TMT image quality at Mauna Kea, La Palma and Armazones

Paul Hickson
2017-03-23

Abstract

The preferred location for the Thirty Meter Telescope is site located on the flank of Mauna Kea. As a backup, a alternate site has been chosen on the flank of Roque de los Muchachos on La Palma. Such sites typically have stronger low-level turbulence that do summit sites. This report explores the effects of the stronger surface-layer turbulence on the image quality of the telescope. It is predicted that opening the dome vents substantially degrades the seeing due to the influx of turbulent air. For observations at high airmass, the effect is less noticeable as the seeing is already degraded by the longer propagation path.

1 Introduction

Large telescopes such as the TMT are at least partly sheltered from low-level turbulence by virtue of their tall enclosures. The question then arises as to what seeing should be used when assessing the performance of different potential sites. The seeing is a strong function of height above ground, decreasing roughly exponentially with increasing height. the TMT project has adopted the seeing at a height of 60 m as representative for estimating the performance of the telescope.

There are several factors that lead one to question the assumption that the 60-m seeing is the appropriate criterion. First, the TMT will spend much of its time observing away from the zenith, at elevations as low as 25°. The dome aperture will in that case necessarily be much lower, admitting the stronger turbulence present at low heights. A second factor is due to the large vents installed around the enclosure. These are needed to ensure adequate flushing of air to reduce effects of internal temperature differences that lead to mirror and dome seeing. Such shutters, when open, will admit turbulent outside air into the dome. For these reasons, we expect that the seeing outside the dome will have an impact on the telescope image quality.

Such effects can in principle be studied by computational fluid dynamics (CFD) modelling. This would requires a full and detailed model of the telescope and enclosure, a realization of the external turbulence, and a resolution sufficient to follow turbulent cells on scales as low as the Fried length r_0. While much progress has been made with CFD simulations, there is always some concern that the detail, physical assumptions, and resolution, may not be sufficient to accurately predict the dome seeing. It would thus seem prudent to makes some simple analytic estimates based on plausible assumptions about air entering the dome aperture, and the filtering effects of dome vents.

2 TMT enclosure

The TMT enclosure is shown in Figures 2 and 3. It is a calotte design of external radius $R = 33$ m, having a circular aperture. The overall height of the enclosure, with the telescope pointing at zenith and the shutter open, is 50.5 m. The height of the Nasmyth axis above ground level is $h_0 = 23$ m. The height of the bottom of the aperture when the telescope is observing at its greatest zenith angle (65°) is approximately 18 m. Three rings of dome vents ring the enclosure. The base of the lowest ring is 10 m above ground. The dimensions of each individual vent opening is approximately 3.7×3.7 m. They are closely spaced horizontally, but separated by as much as 2.7 m vertically.

