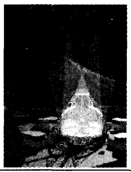
Venice 2001
Beyond
Conventional
Adaptive
Optics



Design of the Dual Conjugate Adaptive Optics Test-Bed

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ABSTRACT

In this paper, we describe the Multi-Conjugate Adaptive Optics laboratory test-bed presently under construction at the University of Victoria, Canada. The test-bench will be used to support research in the performance of multi-conjugate adaptive optics, turbulence simulators, laser guide stars and miniaturizing adaptive optics. The main components of the test-bed include two micro-machined deformable mirrors, a tip-tilt mirror, four wavefront sensors, a source simulator, a dual-layer turbulence simulator, as well as computational and control hardware. The paper describes in detail the opto-mechanical design of the adaptive optics module, the design of the hot-air turbulence generator and briefly the configuration chosen for the source simulator.

1. INTRODUCTION

1.1. Background and Motivation

Adaptive Optics (AO) has proven its effectiveness in obtaining images from ground-based observations with resolutions comparable to those achieved from space. It is anticipated that adaptive optics will become a necessary component of all existing and future ground-based telescopes. Although the technology has reached certain maturity, many advances are still needed to improve performance, and reduce the size and cost of AO systems.

A major limitation of classical adaptive optics systems is the relatively small field of view available for correction. This is due to the fact that the observed characteristics of the turbulence in the atmosphere change with the angle of observation. Therefore, if an AO system is analysing the distortion of the light from a certain guide star, there is a limiting angular separation from that guide star at which the science source of interest can lie. This limiting angular separation is called the isoplanatic angle and represents the size of the corrected field-of-view. Another problem is the limited sky coverage possible with conventional AO systems, which on average is approximately five percent. This is due to the low probability of finding a bright enough guide star that is separated from the science object by less than the isoplanatic angle.

These problems can be rectified by using Multi-Conjugate Adaptive Optics (MCAO) (Dicke (1975), Beckers (1988), Johnston et al (1994)). MCAO uses multiple guide stars to correct a larger field of view. However, given the limited number of suitable *natural* guide stars, the use of *laser* guide stars becomes important. By using lasers to generate artificial guide stars, it is possible to create an array of guide stars around the science object. MCAO also leads to a more complete analysis of the turbulence of the atmosphere. The beams from the multiple guide stars propagate through slightly different sections of the atmosphere, and each wavefront is analysed by a separate wavefront detector. This allows mapping of larger sections of turbulence in the atmosphere. Also with an MCAO system, multiple deformable mirrors (DM) are conjugated to (ie: image) different altitudes of the atmosphere. The simplest MCAO system has two mirrors—one conjugated at the entrance pupil of the telescope, and one conjugated at some higher altitude. In this way, the atmospheric turbulence can be mapped out in three dimensions, with the higher conjugate mirror correcting for a specified altitude in the atmosphere, and the other one correcting the distortion at ground level.

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In this paper, we describe the design of a dual-conjugate adaptive optics system presently under development at the University of Victoria. The facility will house two deformable mirrors, a source simulator emulating three laser guide stars, a dual-layer turbulence generator and the required control hardware. Expected to become operational in 2002, the test-bed will be used over the next decade to advance research in MCAO, design of deformable mirrors, laser guide stars as well as turbulence modelling and generation.

1.2. Overview of the Test-Bed

The optical and mechanical design of the test-bed has been largely driven by the particular choice of the deformable mirrors. These are continuous micro-machined mirrors manufactured by Boston Micromachines Corporation. They have a clear aperture of 3.3 mm and are deformed with 140 actuators arranged in a square grid. Although the mirrors have an open-loop bandwidth of 6.6 kHz, their shape can be updated at a sampling rate of 100 Hz. In the optical design of the test-bed, the mirrors are conjugated at 0 km and 10 km in the atmosphere.

