Structural Optimization of the Retractable Dome for Four Meter Telescope (FMT)

Nian Pan¹, Yuxi Li², Yue Fan¹, Wenli Ma¹, Jinlong Huang¹, Ping Jiang¹, and Sijie Kong¹,³
¹ Institute of Optics and Electronics, Chinese Academy of Sciences, Chengdu, Sichuan, 610209, China; wopannian@163.com
² Department of Modern Mechanical Engineering, Waseda University, Tokyo, 1698555, Japan
³ University of Chinese Academy of Sciences, Beijing, 100049, China

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Abstract

Dome seeing degrades the image quality of ground-based telescopes. To achieve dome seeing of the Four Meter Telescope (FMT) less than 0.5 arcsec, structural optimizations based on computational fluid dynamics (CFD) simulation were proposed. The results of the simulation showed that dome seeing of FMT was 0.42 arcsec, which was mainly caused by the slope angle of the dome when the slope angle was 15° and the wind speed was 10 m/s. Furthermore, the lower the air speed was, the less dome seeing would be. Wind tunnel tests (WT) with a 1:120 scaled model of the retractable dome and FMT indicated that the calculated deviations of the CFD simulation used in this paper were less than 20% and the same variations of the refractive index derived from the WT would be a convincing argument for the validity of the simulations. Thus, the optimization of the retractable dome was reliable and the method expressed in this paper provided a reference for the design of next generation of ground-based telescope dome.

Key words: telescopes – Dome seeing – Computational fluid dynamics – Wind tunnel tests

Online material: color figures

1. Introduction

Imaging is an important way for ground-based optical telescopes to explore the mysteries of the space. However, seeing is one of the main factors that affects the imaging quality of ground-based optical telescopes, and seeing can be divided into atmospheric seeing and dome seeing (Woolf 1979).

Dome seeing is an impact of the varied refractive index on the image quality of ground-based optical telescopes, which is mainly caused by the turbulence around the dome; the mixing of hot and cold air from surfaces inside and outside the dome and hot air from the ground. At present, the choice of the dome structure, the structural optimization, and the rational arrangement inside the dome are the main measures to restrain dome seeing (Harding et al. 1979; Racine et al. 1991; Ford 1993; Dalrymple 2004; Roberts & Figgis 2003; Nian & Li 2015).

Retractable domes allow telescopes to fully expose the ambient night atmosphere, and any warm air will quickly dispersed. Because the shell of the retractable dome is left down at the work condition, high turbulence will not be produced. Hot air from the ground can be reduced by installing the telescope above the boundary layer of the ground (Bettonvil et al. 2010). Thus, the dome seeing of a retractable dome will be less than the others under the same conditions. More and more ground-based optical telescope domes have adopted this structure (Fugate 2003; Bettonvil et al. 2008; Jägers et al. 2008), and a performance analysis of this dome structure becomes very meaningful.

Previous analyses of domes focused mainly on their aerodynamic properties; for instance, Ando et al. (1991), Siegmund (1990), and Schneermann (1994) used wind tunnel tests (WT) to study the flusing time, the uplift effect, and the pressure inside the dome. Young (1996), Young & Vogiatzis (2004), Vogiatzis (2008), Chylek et al. (2004), MacMynowski et al. (2006), MacMynowski & Andersen (2010), and Padin (2002) utilized computational fluid dynamics (CFD) simulation to avoid a long preparation period and the high expense of WT tests to study the wind load of a telescope and search for the optimization plan of the dome. Few articles used these aerodynamic parameters to establish relations with the observational performance of telescopes, especially for the retractable dome.

To design a reasonable dome for the Four Meter Telescope (FMT), quantitative analysis of the variation of the refractive index caused by the dome were presented and then structural optimization based on CFD simulation were proposed. Finally, WT tests used a 1:120 scaled model of the retractable dome were conducted to verify the effect of optimization.

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2. Theory

The quality of optical transmission in the medium is directly related to the uniform of refractive index (Tyson 1991) according to the Gladstone-Dale relation (Gladstone & Dale 1864), and the state equation refractive index can be expressed as

\[
\frac{dn}{n} = \frac{k_{GD}}{R T_0} \left( \rho_0 V dV - \frac{1}{T_0} \left( \rho_0 - \frac{P_0}{2} \right) \right) \text{d}T_0,
\]

where \( P_0 \) is the total pressure, \( \rho_0 \) is the air density, \( T_0 \) is the air temperature, \( R \) is the gas constant, and \( k_{GD} \) is the Gladstone-Dale constant, if the observing wavelengths of telescope are in the range of \( 0.38 \sim 1 \mu m \), \( k_{GD} \) approximates to \( 2.23 \times 10^{-4} \).

