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First results from optical turbulence measurements at Cerro Las Campanas in 2010

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ABSTRACT

We report preliminary results from optical turbulence measurements carried out in 2010 at Cerro Las Campanas, the future site for the Giant Magellan Telescope (GMT). The instruments involved are MooSci, a lunar scintillometer for the near-ground optical turbulence profile, Differential Image Motion Monitor (DIMM) for the whole atmosphere total seeing, and MASS Multiple Aperture Scintillation Sensor (MASS) for high-altitude optical turbulence estimation. The main purpose of these measurements is to anticipate the optical turbulence strength above the future GMT enclosure, and to provide a means to model the future adaptive optics performance. We also discuss the significance of such a combination of instruments and some hypothetical limitations.

Key words: atmospheric effects – site testing.

1 INTRODUCTION

A well acknowledged necessity in astronomy is the determination of the seeing statistics at a certain location before building a telescope there. Anticipating the effective seeing at a future installation is even more important.

Site characterization campaigns in remote locations often rely on seeing measurements obtained with such portable instruments as Differential Image Motion Monitor (DIMM), initially developed for the Very Large Telescope Interferometer (VLTI) site testing campaign (Sarazin & Roddier 1990), along with a few complementary instruments (Schöck et al. 2009; Kornilov et al. 2010). DIMM is also used in well-established observatories (Dali Ali et al. 2010). A few observatories may base their seeing estimation upon other instruments if the facility is adequate enough to receive more demanding instruments (Chun et al. 2009) such as the Generalized Scidar for example (Masciadri et al. 2010).

It appears, however, that despite its efficiency, DIMM sometimes overestimates the seeing, when compared to the seeing as measured in a large telescope (Sarazin et al. 2008; Floyd, Wilson & Roggemann 2010). This disagreement may be related to ignored effects. A few possibilities have been discussed, but the overall problem has not been settled yet.

One possibility is the effect of a relatively limited optical turbulence Outer Scale. The Outer Scale is larger than DIMM dimensions but it can affect large telescopes. It can be estimated by other means (Ziad et al. 1994). Another possibility is the difference in elevation between DIMM and the top of the large telescope enclosure (Sarazin et al. 2008). In this case, DIMM will experience a zone of turbulence that is not experienced by the telescope, and this is the main effect we are discussing in the following sections. This issue may be complicated with orographic effects related to the site itself and to the different buildings around the telescope, including the dome itself. Another possibility is that in the atmospheric surface layer, the optical turbulence is sometimes non-Kolmogorov (Berdja 2010), due to temperature and refractive index fluctuations that do not always follow the Obukhov–Kolmogorov model (Lombardi et al. 2010). These effects, and probably others to be investigated, are not exclusive and may occur simultaneously.

The atmospheric surface layer just mentioned is the layer just above the ground in which buoyant phenomena dominate over the mechanical (shear) production of turbulence that occurs higher in the free atmosphere. Some interinstrumentalists prefer a more arbitrary, instrument capability-related, definition of a Ground-Layer of optical turbulence. It refers to the portion of the atmosphere that is not detected by MASS Multiple Aperture Scintillation Sensor (MASS), roughly below 500-m altitude. It is this latter definition that we adopt in the following.

Cerro Las Campanas (70°41′0 West, 29°02′9 South, 2551-m altitude) has already been chosen for the installation of the future Giant Magellan Telescope (GMT; Thomas-Osip et al. 2010). Its seeing statistics have been investigated (Prieto et al. 2010). However, we now want to anticipate the seeing that will be experienced by the future installation and the fraction of the Ground-Layer optical turbulence to be experienced by the future Ground-Layer Adaptive Optics (GLAO) system.

The following discussions concern the simultaneous measurements with these instruments from 16 nights during the months

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★E-mail: aberdja@ctio.noao.edu (AB); gprieto@lco.cl (GP); jet@lco.cl (JET-O) of 2010 August, September and October and our first operational phase with MooSci. We emphasize the seeing as well as the optical turbulence in the Ground-Layer above the height of the GMT. We first discuss the interinstrument comparisons that permit such estimations. Then we present separately the seeing and the Ground-Layer optical turbulence strength above the GMT height. Finally we review some properties of the optical turbulence that may affect these measurements.

