Site testing for space situational awareness with single-detector stereo-SCIDAR

Elliott Thorn, **Doris Grosse**, **Francois Rigaut**, **Francis Bennet**

Research School of Astronomy and Astrophysics, Australian National University, Canberra, ACT 2611, Australia
Space Environment Research Centre (SERC) Limited, Mount Stromlo Observatory, Weston Creek, ACT 2611, Australia

ABSTRACT

A single-detector stereo-SCIDAR system is being developed by the Research School of Astronomy and Astrophysics (RSAA) in conjunction with the Space Environment Research Centre (SERC) to characterise atmospheric turbulence above the Australian National University's Mount Stromlo observatory just outside Canberra. The EOS Space System's telescope at the Mount Stromlo observatory is to be used in future to track space debris to improve space situational awareness (SSA). Adaptive optics (AO) systems will be used to improve the resolution of the 1.8m debris ranging telescope located at the site. The SCIDAR system will measure valuable data including refractive index structure constant, C_n^2, and wind speed profiles. Also of interest are values of the Fried parameter, r_0, and the turbulence temporal coherence time, τ_0, which will be used to optimise the AO systems' deformable mirror actuator pitch and correction rate. This system will be used in two modes: generalised SCIDAR and generalised stereo-SCIDAR. The generalised SCIDAR mode will overlap the pupil images of double stars on the detector whilst the generalised stereo-SCIDAR mode will separate the pupil images. Post-processed short exposures of the scintillation patterns of these double stars will extract altitude information of atmospheric turbulent layers. A stereo-SCIDAR system designed by another organisation separated pupil images onto a *pair* of separate detectors. However, our optical design utilises a compound roof prism to separate the pupil images and record them on a *single* detector. We discuss the optical and mechanical design of a stereo-SCIDAR system to measure the scintillation patterns of double stars separated by 10 to 25 arcseconds up to an altitude of approximately 15 km.

Keywords: SCIDAR, generalised stereo-SCIDAR, adaptive optics, atmospheric turbulence

1. INTRODUCTION

SCIDAR stands for **sci**ntillation **d**etection **an**d **r**anging and was first proposed, though not in name, by Vernin and Roddier[1]. The technique measures the scintillation pattern of two stars to profile atmospheric turbulence. Experiments were conducted between 1971 and 1972 at the Coudé focus of the Haute-Provence Observatory 152 cm reflector whereby the objective of the telescope was optically conjugated to an echelette mirror grating whilst observing a single star. The reflected fluxes—the split beam of light from the observed star—were then measured using a pair of photomultipliers. The measured electrical signals were subtracted from each other and sent to a computer for real-time analysis. The experiment found evidence of a multilayer structure of turbulence in the atmosphere and also extracted the wind speed and altitude of these layers. These experimental results effectively set the scene for investigations of the atmospheric turbulence structure.

The method used by [1] was enhanced by [2] in 1998 by introducing the concept of a movable analysis plane—generalised SCIDAR—via a translating photomultiplier illuminated through a pinhole. By sliding the photomultiplier back and forth the observer was able to effectively *wipe-out* a particular turbulent layer while emphasising layers above or below it. This technique would allow profiling of the entire atmosphere and the possibility of imaging lower turbulent layers that had, until then, been inaccessible to classical SCIDAR systems. Whilst this was an important development in the evolution of SCIDAR there was a brightness difference limitation of approximately two magnitudes between targets.

The next step forward was stereo-SCIDAR—an extension of the generalised SCIDAR concept—and was implemented by [3] in 2013. This was a stereoscopic system used to image scintillation patterns of double stars

utilising a reflective pickoff optic, which separated the pupil images, in order to direct light from each star to its own dedicated detector. By taking advantage of the generalised SCIDAR concept of a movable analysis plane, the system was capable of conjugating to different altitudes in step increments. This process resulted in increased altitude resolution and allowed the construction of a full turbulence profile at each resolution. An advantage of using a dedicated detector-per-star was the ability to independently adjust the gain of each camera in order to observe lower magnitude targets. This overcame the previously mentioned brightness limitation of single-detector generalised SCIDAR systems. The effect of overcoming this limitation was opening up the sky to observation by increasing the number of possible targets dramatically. Separating the pupil images in this way also led to an at least two-fold increase in the signal-to-noise ratio of the cross-correlation function which extracted the height information from the measurements; also reported was easier real-time wind-velocity profile reconstruction [4].