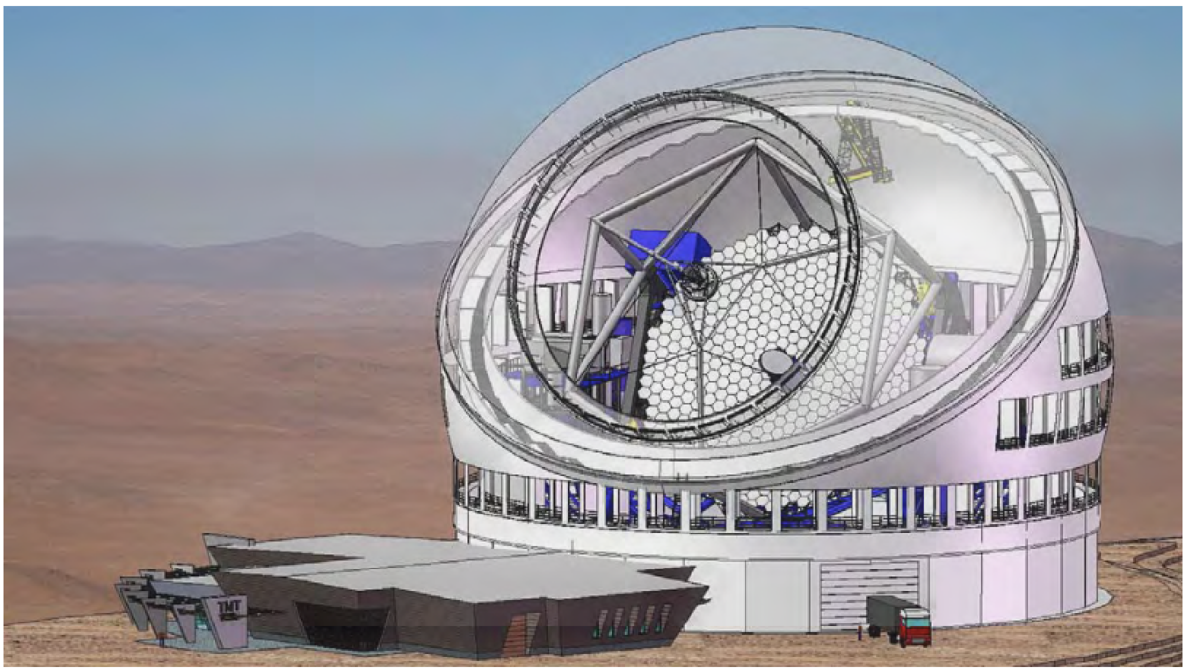

Figure 1: View of the TMT enclosure, showing the circular opening and the rings of dome vents.

3 TMT sites

The preferred location for TMT is the 13N site on Mauna Kea. This is located on the flank of the mountain, where the surface-layer turbulence is relatively strong compared to locations on the summit ridge. The backup site for TMT is ORM on La Palma. The site chosen is also located on the flank of the mountain, well below the summit.

The MK 13N site has been intensively investigated by the TMT site testing team (Skidmore et al., 2009). The median seeing at at height of 7m, and an estimate of the seeing at 60 m height are listed in Table 1. The 60-m value is derived primarily from sodar measurements. For ORM, the 60-m seeing has been estimated by TMT from scidar measurements made

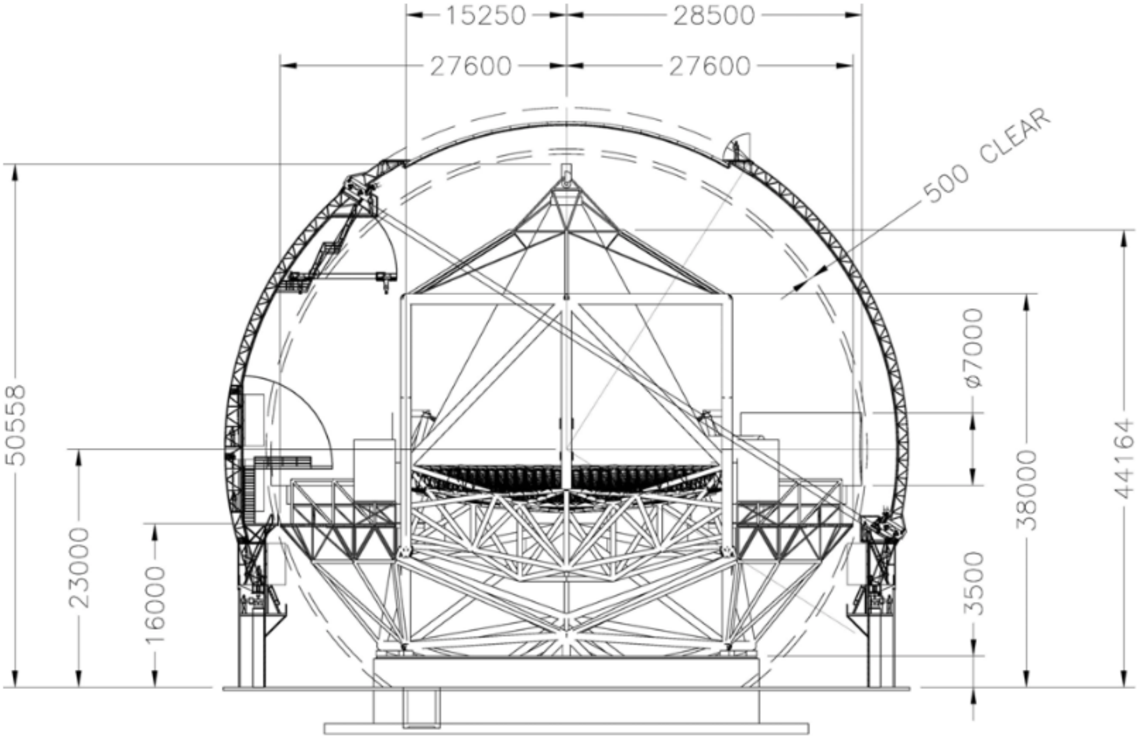

Figure 2: Dimensional view of the TMT enclosure.

