Developing a Simulation of SCIDAR

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Introduction

Scintillation Detection and Ranging (SCIDAR) is a triangulation technique that uses scintillation patterns to characterize the atmospheric turbulence profile (Fig. 1). Atmospheric turbulence, which can be represented by a phase screen, is characterized by variations in the index of refraction of air (Fig. 2). Turbulence can degrade image quality and lead to photometric errors. When a wavefront is propagated through the atmosphere, this results in intensity variations at the telescope aperture. Conventional SCIDAR is constructed with only one camera and does not separate light from stars, resulting in overlapping pupil images and loss of contrast. Stereo-SCIDAR was developed to increase the efficiency and quality of the conventional SCIDAR instrumentation. Stereo-SCIDAR employs two separate cameras to obtain two separate pupil images. This has many important implications, including an improvement in wind velocity estimation and observation of targets with a greater difference in brightness (Fig.3).

Fig. 1 The University of Hawaii 88" telescope, or UH88, utilizes SCIDAR techniques.

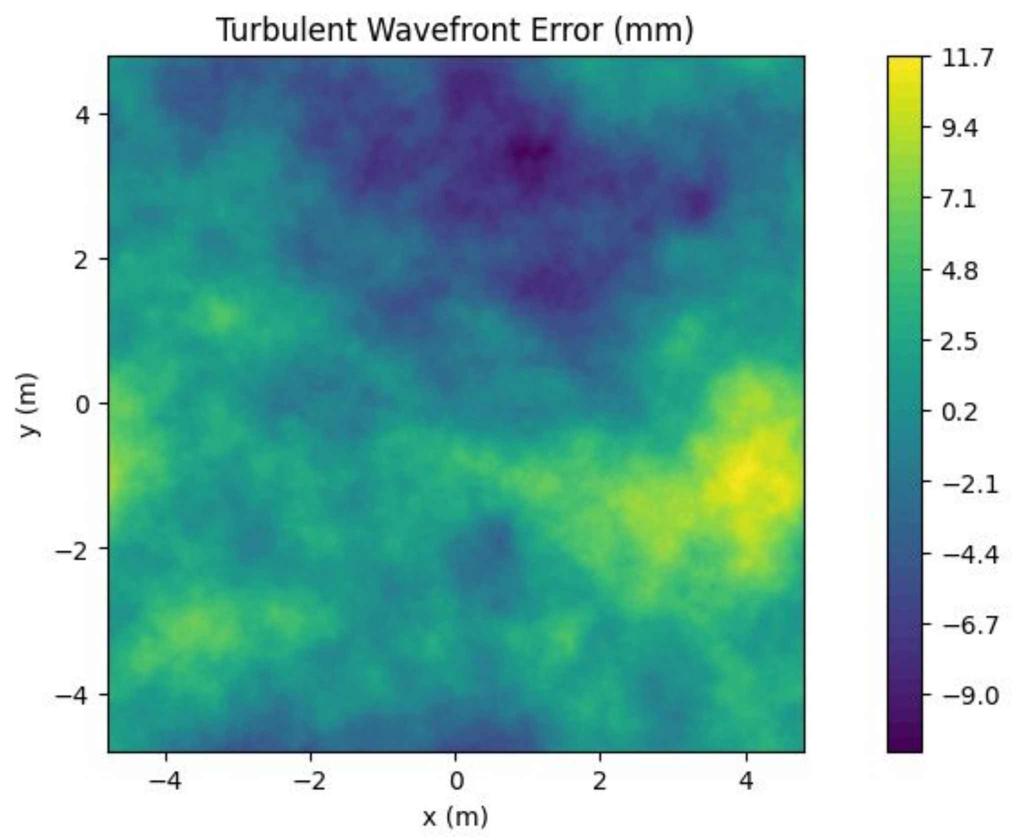

Fig. 2 Atmospheric turbulence can be visualized by a phase screen

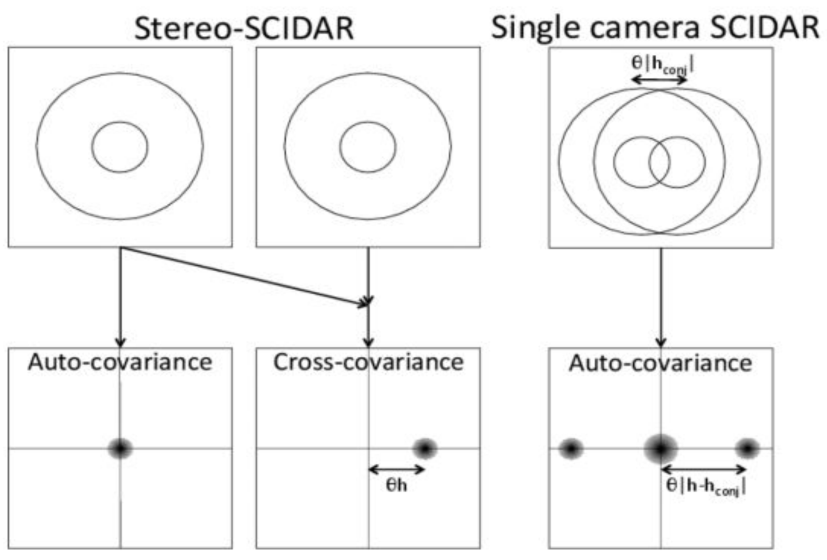

Fig. 3 Conventional SCIDAR features overlapping pupil images, resulting in a loss of contrast, whereas stereo-SCIDAR separates the images.

Methods

This project used POPPY, a simulation package, to simulate a stereo-SCIDAR system that separates pupil images and directs the light to a single camera. A monochromatic wavefront was propagated through a turbulent atmosphere and telescope. Plots showing the intensity variations in the wavefront object were generated. The scintillation patterns for an off-axis star were obtained by modifying the POPPY source code. An off-axis star travels through a section of the atmosphere that is slightly different from the on-axis star (Fig. 4). An off-axis star is specified by its angular separation, θ, from the on-axis star, and the height *h* of the atmospheric layer above the telescope is known, then the distance needed to shift, x, can be computed by the relation:

$$\tan(\theta) = \frac{x}{h}$$

The distance x was used to shift the phase screen by the corresponding number of pixels.

