TMT Alternative Site

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1. INTRODUCTION

1.1 PURPOSE

This document explains the selection of the alternate site for TMT, the Observatorio del Roque de los Muchachos (ORM). It demonstrates the ability for the site to meet the requirements and support all of TMT core science programs and describes site specific considerations during construction and operations.

1.2 BACKGROUND

In July 2009, the TIO Board of Governors selected the 13 North (13 N) site on Maunakea (MKO), Hawai'i, as the preferred site for the construction of TMT. The site analysis is documented in (RD5) and (RD6).

From February 2016 through October 2016, six potential sites (in Chile, China, India, Mexico and Spain) were evaluated by TMT to provide an alternative location for the observatory in case access to MKO would not be possible in a timely way.

The evaluation process considered:

- Astronomical properties of the sites for carrying out the TMT science mission
- Legal arrangements for TIO to operate in the host country
- Processes and timescales for obtaining the necessary permits
- Schedule for initiation of construction
- Logistical issues for siting the observatory and transporting materials to the site
- Cost to construct and operate TMT at the site
- Evaluation of the risks to schedule and cost

From the six potential sites, ORM was selected as the alternate site for TMT.

1.3 SCOPE

This document summarizes the work done to characterize the TMT site at ORM and select it as the alternate site for TMT. It discusses the changes in design necessary to effectively operate TMT at ORM compared to the primary MKO site.

Section 2 describes the relative characteristics of the ORM site and compares them to Maunakea.

Section 3 shows how TMT at ORM meets the project's science requirements.

Section 4 shows how the observatory's key performance parameters would change at ORM from those at MKO.

Section 5 highlights the few key project design changes that would be implemented at ORM.

Section 6 includes other site specific conditions at ORM including construction efforts, permitting, and operations cost modeling.

Section 7 discusses the key operation and maintenance activity differences between the two sites.

Section 8 discusses how the observatory's planned education, outreach, and broader social impact efforts would change with an ORM final site selection.

1.4 APPLICABLE DOCUMENTS

N/A

1.5 REFERENCE DOCUMENTS

RD1 TMT Alternate Site: Observatorio del Roque de Los Muchachos (TMT.SIT.TEC.16.083)

RD2 TMT Mid Infrared Sensitivity Analysis (TMT.SIT.TEC.21.002)

RD3 TMT La Palma Permitting Summary (TMT.SUM.MGT.22.005)

RD4 Impact Assessment on ORM Facilities (TMT.FAC.TEC.17.001)

RD5 Schöck, M., Nelson, J., Els, S., Gillett, P., Otárola, A., Riddle, R., Skidmore, W., Travouillon, T., Blum, R., Chanan, G., De Young, D., Djorgovski, S. G., Salmon, D., Steinbring, E., Walker A., "Thirty Meter Telescope (TMT) Site Merit Function" 2011, RMxAC 41, 32. http://www.astroscu.unam.mx/rmaa/RMxAC..41/PDF/RMxAC..41_mschoeck.pdf

RD6 Schöck, M., Els, S., Riddle, R., Skidmore, W., Travouillon, T., Blum, R., Bustos, E., Chanan, G., Djorgovski, S. G., Gillett, P., Gregory, B., Nelson, J., Otárola, A., Seguel, J., Vasquez, J., Walker, A., Walker, D., Wang., L., "Thirty Meter Telescope Site Testing I: Overview," 2009, PASP 121:878 (May 2009) https://iopscience.iop.org/article/10.1086/599287

RD7 https://beta.nsf.gov/funding/environmental-compliance/thirty-meter-telescope

RD8 Science Requirements Document (TMT.PSC.DRD.05.001)

RD9 Gran Telescopio de Canarias Estudio Geotécnico de Detalle en el Sitio de Emplazamiento Del G.T. C Volumen I: Características del Terreno (TMT.SIT.TEC.16.014)

RD10 Geological Risk Assessment (TMT.SIT.TEC.16.004)

RD11 ORM - Summary of the site testing results at the Roque de los Muchachos Observatory 2016 (TMT.SIT.TEC.16.011)

RD12 ORM-Summary of the site testing results at the Roque de los Muchachos Observatory 2022 (TMT.SIT.TEC.22.001)

RD13 Japanese report -private communications, provided per request by NAOJ

RD14 Canadian Astronomy Long Range Plan 2020-2030 https://casca.ca/?page_id=11499

RD15 TMT Education, Outreach and Broader Societal Impacts Plan (TMT.PMO.MGT.21.030)

RD16 TMT ORM Site Cooperation Agreement (TMT.SIT.COR.17.001)

