Towards a Network of Small Aperture Telescopes with Adaptive Optics Correction Capability

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ABSTRACT

A low cost and compact Adaptive Optics (AO) system for a small aperture telescope (Meade LX200ACF 16") has been developed at UNSW Canberra, where its performance is currently being evaluated. It is based on COTS components, with the exception of a real time control loop implemented in a Field Programmable Gate Array (FPGA), populated in a small form factor board which also includes the wavefront image sensor. A Graphical User Interface (GUI) running in an external computer connected to the FPGA imaging board provides the operator with control of different parameters of the AO system; results registration; and log of gradients, Zernike coefficients and deformable mirror voltages for later troubleshooting.
The U.S. Air Force Academy Falcon Telescope Network (USAFA FTN) is an international network of moderate aperture telescopes (20 inches) that provides raw imagery to FTN partners [1]. The FTN supports general purpose use, including astronomy, satellite imaging and STEM (Science, Technology, Engineering and Mathematics) support. Currently 5 nodes are in operation, operated on-site or remotely, and more are to be commissioned over the next few years. One of the network nodes is located at UNSW Canberra (Australia), where the ground-based space surveillance team is currently using it for research in different areas of Space Situational Awareness (SSA). Some current and future SSA goals include geostationary satellite characterization through imaging modalities like polarimetry and real time image processing of Low Earth Orbit (LEO) objects. The fact that all FTN nodes have the same configuration facilitates the collaborative work between international teams of different nodes, so improvements and lessons learned at one site can be extended to the rest of nodes.
With respect to this, preliminary studies of the imagery improvement that would be achieved with the AO system developed at UNSW, installed on a second 16 inch Meade LX200ACF telescope and compared to the existing UNSW Canberra FTN telescope are reported. The ongoing, side-by-side test results of the AO system compared to those obtained without correction are reported.

1. INTRODUCTION

Adaptive Optics(AO) is a widespread technique in telescopes with big apertures, but it is not typically used in telescopes with apertures smaller than 1 meter, with cost and complexity some of the limiting factors. Other reason that can constraint the use of AO for small apertures is that the aberrations caused by the turbulence in the atmosphere are stronger, and that their relatively small diameter gathers less light. Nevertheless, there are some research efforts to address the implementation of a low cost AO system for amateur range telescopes [1,2,3].

In this work, we designed a reconfigurable opto-mechanical structure based in Commercial off-the-shelf (COTS) components, which includes a novel centroiding algorithm implemented in the FPGA, based in the 1st Fourier component, and better suited for low S/N ratios [4]. In this first design the AO system is meant to be used as Single Conjugate Adaptive Optics (SCAO) Natural Guide Star (NGS). Other researchers have also investigated the use of Field Programmable Gate Array (FPGA) as the AO control hardware platform [5,6].

The real-time control loop has been implemented in a low cost FPGA populated in a small form factor board that integrates the Shack-Hartmann (SH) wavefront sensor, and that also includes standard interfaces to communicate with an external computer through USB for debugging and storage purposes. More details about the design of the AO system can be found in [7].

The aim of this work was evaluate the possible implementation of the AO system developed for the Meade LX200ACF 16" telescope in UNSW Canberra, on the telescopes of the FTN [8], using the experience and lessons learned during the design of the AO system. For this purpose, a set of AO simulations with YAO software package [9] were performed, in order to study the predicted performance of an AO system implemented in the telescopes of the FTN.

2. OPTO-MECHANICAL SETUP

Fig. 1 (left) shows the AO testbed attached the 16” Meade LX200ACF telescope from UNSW Canberra, which consists in a cage system comprising bars, cubes and optics holders, and attached to the telescope rear port through an aluminum square flange. This flange is the only point where the system is attached to the telescope, which will ease the adaptation to the 20” Falcon telescope. The dimensions of the AO system are 700 x 600 x 70 mm and the weight is approximately 10 kg. Optics holders can be shifted longitudinally, which again facilitates the adaptation of the AO system to the different telescope diameter and F-number of the FTN telescopes.

