# MooSci: A Lunar Scintillometer

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## ABSTRACT

MooSci is a linear array of photodiodes that measures time varying intensities of light reflected from the Moon, lunar scintillation. The covariance between all possible pairs of photodiodes can be used to reconstruct the ground layer turbulence profile from the ground up to a maximum height roughly determined by the distance between the furthest pair of detectors. This technique of profile restoration will be used for site testing at various locations. This paper describes the design of a lunar scintillometer and preliminary results from Las Campanas Peak.

**Keywords:** lunar scintillation, ground layer turbulence, site testing

## 1. INTRODUCTION

Scintillation, the twinkling of stars, is closely related to the turbulence profile of the atmosphere and the "seeing" of a telescope's site. Beckers[1] proposed a linear array of photo detectors to measure the scintillation of the Sun. This idea was adapted by both Hickson & Lanzetta[2] and Rajagopal & Tokovinin[3] to use the Moon to measure lunar scintillation. Unlike the scintillation in the high atmosphere that causes stellar twinkling, the scintillation of extended objects is caused by turbulence in the lower atmosphere, making the technique potentially useful in determining the strength and prevalence of ground layer effects.

This paper describes an instrument that builds upon previous instruments and techniques to improve the data collection processes of measuring lunar scintillation. What we describe is the design of MooSci, an 11 channel lunar scintillometer.

## 2. SCINTILLATION

### 2.1 Physics of Scintillation

The physics of scintillation is a well-studied area of atmospheric science and is of particular interest to those in astronomy. To summarize previous works[1,2,3,4,5], scintillation can be viewed as variations in the brightness of light coming through various turbulent layers in the Earth's atmosphere that cause perturbations at various scales. These perturbations can be thought of as acting as lenses. Converging lenses will increase the intensity of light over a particular detector, while diverging lenses will decrease the intensity. By monitoring the changes in intensity over time, the character of the scintillation and the structure and strength of the turbulence above an astronomical site can be determined. A study by Tokovinin[5] reinforced the idea that for measuring scintillation near the ground, or lowest levels of the atmosphere, extended sources should be used instead of stars.

### 2.2 Lunar Scintillation

The detection of scintillation from extended objects such as the Sun, planets, and the Moon can allow estimation of the atmospheric turbulence near the ground (Tokovinin[5]). The three choices have their different strengths and weaknesses. The Sun for instance, is the brightest and easiest to detect, but the atmospheric conditions during the day are not necessarily representative of those during the night, which are of the most interest to some astronomers. Planets, although almost always present in the sky, are small and produce fairly weak signals. The Moon is the ideal candidate in that it produces adequate signal from an extended light source. The variations in the signal occur at one part in $10^{-4}$, thus a formal signal-to-noise ratio (S/N) in excess of $10^4$ is required to measure such fluctuations in the signal. The downside to using the Moon is that for the technique described here to work, the phases of the Moon only allow for measurements to be taken within ±6 days from the full Moon.

### 2.3 Scintillation Model

Tatarskii[4] developed the theory of light propagation through weak turbulence. Later studies by Hickson & Lanzetta[2] and Tokovinin et al.[35], developed new methods and models for adapting previous models to lunar scintillation. MooSci utilizes a model similar to Tokovinin's LuSci[3], that relates the covariance of the lunar signal ($C_I$) to the weighting function ($W(r,z)$) and the $C_n^2$ profiles of the atmosphere, where the $C_n^2$ is a measure of the relative strength of turbulence as a function of altitude.

$$C_I(r) = \int_0^\infty W(r,z) C_n^2(z) dz \tag{1}$$

The current model incorporates into the weighting function the Moon's phase, apparent diameter, local wind speed, and the angle of the Moon's terminator with respect to the baseline of MooSci's detectors. Reconstruction of the $C_n^2$ profile begins after the weighting functions and covariances of the individual baselines are calculated.


Figure 1. Given established methods for reducing data from Tokovinin's LuSci[3], MooSci has the baseline of a single LuSci mirrored around a central axis. The locations of the detectors are 0, 12, 15, 17, 21, 40, 59, 63, 65, 68, and 80cm.

