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Dual-conjugate adaptive optics instrument for wide-field retinal imaging

Jörgen Thaung[1], Mette Owner-Petersen[2], Zoran Popovic[1]

[1] Department of Ophthalmology, Göteborg University, Göteborg, Sweden; [2] Telescope Group, Lund Observatory, Lund University, Lund, Sweden

Introduction

Clinical retinal imaging is limited by the wavefront aberrations of the human eye. The introduction of adaptive optics (AO) in retinal imaging has been successful in correcting for most aberrations and enabling diffraction limited imaging, albeit only over small fields of view (FOV). This is due to the fundamental limitation of conventional single-conjugate AO (SCAO) with only one retinal guide star (GS) and one deformable mirror (DM), which enables good correction close to the GS, the 'isoplanatic patch'. Full correction is not achieved as one moves away from the retinal position of the GS, thereby decreasing image quality.

Beckers[1] introduced the concept of multi-conjugate adaptive optics (MCAO) as a means of increasing the size of the isoplanatic patch. The principle of astronomical MCAO is to accomplish this by opticallly conjugating several DMs to different altitudes in the atmosphere. In ophthalmology this is equivalent to conjugating the DMs to different planes in the eye.

The technique of MCAO is just emerging. There is only one published paper on multi-conjugate AO (MCAO) for the eye[2]. The first physical implementation in a large-scale astronomical observatory was achieved on 25 March 2007 when the Multi-Conjugate Adaptive Optics Demonstrator (MAD) achieved 'First Light' at the ESO Very Large Telescope (VLT). MAD allowed the scientists to obtain corrected images over the full 2x2 arcminute FOV, substantially larger than the 15x15 arcsecond FOV of conventional AO systems - a corrected FOV increase by a factor of 8.

We present a closed-loop dual-conjugate adaptive optics (DCAO) system for wide-field high resolution imaging of the retina.

Methods

The DCAO system (Fig. 1) uses five retinal GSs and two DMs; one 15 mm 37 channel pupil conjugate mirror and one 40 mm 79 channel mirror conjugated to a plane in the vitreous body approximately 3 mm in front of the retina, both OKO MEMS mirrors (Fig. 2). Continuous relatively broadband near-infrared light (835±14 nm) from a super-luminescent diode (Superlum Ltd, St. Petersburg, Russia) is fed through five single-mode fibers to form five separate collimated rays. These are relayed over the DMs and a Badal system into the eye. The periferal GSs are symmetrically placed 0.62 mm [2.2 deg) from the central GS. Reflected light passes back through the system and into the WFS arm, where a novel spatial filter[3] filters the light from the five GSs with one adjustable aperture (Fig. 3). All five Hartmann patterns are imaged on a single wavefront sensor (WFS) camera (Fig. 4).

Optical simulations were performed with the Zemax optical design software using the Navarro 99 eye model[4].

Results

The system runs with a closed loop correction frequency of approximately 12 Hz in DCAO mode and 14 Hz in SCAO mode. Averaging 5 WFS images lowers the correction frequency to approximately 4 Hz.

Simulated estimates of DM stroke (full Badal defocus correction) was 3.75 µm PTV for the pupil conjugate mirror and 20 µm PTV for the second mirror.

Real images of a model eye with a fiber bundle as a retina are shown in Figures 5-7. The corrected FOV corresponds well to optical simulations in Zemax, which indicate an increase of the retinal isoplanatic patch from a diameter of 1 degree using SCAO to approximately 7 degrees using DCAO (Fig. 8-11).

Discussion

The main advantage of a DCAO system is a clinically useful corrected FOV, i.e. imaging area, that is approximately 50¨ times larger than in SCAO. In our system a 2x2 mm^2 (7.2x7.2 deg^2) retinal field roughly corresponds to 15.7x15.7 mm^2 on the science camera. The Airy radius at 570 nm is roughly 13 µm in the image plane, so the pixel size should be around 6.5 µm and the camera format should be 2415x2415 pixels in order to satisfy the Nyquist sampling criterion. Enlarging the pixel size to 7.5 µm will provide a slight undersampling at 570 nm and a slight oversampling at 830 nm. For a 2048x2048 camera format the field will be 15.4x15.4 mm^2, closely matching a 2x2 mm^2 retinal field which should potentially be well corrected and unvignetted using DCAO.

