

# Estimation of anisoplanatism in adaptive optics by generalized SCIDAR profiling

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## ABSTRACT

We present the results of contemporaneous seeing measurements using a multi-object Shack–Hartmann wavefront sensor, SCIDAR optical turbulence profiling, and a DIMM seeing monitor at the William Herschel Telescope in La Palma. The data are used to determine the accuracy with which angular anisoplanatism can be predicted from generalized SCIDAR turbulence profile measurements. Theoretical predictions of the angular correlation of the Zernike aberration coefficients, based on the SCIDAR profiles, agree with direct measurements from the wavefront sensor to within 7 per cent rms. Estimates of the total seeing (integrated optical turbulence strength) from the methods agree to 10 per cent rms. We conclude that SCIDAR represents a reliable means for calibration of the spatially and temporally variable point-spread function for imaging with adaptive optics in astronomy.

**Key words:** atmospheric effects – instrumentation: adaptive optics – site testing – telescopes.

## 1 INTRODUCTION

Adaptive optics (AO) systems can partially compensate for the effects of atmospheric turbulence, to greatly improve the imaging performance of ground-based telescopes. AO systems are now in operation on many of the largest astronomical telescopes, including the European Southern Observatory Very Large Telescope (VLT) (Brandner et al. 2002), Subaru (Gaessler et al. 2002) and Gemini (Close et al. 2002). At the William Herschel Telescope (WHT), the NAOMI (Nasmyth Adaptive Optics for Multi-purpose Instrumentation) AO system has recently been commissioned for optical and infrared observations (Benn et al. 2001).

The corrected field of view for AO is limited, typically to less than 1 arcmin, by the effects of anisoplanatism. Wavefronts from different directions in the field are sheared by an amount proportional to altitude, and so are subject to different aberrations at each turbulent layer in the atmosphere above the telescope. Anisoplanatism results in a progressive degradation of the corrected point-spread function (PSF) with field angle from the guide star used for AO wavefront sensing. The degree of anisoplanatism depends on the altitude profile of optical turbulence strength,  $C_n^2(h)$  (the structure constant of the refractive index  $n$  as a function of altitude  $h$ ). The profile varies continuously, with significant changes typically occurring on time-scales of a few minutes.

Accurate deconvolution and photometric exploitation of AO image data therefore require calibration of the spatially variable PSF,

with good time resolution. In many observations bright field stars will not be available for this purpose. However, an estimate of the partially corrected PSF in the direction of the guide star (i.e. on-axis) can be derived from the wavefront sensor measurements of the AO system (Harder & Chelli 2000). The off-axis (anisoplanatic) PSF can then be estimated if a contemporaneous, or near-contemporaneous, measurement of  $C_n^2(h)$  can be made (Ellerbroek 1994; Wilson & Jenkins 1996; Fusco et al. 2000).

SCIDAR (SCIntillation Detection And Ranging) is now a well-established technique for the determination of  $C_n^2(h)$  (Klückers et al. 1998; Avila, Vernin & Sánchez 2001). In this method, a large number of short-exposure images are recorded of the scintillation pattern for a double star in the telescope pupil.  $C_n^2(h)$  is found via an integral inversion of the averaged autocorrelation of the scintillation pattern.

Here our objective was to determine experimentally the accuracy with which the anisoplanatic decorrelation of the wavefront aberration could be predicted from SCIDAR measurements of  $C_n^2(h)$ . Simultaneous observations of binary stars were made with a Shack–Hartmann wavefront sensor (WFS) to measure the wavefront correlation and SCIDAR to estimate the  $C_n^2(h)$  profile.

The WFS also provided estimates of the seeing coherence length  $r_0$  (Fried’s parameter).  $r_0$  is a measure of the total atmospheric optical turbulence strength, and is proportional to the reciprocal of the seeing-limited image FWHM,  $\Omega$ , of a point source for a large telescope:

$$\Omega \simeq \lambda/r_0, \quad (1)$$

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where  $\lambda$  is the observing wavelength.  $r_0$  is related to the integrated turbulence profile by

$$r_0 = \left[ 0.42k^2 \cos^{-1} z \int C_n^2(h) dh \right]^{-3/5}, \quad (2)$$

where  $k = 2\pi/\lambda$  and  $z$  is the zenith angle of the observation. Hence the integrated turbulence strength for the SCIDAR profiles could be compared with the WFS values via equation (2). Estimates of  $r_0$  were also available from the Isaac Newton Group's Differential Image Motion Monitor (DIMM), for the first half of the night.