The wavefront path design accommodates three monochromatic guide stars that can be placed at either 90 km or at infinity. The design relies on the natural separation of the beam into three parts because of differences in locations of the guide stars in the field of view. In total four wavefront sensors will be procured from Adaptive Optics Associates (AOA) or built in-house: three for the guide stars and the fourth to collect data from the science source output in order to quantify the quality of the correction achieved with the DMs. A mini-wavescope, also supplied by AOA, will be part of the test-bed and is intended for use as an auxiliary tool for system calibration and identification. The foreoptics of the complete layout emulates a 32 cm, F/40 telescope, which itself was scaled down from an 8 meter telescope, while maintaining a 2' field of view. The tip-tilt mirror procured from Ball Aerospace is placed at 0 km in the foreoptics, before the deformable mirrors.

A turbulence generator and a source simulator are being constructed for the test-bed since the test-bed is intended for use as a stand-alone research facility. Several concepts were considered for the turbulence generator: a holographic simulator (Otsubo et al, 1997), a spatial light modulator based on liquid-crystal technology (Love, 1997; Kelly et al, 2000; Cho et al, 1998), a phase plate based simulator (Paxman et al, 1999; Roggemann et al, 1995) and the hot-air turbulence generator (Fuchs, et al, 1996). The latter was identified as the most suitable concept for our facility, after comparing the versatility, capabilities, and cost of the alternatives. The proposed design follows closely that developed by Jolissaint (2000) and aims to produce turbulence with $C_n^2 \delta h \sim O(10^{-10})$ and D/r_0 of approximately 9. For a dual-conjugate adaptive optics system with two deformable mirrors, a virtual three-dimensional atmosphere with multiple turbulent layers of different altitudes must be created which can then be mapped out by three wavefront sensors. Therefore, the turbulence generator must provide dual layer turbulence. With an appropriately designed fold of the beam, a single hot-air turbulator has been designed to provide both turbulence layers for the beam: one at 5 km altitude and the second at 15 km altitude.

The source simulator will accommodate three guide stars with a fixed triangular geometry and a white science source that can be placed at an arbitrary location in the field of view. The guide stars can be located either at infinity to emulate natural guide stars (NGS), or at 90 km to emulate sodium backscatter produced with lasers in a real adaptive optics system. Since the guide stars are held fixed above the turbulence, they can also be used to derive tip-tilt information, thus obviating the need for natural guide stars.

In Section 2, we present in detail the opto-mechanical design of the complete optics system, starting with the fore-optics, followed by the adaptive optics module which houses the two deformable mirrors and finally, the wavefront path. Section 3 briefly describes the design of the turbulence generator to be used with the facility.

2. OPTO-MECHANICAL DESIGN

2.1. System Requirements

The UVic AO testbed is intended to demonstrate the feasibility of using MCAO to improve the performance of a large diameter telescope. Because of the space limitations of a laboratory environment, the testbed is designed to constitute a scale model of an 8 metre telescope equipped with 80 mm diameter deformable mirrors. The deformable mirrors planned for this test-bed have a 3.3 mm aperture and hence the scale of the testbed is chosen as 1/25 of real scale. If a telescope were used to collect input light for the testbed, that telescope would be 32 cm in diameter.

In the laboratory setting, a set of optics is necessary to simulate the characteristics of a 32 cm telescope in only a few metres of space. This is accomplished with two foreoptics, chosen to generate an F/40 beam. The foreoptics must also allow for the simulation of light sources and atmospheric turbulence over the field of view. Because some telescopes employ the secondary mirror as a tip-tilt corrector, a tip-tilt mirror can be located either in the foreoptics (to mimic a secondary mirror) or in the adaptive optics module proper.

The design of the adaptive optics is driven by the f-ratio, the size of the two deformable mirrors, the size of the field of view and, its primary function – to correct the beam for atmospheric turbulence. The beam should be collimated and reflect off both deformable mirrors. For optimal performance, the deformable mirrors should be positioned at the conjugates to the nominal heights of the turbulent layers of the atmosphere. The adaptive optics must also split the beam into two samples – one to form a science image, and one to be analyzed to control the corrective surfaces.

