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# Characterising atmospheric optical turbulence using stereo-SCIDAR

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**Abstract.** Stereo-SCIDAR (SCIntillation Detection and Ranging) is a development to the well known SCIDAR method for characterisation of the Earth's atmospheric optical turbulence. Here we present some interesting capabilities, comparisons and results from a recent campaign on the 2.5 m Isaac Newton Telescope on La Palma.

## 1. Introduction

The Earth's turbulent atmosphere has a detrimental effect on astronomical observations. For imaging random phase aberrations blur the image reducing the attainable spatial resolution. For photometric observations, scintillation induced by the turbulence can be a dominant noise source [1].

Several techniques have been implemented to estimate the atmospheric turbulence profile, measured as the refractive index structure constant, $C_n^2(h)$, and wind velocity, both as a function of altitude. The most widely exploited are MASS (Multi Aperture Scintillation System, [2]), SCIDAR (SCIntillation Detection And Ranging, [3]) and SLODAR (SLOpe Detection And Ranging, [4]). MASS is not intended as a high vertical-resolution technique. It has a limited logarithmic vertical resolution and the high altitude response is very broad [2]. Here, we only address high altitude-resolution techniques and therefore we will only discuss SLODAR and SCIDAR. Both SLODAR and SCIDAR are triangulation techniques in which the atmospheric turbulence profile is recovered from either the correlation of wavefront slopes in the case of SLODAR, or scintillation intensity patterns in the case of SCIDAR, for two target stars with a known angular separation

Section 2 briefly describes stereo-SCIDAR instrument and how it works, a full description can be found in [5, 6]. Section 3 states the parameters which can be derived and gives short examples of how they can be applied, and section 4 shows that turbulence profiles are important photometric measurements as well as imaging.

## 2. Stereo-SCIDAR

Stereo-SCIDAR is a stereoscopic system in which the distance to a turbulent layer is estimated by measuring the offset of a covariance peak in the cross-correlation function of the scintillation pattern from two stars separated by angle $\theta$. The strength of the turbulence is proportional to the magnitude of the covariance (figure 1). The velocity of the turbulent layers can also be

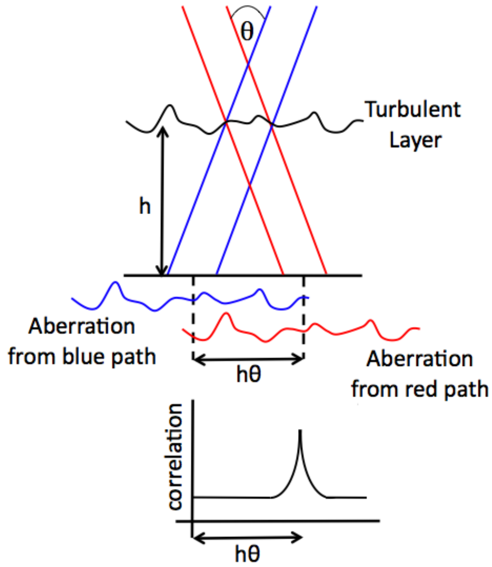


**Figure 1.** If a turbulent layer at height, $h$, is illuminated by two stars of angular separation, $\theta$, then two copies of the aberration will be made on the ground separated by a distance $h\theta$. By cross correlating either the centroid positions from a Shack–Hartmann wavefront sensor (SLODAR) or the intensity patterns (SCIDAR) we can triangulate the height of the turbulent layer and the amplitude of the correlation peak corresponds to the strength of the layer.

estimated optically by tracking the covariance peaks through the spatio-temporal covariance function. The reader is referred to Shepherd *et al.* [6] for a full description stereo-SCIDAR including how it works and the opto-mechanical design.

By separating the scintillation patterns onto separate detectors instead of overlapping them on a single camera (as with traditional SCIDAR instruments) we reduce the noise in the profile estimation. This is because, in conventional SCIDAR instruments, the intensity speckles lose contrast in the overlapping patterns, reducing the visibility of the covariance peaks (figure 2).