Actual correction is currently slightly less due to the eye's relatively large longitudinal chromatic aberration (LCA), approx. 2D over the visible spectrum. The measurement wavelength is 835 nm and an imaging wavelength would be in the visible spectrum. Simulations in Zemax show a difference of 18.6 mm between the 830 nm and 570 nm focal planes in the imaging arm. The introduction of a chromatic aberration corrector into the imaging arm slightly lowers the on axis Strehl ratio. However, the corrected FOV increases by approximately 0.5 deg (Fig. 10-11).

References

1. J. M. Beckers, "Increasing the size of the isoplanatic patch with multiconjugate adaptive optics," in ESO symposium on Large Telescopes and Their Instrumentation (European Southern Observatory, Garching, Germany, 1988), pp.693-703
2. P. A. Bedggood, R. Ashman, G. Smith, and A. B. Smith. Multiconjugate adaptive optics applied to an anatomically accurate human eye model. Opt. Exp. 14(18), (2006) pp.8019-8030
3. M. Owner-Petersen, J. Thaung, and Z. Popovic. Multi-object wavefront sensor with spatial filtering. US/PCT patents pending.
4. I. Escudero-Sanz and R. Navarro. Off-axis aberrations of a wide-angle schematic eye model. J Opt Soc Am A Opt Image Sci Vis.;16 (8). (1999) pp. 1881-1891

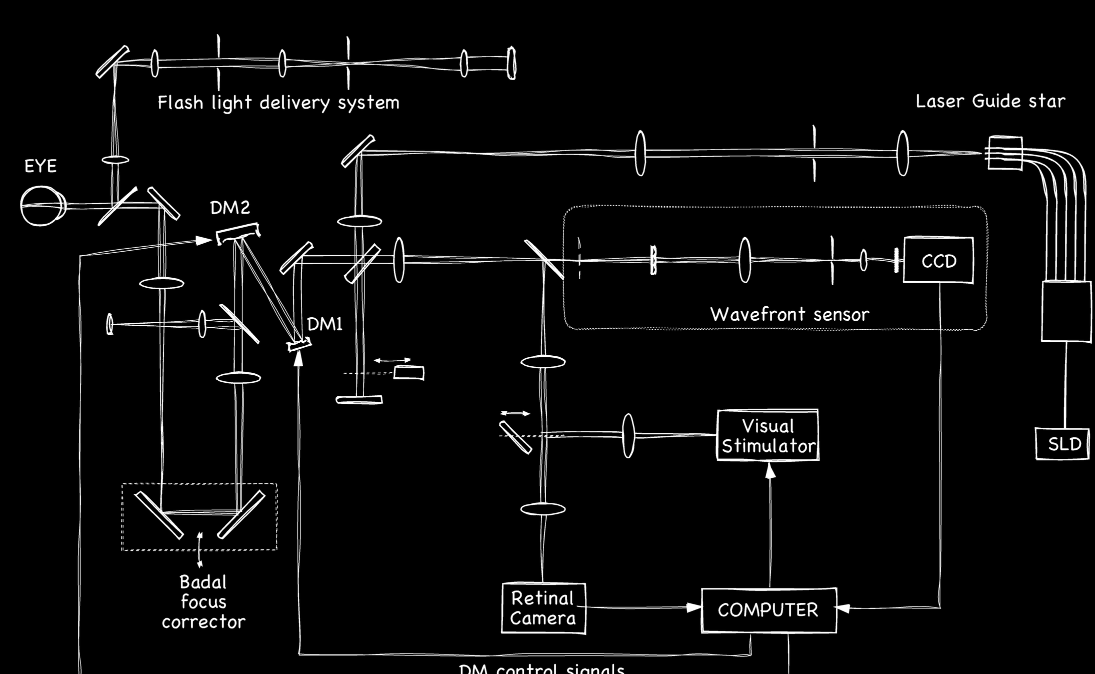

Figure 1
Schematic diagram of the DCAO setup.

