Approximate measurement of the surface-layer turbulence with a simple lunar scintillometer

A. Tokovinin

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1 Do we need a simple method for SL characterization?

Optical turbulence within 5–100 m from the ground is usually strong. It gives often a dominant contribution to the seeing. Measuring the strength and the thickness of this surface layer (SL) over astronomical sites is needed for several reasons:

1. Site-testing instruments are usually located only at ∼5 m above ground. Measuring turbulence just above the site monitor permits to extrapolate its results to a future telescope located in a higher dome, and to determine the optimum dome height.
2. The difference of SL between locations on a given site is relevant to the choice of the siting of future telescopes.
3. Sites in Antarctica have very strong SL turbulence, hence its characterization is of primary importance to Antarctic site-testing.
4. The performance of the ground-layer adaptive optics depends on the SL turbulence parameters.

Usually the SL is studied by micro-thermal sensors on a mast. This method sensitively depends on calibration, and some recent studies at Paranal or Pachon are now in doubt. A review of available techniques [2] reveals a need for a simple and direct optical method of SL characterization.

Scintillation of an extended light source such as Sun is mostly produced in the SL. Suitable statistical analysis can retrieve the SL characteristics, as done in the SHABAR instrument. This method proved pivotal in selecting the site of the ATST solar telescope [3]. A lunar SHABAR is being developed by P. Hickson [1]. A lunar or solar SHABAR uses spatial correlation between signals of several light sensors arranged in a linear configuration. SHABAR needs pointing and tracking.

If turbulence is carried by the wind in front of a single sensor, the analysis of the temporal correlations can replace the spatial sampling of SHABAR. However, we need to know the wind speed. Moreover, the wind speed and direction change with altitude. This introduces complications and uncertainties. On the other hand, the simplicity and elegance of a single sensor pointed to the sky is appealing. Here we investigate this approach, trading simplicity against approximations.

2 Main relations

The scintillation theory is well developed. In case of the Sun or the full Moon, the signal is averaged spatially by the source over a circle of diameter θz, where $\theta \approx 30''$ is the angular diameter and

$z = h \sec \gamma$ is the distance to turbulence (range) for a layer at altitude h and a zenith distance γ. Additionally, the signal is averaged by the receiver aperture, assumed circular of diameter d. The combination of these two filters roughly corresponds to the effective diameter $d_e = \sqrt{(\theta z)^2 + d^2}$. The scintillation produced by a turbulent layer increases in proportion to z^2 for small distances $z \ll d/\theta$, reaches maximum value at $z \sim d/\theta$ and then decreases slowly with altitude as $z^{-1/3}$. In fact, for $z > 1$ km the d_e exceeds 10 m and because of the finite turbulence outer scale the signal from high layers decays faster than $z^{-1/3}$.

Usually we do not want to measure turbulence in the immediate vicinity of the instrument, likely distorted by the instrument itself. By selecting a sufficiently large aperture diameter $d = 0.05$ m, we reduce the response of a scintillometer at distances $z < d/\theta \sim 5$ m.

Diffraction of light plays important role in the physics of scintillations at spatial scales smaller than the Fresnel radius $r_F = \sqrt{\lambda z}$. It turns out that for Moon or Sun, the condition $r_F \ll d_e$ is always fulfilled. Hence diffraction is not important, scintillation is described by the geometrical optics (caused by the wave-front curvature) and is achromatic. In this regime, the effects of saturation can be fully neglected. The spatial scales exceed few cm, hence the results are not affected by the inner turbulence scale.

