The 24hSHIMM: a continuous day and night turbulence monitor for optical communications

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ABSTRACT

We present the 24-hour Shack-Hartmann Image Motion Monitor (24hSHIMM), the first truly continuous, 24-hour optical turbulence monitor. Atmospheric optical turbulence is a significant limitation for free-space optical communications and other technologies. Knowledge of the turbulence conditions allows for the selection of favourable sites for optical ground stations. It also enhances operations though providing data for assimilation into turbulence forecasting models and real-time monitoring of conditions. The 24hSHIMM uses a Shack-Hartmann wavefront sensor to measure a low-resolution vertical optical turbulence profile, from which the coherence length, angle and Rytov variance are calculated. Additionally a vertical wind speed profile from meteorological forecast data is used to calculate the coherence time. Due to its portability, the instrument can operate in a wide variety of locations, even urban, to provide continuous information about the atmospheric turbulence. To demonstrate this, we show parameters recorded at the astronomical observatory in La Palma for a continuous 36-hour period. With its wide array of capabilities, the 24hSHIMM offers strong support for future research in free-space optics.

Keywords: Shack-Hartmann wavefront sensor, atmospheric optical turbulence, free-space optical communications, optical turbulence monitoring, short-wave infrared.

1. INTRODUCTION

Atmospheric optical turbulence presents a significant challenge for ground-based optical instrumentation as it causes images of point sources to rapidly change in brightness (scintillation) and to break up into speckles. It arises from layers of air in the atmosphere with different temperatures (and therefore densities) mixing together to produce a spatially varying refractive index field. This causes phase distortion of light waves passing through it. Atmospheric turbulence monitoring and mitigation is a mature technology in the field of astronomy. Adaptive optics (AO) has been employed to correct for this wavefront distortion in both astronomical telescopes[1] and solar telescopes,[2] improving the resolution of images. Turbulence monitoring instruments have played an important role in validating the performance of adaptive optics systems.[3] They have also been used in site monitoring to select locations with favourable atmospheric turbulence conditions for some of the worlds most advanced telescope facilities and to study long-term conditions at observatories.[4,5] Today, the vast majority of turbulence monitoring instrumentation is found at astronomical observatories and designed to operate at night. Popular techniques include small-telescope instruments such as the Differential Image Motion Monitor (DIMM)[6] and Multi-Aperture Scintillation Sensor - DIMM (MASS-DIMM).[7] Additional higher-performance turbulence profiling techniques include the SCIntillation Detection And Ranging (SCIDAR)[8] and SLOpe Detection And Ranging (SLODAR).[9] There are also techniques for monitoring turbulence during the daytime, but these are typically limited to observations of the sun - for example the Solar-DIMM (S-DIMM)[10] and S-DIMM+.[11] These instruments are far less widespread. Until now, the Profiler of the Moon Limb (PML)[12] is the only instrument that has been shown to operate during the the day and night. This technique uses observations of the lunar and solar limbs to measure a turbulence profile.

In recent years there has been significant development in free-space optical (FSO) technologies. However, as in astronomy, atmospheric optical turbulence severely limits the performance of such systems. Scintillation,

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beam wander and speckling all lead to a reduction in the achievable bandwidth and increase the bit error rate in free-space optical communications (FSOC).[13,14] Other technologies such as space surveillance and tracking (SST),[15] long range quantum key distribution (QKD)[16,17] and deorbiting of space debris by laser ablation[18] are similarly affected. AO and monitoring techniques therefore find important applications in these areas. Turbulence monitors offer a method of selecting optimal sites for optical instrumentation, including optical ground stations. They also enhance operation scheduling through proving both real-time information on site conditions and data for assimilation into turbulence forecasting models.[19,20] However, a key difference to astronomy is that FSOC and SST systems will need to work 24-hours a day in a wide variety of turbulence strengths and in locations with sub-optimal turbulence conditions such as cities.

Figure 1. A photo of the 24hSHIMM operating during the daytime in La Palma.

To support these emerging technologies, we have developed the 24-hour Shack-Hartmann Image Motion Monitor (24hSHIMM)[21] - the first truly continuous day and night turbulence monitor. This system is a development of the night-time SHIMM[22] monitor. However, the work presented here describes a significant upgrade to both the hardware and data analysis. The 24hSHIMM utilises an off-the-shelf, small, commercial telescope and computerised mount in conjunction with a Shack-Hartmann wavefront sensor operating in the short-wave infrared to estimate turbulence parameters from observations of a single target star. It is capable of measuring a low-resolution vertical turbulence profile at all hours of the day, even in strong turbulence, and uses this to derive estimates of the optical turbulence coherence length, angle and Rytov variance. It also makes use of a wind speed profile retrieved from the reanalysis of the ERA5 meteorological forecast[23] to estimate the coherence time and implements a method of correcting the measured profile for the effect of scintillation. Considering also the portability of the instrument, these properties make it ideal for deployment in urban and suburban locations to support the development and operation of technologies such as FSOC, QKD and SST.

