# Adaptive Optics for MAST

***Prepared by AO Team, USO***

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Abstract

This document details a proposal for an adaptive optics system for Multi-application Solar Telescope (MAST) to be installed at the Udaipur Solar Observatory (USO). The objective of the system is high resolution imaging for compensating the aberrations due to atmospheric turbulence. We propose to use a Shack-Hartmann wavefront sensor to sense the distortions of the wavefront, a Tip-tilt mirror and a membrane mirror to correct global and local tilt of the distorted wavefront respectively. A simple work station with Linux as an Operating system will serve as a control computer. Simulations showed that a bandwidth of 100 Hz is necessary to correct the distorted wavefront and a fast camera of 955 fps from DALSA is being planned to achieve this. The optical design of the Adaptive optics system and some of the issues raised while developing the prototype adaptive optics system using a 15 cm telescope are addressed in this document.

## 1. **Introduction**

The proposed Multi-application Solar Telescope (MAST) of Udaipur Solar Observatory (USO) is an off-axis 50 cm reflector which will provide a full field-of-view of 6 arc-min. A spatial resolution of 0.5 arc-sec could be achieved with this telescope using the Adaptive optics (AO) system for a limited field-of-view of ~ 15 arc-sec. The salient features of the telescope are

- Off-axis design
- Clear aperture of the telescope is 50 cm
- Maximum available field of view is 6 arc-min
- Wavefront error of the feed to Back-end Instruments is around $\lambda/10$ (*rms*) over FOV

More details on the telescope and the progress can be found in the MAST web page http://www.prl.res.in/~uso/mast/mast.html. The telescope will be equipped with an AO system and two back-end instruments, a narrow-band filter based imager and a spectrograph. The output of the AO system is planned to feed the Back-end instruments.

In recent times high resolution imaging with AO has enabled the solar physics community to study the finer details appearing in the solar environment at sub arc-sec length scales [1-4]. Most of the solar telescopes around the globe are either equipped with AO or planning for the same. Keeping in view the science goals of the MAST, an AO system is essential for achieving better resolution. Here it would be important to note that AO alone may not be sufficient to achieve the diffraction limited performance of the MAST. It is known that for several existing solar AO systems, there is a need for an off-line compensation technique on AO corrected images to enhance the resolution of the telescope to the diffraction limit. The possible options of an off-line technique at USO could either be speckle interferometry or phase diversity technique. While we have carried out extensive research [8] with the former, the latter is still in the developmental phase. The seeing at the lake site of Udaipur Solar Observatory (USO) is around 3-6 cm, median value being 4.5 cm at 656.3 nm [6]. Under the prevailing moderate seeing conditions at USO, development of a successful AO system will be a challenging task.

As a preparatory for AO for MAST, USO is involved in developing a prototype AO on an existing 15 cm Coudé telescope. An image stabilisation system using a tip-tilt mirror and correction of simulated distortions using a micro-machined membrane deformable mirror (MMDM) have been demonstrated. We employed an algorithm based on sum of absolute difference (SAD) to estimate global/ local tilt of the wavefront. A fast camera with 955 fps was used for closed loop update rate of 1 kHz. With this experience and for immediate realisation of MAST-AO, the identified AO components are described in section 2 and the optical set-up for it is discussed in section 3. Some of the key issues related to the implementation of the AO system are addressed in section 4.

## 2. **Components of the AO system at USO**

The prototype AO has helped us in understanding the practical difficulties and realising the solutions before the arrival of MAST. The process is on the verge of completion. We have identified the major components to be used for MAST-AO system. Shack-Hartmann Wavefront Sensing (SHWFS) could be used with a fast camera (955 fps) from DALSA along with a lenslet array. The 8 bit DALSA Camera has 260 × 260 square pixels with a pitch of 10 microns. In SHWFS, incoming (distorted) wavefront is sampled using a lenslet array. Form the multiple images formed by the LA, local tilt of the wavefront is obtained by estimating motion of the each image with respect to a reference image. A 37 Channel 15 mm MMDM and piezo actuator driven Tip-tilt mirror (TTM) will be used as a correcting elements. Maximum tilt that can be achieved with this tip-tilt mirror is 8 mrad, which is more than sufficient to correct the global tilt of the wavefront at this site. The MMDM actuators works on the principle of electrostatic force of attraction or repulsion. Inter actuator spacing of the MMDM is 1.8 mm, which are placed along concentric circles as shown in Figure 1. Depending on the requirement we can employ 19 or 37 channels for correction.