2 INTERINSTRUMENT COMBINATION

We have used so far three instruments at Cerro Las Campanas.

(i) DIMM gives the whole atmospheric global seeing. It estimates seeing from the statistics of wavefront slope differences measured through two small pupils at some distance apart (Sarazin & Roddier 1990).

(ii) MASS gives the optical turbulence strength $C_n^2(h)$ as a function of altitude, centred at six altitudes 0.5, 1.0, 2.0, 4.0, 8.0 and 16.0 km above the instrument. It estimates $C_n^2(h)$ from the the statistics of stellar scintillation as measured through four sub-apertures of different sizes (Kornilov et al. 2003).

(iii) MOOn SCIntillometer (MooSci) is an enhanced copy of LUnar SCIntillometer(LuSci; Tokovinin, Bustos & Berdja 2010). It gives a continuous distribution of the optical turbulence strength $C_n^2(h)$ in the Ground-Layer. It estimates $C_n^2(h)$ from the spatial covariance of lunar scintillation as measured through a linear array of equal-size detectors (Villanueva et al. 2010). MooSci is complemented by an anemometer for near-ground wind velocity measurements (Tokovinin et al. 2010).

DIMM and MASS are installed on the same mount, and they both point simultaneously to the same star. They are mounted on a 7-m tower to the north of the peak of Cerro Las Campanas (Prieto et al. 2010; Thomas-Osip et al. 2010). MooSci on the other hand is installed to the southwest of the peak of Cerro Las Campanas, at a distance of 60 m from the DIMM tower. Because of the levelling difference on the mountain peak, MooSci is situated 10 m below DIMM and MASS level.

MASS and DIMM point southwardly and MooSci points northwardly towards the Moon. In this case, even if the instruments may experience different high altitude optical turbulence zones, the actual configuration permits to experience the same low altitude optical turbulence, just above of the peak. Geometrically speaking, the Ground-Layer optical turbulence is common to the instruments, provided that one supposes a horizontal distribution of optical turbulence strength right above the mountain peak as mentioned later.

The estimation of the errors affecting optical turbulence strength measurements is a delicate exercise. Moreover, optical turbulence measurements are merely extrapolations based upon pre-supposed models. For example, MooSci output is a series of power-law functions which approximate the actual optical turbulence strength profile (Tokovinin et al. 2010). MASS profile is also a broad estimation of the real optical turbulence strength profile. Therefore, we are interested only in the general variational patterns, temporal and spatial. In this case, errors are detrimental only when they are systematic offsets.

When the atmospheric optical turbulence is close to the pre-supposed models underlying each instrument, then the measurements given by these instruments will converge. If the measurements fail to converge, it may imply that some of the hypotheses are not valid.

DIMM and MASS both deliver data at a standard rate of one seeing estimation and one high altitude profile estimation, respectively, every minute. MooSci delivers a low altitude optical turbulence strength profile every two minutes. In fact, the inversion procedure is shown to be more stable at this rate than at the higher one-minute rate.

In order to make the results combinable, we perform a binning of the DIMM and MASS outputs that matches MooSci data. In this case it is just a two points sliding average applied to the original data. We have thus three sets of data corresponding each to two-minute bins. The next step is to put all data into the same common time sampling. This is simply achieved by selecting those DIMM and MASS data with time-stamps that coincide within a time margin of one minute of a MooSci profile.

The volume of collected data depends upon weather conditions and cloudiness. Specifically for MooSci, it depends also upon the moon phase (we observe during a week around the new moon), the moon altitude above the horizon, and upon wind velocity. In addition to the ambient conditions, the convergence of the lunar scintillometer optical turbulence strength profile reconstruction algorithm limits the number of retrieved profiles.

After synchronizing MooSci profiles with MASS and DIMM results, within two-minute bins as described above, we obtain a total of 345 synchronized profiles in August, 156 in September and 285 in October.