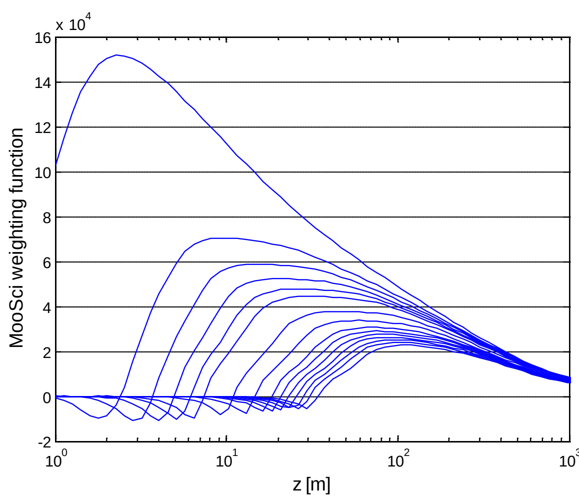


Figure 2. Sensitivity functions for the 15 possible MooSci baselines from detectors 1-6. Each curve represents a baseline between two detectors ranging from 2-40cm, with the 2cm baseline on the far left. Sensitivity decreases with longer baselines, as peak altitude increases.

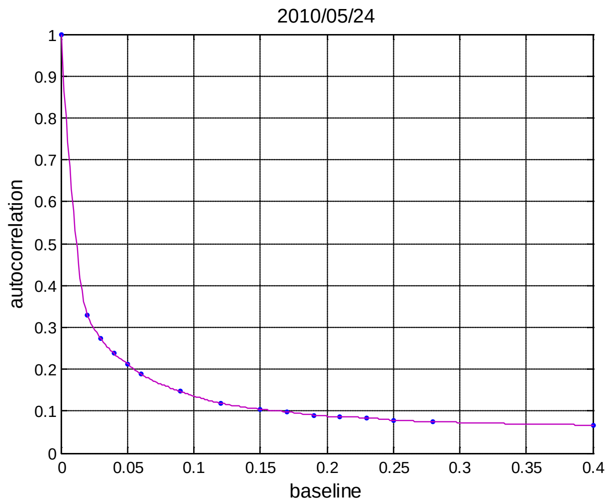


Figure 3. The average normalized covariances for one hour of data on one half of the MooSci detectors. The data points indicate the actual baselines.

### 2.4 Scintillation Campaigns

Current campaigns attempt to incorporate one or more instruments with that of the scintillometer. The MASS-DIMM is a popular counterpart to the lunar scintillometer as it performs the same function as the lunar scintillometer, to probe atmospheric turbulence, but measures from 500m to the upper atmosphere. The goal of MooSci is to probe that first 500m with the accompanying existing MASS-DIMM instrument, to achieve a complete reconstruction of the turbulence profile. Given the detectors spacing as shown in Fig. 1, the various baselines have peak sensitivity at altitudes that range from 10m to 250m as shown in Fig. 2, for detectors 1-6. After integrating detectors 7-11 into the weighting function, the sensitivity should increase beyond 500m.

## 3. INSTRUMENT DESIGN

### 3.1 Design Tests

MooSci has been designed carefully to accurately measure lunar scintillation. A simple test was performed on the optical systems the instrument, one channel was covered to keep light out, while all other channels were illuminated with signal equal to that expected by the full Moon. The signal increase in the adjacent detectors was much less than the $10^{-4}$ of the expected signal variations. If not properly addressed and accounted for, this could lead to over estimating the covariance between detectors.

Tests were also preformed to ensure that there were no phase shifts in the electronic signals. All of the detectors were illuminated with a light emitting diode (LED) driven by a square wave. The outputs of all channels were then measured individually with an oscilloscope to ensure that there were no phase shifts in the rise times from the LED. Any phase shift could cause correlated signals to look uncorrelated, under estimating the covariance. Below we describe the various aspects of the MooSci design in detail.