with a telescope located close to the summit ridge. The seeing at the proposed TMT site has not been measured, but two years of measurements by ESO at a site 125 m below the Nordic Optical Telescope, indicated a median seeing of 0.80 arcsec. The TMT site is about 25 m lower than this, so the seeing may be worse (Racine 2005). However we shall take the measured value at the ESO site as representative.

For comparison, we include Cerro Armazones, site of the European ELT. The aim is to illustrate what seeing TMT would have if it were located on the summit of a similar mountain.

Table 1: Assumed site characteristics

Site	MK	ORM	Armazones
Latitude	19.83	28.76	-24.59
Longitude	-155.48	-17.89	-70.19
Altitude (m)	4050	2250	3064
Median Seeing (7m) ε_7	0.73	0.80	0.64
Median Seeing (60m) ε_{60}	0.50	0.55	0.50

In order to estimate the impact of the low-level seeing, we need a turbulence profile. For this an exponential profile was fit to the turbulence values at 7 m and 60 m,

$$\varepsilon(h)^{5/3} = \varepsilon_7^{5/3} \exp[-(h-7)/H],$$

where the scale height H is given by

$$H = \frac{53 \times 3/5}{\ln(\epsilon_7/\epsilon_{60})}.$$

4 Effect of dome vents

Air entering a dome vent will carry turbulent cells on all scales smaller than the dimension of the vent opening. Since the larger eddies are blocked by the vents, one expects that the seeing produced by the air passing through the vents will be less than that of the outside air. Essentially, the Kolmogorov spectrum of the exterior turbulence will be cut off at the dome vent scale, and so the turbulence spectrum will be better approximated by a von-Karman spectrum having an outer scale comparable to the average vent size.

Seeing produced by von-Karmen turbulence has been studied by Tokovinin (2002). He finds that the seeing FWHM ϵ, for a large-aperture telescope, is reduced by a factor

$$f(L_0/r_0) \equiv \frac{\varepsilon}{\varepsilon_0} \simeq \sqrt{1 - 2.183(L_0/r_0)^{-0.356}},$$

where ε_0 is the seeing FWHM for a Kolmogorov spectrum and and L_0 is the outer scale of the turbulence. The equation was found to be a good approximation to the results of numerical calculations.

For light of wavelength λ, the Fried parameter is related to the Kolmogorov FWHM by the well-know relation

$$\varepsilon_0 = 0.98\frac{\lambda}{r_0}.$$

A plot of this relation is shown in Figure 3, as a function of the ratio L_0/r_0.

5 Estimating the effect on image quality

We wish to estimate the seeing as a function of zenith angle ζ, for the two TMT sites. We do this for two cases, with the first corresponding to all the dome vents being closed, and the other for all the dome vents being open. For the first case, the seeing is estimated by taking the seeing $\epsilon(h)$ evaluated at the effective height h_ζ of the centre of the calotte aperture, and multiplying this by $\sec^{3/5}\zeta$ to account for the effect of the airmass. Thus,

