Anisoplanatism across wide fields at high frame rates

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ABSTRACT

In this paper we present a preliminary analysis of variation in the isoplanatic patch size over short timescales and wide angular separations. We tested a visible band photon counting camera running with four $1K^2$ detectors to provide a contiguous field of view of $1000 \times 4000$ pixels. Resolution was 35–100 mas per pixel at frame rates from 20–111 hz, providing data on atmospheric turbulence at angular separations of up to 400 arcseconds. We discuss the potential of such cameras to perform high resolution optical surveys using developments of standard lucky imaging techniques, and the implications of our results for adaptive optics systems design.

Keywords: instrumentation: high angular resolution —methods: data analysis — techniques: high angular resolution — techniques: image processing

1. INTRODUCTION

Anisoplanatism is a familiar effect in the field of ground based high resolution astronomical imaging. Differing light propagation paths for stars of angular separation larger than a few arcseconds result in different turbulent wavefront perturbations. As a result correcting for these turbulent perturbations, or selecting moments when they are of lesser severity, with regard to a reference star will produce a point spread function (PSF) that varies over the field of view.

Considerable effort has been made to characterise the variation of the PSF in adaptive optics (AO) images with the aim of improving data analysis techniques, and progress is also being made in wide field AO designs such as multi-conjugate AO.\textsuperscript{1–3} However, only relatively recently has there been some investigation into the variation of AO performance at short (i.e. shorter than a second) timescales.\textsuperscript{4–7} Similarly, work exploring the properties of anisoplanatism at high temporal resolution is rare.\textsuperscript{8}

Lucky imaging data is potentially an excellent source of information for furthering such investigations, since it relies on short exposure times and good sensitivity to faint sources, which results in a greater number of stars with useful signal to noise levels in each short exposure. The Cambridge lucky imaging camera tested in summer 2009 has the added advantage of covering a relatively large field of view with good resolution, thanks to the use of 4 CCDs running in parallel. Also, since the technique has application to a range of science applications it is possible to collect data useful to probing the atmospheric turbulence as a by-product, without dedicating telescope time solely to this purpose.

Such data is useful at two levels. First, it provides a direct probe of tip-tilt anisoplanatism. Characterising this aspect of atmospheric turbulence is important for determining the potential for lucky imaging across wide fields, but also for use of laser guide stars (NGS) in adaptive optics. The propagation of the LGS light from ground to the sodium (or scattering) layer height and back again makes it insensitive to tip-tilt, and so a natural guide star is required to supplement the higher-order wavefront information with an estimation of the tip-tilt. Although the NGS may be much fainter than required for full AO correction, it still creates a a limiting factor with regards to sky coverage. Reference 8 gives this limit for a tip-tilt NGS as V$\sim$17 mag within about 1 arcminute of the target for the VLT, while ref. 9 cite an R-band magnitude of 17.5 within 25 arcseconds for the Altair AO system at the Gemini North. However, to our knowledge with the exception of reference 10 the tip-tilt...
anisoplanatism remains uncharacterised at large separation angles, and there has been no investigation into its variability.

Second, the datasets also provide an indirect probe of the atmospheric turbulence profile, and how it varies over short timescales, since the level of tip-tilt anisoplanatism provides an estimate of the second moment of the $C_N^2$ profile.\cite{11} We can also examine the isoplanatic patch size by measuring the Strehl ratio across the field in reduced lucky imaging data. In both cases, the frame selection techniques developed for lucky imaging mean we can attempt to determine how these measures vary in relation to the Strehl ratio of the guide star estimated in each short exposure.

## 2. OBSERVATIONS AND INSTRUMENTATION

In July 2009 we temporarily installed a wide field lucky imaging camera at the Nordic Optical Telescope, situated at the Observatorio del Roque de los Muchachos, La Palma. The camera contained reimaging optics allowing use of different focal lengths and filters. Four e2v CCD201 electron multiplying CCDs were run in parallel at pixel rates allowing full frame imaging of 1072x1040 pixels at 20.8 frames per second, or reduced frame sizes at higher frame rates. CCD cycles were synchronised, and gain voltages were independently variable. This enables lucky imaging across CCDs, so that for example a bright guide star can be imaged on one CCD without saturation while a faint object is imaging on an adjacent CCD at high gain to improve signal to noise. A variety of targets were observed in seeing ranging from $\sim 1.8$ arcseconds FWHM right down to $\sim 0.4$ arcseconds FWHM. Figure 1 gives an illustration of one dataset, a field of view centred on M15. The data were reduced using a custom pipeline.\cite{12}