### 3.2 Field of View

MooSci's field of view is set by the mechanical design rather than the optical components. There are no lenses used in the MooSci design. A 5.8x5.8mm Hamamatsu S2387-66R photodiode sits 16mm below the bottom of two 25.4mm, 12.7mm diameter optical tubes available from Thorlabs. There are two retaining rings that hold a Thorlabs WG30530 3mm thick sapphire window 8mm below the edge of the tube. The window is used to protect the photodiode and components from the elements. The 8mm spacing allows room for the retaining rings and for the lens cap that is placed over the window and optical tube when the scintillometer is not in use. This gives the detector a 6° field of view and sets the requirement that our mount be able to track to within ±3° of the Moon.

### 3.3 Electronics

One of the key challenges to the MooSci design is obtaining S/N > $10^4$, while meeting our band pass requirements. The band pass requirements are set by the rate at which lunar scintillation, or the light intensity fluctuations, occurs. In the case of lunar scintillation, that is at frequencies of less than 500Hz. These requirements are accomplished by using the circuit in Fig. 4. Begin with taking the current produced by the 5.8x5.8mm Hamamatsu S2387-66R photo diode and invert that into a voltage via an LT1793 op amp with a 20MΩ feedback resistor. This op amp will also have a 10pF capacitor in parallel that acts as an active filter, filtering signals greater than ~800Hz. The output then feeds into another LT1793 that inverts the signal and applies a gain of ~15. The second stage has another higher fequency filter set by the 100k resistor and the 1000pF capacitor whose bandpass is set by to ~1.6kHz. This signal is then fed into a LT1920 instrumentation amplifier. The signal is subtracted from a 5VDC signal and multiplied by another factor of 1.8. The 5VDC is provided by a LT1027 voltage regulator with a 4.99k resistor as a source to ground. The signal is centered between ±10VDC to allow for the optimal use of a 16-bit ADC that converts the analog voltage to a digital signal for subsequent processing. All components are operating from a ±15VDC power supply with 1μF tantalum capacitors tied to ground to filter out any voltage spikes or high frequency noise.

The signals from the Moon are dependent on phase, position, and location. The most obvious and noticeable change in signal is due to the changing phases of the Moon. The signal increases as the Moon approaches full, and then decreases as it wanes. The position of the Moon in the sky also affects the signal, although not to the extent of the phases. The signal increases as the Moon approaches zenith, or is highest in the sky. The location of the Moon also affects the signal values. When the Moon is at perigee it is brighter and larger than when at apogee. This has effects both on signal and the reconstruction model. These signals can range from 5-18V with a consistent 100Hz noise of only .18mV. This yields S/N ratios in the range from $2.8\text{x}10^4$ when the Moon is low in the sky and out of phase, to S/N ratios of $10^5$ when the Moon is full and at zenith. These S/N rations are adequate to measure the scintillation of the Moon.

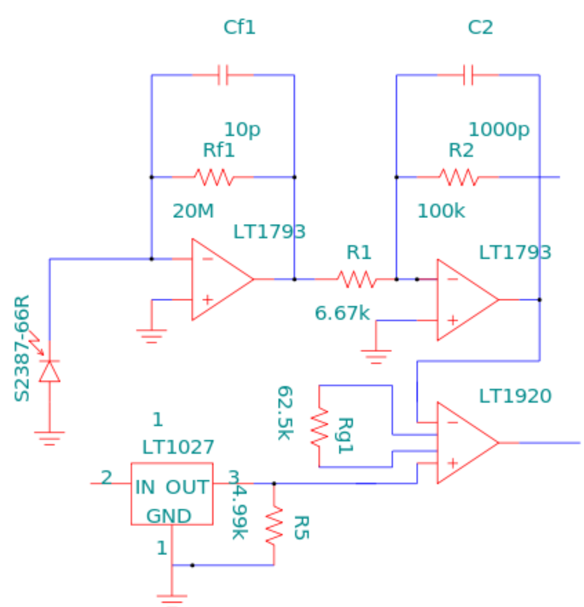


Figure 4. Photo detector circuit located in each of the 11 MooSci modules. The S2387-66R photodiode produces a photocurrent that drives the rest of the circuit. The two LT1793 op amps amplify and invert the signal. The LT1027 provides a constant 5VDC offset for the LT1920 instrumentation amplifier. The output is measured from the LT1920 after it compares the two signals and provides the final amplification.