In order to save on cost and increase ease of implementation we have designed a single-detector SCIDAR system that can be configured as a generalised SCIDAR system or as a generalised stereo-SCIDAR system. A compound roof prism will be used to separate the pupil images of double stars and image the pupils onto a single detector. In this paper section 2 will expand upon the conceptual elements of the SCIDAR technique, section 3 details the optical and mechanical design of the system, and section 4 discusses the current state of the project.

2. CONCEPT

Henceforth, we will be referring to the systems in the following way: generalised SCIDAR (GS) and generalised stereo-SCIDAR (GSS). SCIDAR systems measure the scintillation patterns of stars in order to extract useful information about the turbulence through which the starlight travelled before reaching the system. Double stars separated by some angular separation, θ, are observed using a telescope, Fig. 1a. Generalised SCIDAR—the capability of conjugating to different altitudes in the atmosphere—requires the inclusion of a moveable analysis plane. Adding the extra propagation distance allows the scintillation to increase until it becomes measurable [5]. By separating the pupil images of the stars the system can then be classified as stereo-SCIDAR, Fig. 1b.

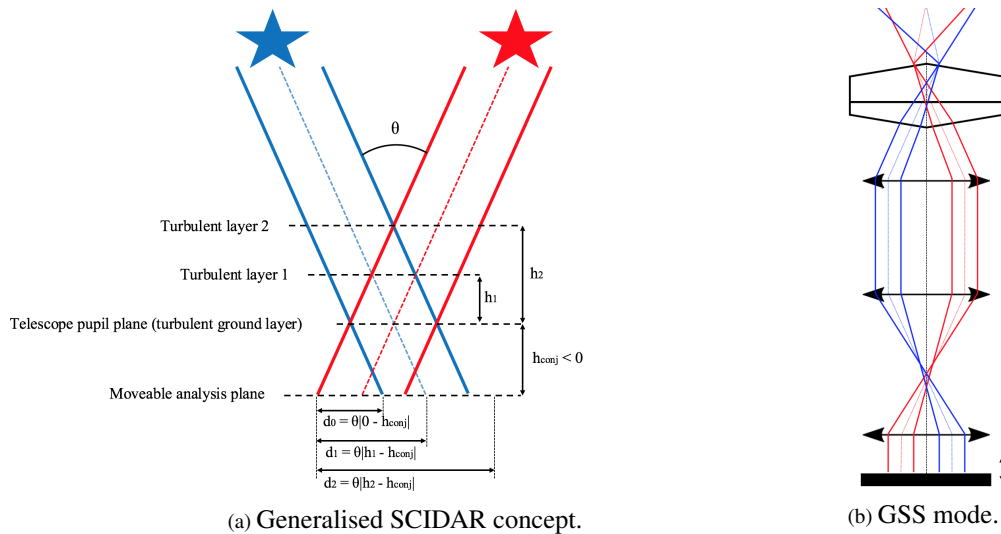(a) Generalised SCIDAR concept.

(b) GSS mode.

Fig. 1: a) Generalised SCIDAR diagram showing double stars, different turbulent layers, ground layer and conjugation distance. b) Optical layout of GSS mode showing all three system lenses and pupil-separating prism. Note the vertical arrow at bottom right signifying the movable detector. Also note the blue and red colour-coding of the different stars.

The moveable analysis plane provides the advantage of sensitivity to ground layer turbulence. Of course, there is a trade-off between sensitivity to the ground layer and altitude resolution due to an increase in the propagation distance, eq. 1:

$$\delta h(z) = 0.78 \frac{\sqrt{\lambda z}}{\theta} \tag{1}$$

Where z is the propagation distance to the turbulent layer and $z = |h - h_{conj}|$, λ is the wavelength of interest, h is the altitude of the turbulent layer and h_{conj} is the detector conjugate altitude [6]. It can be seen that by conjugating below the ground layer—increasing the propagation distance—the resolution degrades.

SCIDAR systems are only capable of extracting the turbulence profile of the atmosphere while the scintillation patterns are overlapping, hence there is a maximum altitude at which layers may be measured [4] and this is given by eq. 2:

$$h_{max} = \frac{D}{\theta} \tag{2}$$

Where D is the telescope aperture. However, telescope aperture-induced diffraction causes distortion of the image. This distortion is manifested in diffraction rings of different sizes, the largest ring being at the edge of the pupil image. The edge of the pupil may be neglected but there is a trade-off whereby the maximum measurable height is reduced as shown in eq. 3:

$$h_{max} = \frac{(D - r_F)}{\theta} \tag{3}$$

Where r_F is the Fresnel radius and is given by $r_F = \sqrt{\lambda h_{conj}}$, [7].