In Section 2 we summarize the observations. Sections 3 and 4 detail the results relating to angular anisoplanatism and Fried's parameter respectively.

## 2 OBSERVATIONS

The observations were made at the GHRIL (Ground-based High-Resolution Imaging Laboratory) focus of the WHT. A dichroic beamsplitter was used to divide the incoming starlight between the SCIDAR and Shack–Hartmann optical systems, with SCIDAR using wavelengths shorter than 550 nm.

Details of the SCIDAR method, including the specific experimental setup used here, have been described by Klückers et al. (1998). The SCIDAR optics were arranged to record the stellar scintillation pattern over a subsection of the WHT pupil approximately 1 m in diameter, with 1-cm sampling per detector pixel. Data were recorded with the SCIDAR optics in both the conventional and 'generalized' arrangements. In the conventional format, the conjugate plane of the imaging system is at the pupil plane of the telescope. Since a propagation distance of a few kilometres is required to produce measurable scintillation from a turbulent layer, low-altitude turbulence cannot be observed in this format. Generalized SCIDAR is a more recent development of the technique, in which the optics are placed at a conjugate plane which is effectively *below* the telescope pupil, so that scintillation can be detected for even the lowest turbulent layers.

The Shack–Hartmann wavefront sensor was essentially that described by St-Jacques et al. (1997) which was used for the Joint Observatory Seeing Evaluation (JOSE) project at the WHT (Wilson et al. 1999). The WFS comprised a lenslet array which defined 8 by 8 subapertures across the pupil of the 4.2-m WHT, and a large format ( $512 \times 512$  pixel) frame-transfer CCD camera to record the

subaperture image positions at frame rates of  $\sim 30$  Hz. For binary stars with separations greater than 14 arcsec, the two resulting spot patterns were fully separated on the CCD. Hence the seeing-induced wavefront phase aberrations for the directions of the two stars could be recorded simultaneously and their anisoplanatic decorrelation measured.

Contemporaneous observations were made on the night of 1998 June 11–12 of the binary stars  $\kappa$  Her (28-arcsec separation),  $\theta$  Ser (22 arcsec) and 100 Her (14 arcsec). Observations of  $\pi$  Boo (5 arcsec), 95 Her (5 arcsec) and  $\gamma$  Del (10 arcsec) were also made. These closer binaries permitted SCIDAR profiling of  $C_n^2(h)$  to higher altitudes than for the wider pairs. However, they could not be used for anisoplanatism measurements since the spot patterns were merged on the JOSE detector. For these objects, one of the pair was vignetted in the JOSE system, so that  $r_0$  could be measured from the single-star WFS data.

The observations are summarized in Table 1. Each SCIDAR run consists of 40  $C_n^2(h)$  profile measurements at intervals of 30 s. The table lists the target binary stars and their separations, the optical format (generalized or not) and the maximum sampling altitude for each SCIDAR run, and the type of contemporaneous JOSE observations made (single or binary stars).

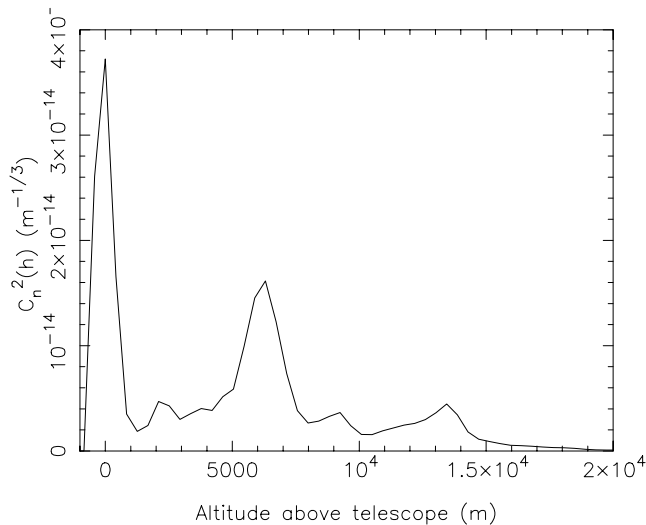
Fig. 1 shows an example of a  $C_n^2(h)$  SCIDAR profile for 1998 June 11. A strong layer is seen close to ground level, with a second strong contribution at around 6 km above the telescope, as well as significant turbulence at altitudes up to 15 km. This is typical of the general shape of the profile throughout the night, although significant variations were apparent.