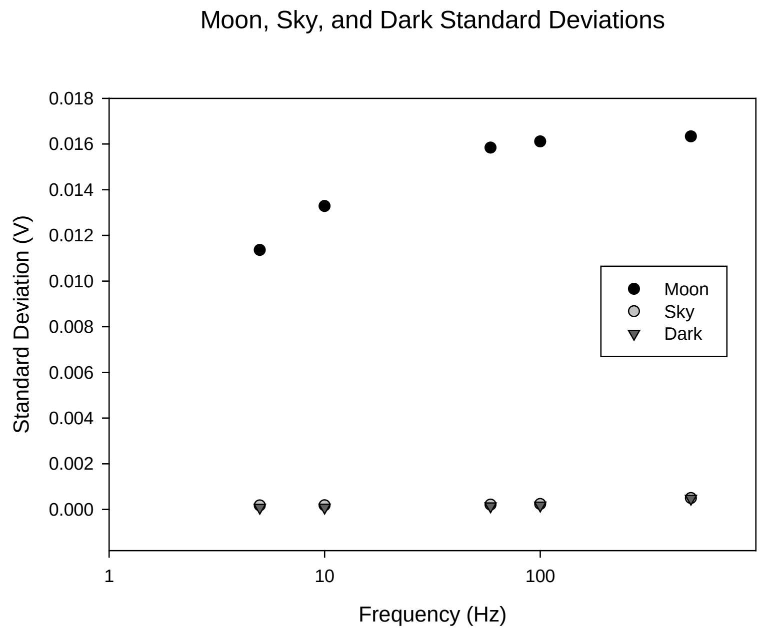


Figure 5. Noise plots of typical signals types taken from College Station, TX. The noise from the Dark and Sky measurements is dominated by the instrument's electrical noise that increases as the square root of the frequency. The noise measured in the Moon signal is dominated by the lunar scintillation. Electronic noise is less than $10^{-4}$ of the measured signals.

Each individual MooSci module contains an electronic circuit that is mounted inside and grounded to an aluminum enclosure. Each of the eleven channels is cable fed into one of two busses that are connected to the ADC/power box with 12-pin cables. The USB-1616FS ADC samples all eleven channels simultaneously at 10kHz. It then transfers the signal via USB to a portable laptop where it is recorded.

All of the MooSci components are powered with 120VAC fed into a bus from a single power cable. The ADC has a 9V, 3A DC power supply that runs off of the 120VAC bus. A second ±15VDC power supply is housed inside the electronics box that supplies all eleven modules with power.

### 3.4 Mechanical Design

The scintillometer consists of a commercial telescope mount and five pieces of hardware: 11 modules, a beam on which the modules are mounted, 2 electrical bus boxes that relay the signals, a dovetail plate used to mount the instrument to the mount and an electronics box. Each of the 11 photodiodes and accompanying circuits is housed in one of 11 individual modules. With each detector in its own module, there is minimal chance of optical crosstalk. Each module is a 127x19x43mm light-tight aluminum enclosure with a removable top and threaded for the optical tubing. The module itself is mounted with the optical tubing to a 0.82m beam with holes drilled at the positions shown in Fig. 1 to hold the optical tubes. The circuit is connected via a four pin cable to one of two busses. The two busses, one relays channels 1-6 and the other channels 7-11, are mounted onto the underside of the beam. 12 pin cables connect the busses to the electronics box. The electronics box contains the ADC, a ±15VDC power supply, and the various electrical terminals housed in a steel NEMA enclosure. The box has an input for the 120VAC with ON/OFF switch and a pass-through for the ADC's USB connection to the laptop. Both the beam and the electronics box are mounted onto a dovetail plate that allows the entire assembly to be mounted onto the telescope mount. MooSci has a small web cam mounted to the beam which allows the user to ensure that the pointing of the MooSci is accurate during observations, as well as a guide scope to aid in the alignment of the mount.