An appropriate detector records short exposure images of the scintillation pattern of the double star pupil images [8]. Post-processing of the image data can then be undertaken and extraction of the C_n^2 profile, turbulent layer height information and the wind speed is possible.

3. SYSTEM REQUIREMENTS AND DESIGN

System requirements, such as the double star angular separation, measurement height and conjugate layer propagation distances, are specified in Table 1.

Table 1: Requirements.

Parameter	Requirement
Double star separation	10 - 25 "
Measurement height, h	At least 15 km
Height resolution, δh	< 1 km
Fried parameter, r_0	5 cm
Conjugate layer propagation distance, h_{conj}	-1 to -3 km
Nominal system wavelength, λ	570 nm
Temporal resolution	Resolve 30 m/s windspeed with resolution of 10 cm

The optical layouts of the GS mode and the GSS mode are shown in Fig. 2a and Fig. 2c, respectively. The appearance of the pupil images overlapping and separated is shown in Fig. 2b and Fig. 2d, respectively. In GS mode, if the analysis plane were to be moved an increasing distance below the ground layer, the pupils would begin to move apart.

The SCIDAR system in either mode will be used to image the pupils of target double stars, separated by 10 to 25 arcseconds, onto an imaging camera. A wide-field USB acquisition camera will be used to aid in acquiring the targeted stars. The optical design of the GS mode is such that the pupil images overlap in the detector plane. However, in GSS mode the pupil images are separated in the detector plane by a compound roof prism located earlier in the system. The compound roof prism is comprised of two roof prisms made of different materials bonded together, in a similar fashion to an achromatic lens. The first prism encountered by the rays from the telescope induces the beam separation and the second prism is designed to reduce the chromatic aberrations induced by the first.

The system layout and specified opto-mechanical components are shown in Fig. 3 and these annotated figures are expanded upon in Table 2.

The imaging camera will be mounted on a x, y, z precision linear stage. Lockable actuators allow precise concentricity positioning of the imaging camera with respect to system lenses as well as providing linear translation along the optical axis to change the conjugate altitude, allowing different layers of the atmosphere to be probed. The USB wide-field acquisition camera will be mounted on a linear stage allowing linear translation to find best focus.

The entire system setup will fit conveniently on a breadboard which measures 350×1450 mm and should be straightforward to compact the system and adapt the mounting and interfaces to other telescope designs on a variety of optical ports.

Some custom components require mechanical design. These are detailed in Table 3.

(a) GS mode. Note the overlapping pupil images on the detector. The blue dashed arrow at bottom right denotes the ability of the detector to translate.

(b) Pupil images overlapping on detector.

(c) GSS mode. Note the separation of the pupil images on the detector due to the compound roof prism at far left. The blue dashed arrow at bottom right denotes the ability of the detector to translate.
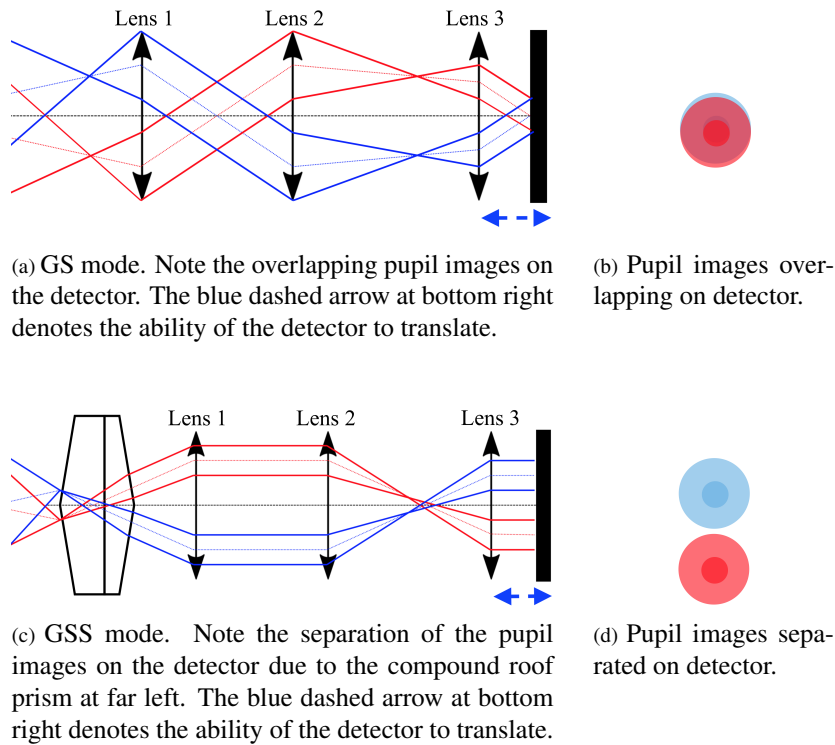
(d) Pupil images separated on detector.

