Simultaneous SCIDAR and Adaptive Optics Measurements: Results and Applications

A.R. Weiß, S. Hippler, M.E. Kasper, M. Feldt

Max-Planck-Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany
European Southern Observatory, Karl-Schwarzschild-Str. 2, D-85748 Garching, Germany

ABSTRACT

We present results of simultaneous measurements of atmospheric parameters using a SCIDAR instrument and the Calar Alto ALFA adaptive optics (AO) system. First results indicated that SCIDAR measurements can indeed be useful for selecting appropriate closed-loop settings of an AO system. We will further establish this assumption by presenting the fully reduced data sets showing the time series of the Fried parameter and the isoplanatic angle as obtained from the two instruments. The data was recorded under varying seeing conditions on a binary star and an open cluster. Additionally, we point out possible applications of simultaneous SCIDAR measurements in AO observations and systems.

Keywords: adaptive optics – SCIDAR – turbulence profiles – Fried parameter - anisoplanacity

1. INTRODUCTION

Adaptive Optics (AO) has become a standard technique in recent years and is used on a number of telescopes as well as being a planned component of most observatories under construction. Although AO systems are generally operating quite successfully, the interpretation of images poses problems different from those encountered in seeing-limited imaging. High accuracy photometry and astrometry require an at least fair knowledge of the system’s point spread function (PSF) over the whole field of view (FOV), as do most deconvolution techniques. Unfortunately the PSF of a typical AO system is neither space- nor time-invariant.

Various methods have been proposed to overcome this problem; for pupil-conjugated AO they mostly amount to intermittent observations of crowded fields, potentially misleading as the relevant parameters vary quite rapidly (see section 3), or blind and myopic deconvolution techniques that synchronously try to optimize estimates for object and PSF, thus being very sensitive to noise.

However, Veran et al. (1997) showed that an estimate of the on-axis (i.e. the guide star’s) PSF can be calculated from AO-loop mirror signals. This result was extended to off-axis PSFs by Fusco et al. (2000), given the vertical structure of turbulence, which can be obtained from balloon or sounding experiments as well as SCIDAR (Scintillation Detection and Ranging).

Our main goal was to validate that parameters of atmospheric turbulence as derived from simultaneous measurements by an AO and a SCIDAR system are consistent, thus establishing SCIDAR as a useful tool for advanced AO applications. Another question was the rate of change of relevant atmospheric parameters.

The following subsections will give short overviews of the systems and principles used in our observations.

THE ALFA AO SYSTEM AND OMEGA CASS NIR CAMERA

The ALFA AO system is based on a Shack-Hartmann sensor with several interchangeable lenslet arrays, and is described in detail in Hippler et al. (1998), Wirth et al. (1998) and Kasper et al. (2000). The typical spatial sampling with a keystone design lenslet array (Kasper et al. 2001) with 28 subapertures allows to determine the coefficients for typically 18-32 Karhunen-Loève modes. These modes are applied to a 97-actuator deformable mirror at frame rates between 25 and 1200 Hz.
The near-infrared science camera OMEGA-Cass (Lenzen et al. 1998) used with ALFA is a multi-mode camera for imaging and spectroscopy. The camera is equipped with a 1024x1024 pixel HAWAII HgCdTe focal plane array from Rockwell. A cryogenic re-imaging optics allow to change the imaging scales between 0.04" (very high resolution), 0.08" (high resolution), and 0.12" (wide field). Unfortunately during the time of observation described in this paper, only the high resolution mode was available.

**SCIDAR**

The principle of SCIDAR builds on the fact that plane waves incident on the atmosphere are altered both in amplitude and phase until they reach the primary mirror of an telescope. Usually and especially at astronomical sites, the modifications in amplitude can be neglected in comparison to those imposed on the phase. Therefore, astronomical AO systems correct phase aberrations only. However, the variations of amplitude that are basically an effect of Fresnel scattering at turbulent layers are strong enough to be detected. Observing binary stars with a separation of some tens of arcseconds then allows the observer to “triangulate” the distance and strength of the turbulent layer that causes the disturbance. Fig. 1 shows a schematic view of a SCIDAR system. A propagation distance of about 2 km is necessary for the amplitude variations or scintillations to become detectable. In order to be able to measure ground layer
turbulence, an different lens (of shorter focal length) has to be introduced into the system to image the pupil plane of the telescope at a point virtually below ground. This generalized SCIDAR setup is also shown in Fig. 1.