The detector light path is constrained by the sizes and input requirements of the detectors (a CCD to record the science image, and wavefront sensors to sample the wavefront from the guide stars). The CCD must be placed at the focal plane of the optical system. The wavefront sensors are based on 100 mm x 100 mm x 100 mm closed circuit TV cameras and have apertures of 10 mm, which analyze wavefronts based on collimated input beams.

Finally, the sources for the testbed may include both monochromatic sources (intended to simulate laser guide stars) and broadband light sources (intended to simulate natural guide stars and the science target). Hence most of the system, with the exception of paths for monochromatic laser guide star light, must be designed to minimize chromatic aberrations.

2.2. Foreoptics

As noted earlier, the foreoptics must emulate a 32 cm F/40 telescope as well as accommodate the tip-tilt mirror, the dual-layer hot-air turbulence generator and the source simulator, all within the constraints of a 4'x8' optics bench. The required optics were chosen based on the pupil diameter specification, which in turn was set by the strength requirements for the turbulence generator. In addition, it was decided to use turbulence layers placed corresponding to heights in the real atmosphere of 5 km and 15 km. Given the necessary folding of the beam, it was desirable to place the two turbulence layers so that a single turbulence generator box could be used by allowing two beam passes through it (see Figure 1).

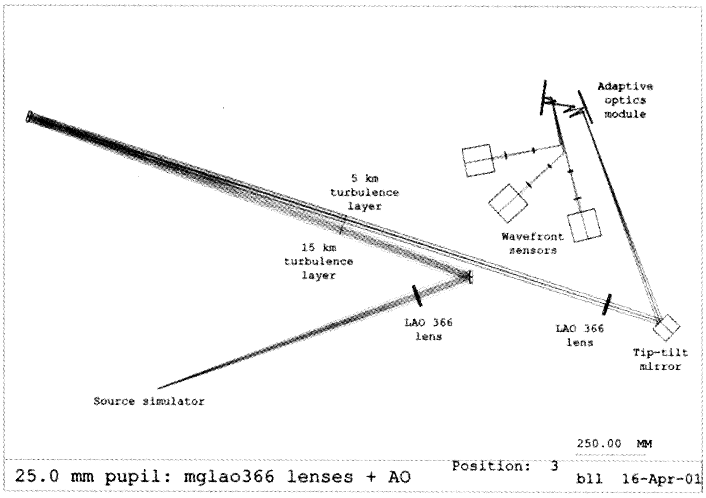


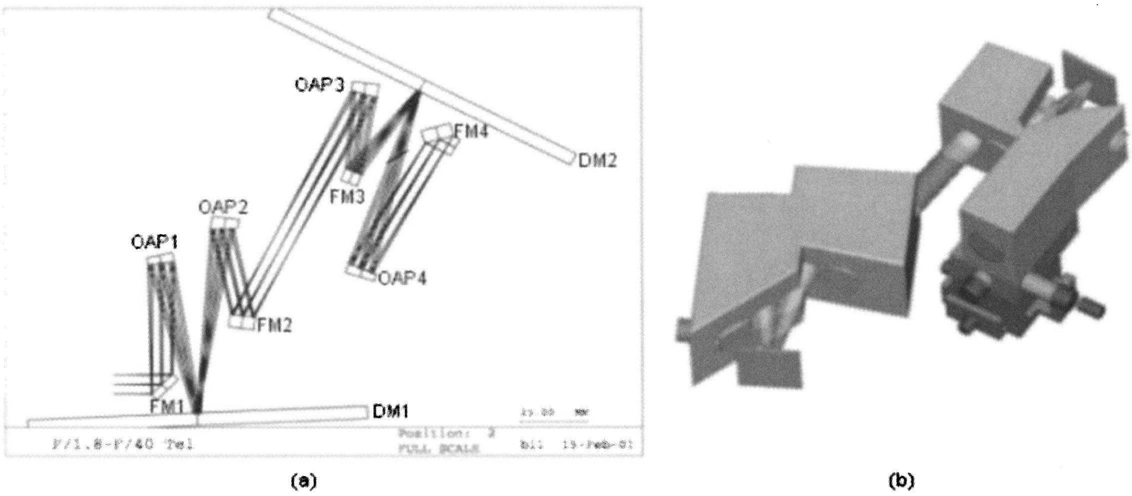
Figure 1. Optical schematic of refractive foreoptic design