Fig. 2: a) GS mode optical layout, b) GS mode pupil images, c) GSS mode optical layout and d) GSS mode pupil images.
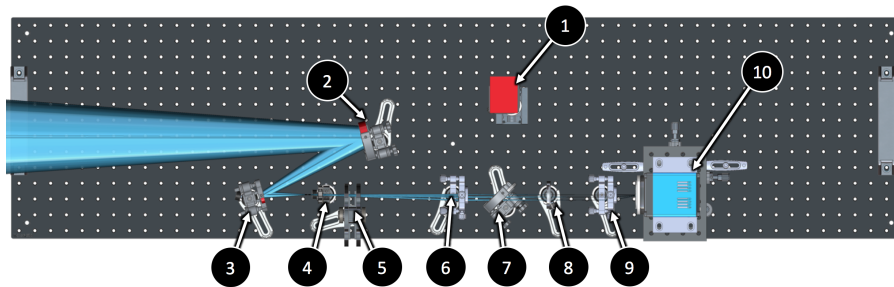
Fig. 3: Mechanical layout of GSS mode. The blue cone at left represents the light path through the system.

Table 2: System components.

Number	Component	Description
1	Acquisition camera	Wide-field USB camera to aid in acquiring targets
2	2" Fold mirror	Folds beam from Coudé lens optical axis
3	1" Fold mirror	Folds beam onto camera optical axis
4	Lens one	Collimates beam before passing through prism (prism not shown)
5	Filter wheel	Allows selection of bandwidth to pass through system
6	Lens two	Lens two and lens three act as a relay
7	Dichroic	Passes light below λ_{acq} to acquisition camera and light above λ_{acq} to imaging camera
8	Field stop	Prevents stray light from reaching the detector
9	Lens three	Collimates beam to allow imaging of pupil and part of a relay with lens two
10	Imaging camera	PCO Edge 4.2

Table 3: Custom components.

Mode	Component	Description
GSS	Acquisition camera mount	Adapter between USB camera and mount
GSS	Extension block	Raises imaging camera to required height and interfaces large stage with small breadboard
GSS	Imaging camera mount	Interface between PCO Edge and breadboard
GSS	Prism mount	Secures prism and is adjustable
GS	Imaging camera mount	Secures imaging camera
GS	Adapter	Interfaces imaging camera mount with stage
Common	Laser bracket	Interface between alignment laser and mount

4. CURRENT STATE OF THE PROJECT

All optical design for the generalised SCIDAR mode has been completed and the bill of materials has been finalised. There is a need to converge on the final dimensions of the pupil-separating prism for the GSS mode to finalise the specification of the achromatic prism. Two observation campaigns are planned in order to take advantage of the delay between the completion of each system mode. The GS mode variant will be completed first whilst the prism is being manufactured and procured. A list of appropriate target double stars has been compiled and we hope to observe these beginning in January 2017. A much longer target list of appropriate double stars has been compiled for the GSS mode—the list is longer due to this mode's increased sensitivity and capability to detect fainter targets—and we hope to begin these observations in March 2017.

Recently, testing of the chromatic aberrations of the exit optic after the telescope's Coudé path—a large converging lens—was carried out. It was determined that the aberrations induced by this lens are unacceptably high and that a parabolic beam expander should replace it.

5. CONCLUSION

A single-detector SCIDAR system, to be used in two modes (generalised SCIDAR mode and generalised stereo-SCIDAR mode), is being developed for Mount Stromlo observatory to measure the refractive index structure constant, wind speed, Fried parameter and temporal coherence time of the atmosphere above the site. To allow the usage of a single-detector stereo-SCIDAR a novel pupil-separating compound roof prism will be inserted into the system. These measurements will improve the design of the adaptive optics (AO) systems currently under development and provide optimised values to specify the deformable mirror actuator pitch and correction rate. These enhanced AO systems will be utilised to allow improved telescope tracking and imaging of space debris and to increase knowledge about the orbital environment. We seek to begin a generalised SCIDAR measurement campaign in January 2017 followed by a generalised stereo-SCIDAR measurement campaign in March 2017 to collect data. The total SCIDAR campaign at Mount Stromlo will be ongoing to collect a minimum of one year of statistics, with two or more observations per week on average.

ACKNOWLEDGEMENTS

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