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NUMERICAL WIND MODELING FOR SITE EVALUATION

Konstantinos Vogiatzis[1]

RESUMEN

Se presentan simulaciones numéricas del flujo de aire sobre varios sitios potenciales para emplazamiento de futuros telescopios. De las simulaciones se deriva información como la velocidad del viento y los perfiles de temperatura, los niveles de turbulencia (velocidad fluctuante RMS), la longitud de estelas y el espesor de la capa límite. Esta información es posteriormente utilizada para modelar el seeing local, proporcionando así una herramienta esencial de evaluación en el proceso de selección de sitios. Se presenta la metodología para el modelo del seeing y la estrategia para configurar el dominio de la simulación. Posteriormente se presenta una compilación de simulaciones de algunos sitios posibles para proyectos de telescopios. Anteriormente, los resultados incluían la evaluación de la capa límite como una función de la velocidad y dirección del viento para un sitio dado o una comparación entre sitios vecinos cuando esto era aplicable. Como el seeing local (el seeing combinado del espejo, el domo y el terreno) es afectado severamente por el desarrollo del sitio y la geometría del edificio, el enfoque de este tipo de estudios ha cambiado hacia la evaluación de las interacciones entre el flujo del aire, la topografía y las estructuras desarrolladas. Se presentan ejemplos que demuestran el valor de esta clase de simulación como una herramienta estratégica para el diseño y la operación del telescopio.

ABSTRACT

Numerical simulations of airflow over various potential sites for telescopes have been performed. Information such as wind speed and temperature profiles, turbulence levels (fluctuating velocity RMS), wake lengths and boundary (ground) layer thickness are retrieved. This information is then used to model local seeing, thus providing an essential evaluation tool in the site selection process. The seeing modeling methodology is presented along with the domain configuration strategy. A compilation of simulations follows, carried out over possible site locations for telescope projects. In the past, results included evaluation of ground layer as a function of wind speed and direction for a given site or even comparison between neighboring sites when applicable. Since the local seeing (combined mirror, dome and ground layer seeing) is strongly affected by site development and enclosure geometry, the focus has now shifted to airflow-topography-structure interactions. Examples demonstrate the value of this type of modeling as a design and operations strategy tool.

Key Words: **SITE TESTING — TURBULENCE**

1. INTRODUCTION

Computational Fluid Dynamics (CFD) can be a useful tool for site characterization since it allows for cost effective estimates of site quantities that are difficult or expensive to measure. Such computations can also be performed for any number and combination of input parameters. The accuracy of the results produced by such methods is subject to certain limitations. These can be of two categories, either numerical or physical. The accuracy related to the numerical category includes grid quality and resolution, as well as the solver methodology. Grid quality is proven to be high (the software in use has quality check/warning capabilities), while its resolution is dictated by that of the available Digital Elevation Map (DEM). The solver is very accurate and the turbulence model used is the one recommended for the particular type of flow (High Reynolds Incompressible). We did not focus on these issues in this study. For the physical category, the boundary conditions are the main factors that can affect the accuracy of the simulation results (velocity field and temperature field) because usually they are not known with certainty. For the velocity field, the unknown quantities are the incoming velocity profile and turbulence level. For the temperature field, besides the incoming temperature profile, one has to worry about either the ground temperature distribution or the heat flux. Finally, depending on the topography, the size of the computational domain may also play a role in the development of the ground layer (GL).

In the past, CFD results provided evaluation of ground layer as a function of wind speed and direction for a given site or even comparison between

[1]TMT Observatory Corporation, Pasadena, CA, USA (voyages@noao.edu).