## 3. Atmospheric Parameters at La Palma

Stereo-SCIDAR provides measurements of the refractive index structure parameter, $C_n^2(h)$, as a function of altitude, $h$, (figure 3) and the turbulence speed, $|V(h)|$, and direction $V_\theta(h)$ (figure 4). Using these parameters it is possible to derive several other optical parameters:

$$r_0 = \left(0.423 \left(\frac{2\pi}{\lambda}\right)^2 \cos(\gamma)^{-1} \int C_n^2(h) \mathrm{d}h\right)^{-3/5}, \tag{1}$$

$$\theta_{\mathrm{FWHM}} = \frac{0.98\lambda}{r_0}, \tag{2}$$

$$\theta_0 = \left(2.914 \left(\frac{2\pi}{\lambda}\right)^2 \cos(\gamma)^{-8/3} \int C_n^2(h) h^{5/3} \mathrm{d}h\right)^{-3/5}, \tag{3}$$

$$\tau_0 = \left(2.914 \left(\frac{2\pi}{\lambda}\right)^2 \cos(\gamma)^{-8/3} \int \frac{C_n^2(h)}{V(h)} \mathrm{d}h\right)^{-3/5}, \tag{4}$$

$$\sigma_I^2 = 10.7 D^{-4/3} t^{-1} \cos(\gamma)^{\alpha(V_\theta(h))} \int \frac{C_n^2(h) h^2}{V(h)} \mathrm{d}h, \tag{5}$$

where $r_0$ is the Fried parameter, $\theta_{FWHM}$ is the Full Width at Half Maximum (FWHM) of the point spread function (PSF) or seeing, $\theta_0$ is the isoplanatic angle, $\tau_0$ is the coherence time and $\sigma_I^2$ is the scintillation variance. Other required parameters for the above calculations are the zenith angle, $\gamma$, the wavelength of the observation, $\lambda$, the telescope diameter, $D$ and the air

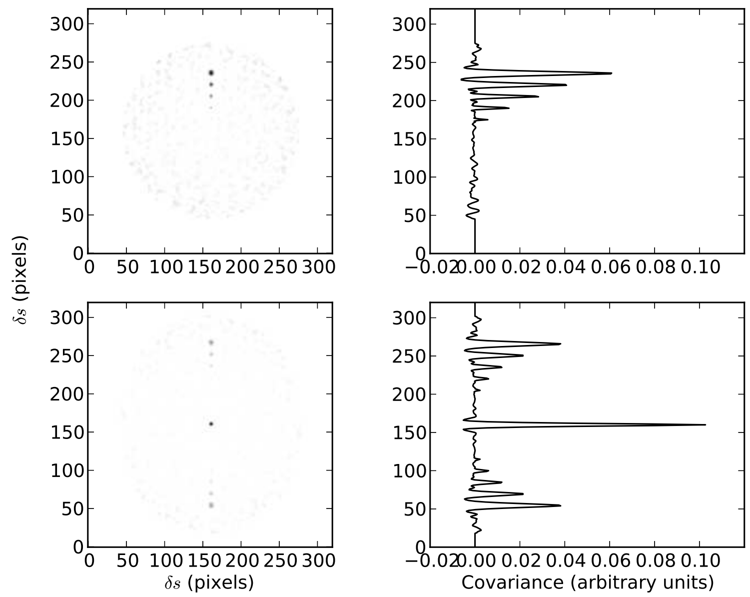


**Figure 2.** 2D covariance plots for Stereo-SCIDAR (upper) and single camera Generalised-SCIDAR (lower) for an atmospheric simulation containing six equal strength turbulent layers at 2 km spacing between 0 and 10 km, inclusive. A vertical cut through each covariance function is shown on the right. $\delta s$ is the position in the covariance function. We see that for single camera SCIDAR we have two sets of spatially separated peaks and one set of overlapping peaks at the centre. For Stereo-SCIDAR we only have one set. Both plots have the same contrast scale, the correlation peaks for Stereo-SCIDAR are larger in magnitude than that of single camera Generalised-SCIDAR.

mass exponent, $\alpha$. Note, that the value of the airmass exponent, $\alpha$, will depend on the wind direction and vary between -3 for the case when the wind is transverse to the azimuthal angle of the star, up to -4 in the case of a longitudinal wind direction. This is a geometric correction. In the case where the wind direction is parallel to the azimuthal angle of the star, the projected pupil onto a horizontal layer is stretched by a factor of $1/\cos(\gamma)$, which changes the projected wind speed.

