# Holographic Adaptive Laser Optics System

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## ABSTRACT

We have created a new adaptive optics system using a holographic modal wavefront sensing method with the autonomous (computer-free) closed-loop control of a MEMS deformable mirror (DM). A multiplexed hologram is recorded using the maximum and minimum actuator positions on the deformable mirror as the "modes". On reconstruction, an input beam is diffracted into pairs of focal spots and the ratio of the intensities of certain pairs determines the absolute wavefront phase at a particular actuator location. The wavefront measurement is made using fast, sensitive silicon photomultiplier arrays with the parallel outputs directly controlling individual actuators in the MEMS DM.

In this talk we will present the results from an all-optical, ultra-compact system that runs in closed-loop without the need for a computer. The speed is limited only by the response time of any given DM actuator and not the number of actuators. In our case, our 32-actuator prototype device already operates at 10 kHz and our next generation system is being designed for >100 kHz. As a modal system, it is largely insensitive to scintillation and obscuration and is thus ideal for extreme adaptive optics applications. We will present information on how HALOS can be used for image correction and beam propagation as well as several other novel applications.

## 1. INTRODUCTION

Conventional adaptive optics systems typically use curvature or Shack-Hartmann based wavefront sensing. One limitation faced by these techniques is the large computational overhead which in turn requires the use of high speed computers or very expensive, custom designed chipsets. Many applications including surveillance, astronomy and free space optical communications could benefit from improvements in both speed and actuator number but current systems are generally limited to 1kHz with ~100 subapertures. We are investigating a solution based on holographic wavefront sensing that can go beyond 100 kHz and thousands of actuators. The holographic adaptive laser optics system (HALOS) uses a multiplexed hologram and MEMS-based deformable mirror all without the need for any computer in the loop. It is compact, lightweight and rugged and can be adapted for many different applications.

## 2. HOLOGRAPHIC ADAPTIVE LASER OPTICS SYSTEM

The operation of HALOS is best understood when considering a description of how it is constructed. The process begins with a plane wave reflected off a deformable mirror with a single actuator driven to its maximum extent so that a minimum phase delay is imparted on the wavefront at that location. A hologram is recorded between this object beam and a diffraction limited reference beam focused to some distant point A (Fig 1a).

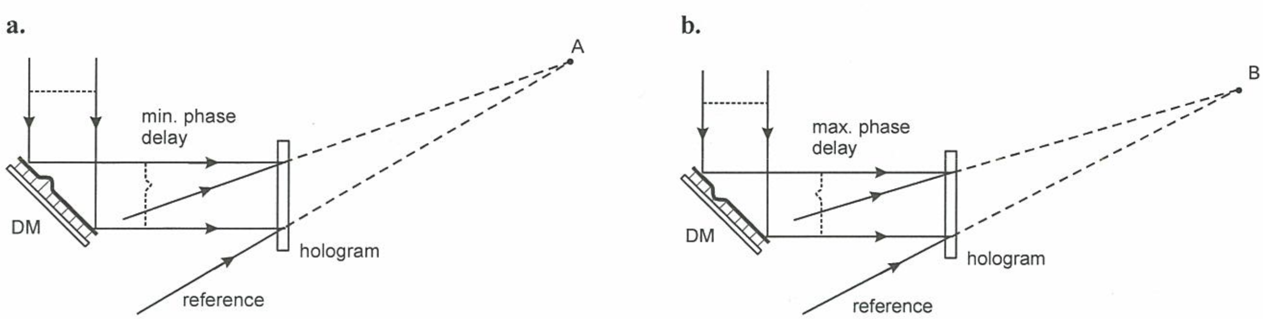


**Fig 1: a.** A hologram is constructed with the minimum phase delay imparted by a single actuator, and a reference beam focused to a point A. **b.** A second hologram is multiplexed with the maximum phase delay and a reference beam focused to point B.

A second hologram multiplexed with the first: in this case, the using a reference beam focused to a different spatial location B and an object beam generated with the maximum phase delay possible from the same actuator in the DM (Fig 1b). If the DM actuator is now set to some arbitrary stroke it will produce an arbitrary phase delay at that particular location on the wavefront. With this beam incident on the hologram, the phase matching condition is such that there will be two wavefronts reconstructed, one focused to each of the points A and B (Fig 2).

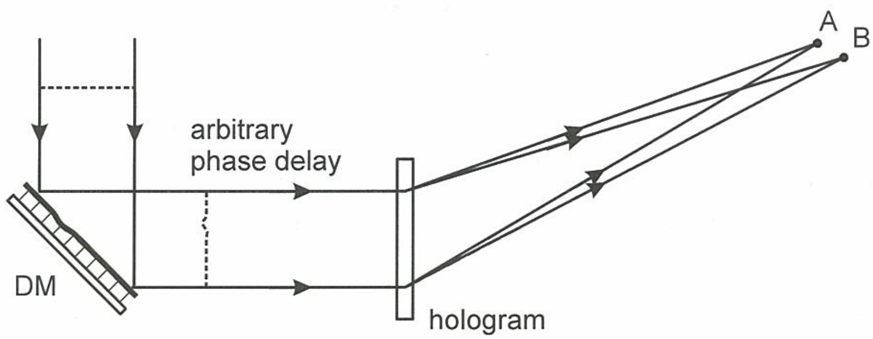


**Fig. 2:** Multiplexed reconstruction. If an arbitrary phase delay is applied to the reconstructing object beam there will be two focal spots on replay.