RD17 WFOS OMDR Atmospheric Dispersion Corrector (TMT.INS.TEC.17.065)

RD18 Committee for a Decadal Survey of Astronomy and Astrophysics, National Research Council, Pathways to Discovery in Astronomy and Astrophysics for the 2020s. 2021: The National Academies Press. https://doi.org/10.17226/26141

RD19 IRIS ADC Optical Design Summary (TMT.INS.TEC.16.134)

1.6 REFERENCE DOCUMENTS

Acronym Name	Acronym Definition
ADC	Atmospheric Dispersion Corrector
AO	Adaptive Optics
CATELP	La Palma Astrophysics and Technology Center
DEOPS	Design of Operations
ELT	Extremely Large Telescope
EOBSI	Educational Outreach and Broader Societal Impacts
GTC	Gran Telescopio Canarias
HR	Human Resources
IAC	Instituto Astrofí sica de Canarias
ID	Identifier
IR	InfraRed

IRIS	Infrared Imaging Spectrograph
KPP	Key Performance Parameters
LGS	Laser Guide Star
MCAO	Multi-Conjugate Adaptive Optic
MK	Maunakea
MKO	Maunakea Observatories
NAOJ	National Astronomical Observatory of Japan
NFIRAOS	Narrow Field Infrared Adaptive Optics System
NGSAO	Natural Guide Star Adaptive Optic
NSF	National Science Foundation
OMDR	Opto-Mechanical Design Review
ORM	Observatorio del Roque de los Muchachos (Canary Islands Site)
PASP	Publications of the Astronomical Society of the Pacific
PDR	Preliminary Design Review
PSS	Point Source Sensitivity
RD	Reference Document
REQ	Requirement
SAC	Science Advisory Committee
SE	Systems Engineering
SRD	Science Requirements Document
STEM	Science, Technology, Engineering, Math
TBC	To Be Confirmed
TIO	TMT International Observatory
TMT	Thirty Meter Telescope
ULL	Universidad de la Laguna, Tenerife, Spain
USA	United States of America
WFOS	Wide Field Optical Spectrograph

2. ORM SITE CHARACTERISTICS AND SELECTION

2.1. ORM SITE SUMMARY CHARACTERISTICS

The overall observing conditions at ORM are in most instances similar to MKO, with some distinct differences discussed here. (RD1) provides detailed data and analysis of the ORM site based on more than 20 years of collected site data, with broad characteristics shown in Table 2-1. Of particular note are the fraction of usable time, which is an identical 72% (see Figure 2-1 as well) for both MKO and ORM, and the comparable turbulence characteristics and extinction values. Like MKO, a notable feature of the ORM site is a nearly constant atmospheric thermal inversion layer that is well below the mountain summit, ensuring cloud cover generally remains below the summit. An analysis of the observing logs for five ORM observatories over a five-year period shows total weather-related downtime ranging from 20–30%, without accounting for the different closure conditions at each facility (RD12), consistent with the 72% fraction of usable time reported in (RD1). The amount of open, good seeing time with TMT on ORM would essentially be the same as that on MKO.

Table 2-1: Main site characteristics for the TMT MKO and ORM sites. The data for the E-ELT site at Armazones are also included for comparison.

Site Characteristics (median values, unless stated)	MKO (USA)	ORM (Spain)	Armazones (Chile)
Altitude of site (m)	4050	2250	3060
Fraction of yearly usable time considering all adverse weather conditions (%)	72	72	86
Seeing at 60m above ground (arcsecond)	0.50	0.58	0.50
Isoplanatic angle (arcsecond)	2.55	2.31	2.05
Atmospheric coherence time (ms)	7.3	6.0	5.0
Calculated adaptive optics Strehl merit function	1.0	0.93	0.92
Precipitable water vapor (% time < 2 mm)	54	20	50
Mean nighttime temperature (^{o}C)	2.3	7.6	7.5
Atmospheric Extinction (V_{mag}/airmass)	0.11	0.13	0.13

MKO is an exceptional site for adaptive optics and Table 2-1 and (RD1) show that ORM has only a slightly smaller isoplanatic patch and a slightly shorter coherence time than does MKO, with both values being slightly better than Armazones. Seeing conditions are also similar, with ORM having slightly larger median seeing and a stronger ground layer than MKO.

The main difference between the sites is the lower altitude of ORM, which results in a higher average temperature and larger precipitable water vapor at ORM compared to MKO. These site qualities effectively increase the needed exposure times at ORM compared to MKO, in particular at the shortest and longest observing wavelengths. Combined with seeing and AO performance differences, these effects result in an approximate 16% relative increase in observing time at ORM for TMT's first light instruments (RD1 Table 10, RD2). Adaptive queue scheduling will ensure that mid-infrared observations that require low water vapor can take place under such conditions.