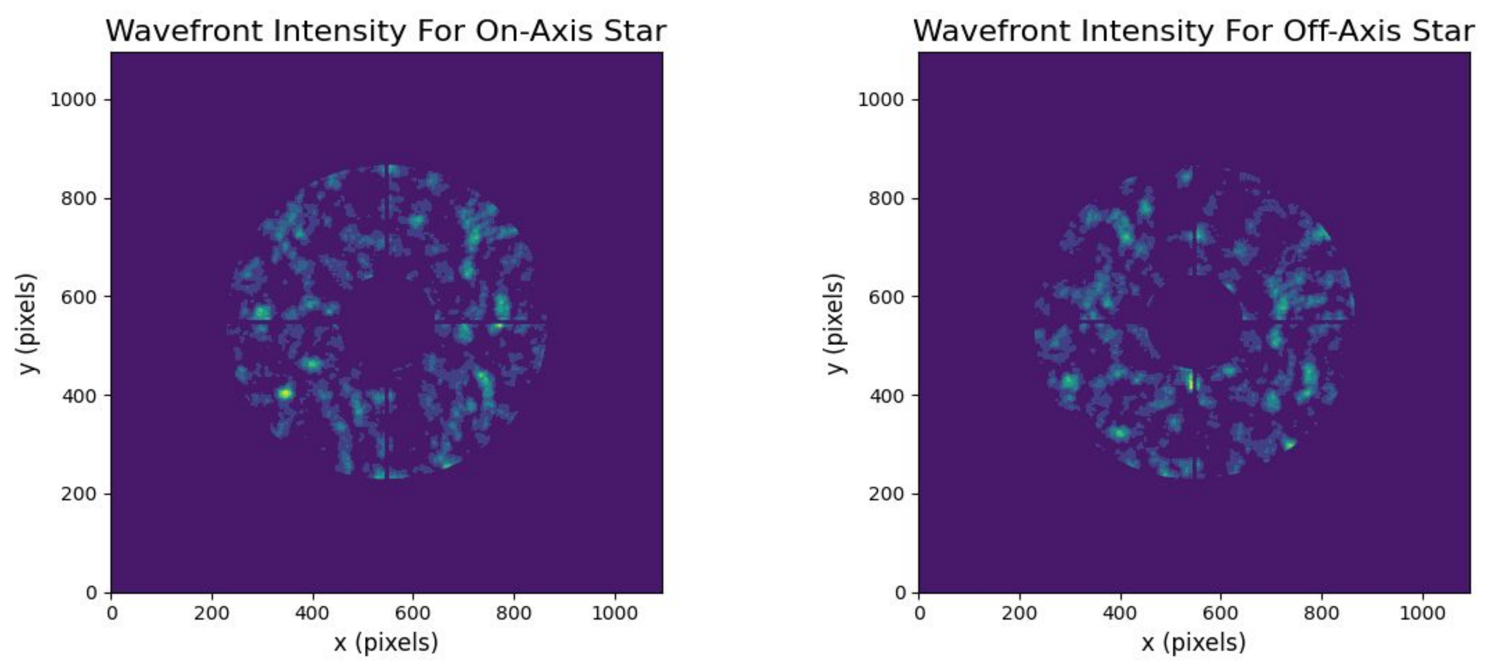

Fig. 4 Scintillation patterns for two different stars at different angular positions for the same atmosphere