SCIDAR runs 26, 28, 31 and 32 were made with SCIDAR in the conventional (non-generalized) format, so that the lowest turbulent layers were not sensed. Estimates of the unsensed layers in these profiles were made from the measured values in the adjacent generalized profiles. For example, the ground-level turbulence (below 2-km altitude) for run 26 was made equal to that for run 27.

Runs 25, 26, 27, 30 and 31 were made using binaries with relatively wide separations, yielding low maximum sensing altitudes ( $\sim 10$  km), so that very high-altitude layers were not sensed. The profile in Fig. 1, made using a narrow binary, shows significant turbulence at around 14-km altitude. This layer was present in all observations with higher maximum sensing altitudes made throughout the night. Hence corrections were also estimated for these

**Table 1.** SCIDAR and JOSE observations at the WHT, 1998 June 11–12.

Time (hours after 0 h UT 1998 June 11)	Target	Binary sep. (arcsec)	SCIDAR run number	Generalized	SCIDAR max. alt.	JOSE obs.
21.4–21.7	$\pi$ Boo	5	22	Yes	19.2	n/a
21.9–22.2	$\pi$ Boo	5	23	Yes	19.2	n/a
22.4–22.7	$\pi$ Boo	5	24	Yes	19.2	n/a
22.9–23.2	$\kappa$ Her	28	25	Yes	8.3	Binary
23.4–23.8	$\kappa$ Her	28	26	No	10.7	Binary
23.9–24.3	$\kappa$ Her	28	27	Yes	8.3	Binary
24.5–24.9	95 Her	5	28	No	21.0	Single
25.0–25.3	95 Her	5	29	Yes	17.7	Single
25.5–25.9	$\theta$ Ser	22	30	Yes	10.4	Binary
25.9–26.2	$\theta$ Ser	22	31	No	13.0	Binary
26.7–27.1	100 Her	14	32	No	18.1	Binary
27.1–27.5	100 Her	14	33	Yes	20.3	Binary
27.7–28.1	100 Her	14	34	Yes	20.3	Binary
28.5–28.8	$\gamma$ Del	10	35	Yes	18.5	Single
28.9–29.2	$\gamma$ Del	10	36	Yes	21.0	Single



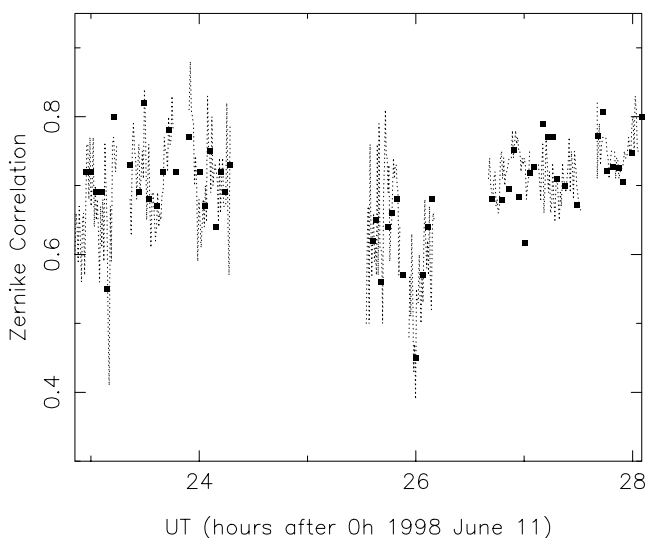
**Figure 1.** Example of SCIDAR  $C_n^2(h)$  profile for 1998 June 11–12.

unsensed altitudes. For example, the high-altitude turbulence for run 30 (above 10.4 km) was made equal to that for run 29.

