RevMexAA (Serie de Conferencias), **31**, 10–17 (2007)

STATUS OF THE TMT SITE EVALUATION PROCESS

Matthias Schöck,[1] Sebastian Els,[2] Reed Riddle,[1] Warren Skidmore,[1] Tony Travouillon,[1]
and the TMT Site Selection Team

RESUMEN

El Telescopio de Treinta Metros (TMT) está en el proceso de adquirir datos para caracterizar cinco sitios seleccionados como candidatos para su emplazamiento. El equipo para la evaluación de sitios incluye instrumentos para medir tanto el *seeing* como su perfil, así como para medir las condiciones metereológicas, nubosidad y vapor de agua precipitable, entre otros parámetros. Todos los equipos para caracterización de sitios y sus datos han pasado por una intensiva calibración y verificación, para asegurar que se realice una comparación confiable y cuantitativa entre los sitios seleccionados. Presentamos aquí una actualización del trabajo realizado en la selección de los sitios, la caracterización de los equipos y la precisión resultante de los datos obtenidos.

ABSTRACT

The Thirty Meter Telescope (TMT) is currently acquiring site characterization data at five candidate sites. The site testing equipment includes instruments for measuring the seeing and seeing profiles, meteorological conditions, cloudiness, precipitable water vapor, etc. All site testing equipment and data have gone through extensive calibrations and verifications in order to assure that a reliable and quantitative comparison between the candidate sites will be possible. Here, we present an update on the status of the site selection work, the equipment characterizations and the resulting accuracies of our site selection data.

Key Words: **SITE TESTING — TELESCOPES**

1. THE TMT SITE SELECTION PROCESS

TMT needs to be built on the best available site to obtain the maximum return from its science potential. Careful site selection has therefore been extremely important to TMT from the very beginning of the project. The site selection process started in 2001/2002, in a collaboration between the AURA New Initiatives Office (NIO) and the California Extremely Large Telescope (CELT), with the pre-selection of five candidate sites to be studied in detail. On-site testing via the operation of remote site monitoring stations has been in progress since 2003 and will continue until the final selection of the TMT site.

The selection of the TMT site depends on a multitude of parameters, both technical and non-technical, and it is not a priori obvious how to combine these parameters to arrive at the final site decision. A series of steps have therefore been taken by the TMT Project to develop a method of dealing with the complexity of the TMT site selection process. These include quarterly reviews of the site selection process and data, quarterly results update reports, presentations of site results at TMT SAC and other project meetings, as well as the issuing of intermediate reports. The Site Selection Process is also reviewed twice by an External Advisory Panel (EAP). These steps serve to provide information for the parties involved in the site decision and to fine-tune our data analysis and site comparison methodology. They will lead to the site selection around the middle of 2008.

2. TMT SITE SELECTION REQUIREMENTS

The TMT site needs to be suited for producing astronomical data of superb quality and for building and operating an observatory of the size and complexity of TMT. Strict technical requirements as they apply to other parts of the project do not exist for the TMT site, as there are no hard cut-offs for the parameters entering the TMT site decision beyond which a site becomes unsuitable. Instead, the site selection process involves measuring and predicting both the technical and programmatic properties of the sites and balancing them so as to determine the site that best meets the TMT needs. The process employs a site ranking metric which provides a method for an objective comparison of the technical properties of the candidate sites and their science producing implications. This section provides a brief summary of the TMT site selection requirements.

[1] Thirty Meter Telescope Project, Pasadena, California, USA (mschoeck@tmt.org).

[2] AURA-NIO, Cerro Tololo Inter-American Observatory, La Serena, Chile.

2.1. *Science-Based Requirements and Site Astronomical Criteria*

The TMT site is required to enable maximum use of TMT as a facility planned to operate in the 0.3 to 30 μm wavelength range with adaptive optics as an integral element in achieving the specified performance. One of the most important properties of a qualified site is a high percentage of time on the sky with favorable combinations of factors such as absence of clouds, good seeing and low precipitable water vapor. Important features are:

Key astronomical features:
- High fraction of clear nights
- Excellent image quality (large r_0)
- Large isoplanatic angle, θ_0
- Long turbulence coherence time, τ_0
- Small outer scale, L_0
- Large fraction of remaining nights: spectroscopic
- Low precipitable water vapor
- Low typical temperatures
- High altitude

