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Turbulence and wind speed profiles for simulating the TMT AO performances

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Abstract. The site testing campaign of the Thirty Meter Telescope gathered an extensive amount of turbulence profiles. This data is modeled to describe the statistical characteristics of each site and act as "standard atmospheres" for use in AO simulations.

1 Introduction

In this paper, we present a new database of turbulence profiles gathered for the Thirty Meter Telescope (TMT) project [1]. The data represents to date, the largest comparable study of different astronomical sites. The data covers the five TMT candidate sites and the test location of Mt Palomar in California. Three sites in Chile were studied, namely Cerro Tolar, Armazones and Tolonchar as well as two sites in the Northern hemisphere: San Pedro Martir On the Mexican peninsula of Baja California and Mauna Kea 13 North located to the North the ridge of Mauna Kea in Hawaii. These data, were taken with identical sets of equipments on each site, making them perfectly comparable. The dataset, which will be described in more details in the next section is used as a reference to determine the expected performance of the TMT adaptive optics system (AO), NFIRAOS.

As we will show in Sec. 3, defining standard profiles is not a straight forward problem. In an ideal world, performance simulations should be run on individual cases, using individual turbulence profiles and site characteristics. However, such a scenario is often not possible as the runtime of the simulations are long and can only be realistically done a finite sets of conditions. For this reason, we need to reduce the number of cases to be run by using standard sets of cases, usually involving median profiles or an accepted range of percentiles. The difficulty is that there are many ways to define "median profiles". Indeed, taking the median value of each turbulence layer to reconstruct a median profile doesn't equate to the selection of profile with median seeing due to the non linear addition of turbulence. We therefore present several options that have been considered for use in the simulation of TMT performances.

2 The data set

The goal of the TMT site testing campaign was to measure a series of atmospheric parameters at 5 preselected locations based on a satellite study [2]. To carry out a proper selection, two criteria were thought of being vital. First, that the site study spanned a period of time which was long enough to be considered statistically meaningful, hence avoiding bias due to low number statistics, seasonal variability and unusual climatic behavior. The second criterion, was to measure the parameters of interest with the same suite of instruments to avoid, instrumental effects and limitations. In addition, some cross calibration campaigns were carried out to not

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only verify the comparability of each suite of instrument, but also to quantify both their absolute and relative accuracy.

The parameters that were chosen to be measured based on their importance of their impact on the future observatory as well as the ability to measure these parameters in a robotic fashion. As such, all 5 sites were equipped with instruments running in an automated manner which is a necessity considering the remoteness of the sites and relative distance. Unmanned campaigns also have the advantage of not introducing bias due to the outdoor conditions. Following this philosophy, TMT measured weather parameters (air temperature, wind speed, humidity pressure and heat fluxes), precipitable water vapor content, dust particles, seeing, wind and turbulence profiles. It is those last parameters that are the most important for AO performance . The wind profiles were only measured in the ground layer (GL) using sonic anemometers and SODARs which had a combined vertical range of 800m. For the free atmosphere, we rely of wind speed profiles measured by near by stations launching regular weather balloons as well as the NCEP/NCAR reanalysis grid data. For the turbulence profile, we are not limited to outside data to measure the free atmosphere. Our sets of equipment include MASS/DIMM units [3]. The DIMM (Differential Image Motion Monitor), is a widely accepted standard way to measure the seeing. The MASS (Multi Aperture Scintillation Sensor) is approaching the level of acceptance of the DIMM for the measurement of free atmosphere turbulence. This instrument, which can be described as a low resolution profiler, measured the optical turbulence in 6 layers centered on the heights of: 0.5, 1, 2, 4, 8 and 16 km. the missing GL can be inferred from the difference between the DIMM and MASS integrated turbulence since the DIMM is sensitive to the entire atmosphere and the MASS to all the atmosphere above 500m. With the addition of this deduced GL, we obtain a turbulence profile of 7 layers on all 5 sites spanning between 2 to 5 years depending on the site. It is, to our knowledge the largest sample of comparable turbulence profiles obtained for astronomical research. The cross calibration of our MASS/DIMM instrument showed that the relative error of the DIMM is 0.02" and 0.05" for the MASS. It is the goal of TMT to make this data fully available to the public by the end of 2009, allowing AO groups to use this extensive turbulence data for their own simulations. In addition to the MASS/DIMM turbulence, a smaller sample of SODAR turbulence data were measured at the sites. While the statistics gathered with this instrument are smaller than the MASS/DIMM, they increase our knowledge of the GL conditions by sampling both wind and turbulence with a vertical range of 5m up to 200m elevation and 20m to an elevation of 800m.

