A concept of Lunar Scintillometer (LuSci)

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1 The need for a new instrument

Methods of optical turbulence measurement for characterization and monitoring of astronomical sites has come a long way. Yet, an important region between 5 m and 100 m above ground remains poorly characterized. Turbulence in this surface layer (SL) is usually strong and makes a non-negligible contribution to the DIMM seeing measurements made from 5 m above ground. Measurements of turbulence in the SL are needed for the following:

1. Extrapolate DIMM seeing to the height of future telescope, determine optimum dome height.
2. Select a suitable telescope location at a given site.
3. Optimize specific techniques such as ground-layer adaptive optics
4. Characterize and understand sites with a strong SL, especially Antarctic sites.

To address these tasks we need to measure few key parameters of the SL turbulence, such as its strength (integral over certain altitude range) and thickness. A low-resolution SL turbulence profile will be sufficient.

Usually the SL is probed by micro-thermal sensors on a mast. This method relies on the absolute sensor calibration. Sparse sampling of patchy and non-stationary SL turbulence is a fundamental problem of this approach. The results of recent micro-thermal studies at Paranal and Pachon are now being questioned in the light of new data. The mast height is also a serious limitation.

Acoustic sounders (SODARs) are a better choice for the SL. However, commercial SODARs sense turbulence only above 20-40 m. A development of a low-altitude special SODAR for SL studies is required. SODAR calibration is notoriously difficult and uncertain, despite recent progress by T. Travouillon [4]. Alternative *optical* techniques of checking the SODAR are needed.

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 for the ATST solar telescope [2]. 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.

Lunar scintillometer has evident drawbacks. It can work only a fraction of time because of restrictions on the Moon's phase and altitude. It will be most suitable for short campaigns and for calibrating other techniques such as SODAR.

In this document, a concept of a simple lunar scintillometer dubbed LuSci is presented.

2 Altitude response and profile restoration

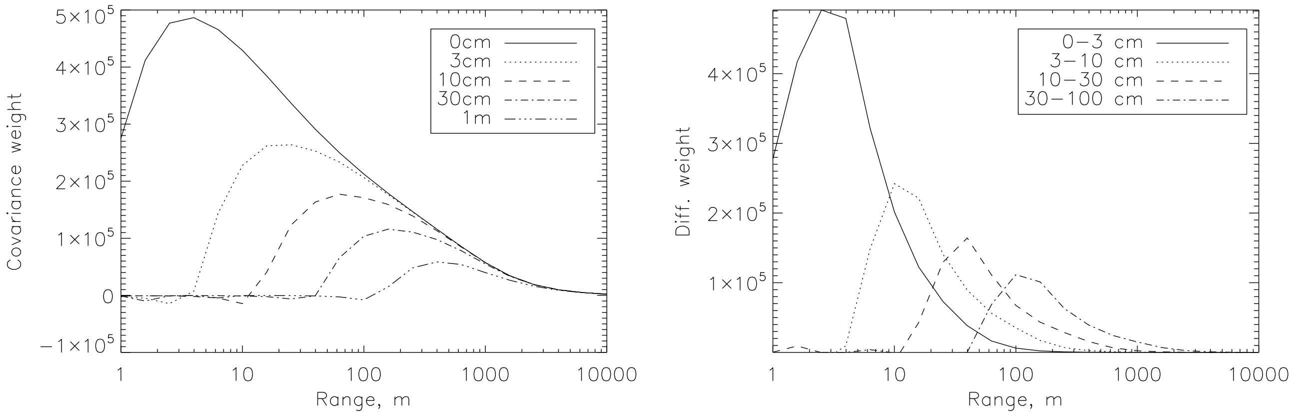

Figure 1: Weighting functions for the covariance of lunar scintillations at several baselines (left) and their pairwise differences (right).

Formulae to calculate the scintillation covariance for a full Moon can be found, e.g. in Hickson & Lanzetta [1]. Useful discussion of the principles and an extension to the Moon phases are given by Kaiser [3]. The scintillation is produced by wave-front curvature fluctuations form centimeters to meters in size (no influence of inner or outer turbulence scale), as a purely geometric-optics effect (no dependence on wavelength or saturation).

The covariance of normalized intensity fluctuations $C(r)$ is

$$C(r) = \frac{\langle \Delta I(x) \Delta I(x+r) \rangle}{\langle I \rangle^2} = \int_0^{+\infty} \mathrm{d}z \; C_n^2(z) \; W(z,r), \tag{1}$$

where the *weighting function* (WF) $W(z,r)$ (in $\mathrm{m}^{-1/3}$) determines the contribution of each atmospheric layer to the covariance. The scintillation index is $\sigma_I^2 = C(0)$. Here z is the distance to the layer (range).