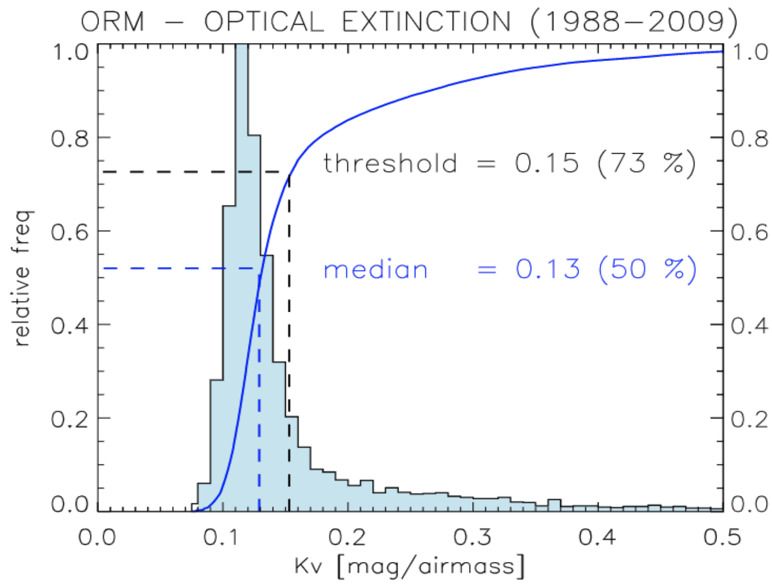

Figure 2-1: 21 years of total atmospheric V band extinction at ORM as measured by the Carlsberg Meridian Telescope (RD12). The threshold value 0.153 magnitudes/airmass represents the limit of photometricity; anything larger than that indicates the presence of dust or cloud or some other form of obscuration. The data indicate the site is photometric 73% of the time.

While the median dust concentration is slightly higher at ORM compared to MKO (see Table 2-2, taken from RD1), the number of nights with levels high enough to force closure is actually smaller at ORM. Operational impacts due to dust (Calima) events are accounted for in the determination of usable time in Table 2-1 (see Section 1.2.4 from RD1 for details).

Table 2-2: Mass density distribution of dust at ORM and MKO. For reference, ORM's Gran Telescopio Canarias triggers close dust monitoring at concentrations ≥15 mg/m3 and closes when the levels reach 100 *mg/m³.*

		Fraction of time exceeding		
Site	**Median (mg/m³)**	**≥15 mg/m³**	**≥50 mg/m³**	**≥100 mg/m³**
ORM	1.006	11.5%	2.3%	0.54%
MKO	0.815	6.8%	3.6%	2.40%

ORM has a slightly higher median dust concentration than MKO, but an overall lower number of nights with high enough concentrations to trigger dome closure. The well-known Calima events that bring Saharan dust to the Canary Islands are the primary causes of the large dust events and occur several times per year. In most cases, the dust remains at altitudes below that of ORM.

One clear ORM site advantage is the lack of cyclone weather systems. Figure 2-2 from (RD1) shows the tracks and intensity for all known tropical cyclones over the period 1947–2008. Hawaii has been in the path of many systems while the Canary Islands has only had a single recorded cyclone since 1851.

