE - Maunakea Spectroscopic Explorer
NFIRAOS - first light AO module for TMT
NIR - Near infrared (1-2μm)
NOT - Nordic Optical Telescope
NSF - US National Science Foundation
ORM - Observatorio del Roque de los Muchachos (Canary Islands)
PSS - Point Source Sensitivity
PWV - Precipitable Water Vapour
SMF - Site Merit Function
SCAO - Single Conjugate Adaptive Optics
SODAR - Sound Detection and Ranging
SCIDAR - Scintillation Detection and Ranging
TIO - TMT International Observatory
TNG – Telescopio Nazionale Galileo
UV - Ultraviolet (310nm-340nm)
VLOT - Very Large Optical Telescope (Canadian generic term for 30-m class telescopes)
WFE - Wavefront error
WFIRST - Wide Field Infrared Space Telescope
WFOS - Wide Field Optical Spectrograph (first light TMT instrument)