For a given baseline r, the beam footprints start to overlap at range $z = r/\theta \approx 100\,r$, with $\theta = 0.5^\circ$ being the Moon's angular diameter. The WF reaches maximum at $z \sim 600r$ and then declines smoothly as $\propto z^{-1/3}$. Because of the finite turbulence outer scale, the decline is faster than $z^{-1/3}$ at altitudes above 1 km where the beam footprint diameter exceeds 10 m.

Figure 1 shows the WFs calculated for 5 baselines r. The receiving aperture diameter is 11.3 mm, approximating a square 10x10 mm^2 detector. The low-altitude cutoff is sharp and proportional to the baseline. All WFs at 10 km would be 6E-6 $\mathrm{m}^{-1/3}$ with the infinite outer scale, but a realistic $L_0 = 25$ m is assumed here.

It is clear that the WFs contain rich information on the turbulence profile in the first kilometer. Even simple pair-wise WF differences (Fig. 1, right) can isolate and measure specific zones in the SL. Methods of restoring turbulence profiles from covariances are discussed in [2, 1, 3].

If only few parameters of the SL turbulence are needed, we can take covariance measurements with a small number of baselines and use simplified parametric restoration techniques. Such restoration has proven useful in the case of MASS profiler where 6 parameters are derived from 10 scintillation indices. Potentially interesting approaches to restoration are:

1. Fit data to a model with 4-5 turbulent layers at fixed altitudes, in analogy with the fixed-layer method of MASS.
2. Fit 2-3 layers with free altitudes (floating layers).
3. Fit a sum of decaying exponents or other functions.
4. Use linear combinations of WFs to approximate desired altitude response such as box-car, linear, etc.

Instead of measuring spatial covariances, we can take the signal of just one sensor and compute its temporal power spectrum or covariance. If the wind profile in the SL is constant, spatial and temporal covariances are equivalent. Given a known wind profile in the SL, we can restore the turbulence profile from the temporal covariance with just one sensor.

Spatial and temporal covariances are complementary rather than exclusive. We plan to implement both. More modeling of the restoration techniques is needed, but is is already clear from Fig. 1 and from prior experience with SHABAR and MASS that this method will work.

3 Single-channel prototype

The scintillation from the Moon is very weak. Taking a typical $W(z) \sim 2\,10^5$, a 1 arcsec seeing will produce a signal $\sigma_I^2 = 1.4\,10^{-7}$, or rms light fluctuations of 0.4%. At least 10 times better sensitivity is needed, corresponding to a signal resolution of 15-16 bits. A single-channel scintillometer has been prototyped to demonstrate how this goal can be reached.

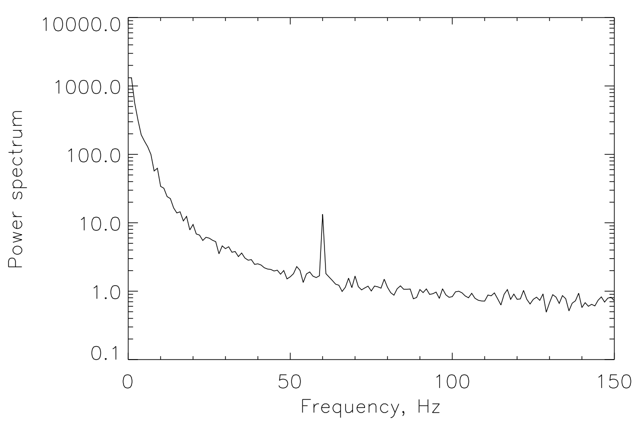

Figure 2: Low-frequency portions of the power spectrum (in arbitrary units) of the Moon flux recorded on Sept. 7, 2006 at Cerro Tololo. The weak line at 60 Hz is caused by the pickup noise.

We used a 1 cm^2 Si photo-diode FDS1010 from Thor Labs (www.thorlabs.com). It is operated with zero bias to eliminate the dark current. The first trans-impedance amplification stage is based on the low-noise amplifier OPA627 (Burr-Brown) with a feedback resistance of 10 MOhm. The second stage is AC-coupled and amplifies the fluctuations 100 times, to overcome the limited dynamic range [1]. The DC and AC signals from the two amplifiers are fed to the analog-to-digital converter (ADC) UDAQ 1616DA from CyberResearch. This is a multi-channel data acquisition module with USB interface. Signals are sampled at 20 kHz rate sequentially. Each 10 samples are then averaged to reduce the noise and to reach the effective sampling rate of 1 kHz per channel.