We favoured here quality over quantity, noting that we judge the interinstrument agreement through systematic offsets, which are relatively insensitive to the number of synchronized profiles, rather than through correlation coefficients for instance, which are contrariwise dependent upon them. The nightly number of synchronized profiles (labelled ‘nightly *N*’) are displayed in the fourth column of Table 2. We can clearly see that the interinstrument agreement quality does not depend upon the nightly number of synchronized profiles.

The continuous optical turbulence strength profile from MooSci allows us to consider any altitude and to isolate the turbulence strength integral between two given altitudes above the instrument. This is achieved through a simple interpolation of the output profiles (Tokovinin et al. 2010). We consider in all cases only the optical turbulence above the height of the MASS–DIMM. Consequently, when we say that we estimate optical turbulence strength integral up to a certain altitude, it means that it is the integral between the MASS–DIMM level and that altitude.

The meaningfulness of the measurements, as well as the underlying hypotheses, can be practically determined by the comparison of the outputs from different instruments. Fig. 1is an example of such a comparison. We determine the seeing above approximately 500-m altitude from both the MASS and the combination of MooSci and DIMM measurements. When we have a satisfying agreement as in this example (correlation coefficient of 89.3 per cent and more importantly for what follows, a mean offset of ‘only’ 0.08 arcsec), it means that the instruments give a coherent picture of how the optical turbulence is vertically distributed.

However, the instruments do not agree every night. When they do not, we have an important bias that often lasts many hours, or sometimes even the whole night. We label every night according to the level of the agreement between the instruments in assessing the seeing over 500-m altitude. This labelling appears in Tables 1 and 2, in the fifth and fourth columns, respectively. If the night presents a relatively good agreement, like in Fig. 1, it is labelled ‘G’ for ‘good’, and when it presents a bad agreement, it is labelled ‘B’ for ‘bad’. We consider it to be a bad night when we obtain a

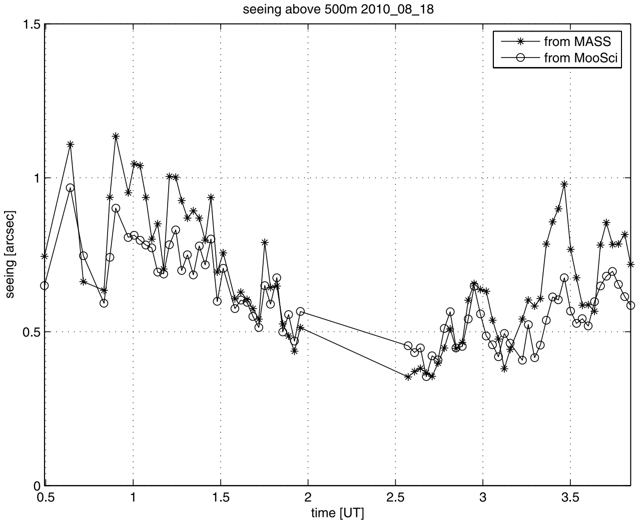

Figure 1. Seeing above 500 m from MASS and inferred from a combination of MooSci and DIMM measurements.

Table 1. Comparison night by night of the average measured DIMM seeing $\epsilon_{\rm DIMM}$ in arcseconds, the average estimated GMT seeing $\epsilon_{\rm GMT}$ in arcseconds, the average seeing improvement $\Delta\epsilon$ in arcseconds, and the agreement quality between DIMM, MASS and MooSci, where 'G' means a good agreement, and 'B' means a bad agreement. The errors assigned are the nightly standard deviations.