The total differential of refractive index \( dn \) can be expressed as

\[
n \cong 1 + k_{GD} \left( \frac{P_0}{RT_0} - \frac{\rho_0}{2RT_0} \right) V^2.
\]

From Equation (2), the uniform of the refractive index is under the control of the pressure, the temperature, and the speed of medium; it is no longer applicable to use the empirical formula of dome seeing \( \theta = (0.15\Delta T^{6/5})'' \) proposed by Racine (Nian & Li 2015), where \( \Delta T \) is the temperature difference between the air inside and the air outside of the dome.

And the full width at half maximum (FWHM) \( \theta \) is often used to calculate the seeing of the telescope (Wilson et al. 1999); the expression of FWHM is

\[
\theta = 0.98 \frac{\lambda}{r_0},
\]

where \( r_0 \) is the atmospheric coherence diameter, and \( \lambda \) is the observing wavelengths of telescope.

For a plane wave, the atmospheric coherence diameter \( r_0 \) is mathematically computed as

\[
r_0 = \left( 0.423k^2 \int_0^{\Delta z} C_n^2 dz \right)^{3/5},
\]

where \( k \) is the wave number, \( C_n^2(z) \) is the refractive index structure constant expressed as (Zhong 2005), and \( z \) is the distance of transmission.

\[
C_n^2(z) = \frac{\langle dh^2 \rangle}{z^{2/3}}
\]
if the dome seeing $\theta$ is 0.5", the wind speed is 10 m/s, the distance of transmission $z$ is 15 m, and the observing wavelength $\lambda$ is 0.5 μm. According to Equation (3) ~ Equation (5), the atmospheric coherence diameter $r_0$ is 22.24 cm, and the variation of the refractive index $dn$ is $3.21 \times 10^{-7}$. Thus, to ensure the dome seeing of the FMT, the variations of refractive index must be less than $3.21 \times 10^{-7}$.

According to Equation (2), the variation of the refractive index relates to the speed, temperature, and pressure of the

Figure 3. FMT with protective dome retracted: (a) three-dimensional model and (b) the slope angle of dome.
(A color version of this figure is available in the online journal.)

Figure 4. Exterior flow field of the CFD simulation.
(A color version of this figure is available in the online journal.)

Figure 5. Meshing of telescope and flow field.
(A color version of this figure is available in the online journal.)
medium. Thus, the temperature, the speed, and the air pressure surrounding the dome must be calculated.

As a fluid, the equations for the conservation of energy, mass, and momentum are used to solve the temperature, speed, and air pressure (Anderson et al. 2009). Considering the complexity of the problem, analytic solutions of the equations for the conservation of mass, momentum, and energy are difficult to attain. With the development of CFD simulation and the computational power of the computer, the complex flow field can be accurately modeled by CFD both spatially and temporally. Each of the steps are described below.

3. Initialized Model

The workflow of the CFD simulation is shown in Figure 1. It mainly contains three parts. First, the goals and the domain of the analysis need to be defined. Second, the analyzed model including the solid and fluid model needs to be established and the calculational domain needs to be discretized. Then, the boundary conditions and the solver are set. Third, solve and verify the results of the simulation.

3.1. Geometry

The FMT is a state-of-the-art optical instrument for research in atmospheric compensation and adaptive optics techniques. Many features, including active mirror support and precise mirror temperature control, have been incorporated in the telescope to permit optimal performance of the imaging system. As shown in Figure 2, the optical layout illustrates that the diameter of the primary and secondary mirrors are 4 m and 0.66 m, respectively.

To minimize the degrading influence of the dome seeing on imaging, a cylindrical retractable dome (shown in Figure 3) with a 27° sloping roof was proposed during the conceptual design phase of the telescope. The dome was designed to retract vertically to a position that allowed the telescope to have an unobscured view of the horizon at all azimuthal angles. The dome outer diameter D was 24 m with a wall thickness of 0.8 m and a 12.2 m diameter circular opening, which the telescope saw through, and the pier height was 14 m to reduce the impact of hot air from the ground on the dome seeing.

Supposing that the site of telescope was located at an altitude of 3193 m in Li Jiang (longitude = 100°47, latitude = 26°83), where the maximum of the temporal mean wind speed was 10 m/s, and the average temperature was 283.15 K (Racine et al. 1991). The dome was placed on a flat surface in smooth flow.