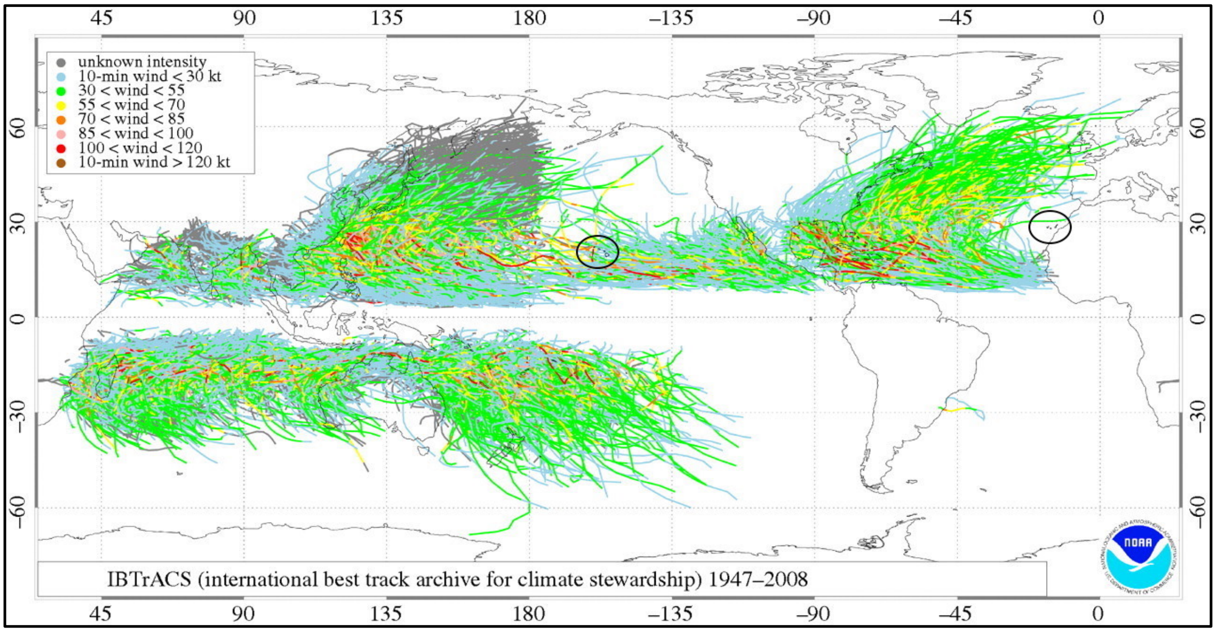

Figure 2-2**:** The observed tropical depression, storm, and hurricane tracks and intensities for all known storms over the period 1947–2008. The locations of Hawaii and the Canary Islands are circled. While Hawaii is routinely impacted by tropical storms, La Palma has very few.

Figure 2-3 shows the cumulative frequency of nighttime sustained wind and gust speeds for several different telescopes on ORM. Speeds remain below typical operational limits of 15 m/s velocities more than 90% of the time.

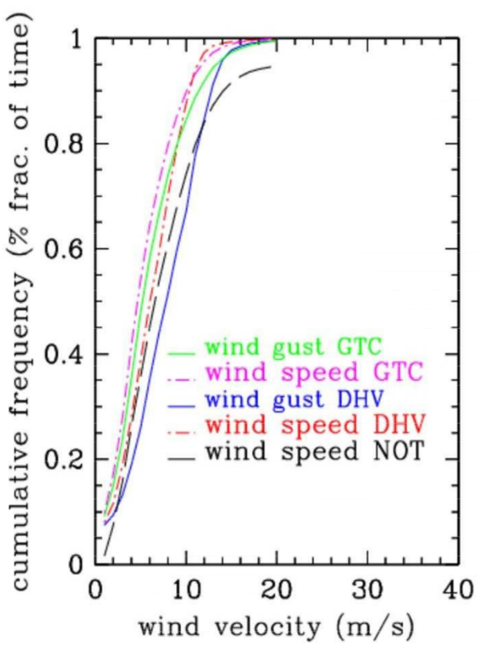

Figure 2-3: Cumulative nighttime wind speed and gust frequencies at different telescope locations on ORM. Typical closure limits of 15 m/s are reached less than 10% of the time.

The lower altitude of ORM compared to MKO does lower observational efficiency in the ultraviolet and mid-infrared. It also means the atmospheric dispersion is approximately 22% greater at ORM compared to MKO at the same zenith angle (RD12). We discuss these effects on instrument design in Section 5.

2.2. ORM SITE SELECTION AND ENDORSEMENTS

Of the six candidate alternative sites mentioned in Section 1.2, we selected the Observatorio del Roque de Los Muchachos (ORM) on La Palma, in the Canary Islands, Spain, as our alternate site in October 2016. Several factors figured highly in this choice:

1) The importance of TMT remaining in the Northern Hemisphere,
2) The excellent astronomical quality of the ORM site (Section 2.1), and
3) Cost considerations (Section 7).

As with Maunakea, our analysis (RD1, RD2) and Instituto de Astrofísica de Canarias (IAC) reports (RD11, RD12) show that the scientific performance requirements will be met at the ORM site. The TMT SAC endorsed the choice of ORM as the alternate site, citing the first two factors above in their endorsement, especially noting ORM's excellent conditions for AO and extreme AO observations.

Astro2020 (RD18) accepts both sites as viable, stating, *"The TMT will either be sited on Maunakea in Hawaii, or at Roque de los Muchachos Observatory on La Palma in the Canary Islands"* and the panel on Optical and Infrared Observations from the Ground mentions: *"while MKO is the superior site—the ORM site is acceptable".*

The Canadian Long Range Plan also endorsed ORM as the alternate site (RD14). NAOJ conducted an independent assessment of the ORM site and confirmed the characteristics we report in the previous section (RD13).

