RAA 2020 Vol. **20** No. **11**, 180(4pp) doi: 10.1088/1674-4527/20/11/180

http://www.raa-journal.org *http://iopscience.iop.org/raa*

Research in Astronomy and Astrophysics

Imaging atmospheric turbulence, using entropy to quantify turbulence strength

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Received 2020 January 10; accepted 2020 May 19

Abstract Vertical profile of turbulence strength (C_n^2) is one of the most important attributes for evaluating a site's astronomical performances. Although seeing is commonly used for describing turbulence strength, it can only represent the integral of all layers of the turbulence above the observer. Other techniques which can be applied to produce C_n^2, such as DIMM-MASS, SCIDAR, etc., all rely on rather complex systems to do the measurements. In this paper, we present an idea to evaluate the relative strength of turbulence with entropies of short exposure images taken at different conjugated heights of the turbulence. Initial experimental results are also presented in the paper.

Key words: techniques: telescope — site testing

1 INTRODUCTION

As known ever since Newton, turbulence is one of the culprits that deteriorate the image quality of a ground-based telescope. It can blur images taken with long exposure time or create multiple replicas of the object in the so-called speckle image with short exposure. To characterize and further alleviate the impact of atmospheric turbulence, many theoretical/techncial efforts have been explored. Metrics and measurement methods for quantizing the strength of turbulence have been proposed in a huge number of papers. Among them, the most popular quantities to represent turbulence strength are refractive index profile, $C_n^2(h)$, where h is the altitude, and the total integral of $C_n^2(h)$ for heights above ground, the seeing θ_0.

The beauty of the these two parameters is that they are measurable with special scientific instruments. Although $C_n^2(h)$ is ideal for investigating turbulence strength at different heights, to measure such a profile requires either a balloon equipped with a highly sensitive thermometer or employing a technique called SCIntillation Detection and Ranging (SCIDAR) which needs a telescope with diameter larger than 50 cm. For both cases, it is hard to setup and difficult to monitor continuously for long term which is important for such a profile that has a statistical nature. This leads to the popularity of relying on seeing as a merit to evaluate a site's imaging performance. It is a representation of image quality obtained considering only the overall turbulence above the observing height, and thus could be easily combined with designed image quality achieved by a telescope to predict how a telescope could perform at a certain location. Sarazin & Roddier (1990) devised a simple instrument called a Differential Image Motion Monitor (DIMM) for seeing measurement. The instrument is portable, rugged, and easy to maintain which is perfect for long term monitoring of a site's performance and thus it has become a standard instrument for the purpose of site testing. However, the instrument cannot measure the turbulence's structure profile which has become more and more important ever since the implementation of adaptive optics (AO).

Due to the fast development of AO whose performance is strongly correlated with $C_n^2(h)$, study of turbulence structure is necessary. New instruments, such as DIMM-multi-aperture scintillation sensor (MASS), lunar scintillometer, single star SCIDAR, etc., (Masciadri & Sarazin 2009) that can measure turbulence strength at various heights have been proposed and utilized with good results. We hereby also propose a new method for measuring the layered structure of turbulence along the line of sight of a telescope which only requires attaching a fast CMOS to an existing telescope that has an adjustable refocusing stage. By doing fast exposure at different conjugate heights and adopting a new metric, the method is fast and simple for investigating local turbulence at various heights, which is beneficial for the design and operation of an AO system.

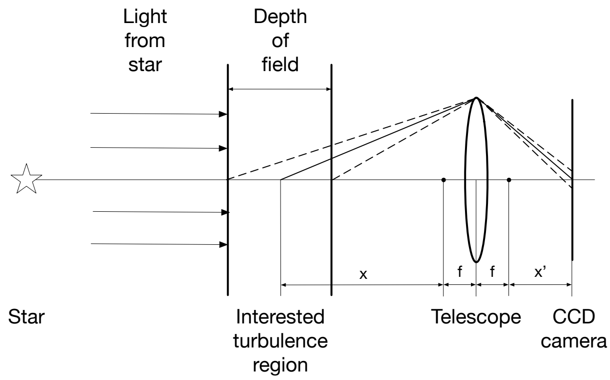

Fig. 1 Schematic of the method. Light from the bright star illuminates the turbulence within the depth of field. The CCD camera will take short exposures to image the turbulence of this region.