Other performance related features:
- Low wind speed distribution to limit buffeting
- Minimal change of temperature during the night
- Minimal seasonal temperature variations
- Minimal day-night temperature variations

Cost related features:
- Easy physical access
- Good human access
- Availability of site

Other engineering / safety features:
- High mechanical integrity of soil
- Low seismicity

Flowing from the science-based requirements, a list of site astronomical criteria was developed that will enter the site decision. The range of potentially important site characteristics includes:

Weather-related characteristics:
- Cloud cover
- Photometric conditions
- Low-elevation wind (below 800 m)
- High-elevation wind (> 800 m; not measured)
- Temperature
- Ground-level humidity
- Precipitable water vapor

Turbulence-related characteristics:
- Overall seeing
- Turbulence profiles
- Isoplanatic angle
- Turbulence time constant
- Outer scale of turbulence (not measured)

Other characteristics:
- Low-elevation dust
- High-elevation dust (not measured)
- Light pollution
- Atmospheric transparency
- Sky brightness
- Sodium layer properties (not measured)

Note that not all of these parameters are measured during the TMT site selection process (as indicated above) as this would have been beyond the means of the TMT site selection project.

2.2. *Observatory Technical and Programmatic Requirements*

In addition to being scientifically qualified, the TMT site must also meet observatory technical and programmatic needs. Obtaining legal possession and access to the site when required in the construction schedule is a primary factor, but other considerations such as labor, logistics, geological conditions and the permitting process will also be considered in the site selection. These aspects are summarized in Table 1.

3. CANDIDATE SITES

TMT selected five sites as candidate observatory sites and began on-site testing in 2003 (see Table 2 in Section 4 for details of the instrument deployment schedule). This selection was based on satellite studies of cloud cover and precipitable water vapor done by Dr. D.A. Erasmus and was supplemented by existing knowledge from previous site selection studies and from established observatory sites. Views of each of the candidate sites are shown in Figure 1. General descriptions of the sites and their locations are given in the following.

3.1. *Cerro Tolar*

A low elevation site (2290 m) in northern Chile, Cerro Tolar is in the Atacama desert and has an extremely arid climate. Tolar is located at a distance of only 8 km from the coast, at 16 km from the closest paved road and 18 km north-north-east of Tocopilla, a town of 25,000 inhabitants. [Note: All distances given in this section are straight line distances. Driving distance are usually 50–100% longer than this].

TABLE 1

OTHER ASPECTS ENTERING THE TMT SITE DECISION

Issue	Method
Construction and operating cost and method	TMT cost estimate
Cultural, environmental and land use issues	Consultations with local groups; archaeological, fauna and flora studies; assessment of historical preservation and environmental issues
Labor force issues	Evaluation of labor supply, skill level, local conditions
Proximity to astronomers and astronomy infrastructure	Evaluation of existing observatories, organizations
Geological and geotechnical conditions	Geological and geotechnical studies
Foundation conditions	Evaluation of telescope pier and enclosure foundations
Vibration transmission	Evaluation of the vibration transmission through the soil from the enclosure and other equipment to the telescope structure
Compatibility with surrounding area	Studies of conditions and how TMT will fit in
Economic impact of siting TMT	Study of TMT's impact
Permitting, land ownership etc.	Coordination with local authorities
Transportation	Evaluation of local situation
Customs and immigration issues	Evaluation of applicable regulations

The closest commercial port, airport and major population center is Antofagasta (population 225,000), 190 km south of Tolar. There is a primitive four-wheel drive road to the summit, where some radio equipment is installed.

3.2. *Cerro Armazones*

Cerro Armazones, a medium elevation site (3064 m) in northern Chile, is also located in the Atacama desert and close to the coast (36 km), with a climate very similar to that of Tolar. It is 22 km from ESO's Very Large Telescope (VLT) on Cerro Paranal and 110 km south of Antofagasta, the closest city. A good, but steep and narrow switch-back road to the summit exists. The closest hard-packed road is ∼18 km from Armazones, connected by a rough dirt road. Armazones is the site of a small observatory operated by the Universidad Católica del Norte in Antofagasta. This observatory is not located on the summit, but on a saddle ∼350 m below the summit. A new observatory utilizing a hexapod mounted telescope is being built by the University of Bochum on Cerro Murphy, a small peak 1.5 km south-west of Armazones and ∼225 m lower.