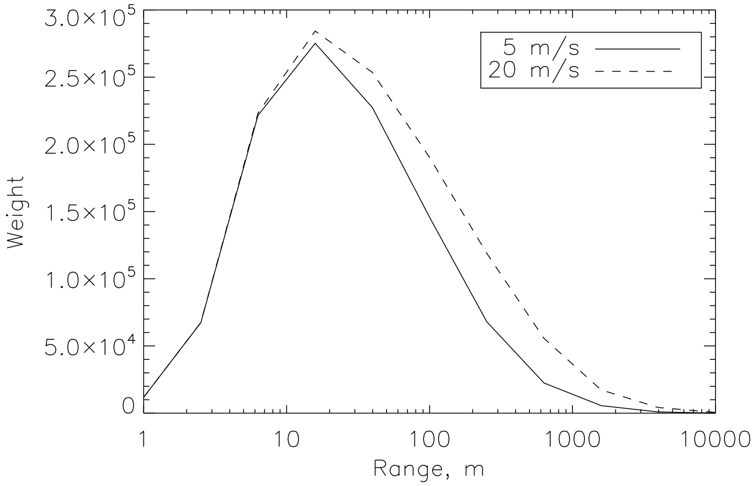

Figure 1: Weighting function of the scintillation signal high-pass filtered above 1 Hz, for two wind speeds.

When turbulence is carried by the wind speed V, the characteristic frequency of the scintillation signal will be $\nu_0 = V/d_e$. Hence high layers will produce only slow scintillation with $\nu_o \propto 1/z$. By temporal filtering the scintillation signal we can isolate contributions from different layers and partially restore the $C_n^2(h)$ profile in the SL.

3 Modeling

I calculated the response of a scintillometer with $d = 0.05$ m to layers at different distances z with a unit turbulence integral $J = C_n^2 \mathrm{d}h$. Such response is called weighting function (WF). I included the temporal filtering of the signal (a high-pass single-pole filter with 3dB frequency $\nu_c = 1$ Hz) and finite outer scale $L_0 = 25$ m. The combined effect of temporal filtering and L_0 damps the weight at high altitudes (Fig. 1), for a wide range of wind speeds.

Even without exact knowledge of the wind speed, a scintillometer with a single aperture provides some measure of turbulence in the SL. Usually the SL is much stronger than higher layers, and hence its contribution to the scintillation will be dominant, depending but little on the exact fall-off of the WF at high altitudes.

The scintillation index $\sigma_I^2 = \langle (\Delta I/I)^2 \rangle$ is a product of the WF W and the turbulent integral J. For a $1''$ seeing, $J = 6.8 \times 10^{-13}$ m$^{1/3}$ and $W \sim 2 \times 10^5$ m$^{-1/3}$, hence $\sigma_I \approx 3.7 \times 10^{-4}$. To measure reliably a 10 times smaller SL seeing, the resolution of the intensity reading must be at least 3×10^{-5}, preferably more. This corresponds roughly to a 16-bit signal digitization. If the AC and DC components of the signal are digitized separately, as in [1], the required resolution is much less.

Can we restore the $C_n^2(h)$ profile in the SL from the temporal spectrum of the scintillation? For a constant wind speed $V(h)$ the task is exactly equivalent to the SHABAR data analysis. On the other hand, if $V(h) \propto h$, then all layers will have the same characteristic frequency ν_0 and their spectra will overlap, preventing restoration. These two situations – favorable and unfavorable – are depicted in Fig. 2.