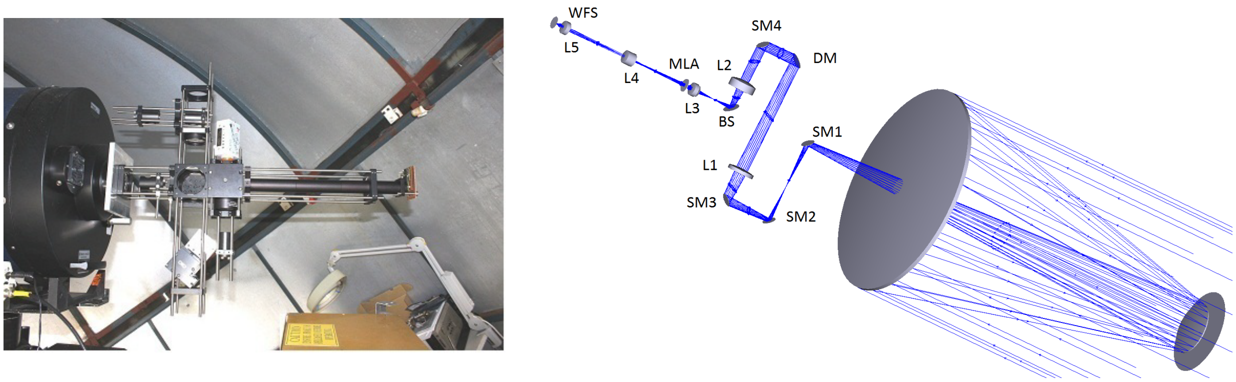

Fig.1. (left) AO system attached to the rear port of the 16” Meade LX200ACF Telescope, (right) optical setup

Figure 1 (right) shows the optical setup comprising 5 achromatic lenses (L1 to L5). Lens L1 collimates the light beam coming from the telescope. The OKO PDM-19 Deformable Mirror (DM) is situated at the back focal plane of L1. Fold mirrors (SM1 to SM4) in a 45 degrees angle configuration make the system more compact. Lens L2 and L3 comprise a Kepler telescope system, which reduces the beam diameter in a factor of 2. Between lenses L2 and L3 a beamsplitter divides the beam between the science camera and the rest of the AO system. The Micro Lenslet Array (MLA) is situated after L3, and before a telecentric system formed by lens L4 and L5, which scales the light beam to the pixel size of the CMOS image sensor in the FPGA imaging system board.

3. CONTROL HARDWARE

The small form factor FPGA imaging system board, of dimensions 55 x 55 mm, includes a low cost Xilinx Spartan XC3SD3400A FPGA and a MT9M0001 Aptina CMOS image sensor. The board also includes extended memory (QDR SRAM and Video FIFO), and useful peripherals interfaces (UART, HDMI, LVDS and VGA). The real time processing of the AO loop is computed in the FPGA, and an external computer is used to control parameters of the image sensor. From a GUI the user can calibrate and align the SH centroids in the CMOS image sensor, send commands to this sensor in real time, and store intermediate values of centroid gradients, Zernike coefficients and deformable mirror voltages for later troubleshooting.

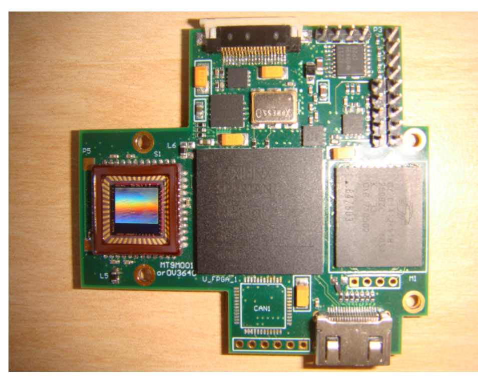

Fig.2. FPGA+CMOS imaging board

4. ON-SKY RESULTS

The capability of the AO system to correct images distorted by atmosphere turbulence is currently being tested on-sky in the 16” UNSW Canberra telescope with a set of bright double stars. Fig. 2 shows two frames of the double star Alpha Centauri (apparent magnitude -0.01) captured with the AO system ON (left) and OFF (right). The image size is 200 x 200 pixels, which corresponds to a FOV of 68 x 68 arcsec in the science camera (Pixelink A-741).

