TMT

ALTERNATE SITE:

OBSERVATORIO DEL ROQUE DE LOS MUCHACHOS

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1. EXECUTIVE SUMMARY

From February 2016 through October 2016, several potential sites for the TMT were evaluated to provide an alternative location for the observatory. Although Maunakea remains the preferred setting for building TMT, an alternate site is needed for the case that access to Maunakea is not possible in a timely way.

The site evaluation process was multi-dimension and included the astronomical properties of the sites for carrying out the TMT science mission, the legal arrangements for TIO to operate in the host country, processes and timescales for obtaining necessary permits, the schedule for initiation of construction, logistical issues for siting the observatory and transporting materials to the site, the cost to construct and operate the TMT at the site, and an evaluation of the risks to schedule and cost.

All of the alternative sites considered were excellent for carrying out the core science of the TMT and the interactions with potential host countries and organizations were uniformly very positive.

On October 31st, 2016, the TIO Board of Directors selected the 'Observatorio del Roque de Los Muchachos' (ORM), in La Palma, on the Canary Islands (Spain) as the alternate site for TMT. This decision was based on:

- The scientific importance for TMT to be located in the Northern Hemisphere and position itself as a unique facility.
    - A Northern Hemisphere TMT will secure full sky coverage to the worldwide astronomy community in combination with the two other ELT projects, both to be located in the Southern Hemisphere.
- The very good quality of the ORM site, which can support TMT core science programs.
- The range of benefits provided by the ORM site including:
    - Lower costs of construction and operations
    - Shorter timeline to initiate construction
    - Shorter timeline to 'first-light'
    - Lower project risks based on existence of support infrastructure

Our study shows that the turbulence profile above ORM is similar in character to that of Maunakea, and only second among all five sites considered regarding Adaptive Optics (AO) performances. Using the ORM turbulence profile with our own performance model for NFIRAOS, TMT's AO facility, we could demonstrate that the TMT will perform excellently in its diffraction-limited regime at ORM.

Nevertheless, the ORM site being lower in elevation and overall warmer than Maunakea, a lower sensitivity and efficiency is expected for the TMT at this location, particularly at thermal wavelengths. If TMT is built on ORM, this concern will be addressed by implementing some operations adjustments to better optimize the science output of the TMT, mainly the use of a flexible scheduling of TMT science programs (to best adapt their execution to the ambient conditions), and a prioritization of the instrumentation suites combined with an aggressive instrument development plan (e.g. focus on AO-fed instruments, development of GL AO, or early deployment of high-resolution spectrographs).

Also, because there are various stories in the community regarding dust above the ORM site, an intensive analysis has been carried out by the TMT project. This study shows that the operational and scientific risks related to dust at ORM is well within the range of the other potential sites for TMT.

2. INTRODUCTION

While Maunakea remains the TMT International Observatory (TIO) baseline and preferred site for TMT, the TIO project office led a study to characterize and evaluate alternate sites to ensure that construction could begin in a timely fashion.

The material presented in this document was also provided to the TMT International Observatory (TIO) Science Advisory Committee (SAC) and Board of Directors to inform the selection of an alternate construction site for TMT. Table 1 below lists the sites considered in this study and the source of the site-testing data that were analyzed. It is important to note that all sites considered are excellent sites for astronomy and each would have enabled TMT core-science programs.

Table 1: Table of latitude, longitude and altitude for all sites in this report.

	Altitude	Latitude	Longitude	Comments
Maunakea (Current TMT site, MKO13N), *USA*	4050m	19.82°	155.5°W	Data from TMT site-testing
Observatorio del Roque de los Muchachos (ORM), *Spain*	2250m	28.8°	17.9°W	Data from IAC and ESO site-testing groups
San Pedro Mártir (SPM), Cerro El Altar - *Mexico*	2790m	30.75°	115.5°W	TMT site-testing data on Cerro Pelado (2km away)
Cerro Vicuña Mackenna, *Chile*	3114m	-24.59°	70.0°W	TMT site-testing data on Cerro Armazones (25km away)
Cerro Honar, *Chile*	5400m	-23.07°	67.8°W	TMT site-testing data on Cerro Tolonchar (100km away)
Hanle, *India*	4500m	32.8°	78.9°W	Some site-testing measurements available
Ali, *China*	5100m	32.3°	80°W	Some site-testing measurements available

3. CONSIDERATIONS FOR ALTERNATE SITES

The majority of TMT science programs will be carried out at visible (seeing-limited) and near-infrared (often using adaptive-optics) wavelengths, with a smaller amount of time anticipated to be dedicated to mid-infrared observations. The greatest advancement in capability of the TMT over existing facilities will be to combine adaptive optics assisted observations with an extremely large aperture to deliver diffraction-limited observations with unequalled spatial resolution.

