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THIRTY METER TELESCOPE (TMT) SITE MERIT FUNCTION

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RESUMEN

TMT generó una vasta base de datos multi-dimensional de características de sitio para los cinco lugares geográficos candidatos para el proyecto. De manera de adoptar una decisión informada sobre donde emplazar el proyecto, el conjunto de datos, en cada sitio, fue reducido a un único valor por medio de la función de mérito de sitio. Este manuscrito describe algunos coeficientes relevantes involucrados en la función de mérito, con énfasis en la interpretación de los resultados en cada caso y sus limitaciones.

ABSTRACT

TMT collected a large multi-dimensional data set of site characteristics at its five candidate sites. In order to make an informed site decision, this data set was reduced to a one dimensional metric, the site merit function. This paper describes examples of some of the coefficients of this merit function, with an emphasis on the interpretation of the results of such an approach and its limitations.

Key Words: site testing — telescopes

1. INTRODUCTION

1.1. *TMT Site Testing*

The Thirty Meter Telescope Project (TMT), spent five years on on-site testing of five candidate observatory sites: Cerros Tolar, Armazones and Toloncharin northern Chile, San Pedro Mártir (SPM) in Baja California, Mexico, and the 13N site just below the summit of Mauna Kea in Hawaii. During this period, data about the atmospheric conditions at the sites were taken with a large number of instruments, with a strong emphasis on the use of identical equipment at all sites and the calibration and inter-comparability of the results.

The final, TMT-internal site testing report was finished in April of 2008, with the results being publicly reported in a paper series starting in April 2009 (Schöck et al. 2009). In January 2010, the site testing data themselves were made public in an online database (`http://sitedata.tmt.org`). Details about the site testing process, the sites, the instrumentation, the results and the data are given in the paper series and at the database website.

1.2. *TMT Site Selection*

The TMT site selection process was based on both technical and non-technical (programmatic) aspects. The TMT Project and Science Advisory Committee (SAC) decided early on that no strict requirements were going to be imposed on any specific site parameter. Instead, the site selection was based on balancing all parameters and thus determining which site best meets the TMT needs. For the parameters measured at the sites, this was done by means of a site merit function. Based on the results of the merit function in combination with all other factors influencing the site decision, the TMT Board of Directors down selected to one South American and one North American site in May 2008, Armazones and Mauna Kea 13N. In July 2009, Mauna Kea 13N was selected as the preferred site for TMT.

2. THE FORM OF THE SITE MERIT FUNCTION

TMT will be used in many different modes of observations, each of which being affected differently by the site conditions. Obviously, it is impossible to predict exactly what observations will be made with TMT over its expected 50-year lifetime, and what

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the fractions of time used for the different modes are. There is therefore some uncertainty and arbitrariness involved in compressing the many-parameter space of the site measurements into the one-dimensional output of the site merit function. In addition to producing merit function results in the first place, it is therefore just as important to understand their uncertainties and limitations. This is reflected in the approach taken with the TMT site merit function, and is one of the main messages we are attempting to convey with this paper.

We divided the science observations carried out with TMT into three broad categories: seeing-limited science which will predominantly take place at visible wavelengths; near-infrared (NIR) adaptive optics (AO) observations; and mid-infrared (MIR) AO observations. The TMT SAC and user community estimated that initially 50% of the time will be spent on seeing-limited observations, with 40% used for NIR AO observations and 10% for MIR AO. As AO operations mature, the ratios are expected to change to 30/60/10% within no more than a few years. Thus, the latter is the state of operation we expected for the majority of the TMT life time. Interestingly, this is very similar to the estimates by ESO for the E-ELT, if their three NIR science cases are combined (see the E-ELT site merit function presentation at this conference).

The TMT site merit function takes the form

$$M = \sum_{i=1}^{3} w_i \prod_j C_{ij} \, , \tag{1}$$

where $i = 1$–3 are the three modes of observations, w_i are their weights (the percentages given above), j is a parameter counting through the site characteristics and the C_{ij} represent the "scientific productivity" of TMT as a function of these characteristics. Ideally, each C_{ij} has units of $1/T_{\rm min}$, where $T_{\rm min}$ is the minimum integration time required to achieve a certain science goal. As each coefficient, C_{ij}, is normalized to the value of the best site (in this parameter), we generally only require the functional dependence of $T_{\rm min}$ and not absolute values.

3. SITE MERIT FUNCTION COEFFICIENTS

Only some of the aspects of the site merit function can be presented here, with a more detailed treatment to be published shortly in Schöck et al. (2011).

3.1. C_1 – *Clear Fraction*

Arguable the simplest site parameter to deal with in the context of the site merit function is the fraction of clear time. This affects the 3 observing modes equally and we can simply set

$$C_1 = \frac{f_{\rm clear\_time}}{f_{\rm clear\_time,best\_site}} \, , \tag{2}$$

where $f_{\rm clear\_time}$ is the percentage of time the sky is clear above the site.

