

Telescope Wavefront Aberration Compensation with a Deformable Mirror in an Adaptive Optics System

Hamid Hemmati, Yijiang Chen, and Ian Crossfield
JPL, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA 91109

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ABSTRACT

With the goal of reducing the surface wavefront error of low-cost multi-meter-diameter mirrors from about 10 waves peak-to-valley (P-V), at 1 μ m wavelength, to approximately 1-wave or less, we describe a method to compensate for slowly varying wavefront aberrations of telescope mirrors. A deformable mirror is utilized in an active optical compensation system. The RMS wavefront error of a 0.3m telescope improved to 0.05 waves (0.26 waves P-V) from the original value of 1.4 waves RMS (6.5 waves P-V), measured at 633nm, and the Strehl ratio improved to 89% from the original value of 0.08%.

1. INTRODUCTION

Planetary optical communication links and Lidar systems require inexpensive non-diffraction-limited quality optical apertures with effective aperture diameters on the order of several meters to tens of meters. Diffraction-limited quality telescopes, such as those utilized in imaging are not required. An overall surface error of up to 20 times greater than the diffraction limit will be adequate.¹ The telescopes may be formed via a monolithic or segmented primary mirror single large apertures, or an array of multi-meter diameter telescopes. Recent availability of ultra-low-noise photon-counting detectors or detector arrays allows for efficient signal summing from individual detectors.² By employing a deformable mirror in an active optics system, our goal is to reduce the slowly varying surface wavefront error (WFE) of low-cost multi-meter-diameter mirrors from about 10 waves peak-to-valley (P-V), at 1 μ m wavelength, to approximately 1-wave or less.

Dynamic and direct actuation of thin primary and secondary telescope mirrors in an “active optic” compensation of surface aberrations has been implemented on multiple telescopes so far.^{3,4} Dynamic (real-time) holography via liquid-crystal spatial light modulators (SLMs) in a re-imaged pupil to correct low-optical-quality primary mirrors has been demonstrated also.⁵ With the SLMs, current throughput efficiency is less than 60%. Deformable mirrors are not applied to any of the above systems, except with small (~1-cm) diameter lenses that model the human eye.⁶ Use of deformable mirrors for wavefront control of the next generation space telescope was proposed by Redding et. al.⁷

Utilizing a deformable mirror and a wavefront sensor in an active optical system, we report here a proof-of-concept demonstration for compensation of aberrations in a 0.3m diameter telescope. Our aim is to extend this approach to multi-meter diameter non-diffraction-limited quality mirrors. The types of aberrations to be compensated include astigmatism, coma, defocus, trefoil and higher order aberrations. One possible configuration for compensation of aberrations of large diameter telescope mirrors via deformable mirrors is schematically shown in Figure (1). Although a wavefront sensor is employed in our initial setup, recent experiments show that for certain applications, a simple CCD array may replace the wavefront sensor.^{8,9} The focal spot size or M^2 of the optical system is minimized via feedback to the deformable mirror. The number of actuators and the stroke per actuator required in the deformable mirror depends on the extent of the wavefront aberrations; e.g. an optical system with 10-waves of aberrations (P-V) at 1 μ m wavelength, will require at least 5 μ m of stroke in the deformable mirror. This requirement and significantly higher stroke levels are within the state of the technology of today’s commercially available deformable mirrors.¹⁰ Due to the slow varying or quasi-static nature of the aberrations of an optical system, caused by gravitational sag or thermally-induced mechanical drift, the optical system does not require high bandwidth compensation.

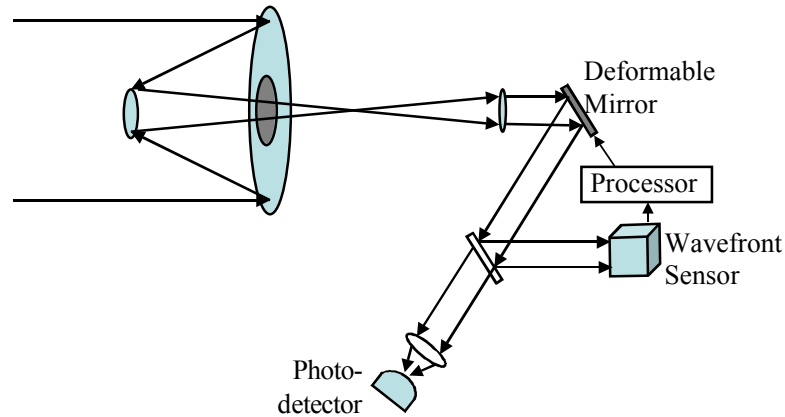


Figure 1. Schematic of a generic active optics system for compensation of optical system's aberrations.

2. ANALYSIS

We first analyzed an "active optic" system by modeling an ideal deformable mirror (DM) as a high pass filter where the threshold frequency is characterized by its actuator spacing. This high-pass spatial filter is applied to the wavefront error to remove all spatial frequencies below the cutoff frequency of $(N-1)/(2D)$, where N is the number linear actuators (in a $N \times N$ array), and D is the diameter of the telescope primary mirror.¹¹

Two spherical, low-cost, 1.5-m diameter, F/1, non-diffraction-limited quality mirrors, from different suppliers are being characterized experimentally. The manufacturer measured RMS wavefront error is approximately 4 waves (10.5 waves P-V) at $1\mu\text{m}$. The wavefront map of the mirror is first characterized in the laboratory utilizing the Foucault technique; followed by generation of a pupil map of the mirror with Code V[®] modeling program.¹² Upon applying a simulated 16×16 element deformable mirror with the initial wavefront of a 1.5-m mirror, the RMS wavefront error decreases to 0.27 waves (1-wave P-V), from 4-waves (10.5-waves P-V). Our analysis, assuming a realistic DM show that an ideal DM approximates a real DM reasonably well and can be reliably employed to estimate performance of a deformable mirror compensating slow-varying aberrations.