As a result, in addition to the general characteristics of the sites (such as fraction of clear-nights and median seeing), this study emphasized the atmospheric parameters that define the ability of a site to support adaptive optics observations (such as atmospheric coherence time and spatial extent of the isoplanatic patch). The impact of atmospheric dust (surface and high-atmosphere) is also discussed.

The strategic advantages of having a Northern Hemisphere site and unique complementarity to the E-ELT, and GMT were also considered. Additional important factors for the alternative site investigations were related to site logistics, schedule and uncertainties for obtaining permits, cost of construction and operation, as well as the ability to make a fast start on construction for the case that Maunakea becomes infeasible. These particular aspects highlighted the fact that both sites in China and India would imply a considerable increase in cost and construction time, hence risk, to the project. The remainder of the investigation thus focused on the other alternate sites.

Discussions with the potential hosts of the sites were very positive and productive. During visits by the technical and Board-level teams, the hospitality extended by our potential hosts was purely outstanding and very much appreciated. The quick responses and expert assistance we received was tremendous on a wide level of topics. All sites were equal and excellent regarding the ease of working with the official relevant organizations.

4. THE SELECTION OF TMT'S ALTERNATE SITE

At the October 2016 TIO Board meeting, there was a detailed discussion for over two days about the relative merits of the alternative sites considering all of the many and diverse factors described above.

It was clear, based on the analysis done by the TMT Project and SAC, that if only scientific productivity was considered, Honar, in Chile, was the stand out site. A sophisticated site merit function was used to put that result on a quantitative basis and enable performance comparison between sites. However, the logistical issues associated with the very high elevation of a remote site in Chile were considered formidable and the schedule for, and total cost of, construction were significantly higher than any of the other sites.

Although arguments could be made in favor of either hemisphere, the advantages of being the only ELT in the Northern hemisphere carried the most weight. There are some unique scientific opportunities afforded by the Northern Hemisphere, and from the larger perspective of world-wide astronomy and astrophysics research, a Northern location complements the two planned ELTs in the Southern Hemisphere.

The two Northern Hemisphere alternative sites (ORM and SPM) were both attractive. Each offers very good conditions for astronomy observations and excellent partner/host organizations. For both Northern sites, it was also determined that it was feasible to obtain permits for the construction of a project of the magnitude of the TMT. The site merit function (see next section) for ORM in Spain and SPM in Baja California were essentially identical. The principal difference had to do with the remoteness of the SPM site which is a 4.5 hour drive from the nearest large city. This led to a requirement of a different operations model for SPM, the need for establishing a long-term camp during construction, and the need for significant infrastructure at the observatory during operations.

On October 31st, 2016, the TIO Board of Directors selected the 'Observatorio del Roque de Los Muchachos' (ORM), in La Palma, on the Canary Islands (Spain) as the alternate site for TMT. As discussed above, the decision was based on:

- The scientific importance for TMT to be located in the Northern Hemisphere and position itself as a unique facility.
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5. OBSERVATORIO DEL ROQUE DE LOS MUCHACHOS (ORM)

ORM is already the site for 12 telescopes with a large range of apertures up to the 10m Gran Telescopio Canarias (GranTeCan). ORM was also recently selected as the site for the Cherenkov Telescope Array, which will have, once fully deployed, four 23m and fifteen 12m telescopes. A suitable area exists for siting the TMT at the Observatory.

Table 2 compares a number of properties for ORM and Mauna Kea. The ORM site can support all TMT core-science goals, though with lower sensitivity than Maunakea at some wavelengths in the UV and mid-IR. The number of expected useable nights is similar at the two sites.

Table 2: Main site characteristics for MKO and ORM

Site Characteristics (median values, unless stated)	**MKO (USA)**	**ORM (Spain)**
Altitude of site (m)	4050	2250
Fraction of yearly useable time (%)	72	72
Seeing at 60m above ground (arcsecond)	0.50	0.55
Isoplanatic angle (arcsecond)	2.55	2.33
Atmospheric coherence time (ms)	7.3	6.0
Calculated Adaptive Optics Strehl merit function	1.0	0.93
Precipitable water vapor (% time < 2mm)	54	≥20
Mean nighttime temperature (^{o}C)	2.3	7.6
Extinction (V_{mag}/airmass)	0.111	0.137

AO-Based Observations: The values of the isoplanatic angle and coherence time for ORM and Maunakea suggest that near-IR adaptive optics observations would be particularly effective at these sites. This is highlighted in Table 2 by the relative comparison between the values of the AO Strehl merit function for both sites (normalized to 1.0 for MKO).