3.3. *Cerro Tolonchar*

Cerro Tolonchar is the eastern-most of the Chilean sites, south of the Salar de Atacama, and only 25–80 km from several 5000–6000 m peaks of the Andes. Because of its eastern location and higher altitude, it experiences more precipitation and clouds than Tolar and Armazones, especially during the "Bolivian Winter" from approximately mid December to mid February. Tolonchar is also the highest (4480 m) and most remote of the TMT candidate sites. The closest settlement is Socaire (300 inhabitants) 38 km to the north, with the closest towns being Toconao (550 inhabitants) at 80 km, San Pedro de Atacama (an eco-tourism town of 1,500 people) at 115 km and Calama, the next large city with a commercial airport (120,000 inhabitants), at 190 km. The driving time is currently 2 h from Socaire, 3 h from San Pedro de Atacama and 4.5 h from Calama. Antofagasta, 250 km distant, can be reached via a different route in ∼5.5 h. These times can be reduced by 30–60 min through the construction of a good road to Tolonchar, connecting with the existing road from Socaire to Paso Sico (closest distance ∼17 km). Currently, a rough 4WD road exist from the Paso Sico road to the base of Tolonchar. For the site testing process, TMT has constructed a road from the base to the summit which is designed to be usable, with some improvements, for the observatory should TMT be built there.

3.4. *San Pedro Mártir*

San Pedro Mártir (SPM) is located in northern Baja California, Mexico, inside a national park and

Fig. 1. Views of the five TMT candidate sites.

is the site of the Observatorio Astronómico Nacional de San Pedro Mártir. It is a medium-elevation site (2830 m), ∼65 km from the Pacific coast in the west and 55 km from the Sea of Cortez (Gulf of California) to the east. The terrain is gently rising from the north, west and south, with a steep cliff dropping more than 2000 m to the desert in the east. The highest point of the area and, in fact, of Baja California, Picacho del Diablo (3095 m), is approximately 6 km to the south-east of the observatory. The area is inside a pine forest and receives more precipitation than the other TMT candidate sites, but most of that comes down in a small number of strong events with mostly clear time in between. The closest town is Ensenada (300,000 inhabitants) at 4 h driving time and 140 km line-of-sight distance. The closest commercial airports are in Tijuana (at 220 km) and San Diego (250 km). There is an existing road all the way to the observatory. It is paved to the national park entrance, ∼20 km from the observatory.

3.5. *Mauna Kea 13N*

The TMT candidate site on Mauna Kea on the Big Island of Hawaii is a location referred to as "13 North" (13N) on the northern shield, approximately 150 m below the summit. It is adjacent to the Submillimeter Array (SMA) extension area. With ∼4050 m elevation, 13N is the second highest of the TMT candidate sites. The conditions are usually dominated by a stable north-easterly flow, but can produce severe weather and precipitation, in particular in the winter. As a developed site with several observatories, much of the infrastructure required for TMT exists on Mauna Kea. Only a short piece of road would have to be constructed to the 13N site.

4. THE TMT SITE SELECTION INSTRUMENT SUITE

The TMT site decision will be based on both technical and programmatic aspects. Technical site

Fig. 2. The TMT site selection instrument suite.

properties are assessed predominantly through data acquired in a multi-year study of the site conditions using identical equipment. To acquire these data, the TMT site testing team has been operating remote site monitoring stations at each of the candidate sites. Considerable effort has gone into calibrating all equipment through side-by-side comparisons of identical instruments and, when possible, by comparison with other instruments. This section contains a summary of the instrument suite, the deployment dates to the sites and the measurement uncertainties we have determined for the individual parameters.

4.1. *Instrument Overview*

The following instruments have been deployed at the candidate sites (see also Figure 2):

- **Differential Image Motion Monitors (DIMM):** The TMT DIMMs are mounted on small (35cm) but robust custom-made telescopes installed on 7 m towers. A DIMM measures the integrated seeing in the air column above the telescope.
- **Multi-Aperture Scintillation Sensors (MASS):** Scintillation-based instruments which measure 6-layer turbulence profiles, the isoplanatic angle and the turbulence coherence time. Can also be used for atmospheric transparency estimates.
- **Sound Detection and Ranging (SODAR) acoustic sounders:** Phased-array acoustic emitter/receiver systems which produce low elevation (10 – 800 m) turbulence and wind profiles.
- **Automatic Weather Stations (AWS):** Commercial weather stations with temperature (air and soil), wind speed and direction, humidity, barometric pressure, precipitation, solar irradiation, heat flux and net radiation sensors. Stand-alone units mounted 2 m above the ground. Air temperature sensors are also in-