Respectively, the exterior flow field around the dome, shown in Figure 4, was located 5D upstream, 5D downstream, 5D away from the sides of the dome, and the ceiling was located 5D above the dome. Because the maximum of the temporal mean wind speed was 10 m/s, and the Ma was smaller than 0.3, the flow could be regarded as incompressible. The location of the flow field boundaries at these distances was assumed to be appropriate for these computations and the uncertainty from the domain boundaries was negligible (Mamoua et al. 2008).

3.2. Meshing

After defining the geometry, the calculational domain needed to be discretized. Considering the speed and precision of the calculation, the unstructured grid (Anderson et al. 2009) was adopted. The local meshing of the telescope and flow field was shown in Figure 5 where the minimum grid size was 20 mm.

3.3. Physics

The surfaces of the telescope and the dome were given a smooth and no-slip boundary, and the sides and the ceiling of the calculational domain were given free-slip boundaries with a zero normal velocity component. Table 1 lists the basic air parameters.

To simplify the calculation, the ground temperature, the dome, and the telescope were fixed at 283.15 K. A vertical temperature gradient of −6 K/km for the air was incorporated. Since the Reynolds number (listed in Table 1) was $2.17 \times 10^5 > 10^3$, the flow belonged to turbulence. The effects of turbulence were incorporated by selecting the Shear Stress Transport (SST) turbulence model, which could accurately predict the beginning and the separation of fluid under negative pressure gradient condition (Anderson et al. 2009). The calculations were fully three-dimensional and unsteady. Commercial software ANSYS CFX was used to solve the equations for conservation of mass, momentum, and energy.

3.4. Solver Settings

Time step is one of the most important parameters for transient CFD simulation. Generally, the time step can be decided by the courant number (Pan et al. 2015, 2014).

The physical meaning of the courant number is the number of grids past through by the fluid within a time step, and the

| Physical Properties | Value |
|---------------------|-------|
| Density (kg.m$^{-3}$) | 0.9025 |
| Pressure (Kpa) | 68 |
| Kinematic viscosity (m$^2$/s) | $1.86 \times 10^{-5}$ |
| Reynolds number Re | $2.17 \times 10^5$ |
| Turbulent intensity | 2.01% |
| Eddy length scale(m) | 1.68 |
value of courant number always varies from 2 to 10. The definition of the courant number is

\[ \text{courant} = \frac{V \Delta t}{\text{elementsize}}, \]

where \( \Delta t \) is the time step, and \( \text{elementsize} \) is the minimum grid size.
According to Equation (6), the courant number used in the simulation was linearly related with the time step ($\Delta t$), when the wind speed and the size of meshing (elements size) were determined. The shorter the time step of the transient simulation, the more accurately the courant number indicates what the changes in flow field will be.

If the courant number was 2, the speed of air was 10 m/s, and the minimum grid size was 20 mm, then the time step was 0.004 s. The whole model was calculated by the HP Z800 Workstation, with the 48 GB memory (RAM) and the X5675@3.07 GHz CPU. To avoid overflow of numerical solution, the total physical time simulated was 5 s.

3.5. Post Processing

The mesh independence of the CFD computational results was established by the comparisons of the aerodynamic computational results that were predicted on different meshes (Xiao et al. 2012). Figure 6 was an example of such a test for the average speed of the monitoring points. Variations in the number of tetrahedral elements caused small differences. Therefore, the CFD computational results were independent of the mesh.

To obtain the optimal accuracy, the 2,075,502 tetrahedral-element CFD computational grid was chosen in this study because this number of tetrahedral elements was not too large and the price of the computations was not prohibitive.

The monitoring point 2 (shown in Figure 6) was located inside the main tube, and the variation of refractive index for the monitoring point 2 would reflect the change rule of refractive index in the optical path of imaging. The power spectrum density (PSD) of the variation of refractive index calculated from CFD simulation for the point 2 was shown in Figure 7.

Because the mean wind speed was 10 m/s, and the dominant length scale was 4 m (the diameter of the primary mirror), the knee frequency of the PSD should be $10/4 = 2.5$ Hz, according with the Von Karman PSD ($\sim f^{-11/3}$) (MacMynowski & Andersen 2010). This indicated the reliable of the results of CFD simulation.