With the above constraints and requirements, a refractive foreoptic design was developed. The design uses two achromatic Melles Griot LAO 366 lenses and two folding mirrors as shown in Figure 1 with rays simulating guide stars an infinite distance away. These lenses have focal lengths of 1000 mm and, for an F/40 beam, generate a 25.0 mm pupil diameter. One turbulence simulator is to be constructed, wide enough for the beam to pass through one half to simulate the 15 km turbulent layer, and the other half to simulate the 5 km turbulent layer. In this design the source simulator must be moved towards the first foreoptic by 5 cm to simulate guide stars at a height of approximately 90 km.This design degrades the image to a Strehl ratio of 0.94 after the second lens. The two achromatic lenses and folding mirrors will be mounted in Melles Griot 07 LHF 014 lens holders, and supported by Melles Griot 07 PCA 501 height adjustable posts, the latter to allow alignment in two axes.

2.3. Adaptive Optics Module

The adaptive optics module must take input light generated by foreoptics, collimate it, reflect it off a DM located conjugate to a high atmospheric layer, reflect it off a DM conjugate to turbulence at the ground, send a portion of the collimated light to the wavefront sensing devices, and focus the remaining light onto a CCD which will record the corrected image. The requirements are complicated by the small aperture of the micro-machined deformable mirrors, which come mounted on a 5"x5" board containing the control electronics. Several design iterations were explored with Code V by varying the f-ratio of the incoming beam and the focal length of the reflective surfaces, as well as introducing additional optics into the design. The final design shown in Figure 2 was chosen as the best compromise between the specified constraints and the objective of producing a layout with a reasonable amount of space between the optical elements in order to reduce the alignment and mounting challenges.

As can be seen from Figure 2, light from the foreoptics hits a flat mirror, which directs the light to an OAP, which collimates the beam and reflects it to the first DM (conjugate to 10 km). The DM reflects the light to an OAP located one focal length from the 0 km conjugate. The OAP focuses the beam, which is reflected off a flat mirror and up to another OAP. This third OAP re-collimates the beam and sends it to a flat mirror, which redirects the light to the second DM, located at another 0 km conjugate. The collimated light passes through the beamsplitter, which reflects a portion of the light for the wavefront sensors and passes the corrected image. The corrected image is focussed by one last OAP, and the converging beam that results is directed by one last flat mirror to the focal plane. Only a few millimetres of space exist between the last flat mirror and the focal plane, but it should be possible to fit a bare CCD chip at the focal plane to record the corrected image.



(a)

(b)

Figure 2. (a) Optical and (b) mechanical schematics of adaptive optics module and mounting system

