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The Wavefront Control System for the Keck Telescope

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Abstract

The laser guide star adaptive optics system currently being developed for the Keck 2 telescope consists of several major subsystems: the optical bench, wavefront control, user interface and supervisory control, and the laser system. The paper describes the design and implementation of the wavefront control subsystem that controls a 349 actuator deformable mirror for high order correction and tip-tilt mirrors for stabilizing the image and laser positions.

Keywords: adaptive optics, laser guide star, deformable mirror, Keck Telescope

1. Introduction

The wavefront control system (WFC) is one of the principal components of the Keck laser guide star adaptive optics (AO) system. The AO system will be mounted at the f/15 Nasmyth focus of the telescope and will feed a high resolution infrared camera (1 – 2.2 μm) and a high resolution infrared spectrograph. A sodium laser guide star based on the Lick Observatory system [1] will be projected from the side of the telescope.

In this paper we will describe the design of the WFC subsystem and its implementation, focusing on control of the deformable mirror. We will discuss current estimates of overall system wavefront control performance.

2. Wavefront control system design

The hardware structure of the WFC system is shown in Figure 1. It has four main parts:

- a command processor which manages the interface between the WFC and the user interface and supervisory control systems;
- the up-link tip-tilt controller which fixes the laser guide star position on the wavefront sensor;
- the down-link tip-tilt controller which controls overall image position;
- the deformable mirror (DM) controller which corrects high-order wavefront aberrations.

The tip-tilt controllers are described in detail in a companion paper in this Proceedings and will not be discussed further in this paper.

The command processor (CP) is implemented on a Force Sparc-5 computer running the Unix operating system. Communication throughout the Keck AO system is controlled by EPICS (Experimental Physics Industrial Control System) [2]. The CP translates EPICS communications into commands which to the real-time control processors. The CP receives diagnostic data from the real-time systems and either sends it directly to the user interface and supervisory control systems or saves it on the local WFC disk for later analysis. The raw sensor data, calculated Hartmann spot centroids, reconstructed phase errors, and DM position commands can be saved at the full system sample rate. The CP is also responsible for system calibration operations and reconstruction matrix calculations.

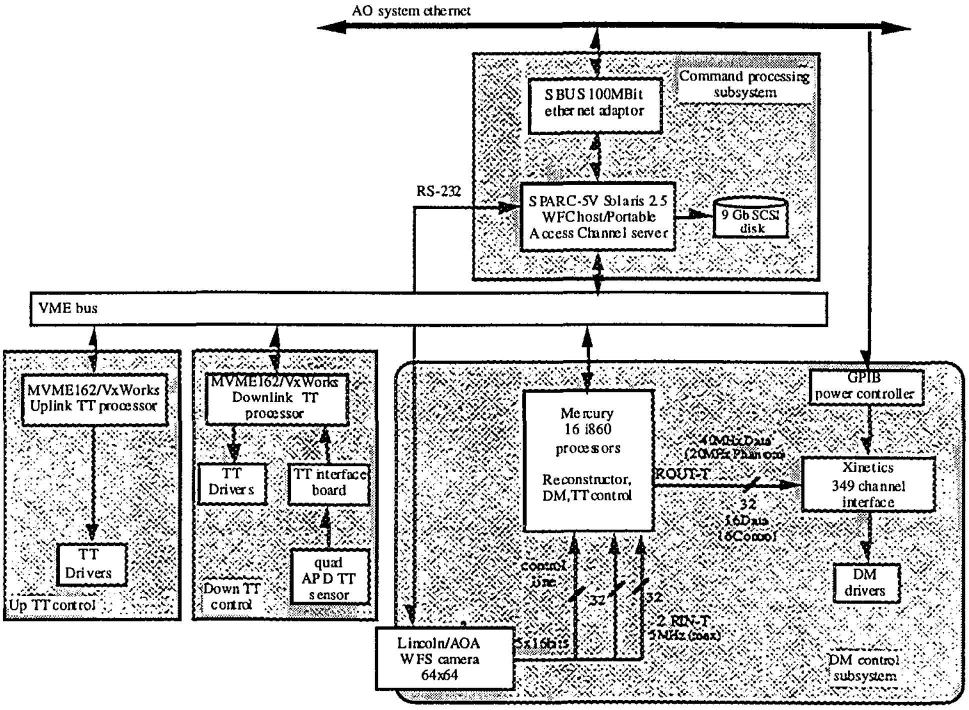

Figure 1. The hardware architecture of the Keck wavefront control main component systems: the command processor, up and down-link tip-tilt control, and deformable mirror control.