The SCIDAR system we used for our measurements was designed and built at Blackett Lab, Imperial College, London. All results shown here were derived using the generalized SCIDAR mode with image depths of either 2.89 km or 1.93 km, and a sampling frequency of 383 Hz.

2. DATA REDUCTION

All measurements were done at an altitude of 60°-70°. To make them comparable, values were scaled by their respective airmass after data reduction.

K-BAND IMAGES

K-Band images of the observed objects were recorded during open- and closed-loop operation (Fig. 2). From these images we obtained independent estimates of the Fried parameter \( r_0 \) (open loop) and the isoplanatic angle \( \theta_0 \) (closed loop). The Fried parameter was calculated by measuring the FWHM of all seeing discs in the field and taking the average of

\[
r_0 = \frac{\lambda}{FWHM},
\]

the isoplanatic angle by fitting the measurements of all Strehl ratios \( S_i \) at angular distance \( \theta_i \) from the guide star to

\[
\theta_0 = \theta \left( \ln \frac{S_i}{S_0} \right)^{-\alpha},
\]

with \( S_0 \) being the on-axis (guide star) Strehl ratio (SR). The parameter \( \alpha \) was selected as \( \frac{1}{2} \), rather than the theoretical value of \( \frac{3}{5} \), which only holds in case of perfect correction.

![Figure 2: Open (left) and closed (right) loop images of the binary \( \gamma \) Del that was used for SCIDAR and part of the Omega Cass measurements. Sampling on both images is 0.08"/pixel.](image)

SHACK-HARTMANN-SENSOR (SHS) AND CONTROL SYSTEM DATA

SHS gradients \( g \) were recorded both in open- and in closed-loop operation of the AO system. With a suitable estimator (in our case a least squares estimator obtained by singular value decomposition from a previous calibration), the decomposition of the pupil plane phase in Karhunen-Loève modes can be calculated via \( \hat{a} = D^*g \) (with the modal coefficients \( \hat{a} \) and the estimator \( D^* \)) in the case of open-loop measurements. An estimate of the noise \( n \) in the gradient measurements is obtained from the autocorrelation of the time series. Finally, the estimate of \( r_0 \) is calculated by an iterative process over the seeing-dependent terms in the following equation

\[
\left\langle aa^t \right\rangle_{op} = \left\langle \hat{a} \hat{a}^t \right\rangle - D^* \left\langle nn^t \right\rangle D - C \left\langle a^t a^t \right\rangle C^t.
\]
where \( \langle \mathbf{a} \mathbf{a}^\dagger \rangle \) are the modal variances as obtained from the measurements, \( \langle \mathbf{a} \mathbf{a}^\dagger \rangle_{\text{th}} \) are the theoretical variances of Karhunen-Loève modes under Kolmogorov turbulence conditions (dependent on \( r_0 \)), \( \mathbf{D}' \langle \mathbf{n} \mathbf{n}^\dagger \rangle \mathbf{D}^\dagger \) describes the propagation of measurement noise on the modal estimates, and \( \mathbf{C} \langle \mathbf{a} \mathbf{a} \mathbf{a} \rangle \mathbf{C}^\dagger \) is the cross-talk term that considers the impact of non-controlled modes on the controlled ones by misinterpretations of the SHS measurements; this term is obtained from simulations of the SHS and is heavily dependent on \( r_0 \).

For closed-loop measurements, things are more complicated. Veran et al. (1997) showed that the shape of the deformable mirror approximately follows the motion of the low order atmospheric modes. As we did not record the mirror commands but the gradients, the momentary mirror shape in terms of modes is derived from a simulation of the ALFA control system using the closed-loop gradients as input; from these the modal covariances can then be calculated. Finally, a similar iterative process as above using

\[
\langle \mathbf{a} \mathbf{a}^\dagger \rangle_t = \langle \hat{\mathbf{a}} \hat{\mathbf{a}}^\dagger \rangle - \mathbf{D}' \langle \mathbf{n} \mathbf{n}^\dagger \rangle \mathbf{D}^\dagger + \mathbf{C} \langle \mathbf{a} \mathbf{a}_\perp \mathbf{a} \mathbf{a}_\perp \rangle \mathbf{C}^\dagger
\]

yields the desired estimate of \( r_0 \). As should be noted, the only difference between equations (3) and (4) is the sign of the cross-talk term, due to the fact that closed-loop operation generally underestimates energy in the low-order terms of atmospheric turbulence.

All of our gradient measurements were done using a keystone design lenslet array with 28 subapertures. Loop frequency was 300 Hz and 24000 gradients, corresponding to about 80 seconds of data, were recorded for each observation.