In Fig. 2 (right) the Fast Fourier Transform (FFT) of the temporal variation of Full Width Half Maximum (FWHM) is shown for the 196 frames captured by the science camera at a rate of 7 fps, for both the AO corrected (blue) and non-corrected (red) images. It is noted that when the AO system is correcting, the variability in the oscillations of the FWHM is lower than in the case that the AO system is not correcting the turbulence, as evidenced by reduction in spectral energy.

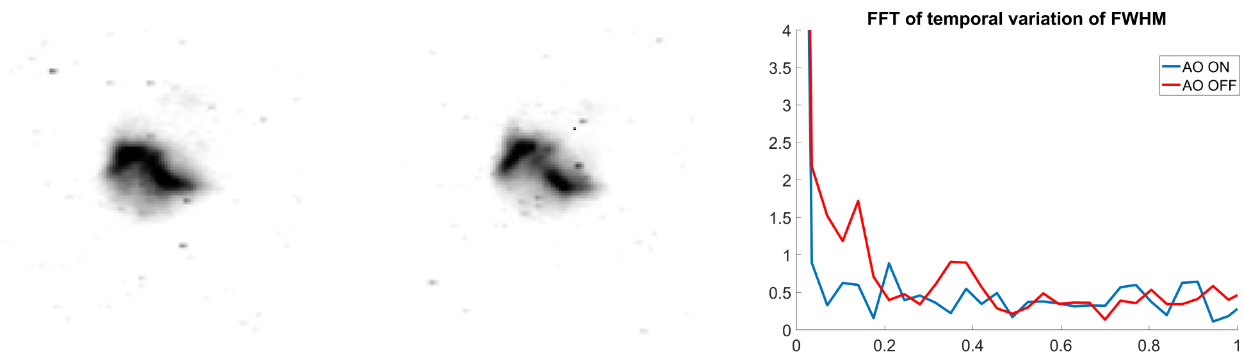

Fig. 2. (left) Alpha Centauri with AO system OFF, Alpha Centauri with AO system ON (middle) and FFT of the temporal variation in the FWHM of images captured in the science camera (Images are inverted).

5. AO SIMULATIONS FOR THE 0.5M (20”) FTN FALCON TELESCOPES

As a first stage towards the implementation of the AO system on the 0.5 meter (20”) telescopes of the FTN, several simulations were performed, with the YAO simulation package. This package, created in 2001, has been used to simulate the AO performance in several telescopes around the World: GeMS, Vasao, Kapao, CANARY, Altair, Gravity, Imaka, Guieloa and Siding Spring AO, among others, demonstrating to be a reliable and well debugged software platform.

Table 1 shows the performance in terms of the Strehl ratio, when comparing the current system implemented in the Meade LX200ACF 16” with the hypothetical performance when installed in the 20” telescopes of the FTN, for different D/r_0 ratios.

D/r_0	Aperture		Shack-Hartmann		DM	Strehl AO ON	Strehl * AO OFF
	D	D(pix.)	Nsub	Pix./sub	Nact		
2	20”	300	10x10	30	21	0.793	0.169
5	20”	300	10x10	30	21	0.364	0.040
10	20”	300	10x10	30	21	0.061	0.010
2	16”	300	10x10	30	21	0.763	0.169
5	16”	300	10x10	30	21	0.263	0.040
10	16”	300	10x10	30	21	0.040	0.010

Table 1. Strehl ratio for AO system in 20” and 16” telescopes as a function of D/r_0
* (Racine approximation, “The Telescopic Point-Spread Function”, 1996)

