High-resolution ground layer turbulence from inside the CFHT dome using a lunar scintillometer

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Abstract. For ground layer adaptive optics systems, knowledge of the local height- and time-resolved ground layer (GL) turbulence is crucial to link local topography with optical turbulence. Such turbulence profiles have been obtained in the years 2009 and 2010 over 250 hours on Mauna Kea, Hawaii. Results from measurements inside the Canada-France-Hawaii Telescope (CFHT) dome indicate severe degradation of image quality due to a poorly vented dome and thus provide input for dome modifications and design aspects for a new ground layer adaptive optics system. The outside median GL seeing above 6 metres was determined to be $0.48\pm0.01"$.

1. Introduction

The lunar scintillometer Portable Turbulence Profiler (PTP) measures integrated moonlight with photo diodes to record intensity fluctuations due to atmospheric turbulence in the ground layer. We describe its design and measurement setup as well as first results from the measurement campaign at the CFHT. The primary goal of this study is to measure the turbulence contribution to the optical seeing from inside and outside the CFHT, and to compare with other existing seeing-instruments, such as the MKAM DIMM-MASS system and the CFHT dome DIMM instrument.

The principle of a lunar scintillometer is as follows: an array of photo diodes, separated by different baselines, is used to record intensity variations of moonlight, integrated over the lunar disk, at a sampling rate of order 1 kHz. Each diode has a slightly different line of sight to the Moon and probes a different atmospheric volume up to a certain height, above which two diodes share a common path. Thus, each diode pair with its unique separation baseline has its own response function defining the sensitivity range. By cross-correlating intensity fluctuations between different diode pairs, a height-resolved measurement of the turbulence strength in the ground layer up to about 1 km can be obtained. Above this height, the single diode pares share the same line of sight to the moon and the end of its sensitivity range is reached. One of the main advantages of such a device is that it measures dimensionless intensity variations that are directly related to the $C_N^2$-profile. No calibration of the instrument is needed.

The important atmospheric parameters seeing $\varepsilon$, Fried parameter $r_0$, atmospheric timescale $\tau_0$, and the isoplanatic angle $\theta_0$ define optical turbulence in the atmosphere. All these parameters can be determined if the height-dependent $C_N^2(h)$ (and the wind speed profile) is known. This
structure constant defines the turbulence strength throughout the atmosphere and is the mean-square difference of index-of-refraction fluctuations of two horizontal locations, separated by 1 m. Several models of this turbulence profile have been suggested over the years [1–3], to note just a few. However, as stated by Beckers [4], the actual profiles vary from site to site and from time to time, and average profiles can only give a guideline. It is therefore important to characterize each site with respect to the $C_n^2$-profile, especially on the ground, where it is influenced by local topography, not just once but over years. In order to understand the long-term changes and fluctuations that could have local, diurnal, seasonal or other causes. The ground layer contributes a significant fraction (up to 80%) of the integrated $C_n^2$ [5]. Thus it is critical to vertically resolve $C_n^2(h)$ in the first km of the atmosphere to understand better the local effects of the topography and specifically the effect of the telescope dome and its microclimate on seeing on the optical turbulence, and hence the seeing. This requires measurements of the seeing from inside the dome to be carried out during normal telescope operations when the moon is suitably located so that moonlight enters through the slit in the dome. Fig. 1 shows the PTP acquiring data inside the CFHT dome, lit by moonlight. At other times, the seeing monitor was located outside and measured seeing concurrently with the DIMM-MASS monitor for comparison and cross-correlation.

### 2. Instrument Description

The PTP designed was designed and built at the University of British Columbia as an in-house project. The detector design is similar to the one used in the Arctic [6; 7]. Observations were made with the PTP from December 2009 until August 2010. A technician or telescope operator sets up the instrument at the beginning of the night near the DIMM-MASS weather station MKAM tower or, if the astronomical target at CFHT is favorable and moonlight enters the dome, the PTP is set up inside. As the slit moves during observation, the PTP is in this case repositioned accordingly.