## 3. VARIATION OF THE ISOPLANATIC PATCH SIZE

### 3.1 Choice of dataset

To infer the isoplanatic patch size from an image, we must first determine the Strehl ratio of the stars in the field. This requires accurate measurements of both the flux and peak intensity of the stars. Ideally, we would perform such measurements on crowded fields such as figure 1, since this gives a high density of Strehl ratio estimates. However, the standard PSF fitting packages used to perform photometry on such crowded fields assume a constant PSF over the field of view,\cite{13, 14} and so are not suited to estimating the variation in the Strehl. Accordingly, for this preliminary work we have used simpler techniques to analyse a relatively uncrowded field about the radio active galaxy 3c405. This dataset was obtained over 1 hour, longer than most of the lucky imaging datasets obtained with the camera, resulting in good signal to noise even when data reduction is performed on a selection of 10% of the total number of short exposures. The seeing FWHM for the dataset was estimated at 0.4 arcseconds, giving a ratio between the telescope diameter and the Fried coherence length of $D/r_0 = 6.7$ at the observation wavelength of 770nm.

### 3.2 Method of analysis

The dataset for 3c405 was reduced using standard lucky imaging procedures.\cite{12} A reduced image was created using a 10% selection of the images with the highest estimated guide star Strehl ratio (i.e. all images lying on the 90th to 100th percentiles as ranked by estimated Strehl). This reduced image was then used to select the stars in field for Strehl ratio estimation, and a region containing only sky flux for background estimation on each CCD. The stars were chosen to have a good signal to noise ratio, and no close companion stars so that simple aperture photometry could be applied. A photometry aperture of diameter 3 times the seeing FWHM was used. The guide star is both bright and well isolated, and the photometry aperture correction factor was estimated by comparing the flux with apertures centred on the guide star of diameter 3 and 9 times the seeing FWHM.

For each star selected, the region of interest was resampled to 4 times the original resolution using a cubic smoothing kernel.\cite{15} The location of the resampled pixel of greatest value was then chosen as the nominal position of the star in the field, with the greatest value used as an estimate of the peak intensity. Since the original dataset is well sampled and has a good signal to noise ratio this should provide a reasonable estimate of the peak value. Aperture photometry was then performed on the original image using an aperture centred about the nominal
Figure 1. A mosaic image created from a single dataset. The field of view is the centre of the globular cluster M15. The dataset was created using 4 CCDs running in parallel to provide 32.5 mas pixel spacing across a field of 120 by 30 arcseconds (the resulting images from only 3 of the 4 CCDs are shown here). A single guide star (marked with an X in the image) was used to estimate tip-tilt across all 4 CCDs. Crowded fields such as this are potentially an excellent source of information on the effects of anisoplanatism, but the crowding makes photometry and PSF characterisation difficult.
Figure 2. A mosaic image created from a single dataset. The field of view is centered on the radioactive galaxy 3C405, with North up and East left. The dataset was created with the same camera setup as Figure 1. The stars selected as suitable for Strehl ratio estimation are encircled at the diameter of the photometry aperture (3 times the seeing FWHM). The guide star is also marked with an X.
star position. The aperture correction factor determined from the guide star as described above was applied to estimate the total star flux.

The ratio of the peak intensity to the total flux was then divided by the corresponding ratio of a model Airy PSF (generated accounting for the central obscuration of the telescope, but neglecting secondary effects due to mirror supports, etc.) to estimate the Strehl ratio of the star. Finally, the values of the pixels in the star aperture were binned by radius from the nominal centre to create an average radial profile of the star. Linear interpolation was then applied to this profile to estimate the FWHM of the star.

This process was then repeated, using the same chosen stars, on images created using a 10% selection of the images with the lowest estimated guide star Strehl ratio (0th to 10th percentile), and a 10% selection about the median Strehl (i.e. lying between the 45th and 55th percentiles).

For reference, we also analysed the long exposure image. A simple average image of the full dataset revealed some shifting of the field of view during the hour of data collection, possibly due to autoguider error. To circumvent this issue we created an “idealised autoguider” image using standard lucky imaging reduction techniques, except with the applied shifts determined by taking a 2 second running average of the guide star positions. This resulted in an image with FWHM very similar to taking a simple average over the first 4 minutes of exposures (but with better signal to noise).

