Final Report: Advancing Curvature Adaptive Optics

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ABSTRACT

We have taken important steps in attacking two key issues in curvature adaptive optics as applied to the SSA problem:

1. We have set up a high speed wave front characterization camera capable of measuring Shack-Hartmann data over the DM pupil at speeds in excess of 10,000 frames per second. This is the first step towards tying DM response to FEA models. It will lead to active damping of the DM through the application of shaped voltage profiles.
2. We have purchased and are integrating into our system an EMCCD to replace an inefficient combination of a fiber coupled lenslet array and avalanche photo-diodes. This will allow for dynamic reconfiguration of the wave front sensor as conditions change.

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Advancing Curvature Adaptive Optics

I. Introduction:

The objective of this work was to advance our understanding of curvature adaptive optics as applied to parameters typical of ground based measurements is support of Space Situational Awareness. The combination of target proper motion, apparent size and integrated total magnitude define a daunting parameter space that taxes the limits of imaging science. Work on the project focused on two major areas: the characterization of curvature deformable mirrors and the implementation of new capabilities for curvature AO based on the use of photon counting area arrays.

II. Characterizing Curvature Deformable Mirrors

A curvature deformable mirror (DM, Figure 1) is a sandwich of piezoelectric material poled through the thickness with a central ground layer and lithographically applied electrodes on both sides. The front electrodes include a large central focus electrode containing the working pupil image. Voltage on an electrode creates a local electric field through the thickness of the disk and the transverse piezoelectric effect causes the activated electrode to expand or contract in area causing the disk to curve over the actuated region. The long actuators at the outer edge of the deformable mirror (Figure 1) are largely outside the working pupil so their action is to set the slope at the edge of the working pupil, again exactly the quantity measured by the WFS. The fixed edge of the DM provides Neumann boundary conditions to the DM while the edge benders apply Dirichlet boundary conditions to the working pupil.

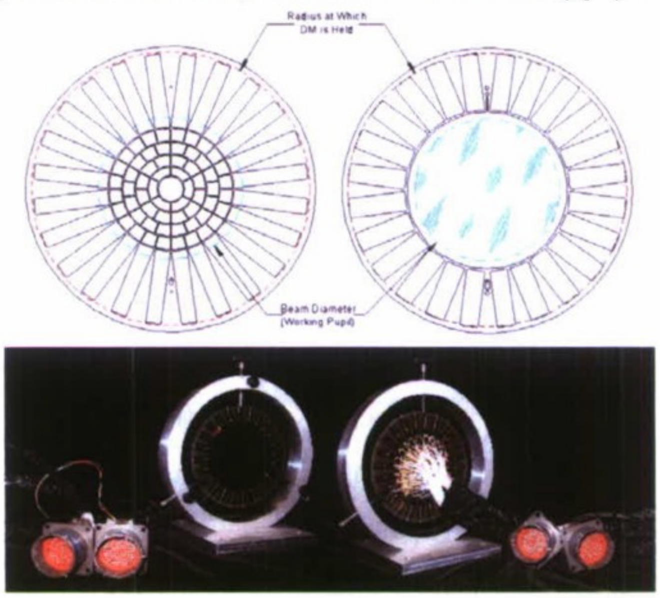

Figure 1 (Top)Back (left) and Front (right) actuator patterns of our 85-element deformable mirror. The smaller curvature actuators operate in a unimorph mode. The long edge actuators on both sides operate as a bimorph.. (Bottom) Front (left) and back (right) views of a completed DM. In practice, we hold the DM between two o-rings that constrain it over its entire circumference.

We hold curvature deformable mirrors only at their edges so we generate an acoustic wave across the face of the DM when we move any actuator. This wave damps in time due to the internal material losses as well as electromagnetic losses specific to piezoelectric materials. Any wave has curvature, which generates strain, which in turn generates fields.

Describing the surface of the DM at any given moment involves a convolution in time with the actuation history of each actuator. Fortunately, the net deformation is largely in the individual motions so we need only to understand what each actuator does individually. We have run models of this process (Figure 2) which take into account both the structural and piezoelectric forces. Unfortunately, almost no piezoelectric materials have been characterized well enough so that their internal damping can be predicted with high confidence.