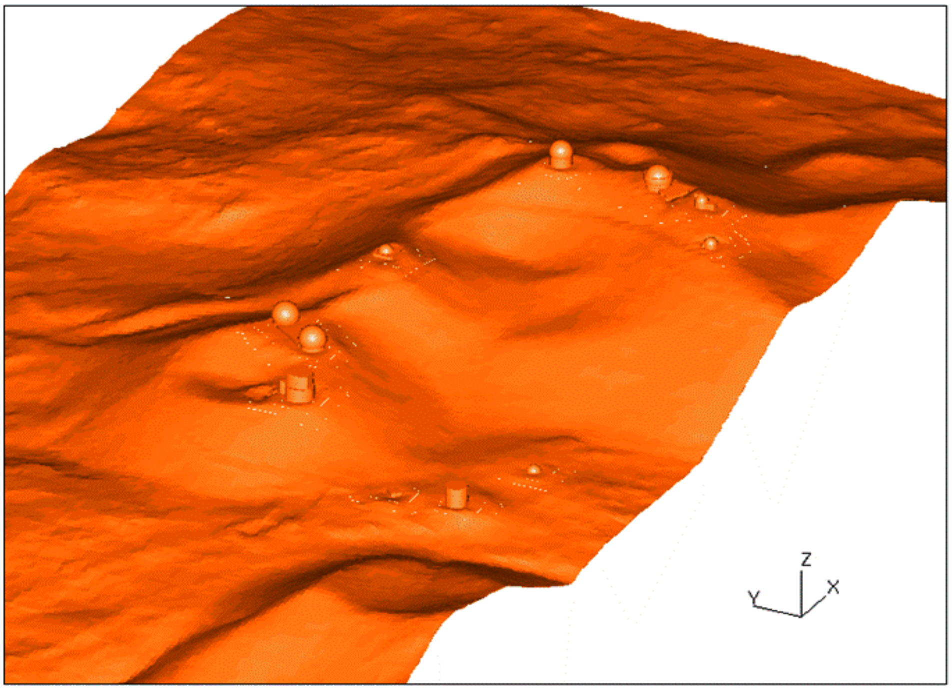

Fig. 1. Surface detail of the CFD model at 1 m resolution for the Mauna Kea summit, Hawaii.

neighboring sites when applicable. Examples include the studies by Vogiatzis & DeYoung (2004) and Vogiatzis & Hiriart (2004). Those studies were isothermal and evaluated the sites based on mechanical turbulence monitoring. Summit development and structure interactions were not taken into consideration.

During site testing seeing measuring equipment is typically deployed between 2 m and 7 m above the ground. The GL part of the seeing measured is therefore far from the expected one. Once the summit is developed and an observatory with a given range of operating zenith angles is built the observed GL will be different. The local mechanical turbulence will be altered, the layer close to the ground will be skipped but enclosure turbulence along with dome seeing will be added to the phenomena affecting image degradation. To understand the net effects of these changes a GL seeing model is needed that can relate the CFD results to image quality and at the same time predict the behavior of the developed site and the enclosure design.

Since air (fluid) and the ground temporal thermal scales differ by orders of magnitude, the tracking of both air and ground temperature to compute the ground layer seeing during a night is computationally intense. Instead, steady state simulations are performed with varying environmental parameters. In the following study a set of CFD simulations of three mountains Mauna Kea in Hawaii (see surface detail in Figure 1), San Pedro Mártir in Baja, Mexico and Cerro Tolonchar in northern Chile are presented. Certain effects on the seeing are found from these simulations to be present on all sites. These are compared to data obtained during the ongoing Thirty Meter Telescope (TMT) site testing campaign on Cerro Armazones, Chile.

2. SEEING MODEL

The seeing CFD post-processing model relates mechanical and thermal turbulence output to refractive index structure function coefficient values. The theory behind the model is described by Wyngaard et al. (1971). To that end velocity and temperature profiles, along with mechanical and thermal turbulent energy dissipation rate and eddy viscosity profiles are required and provided by the CFD calculations. Thus three-dimensional quasi-static C_N^2 fields are generated. Diameter values of the seeing disk encircling 80% of the energy (EE80) along a given optical path are estimated by integrating the corresponding profiles. More can be found in Els & Vogiatzis (2006) for GL implementation and Vogiatzis & Angeli (2006) for dome seeing implementation.