2. 36-HOUR DEMONSTRATION

Fig. 2 presents the results of a 36-hour demonstration of the instrument at Roque de Los Muchachos Observatory, La Palma from the 14th-16th May 2022. There is a gap in the measurements from around 5am to 8am UTC on the 15th due to extremely high levels of wind. During this time, wind-shake spot motion was larger than the wavefront sensor field of view, therefore measurements were not reliable and have been excluded from the graph. All target stars observed during the day were magnitude zero or brighter in the J band. To increase the accuracy of estimates of τ_0, the wind speed of the ground layer is taken from a local anemometer. Overall, there is strong contrast between night and day conditions in r_0 and τ_0 but very little difference in θ_0 and σ_R^2. This suggests that daytime solar heating was increasing the surface layer turbulence strength but not affecting higher altitude turbulence.

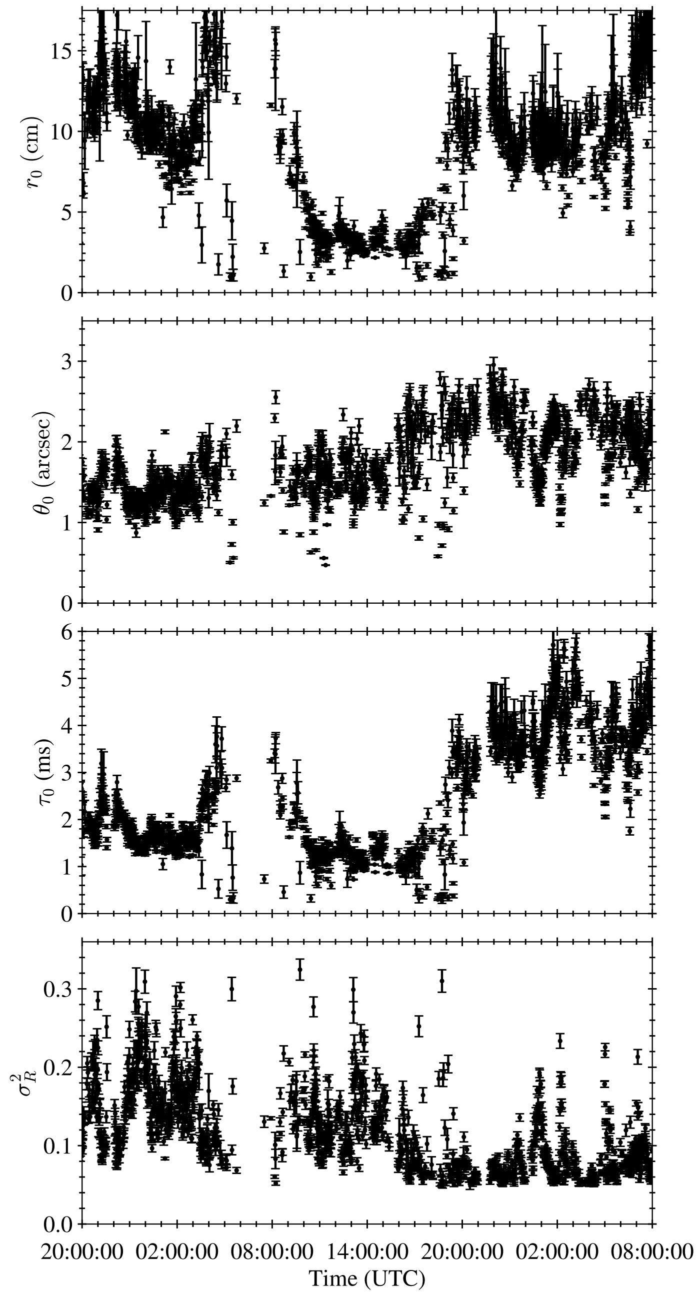

Figure 2. Turbulence parameters recorded by the instrument for a 36-hour experiment at the observatory in La Palma. There is a gap around 5am UTC on the 15th May due to wind speeds in excess of $50\,\mathrm{km\,h^{-1}}$, otherwise all of the recorded data is presented. Parameters have been corrected to their values at zenith and are reported at a wavelength of 500 nm.

3. CONCLUSION

In this paper we present the 24-hour Shack-Hartmann Image Motion Monitor (24hSHIMM), the first truly continuous vertical optical turbulence monitor. The instrument uses a Shack-Hartmann wavefront sensor to measure a four-layer vertical optical turbulence profile. With a wind speed profile also obtained from the reanalysis of the ERA5 meteorological forecast, the instrument can estimate the optical turbulence coherence length, time, angle and Rytov variance. Additionally, the reconstructed vertical profile is used to correct for the effects of scintillation on measurements. These techniques are demonstrated here in the results from a continuous 36-hour measurement at the astronomical observatory in La Palma. The instrument is sufficiently low-cost and portable enough to be deployed at any location, including urban and suburban, to measure turbulence at all hours of the day and night. These capabilities make the instrument well-suited to support 24-hour free-space optical communications activities in addition to a wide range of other free-space optical technologies. The instrument enables site monitoring for optical ground stations, validation of and feedback into the design of adaptive optics systems and provides data for assimilation in turbulence forecasting models to enhance operation scheduling.

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