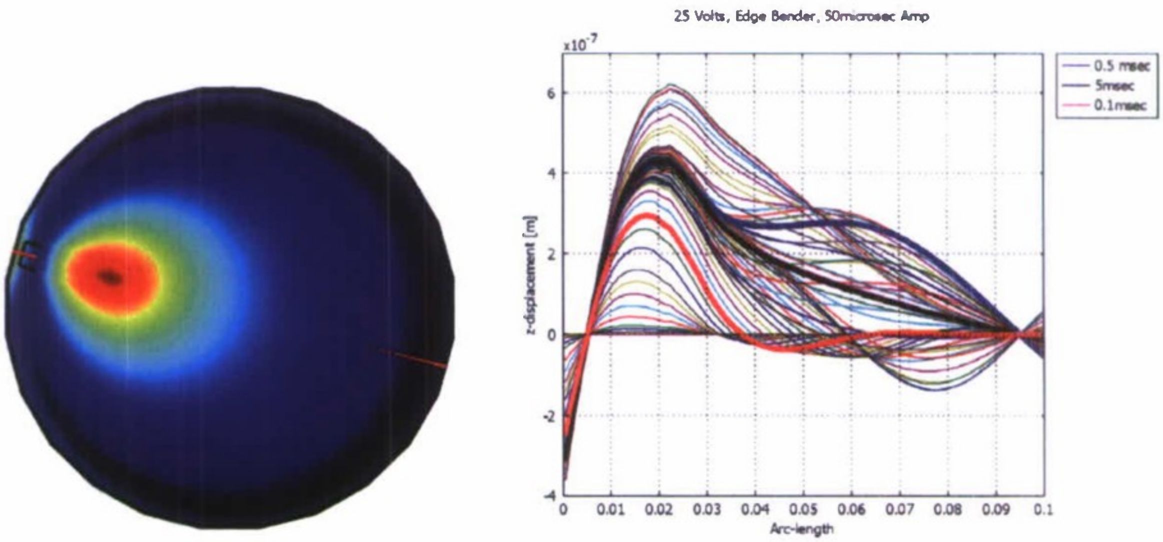

Figure 2. (Left) FEA solution at 0.005 sec of the transient motion of our deformable mirror assuming we apply 25Volts to one of the edge benders. Part of the electrode shape can be seen as well as the line along which the deflection is evaluated. (Right. Times slices of the DM transient response. The red trace is at 0.1msec, the blue trace is a 0.5msec (the loop update time) and the black trace is the asymptotic solution. These models include the fact the edge benders work in a bimorph mode so that there are edge-bending electrodes on both the front and back of the DM that are shorted to one another.

Characterization of actuator ringing on real deformable mirrors is required in order to tie the models to the AO performance predictions. Understanding how the ringing and damping interact when combined with accurate models allows for reprogramming of the actuation strategy to limit unwanted motions of the DM surface.

To make the required measurements, we designed a high-speed wave front sensor to measure and characterize the surface of the DM as it deforms. We purchased a high-speed camera (Figure 3) capable of delivering in excess of 10,000 frames per second for a 220X220 frame at 12 bit pixel depth. Although the camera has a touch screen and can operate as a stand-alone device, we control camera integration through a multichannel high speed Matlab interface which also controls the voltages sent to the DM (Figure 3). This allows synchronization of signals and responses. Image data is stored in a high-speed frame buffer aboard the camera and then downloaded to a computer.

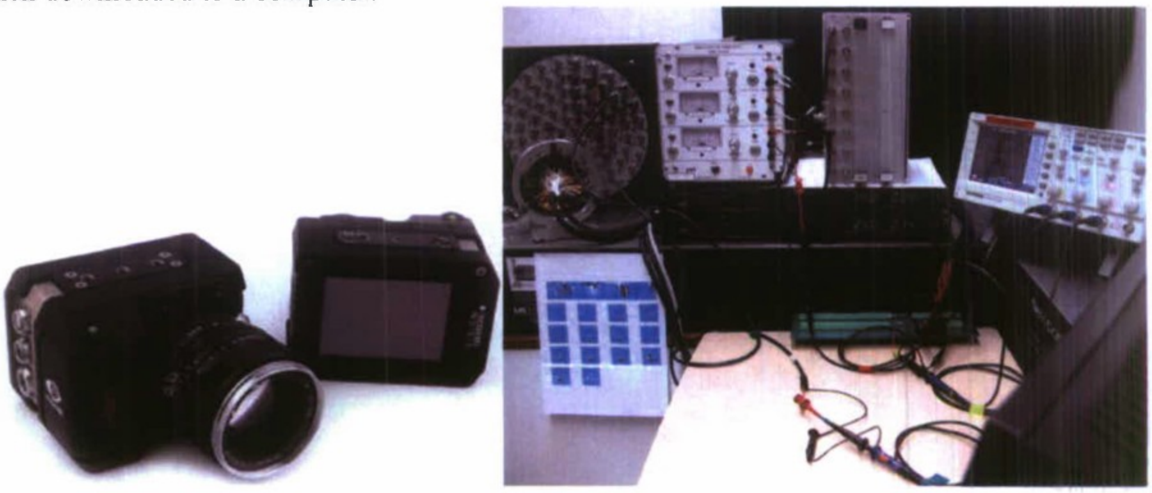

Figure 3. (Left) The Phantom Miro eX4 High Speed Camera has a format of 800X600 pixels and can get full frame video at 1200 frames per sec. Readout rates can exceed 10^5 fps for sub-frames. (Right) Our existing multichannel DM actuation test system. We added the camera trigger signal as one more channel of control to synchronize camera triggering with voltage application. As many as 16 different channels are controlled through a Matlab interface.