3. SCIENCE REQUIREMENTS

Top level science requirements listed in Tables 3-1 to 3-4 are extracted from the Science Requirements Document (RD8). The key astronomical, performance, cost, engineering, and safety requirements identify site characteristics needed to achieve TMT's science goals. The third column lists the representative average values of the respective site characteristics and demonstrates the ability to meet the site specific science requirements at the ORM site.

Table 3-1: Requirements Related to Key Astronomical Features (SRD 3.1.1, RD8)

REQ ID	Requirement	ORM	Reference
REQ-0-SRD-0400	The site shall have a high fraction of clear nights.	72% of yearly time useable	RD1, RD12
REQ-0-SRD-0405	The site shall have excellent image quality (large r_0, easier to achieve AO performance).	0.58 arcsecond seeing at 60m above the ground	RD1
REQ-0-SRD-0410	The site shall have a large isoplanatic angle (larger field of view for AO).	2.31 arcsecond	RD1
REQ-0-SRD-0415	The site shall have a long coherence time of atmosphere (easier for AO).	6.0 ms atmospheric coherence time	RD1
REQ-0-SRD-0420	The site shall have a smaller outer scale (L_0, improved image quality, easier AO).	~25 m	Same assumption as used for MK[1].
REQ-0-SRD-0425	The site shall have a high fraction of spectroscopic nights.	>72% of yearly time useable	RD1, RD12
REQ-0-SRD-0430	The site shall have low precipitable water vapor distribution (lower IR absorption).	20% of time < 2 mm	RD1, RD12
REQ-0-SRD-0435]	The site shall have low typical temperatures (lower thermal background).	7.6±5.5°C mean nighttime temperature 9.9±6.1°C mean daytime temperature	RD1, RD12
REQ-0-SRD-0440	The site shall have high altitude (transparency, low water vapor, low temperature, smaller atmosphere dispersion).	2250m	RD1, RD12

[1] Note that AO simulations are generally done with a value of 30 m in order to be slightly conservative.

Table 3-2: Requirements Related to Other Performance Related Features (SRD 3.1.2, RD8)

REQ ID	Requirement	ORM	Reference
REQ-0-SRD-0455	The site shall have low wind speed distribution to limit telescope buffeting.	Night-time ground (10m height at GTC site) wind speed 5.3 m/s median, 3.4 m/s std. dev.	RD12
REQ-0-SRD-0460	The site shall have minimal change of temperature during the night (telescope and instrument athermalization).	2.8°C **	**private communication IAC (Julio Castro-Almazán 2022)
REQ-0-SRD-0465	The site shall have minimal seasonal temperature variations.	7.6±5.5°C mean nighttime temperature 9.9±6.1°C mean daytime temperature	RD12
REQ-0-SRD-0470	The site shall have minimal day-night temperature variations.	Average day 9.9°C Average night 7.6°C	RD12
REQ-0-SRD-0475	The site shall have a latitude complementary with existing or future observatories (science opportunities).	28.80° Only ELT in the Northern Hemisphere	RD1

Table 3-3: Requirements Related to Cost Related Features (SRD 3.1.3, RD8)

REQ ID	Requirement	ORM	Reference
REQ-0-SRD-0480	The site shall have easy physical access for minimizing construction costs.	Reduced risk on construction schedule, lower site-related construction cost, and simplified construction logistics, due to the lower altitude of the site	
REQ-0-SRD-0485	The site shall have good human access for minimizing operating costs.	Existing infrastructure and lower altitude	
REQ-0-SRD-0490	Unrestricted access to the chosen site shall be available.	Unrestricted access to the mountain	

Table 3-4: Requirements Related to Other Engineering/Safety Features (SRD 3.1.4, RD8)

REQ ID	Requirement	ORM	Reference
REQ-0-SRD-0495	The site shall have a high mechanical integrity of soil.	Geotechnical reports from the recent construction of the GTC located near to the TMT site. New geotechnical report will be undertaken if the site is selected.	RD9
REQ-0-SRD-0500	The site shall have a low seismicity.	ORM presents a significantly lower seismic hazard than MK, allowing for relaxed seismic requirements to realize a project cost benefit	RD10

4. KEY PERFORMANCE PARAMETERS

The Key Performance Parameters (KPPs) are used as leading indicators to assess the overall technical compliance of the design solution. The KPPs that are monitored and controlled to ensure the performance of TMT are listed in Table 4-1 below. As indicated, the ability for the observatory to meet these technical goals is most dependent on the system designs and is mostly independent of the site.

There are some differences between the MKO and ORM site designs that are worth noting. While the amount of heat produced by the equipment is the same at each site, the summit facility design on ORM has the utility room located further away from the telescope and may protect better against impacts of heat dissipation.