3. VALIDATION

In March-April 2004 a campaign took place at the Cerro Tololo Inter-American Observatory (CTIO) in

Chile, to perform measurements by a variety of instruments including Differential Image Motion Monitors (DIMM), Multi Aperture Scintillation Sensors (MASS), sonic anemometers, thermocouples and micro-thermal probes for calibration and validation purposes. The fact that instantaneous vertical velocity, temperature and C_N^2 profiles were measured in the first 30 m along with total and first kilometer seeing created an opportunity for CFD validation as well. Radiosonde launches provided relatively accurate velocity, temperature and humidity profiles up to an elevation of $\sim$ 20 km at the vertical resolution required to initialize a CFD simulation. The key issue was the location the sounding measurements should be performed. Since the profiles were to be used as input, a location a few km upwind of the site should be chosen. The ideal location should be in a relatively flat area which is neither inside a wake of another peak nor upslope of the peak of interest. From the available launches upwind of Tololo we selected that of April 5th, from 23:00 to 00:00 local time. The prevailing wind was from the north. Criteria for the selection were consistency between launching location wind direction and summit wind direction, wind speed reliability (not too low, coupled with sonde ascend rate), cloud coverage and, above all, measurement availability. The corresponding total seeing measured by the DIMM was $\sim$ 1.0 arcsec, while the seeing above 500 m provided by the MASS was 0.73 arcsec. The GL seeing then for the first 500 m became 0.58 arcsec. The corresponding ground layer seeing value estimated by the code was 0.63 arcsec and for the first 30 m about 0.17 arcsec. For this particular case the Richardson number profile indicated that after 400 to 500 m the model was no longer valid and would overestimate the seeing should it be used. The corresponding thermocouple data suggested 0.21 arcsec for the first 30 m. Therefore overall agreement was good but further confirmation data are required.

4. GROUND LAYER SEEING

Figure 2 presents all GL seeing values (DIMM-MASS) recorded on Cerro Armazones between 2004 and 2006. The values have been normalized by the median seeing and they are plotted as a function of the quotient of radiation flux divided by wind speed. It can be seen that the occurrence of the low and high GL seeing values drops for high negative values of the net radiation to wind speed quotient, i.e. the area within the dashed lines starting at approximately -50 J m^{-1}. In this regime the GL seeing is confined in the range between approximately 0.4 and 1.3 (indicated by the dashed and dotted lines respectively). This is a regime governed by radiation and/or very low wind speeds. The resulting temperature gradient above the site is rather predetermined and GL seeing will show a more constant trend. In this case differences between sites will depend on the ground emissivity (type of soil). Convection heat flux values in this regime are small because of low wind speeds and cannot influence the resulting temperature gradients enough to reverse this trend. Moreover, under strong radiation there will always be significant temperature gradients, so small GL values cannot be detected. The domain of small absolute radiation values is dominated by convection. In this regime mechanical turbulence can be prominent and wind speed direction can also greatly influence GL seeing through wakes. Therefore the expected GL values can cover a wide range since the temperature gradients will do so.

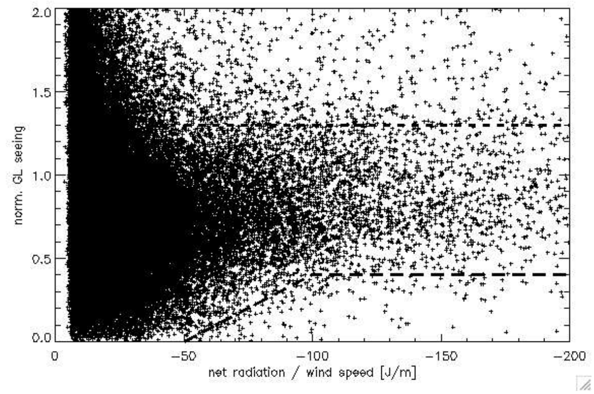

Fig. 2. Normalized GL seeing as a function of the quotient of radiation flux divided by wind speed for Cerro Armazones, Chile.