### 3 ANGULAR ANISOPLANATISM

Analysis of anisoplanatism for the binary WFS data was performed via the Zernike modal decomposition of the measured phase aberrations. The correlation of the Zernike coefficients at ground level can be calculated numerically for a given  $C_n^2(h)$  profile and field separation angle using the method of Chassat (1989). The correlation is found as a weighted sum of the correlations for layers at discrete altitudes above the telescope. For each layer, the linear separation of telescope pupils projected in the direction of each star depends on the binary star separation and the zenith angle of the observation.

Fig. 2 compares the JOSE measured correlations for fifth-order Zernike coefficients with the values predicted from the contemporaneous



**Figure 2.** Angular correlation for fifth radial order Zernike coefficients, at the WHT on 1998 June 11. Solid squares are values measured with the JOSE WFS. Dotted lines show theoretical values calculated from the SCIDAR  $C_n^2(h)$  profiles.

poraneous SCIDAR profiles. This radial order roughly matches the spatial order of correction of the NAOMI AO system at the WHT.

The rms fractional error of the SCIDAR correlation predictions for these data is 7 per cent. Here we used SCIDAR values that were the mean of all SCIDAR data samples that overlapped each JOSE measurement of duration approximately 1 min. Since there is a contribution from errors in the estimation of the (time varying) strength of unsensed layers for some profiles, this may be treated as an upper limit to the intrinsic uncertainty of the SCIDAR predictions. The rms error for the predictions from SCIDAR runs 34 and 35, which did not require any correction, is 5 per cent.

As an example of the expected accuracy of the off-axis PSF calibration by SCIDAR profiling, consider an AO corrected  $K$ -band imaging observation at the WHT. We assume that a bright natural guide star is available for wavefront sensing, so that the residual uncorrected seeing aberrations result from anisoplanatism and the finite order of correction of the AO system, rather than from photon starvation or servo-bandwidth limitations. If corrections are made up to the fifth radial order of Zernike aberrations, and  $r_0 = 15$  cm at 500 nm, then we expect to achieve an on-axis Strehl ratio (normalized central intensity of the PSF) of 0.75, and a 50 per cent encircled energy diameter  $D_{50}$  of 0.15 arcsec. For the mean  $C_n^2(h)$  profile observed at the WHT on 1998 June 11–12, the Strehl ratio at 30-arcsec field angle from the guide star would be reduced by anisoplanatism to 0.45, and  $D_{50}$  increased to 0.28 arcsec. From SCIDAR profiling the off-axis Strehl ratio could be estimated to an accuracy of  $\pm 0.035$  and  $D_{50}$  to  $\pm 0.02$  arcsec. These values represent an order of magnitude improvement in the off-axis PSF parameter estimation over the case where no  $C_n^2(h)$  estimate is available, i.e. where the on-axis PSF estimate is used across the entire field.

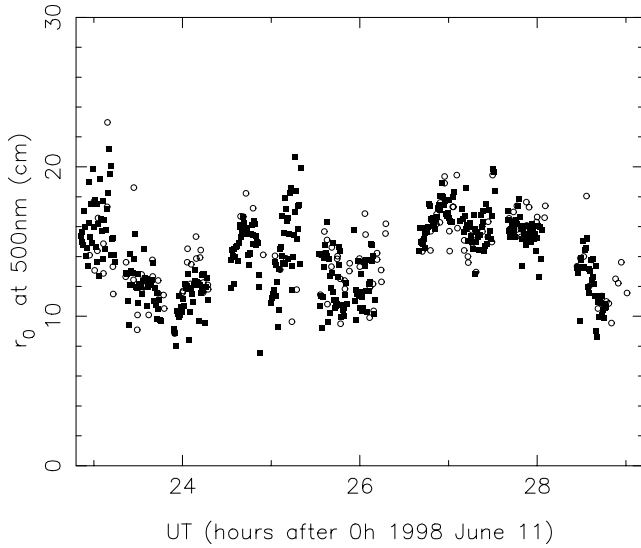
Clearly it is not possible to perform AO science exposures and SCIDAR profiling (which require the telescope to track a bright binary star) simultaneously on the same telescope. The observations must therefore be interleaved, or made on separate telescopes at the same site. The increased uncertainty in the SCIDAR anisoplanatism prediction for non-contemporaneous data can be estimated from the 1998 June 11 observations, by correlating the JOSE data and SCIDAR predictions with a fixed time delay between the data sets. For a delay of 5 min, the rms fractional error for the fifth-order Zernike correlation increases to 10 per cent. For a 10-min delay it is 15 per cent. In practice a compromise must be made between the required accuracy of the anisoplanatism calibration and the science exposure time.