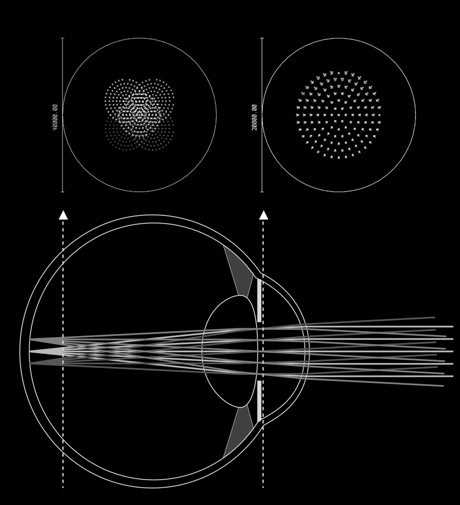

Figure 2
DM conjugate planes in the eye.

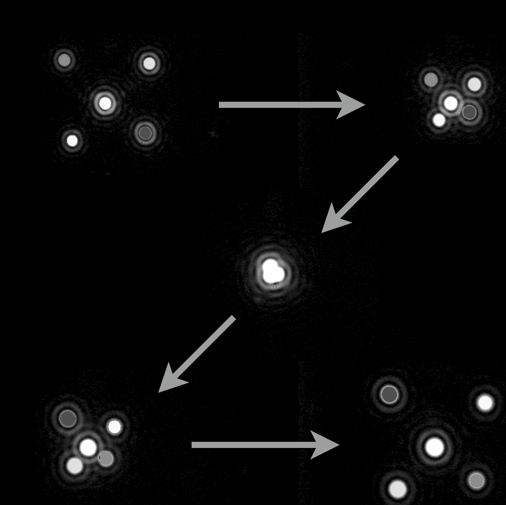

Figure 3
Through focus images at the WFS spatial filter plane.

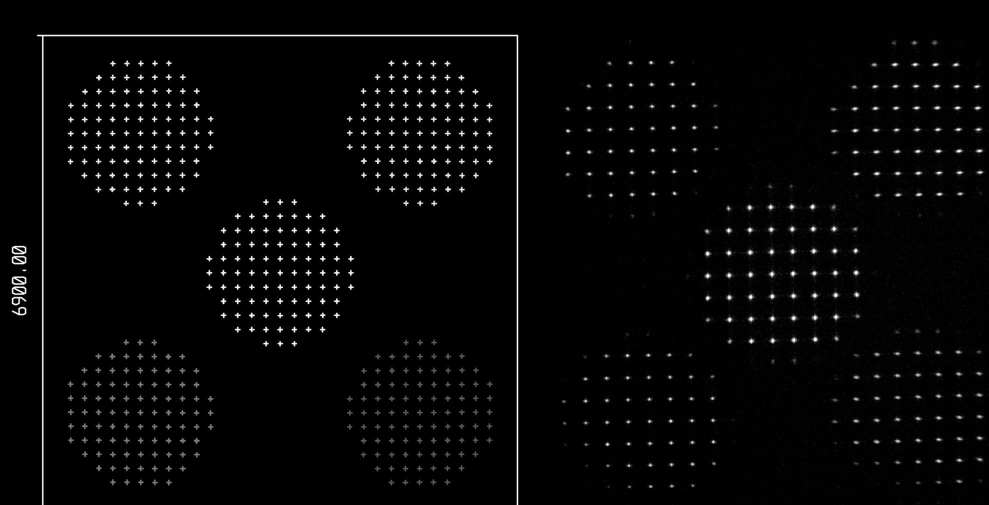

Figure 4
Zemax simulation (left) and actual image (right) of the five GS Hartmann patterns on WFS camera.