Dust and Extinction: There is a perception in the community that ORM is compromised by the presence of dust. There are two potential consequences of dust at a site. One is due to dust at "ground level", which can potentially affect instrumentation, primary mirror sensors and actuators, and the cleanliness of optics. The second is due to dust at higher altitude in the atmosphere, which can increase extinction, particularly at shorter wavelengths.

In spite of the known sporadic episodes of Sahara dust reaching the Canary islands at sea-level, the average dust levels at the altitude of ORM are comparable to Maunakea 13N. Table 2 shows that, although there is increased likelihood of enhanced extinction events at ORM during the summer, the extinction statistics for usable nights, regardless of cause, are comparable to those of MK 13N.

Table 3 shows the median mass distribution of the dust at both sites, as well as the cumulative distribution for three distinct mass bins. There is no evidence that observatory-level dust causes significant loss of observing time from our analysis of long-term dust measurements and observing logs of telescopes in operations. The effect of dust on telescope optics is found to be comparable between sites.

Operationally, values above 15 $\mu g/m^3$ impose some telescope pointing constraints, while mass densities above 100 $\mu g/m^3$ require the enclosure to be closed. Note that such events appear to be statistically more frequent at MKO than ORM, relativizing the impact of dust on telescope operations between both sites.

Table 3: Mass distribution of the dust density at MKO and ORM

		Fraction of time exceeding		
Site	**Median $\mu g/m^3$**	**≥15 $\mu g/m^3$**	**≥50 $\mu g/m^3$**	**≥100 $\mu g/m^3$**
ORM	1.006	11.5%	2.3%	0.54%
MK13N	0.815	6.8%	3.6%	2.4%

Mid-IR Observations: The lower sensitivity at mid-IR wavelengths is due to molecular line broadening, higher average precipitable water vapor and higher mean temperatures comparing ORM to Maunakea. This can be addressed, to some extent, by implementing an operations model including flexible scheduling, which will allow switching to mid-IR instruments whenever the ambient conditions are adequate, taking advantage of the limited windows when mid-IR sensitivity is at its highest level.

Site Merit Function: Top Level Result:

A site merit function, SMF, (Schoeck et al. 2011, RevMexAA, 41, 32) was developed during the first TMT site study. The same function (Table 4) was used in this recent study to quantitatively compare the relative merit of each alternate site for the main TMT observing regimes: seeing-limited observations in the visible range, near-IR observations with/without the support of adaptive optics, and mid-IR observations. We used the following realistic weighting between observing regimes for calculating the total SMF for each site: 40% visible, 50% near-IR and 10% mid-IR. To emphasize the comparative aspect of this study, the SMF values were normalized to 1 for the best site (i.e. the best site among the 5 sites considered). The SMF uncertainty is of the order of 10%.

Note that for the mid-IR regime, we adopted a revised and more accurate form of site merit function than our earlier studt, which has the effect of amplifying the difference between each sites to support mid-IR observing modes (based on their PWV, pressure and temperature).

Table 4: Normalized site merit function metrics

Normalized Site Merit Function values	**MKO**	**ORM**
Visible (seeing-limited) metric	0.8	0.7
Near-IR metric	0.9	0.7
Mid-IR metric	0.4	0.1
Total Metric	**0.8**	**0.7**

This study of the merit of both sites applied to the various wavelength regimes of TMT shows that ORM and MKO will perform comparatively well in the visible and near-IR ranges. At mid-IR wavelengths, the site merit function confirms that TMT at MKO will outperform TMT at ORM, emphasizing the importance to carry out such programs when atmospheric conditions are most adequate.

6. CONCLUSION

Overall, all four alternate sites considered for TMT were excellent locations to build our telescope and could support all TMT science cases. Roque de Los Muchachos Observatory is the lowest altitude site among all considered but it is a site that provides atmospheric characteristics at visible and near-IR wavelengths very similar to the properties measured for MKO. The expected AO performances at ORM are very close to MKO's. Also, ORM provides the safest access to first-light within a reasonable schedule (expected around 2027), minimizing the cost impact of the delay the project has undergone since 2015, while enabling the vast majority of TMT science cases.

If TMT is built at ORM rather than Maunakea (our preferred site), some adjustments, in terms of prioritizing operations and instrument/technical developments, will be made to minimize the impact of a lower altitude site, and optimize the efficiency and scientific production of the TMT.