Date	$\epsilon_{\rm DIMM}$	$\epsilon_{\rm GMT}$	$\Delta\epsilon$	Quality
18/08	0.85 ± 0.12	0.77 ± 0.11	0.08 ± 0.02	G
19/08	0.80 ± 0.07	0.78 ± 0.07	0.02 ± 0.01	B
20/08	0.83 ± 0.16	0.77 ± 0.15	0.06 ± 0.03	G
21/08	0.71 ± 0.06	0.68 ± 0.06	0.02 ± 0.01	B
22/08	0.93 ± 0.16	0.80 ± 0.14	0.14 ± 0.06	G
23/08	1.39 ± 0.18	1.27 ± 0.19	0.12 ± 0.05	G
26/08	0.87 ± 0.08	0.82 ± 0.08	0.04 ± 0.02	B
23/09	0.95 ± 0.08	0.83 ± 0.10	0.11 ± 0.04	G
24/09	0.92 ± 0.07	0.83 ± 0.07	0.09 ± 0.02	G
25/09	1.04 ± 0.12	0.90 ± 0.10	0.13 ± 0.08	G
20/10	0.68 ± 0.09	0.65 ± 0.09	0.03 ± 0.01	B
21/10	0.73 ± 0.11	0.70 ± 0.11	0.03 ± 0.01	B
22/10	0.93 ± 0.06	0.87 ± 0.06	0.06 ± 0.03	G
24/10	0.92 ± 0.07	0.82 ± 0.06	0.10 ± 0.03	G
25/10	0.96 ± 0.08	0.85 ± 0.08	0.11 ± 0.03	G
26/10	0.78 ± 0.06	0.68 ± 0.07	0.10 ± 0.03	G

clear offset of more than 0.25 arcsec that persists for the whole set of measurements. Approximately, 2/3 of the nights are labelled as good. Further details regarding the instrument comparisons can be found in Thomas-Osip et al. (in preparation).

Very often, this kind of disagreement is explained by the fact that the instruments do not point in the same direction. We implicitly suppose a horizontal distribution of the optical turbulence over the mountain, and this hypothesis may fail, not only for the high-altitude optical turbulence (Masciadri, Avila & Sánchez 2002) but also when dealing with optical turbulence very close to the ground. A practical and probably partial precaution is that DIMM and MASS are situated to the north of the peak, pointing southward, and MooSci is situated to the south, pointing to the Moon in the northern direction. Some other possible systematic biases from the theoretical viewpoint are discussed in Section 5.

Table 2. Comparison night by night of the average ratio of the Ground-Layer optical turbulence strength integral above GMT to the total Ground-Layer optical turbulence integral, and the agreement quality between DIMM, MASS and MooSci, where 'G' means a good agreement, and 'B' means a bad agreement.

Date	GL C_n^2 ratio	Quality	Nightly N
18/08	0.63 ± 0.03	G	72
19/08	0.69 ± 0.02	B	9
20/08	0.68 ± 0.06	G	15
21/08	0.68 ± 0.08	B	8
22/08	0.48 ± 0.02	G	92
23/08	0.57 ± 0.02	G	126
26/08	0.71 ± 0.05	B	23
23/09	0.52 ± 0.03	G	56
24/09	0.50 ± 0.02	G	42
25/09	0.55 ± 0.07	G	58
20/10	0.66 ± 0.03	B	19
21/10	0.60 ± 0.03	B	50
22/10	0.58 ± 0.05	G	55
24/10	0.51 ± 0.02	G	54
25/10	0.55 ± 0.03	G	77
26/10	0.52 ± 0.03	G	30

3 THE SEEING ABOVE GMT

Making the assumption (and noting the caveats mentioned in the previous section) that the optical turbulence strength distribution above the peak of Cerro Las Campanas is almost horizontally stratified, it is possible to combine DIMM and MooSci data to predict seeing above any altitude. This is achieved simply by subtracting the MooSci-estimated optical turbulence strength integral from the DIMM level (10 m above MooSci) to the desired altitude, from the total given by DIMM. If we consider that GMT will be sensitive only to the optical turbulence occurring above 60 m, we can then estimate $\epsilon_{\rm GMT}$, the seeing experienced by GMT, and compare it to $\epsilon_{\rm DIMM}$, the total seeing given by DIMM.

The model used with DIMM is the usual near-field approximation of a Obukhov–Kolmogorov-based optical turbulence (Roddier 1981). The model used with MooSci is a von Kàrman optical turbulence model with a constant Outer Scale $L_0 = 25$ m (Tokovinin et al. 2010).