3 Creating a standard profile

3.1 Defining a median profile

As mentioned in the introduction, there is no simple answer to the problem of defining a simple "median profile" of turbulence. Before the statistical solution we can provide to this problem, it must be stated that turbulence in its nature, varies greatly on several different time scales. Seasonal variations can be so great that individual layers can have their monthly average vary by an order of magnitude from one season to the next, particularly near the altitude of the jet stream and below. Additionally, we found that the altitude of the major contributing layers change from season to season. This emphasizes the need to define standard profiles for the different seasons and run simulations for these different cases. This is particularly true for AO system with multiple conjugation heights. Since these heights are set for a given system, the motion of the turbulence layers will change the performance of the system as the turbulence moved closer or further away from the height of conjugation. On a nightly time scales, the variations are not as important but more predictable and systematic. They also apply more to the lowest levels where the thermal interaction between the ground and the sun have an impact.

Having mentioned the need to have standard profiles for each season, the question now to define a standard or median profile. Medians are more accepted than averages due to their

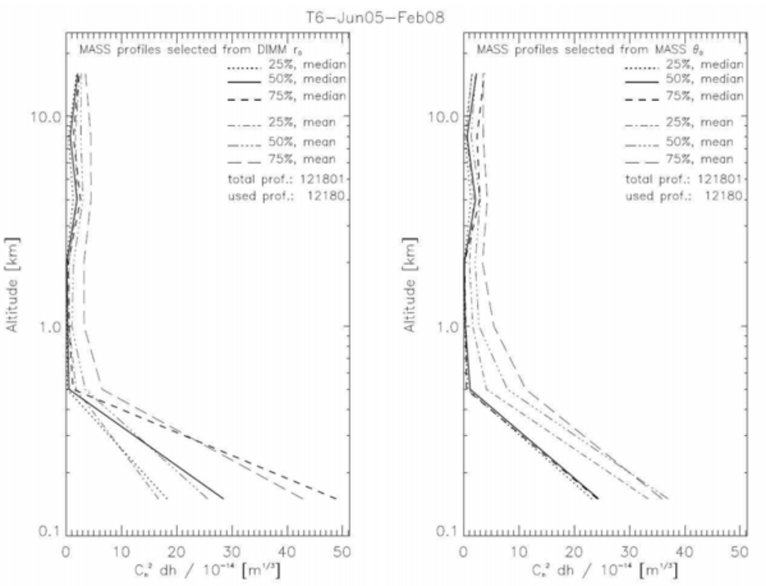

Fig. 1. MASS profiles of Mauna Kea 13N selected by r_0 (left) and θ_0 (right).

easy extrapolation to another percentile and due to the log-normal distribution of turbulence. Indeed, the average value of a given turbulence layer or seeing can be significantly higher than the median due to rarely occurring but extremely high values. We will therefore concentrate on median values for the rest of the paper.

A median profile, composed of individual layers with the median value of all the measurements taken at this particular layer, does not have a median seeing and therefore cannot represent the overall median conditions. the first approach we have therefore taken is the following one: Calculate the median seeing of a given site (and given season if wanted) and identify the profiles which are within a given percentage around this median seeing (we use 5%). We then take the median of each layer of these selected profiles. The resulting profile will be close to have median seeing. An example of such selection in show on the left hand plot of Fig. **??** in the case of Mauna Kea 13N.

This selection, of course assumes that the kind of simulation the profile is used for is in large part driven by the seeing (as it would be the case for most regular adaptive optics system). We can see, however, that some AO element may be driven by the coherence time (bandwidth limitations) or the isoplanatic angle (MCAO conjugation). The selection we propose can be adapted accordingly, as shown on the right hand plot of Fig. **??** where the profiles are selected around the median isoplanatic angle. It can be noticed ont his figure that the resulting profiles are significantly different from the ones selected by seeing. The selection criterion is therefore crucial.