**SCIDAR MEASUREMENTS**

For each individual SCIDAR measurement, consisting of 2048 frames, the mean-normalized autocovariance function was calculated. Then, a section parallel and an averaged section of directions not contributing to the line of separation of the binary’s components were extracted and subsequently subtracted to obtain a profile \( A(r) \) that is both background noise reduced and has its central peak eliminated. From this profile, the vertical structure of turbulence \( C_n^2(h) \) was obtained by inverting the equation

\[
A(r) = \int_{-h_{\text{max}}}^h C_n^2(h) K(r,h)dh,
\]

where \( K(r,h) \) describes the (analytical) profile produced by a layer with a \( C_n^2 \) of unity at an altitude of \( h \). We used a conjugate gradients algorithm for this purpose, but it can also be done using Maximum Entropy methods or a CLEAN algorithm.

With the turbulence profile known, estimates of the Fried parameter \( r_0 \) and the isoplanatic angle \( \theta_0 \) were calculated using the relations:

\[
r_0 = \left[ 0.423k^2 \int_0^\infty dh C_n^2(h) h^{-3/5} \right]^{-3/5},
\]

and

\[
\theta_0 = \left[ 2.914k^2 \int_0^\infty dh C_n^2(h) h^{-1/3} \right]^{-3/5}.
\]

It is important to note that while the Fried parameter is only dependent on the integrated strength of the turbulence, the isoplanatic angle shows a strong dependence on its vertical distribution.
3. RESULTS

SCIDAR RESULTS OVERVIEW

We picked two consecutive days out of four with a seeing of around 0.5” on the first day and 0.9” in K-Band on the second.

An overview of both days is shown in Fig. 3. The general structure of turbulence on both days is quite similar, with the region of highest activity extending from ground level to a height (above ground) of 12 km. Weak and intermittent turbulence can also be seen at greater altitude.

The most prominent layer on both days is the ground layer, with a notable difference between the first and the second day, changing from a maximum value of $2 \times 10^{-16} \text{ m}^{-2/3}$ to $6 \times 10^{-16} \text{ m}^{-2/3}$. This also shows in the big difference of the Fried parameter measurements on both days with a mean of 17.6 cm on August 31st and 10.2 cm on September 1st; a total rms variation of around 15% and a mean sample to sample difference of 10% in $r_0$ is seen on both days.

With a detailed look, the two days show some differences in the turbulence above 1 km. On the first day, there seem to exist three upper layers at around 3, 6, and 9 km with the first one building up during the course of the observation and the last one decaying. The second day, however, seems to be dominated by one upper layer only, that varies in altitude between 7 and 10 km; additionally, the ground layer extends to a 2 km on the second day, while it is limited to the ground (within the instrument’s resolution limit) on the first. As can be seen comparing the values of the isoplanatic angle of both days, this leads to the situation that the anisoplanatic angle with an average of 13.5” on the second day is...
around the same size as that on the first, which averages around 12.3". Again the mean sample to sample difference in \( \theta_0 \) is around 10% on both days.

**FRIED PARAMETER MEASUREMENTS**

Fig. 4 shows the results of all Fried parameter measurements from the different instruments for the two selected days. As can immediately be seen, the \( r_0 \) estimates from the Omega Cass images agree very well with the SCIDAR measurements on both days. Even when SCIDAR data is missing the values seem to fill the gaps sensibly and nicely, which gives us confidence in the reliability of parallel SCIDAR measurements for assisting AO.

![Figure 4: Fried parameter measurements overview on August 31, 2000 (top) and September 1, 2000 (bottom). SCIDAR values (diamonds, error bars not plotted for better visibility), open- (empty squares) and closed-loop (filled squares) estimates and open-loop NIR image measurements (empty triangles).](image)

More important and very interesting are the estimates obtained from the ALFA control systems. Even on the first day, with very good seeing conditions of around 0.5" in K-Band, there seems to be a slight overestimation of \( r_0 \) from open-loop data; this overestimation is much more pronounced on the second day, were K-Band seeing was around 0.9". This fact is even more surprising taking into account the excellent agreement of Fried parameter estimates from closed-loop gradients on both days, with only a hint of underestimation. However, the unsuspected mismatch of open-loop estimates and actual \( r_0 \) might be due to limitations of the centroiding algorithm used in ALFA: on the SHS’s CCD, a subarray of 3" by 3" around the calibration PSF peak position of each lenslet is used to search for the brightest pixel during operation. Even under very good seeing conditions the peak of the momentary PSF could sometimes lie outside this area, especially if static telescope aberrations already cause an offset, thus leading to a wrong and less displaced pixel identified for the centroiding operation which subsequently causes a systematic underestimation of the wavefront’s gradients. With this explanation, overestimation should become worse with decreasing \( r_0 \), as is the case with our
measurements. Closed-loop estimates are not affected by this problem, because the very goal of AO is to keep the sublenslet’s PSFs close to their calibrated positions.