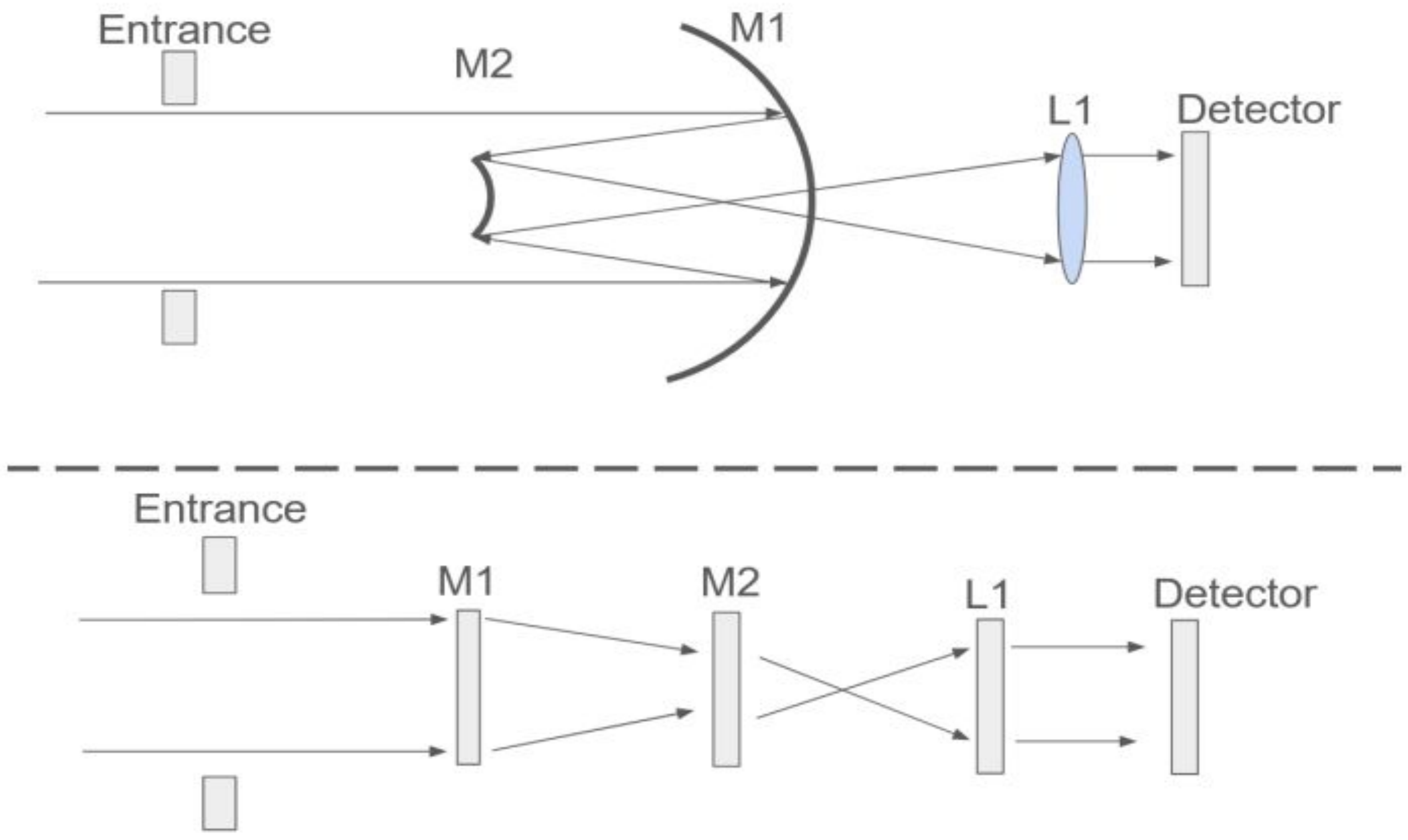

Fig. 5 **Top:** Schematic showing the layout of the telescope. **Bottom:** A representation of the system using POPPY.

Ray Transfer Matrix Analysis

Ray transfer matrix analysis treats a light ray as a vector with two components: the height above the optical axis, and angle relative to the optical axis. Propagation of the ray through free space and lenses can regarded as matrix transformations. For a propagation through free space, the ray transfer matrix is given by:

$$\begin{bmatrix} 1 & d \\ 0 & 1 \end{bmatrix}$$

Where d is the distance of propagation. The ray transfer matrix for a thin lens of focal length f is given by:

$$\begin{bmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{bmatrix}$$

Ray transfer matrix analysis was used to locate the focal length of the optical system for a light ray at a particular conjugation distance. The lenses and regions of free space were represented as a sequence of ray transfer matrices (Fig.5). In the final step of propagation, the distance at which the ray encountered the optical axis was determined using an optimization algorithm. This corresponded to the focus of the system.

SCIDAR is unable to measure turbulence at low altitudes because larger propagation distances are required to obtain scintillation patterns. This was resolved in this project using negative conjugation, where the telescope is focused at a point that is lower than the turbulent layer. This allows for the characterization of ground-level turbulence.

Limitations and Future Work

In this project, the atmosphere was only modelled with a single layer, when it reality it consists of multiple layers. The simulation also only generates a single instance of the atmosphere, even though the atmosphere is time-varying. Future work might include these factors for a more comprehensive model of the system. Other optical aberrations such as astigmatism, which varies with the angular position of stars being imaged, may also be present in real SCIDAR instrumentation and could also be incorporated into the simulation.

Conclusions

The POPPY package was used to create a computer simulation of stereo-SCIDAR instrumentation. This was used to generate scintillation patterns that would be imaged by a telescope for various stars located on and off-axis. The simulation can be developed further to account for other features, such as astigmatism and a multi-layer, time-varying atmosphere.

References

1. Shepherd, H. W., Osborn, J., Wilson, R. W., et al. 2014, MNRAS, 437, 3568. doi:10.1093/mnras/stt2150