In Section 2, we will introduce the principle of the method. Description of setup and field results will be given in Section 3. We will draw a conclusion in Section 4.

2 PRINCIPLE

The idea of the method is quite simple as illustrated in Figure 1. A telescope can be considered as a thin lens. f is the focal length of the telescope, while x' is the distance of the image plane from the focal point, and x is the distance of the conjugate object plane from the other focal point. When $x' = 0$, as is the case for normal usage of astronomical observation, the telescope is focused to infinity, where $x = \infty$. However, when one moves the imager, either a CCD or a CMOS, away from the focus, the object plane, which is the "plane of interest", would also move from infinity to a finite closer distance as we know from the Newtonian thin lens equation. At the same time, for a powered finite sized aperture focusing at a finite distance, the effect of depth of field also begins to play its role. Because the depth of field would "isolate" objects within certain distances by smearing other objects outside this range, by combining these two factors, one could image turbulence at a distance within the depth of field by moving the imager to the conjugated image plane. If the imager could move continuously, one could obtain a series of short exposure images of turbulence like the one shown in Figure 2 at different distances from the telescope along the line of sight, and from these obtain information on the vertical strength distribution of turbulence utilizing a certain metric.

The metric we propose to use to represent the turbulence strength from these images is the classical "Shannon entropy" from information theory as described in Gonzalez et al. (2003). We repeat the definition of this entropy in Equation (1), where E is the value of entropy, p is the histogram of the grayscale image and i is the number of bins in the histogram, which in our case we chose to be 256.

$$E = \sum_i p(i) \cdot \log_2(\frac{1}{p(i)}) \,. \qquad (1)$$

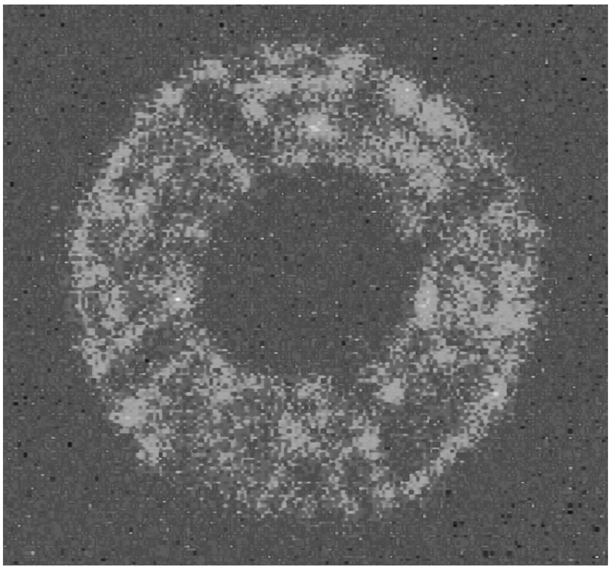

Fig. 2 An image obtained with an 80 cm telescope focused at a finite distance. One can see the shapes of the telescope's primary, secondary and spider. The most important is the "boiling blob structure" displayed in the image which is caused by atmospheric turbulence. The structure of the boiling blob becomes more chaotic when turbulence is stronger.

The reason to use Shannon entropy is that the value of entropy represents the chaotic nature of random processes, such as the random behavior of the turbulence image. It is observed that when turbulence is strong, the image of the turbulence would also be more chaotic, which would lead to a higher entropy value than the image obtained when turbulence is weaker. Therefore, in principle, it could be utilized as a metric to reflect the turbulence strength.

In the following section we will demonstrate how we did our tests and the results we have obtained so far.