#### 2.1. Basic Principle

The basic principle is to measure the intensity covariance function $B(r)$ via intensity fluctuations over different baselines and relate it directly, with the appropriate response function, to the $C_n^2$-profile. This is done by placing diodes on a linear bar, separated such that each diode pair subtends a different separation distance (baseline). Light from the moon passes through the turbulent atmosphere and phase distortions occur as discussed previously. Such phase
distortions create intensity fluctuations (scintillation) at the detector. Due to the overlapping fields of view above a certain height for each diode pair, which depends upon their baseline and orientation, the recorded intensity fluctuations are partly correlated, because part of the recorded light shares a common path. By calculating the covariances of the mean-subtracted and DC-normalized intensities, the amount of correlation is determined and with many baselines, a turbulence profile can be extracted. The electrical current, produced by each photodiode due to moonlight, is preamplified. This DC signal is then recorded with a high-resolution fast 24 bit analog to digital converter card. The intensity fluctuations we are interested in are of the order 0.01%, hence we need to record voltage changes down to µV-precision. A quarter moon produces DC values of about 400 mV, which means we need to resolve 40 µV. The electrical current, produced by each photodiode from the incoming moonlight, is amplified by a low-noise FET operational amplifier employing a 100MΩ feedback resistor and subsequently digitized by a National Instruments data acquisition computer using an 8 channel 24 bit ADC card. DC-signals are digitized directly with no filtering. A control program written in the Labview SignalExpress environment ensures proper data storage.

2.2. Systematics and Noise Treatment

With an instrument capable of recording such high-precision fluctuations, it is important to understand the systematics. The advantage of a lunar scintillometer and its data analysis is that no calibration is required because normalized intensity fluctuations directly relate to a covariance function, which in turn directly enables us to estimate the turbulence profile $C_N^2$. In the following, possible noise sources that affect a lunar scintillometer are outlined.

All light sources that fluctuate at least on levels of 0.01% and whose light might find its way into the photo detectors will cause serious data contamination due to optical interference (not to be confused with coherent interference of light). Entrance aperture restrictions and a tracking device that ensures a perpendicular line of sight to the moon help to decrease the influence of this effect. Each photodiode was fitted with a circular baffle that limited the field of view to a ±3° radius centred on the Moon and a low-cost amateur astronomical mount was chosen for the tracking. Even with such a large aperture, the sky background contribution is less than 10% of the DC value. Electrical interference may cause contamination of the diode signals on their way to the acquisition card. We reduce this by shielding and properly grounding the diodes with their directly-attached preamplifier board. These units are located inside an enclosed aluminum bar. Nevertheless, we do see a 60 Hz interference, which we filter out via software.

Such data contamination is usually readily identified by the analysis code and the one-minute data section is removed. With this list it becomes clear why the amount of useful data may be reduced, compared to the total raw data acquisition time. 20% of data taken outside near the MKAM tower, and 45% of data taken from inside the CFHT dome was discarded.

2.3. Theoretical Aspects

As already stated, intensity fluctuations due to turbulence can be used to determine the $C_N^2$-profile, from which all atmospheric parameters can be derived to characterize optical turbulence for astronomical observations. The intensity covariance function $B_{l,ik}$ is related to the turbulence profile, via the following equation [6; 8; 9].

$$B_{l,ik} = \int_0^\infty dh C_N^2(h) h \sec \zeta K_{ik} (\vec{r}_{ik}, h).$$

(1)

The response function $K_{ik} (\vec{r}_{ik}, h)$ is a function of baseline $\vec{r}_{ik} = \vec{r}_i - \vec{r}_k$. It is the product of several filter functions that can be determined prior to observing, as they don’t depend on the data, but only on the response of the instrument to the current moon intensity distribution at
the time of observation, a chosen turbulence model and instrumental design parameters such as baseline separations and sensitive photo detector area.

The intensity covariance function $B_{I,ik}$ for two diodes $i,k$ is:

$$B_{I,ik} = \left\langle \left( \frac{I_i}{\langle I_i \rangle} - 1 \right) \left( \frac{I_k}{\langle I_k \rangle} - 1 \right) \right\rangle.$$

(2)

$I_i = I(\vec{r}_i)$ represents the intensity recorded by diode $i$ and the inner ensemble average is the time average intensity over a 1 min time interval. This interval choice is justified because it is long compared to the atmospheric coherence time. For each 1-minute data set, the most probable $C_N^2$-profile is estimated by maximizing the posterior probability of the model [6; 7]. The insensitivity of the lunar scintillometer to high-altitude turbulence gives an additional constraint such that the last $C_N^2$ value is set to a very small value, close to zero. Interpolating between the reference heights gives $C_N^2$ values at other heights. The turbulence integral is defined by

$$J(h) = \int_h^\infty dx C_N^2(x).$$

(3)

This gives the contribution from turbulence at height $h$ up to the outer range of the sensitivity of the lunar scintillometer at $\sim 1$ km.

3. Results of the CFHT GL Turbulence Test Campaign

The PTP was routinely deployed whenever the Moon was within one week of full Moon. If CFHT operations allowed, data were taken from inside the dome through the open dome slit if a direct line of sight to the Moon was available. If not, the PTP was set up outside and data were taken from near the MKAM tower. Regular data acquisition began in mid-May 2010 until end-August 2010, $\sim 220$ hours of outside data and $\sim 37$ hours of data from inside the dome were recorded.