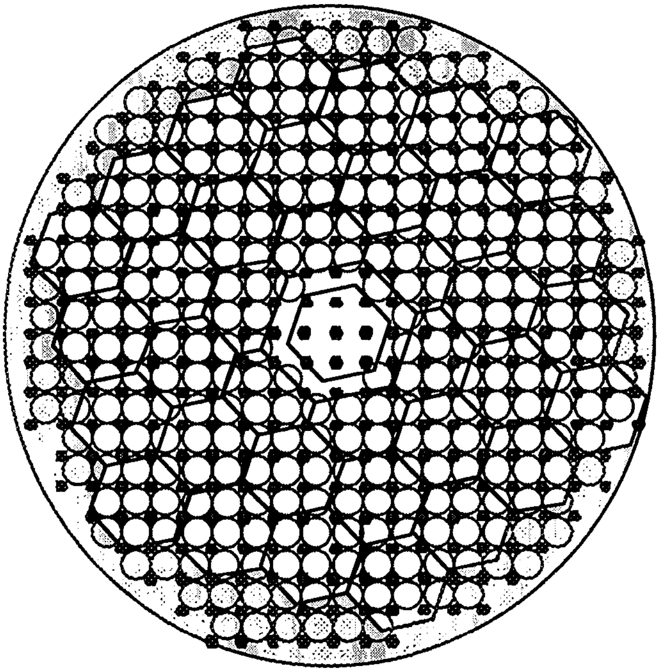

Figure 2. The mapping between the Keck telescope aperture (shown rotated), the deformable mirror actuators (the small hexagons), and the wavefront sensor subapertures (the circles). The subaperture spacing is 0.56 m. At any particular time approximately 240 subapertures are illuminated.

Deformable mirror control

The DM real-time control loop is based on three main components: the Shack-Hartmann wavefront sensor camera built by Adaptive Optics Associates using a Lincoln Laboratories low-noise (< 6 e- at 1 kHz frame rate), a Mercury Computer parallel computer system with 16 Intel i860 processors, and a Xinetics 349 actuator DM. The mapping of the deformable mirror and wavefront sensor subapertures to the Keck telescope aperture is shown in Figure 2. The actuator separation is 0.56 m (at the telescope primary). Wavefront sensor subapertures are aligned to directly correspond to actuators in the Fried geometry [3].

The DM control loop operations are shown schematically in Figure 3. The WFS pixel data is read from the camera at frame rates up to 500 Hz (currently limited by the computer – an upgrade to 1 KHz is being evaluated). The data is immediately distributed among the processors based on a queue-based processor allocation approach. The Hartmann sensor spot positions are calculated using 2x2 pixel areas on the CCD as quadcells. Because 20 subapertures are mapped across the telescope aperture (Figure 2), each subaperture is allocated three pixels – two actively used for the centroid calculation and one as a guard band.