3 TEST SETUP AND RESULTS

We relied on an 80 cm telescope at Xinglong Observatory[1] for the test. The focal distance of the telescope is 8 m. An Andor DU-888E back illuminated EMCCD camera was mounted on the electrical focusing stage behind the telescope's Cassegrain focus. The camera could travel along the electrical focusing stage continuously, and the maximum offset distance for the camera from the focal point was 23 mm. There are 1024×1024 pixels on the camera. The size of each pixel is $13 \times 13 \mu m^2$ which corresponds to a pixel scale of 0.33 arcsec pixel^{-1}. Considering the

[1] http://www.xinglong-naoc.org/html/en/

typical size of the "blob" in the image is approximately the seeing at the conjugate height, and the typical integral seeing for our test site is 2 arcsec, the pixel scale of our setup should be enough to sense turbulence with strength that could degrade image size larger than 0.33 arcsec and verify our supposition. For our observation, since the source we chose was very bright, we set the exposure time of the CCD to be 5 ms, and the frame rate was set to be the maximum frame rate of the camera which is 26 frames per second. No binning was applied since it will change the detection threshold of the turbulence strength. A Johnson V band filter was installed in front of the camera.

With this setup, we pointed the telescope at a bright source close to the zenith. After locating the focal point where the size of the source on the image was smallest, we moved the camera away from the telescope. By doing this, the conjugated object plane was getting closer to the primary of the telescope. In other words, the camera would begin to image the atmosphere at a finite distance rather than stars at infinity when the camera was moving in such a fashion.

The source we chose was a 5 mag V star at a zenith angle around $10°$. It was bright enough to identify the chaotic structure in images (like the one displayed in Fig. 2) with a 5 ms exposure for conjugated heights from 6.4 km to 2.8 km. Out of this conjugated height range, either the "doughnut" shape was too big that light was spread out so that the structure was too weak to identify, or the doughnut shape was too small to observe any structure within it with our setup.

We then set our camera at six different conjugated heights consecutively. At every conjugated height, we acquired 50 frames with 5 ms exposure time which took about 1 min in total, then continued on to the next conjugated height by moving the camera along the electrical focusing stage which would take about another 2 to 3 min each time. We repeated this observation sequence three times. The zenith angles of the star for each of these three exposure sequences were $82°$, $80.7°$ and $79.3°$ respectively.

From these images, we extracted the value within the doughnut shape in the image, and calculated the entropy without any binning. The calculated results are plotted in Figure 3. From top to bottom, the three panels depict entropy variation for each of the observation sequences with the star at different elevation angles. Lines in different colors within one panel represent entropy obtained at different conjugated heights in one observation sequence. The X axis represents the number of frames that was used calculate the entropy value. Therefore, it could also be considered as time since the first exposure at a certain conjugate height. The Y axis is the entropy value, and each curve represents the continuous evolution of entropy observed at a certain height.