Fig. 2 displays a comparison of the DIMM seeing $\epsilon_{\rm DIMM}$ and the estimated GMT seeing $\epsilon_{\rm GMT}$. In this plot, every line connects the measurements of a particular night.

As expected, the GMT seeing is smaller than the total seeing. What we can see from the figure is that for every night, the improvement in seeing, $\Delta\epsilon = \epsilon_{\rm DIMM} - \epsilon_{\rm GMT}$ is almost stationary as shown by the roughly constant slopes of the lines for each night with respect to the one-to-one line.

We display the nightly averages of DIMM seeing, GMT seeing and the seeing improvement in Table 1. The average seeing improvement ranges between 0.02 and 0.1 arcsec. However, if we consider the fourth column that describes the quality of agreement between the three instruments (discussed in Section 2), we notice that when measurements are labelled as good, the nightly average seeing improvement $\Delta\epsilon$ is rather large, with an average close to 0.1 arcsec. We have in this case $\Delta\epsilon > 0.05$ arcsec. When the agreement is bad, then the values of $\Delta\epsilon$ are small, often approaching 0.02 arcsec and in this case we have $\Delta\epsilon \leqslant 0.04$ arcsec.

Good agreement measurements 'G' point then to seeing improvements between 0.05 and 0.14 arcsec on average. Smaller values

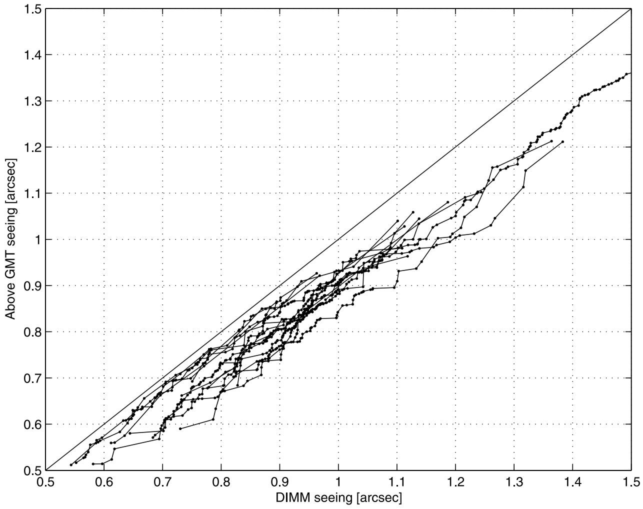

Figure 2. Estimated GMT seeing $\epsilon_{\rm GMT}$ in arcseconds versus measured DIMM seeing $\epsilon_{\rm DIMM}$ in arcseconds. Every line links the measurements of a distinct night. The solid straight line represents a one-to-one correlation for reference only.

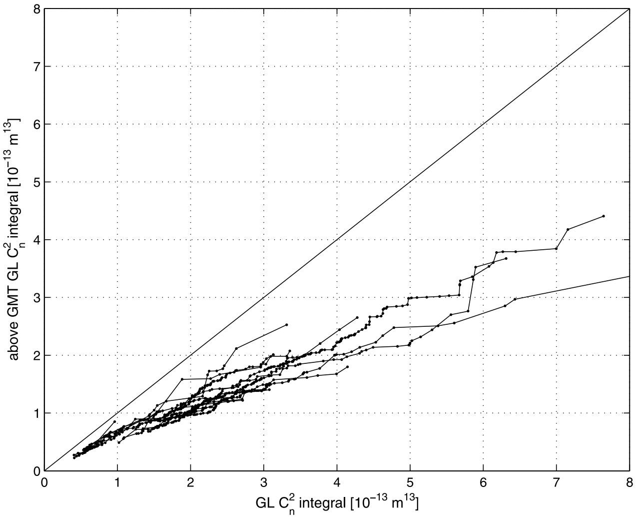

Figure 3. The Ground-Layer optical turbulence strength integral above GMT versus the total Ground-Layer optical turbulence integral. Every line links the measurements of a distinct night. The solid straight line represents a one-to-one correlation for reference only.

happen to be associated with bad agreement measurements ‘B’, and that raises a red flag in the cases where $\Delta\epsilon$ may seem to be very small. These measurements can be put aside for the moment.