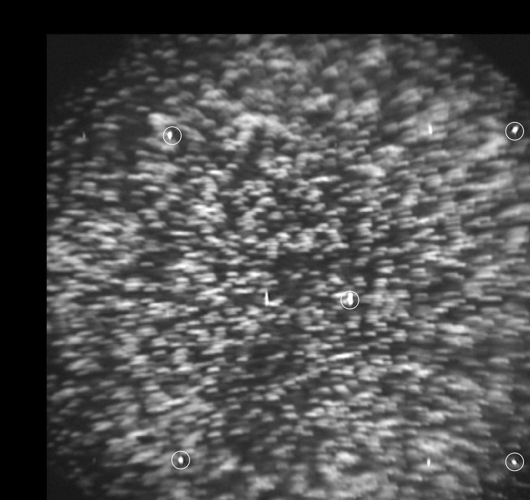

Figure 5
Uncorrected image. The five guide stars are marked with white circles.

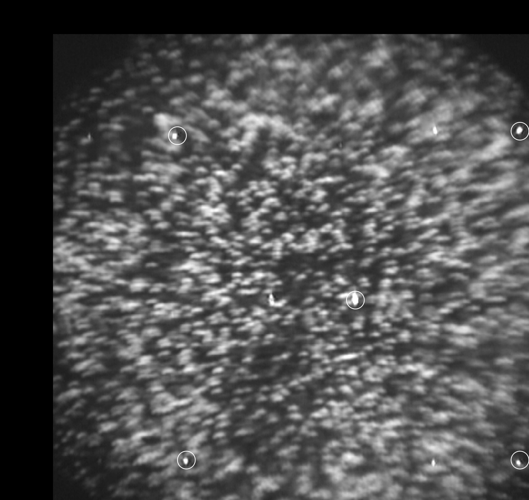

Figure 6
Single-conjugate AO corrected image. Only slight central improvement.

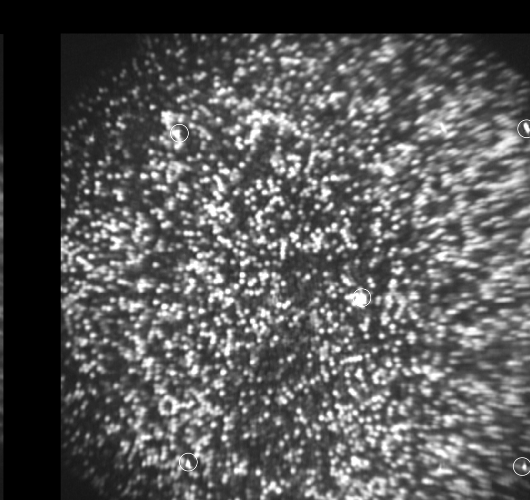

Figure 7
DCAO correction. Central and left field improvent. The two rightmost guide stars were not active.

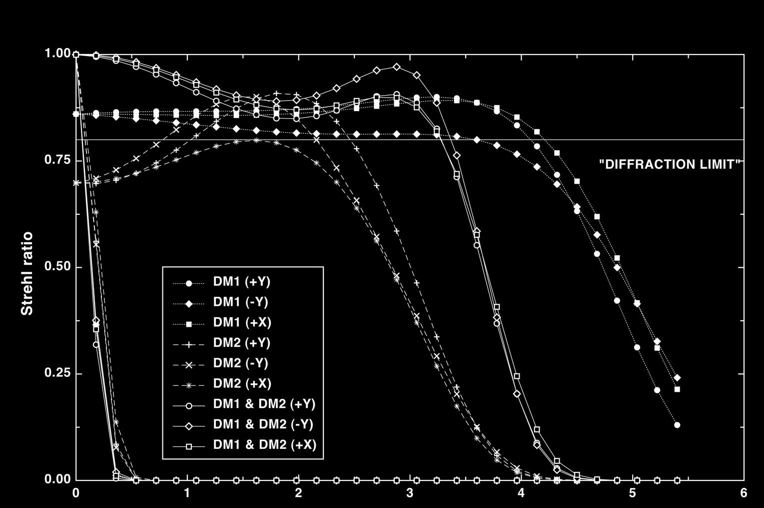

Figure 8
Plot of Strehl ratio vs. field angle at 830 nm in the upper vertical, lower vertical, and horizontal hemimeridians, using single DM and DCAO correction with five active GSs.