$$\varepsilon(\zeta) = \varepsilon(h_\zeta)\sec^{3/5}\zeta,$$

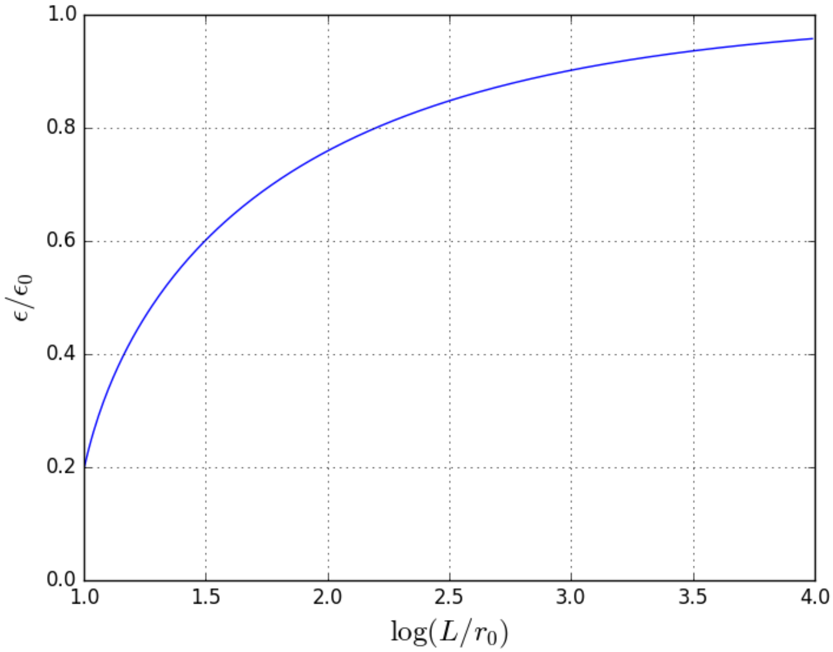

Figure 3: Effect of outer scale of turbulence on seeing FWHM.

The effective height is found by integrating the height weighted by the exponential turbulence distribution over the pupil of the telescope where the beam enters the dome. This leads to

$$h_\zeta = h_0 + R\cos\zeta - D\sin\zeta\left[\frac{1}{x} - \frac{I_0(x)}{2I_1(x)}\right],$$

where $D = 30$ m is the pupil diameter, $x = D/2H$ and I_0 and I_1 are hyperbolic Bessel functions. The exponential weighting results in an effective height that is lower than the geometric centre of the aperture, typically by about one metre.

For the second case, we calculate the seeing at the height h_1 of the first (largest) ring of dome vents and subtract from this (in 5/3 quadrature) the seeing at the effective height of the calotte aperture. This provides an estimate of the additional turbulence that would be admitted by the dome vents. This value is then multiplied by the attenuation factor of Eqn (4), corrected for the shutter geometry, then added to the seeing of the first case, after raising both to the 5/3 power,

$$\varepsilon(\zeta)^{5/3} = \varepsilon(h_\zeta)^{5/3}\sec\zeta + [\varepsilon(h_\zeta)^{5/3} - \varepsilon(h_1)^{5/3}]f_{1\mathrm{d}}(L_0/r_0)^{5/3}.$$

In evaluating this, r_0 is calculated from the seeing at height h_1, and L_0 is taken to be the 3.7-m vertical height of the dome vent apertures. Since the shutters are contiguous, the outer scale in the horizontal direction is not reduced. Therefore, the attenuation factor is corrected for the fact that the turbulence spectrum is reduced in only one of the two dimensions. This leads to a one-dimensional attenuation factor defined by

$$1 - f_{1\mathrm{d}}^{5/3} = 0.5 * (1 - f^{5/3}).$$

6 Results

The results of the analysis are shown in Figures 4 and 5. We see that for observations near the zenith with the dome vents closed, the seeing is close to the 60-m value. However opening the vents degrades the images substantially due to the influx of partially-filtered turbulent air. The seeing obtained is now not much better than the 7-m value.

At large zenith angles, the expected image degradation with airmass is seen, with a further contribution due to turbulent air entering the dome aperture. By a zenith angle of $\sim 60°$, there is little difference between the dome vents open and dome vents closed cases.

At ORM, the outside air between 7 m and 60 m contributes 46% of the total turbulence integral. For observations at the zenith with the dome vents open, this analysis predicts that air inside the dome will contribute about 38% of the total turbulence integral.

The approach taken here only considers the expected spatial filtering of the turbulent field by the dome vents. It ignores the additional turbulence likely to be generated by the edges of the vents and obstructions in the flow. Also, any temperature differences between the outside air and the enclosure and interior structure would likely result in increased temperature (and therefore index-of-refraction) fluctuations.