The required number of actuators is dictated by both the nature of aberration and aperture size. Figure (2a) shows the number of actuators required for reducing the RMS wavefront error from 4 waves to 0.27 waves with telescope aperture diameters in the 1-5m range. Figure (2b) illustrates that the wavefront error of the 1.5-meter mirror improves as the number of actuators in the deformable mirror is increased.

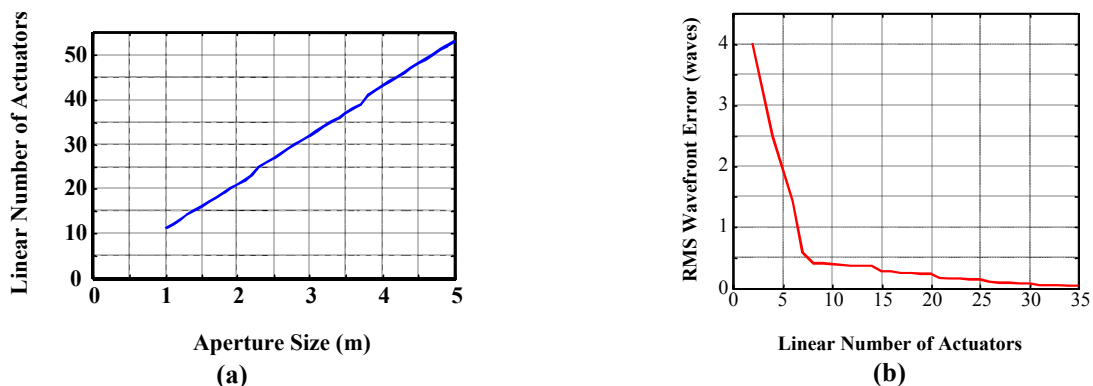


Figure 2. The required (linear) quantity of actuators for a deformable mirror vs. aperture size (2a), and wavefront quality improves with increased numbers of actuators, as simulated for a 1.5m diameter mirror. In these graph, 20 linear actuators refer to a two-dimensional 20×20 element DM.

1. PROOF-OF-CONCEPT

Initial tests of the concept were performed with a 0.3-m diameter telescopes, as depicted in Figure (3). The setup consists of an object to be imaged, two 30-cm amateur astronomy telescopes with aberrations less than 2 waves each, a 19-element thermally actuated deformable mirror with stroke of $5\mu\text{m}$ placed at the pupil plane of the second telescope, a Hartmann wavefront sensor in hexagonal grid with total of 91 spots and resolution or grid pitch of 0.35m and a CCD at the focal plane of the optical system. The refractive and reflective optics in the beam path introduces aberrations in the image. A deformable mirror in a closed loop with the wavefront sensor then corrects this image.

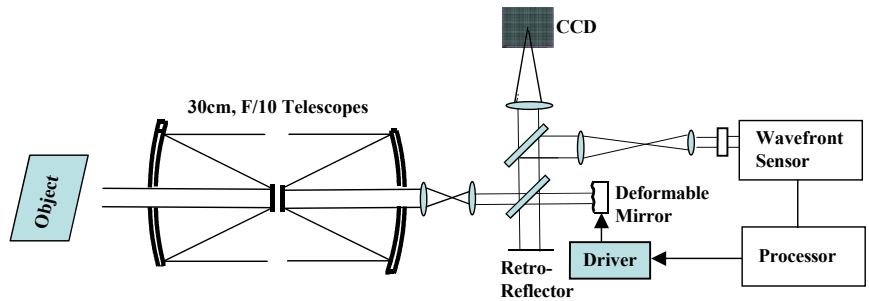


Figure 3. Proof-of-concept setup of adaptive optics system for image compensation.

The uncompensated and the compensated images are shown in Figures (4a) and (4b), respectively.



Figure 4. (a) An aberrated image (6.5 waves peak-to-valley at 633nm), and (b) compensation of aberrations with a 19-element deformable mirror (0.26 waves).

Large aberrations can result in spread caustics, associated with singularities of gradient maps in terms of catastrophe theory, leading to a large focal spot size.^{14,15} Figure (5a) shows how a point source of 633nm light passing through the aberrated optical system is spread dramatically, and how it is compensated (Figure 5b) with the aid of the active optic system. In our next setup, the wavefront sensor, used in the proof-of-concept demonstration described here, is being replaced with a simple CCD array, and implemented with a 1.5-meter mirror.



Figure 5: Focal spots of 633nm monochromatic light after transmitting through the aberrated optical system; (a) before; and (b) after the active optics compensation.

4. SUMMARY

Cost effective implementation of active optical compensation technique to multi-meter diameter optics will enable rapid fabrication of an affordable high quality optical system with dynamic compensation of the system as the thermal and mechanical environment affects it. The proof-of-concept experiment described here, demonstrates that an active optical system employing a deformable mirror can significantly compensate wavefront aberrations of a 0.3-meter telescope arising from either mirror quality or external factors. A larger deformable mirror array size will be required for extending this technique to multi-meter diameter mirrors. The required DM is driven by the quality of the mirror prior to implementation of the active optic system. Thermally actuated deformable mirrors, such as the one utilized here, have proven to be very low-cost and scalable to much larger number of actuators. Additional cost savings are expected with the elimination of the wavefront sensors from the setup.

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