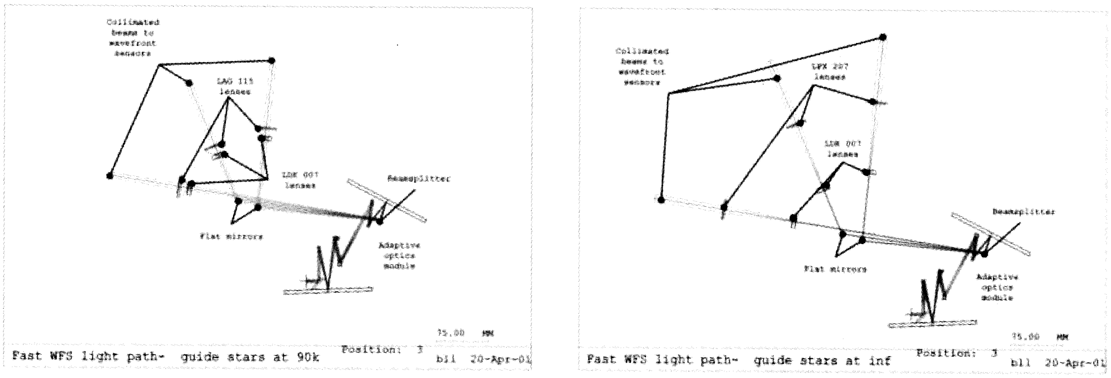
Under ideal conditions, using a detector with a slight curvature matching the focal plane curvature, the adaptive optics module image quality has a Strehl ratio of 1.000 for a source within the two arcminute field of view, and worst 100% geometric spot size 0.00047 mm. For different trial perturbations of the system, where the OAPs are displaced by up to 0.1 mm in each of three dimensions, tilted by up to 0.5 degrees in each dimension, and warped by allowing their radii of curvature to vary by up to 0.5 mm, the Strehl ratio was degraded to a minimum of approximately 0.75. These perturbations confirmed that expensive precision mounts should not be required to align the system. The mounting system will likely consist of two precision machined metal blocks, with surfaces to which the optical elements will be affixed. Holes drilled through the metal blocks will allow for the passage of light. One of the blocks will be mounted on an XYZ translation stage and a rotation stage to allow easy alignment with respect to the other. Because the deformable mirrors come packaged on a 5"x5" printed circuit board, they will be mounted independently of the remaining adaptive optic elements. Figure 2b shows the mounting system for the adaptive optics module.

2.4. Detector Light Path

The wavefront path design accommodates the light from three guide stars placed either at infinity or at 90 km and relies on the natural separation of the beam into three corresponding parts. In particular, at the beamsplitter, the rays from any one guide star source are parallel, but ray bundles from two different sources diverge. The gradual divergence of the sources leads to a complete separation of the ray bundles from each other, a few hundred millimetres from the beamsplitter. Once the sources are separated, flat mirrors can be used to redirect the beam from each source to a separate wavefront sensor, thus allowing the sensors to be well spaced out.

Since the size of each source's bundle of rays is only a few millimetres in diameter and is less than the aperture size of the wavefront sensors, off-the-shelf lenses are used to expand the ray bundles to near the 10 mm aperture diameter of the wavefront sensors. Different configuration lenses are used to expand the sources at a height representing the 90 km sodium layer and the sources at infinity.

Figure 3a shows the light path and lens configuration for sampling the wavefronts of 90 km guide stars with triangular pattern, while Figure 3b shows the same for guide stars at infinity. In both figures, the adaptive optics module is also illustrated to demonstrate the scale and relative layout of the wavefront sensor path. All indicated lenses are from the Melles Griot catalogue. Both configurations share a common diverging lens, LDK 007. The path lengths from the beamsplitter to the first lens to the second lens are identical for all the ray bundles for guide stars at one height, and for both guide star heights the path length from beamsplitter to the first lens is identical. The path length from the beamsplitter to the LDK 007 lens is 278 mm. For the 90 km guide star height, the path length from the LDK 007 lens to the LAG 115 lens is 2.53 mm. For the infinite guide star height, the path length from the LDK 007 lens to the LPX 207 lens is 99.3 mm. The wavefront sensor for a particular star may be placed anywhere beyond the second lens, since the beam is collimated by the second lens.



a)

b)

Figure 3. Light path for laser guide stars at (a) 90km and at (b) infinity

3. TURBULENCE GENERATOR DESIGN

3.1. Specifications

The hot air turbulence generator (turbulator) works on principles similar to those of the real atmosphere: two air flows at varying temperatures and velocities will generate turbulence if mixed. The turbulator is simply a confined space where these air flows can be controlled and forced to mix.