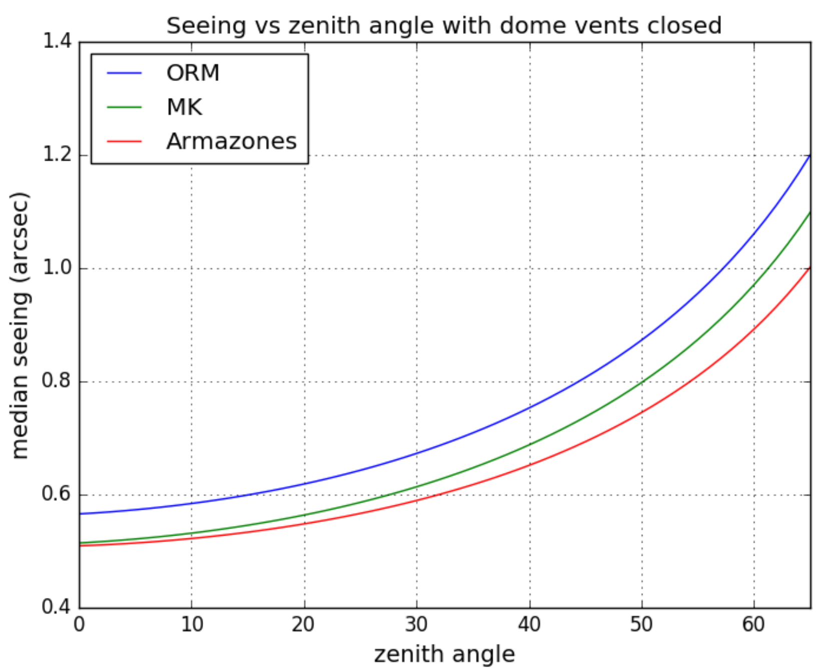

Figure 4: Estimated seeing FWHM as a function of zenith angle at the two TMT sites and Cerro Armazones. This is for the case when the dome vents are entirely closed.

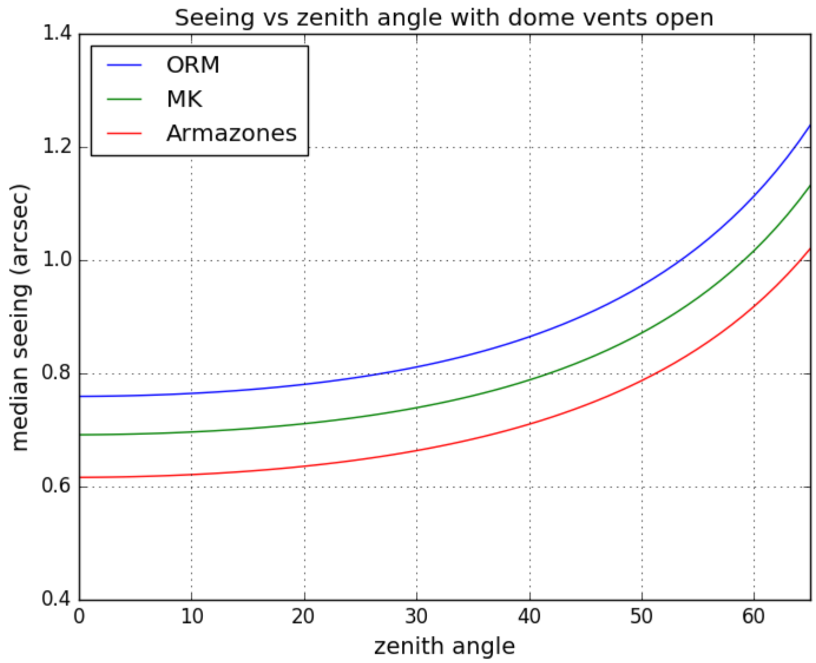

Figure 5: Estimated seeing FWHM as a function of zenith angle at the two TMT sites and Cerro Armazones. This is for the case when the dome vents are entirely open.

References

Racine, R. 2005, "Altitude, Elevation, and Seeing", PASP, 117, 401-410.

Skidmore, W. et al. 2009, "Thirty Meter Telescope Site Testing V: Seeing and Isoplanatic Angle", PASP, 121, 1151-1166.

TMT Observatory Corporation, 2007, "TMT Construction Proposal", available at tmt.org.

Tokovinin, A., 2002, "From Differential Image Motion to Seeing", PASP, 114, 1156-1166.