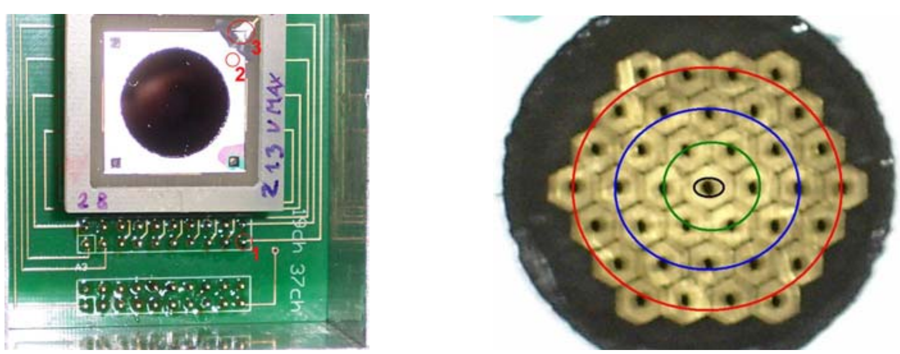

***Figure 1***. Front and Back sides of the Deformable mirror, On the back side of the DM, the actuators are placed along the concentric circles. The first ring involves 1 actuator; along the 2 and 3rd ring 6 and 12 actuators are arranged. The last ring consists of 18 actuators. Inter actuator spacing is 1.8mm

SAD algorithm will be used for estimation of image motion, of image motion, which was implemented using MMX instructions to perform the calculations faster. Regarding the control computer, one of the reasonable options is to go for a workstation with a 64-bit multi-processor and running Red Hat Linux Enterprise OS. The optical design for MAST-AO considers some of the inputs from this section and available off-the-shelf lenses. Software tools for the calibration of TTM and Deformable mirror (DM) are also developed and are ready to use.

## 3. **Optical Design**

In the optical design, main emphasis was on the pupil sizes on DM and wavefront sensor (WFS). As it is known that the MMDM has better response over 80% of its area, we have restricted the pupil size on the DM to be 11-12 mm out of the available 15 mm diameter. Pupil size on WFS is decided by the no. of sub apertures to be used to sample the wavefront. The factors that decide the sub-aperture size are formulated as follows;

A. Features such as pores and sunspots must be resolved for correlation tracking.
B. Optimum sampling of the wavefront will be at $3r_0$ [Sridharan, 2004].
C. Odd number of sub-apertures along the pupil will be convenient to map the sub aperture-actuator geometry.
D. CCD size of 256 × 256 pixels and isoplantic size is around 10 arc-sec.
E. Image due to sub-aperture size should be of sufficient number of pixels to estimate the local tilt of the wavefront.

A and B suggest that the sub aperture size should be in between 10-11 cm that gives 20 – 25 sub apertures. From C and D it was concluded that 5 × 5 will give an optimised value. This will enable us to use a lenslet array having pitch of 500 microns. We have selected a lenslet array with hexagonal lenslets of focal length 97 mm from the catalogue of Adaptive Optics Associates Inc. Figure 4 shows the schematic of lenslet geometry of the proposed system. The close packed hexagonal lenslet geometry allows 19 sub-apertures.