The design adopted for our test-bed is based on the design and achieved performance of the hot-air turbulence generator constructed by Jolissaint (2000). The first critical specification of the hot air turbulator is that it creates a temperature difference of 50K to ensure a large enough C_n^2 and a small enough r_0. The second critical specification is that the speed of the flow be controllable at speeds up to approximately 1.0 m/s. Accurate speed control at low air speeds is necessary to ensure that the generated turbulence has temporal frequency spectrum which is correctable with our deformable mirrors. The size constraints on the turbulator are dictated by the layout of the foreoptic design, which constrains the length of the turbulator on one side. The distance from the center of the mixing window to the end of one inlet is restricted to a maximum of 300 mm. The length to the end of the second inlet is arbitrary (Figure 4). Also, since the foreoptics allow two beam passes through a single turbulator it must be wide enough to allow for both beams to pass through the turbulent zone.

3.2. Proposed Design

The proposed design for the turbulator, shown in Figure 4, is a single box with two inlets on opposite ends. Each inlet has a fan to collect air from the environment, and one inlet has a heating coil to heat the air from room temperature to $\sim 70^{\circ}$C. The heating coil is 100 mm in length, 25mm in diameter, and has a power requirement of approximately 150 W. The proposed fans are CPU cooling fans, purchased from StarTech, with square casings measuring 80 mm x 80 mm x 25 mm. The fans are rated at 32.4cfm which will provide air speeds of 2.4 m/s. The overall outer dimensions of the box and inlets are 150mm x 150 mm x 825 mm; the distances from the center of the mixing window to the inlet fans are 275 mm and 550 mm which satisfy the aforementioned constraints. The ends of the turbulator are completely ducted away from the bench to avoid unwanted turbulence at an exit orifice. There are two slides, controlled manually, that create the variable sized mixing window. At the end of each slide, just prior to entering the mixing window, the two inlet air flows pass through a section of honeycomb to laminarize the flow.

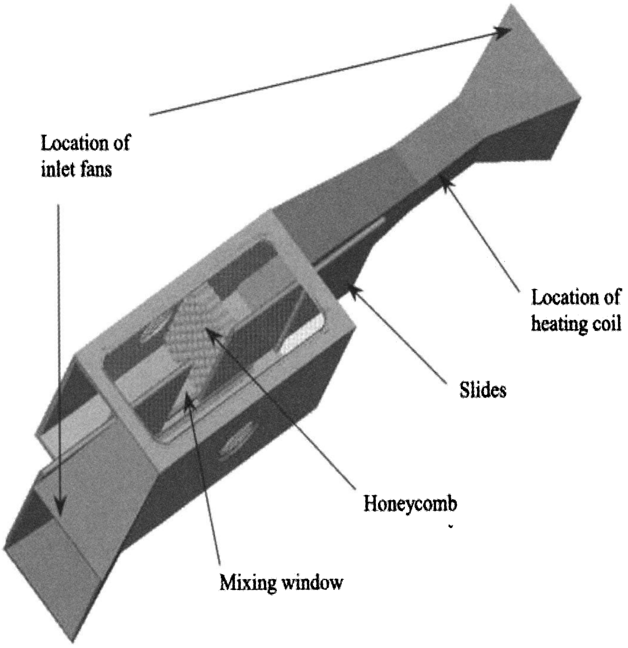


Figure 4. Proposed design of hot air turbulator

4. CONCLUDING REMARKS

In this paper we described the design of the main components of the dual-conjugate adaptive optics test bed presently under construction at the University of Victoria. The first stage of the test bed consisting of a single deformable mirror and a mini-wavescope will be deployed in the summer of 2001. The initial experiments to be conducted will include testing the response and performance of the deformable mirror and closing the loop on a single DM using the mini-wavescope as a wavefront sensor. The hot-air turbulator and the source simulator are planned for construction and characterization in the fall of 2001. The wavefront sensors will be procured early in 2002 and the complete system is expected to be fully operational by the middle of 2002.

Acknowledgements

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