A compilation of the GL results from 45 CFD cases from three sites are presented in Figure 3 similarly to Figure 2. In the simulations we have used up to 5 different wind speeds, up to 5 wind directions, 3 ground heat flux values and 3 upwind temperature gradients. Even though the sample is not large enough to constitute a Monte Carlo simulation the above described behavior is evident. One would argue that comparing the trend observed in the measurements to the CFD results is less straightforward, since the heat fluxes used refer to the combined convection and radiation effect (net ground flux). However, the high end of the range used (80 W m^{-2}) roughly corresponds to a radiation dominated regime and the low (adiabatic) to a convection dominated. Again, the spread in GL seeing values in the radiation regime for different wind directions is smaller

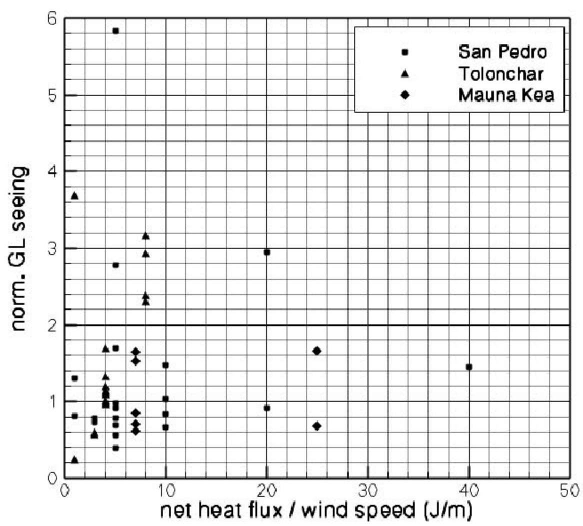

Fig. 3. Normalized GL seeing as a function of the quotient of net ground flux divided by wind speed calculated from 45 CFD cases.

than that for the convection dominated regime, indicating that when convection dominates, wind direction (mechanical turbulence due to topography changes) becomes very important and can push the observed seeing to either side of the average value for the convection dominated regime. Note however that, because of the arbitrary combination of input parameters, direct comparison of the absolute GL values between different wind directions should be avoided. Finally, it is evident in Figure 2 that the average GL seeing values of the radiation dominated regime is less than the mean value of 1, which suggests that the convection dominated part will have an average above unity. Therefore the net effect of topography clearly demonstrates a slightly negative influence on GL seeing.

From the above discussion one can conclude that in order to achieve excellent GL seeing some wind speed is required to balance the radiation and reduce the temperature gradients. A good site in terms of GL seeing is one with smooth slopes standing in the middle of flat terrain, with moderate steady winds and low radiation due to ground properties (not due effective sky temperature, which is a temporary phenomenon). Of course high winds also mean high altitude seeing and in that case GL seeing becomes less important.

5. ENCLOSURE INDUCED SEEING

CFD simulations were performed for a given venting configuration of the Large Synoptic Survey Telescope (LSST) enclosure, which was placed on their selected site, Cerro Pachón, Chile, to take into account the impact of the local topography and the adjacent summit facilities building. The thermal boundary conditions were chosen to: (a) demonstrate the net effect of the enclosure to dome seeing, and (b) simulate a worst case expected ratio of dome to mirror seeing. It is noted that in this study mirror seeing refers to the seeing caused by temperature gradients and turbulence inside the primary mirror surface boundary layer, while dome seeing refers to seeing observed through the rest of the optical path up to 10 m-25 m above the opening. Therefore the primary mirror was given an adiabatic surface. The enclosure and building walls are expected to radiate and be cooler than ambient air temperature and were given a heat flux value, based on competing convection from the selected wind speed and radiation to an effective sky temperature 20 K below surface temperature.

TABLE 1

LSST LOCAL SEEING RESULTS[a]

Azimuth (relative)	90°	0°	180°
Z=20°	073/049	070/117	105/125
Z=40°	103/027	115/102	099/119
Z=75°	057/073	046/053	053/126
Average	092/036	098/124	093/121

[a]Local seeing in milli-arcsec.