For the analysis, $\sim 80\%$ (172 h) of the outside data and $\sim 55\%$ (21 h) from the inside data were used. The rest had shadowed diodes or showed other contamination that made the data unreliable. Data from inside the dome often showed shadow motion on some diodes as well as unusual spikes probably caused by electromagnetic interference. Absolutely photometric nights are required. Every minute of data acquisition is individually tested. In addition, for useful data with the PTP, the Moon should be at least $10^\circ$ in altitude.

An example of the result of a lunar scintillometer can be seen in Fig. 2, where the ground layer turbulence is mapped as a time series of $C_N^2$-profiles, and the corresponding seeing values above the indicated heights are shown below. At the beginning of this specific night, a relatively strong boundary layer in the first 10 to 20 meters was observed. At around 6 UT, turbulence in the 100 m to 300 m region started to gain strength and stayed there for about an hour. The effect on the seeing was evident and bad conditions in the ground layer were detected. After the atmosphere calmed down, 3 hours of weak ground layer made for excellent conditions, while a slight increase in turbulent strength was still evident around 20 m height. Between 10:30 UT and 11 UT another incidence of turbulence was visible in the 100 m to 300 m region. This contamination disappeared from the line of sight to the Moon shortly after and beyond 11:30 UT. The distinct layer around 20 m gained in strength and extended to the ground after 12:30 UT, making for worse seeing conditions until the sun was rising. Over all, this night had a median GL seeing of 0.44" above 6 m, while the DIMM instrument, located right beside the PTP on a 6 m tower, measured 0.45'. Besides the obvious uncertainties of local effects with the two instruments pointing to different positions in the sky, this shows that little free atmospheric turbulence was contributing during that night and most of the seeing was created in the first few hundred meters.
Figure 2: Example of a scintillometer result. The ground layer turbulence map shows many interesting features and the underlying seeing plots gives the information about what resolution performance a telescope at the indicated height, pointing at Zenith at 500 nm, would be able to achieve.

Fig. 3 shows a summary of GL seeing for all outdoor and indoor data. For comparison, the cumulative distribution of total seeing, as detected by the MKAM DIMM instrument, as well as by the CFHT dome DIMM, for the time ranges when PTP data are available, are shown. The CFHT dome DIMM is an instrument located inside the slit. Above 6 m from the instrument, the outside median GL seeing was 0.48"±0.01". This compares well with the results from Chun [10], who find 0.51" as median seeing value in the GL. Their data acquisition spanned over an 18 month period, while the PTP data was mostly recorded within 4 months. The PTP does not detect any free atmosphere turbulence, and hence while the data from the scintillometer only shows GL contribution, the other two instruments show integrated seeing. The strongest turbulence contributions arise from the region between 6 m and 50 m. In addition, the dome DIMM instrument usually detects turbulence through a very turbulent skin layer surrounding the CFHT dome and hence it is not expected that the PTP inside data should compare with its seeing values. With the PTP mostly located on the telescope floor, the line of sight to the moon passes nearly perpendicular through this layer while the line of sight of the dome DIMM generally subtends a larger distance in the strong turbulent region (private communication with R. Racine, 2010).

4. Conclusions
The PTP in Hawaii has recorded ground layer turbulence starting in December 2009 and regularly since May 2010, with 260 hours obtained from inside and outside the CFHT dome. The high-resolution of the PTP in the ground layer revealed outside dome influence from flow detaching and causing turbulence in front of the dome slit in the case of wind conditions perpendicular to the observing direction. While these results may seem obvious in hind sight,
Figure 3: Cumulative distribution plots of ground layer (GL) seeing for all nights together, separated for INDOOR (left panels) and OUTDOOR (right panels) data. While the top two panels summarize GL seeing for heights BELOW the indicated values, the lower row is the summary for GL seeing ABOVE the indicated height. In the second row, the MKAM DIMM data as well as the CFHT dome DIMM data are shown in addition. Values are only taken when PTP data were taken, and separated for indoor and outdoor observation times.

the PTP is able to quantify these effects and reveal the spatial origin and contribution of each height to the optical turbulence in the ground layer.

The general shape of the optical turbulence strength in the boundary layer shows a sharp increase below 20 m to 30 m for the best nights, and below 50 m to 60 m for average nights. For bad nights, this increase is not as distinct anymore, instead a more general gradual increase in turbulence strength from a height of about 100 m to the ground is detected.

More detailed results will be published elsewhere. Those include a detailed analysis of different wind speeds and directions and their effect on dome-seeing. The outside ground layer turbulence results will be discussed with respect to their dependence on wind direction, speed and local topology.

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