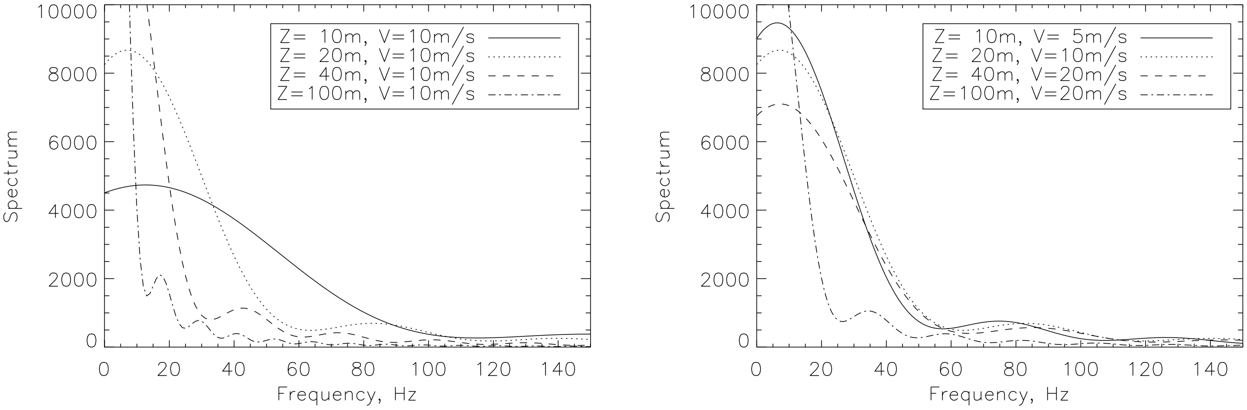

Figure 2: Temporal power spectra of the scintillation produced by layers at different ranges and with different wind speeds. **Left:** wind speed constant with altitude, **right:** worst case when $V(h) \propto h$ in the SL but does not increase at higher altitudes.

We are interested in SL turbulence at altitudes above ~ 5 m (i.e. above the site monitors). At mountain sites the wind speed is nearly constant with altitude for $h > 5$ m, presenting a favorable case for the profile restoration. The WF is nearly constant with altitude (within $\pm 20\%$). We will decompose the experimentally measured power spectrum in a sum of several components with distinct frequencies ν_0 and then associate each component with a specific range by means of the $V(h)$ profile.

The $V(h)$ profile will be determined from the hydrodynamical modeling combined with real-time measurements of the wind speed and direction on a meteorological mast. The results will be presented as a look-up table because the physics of the air flow in the SL is deterministic. Alternatively, such calibration for a specific site can be made from the SODAR data. If no calibration is available, the combination of the wind speed retrieved from the meteorological databases with the local measurements should give a good idea on the $V(h)$ profile. As a first guess, a constant $V(h)$ equal to the measured near-ground wind can be assumed.

4 Discussion

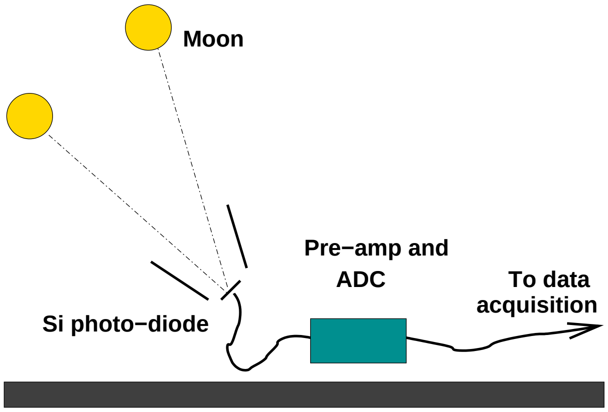

Figure 3: A rough conccept of the single-element lunar scintillometer. The detector is fixed, with a cone limiting the Moon visibility to ±45° from the meridian. The power spectrum can be calculated in the ascquisition module every minute, minimizing the data transmission.

A lunar scintillometer consisting of a single detector can measure an approximate turbulence integral in the SL, even without detailed knowledge of the wind speed. This estimate will be valuable for new and "difficult" sites such as Antarctica. It is not restricted by the height of the mast, is based on the direct optical effect and is "self-calibrated". The SL seeing from scintillometer can be used as a check of other methods such as micro-thermal.

When an approximate knowledge of the wind speed in the SL is available, the thickness of the SL and the $C_n^2(h)$ profile can be restored from the temporal power spectrum of scintillation.

A single-element lunar scintillometer is an approximate but very simple method (Fig. 3). It will work only with near-full Moon, and only for several hours during the night. Nights with very slow ground wind will be difficult to interpret. Thus, this method will be useful for collecting a limited statistics on new and existing sites and for cross-checking other techniques of SL characterization.

A single-channel data analysis can be applied to the multi-sensor SHABAR, strengthening the inversion procedure and providing additional cross-check of the results.

References

[1] Hickson, P. & Lanzetta, K. 2004, PASP 116 1143

[2] Tokovinin, A. How to measure the surface-layer seeing? 2006, unpublished.

[3] Socas-Navarro, H., Beckers, J. et al. 2005 PASP 117, 1296