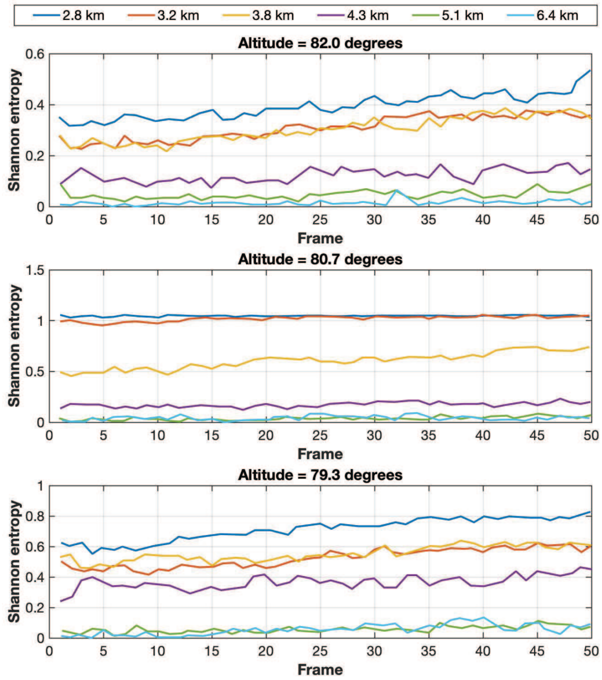

Fig. 3 Entropy calculated for three different observation sequences when the source was at elevation angles of $82°$, $80.6°$ and $79.3°$, from top to bottom respectively. The X axis is the number of frames during one continuous exposure sequence for a certain height. The Y axis is the calculated Shannon entropy.

There are three interesting behaviors of entropy that could be noticed from Figure 3. Firstly, entropies at different heights tend to be separated from each other, in a "layered" fashion. Secondly, entropies at lower heights are higher than entropies at higher heights. Thirdly, entropies for each of the heights evolve with time. These three behaviors actually correspond very well to what we have known about atmospheric turbulence strength. The atmospheric turbulence profile is layer-like. The strength of turbulence is stronger at lower altitudes than at higher altitudes. Turbulence strength evolves with time. Therefore, qualitatively as the first step, using entropy as a metric for representing turbulence strength at different observed heights of the atmosphere is reasonable and feasible.

To further verify the relationship between entropy and $C_N^2(h)$, we calculated entropy of similar images in Figure 2 generated from a numerical Monte Carlo simulation (Conan & Correia 2014) given specific r_0 (coherence length) value. In this simulation, only one layer of turbulence was considered, and because of this, r_0 is directly related to the single layer's C_N^2 value. We generated evolving phase screens with constant r_0 value and utilized these phase screens to generate images to calculate

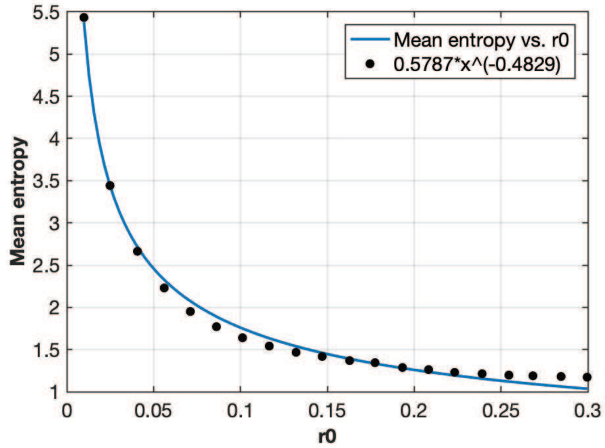

Fig. 4 Entropy calculated with simulated images vs. r_0 used for generating these images. Dots are the simulation results, and the blue continuous line is a fitting curve of these dots.

entropy. After calculating the mean value of entropy for this group of images at this r_0, we changed the r_0 value and repeated this process. In Figure 4, we plot the mean values of entropy vs. the r_0 values with dots, and a polynomial function fitting these dots. We can see that as r_0 is approaching a larger value which indicates a milder turbulence, the entropy value is also dropping down as we have already discussed. This simulation clearly indicates a relationship between the entropy and the strength of turbulence represented by r_0 here. However, further theoretical study is still needed to understand this relationship quantitatively which could help in selecting guiding instrument parameters for this method.

4 DISCUSSION

In this paper, we proposed a new metric, Shannon entropy, that can be used for representing turbulence strength. We also demonstrate a practicable method to obtain knowledge on the turbulence distribution at different heights by adjusting the camera's object plane at different conjugated heights and calculating Shannon entropy. The results of our tests demonstrate that the new metric is qualitatively correlated with atmospheric turbulence strength. Initial simulation indicates a clear relationship between entropy obtained with this method and turbulence strength. For the next step, we are planning to incorporate a more detailed simulation to investigate the relationship between entropy and the commonly used metric $C_N^2(h)$ and theoretical works to more fully understand this relationship.

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