Several simulations for 9 different telescope orientations were performed; three zenith and three wind-telescope relative azimuth angles. The grid detail of the LSST model used is shown in Figure 4 for 75° zenith. In all cases the wind direction was kept fixed at 20° N-NE and the wind speed was chosen to have its expected median value. The integration of the resulting C_N^2 field was performed along the optical path starting 40 m from the telescope elevation axis (outwards) all the way to the camera to estimate the overall contribution from the inside and outside of the enclosure. Intermediate results can also be obtained for any given segment of the optical path to investigate the individual contributions. The dome seeing results, in milli-arcsec, are summarized in Table 1. The first value of each duet corresponds to the first 25 m outside the enclosure and the second to the optical path inside.

The weighted average results take into account the expected telescope orientation probability distribution and the site wind rose. The overall weighted average was estimated at 93/61 milli-arcsec. It is clear from the last row that when mirror flushing

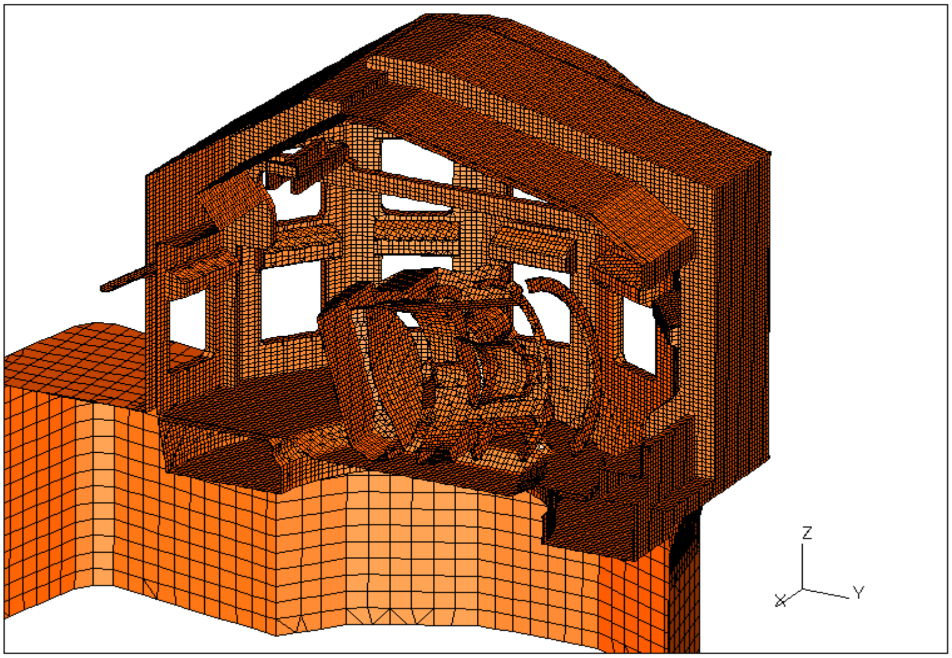

Fig. 4. Cross-section of the LSST model showing grid details at 0.25 m resolution.

is adequate because of unobstructed flow-through (±90° relative azimuth) the contribution of dome seeing is small relative to local seeing. In contrast, the seeing caused by the enclosure-exterior-generated turbulence seems to be uniform in azimuth, even though at high zenith angles (75°) the use of the roof windscreen makes the enclosure more aerodynamically efficient. At 180° azimuth no flow-through occurs through the optical path so seeing is worst.

6. CONCLUSIONS

Computational Fluid Dynamics simulations of potential astronomical sites are a valuable tool for investigating the sensitivity of the seeing conditions above a site under various atmospheric conditions. Even though the direct prediction of the seeing above a site is at the limit of current computational methods, it could be shown that the prediction of occurrence of convection is a natural result of these simulations. It was shown that the dependence of the seeing on the wind speed and net radiation flux is in qualitative agreement with the CFD calculations. The quantitative differences are due to the lack of observations of the sites for which CFD calculations were performed. With the ongoing TMT site survey effort more extensive studies will be performed in the near future. These data, in combination with CFD simulations, will allow investigating the origins of local turbulence of sites.

A numerical strategy of estimating enclosure induced seeing has also been presented. Coupled with a wind buffeting model, it can identify the range of acceptable wind speeds that minimize the combined local seeing caused by an enclosure, provide critical insight into enclosure design and passive ventilation and become useful design tools for the next generation of large telescopes such as TMT and LSST.

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