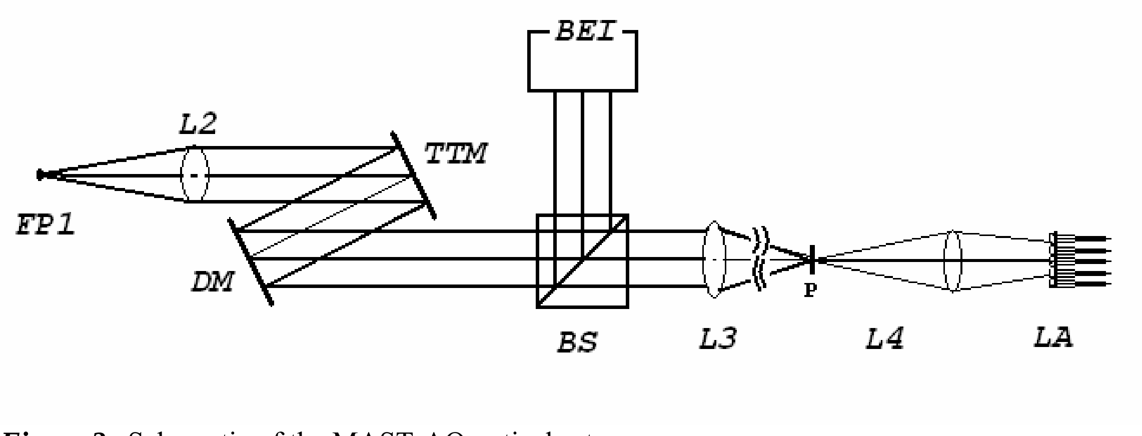


***Figure 2.*** Schematic of the MAST-AO optical set-up.

Output of MAST is a collimated beam of diameter 160 mm with pupil of 50 mm at a distance of 6 m from the port of the Back-end instrumentation. To feed the AO and other back end instruments an imaging lens L1 (not shown in Figure 2 and Figure 3) is used. Figure 1 and Figure 2 show the schematic of the optical set-up for MAST-AO system. The design considerations are as follows.

a The pupil size on the DM should be 11-12 mm.
b The distance between collimating Lens L2 and location of the DM should be sufficient enough to place the TTM at a suitable angle.
c The pin-hole size, which carries a 10 arc-sec FOV (corresponds to one iso-planatic patch), should be sufficient enough to track the features of interest manually, may be 1-1.5 mm.
d The pupil size on LA should not be more than 2.6 – 2.7 mm, this limitation is imposed by the active area of the CCD, which is 2.56 mm.
e The image size of 10 arc-sec FOV due to lenslet should cover 50 pixels on wavefront sensor to accommodate 5×5 images on the camera.
f Off-the shelf lenses should be used.

An f/15 doublet of diameter 15 cm was chosen as L1 for imaging the 6 arc-min field of view, this forms f/45 beam at FP1. Because of an undersized lens L1 the unvignetted FOV will be 5 arc-min only. Lens L1, and the constraint on pupil size on DM decide the focal length of L2 as 500 mm. The lenses L1 and L2 make a pupil size of 11.3 mm. TTM is placed at a distance of 160 mm from L2 and DM is placed at a distance of 310 mm from L2, where pupil plane is re-imaged. Beam foot print on TTM and DM are shown in Figure 4.

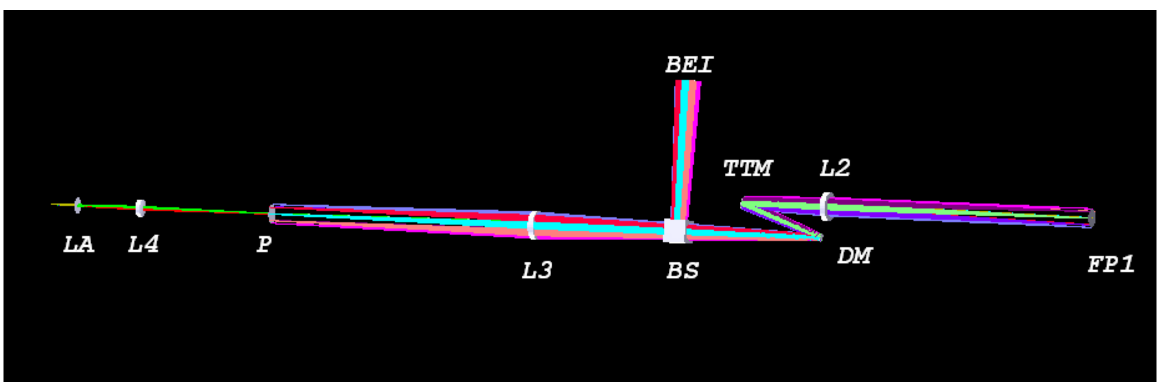


***Figure 3***. Optical set-up of the MAST AO system, designed using optical design Software Zemax$^{TM}$. All the lenses used here are chosen from Lens catalogue of various companies. L1 is from LinosPhotonics, L2 and L3 from Newport and L4 is from Melles-Griot and LA array from Adaptive Optics Associates Inc. catalogue.