Obviously, these values concern only our limited sample. A year of measurements, or more, may provide more significant statistics.

4 THE GROUND-LAYER OPTICAL TURBULENCE ABOVE GMT

GLAO is meant to improve image quality over a large field of view by correcting the effects of the optical turbulence originating at low altitudes (Athey et al. 2006). Regardless of the actual altitude range over which the correction by any specific system can be made, we consider here the Ground-Layer as defined below 500-m altitude. MooSci, however, does have the capability to determine the turbulence strength of any altitude range below 500 m. This can be explored in future analyses based on the GMT GLAO design constraints.

The Ground-Layer optical turbulence strength can be obtained by subtracting MASS total optical turbulence strength (above 500 m) from the DIMM total optical turbulence strength. It can be obtained directly from MooSci as well, integrating from the DIMM level up to 500 m. Because of the occasional instabilities with MASS results, we choose to use only the results from MooSci in this preliminary analysis.

In the future it may be useful to compare the MASS–DIMM results to those of MooSci. However, there will always be the caveat that when the Ground-Layer turbulence is small relative to the total turbulence strength such a comparison is essentially meaningless. To illustrate, let us suppose that MASS determines the optical turbulence strength above 500-m altitude with a relative error of 10 per cent. If the optical turbulence strength below 500 m happens to be 10 per cent of the whole turbulence strength in the atmosphere, then it will suffer from an error that is of the same order of magnitude as the estimation itself, leading from time to time to some embarrassing negative values in the process.

We do not assign a seeing to the Ground-Layer optical turbulence because seeing is the result of propagation from the top of the atmosphere and it does not make sense here. We will represent only the optical turbulence strength, which is also proportional to the corrections to be applied by the Adaptive Optics systems.

Fig. 3 displays the estimated Ground-Layer optical turbulence strength integral above GMT versus the estimated total Ground-Layer optical turbulence integral. In this figure, every line connects the measurements of a given night. The lack of much scatter shows that the relationship is relatively stable over the nights. In Table 2, we display the nightly average of the ratio between the Ground-Layer optical turbulence strength integral above GMT, and the total Ground-Layer optical turbulence integral.

GMT is likely to be sensitive to up to 50–70 per cent of the total Ground-Layer optical turbulence strength. The remaining 40 per cent is avoided because it occurs below the telescope height (60 m).

One may notice that the results are of the same order of magnitude that one would expect if we consider an atmospheric surface layer as in the case of a neutral temperature stratification (Tatarskii 1971). If we consider a theoretical optical turbulence strength vertical profile following a power-law function with index $-2/3$, GMT would be sensitive to around 65.7 per cent of the total Ground-Layer optical turbulence strength. In an unstable convective regime, it would have been around 30 per cent (for a power-law function index of $-4/3$). This does not mean necessarily that the Ground-Layer, as defined here, is a part of, or equivalent to the atmospheric surface layer. Although in the future, it may be found to play a non-negligible role in the optical properties of the former. This point may be clarified through further investigation, notably in combination with meteorological instruments like ultrasonic sensors, more likely to characterize the atmospheric surface layer physical properties.

5 CONSIDERING SOME OPTICAL TURBULENCE UNKNOWNS

Generally speaking, seeing-related optical instruments rely on a certain set of assumptions concerning the behaviour of the optical turbulence in the atmosphere. These conditions, mostly the statistical properties of the optical turbulence, may or may not occur.

Optical turbulence, generated at various heights in the atmosphere through wavefront phase fluctuations, is a random and unpredictable phenomenon. However, its statistic moments are considered to be deterministic and stationary. The spatial statistics depend upon the shape of the spatial power spectral density of phase fluctuations. This power spectrum is a power-law function over a range of spatial frequencies. The range is limited by power spectrum distortions that correspond to the Outer Scale of the phase fluctuation in the lowest frequencies, the largest scales over which the power-law function is still occurring, and to the Inner Scale of the phase fluctuations in the highest frequencies, the smallest scale displaying phase variations (Tatarskii 1971).