### 3.3 Results

![Figure 3. A plot of estimated Strehl ratio against angular separation from the guide star. Dashed lines are curves fitted as described in the text. HWHMs of the Moffat components are 15.3 arcseconds, 12.5 arcseconds and \( \sim 2.5 \) arcseconds for the best, median and worst data sets respectively. More details can be found in the text.](image)

The estimated Strehl ratios for the 3 different selection bands are plotted in figure 3, and the estimated FWHMs in figure 4. The Strehl ratio estimations will vary considerably in accuracy due to the different flux levels of the stars analysed — the Strehl ratio estimate of a faint star is much more sensitive to fluctuations in the level of the sky background, since this will have a larger relative effect on the flux estimation. A curve consisting of a Moffat profile, plus a constant term to represent the Strehl at very wide angles of separation from the guide star, was fit to the plotted points using a least squares routine weighted by star flux. Simple straight line fits to the FWHM estimates are also plotted in figure 4.
The usual definition of isoplanatic angle, $\theta_e$, is the angular separation at which the Strehl ratio drops by a factor of $1/e$. However, in the low Strehl regime presented here this is not a useful measure since the Strehl profile flattens off before it drops by a factor of $1/e$, and so instead we refer to the half width at half maximum (HWHM) of the Moffat component of the fit to the points (neglecting the constant “wide angle Strehl” term). In a high Strehl regime where both measures are valid this would be a factor of approximately $2/e$ times smaller than $\theta_e$ as defined above. We find this HWHM of the Moffat component to be 15.3 arcseconds for the image created from the 10 percent of short exposures ranked with highest estimated guide star Strehl, 12.5 arcseconds for the image created from the median 10 percent, and $\sim 2.5$ arcseconds for the image created from the worst 10 percent.

4. DISCUSSION

Lucky imaging relies upon the fact that the Strehl ratio of stars in an isoplanatic patch varies over time. We should like to determine whether this variation is due mainly to either random fluctuations of a stationary (i.e. fixed mean) random process, or if in fact there is a significant variation at short timescales in the underlying mean of the statistical distribution (corresponding to a variation in the coherence length $r_0$), similar to intermittency effects often observed in turbulent flows. There has been some work on this problem in the field of lucky imaging but there are no conclusive results to date, and we hope to further this work using the wide angle data collected with the current Cambridge camera.

Although the analysis presented here is a preliminary one, the results are intriguing. If $r_0$ were stationary we would expect the isoplanatic angle to remain constant regardless of the selection method, since we would then expect decorrelation in the wavefront perturbations over a uniform spatial scale.

It is already known that $r_0$ can vary significantly over timescales of several minutes. To determine whether the selection algorithm was simply selecting images from a period of better seeing over such a timescale we inspected a plot of the relative rankings of the short exposures. A short section of the plot is displayed in figure 5. Although there do appear to be underlying long term trends in this plot, there is sufficient short
timescale variation that the best 10% of short exposures were selected from moments throughout the 1 hour observation period.

This suggests that the isoplanatic angle can vary at short timescales, correlated with the estimated strehl of the guide star (at least for this $D/r_0$ regime). This could be due to turbulent intermittency in the integrated $C_n^2$ values corresponding to turbulent layers, thereby rendering $r_0$ non-stationary. Regardless of the underlying cause, it may be possible to exploit variation in the isoplanatic patch for high-strehl systems by combining adaptive optics and lucky imaging techniques. Such a system was demonstrated in reference 4, but analysis of the isoplanatic angle was restricted by a smaller CCD size — a situation remedied by the current large format camera.

We note that when the best 10–25% of short exposures are selected for the data reduction, the FWHM is greatly improved in the reduced images over a wide angle, as illustrated in figure 4. The pipeline software we have developed to reduce the lucky imaging data can now handle data across several CCDs, and so it is possible to take advantage of this improved image quality over a large field of view with good spatial sampling. This potentially makes such lucky imaging cameras an excellent tool for survey projects. One can envisage a large multi-CCD system where the data for any given CCD is reduced using reference information from the nearest bright guide star. This would rely on a good characterisation of the PSF variation across the field, but could provide improved resolution and signal to noise at relatively low cost, and with minimal target acquisition times as compared to a full AO system.

5. SUMMARY AND FUTURE WORK

We have briefly reported the capabilities of the most recent Cambridge lucky imaging camera, which is capable of capturing lucky imaging data over wide fields of view at high frame rates and low noise levels. We have presented techniques and results for a preliminary analysis of isoplanatic patch size in the data collected. The results tentatively suggest that the isoplanatic patch size does in fact vary over short timescales. The current analysis method is only suitable to uncrowded fields. We are currently developing software for PSF extraction
and fitting using a variable analytic model of the lucky imaging PSF. We hope to use this software to investigate further the variation of the PSF in reduced lucky imaging data, particularly across crowded fields.

The data is also potentially well suited to analysis of anisoplanatic effects via direct tracking of multiple stars, as in reference 10. These techniques provide a direct probe of variation in the tip-tilt anisoplanatism. However, such investigation requires careful calibration of how the “centroiding error” varies with the star flux and other factors such as crowding. This work is ongoing, and we leave such analysis to a future paper.

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REFERENCES