A lens of focal length 500 mm was chosen as L3, which forms an image of 1.14 mm size for a 10 arc-sec FOV. A beam splitter BS is used either before L3 as shown in Figure 1 and 2 or after L3 depending on the requirement to feed back-end instruments. To have a re-image pupil of size 2.6-2.7 mm, the lens, L4 should have focal length of 115 to 120mm. To use this lens in collimated geometry and to have the required image of

0.5mm, the lenslet array focal length should be 53mm. where as to use the available LA of focal length 97 mm, lens L4 is used to in the converging geometry; Lens L4 of focal length 120 mm is kept at a distance of 240 mm from image plane P and it re-images the pupil of size 2. 7 mm at a distance of 114 mm from Lens L4. A Lenslet array of focal length 97 mm is used to get the desired image size. Schematic of lenslet geometry and foot print of the beam on it is shown in Figure 5. Plate scale on wavefront sensing camera is 0.2 arc-sec per pixel. All the lenses have been chosen from available lens catalogues and diffraction limited performance could be achieved with these lenses for the wavelength of operation from 400-800 nm.

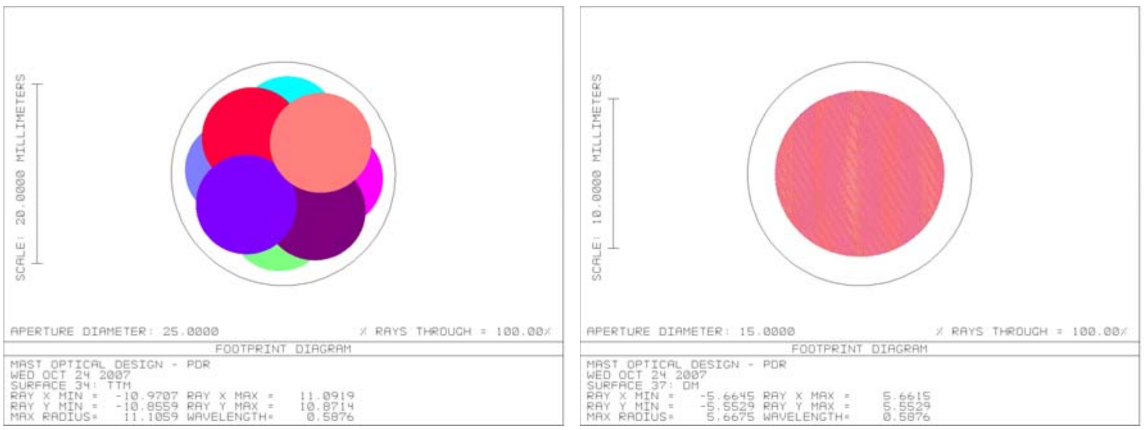


***Figure 3***. Foot print diagram of the beam on TTM (left) and DM (right). On DM, rays corresponding to all the filed angles converge at the same location.

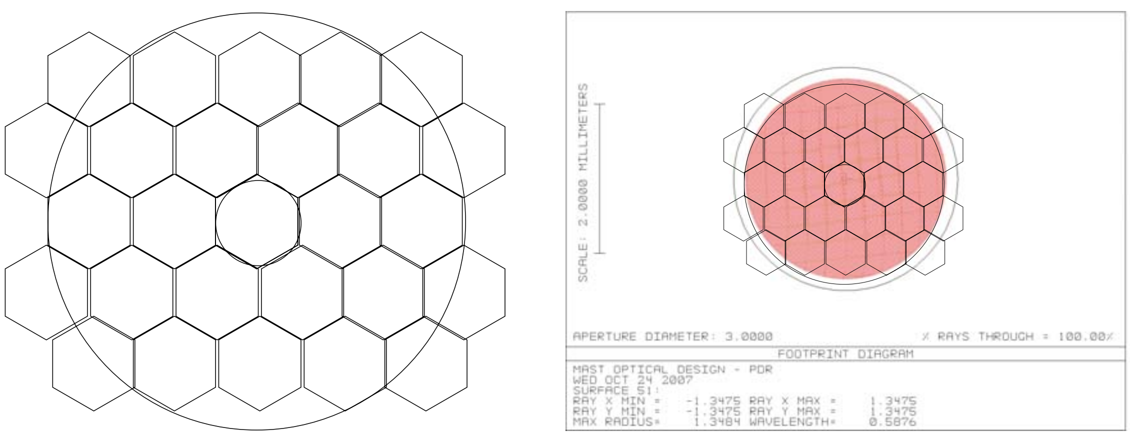


***Figure 4***. Schematic of the lenslet geometry and the beam foot print on lenslet array, circular ring on the lenslet geometry corresponds to re-imaged pupil.