The relative intensities of the foci are related to the phase error present in the object beam. With a one-off calibration we can thus determine the absolute phase information from a measurement of intensity. Furthermore, we can record any number of pairs of multiplexed holograms – one for each actuator position on the deformable mirror. So long as there is a spatial separation of the pairs of foci, we can continue to add as many actuators as we wish to increase the resolution of the system (Fig 3). In this case, the pairs are distributed vertically, though they can be positioned anywhere in the detector plane.

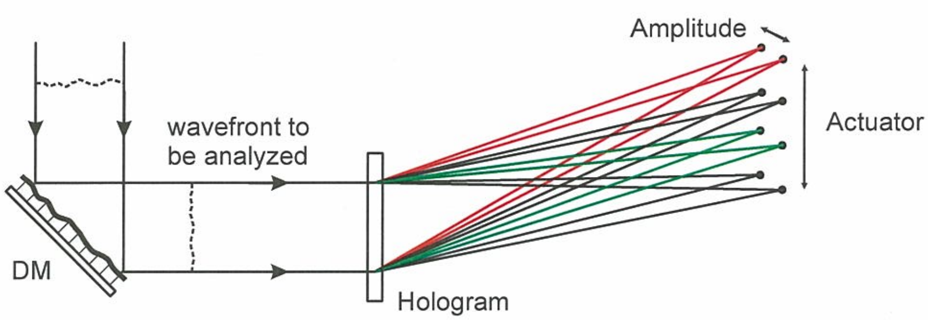


**Fig. 3:** Complete wavefront characterization is achieved with a pair of holograms recorded for each actuator. Focal spot in the reconstructed beams are separated spatially for identification.

The advantage of this system comes from the fact that the measurement of phase is essentially made with a measurement of intensity – something that can be achieved using simple photodetectors. These can be photon counting for low light levels, and very fast – up to MHz speeds or greater. Moreover, if an array of such detectors is used the readout can be made in parallel, so the speed of wavefront sensing is independent of actuator number. This breaks the conventional bottleneck associated with wavefront sensing making it ideal for applications such as directed energy projection and UAV surveillance.

The advantages of HALOS can be summarized as follows:
1. Autonomous closed loop control. The output from each pair of photodetectors can be combined into a single voltage which has a direct relationship to an absolute phase error. After calibration, a simple circuit can perform the feedback correction to the relevant actuator. With no computer, the system is much more compact and lightweight.
2. Speed: With no calculations required, the system speed is sensing is essentially limited only by the readout of the photodetectors which can be many MHz or more. Furthermore, since the detector outputs can be measured in parallel, HALOS performs just as fast for one actuator as it does for 1000.

3. Obscuration/Scintillation: Most adaptive optics systems, being zonal, perform poorly if there is any unexpected obscuration or scintillation. HALOS uses modal sensing, and since a ratio of intensities is being used for the phase measurement any change in intensity across the aperture poses no problem as it will be factored out directly.

## 3. EXPERIMENTS

In order to test the performance of the holographic wavefront sensing we used a 32-actuator micro-electromechanical (MEMS) deformable mirror from Boston Micromachines. Optical holograms were written in dichromated gelatin film ($\lambda$ = 460nm). On reconstruction, pairs of spots were observed – one for each actuator. We then used the outputs from photon counting avalanche photodiode arrays to derive the first moment for the intensities of spot pairs; $((I_1-I_2)/(I_1+I_2))$.

The critical issue in the holographic wavefront sensor is that a first moment translates into a single value for each actuator position to provide a suitable locking signal. To demonstrate this, we measured the first moment of the intensities related to one particular actuator (#19) as that actuator was adjusted from minimum to maximum phase shift. As can be seen in Fig. 4, there is a clear, singly defined function that can be used to determine the phase condition for that particular actuator. Also shown in this graph is the measured first moment for the same focal pairs as a neighboring actuator (#20) is moved. The negligible variation in this curve indicates that there is little cross-talk between channels as desired.

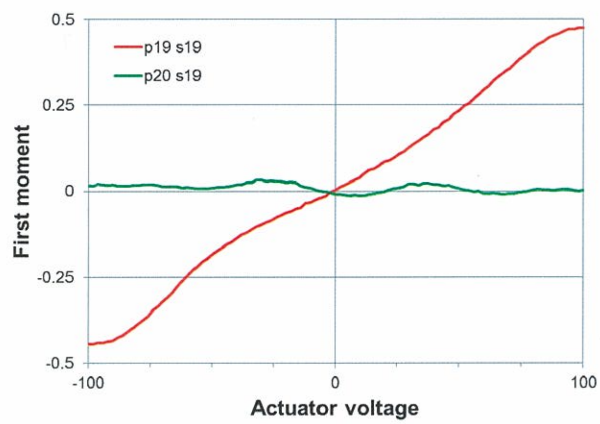


**Fig. 4:** A plot of the variation in first moment for the 19$^{th}$ sensor channel pair as actuators 19 and 20 are varied through their full range of motion.

Once this calibration curve is determined for each pair of sensors and their corresponding actuator, a feedback circuit can be designed to ensure that the actuator is constantly adjusted to any desired set point. This is typically such that the output phase across the entire beam has zero wavefront error. We have constructed such a circuit and demonstrated closed-loop control to 10 kHz with a simple circuit independent of any computer control. Current work is aimed at improving the analog circuitry to a more compact and faster, all-digital control.

## CONCLUSION

We have constructed an autonomous (computer-free) closed-loop adaptive optics system that uses a holographic wavefront sensing method. Our system has 32 actuators and operates at a bandwidth of 10kHz. We are currently configuring the system for fast operation in the infrared under digital control.

## ACKNOWLEDGEMENTS

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