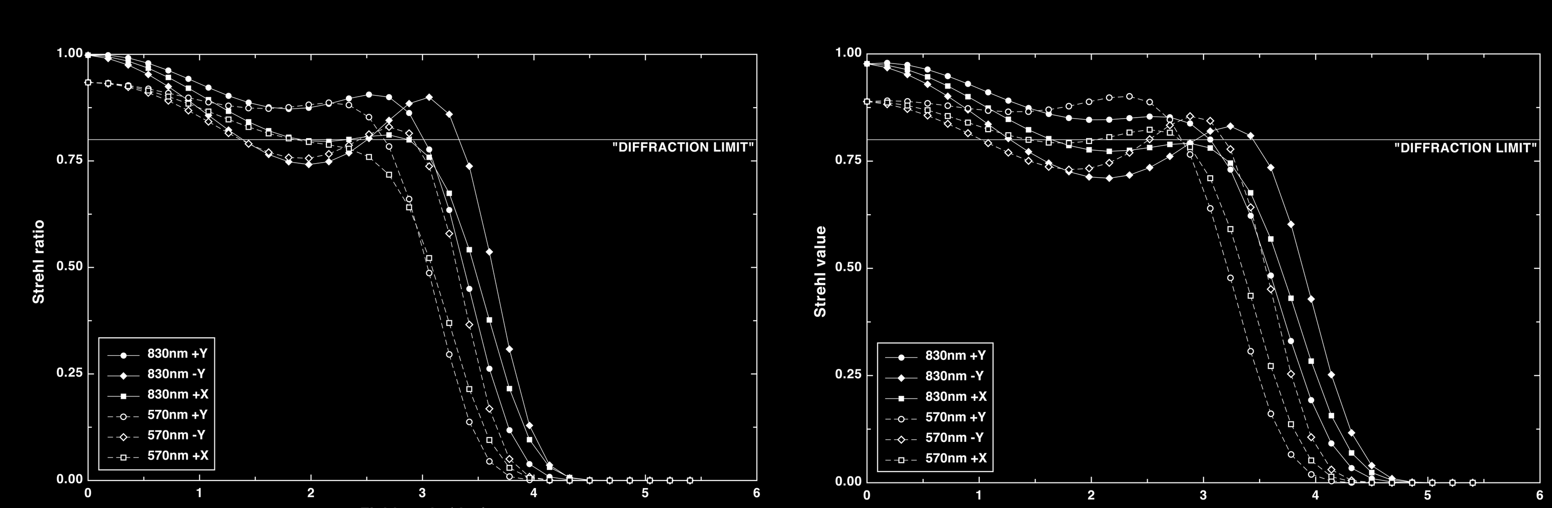

Figure 9
Plot of image plane Strehl ratio vs. field angle in the upper vertical, lower vertical, and horizontal hemimeridians at 830 nm (closed loop measurement wavelength) and 570 nm (imaging wavelength without (left) and with (right) a chromatic aberration corrector.