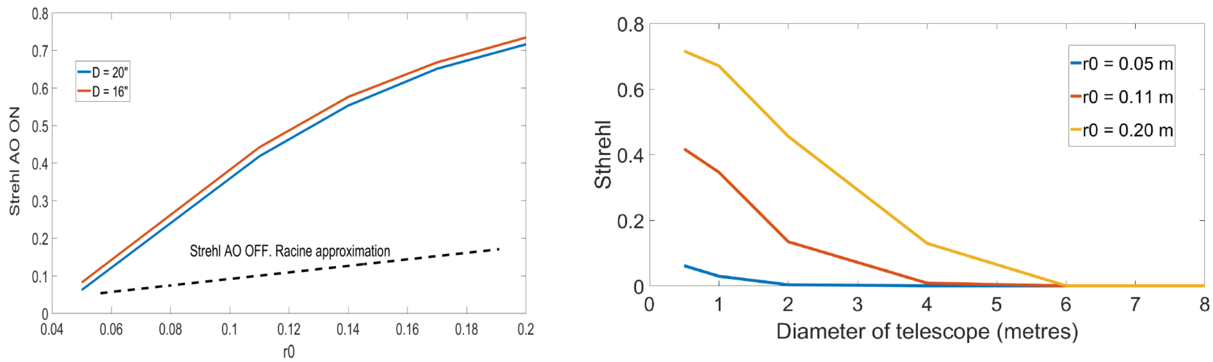

Fig. 3. (left) Strehl ratio for different turbulence strength, (right) Strehl ratio for different Diameters of telescope and three different turbulence strengths.

From Table 1 and Fig. 3 (left), for the selected configuration (300 pixels in the wavefront sensor, 10 x 10 subapertures, 30 x 30 pixels per subaperture, and 21 actuators in the deformable mirror), the performance in terms of the Strehl ratio is very similar for both 16" and 20" diameter apertures.

Fig. 3 (right) shows that the selected configuration works better for smaller apertures than bigger ones, with an obvious improvement in the performance as the turbulence strength decreases (r_0 increases). However, a reader must be cautious in interpreting these graphs, since for a fixed r_0, there are more in a larger aperture, but for the fixed AO configuration presented here, there is a subtle improvement offered by AO even over this trend.

6. CONCLUSIONS

A low cost portable AO testbed has been developed (700 x 600 x 70 mm, 10 kg, 3000 AUD w/ DM), firstly designed for a 16" aperture telescope (LX200ACF). AO simulations of the same system implemented for the 0.5 meter telescopes from the FTN were performed.

The closed loop control is implemented in a standalone FPGA, with less than 1 frame delay, and 6.5 μs delay in the FPGA control loop, working at a frame rate of 285 Hz. A GUI is capable to retrieve and log science data in real time (gradients, Zernike coefficients and DM voltages) for later analysis.

The AO system has been tested with double stars, and results of its performance with α Centauri are presented, showing better stability in FWHM with a closed loop configuration.

AO Monte Carlo simulations with YAO package show agreement with experimental data in LX200 16" telescope. Combining the experience acquired in the AO design stage for the LX200 16" telescope, with the optimized design parameters suggested by YAO simulation package, a feasible AO system can be developed that will improve raw imagery in the 20" telescopes of the FTN. Such a capability would be easily and inexpensively added to each node.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

1. C.Paterson, I.H. Munro, C.Dainty, *Low-cost Adaptive Optics Systems*, Proc. SPIE, v. 4007, pages 185-193, 2000.
2. Teare S.W., Martinez T., Andrews J.R., Wilcox C.C., Restaino S.R., Romeo R., Martin R. and Payne D.M., *A lightweight Adaptive Telescope*, Proc. Of SPIE, Vol. 6306, 630609, 2006.
3. Loktev M., Vdovin G and Soloviev O., *Integrated Adaptive Optics System for Small Telescopes,* Proc. of SPIE Vol. 7015, 70153K, 2008.
4. A. Lambert and M. Cegarra Polo, *Real-time algorithms implemented in hardware for centroiding in a shack-hartmann sensor*, Imaging and Applied Optics 2015, page AOW3F.2. Optical Society of America, 2015.
5. Kepa K., Coburn D., Dainty J.C. and Morgan F., *High Speed Optical Wavefront Sensing with Low Cost FPGAs*, Measurement Science Review, Vol. 8, Section 3, No. 4, 2008.
6. Marichal-Hernandez J.G., Rodriguez-Ramos L.F., Rosa F. and Rodriguez-Ramos J.M., *Atmospheric Wavefront Phase Recovery by use of Specialized Hardware: Graphical Processing Units and Field Programmable Gate Arrays*. Applied Optics, Vol. 44, No. 36, 2005.
7. Manuel Cegarra Polo. *Adaptive Optics for Small Aperture Telescopes*. PhD thesis, UNSW Canberra, 2015.
8. F.K.Chun, R.D.Tippets, M.E.Dearborn, *The U.S. Air Force Academy Falcon Telescope Network*, AMOS 2014.
9. F.Rigaut, M. Van Dam, *Simulating Astronomical Adaptive Optics Systems Using YAO*, AOELT3 Conference, 2013.