Since the Outer Scale varies between a few tens to hundreds of metres, it has no noticeable effect on the instruments. MooSci can only be sensitive to the Outer Scale at high altitudes (Tokovinin et al. 2010) but varying its value within a few tens of metres has no effect on the output profile at low altitudes (below 500 m).

On the other hand, because the detectors of both MooSci and MASS are small (relative to other instruments where the size of the pupils over which the optical turbulence is integrated is far larger than the Inner Scale), they may be affected by a non-zero Inner Scale. The Inner Scale is believed to vary between a few millimetres near the ground to around a centimetre in the troposphere (Tatarskii 1971). If the Inner Scale is really on the order of a millimetre in the atmospheric surface layer, it does not significantly affect MooSci measurements. But an Inner Scale of the order of the centimetre in the high altitudes could affect some MASS measurements, since it approaches the characteristic size of the projected detectors (which is around 2 cm). Optical turbulence Inner Scale appears then to be an issue to be investigated.

The instruments may be sensitive to the occurrence of a non-Kolmogorov optical turbulence in the atmospheric surface layer, that is when the power-law exponent of the power density spectrum of phase fluctuations does not correspond to the expected Obukhov–Kolmogorov optical turbulence exponent. It may affect both DIMM and MooSci, but at different magnitudes. A non-Kolmogorov optical turbulence has already been observed (Goodwin 2009) at another peak at Las Campanas Observatory with SLope Detection And Ranging (SloDAR) and such an occurrence should be investigated and monitored at Cerro Las Campanas, not only for its effects on seeing measurements, but also for its effects on the Adaptive Optics performance (Boreman & Dainty 1996). It has been shown that depending on the power-law exponent, DIMM could overestimate or underestimate seeing, relative to what could be expected in case of an Obukhov–Kolmogorov optical turbulence (Berdja 2010).

Theoretically this issue may be corrected if the optical turbulence model of the different contributions of the atmosphere are known. A major difficulty may come from the identification of the height below which the non-Kolmogorov optical turbulence may occur. It can be reasonably assumed that it is mainly related to the height of the atmospheric surface layer. This assumption is due to the particular physical processes that define this layer. It does not necessarily imply that non-Kolmogorov optical turbulence cannot occur in the free atmosphere since buoyant turbulence may also occur there under certain conditions (Vernin 2002) but they can be treated separately since the Ground-Layer turbulence has been shown to be independent of the free-atmosphere turbulence (Tokovinin & Travouillon 2006; Chun et al. 2009).

The occurrence of non-Kolmogorov optical turbulence may play a substantial role in the way seeing instruments interpret their measurements and extrapolate them to the seeing affecting the future telescope and its components. We think that this effect can play an important role in the disagreements between the instruments we observe certain nights and that this issue should be investigated.

If the problems do not come from for the optical turbulence models, it is possible that the linear function in MASS, and the power-law function in MooSci are not the most suitable ones to approximate the optical turbulence strength profiles after all.

6 CONCLUSIONS

In the above sections, we have shown how the combination of different instruments, DIMM, MASS and MooSci, is a powerful tool and can provide substantial information about what to expect from the future instruments at Cerro Las Campanas. We focused upon the seeing to be experienced by GMT, as well as the portion of the Ground-Layer optical turbulence strength to be experienced by the future GLAO system.

According to the first three months of measurements, GMT is likely to experience a seeing smaller by around 0.1 arcsec on average than the seeing delivered by DIMM in the same location because it sits above a significant surface layer turbulence. The future GLAO system will experience approximately 60 per cent of the Ground-Layer optical turbulence strength. These figures may evolve as more measurements are taken over the coming year.

The quality of the estimates from this combination of instruments may be improved by investigating how certain optical turbulence properties affect the respective turbulence models assumed by each instrument. The optical turbulence Inner Scale, the occurrence of non-Kolmogorov optical turbulence in the atmospheric surface layer, and non-horizontal optical turbulence strength distribution around the mountain top are properties previously neglected that may have a significant although different effect on each of these instruments. These effects may be monitored with complementary instruments.

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