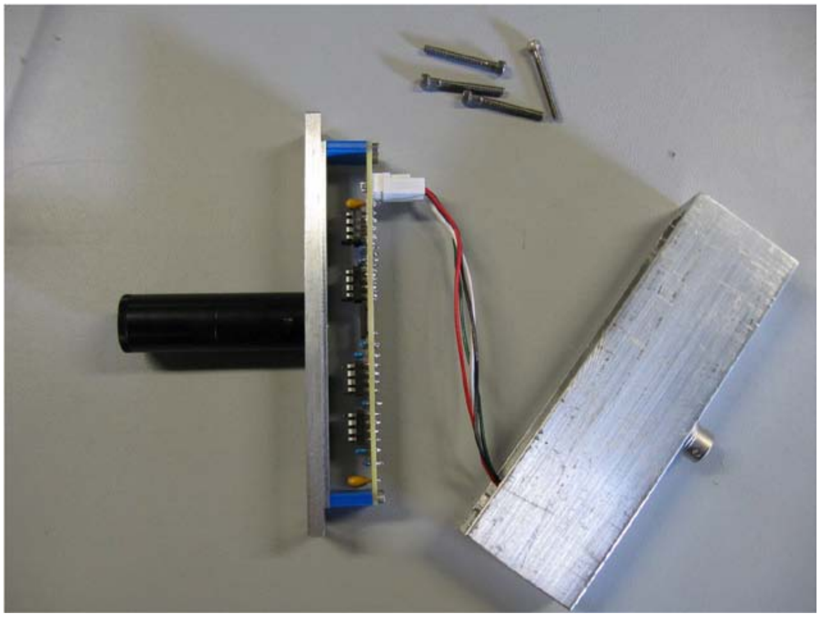

Figure 6. One of the eleven individual MooSci modules. Each module is a light tight aluminum enclosure containing the photodiode and electrical circuit in Fig. 4. The optical tubing sets the field of view and is shown with the lens cap attached. A four pin cable connects the module to a relay bus.

MooSci is mounted onto a Celestron German Equatorial Mount (CGEM) series mount. The CGEM is capable of carrying a 45lb payload. The mount is controlled via a standard amateur telescope style hand paddle and points to an accuracy of 1.5 arc minutes. The CGEM mount will not track past the user set RA limits for the meridian, so the mount must be "flipped" when the target approaches meridian.

# 4. OPERATIONS

## 4.1 Software and User Interface

A LabVIEW program collects the data from the ADC and writes files to the laptop containing the data and the MooSci controls. The LabVIEW interface also displays the average values and standard deviations of all 11 channels in ~5 second intervals and all 11 temporal voltages. The user also may view the power spectrum and temporal voltages for any two sequential channels, also updated every 5s. These displays are useful for monitoring the quality of the data during observations. The program has a simple layout that allows the user to take Moon, Sky, and Dark measurements. Each setting has preset flags on the average value and standard deviation that let the user know if they are taking data consistent with previous measurements. The LabVIEW program acquires 49,972 data points at a rate of 10kHz before updating the visual displays. The program then writes 20 of these intervals (~100s) to a single data file. Each sequentially numbered file has the location, time, date, and type of file (Moon/Sky/Dark) included. There is also a test mode that allows the software to acquire data but does not write any files. This is used for troubleshooting and various other tasks.

## 4.2 Remote Operation

The laptop that operates MooSci is connected using a virtual network computing (VNC) connection that enables remote operations. All of the functionality of MooSci can be operated remotely. The webcam provides the user with real time video of the Moon. With the web cam and remote mount control, any problems with tracking can be easily addressed without the need to visit the instrument. In the event that clouds or any other issues arise, the data acquisition will clearly display anomalies in the data stream that can then be paused while the clouds clear.

Figure 7. MooSci is shown ready for operations at Las Campanas Peak in May 2010. The initial MooSci campaign will be to profile the future site of the Giant Magellan Telescope.

# 5. PRELIMINARY RESULTS

## 5.1 Reconstruction and Results

The first step in reconstructing the turbulence profile is to ensure the data quality of the measurements. The individual intensity variations over the 11 detectors are documented with the time and location of acquisition. This information is very important to calculating the weighting function. First, the stability of the night's measurements is checked to avoid any corrupt data due to an unnoticed occultation by clouds or an error in tracking. Periodic Sky measurements are taken and the quality of the data is checked, although this is not a particular problem since the level of signal and the power spectrum shape can be directly observed by the user on the acquisition program interface during acquisition. The averaged power spectra from the Moon are also checked to avoid any parasitic reflections from adjacent structures and to check if any sources of contamination were present.