Even here complications arise, however, as the definition of "clear time" is not universal. Do we use the fraction of photometric time or of "usable" time, and what constitutes usable time? A cloud cover fraction or a certain thickness of cirrus clouds might be acceptable for one type of operation and not for another. This does not only apply to the three modes used in this merit function, but also to different types of observations within these modes.

Telescope operational time is limited by more than just clear-sky fraction. Under clear conditions, observations may stop for other factors, such as high wind and humidity. Depending on the available data set it might also prove difficult to predict usable time with high accuracy, as these parameters are strongly correlated (e.g., Skidmore et al. 2011, in preparation; Travouillon et al. 2011, in preparation) and their full effect on telescope performance might yet be unknown. For example, a wind-speed limit could depend not only on the local climate, topography and observatory enclosure design, but on the performance of active/adaptive optics and ultimately the orientation of the telescope relative to the wind.

3.2. C_2 – *Effect of Atmospheric Turbulence on Seeing-Limited Observations*

The image size in seeing-limited observations is, to first order, given by the atmospheric seeing, ϵ. Thus, a first-order estimate of the effect of turbulence on seeing-limited observations might be:

$$C_2 = \frac{\epsilon_i^{-2}}{\epsilon_{\rm best\_site}^{-2}} \, . \tag{3}$$

Note that we need to use the seeing actually seen by the telescope, not the seeing measured by the TMT site testing DIMMs at 7 m above the ground (Els et al. 2011, in preparation). Thus, we first need to extrapolate the seeing to the top of the enclosure at ∼60 m. We can see in Table 1 that this produces a significant difference in the merit function results. As a next step, the contributions of mirror and dome seeing, the telescope itself, as well as effects such as the outer scale of turbulence need to be taken into account, which further reduce the differences between the sites. Also note that, as a reference, the

TABLE 1

EFFECT OF ATMOSPHERIC TURBULENCE ON SEEING-LIMITED OBSERVATIONS

Site	C_2 $\epsilon_{7\mathrm{m}}$	C_2 $\epsilon_{60\mathrm{m}}$	C_2 PDF
Tololo (2215 m)	0.64	0.77	0.49
Tolar (2290 m)	1.00	0.92	0.93
SPM (2850 m)	0.64	0.77	0.69
Armazones (3064 m)	0.97	1.00	1.00
MK 13N (4050 m)	0.71	0.96	0.75
Tolonchar (4480 m)	0.97	0.96	0.99

TABLE 2

EFFECT OF ATMOSPHERIC TURBULENCE ON NIR AO OBSERVATIONS

Site	C_3 σ^2	C_3 Simulations
Tololo	0.73	
Tolar	1.00	
SPM	0.80	
Armazones	0.98	0.92–0.98
MK 13N	0.86	1.00
Tolonchar	0.99	

table includes data from approximately one year of data acquisition taken with our equipment at Cerro Tololo.

It is now important to realize that the use of the median seeing, as done for Table 1, is only part of the picture and can be misleading, because the contribution of good seeing to the scientific productivity is much larger than that of bad seeing. Thus, instead of using the square of the median seeing as merit parameter, we should use the following integral over the probability density function (PDF), $P(\theta)$:

$$C_2 = \int \frac{P(\theta_{\mathrm{atm}})\mathrm{d}\theta_{\mathrm{atm}}}{\theta_{\mathrm{obs}}^2 + \theta_{\mathrm{atm}}^2} \,. \tag{4}$$

Here, we now use θ to denote the image size (including seeing, outer scale and telescope effects). θ_{atm} includes the entire atmosphere above 60 m from the ground (the observatory height) and θ_{obs} are all contributions from below this level. This produces the results of the last column of Table 1, which are different from both the other two columns. Thus, we find that working with median values does not always produce accurate results, although it might be the only practical approach in some cases.

C_2 only applies to seeing limited science ($i = 1$ in equation 1) and is set to unity for AO observations. This adds another complication if queue scheduling is considered for an observatory, as the probability distribution of seeing for a given observing mode might be different from the overall distribution if good (or bad) seeing conditions are preferentially assigned to any of the observing modes.