Each of these parameters has its own influence for particular applications. $r_0$ and $\theta_{\mathrm{FWHM}}$ are usually used interchangeably and are a measure of the effect on an image caused by a wavefront which has propagated through the complete atmosphere. The isoplanatic angle defines the angular extent over which the atmospheric effects are correlated. It is this parameter that defines the angular size of an Adaptive Optics (AO) corrected field. Multi-Conjugate Adaptive Optics (MCAO) systems can be used to increase the isoplanatic angle and hence increase the corrected field of view. The coherence time defines the update rate that an AO system must function at in order to minimise residual wavefront errors due to the temporal lag between the wavefront measurements and correction on the deformable mirror (DM). All of this information can be used in real time for AO support, PSF reconstruction, observatory and observation management.

In addition to the above, statistical data on the typical profiles and variability of each of the profiles can be used for instrument development and performance analysis [7].

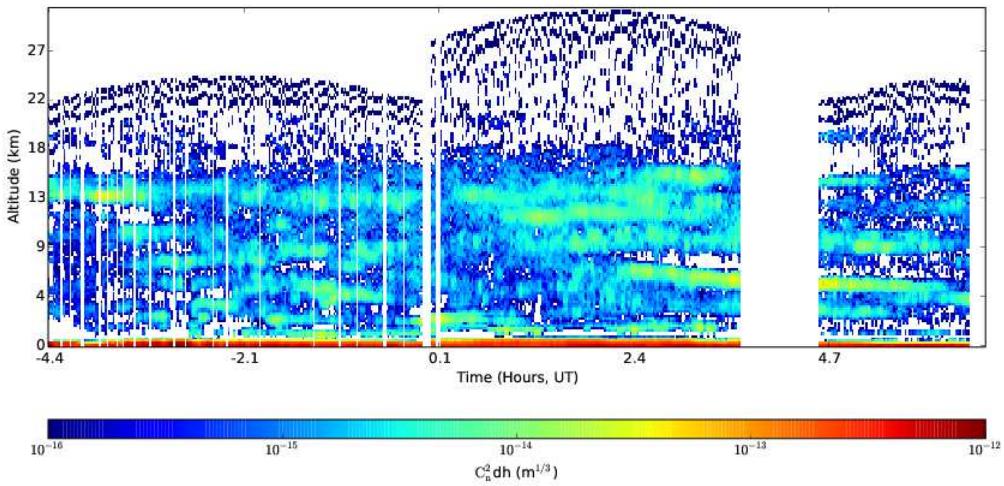


**Figure 3.** Example $C_n^2$ profile from the 2.5 m Isaac Newton Telescope, La Palma, on the 9th October, 2014.

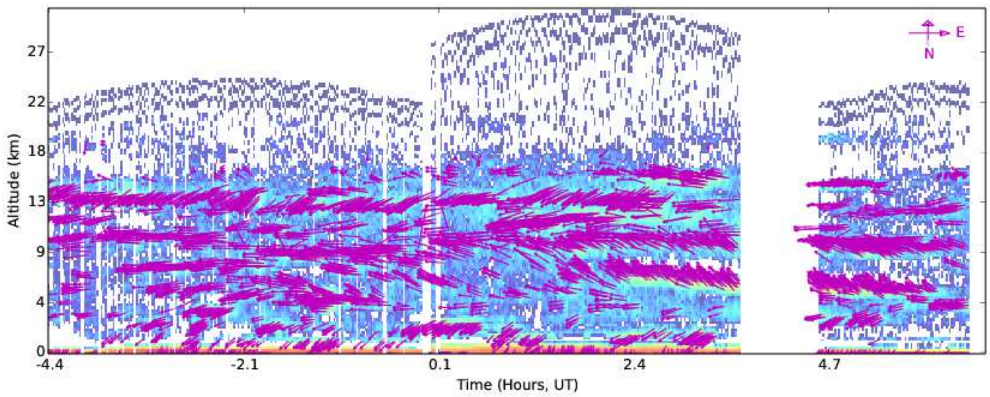


**Figure 4.** Example wind velocity profile from the 2.5 m Isaac Newton Telescope, La Palma, on the 9th October, 2014. The length and direction of the arrow indicating the speed and direction of the optical turbulence.