The lower altitude at ORM means equipment reliability does not have to be derated offering improvements to system reliability and maintainability. The lower altitude also provides an additional hour of maintenance time each day to the daycrew, as acclimatization time is not needed when traveling to the summit.

While the implementation of the utilities and services on ORM will be adapted to the European standards and site elevation, the respective system budgets remain consistent. Similarly, the vibration budget allocations will remain consistent on either site, but there may be less risk of transfer of vibrations from the utility room as it will be located further away from the telescope on ORM.

Table 4-1: ORM Site Impact Key Performance Parameters

Key Performance Parameters (KPPs)	ORM site impact
Acquisition Time - AO	Site independent
Acquisition Time - Seeing Limited	Site independent
Astrometry	Negligible difference between primary and alternate site due to similar turbulence characteristics
Heat Dissipation	Site independent in general. Utility room is located farther away from the telescope which may reduce the heat source exchange close to the telescope.
Maintenance Time	Additional 1 hr/day available to daycrew
Mass	Site independent
NFIRAOS LGS MCAO Wavefront Error	NFIRAOS design has been optimized to MKO. Impact on Strehl due to stronger upper turbulence at ORM is small with current design (up to 3% of Strehl)
NFIRAOS NGSAO Wavefront Error	Negligible impact on Strehl due to small difference in r_0
Absolute Photometry	Site independent
Differential Photometry	Site independent
Pointing Error	Site independent
Preset Time	Site independent
Seeing-Limited Image Quality (PSS)	Metric is normalized to the site
Seeing-Limited Off-Axis Image Quality	Metric is normalized to the site
Pupil Stability	Site independent
Reliability and Availability	No equipment derating needed to account for high altitude
Services	Budget remains consistent. Design of utilities to be adapted to European standards and site elevation
Throughput	Site independent
Vibration	Vibration budget remains consistent. Utility room is located farther away from the telescope which may reduce vibration transfer

5. DESIGN CONSIDERATIONS

There are a few site-specific design requirements that are less stringent for ORM than MKO. For most systems, redesign is not necessary or cost effective. In some instances, some features that have been designed will not have to be implemented and will result in decreased costs and lower risks compared to the MKO site. For example, the telescope structure seismic isolation system can be replaced with a stiff mount.

Some unavoidable design changes are necessary to account for different building codes and standards, such as the electrical power system (50 Hz vs 60 Hz). An analysis is underway to tag any subsystem requirements that are linked to Maunakea characteristics or local codes.

The higher mean temperature at ORM compared to MKO simplifies meeting optical tolerance budgets and increases adaptive optics headroom (with less budget being needed to accommodate optical figure tolerances due to the spread between testing and operating temperatures). The higher mean temperature (7.6℃ vs 2.3℃) only minorly degrades the performance of the current design: simulations show the overall performance differences are small and the overall requirements are still met at ORM with the current design.

Like MKO, ORM has a strong ground layer and a bit more free atmosphere seeing (see Table 5 in RD1). The upper atmospheric profiles are different, but similar enough that NFIRAOS's current final design phase design will remain suitable, if slightly less optimal, at ORM. NFIRAOS is designed to work at two conjugations: the ground layer and 11.8km. Simulations discussed in (RD1) show that with no changes to the NFIRAOS design, the impact on Strehl ratio is very minimal with up to 3% degradation in comparison to MKO. NFIRAOS is designed to be cooled to −30℃ so that the NFIRAOS thermal background is less than 15% of the telescope plus sky background. With the higher mean temperature, NFIRAOS would only have to be cooled to −15℃ to meet the same requirement. The current NFIRAOS design can meet this change in operating temperature. Modifications to the NFIRAOS entrance window to account for the higher median external temperature could be made to increase performance somewhat, with the non-modified design still meeting overall requirements.

TMT instruments will be affected by the lower altitude of ORM compared to MKO, particularly affecting ultraviolet and mid-infrared efficiency, and requiring larger atmospheric dispersion corrections.

WFOS is designed to be sensitive to 310 nm, but it may not be possible to observe at the extreme blue end of the spectra when observing from ORM. The WFOS optical design would be re-evaluated if the site changes, although any adjustments will likely result in only minor changes to the instrument design. A slight increase in the atmospheric dispersion corrector prism wedge angles (from 7.4° to 9.0°) would account for the increase in atmospheric refraction (RD16).