To add the wave front sensing capability we purchased a microlens array and mounting hardware (Figure 4). The lenslet array was bonded to a holding tray which was integrated into the C-mount on the camera. A narrow band filter was added to the assembly to allow operation in laser light with the room light on.

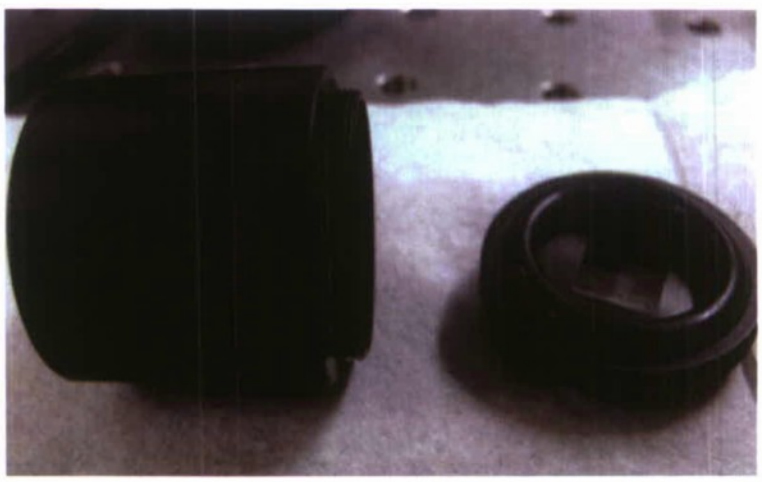

Figure 4. The lenslet array as bonded into its holder. The holder is screwed into the C-mount fitting to mate with the camera. We mount a narrow-band filter ahead of the lenslet array to allow operation with the room lights on.

The Wave Front Sensor optical bench (Figure 5) sample a two inch aperture on the DM with about 17 spot images across the DM pupil.

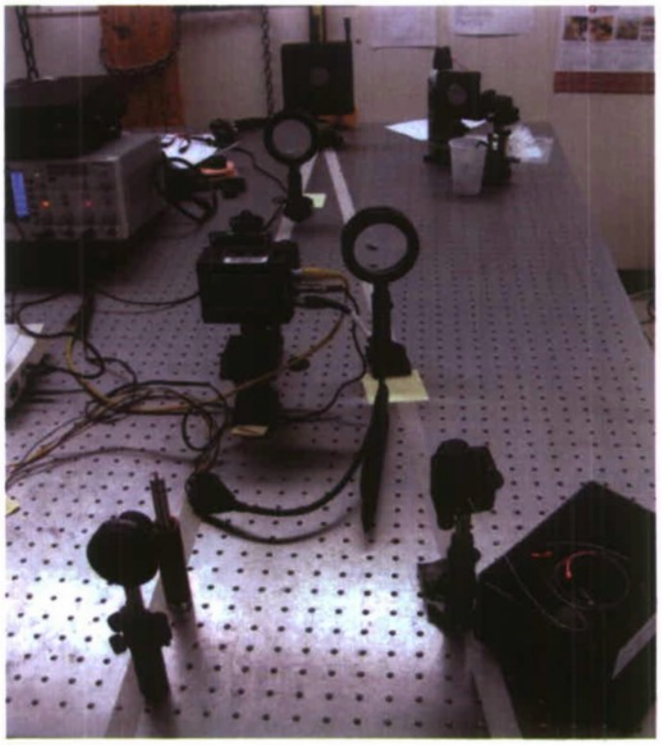

Figure 5. The WFS Optical Bench: The laser diode point source is at the lower right. The collimated laser beam reflects from the DM at the top of the image and a demagnified DM pupil falls on the lenslet array. We can get about 17 spot images across the DM pupil with 15 pixels per spot and download more than 10,000 frames per second.

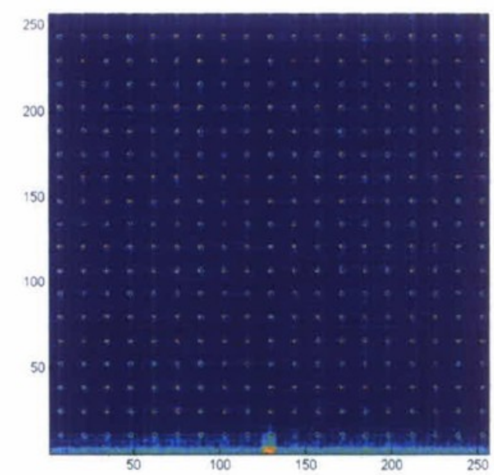

Figure 6. First spot images from the WFS optical bench.