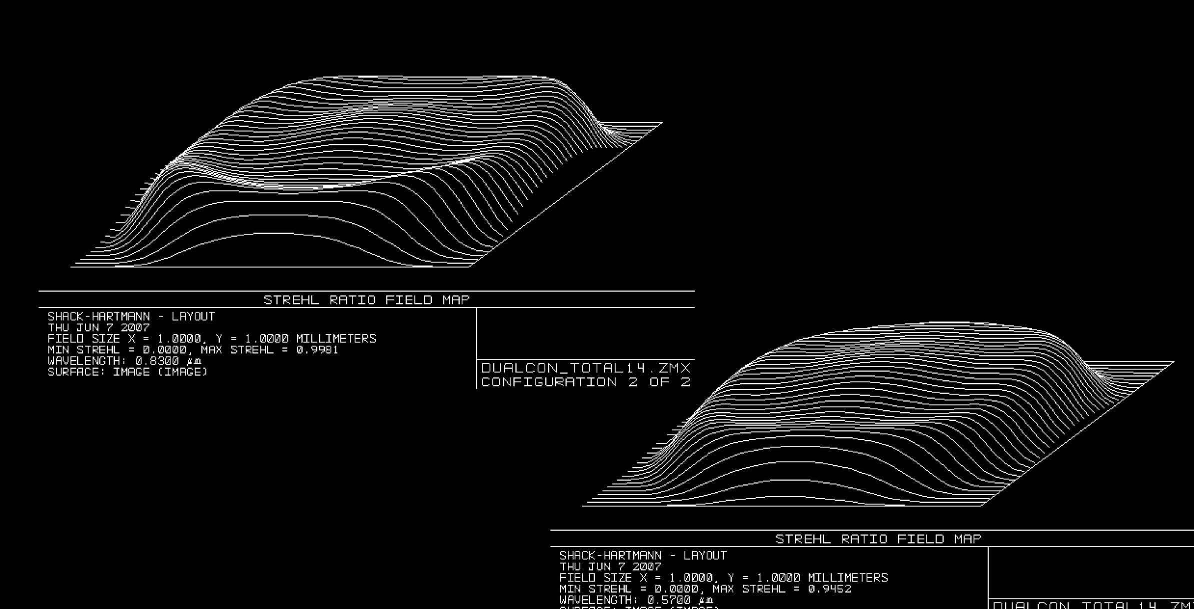

Figure 10
3D-plot of Strehl ratio field map in the image plane at 830 (top) and 570 (bottom) nm with DCAO correction.

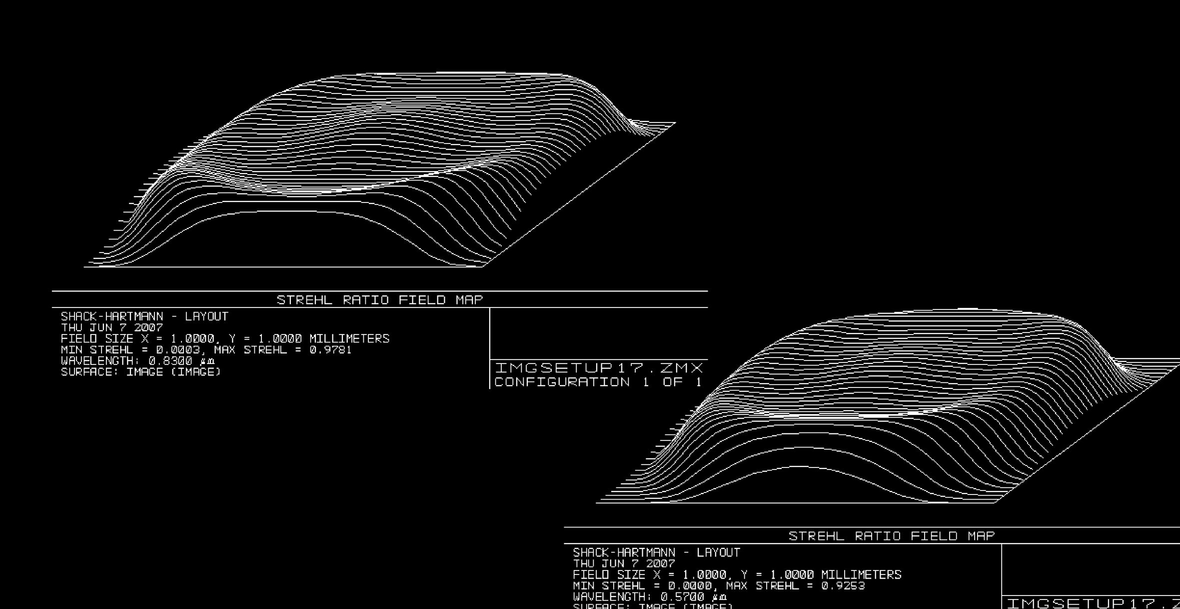

Figure 11
3D-plot of Strehl ratio field map in the image plane at 830 (top) and 570 (bottom) nm with DCAO correction and chromatic aberration corrector.