IRIS would experience slightly higher thermal backgrounds in K-band, but this likely will only have a small impact on IRIS science. Again, the ADC would have to be updated to work at the lower elevation of ORM. The larger wedge required on the ADC would introduce larger distortions which would be ~18% greater which would have to be calibrated carefully in order to reduce their effect on astrometric precision (RD19).

6. SITE FACILITIES AND CONSTRUCTION CONSIDERATIONS

TIO investigated the impact on other ORM facilities during the construction and operations phases (RD4), considering ground movement, vehicle traffic, dust and noise production, and seeing degradation. With policies in place to minimize project impact, we found no severe adverse impacts. If conditions or parameters change to an unacceptable level, we will meet with the other ORM facility operators to produce a plan to lower the impact to an acceptable level.

Summit Facilities and associated infrastructure at ORM are similar to the existing MK design. The Utility Building is physically separated from the Support Building at ORM, thereby moving heat and vibration generating sources farther away from the telescope than at MKO. Changes in construction materials may be made to better account for local availability and labor experience. Mechanical and electrical systems will be revised to be consistent with local norms and standards. The Site Conditions Monitoring System will be farther from the enclosure, leading to more accurate measurements.

Start of construction on ORM awaits only the completion of final details of construction documents and final negotiations with the contractor for the Civil Package.

6.1. LEGAL REQUIREMENTS AND PERMITTING

TIO has obtained all currently required permits for construction on the ORM site (RD3). All permits are in place until 2026.

On July 19, 2022, NSF issued a notice of intent to prepare an Environmental Impact Statement and to initiate Section 106 consultation for a potential NSF investment in the construction and operation of the Thirty Meter Telescope for both the preferred and alternate TMT sites (RD7).

7. OPERATIONS AND MAINTENANCE CONSIDERATIONS

The ORM domain covers an area close to 200 hectares and is located on the Northwestern slope of an extinct volcanic crater, Caldera de Taburiente National Park. Since 1988, the quality of the sky above La Palma has been protected by law to control and reduce the light pollution from neighboring cities and the island of Tenerife.

The sky above La Palma is also a no-flight zone for commercial aircraft. No-fly zone regulations facilitate the operations of laser guide stars, entirely preventing the interruption of AO/LGS assisted observations due to aircraft flybys. MKO laser operations, in comparison, requires interruptions for overhead planes.

ORM's lower altitude will ease coordination and execution of technical, maintenance, and operations activities. This includes a shorter commute time to the summit, with no acclimatization time required. This additional hour of day crew work each day increases the time available to maintain the observatory and will be particularly beneficial for segment exchanges. Maintenance plans will also be updated to remove the impact of derating due to altitude.

An agreement between TIO and IAC is in place that defines conditions for hosting TMT at ORM, its future operation, and terms for its demolition, removal and restoration of the site. TIO will benefit from tax and duty exemption rules applicable to all goods and materials imported for the use in astronomical, scientific and research activities related to TMT.

Joint operations centers are planned in La Palma and Tenerife. TMT technical operations will be based at CATELP in La Palma. This shared ORM facility has the space and capacity to host more than 400 people. TMT science operations will be based in Tenerife, in the former GTC building on the IAC campus near Tenerife-North airport. The proximity to the new IACTec facility is expected to provide science synergy with IAC/ULL faculty and students.

An initial assessment of the expected operations costs on ORM and the differential with MKO is summarized in Table 7-1 and Table 7-2 . The annual operations costs at ORM is estimated to be 12% less than for MKO and is driven by the cost of electricity and staffing. More analysis is needed to refine these estimates.

Table 7-1: Differential operational Cost for non-labor. *Cost estimates obtained in private communication with IAC HR and ORM site manager.

Cost Item (non-labor)	Cost ($M 2020)	Differential w/ MKO ($M 2020)	Comments
Summit Electrical Power	0.8	-2.1	Compared to 2.9 $M/yr for MKO. This is based on average power usage of 910kW and an energy cost of €0.1/kWh (energy cost in La Palma was €0.08/kWh before war in Ukraine; then €0.12/kWh after war started). Energy is ~72% cheaper in the Canaries compared to Hawaii.
Headquarters Electrical Power	0.05	-0.15	Power for headquarters offices in Tenerife and La Palma
ORM accommodation	0.05	-0.15	Food and lodging for two staff always present for supporting night-operations.
ORM Support Services	0.25	+0.15	TMT share of yearly common charges for ORM operations (logistics, first-aid, communication, vehicle fleet, road maintenance, ORM support service staff, residencia + common services building, etc.).
Office rental in La Palma	0.15	-0.45	Rental of office space in La Palma (Tenerife is at zero operations cost, except for energy cost as accounted for above).
Total Non-Labor Costs	13.0	-2.7	

Table 7-2: Summary of Annual Operating Costs for MKO and ORM. (*) refers to local and expat staff for ORM.