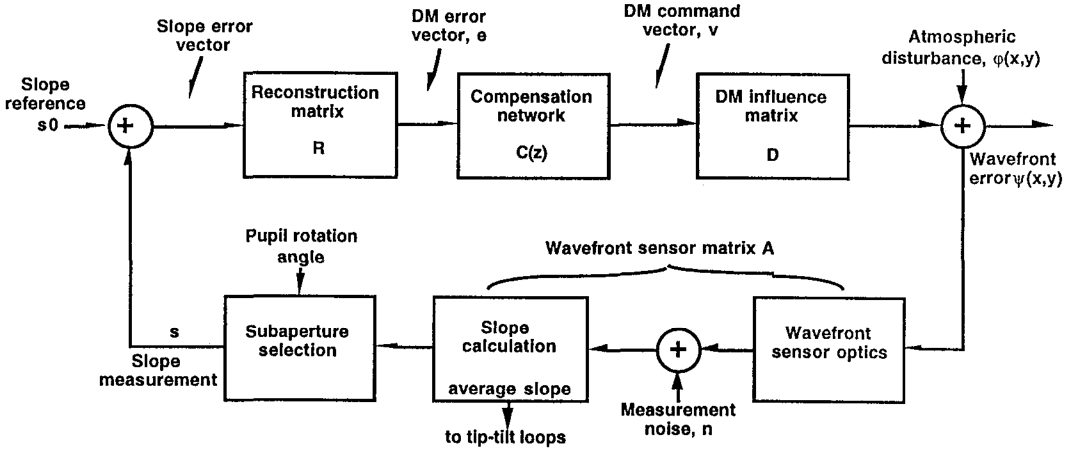

Figure 3. Block diagram of the deformable mirror control loop. Real-time control loop operations go from the slope calculation block in the feedback path through the compensation network in the forward path.

These centroid results are redistributed by broadcasting them to all the processors. The wavefront error is reconstructed by a matrix-vector multiply parallelized across all the processors. The error signals are then applied to a digital compensation network that produces the next DM position command. The total time delay from the end of camera integration through writing the DM position to the mirror controllers is 1.8 ms which will give the system a disturbance rejection bandwidth of up to approximately 50 Hz at 500 Hz sample rate.

Pupil rotation

The alt-azimuth tracking of the telescope combined with the action of the image derotator causes the image of the telescope primary mirror to rotate on both the deformable mirror and the wavefront sensor lenslet array. Because of the non-circular pupil the rotation causes subapertures at the edge of the wavefront sensor to move in and out of the illuminated pupil area. As the pupil rotates the reconstruction matrix must be modified to use only subapertures which are currently illuminated.

For a given reconstruction matrix we have estimated (using Monte Carlo simulation) that the pupil image can rotate approximately five degrees before control performance degrades significantly. At that point new control structures, including the reconstruction matrix and the subaperture origin vector, must be loaded into the real-time controller. This operation can be performed while the system continues to run closed-loop.

1. System performance estimates

An estimate of the wavefront error budget for natural guidestar operation is given in Table 1. The error levels assume 2000 guidestar photons/m^2-ms at the telescope aperture – an irradiance level close to that expected for the Na laser guidestar (approximately m_v=9). The system has been analyzed in three different seeing conditions:

Case A:	$r_0 = 0.4$ m	$t_0 = 10$ ms	excellent seeing
Case B:	$r_0 = 0.18$ m	$t_0 = 2.75$ ms	median seeing
Case C:	$r_0 = 0.066$ m	$t_0 = 1.0$ ms	poor seeing

All atmospheric parameters are given at λ = 550 nm. The correlation times correspond to effective wind velocities ranging from 12 to 21 m/s.

Error source		Set A at zenith	Set B at 30 degrees	Set C at 60 degrees
AO system (nm)				
	Fitting (nm)	63	123	285
	Bandwidth (nm)	19	55	148
	Measurement (nm)	21	40	110
	Calibration (nm)	30	30	30
	Uncorrectable (nm)	20	20	20
Telescope (nm)		105	105	105
Science instr. (nm)		35	35	35
Total error (nm)		135	182	359
Strehl at 1 µm		0.49	0.27	0.01
Strehl at 2.2 µm		0.86	0.76	0.35

Table 1. Error budget for a dim natural guidestar with intensity at the telescope aperture of S_0 = 2000 photons/m^2-ms. The Strehl values neglect errors introduced by the tip-tilt system.

In all cases the adaptive optics system error is dominated by fitting error – the spatial sampling set by the number of actuators on the deformable mirror. The overall system performance is characterized by Strehl ratios calculated at imaging wavelengths of 1 and 2.2 microns. The system will provide good performance for all the defined seeing conditions at 2.2 microns. For excellent and median seeing conditions we expect the system to provide good performance at 1 microns.

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