The average air temperature was presented in Figure 8. Since a vertical temperature gradient was incorporated for the air, the air temperature was higher in the regions closed to the ground. Due to the existence of the dome and the telescope, the uniformity of the air temperature was broken. However, because
the FMT was installed at the height of 14 m, the temperature gradient of the air around the telescope was about 0.3 K. In this condition, according to Equation (2), with the help of pier’s height, the variations of the refractive index \( dn \) was \( 2.04 \times 10^{-7} < 3.21 \times 10^{-7} \). Thus, the impact of non-uniform air temperature from the ground layer on the fluctuation of air refractive index could be effectively decreased.

The mean variation of refractive index is shown in Figure 9. The distribution of refractive index was non-uniform, and the mean variation of refractive index is shown in Figure 11.

### Table 2

| Position | 0° Azimuth | 90° Azimuth | 180° Azimuth |
|----------|------------|-------------|--------------|
| Point 1  | 4.84E-08   | 5.97E-07    | 2.97E-07     |
| Point 2  | 3.43E-08   | 4.34E-08    | 1.60E-08     |
| Point 3  | 6.40E-08   | 8.58E-08    | 5.22E-08     |
| Point 4  | 6.02E-08   | 9.62E-08    | 4.86E-08     |
| Point 5  | 2.39E-07   | 2.55E-07    | 2.45E-07     |
| Point 6  | 3.70E-07   | 1.34E-07    | 1.96E-07     |
| Point 7  | 1.33E-07   | 3.09E-07    | 1.65E-07     |
| Point 8  | 1.43E-07   | 5.74E-07    | 1.69E-07     |
| Point 9  | 2.38E-07   | 2.35E-07    | 4.90E-07     |
| Point 10 | 1.12E-07   | 3.18E-07    | 8.55E-08     |
| Point 11 | 2.04E-07   | 3.17E-07    | 1.32E-07     |
| Point 12 | 1.30E-08   | 1.29E-08    | 1.60E-08     |
| Average  | 1.74E-07   | 2.48E-07    | 1.59E-07     |
non-uniform of refractive index became much more prominent in the windward side of the dome. The maximum variation of the refractive index was $3.415 \times 10^{-7} > 3.21 \times 10^{-7}$, so the conceptual design of the dome for the FMT did not meet the requirement and structural optimization of the dome needed to be done.

| Position | $0^\circ$ Azimuth | $90^\circ$ Azimuth | $180^\circ$ Azimuth |
|----------|-------------------|-------------------|-------------------|
| $r_0$(cm) | 36.5              | 23.9              | 40.6              |

### Table 3
Atmospheric Coherence Diameter

| Position | $0^\circ$ Azimuth | $90^\circ$ Azimuth | $180^\circ$ Azimuth |
|----------|-------------------|-------------------|-------------------|
| $\theta_\nu$(arcsec) | 0.28              | 0.42              | 0.25              |

### Table 4
The Seeing-limited FWHMs

**Figure 13.** Dome layer to Camera path used to compute the dome seeing. (A color version of this figure is available in the online journal.)

**Figure 14.** Maximum value of FWHM at different wind speed.

**Figure 15.** Model of the WT test for the FMT.

**Figure 16.** Model of main tube: (a) the main tube, (b) the distribution of pressure-monitoring points on the primary mirror, and (c) the pressure scanner.

4. The Structural Optimization of The Dome

From Figure 9, we found that the maximum variation of refractive index appeared in the windward side of the dome, and the variations of refractive index with three different slope angles are shown in Figure 10 at the same boundary condition. Only when the slope angle of dome was $15^\circ$, the maximum the variation of refractive index was less than $3.21 \times 10^{-7}$.

This result indicated that the variation of refractive index was mainly caused by the slope angle of the retractable dome. In addition, when the slope angle was $15^\circ$, the variations of refractive index met the requirement.
To evaluate the effect of optimizing, the influence of the retractable dome on the observational performance of the FMT must be investigated.

Supposing that the zenith angle of the telescope was 30°, the speed of air was 10 m/s, and the direction of the flow was 0°, 90°, and 180° azimuth orientation. Note that 0° azimuth orientation corresponded to the FMT opening facing the oncoming wind, while the 0° zenith orientation corresponded to the FMT opening pointing vertically.
The average variations of refractive index for the three different analytical conditions were shown in Figure 11. The distribution of refractive index was non-uniform, though the non-uniform of refractive index still became much more prominent in the windward side of the retractable dome. The maximum variations of refractive index for the three different analytical conditions were all less than $3.21 \times 10^{-7}$.