TABLE 2

DATES OF FIRST DATA ACQUISITIONS OF THE DIFFERENT INSTRUMENTS FOR EACH CANDIDATE SITE[a]

	Tolar	Armazones	Tolonchar	San Pedro Mártir	Mauna Kea 13N
Weather station	Apr 03	Jul 03	Nov 05	Oct 04	Jun 05
DIMM	Oct 03	Nov 04	Nov 05	Oct 04	Jun 05
MASS	Jan 04	Nov 04	Jan 06	Oct 04	Jul 05
SODAR	—	Mar 05	Feb 06	Mar 06	Oct 05
All-sky camera	Oct 05	Oct 05	Nov 05	Jul 05	Jun 06
Sonic anemom.	Feb 06	Feb 06	Mar 06	May 06	Nov 05
Dust sensor	Feb 06	Feb 06	Mar 06	May 06	Nov 05
30 m tower	—	Sep 06	Mar 07	Dec 05	—
IRMA	—	Jan 07	Mar 07	—	Feb 07

[a]Note that we only have three sets of SODARs and three IRMAs, which are rotated among the sites.

stalled on 30 m towers on Armazones and Tolonchar.

- **Sonic Anemometers:** Mounted at the MASS/DIMM telescope level and/or at several elevations on the 30 m towers. Measure wind speed and direction, an approximate temperature value, and can be used to estimate the in-situ turbulence strength. [During their site survey, the Large Synoptic Survey Telescope (LSST) project also had a 30 m tower with sonic anemometers installed at San Pedro Mártir. The data from this are available to us.]
- **All-sky cameras (ASCA):** Provide images of the entire sky in several visible and infrared filters. Used for cloud analyses, sky transparency estimates and light pollution studies.
- **Infrared Radiometers for Millimetre Astronomy (IRMA):** Measure the flux from the sky at 20 μm. The precipitable water vapor (PWV) content of the atmosphere can be calculated from this using a suitable atmospheric model.
- **Dust Sensors:** Commercial particle counters mounted at the MASS/DIMM telescope level. Measure the particle density in five different channels for particle sizes of 0.3, 0.5, 1.0, 2.0 and 5.0 μm.

In addition to the on-site testing, other methods used to characterize the sites are:

- **Computational Fluid Dynamics (CFD) Simulations:** Used to verify results obtained at the candidate sites, to assess the impact of site preparation and construction, and to evaluate dome/mirror seeing and wind shake.
- **Satellite Studies of Cloud Cover and PWV:** Based on meteorological satellite data studies carried out by Dr. D. A. Erasmus. Used for the pre-selection of candidate sites and to put the on-site data into a longer temporal baseline.

4.2. *Instrument Deployment Schedule*

The original goal of the TMT site selection campaign was to take on-site measurements of all major parameters (e.g. weather, seeing) for at least 2 years, and for at least one year for all other parameters. This was achieved or exceeded for most instruments, but was not possible in all cases for practical reasons. Dates of the first deployments of all instruments are shown in Table 2. Note that we do not have five sets of all instruments, so that not all of them have been installed continuously at each site since the dates given in the table.

The site data will be put into context of longer-term data sets (Erasmus satellite studies; data from existing observatories) as much as possible, as well as by Computational Fluid Dynamics (CFD) simulations, to investigate whether there is reason to believe that the on-site testing period was non-representative for any of the sites.

4.3. *Instrument Calibrations and Results Verifications*

Data taken with our instruments are only considered useful for the TMT site selection process if the reliability and uncertainties of the measurements are known. As a result, we have gone through great efforts to understand all instruments and results, including:

TABLE 3

SUMMARY OF THE MEASUREMENTS ERRORS AS DETERMINED FROM THE INSTRUMENT CALIBRATIONS

	Relative[a] Error	Absolute[a] Error	Comments
Weather station sensors			
Temperature	$\lesssim 1°$C	$\lesssim 1°$C	
Temperature on 30 m tower	0.1°C	0.1°C	
Wind speed	10%	10%	
Wind direction	$\lesssim 5°$	$\lesssim 5°$	limited by setup accuracy
Humidity	10%	10%	
Pressure	1 hPa	1 hPa	vendor quoted accuracy
Solar irradiance	n/a	n/a	not needed
Precipitation	n/a	n/a	used for equipment safety only
Heat flux	5%	5%	vendor quoted accuracy
Net radiation	3%	3%	vendor quoted accuracy
DIMM			
Seeing	$0\farcs02$	similar	
MASS			
Free-atmosphere seeing	$0\farcs05$	similar	
Individual layers (C_n^2dh)	10^{-14} m$^{1/3}$	similar	
Isoplanatic angle	$0\farcs02$	$\ll 0\farcs2$	
Coherence time	$\sim$ 20%	$\sim$ 20%	estimate by the MASS team
Transparency	i/p	i/p	work in progress
Cloud cover	i/p	i/p	work in progress
SODAR			
Wind profiles	20%	$\sim$ 1 m s^{-1}	offsets exist between SFAS and XFAS
GL seeing	10%	similar	
Individual layers	$\sim$ 20%	similar	
Sonic anemometer			
Wind speed	$<$ 5%	$<$ 5%	
Wind direction	$\lesssim 5°$	$\lesssim 5°$	limited by setup accuracy
Sonic temperature	$\lesssim 3°$C	$\lesssim 3°$C	work in progress; offsets exist
Turbulence	tbd	tbd	
Dust sensor			
Particle count	10%	n/a	
All-sky camera			
Cloud cover	i/p	i/p	work in progress
Transparency	i/p	i/p	work in progress
Light pollution	tbd	tbd	
Sky brightness	tbd	tbd	
IRMA			
Precipitable water vapor	0.25 mm	i/p	

[a]Here, 'tbd' stands for 'to be determined', 'i/p' stands for 'in progress', and 'n/a' for 'not applicable'. Errors are upper limits to the uncertainties of the probability distributions of the respective quantities.

- Side-by-side comparisons of identical instruments.
- Side-by-side comparisons of different instruments measuring the same parameters.
- Sensitivity analyses of the dependence of the results on input parameters.
- Independent verification of all in-house analysis software by at least two people.
- Independent verification of all results and statistics by at least two people.

The uncertainties determined for our instruments are given in Table 3. All values given in the table are limits for the statistical properties of the parameters, not for the individual measurements.

A note concerning terminology: We use the term 'absolute error' of a measurement to describe the *accuracy* of the measurement (defined as the closeness of agreement between the average value obtained from a large series of test results and an accepted reference value). It describes how well our measurements agree with the absolute values of the respective parameters (the "truth"). The term 'relative error' is used to describe the expected relative differences between the measurements taken with identical equipment at different sites, the *reproducibility*. Both accuracy and reproducibility are difficult to determine in practice. For our results, they are based on the comparison of different equipment at the same sites, whenever possible. When this is not possible, we estimate them based on investigations of the *repeatability* of the measurements (the expected relative differences between the measurements taken with identical equipment at the same site) and on sensitivity and bias analyses of the instruments.

Also note that some of the calibrations are performed either periodically, such as every time a site is visited, or at least once at the beginning and once at the end of the site testing program. In this way, it is possible to determine whether calibrations stay constant or if drifts or jumps in time need to be accounted for.

The TMT site selection work could not happen without the contributions of many people at various institutions. A special thanks to everybody who has supported, and is still supporting, the TMT site selection program, in particular the entire TMT project including its partner institutions and external reviewers, the people at the Cerro Tololo Inter-American Observatory (CTIO), the National Optical Astronomy Observatory (NOAO) and the AURA New Initiatives Office (NIO), the Universidad Católica del Norte in Antofagasta, the Observatorio Astronómico Nacional de San Pedro Mártir of the Universidad Nacional Autónoma de México, Gemini Observatory, Palomar Observatory, the Submillimeter Array (SMA), the University of Hawaii Institute for Astronomy (IfA), the University of Lethbridge, the University of Moscow and the South African Astronomical Observatory (SAAO).

The authors gratefully acknowledge the support of the TMT partner institutions. They are the Association of Canadian Universities for Research in Astronomy (ACURA), the California Institute of Technology and the University of California. This work was supported as well by the Gordon and Betty Moore Foundation, the Canada Foundation for Innovation, the Ontario Ministry of Research and Innovation, the National Research Council of Canada, and the U.S. National Science Foundation.