3.3. C_3 – *Effect of Atmospheric Turbulence on NIR AO Observations*

AO observations also benefit from good seeing, in a different way than seeing-limited observations. With AO, most of the atmospheric error is removed, but what is left is crucial to the performance of a scientific instrument. For the TMT first-light AO system, NFIRAOS (Narrow-Field Infrared Adaptive Optics System), we started with a simple estimate of the rms residual wavefront error, σ:

$$\sigma^2 = 128^2 + \left(\frac{47.7}{r_0}\right)^{5/3} \quad [\mathrm{nm}] \,, \tag{5}$$

where the first term describes uncorrectable residuals of the entire system and r_0 is the Fried parameter of the atmosphere in meters (Fried 1965; Gilles et al. 2008). Scientific productivity can be shown to grow as S^2, where $S = \exp -(2\pi\sigma/\lambda)^2$ is the Strehl ratio at wavelength λ. This is a good approximation when $S > 0.1$, which is generally true for NFIRAOS. It will operate primarily in the J (1.25 μm), H (1.65 μm), and K (2.2 μm) bands and we average over these three bands. As with seeing, we must integrate over the probability distribution of atmospheric seeing. The results are shown in Table 2.

While this model provides a first-order estimate of NFIRAOS wavefront correction at different sites, it is incomplete, ignoring the details of a realistic multi-conjugate AO system. In the last couple years, very detailed simulations of NFIRAOS have been performed, and are still constantly being refined. As they are computationally intensive, results are, for the most part, only available for the two finalist sites, Armazones and Mauna Kea 13N (see Table 2).

Very interestingly, while in the original merit function Armazones was more than 10% more efficient in this parameter than Mauna Kea 13N, the role is reversed for these detailed simulations with a somewhat smaller difference between the two sites. This is due in part to the use of "representative" turbulence profiles rather than integrals over scalar parameter distributions,[10] but mostly to physical difference in the vertical turbulence profile shapes above the sites. Mauna Kea 13N has a larger fraction of its turbulence close to the ground, which is easier to correct for NFIRAOS than high-altitude turbulence.

It must be noted, however, that the simulation results shown here rely on a limited, standard set of profiles. These are representative for median conditions in a very specific sense because simulations of, and integration over, the full set of conditions are not possible due to computing time requirements. As shown above, this can also lead to uncertainties in the result and must be interpreted with care.

3.4. *Other Effects*

Similar considerations apply to the effects of all other site characteristics on the scientific productivity, such as the isoplanatic angle, the atmospheric time constant, precipitable water vapor, average temperatures, nightly as well as annual temperature ranges, effects of wind (wind shake and dome seeing) and temperature gradients. These will be published shortly in Schöck et al. (2011, in preparation).

4. SITE MERIT FUNCTION RESULTS AND SUMMARY

The previous examples have shown that it is not possible to construct a merit function that exactly describes the scientific productivity of an observatory unless the exact observations made during its lifetime are known in advance. This does not imply that such a merit function is not a meaningful tool. On the contrary, the TMT project undertook a large effort to develop this merit function and a great deal of insight into the candidate sites, their conditions and the effect of the site characteristics on the scientific productivity was gained from this. It does mean that it might not be necessary to spend a large amount of time on detailed fine-tuning any particular coefficient (although care needs to be taken to achieve sufficient accuracy, as shown above). Instead, we learned early that it was important for TMT site selection to understand the limitations and the variations of the merit function if different conditions, configurations and observation scenarios are considered. The site merit function thus became not an end-all number from which one simply picks the best site, but a very powerful tool for the sensitivity analysis of the scientific productivity of the observatory as a function of not only the site conditions, but also the specific science observations. We expect the insight gained from this, and maybe even the merit function itself, to continue to be useful throughout operations planning and operations of TMT.

[10]It must be understood that there is no such thing as one representative turbulence profile that works for all applications, which is also the reason why the Armazones results are a range. The Mauna Kea 13N results are normalized to unity, meaning that the Armazones range covers the variations of both sites.

At the time of the final site testing report in April 2008, the merit function results ranked the TMT candidate sites in 3 groups. Tolonchar came out on top in most (but not all) scenarios and was therefore assigned a merit function value of unity (100%). Armazones and Mauna Kea 13N were on average approximately equal, with values of 90–95% of Tolonchar's scientific productivity, with San Pedro Mártir and Tolar in third with values of 70–80%. It should be noted that all TMT candidate sites were significantly ahead of Cerro Tololo, which achieved values around 40%, confirming that they all are excellent sites for an observatory like TMT.

For the down selection to two sites in May 2008, it was decided that construction and operation of TMT on Tolonchar was expected to be too expensive and difficult, and the TMT Board of directors selected Armazones and Mauna Kea 13N as the two final candidates. The final choice of Mauna Kea 13N as the preferred site in June 2009 was supported by additional input such as the detailed NFIRAOS simulations mentioned above. The outcome was that both sites were approximately equal in the merit function metric, with variations on the order of $\pm 10\%$ between them depending on the scenarios considered.

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REFERENCES

Schöck, M., et al. 2009, PASP, 121, 384
Els, S. G., et al. 2009, PASP, 121, 527
Fried, D. L. 1965, JOSA, 55, 1427
Gilles, L., Wang, L., & Ellerbroek, B. 2008, Proc. SPIE, 7015, 701520