To count the variations of the refractive index in the optical path of imaging, 12 monitoring points (shown in Figure 12) were selected in the main tube, and the average variations of the refractive index for the 12 monitoring points are shown in Table 2.

The beam path used to compute the dome seeing is shown in Figure 13. The length of the total beam path was 15 m if the errors of optical system were not considered. According Equation (4), Equation (5), and the average variations of refractive index of the 12 monitoring points in the main tube (shown in Table 2), the average atmospheric coherence diameters $r_0$ for the three different analytical conditions were calculated (shown in Table 3).

\[
\left( \frac{\theta_{\text{FK}}}{\theta} \right)^2 \approx 1 - 2.183 \left( \frac{r_0}{\kappa_0} \right)^{0.356},
\]

where $\theta$ is the seeing-limited FWHM for the Kolmogorov turbulence model, $r_0$ is the wave-front outer scale. Typical values of the wave-front outer scale $\kappa_0$ are around 20 m (Tokovinin 2002).

The seeing-limited FWHMs of FMT for the three different analytical conditions were listed in Table 4.

The maximum value of FWHM at different wind speed is shown in Figure 14. According to Table 4 and Figure 14, the atmospheric coherence diameters $r_0$ were all larger than 22.24 cm, and the dome seeing of FMT were all less than $0.5^\circ$; after optimization, the performance of the dome met the requirement.

5. Experimental Validation

To verify the results of CFD simulation, WT tests were conducted. The 1:120 scaled geometry model of the CFD simulations was used in the WT test (shown in Figure 15) and the model of WT test was placed upon a flat square plane.

The test was performed in an open-jet WT, which was 0.55 m wide and 0.4 m high. The velocity uniformity was $\pm 3\%$ and turbulence intensity was less than 5%. In this configuration, the WT test section had no walls, only the floor. The air flew from the upstream nozzle to the downstream collector and the boundary conditions were listed in Table 1. The zenith angle of the telescope was $30^\circ$ and the direction of the flow was $0^\circ$, $90^\circ$, and $180^\circ$ azimuth orientation. Nine pressure-monitoring points located on the primary mirror (shown in Figure 16) and three speed monitoring points (shown in Figure 17) were selected to set up a database to communicate CFD simulation. The speed of the monitoring point was recorded by the hot-wire anemometer with a sampling frame frequency of 10 kHz and total pressure of the monitoring point was recorded by the pressure scanner (shown in Figure 16).

The average speed and speed deviation of the monitoring points at different flow directions between the CFD simulation. The WT tests are listed in Tables 5–7. The total pressure of the monitoring points on the primary mirror at different flow directions between the CFD simulation and WT tests are listed in Table 8 to Table 10.

From the CFD simulation, we already knew that the maximum variation of refractive index mainly existed at the windward side of the dome, while the monitoring point 1, selected in the WT tests (shown in Figure 17) just located at the windward side of the dome.

The variations of the refractive index for the monitoring point 1 at three different flow directions were shown in Figure 18 and the average variations of refractive index were listed in Table 11 which were all less than $3.21 \times 10^{-7}$.

From the comparison with WT tests, it was clear that the maximum calculated deviations of the CFD simulation were all less than 20%. The same variations of the refractive index derived from the wind tunnel test would be a convincing argument for the validity of the simulations. The optimization of the retractable dome was reliable.

6. Conclusion

To design a reasonable dome for the FMT, complementary studies, involving unsteady CFD simulations and WT tests.
were conducted. The results of the analysis were summarized as follows:

1. The slope angle of retractable dome was the main reason leading the variation of refractive index, which would degrade the observational performance of ground-based optical telescope.

2. When the slope angle of retractable dome was 15°, the dome seeing of the retractable dome for FMT was 0.42 arcsec. Furthermore, the lower the air speed, the less dome seeing would be. Especially when the speed of air was less than 5 m/s, the dome seeing induced by the retractable dome would less than 0.127 arcsec.

3. The unsteady CFD simulation model based on finite volume methods could be used with great accuracy in the flow through an optical telescope and dome. The method expressed in this paper provided a reference for the design of the next generation of large ground-based telescope domes.

The boundary conditions of the CFD simulation and WT were simplified for case of analysis. A number of actual engineering conditions were not considered in the simulation. Therefore, the mathematical model of the refractive index through the dome could be further improved by taking actual engineering conditions into account. Experimental validation of this model would be pursued in future research.

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