Cost Items	MKO ($M/yr)	ORM ($M/yr)
Labor:	12.7	11.2(*)
Non-Labor:	15.7	13
Instrument development:	14	14
Total operations:	42.4	38.2
Community benefits:	3	< 3

8. EDUCATION, OUTREACH, AND BROADER SOCIAL IMPACTS

The TMT Education, Outreach, and Broader Social Impacts (EOBSI) Plan (RD15) describes an innovative plan that addresses the missing millions, implements true community engagement, and promotes cultural and environmental awareness and stewardship. The plan focuses on the local population and needs on Hawaiʻi Island, relevant to our primary site of Maunakea. A final selection of ORM as the TMT site would shift local activities to be more relevant to the community needs and aspirations on La Palma and prompt an additional program partnering with NOIRLab/US-ELTP to continue to provide STEM education and workforce development to the *missing millions* in the US.

The stated beliefs and needs (RD15) that motivated our current plan remain as well as our Maunakea approach of seeking out diverse representatives of the local community to listen and identify needs where we can most directly help. A unique element of the ORM site is that the discussions with the Cabildo Insular de La Palma (Island Council of La Palma), the Ayuntamiento de Puntagorda (Town Council of Puntagorda), and the Instituto Astrofisica de Canarias (Canary Islands Astrophysics Institute) included community need identification and partnership actions to address them. Together, we have formed an initial plan for EOBSI activities (RD16) that focus on:

- Local recruitment of staff, prioritizing the north-western district of the island
- A scholarship program for Puntagorda High School
- Support for the municipality's cultural events and festivals
- Creation of a plaza, thematic center, and planetarium in Puntagorda
- Creation of a natural, cultural, and scientific public park at elevation on the mountain; this park, the *Parque Astronómico y Cultural Llano de las Ánimas*, would feature natural, archaeological, ethnographic, and astronomy themes

The overall program contains a similar mix of activities as those planned for Maunakea and presented in (RD15) and reproduced in Figure 8-1. They provide a focus on helping children and educators with relevant STEM, cultural, and vocational education and resources, with additional activities that strengthen participant ties to the local culture and environment, build bridges among the various existing cultures and practices, and promote environmental stewardship relevant to the island and the Roque de los Muchachos mountain.

We would also recruit local expertise into our EOBSI office to help identify future needs and connect with the local community, in collaboration with our municipal and institutional partners.

This program of activities supports the local community and helps TIO become a responsible and valued community member. A move to ORM would also induce additional activities to reach our aspirations of supporting and inspiring STEM education and workforce development in the US, particularly addressing those traditionally left behind and unheard. No matter our ultimate location, we believe we can and should continue to reach out to the missing millions and inspire them with the wonders of the universe and STEM education and vocational opportunities.

At ORM, we would partner with NOIRLab/US-ELTP to develop EOBSI programs and activities that leverage our status as a preeminent world-class observatory to engage US children and educators in STEM. This plan would be targeted more broadly than either our local MKO or ORM programs and we hope it will capture people's imagination as has missions like the Hubble and James Webb Space Telescopes. With NOIRLab support, TMT and the US-ELTP will be just as well-known and will reach children and educators in all communities across the country.

(A) K-20 Education and Workforce Development	(B) Indigenous Culture Learning	(C) Environment Protection and Conservation
A1. Hawai'i STEM Collaborative (HSTM) Nā Lawai'a No Ke Kai Hohonu • Mobile STEM Education Lab • Teacher Externship at MKOs • Aquaculture Outreach and Training • Alternative Learning Center • Tutoring Students in K-12 • Traditional Hawaiian Canoe Curving **A2. NGSS/STEM Curriculum Development and Teacher Workshops** (Hilo Intermediate School, DOE) **A3. Workforce Pipeline: Vocational Akamai, Scholarship, and Remote Job Readiness Program** (HCC) **A4. After-school Online Astronomy Course**	**B1. Indigenous Culture Exchange** (Hawai'i Island Sister City Association) **B2. 'Ohana Stargazing** ('Ohana Kilō Hōkū)	**C1. Maunakea Reforestation** (The Mauna Kea Forest Restoration Project, The Big Island Resource Conservation and Development Council, Inc)
(D) Community-led Review		
External review committee members include Native Hawaiian cultural practitioner, Native Hawaiian astronomer, educator, and business leader.		

Figure 8-1: The initial slate of EOBSI activities planned for the Maunakea site as presented in the TMT EOBSI plan (RD15). The planned ORM programs present a similar mix of activities and themes.