For more general simulations, we have pushed the concept of profile selection by using a broader selection criterion since the performance of an AO system is really dependent on both turbulence and wind speed profiles. The wind speed intervenes in the form of the coherence time or Greenwood frequency f_G (both quantities are interchangeable) and its impact on the wavefront error. For this reason, we chose to select the profiles around the median open loop wavefront variance due to the combined effects of fitting and servo-lag error:

$$\sigma^2 = 0.28(d/r_0)^{5/3} + (f_G/f_{-3db}) \qquad (1)$$

Figure 2 shows the seasonal profiles from Armazones using this selection criterion

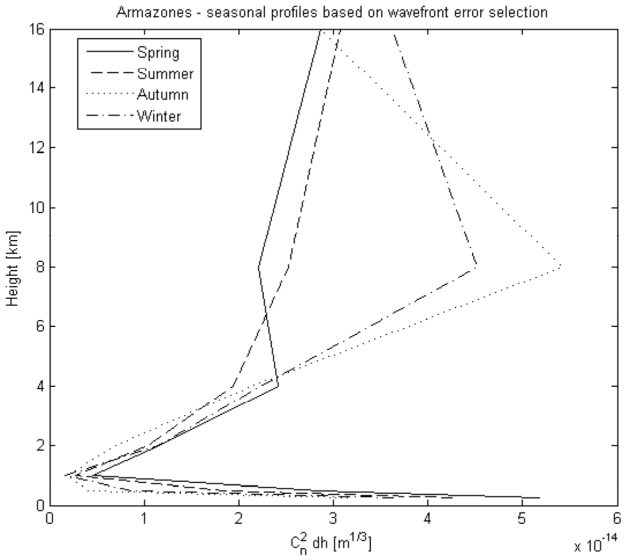

Fig. 2. Seasonal profiles of Armazones selected by their effect on the wave front error.

3.2 A new approach to profile selection

While the selection method proposed is useful is many simulation scenarios, some situations require us to look at real time series of turbulence in order to recreate the changes of performance is a real time situation. For that, one may use a sample of a random night of turbulence and wind observations, however, such sample may not be trivial as all conditions must be "representative" of the site. Instead, we propose an auto-regressive model to recreate a time series of the parameters of interest.

Using seeing as an example, the model uses the temporal covariance matrix C calculated from the entire seeing data set. The size of the matrix n depends on the the temporal resolution required (we use the temporal resolution of the instrument) and the length of the time series needed (we use a night). From the covariance matrix and autocorrelation vector B, we prepare the transition coefficient matrix Φ:

$$\Phi = \begin{pmatrix} BC^{-1} \\ I \end{pmatrix} S \tag{2}$$

where $S = [I \; 0]$ and I $n \times n$ is the identity matrix. To create a time series of length n the following model is run:

$$\varepsilon_{j+1} = \Phi \varepsilon_j + \begin{pmatrix} e \\ 0 \\ \vdots \\ \end{pmatrix} \tag{3}$$

where e is a zero mean Gaussian random number with standard deviation defined by the initial time series. More technical details about the model will be given is a subsequent paper. We give three example of time series recreated using this technique in Fig. 3

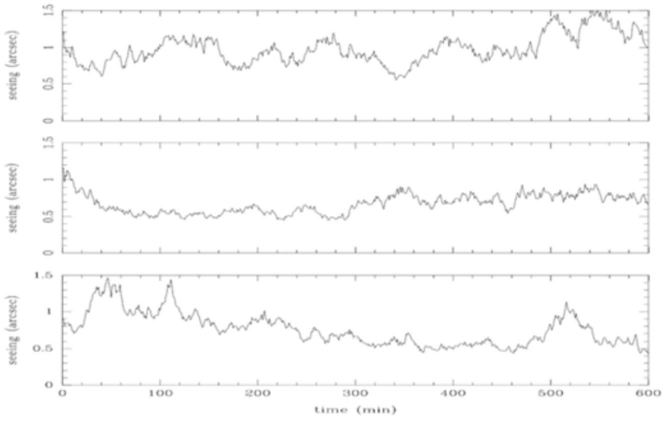

Fig. 3. Synthetic time series of the seeing reconstructed from the statistical analysis.

3.3 Conclusion

With the completion of the TMT site testing campaign, new opportunities in AO simulation present themselves for a array of distinctive sites. We proposed a few different method to reduce the large amount of data to a size management for most types of simulations.

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