From the selected data, the scintillation index variances and covariances are calculated. It is very important to note that the scintillation index on every channel should be calculated by the ratio of the intensity fluctuation and the difference of the average intensity of the Moon signal and the Sky signal. The availability of good Sky measurements allows for the efficient elimination of the individual offsets affecting the various detectors.

From the times and location of the data, the scintillation index model is constructed. The air mass, Moon phase, the angle of the Moon's terminator relative to MooSci's baselines, and the Moon's apparent diameter are all calculated from this information. MooSci's experimental covariance is then introduced into the reconstruction software and the profiles are calculated as shown in Fig. 8.

The baselines and procedures used to reconstruct the profile are the same as LuSci[3] for comparison. Improvements and adaptation to MooSci's increased number of baselines and detectors will be soon to be introduced, and the results from Las Campanas peak will be presented in this manner in a forthcoming paper. Future observations will also be supported by wind data and possibly sonic anemometers to test the occurrence of Kolmogorov or non-Kolmogorov cascade effects in the ground layer. This additional set of information will be integrated into the MooSci model for a better estimation of the turbulence profiles.

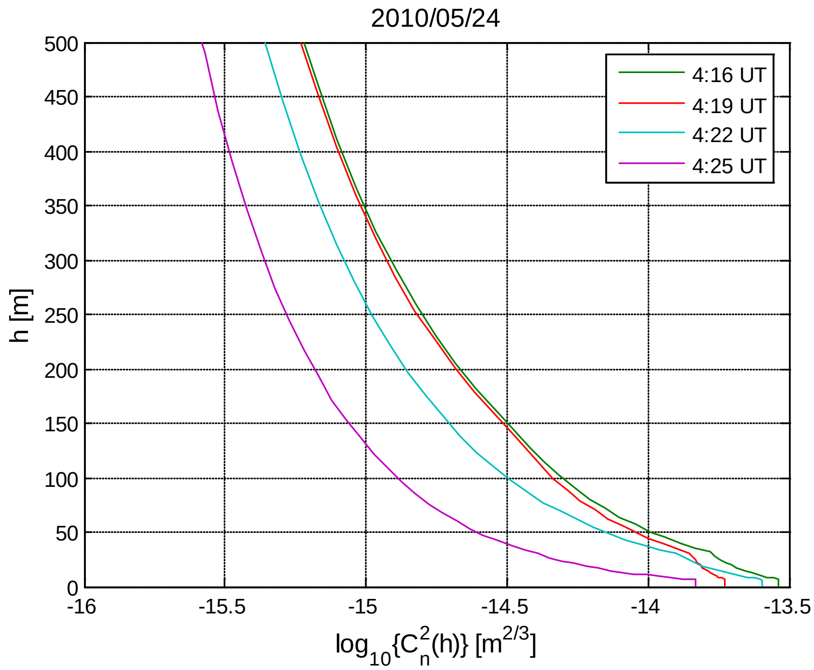


Figure 8. Preliminary turbulence profiles from Las Campanas peak on 24 May, 2010. Each curved line represents a three minute interval of time. Wind effect correction has not been introduced.

## 6. CONCLUSION

Scintillation is not a new topic in astronomy, but being able to understand and measure this scintillation could prove to be a useful tool in understanding what makes the “seeing” of some sites better than others. Much consideration has been taken into what is required to adequately measure and detect lunar scintillation. MooSci has been designed and tested to meet these various requirements. The mechanical, electrical and optical design elements were carefully chosen to produce optimal data quality. Results from the instrument’s initial campaign at the Las Campanas Observatory indicate that MooSci is a thorough and robust lunar scintillometer that is more than cable of profiling the ground layer turbulence. With the initial campaign complete, work can be done to improve the reconstruction process and integrate MooSci’s more dynamic baselines. Future missions at Las Campanas Observatory will be conducted in conjunction with various other instruments to make maximum use of MooSci’s capabilities, with the ultimate goal of profiling Las Campanas Peak, the future site of the Giant Magellan Telescope.

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