If the SCIDAR system can be installed on a neighbouring telescope, the measurements can then be contemporaneous, but an uncertainty will be introduced by the spatial separation of the observations. The magnitude of this effect could usefully be the subject of future studies.

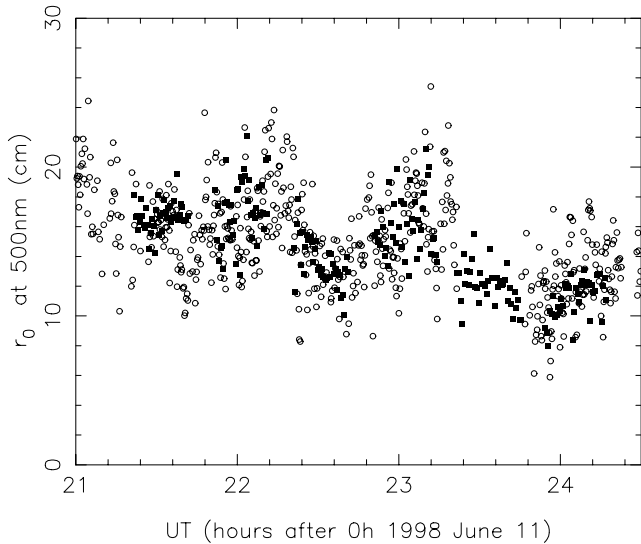
### 4 FRIED'S PARAMETER

Estimates of Fried's parameter  $r_0$  were found from the WFS data by fitting to the variances of the measured Zernike coefficients (Wilson et al. 1999). For SCIDAR, the values were obtained from the integrated  $C_n^2(h)$  profile using equation (2). Fig. 3 compares the estimates of Fried's parameter  $r_0$  for the SCIDAR and WFS data.

The rms fractional difference between contemporaneous SCIDAR and JOSE estimates is 10 per cent of the mean value ( $r_0 = 14$  cm). This is consistent with the estimated uncertainty for the JOSE and SCIDAR  $r_0$  measurements of approximately  $\pm 1$  cm in each case.



**Figure 3.** SCIDAR (filled squares) and JOSE (open circles) estimates of Fried's parameter at the WHT, 1998 June 11.



**Figure 4.** SCIDAR (filled squares) and DIMM (open circles) estimates of Fried's parameter at the WHT, 1998 June 11.

Measurements of Fried's parameter were also available from a DIMM (Sarazin & Roddier 1990; Vernin & Muñoz-Tuñón 1995). The ING DIMM, which is located approximately 100 m from the WHT dome, provided estimates of  $r_0$  at 15-s intervals for the first half of the night. Comparison of the corrected SCIDAR and DIMM  $r_0$  data is shown in Fig. 4. Here, although the general trend of the  $r_0$ -values over periods of several minutes or more is well correlated, there is increased scatter in the comparison on short

time-scales. This is as expected given the spatial separation of the WHT and DIMM locations. The rms difference between contemporaneous SCIDAR and DIMM values is 20 per cent of the mean value.

## 5 CONCLUSIONS

We have made contemporaneous observations with SCIDAR and a Shack–Hartmann WFS at the WHT. Predictions of the angular correlation of the Zernike aberration coefficients, made using the SCIDAR profiles, agree with direct measurements from the WFS to within 7 per cent rms uncertainty. Estimates of Fried's parameter agree to 10 per cent rms. The observations demonstrate that SCIDAR can be used as an effective seeing monitor for AO, to provide reliable measures of anisoplanatism and Fried's parameter. The data can be therefore be used to calibrate the spatially variable PSF for deconvolution and post-processing of AO corrected images. Care must be taken to ensure that the SCIDAR maximum sensing altitude is high enough to detect all turbulent layers.

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