In Figure 6 we show early spot images from the optical bench. We have now obtained movies at 10Kfps of spot image motion as we move various electrodes. We are currently writing the data reduction pipeline to allow extraction of surface shape data from the spot patterns. The primary utility of the facility will be to characterizing the deformable mirror response however, it will also be useful as a "scoring" camera at the AO exit focus and as a high-speed WFS evaluation camera. Importantly, the facility will provide WFS with a spatial order higher than the AO system itself so we can characterize the residual wavefront errors.

III. Using an Area Array in a Curvature Wave Front Sensor

Array detectors are getting faster with lower read noise but any readout noise is a problem since once the detector is read the noise is part of the data regardless of any subsequent processing. In other words, dynamic reconfiguration to accommodate changing conditions or source brightness is pointless. On the other hand, we recognize that the inefficient and technically complex lenslet array/fiber/APD solution will grow more costly and difficult to implement as we move to high order systems. We believe that Electron Multiplying CCD's (EMCCD's) represent the path to incorporating area arrays into curvature wave front sensing while preserving zero read noise.

We wish to put the WFS extra-focal images directly onto an array. A fast EMCCD camera potentially can replace the lenslet array, optical fibers and APDs leading to an order of magnitude (or more) reduction in WFS cost and a potentially higher optical efficiency. We know that EMCCD's have a gain dependent increase shot noise variance up to a factor of two at gains higher than ~10. However, the elimination of lenslet Fresnel losses and fiber coupling losses together with replacing the low QE of Avalanche Photo-Diodes with a >40% higher QE in a thinned back side illuminated EMCCD will result in more than a factor of two gain throughput, more than compensating for this effect.

Getting EMCCD's to work in curvature WFS could be a profound simplification for curvature systems. To illustrate this we show in **Error! Reference source not found.** a block diagram of our AO system with the curvature specific components in Blue and a dotted Red box around the components eliminated by the EMCCD. In addition to the Lenslet/Fiber/APD combination there is also circuitry that counts APD pulses and relays the data to the Control Computer. This is the only function on the input side of the AO data bus which means the eliminating it eliminates the bus itself since the EMCCD integrates directly into the computer. The overall simplification is enormous.

We are currently rewriting the AO control software to allow integration of the EMCCD. We will install it in our system at AEOS in parallel with our APD system there and get real time performance comparisons. This will allow beginning to explore the full potential of having a real time reconfigurable WFS that could oversample the wave front in low noise situations. We have already identified one important issue in moving to EMCCDs. Figure 7 shows an overlay of the outer two rings of our current lenslet array on a 16x16 grid of WFS pixels. We need to measure the movement of the pupil edge in order to get edge slope measurements and the question is how to map the WFS pixels in the best way to obtain this data. We have shown that with some maps the AO system will either not converge or converge to a less than optimal result.

Error! Reference source not found.**a block diagram of our system with the curvature specific components in blue. The red box shows the components eliminated by the EMCCD. APDs produce pulses so we need additional electronics to count pulses, format the data and relay it to the control computer. This is, in fact,**

the only input to the computer so with the EMCCD there is no need for a dedicated input bus since it integrates directly into the computer.

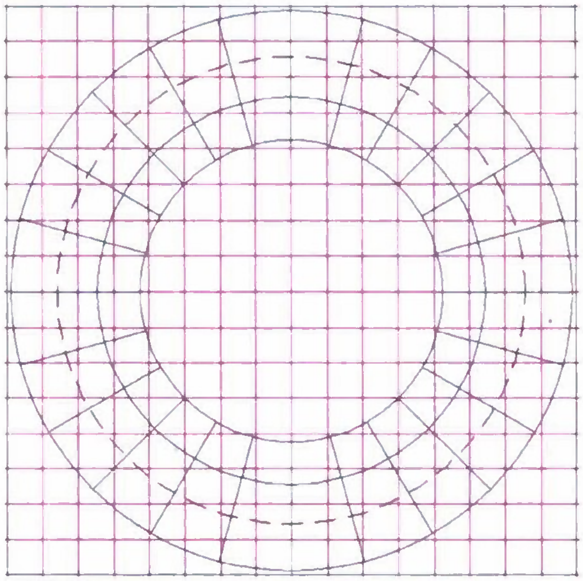

Figure 7. 16x16 WFS pixel pattern shown in red and the outer two rings of the current WFS lenslet shown to the same scale.

IV. Summary.

We have taken important steps in attacking two key issues in curvature adaptive optics as applied to the SSA problem:

1. We have set up a high speed wave front characterization camera capable of measuring Shack-Hartmann data over the DM pupil at speeds in excess of 10,000 frames per second. This is the first step towards tying DM response to FEA models. It will lead to active damping of the DM through the application of shaped voltage profiles.
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