The full Moon gives a photo-current of 90 nA or a photon flux $N = 5.5\,10^{11}$ phe/s. No signal from the sky background was detected, despite only a rudimentary blend. We reached the dark-noise floor of the amplifier and diode which is 2 times less than the photon noise from the Moon. The noise spectrum is white. Thus, our prototype is photon-noise limited and has the photon-noise floor of $\sigma_{I,ph} = (N\tau)^{-1/2} = 4\,10^{-5}$ for $\tau = 0.001$ s (1 kHz sampling). Th power spectrum of full-Moon scintillation measured with the prototype is shown in Fig. 2.

4 Instrument concept

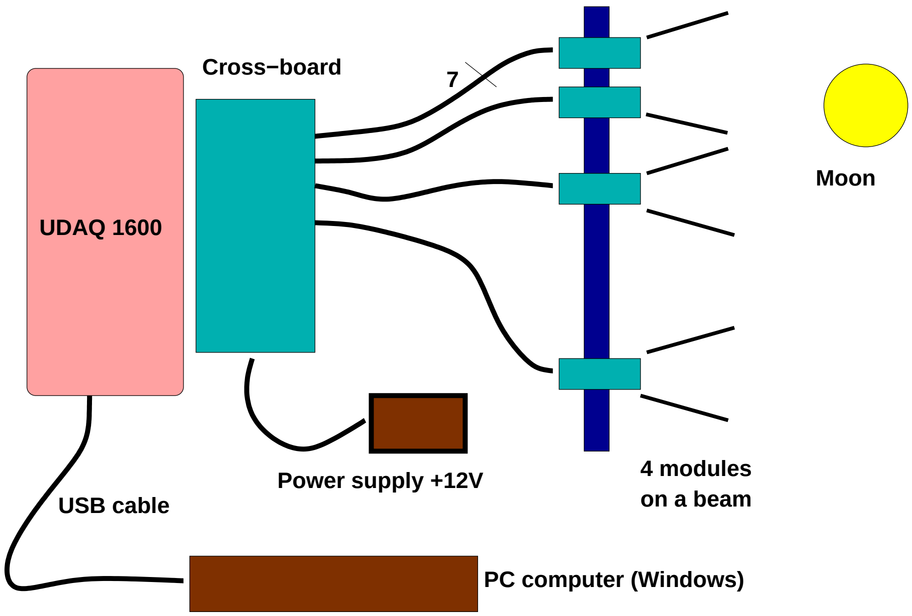

Figure 3: Instrument concept of LuSci.

Our proposed instrument concept is illustrated in Fig. 3. The scintillation will be detected by 4 identical modules arranged in a non-redundant linear configuration, with the baselines ranging from 3 cm to 30 cm. The instrument will be permanently pointed, with its field of view restricted by blends to the Moon hour angles of $\pm 30°$ (4 hours of operation around Moon's culmination). There will be no tracking. The small sky background will be measured before and after the Moon enters the field, and interpolated.

Each module contains a 2-stage amplifier that outputs the DC and AC signals to the ADC via a 7-way shielded cable. The 4 cables connect to the cross-board which also supplies the ± 15 V power to the modules. An ideal solution would be to generate this power from the 5 V USB line, avoiding the problem of different grounds between the instrument and the PC.

The UDAG module has 8 differential inputs connected via a multiplexer to the common ADC. Data acquisition will be organized in segments of few seconds. During each segment, 4 AC signals will be sampled sequentially at 20 kHz rate and averaged in the PC to provide the effective sampling rate of 500 Hz per channel. After the end of this acquisition, a short measurement of the DC signals will be done.

Data of each segment will be normalized by DC signals (accounting also for the background) and cross-correlated. The DC values and covariances will be recorded in the ASCII file, accompanied by a time stamp and the pointer to the binary file where the temporal power spectrum of each channel will be stored. Recording of raw data (ADC counts) on the disk will be available as an option.

5 Manpower estimates

Table 1: Manpower estimates to produce the LuSci

Task	Hours	Person
Electronics design	40	EE+ET
Electronics fabrication	40	ET
Mechanics fabrication	40	Workshop
Software & tests	180	E.Bustos
Restoration & modeling	80	J.Rajagopal
Documentation & tests	80	A.Tokovinin

References

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

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

[3] Kaiser, N., 2004, "Site evaluation using lunar shabar". Pan-STARRS internal memo, http://pan-starrs.ifa.hawaii.edu/project/events/talks/2004-01-23_kaiser.pdf

[4] Travouillon, T. 2006, Proc. SPIE, 6267, paper 50.