## 4. Scintillation noise

The scintillation index (equation 5) can be used to estimate the scintillation noise for photometric observations. As scintillation is a second order propagation effect depending on the local curvature of the wavefront, high altitude optical turbulence is dominant in causing scintillation at the ground. Therefore, scintillation noise is dominated by high-altitude turbulence [8] and it can be assumed that the scintillation noise is isotropic. The data from a turbulence monitor can then be used to estimate the scintillation noise applicable to photometric measurements made at nearby telescopes [9]. The fractional scintillation noise is defined as,

$$\sigma^2 = \frac{\left\langle (I - \langle I \rangle)^2 \right\rangle}{\langle I \rangle^2}, \tag{6}$$

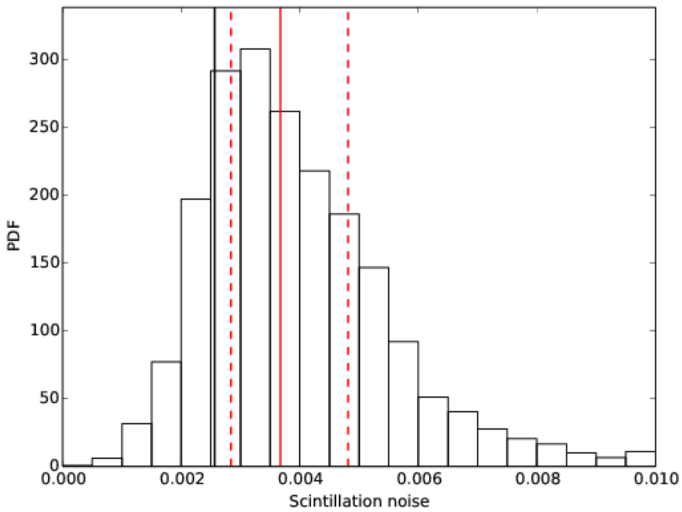


**Figure 5.** Scintillation noise distribution for a 1 m telescope and 1 second exposures, calculated from recent Stereo-SCIDAR results on the INT, La Palma. The red solid and dashed lines denote the distribution median, and first and third quartiles respectively. The black solid line indicates the value from Young's approximation.

where $I$ is the measured intensity and $\langle\rangle$ indicates the expect value.

A standard equation for calculating the expected fractional scintillation variance at any particular site in the long exposure regime was first suggested by [10] and is given by,

$$\sigma_Y^2 = 9 \times 10^{-6} D^{-4/3} t^{-1} (\cos\gamma)^{\alpha} \exp\left(-2h_{\rm obs}/H\right) \tag{7}$$

where $h_{\rm obs}$ is the altitude of the observatory and $H$ the scale height of the atmospheric turbulence structure, which is generally accepted to be approximately 8000 m. Equating Young's equation with equation 5 we see that Young is effectively assuming a turbulent layer of strength $\sim 80 \times 10^{-15}$ at 8 km. All previous work on the detection limits of fast photometry have used this equation to estimate the scintillation noise in their measurements.

Recent results from stereo-SCIDAR on the 2.5 m INT, La Palma, show that the conventional estimation for scintillation noise (Young's equation) [10] underestimates the median fractional scintillation noise by a factor of approximately 1.5 (figure 5).

Real profiles from Stereo–SCIDAR shows that the optical turbulence profile (both turbulence strength and velocity) can evolve rapidly. We have seen periods of strong high layers which survive for the duration of several hours and we have seen small bursts of activity lasting only a few minutes [6]. The altitude and magnitude of these layers varies with time, having significant impact on observations. Therefore, no single number metric can be used to estimate the scintillation noise at any particular time.

Knowing the contemporaneous scintillation noise will enable performance assessment, calibration and optimisation of photometric instrumentation. It will also help to explain and constrain model fits to photometric data (for example, extra-solar planet transit light curves) [11], and to help develop scintillation correction concepts [1, 8, 12].

## 5. Conclusions

Stereo-SCIDAR provides sensitive measurements of the optical atmospheric turbulence variables such as the refractive index structure function and wind velocity profile. From these variables several other useful parameters can be estimated, for example, seeing, isoplanatic angle, coherence time and scintillation index. All of this information can be used in real time for AO support, PSF reconstruction, observatory and observation management and statistical data on the typical profiles and variability of each of the profiles can be used for instrument development and performance analysis. We have shown from recent stereo-SCIDAR data on La Palma that standard scintillation noise estimates, as used by astronomers, tends to underestimate the actual scintillation noise. This has ramifications on understanding the model fits to photometric data.

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