In our earlier publication on these results\textsuperscript{18}, we concluded that SCIDAR underestimates $r_0$ since we were using SCIDAR and open-loop data only. Our explanation was that the dome seeing was worse on the 1.23m as compared to the 3.5m telescope. However, it seems that seeing conditions are more or less the same on both telescopes. At the time of writing, a new dome ventilation system is being installed at the Calar Alto 3.5m telescope. It would be very interesting to run another simultaneous SCIDAR/AO campaign to check if seeing conditions on the 3.5m improved considerably.

As a sidenote, observations on August 31, 2000 were carried out on the same object with both telescopes while those on September 1, 2000 were done on different objects with an angular separation of around 10°. Nevertheless, the agreement between $r_0$ estimations from Omega images and closed-loop gradients do not show any greater discrepancy on September 1\textsuperscript{st} as compared to August 31\textsuperscript{st}, hinting on only a week dependence of the turbulence profile from the viewing direction as long as observations are done close to zenith (both objects were around an altitude of 65° during the measurements).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{image.png}
\caption{Isoplanatic Angle measurements for August 31, 2000 (top) and September 1, 2000 (bottom). SCIDAR values (diamonds, error bars not plotted for better visibility) and closed-loop NIR image estimates (triangles).}
\end{figure}

ISOPLANATIC ANGLE MEASUREMENTS

The results of the isoplanatic angle measurements from SCIDAR and closed-loop NIR images are plotted in Fig. 5. Obviously the values for $\theta_0$ as obtained from SCIDAR and closed-loop NIR images do not agree as well as was the case for $r_0$. There is a clear tendency for overestimation of $\theta_0$ (if we regard the SCIDAR measurements as “correct”) by the image data on the order of 10%. However, the changes in $\theta_0$ seem to be going in parallel on both instruments.
As we already mentioned in section 2, measuring isoplanatic angles from image data can be problematic. One potential problem is that the theoretical 5/3 decay of SR with increasing distance from the guide star is only valid for perfect correction. We already accounted for that fact by assuming a squared decay as proposed by Roddier (1999). Another difficulty is our method of SR estimation, that is usually quite reliable on an image with 0.04" of pixel sampling, but which is error-prone with 0.08" sampling; this is also illustrated in the large error bars associated with the NIR image data.

Considering these problems, the isoplanatic angles as measured by SCIDAR and the AO system seem to be consistent. This is one of the most important results of our work, since it shows that simultaneous SCIDAR measurements will assist greatly in the understanding of off-axis PSFs in AO systems and the interpretation of scientific images.

However, there remains some work to do. Reliable off-axis PSF estimates can only be found if the angular correlations of the involved Karhunen-Loève modes are known; this would also help in finding the correct decay exponent for the SR in equation (2). Work is currently under way to derive off-axis PSF shapes from the obtained turbulence profiles and compare them to those on the closed-loop images.

4. CONCLUSIONS AND FUTURE WORK

We showed that atmospheric parameters derived from AO and SCIDAR measurements are generally consistent:

- The Fried parameter obtained from IR and images and the $C_n^2$-profile do highly agree.
- The Fried parameter obtained from gradients agrees well with both the IR images and $C_n^2$-profiles, with the closed loop estimates being better than the open loop ones due to the measurement technique.
- Isoplanatic angles derived from closed-loop images are generally a bit higher than those derived from the $C_n^2$-profiles, even if a quadratic decay rather than a 5/3 one is considered; this might be due to bad Strehl ratio estimates and is indicated by the large variation within a given series of images.

Furthermore we noted that the turbulence profiles do vary considerably on a timescale of some tens of minutes, thus making SCIDAR a valuable if not necessary tool for future multi-conjugate AO systems.

We are currently working on the off-axis PSF reconstruction as proposed by Fusco et al. (2000). The results from this research could than be used to apply a CLEAN algorithm to scientific images recorded with the ALFA/Omega combination.

The good agreement of closed-loop Fried parameter estimates with SCIDAR measurements gives us confidence that an improved estimator, the maximum a posteriori estimator, which was proposed by Kasper (2000) for ALFA can be successfully implemented and will further improve the performance of the system.

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