4. **Key Issues**

a) ***Implementation of Algorithm to sense image motion***: 19 Sub-aperture images, which will be obtained with the LA are simulated and shown in Figure 6. A circular image of 50 pixels diameter will allow us to take square image of 34 × 34 pixels. Solar image of central lenslet image is considered as a reference image. And from remaining 18 sub-aperture images central 24 × 24 pixels are considered as shown in Figure 5, which enable us to move ±5 pixels for image motion estimation. The tilt angle, α associated with a seeing of '$r_0$' over a circular aperture of diameter 'D' is given by the relation [5] $\alpha \approx 0.6(\lambda/D)^{1/6}(\lambda/r_0)^{5/6}$ *rad.* For D = 10 cm (Sub-aperture size), λ = 0.5 $\mu$m, α varies from 1.0 arc-sec to 1.6 arc-sec as $r_0$ varies from 3 to 6 cm, that corresponds to 5-8 pixels in the present set-up. Though the present algorithm can sense upto 5 pixels, in the closed loop we expect the complete correction even under bad seeing conditions.

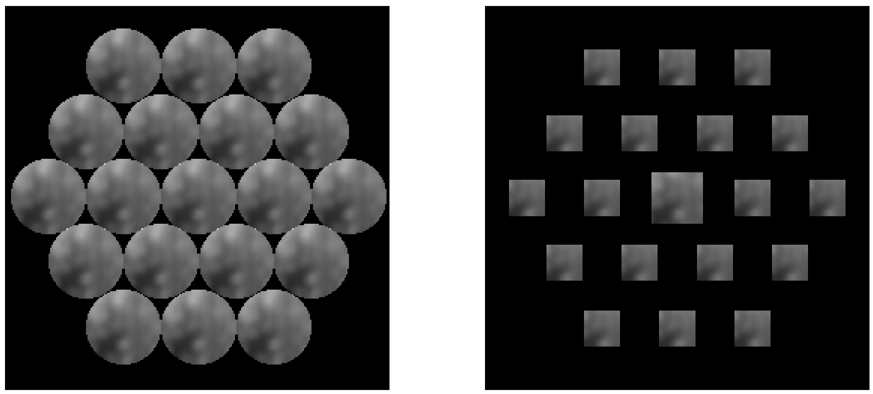

***Figure 6.*** Show simulated images of lenslet array and the implementation of SAD algorithm in the images. From the each circular image of diameter 50 pixels, 24 × 24 square image will be taken for SAD calculations. The central image, which will be a reference image is of size 34 × 34 pixels.

b) ***Calibration of TTM and DM:*** Calibration of TTM will be carried out using a pin-hole of size 0.4 mm at prime focal plane position, FP1, which forms 19 images of size 18 pixels on CCD. Following the procedure as explained in Sridharan *et al.,* [10], by applying the voltages in steps to actuators of TTM and observing the mean image motion from all the sub-apertures we can estimate the gain values for two channels of TTM. Similarly as explained in Raja Bayanna *et al.,* [7] calibration of DM can be carried out. Calibration of DM gives the influence matrix, which will be used to estimate the voltage required for each channel per unit pixel shift.

c) ***Photon Budget of the system:*** It is necessary to calculate the signal in the CCD for a given photon throughput to determine whether the sub aperture size is sufficient to collect enough number of photons when the wavefront sensing camera acquires images at a fast rate. Considering the following points the maximum counts are more than 200, which is sufficient to perform the shift calculation.

- Exposure time = 1 ms
- Efficiency = 0.01
- Bandwidth = 100 nm
- Angle subtended by each pixel = 0.2 arc-sec
- Responsivity of the CCD = 1.2 DN/(nJ/$cm^2$)

Here, for practical reasons we have considered efficiency factor of 1% instead of 15%, which was obtained with the designed optical set-up. Instead of quantum efficiency, responsivity was used, expressed in DN/ ($nJ/cm^2$)

## 5. Conclusions and discussion

An Adaptive optics system for MAST is proposed for achieving better resolution under the moderate seeing conditions at USO. The proposed system consists of 19 sub-apertures to sample the distorted wavefront and a MMDM with 19 usable actuators. A HP based work station with multi-core processors operating on Linux OS is proposed to perform the computation. The optical design of the system is presented here and it can be easily modified for a higher order AO system for improving the resolution further. The MMDM can be replaced with a more robust bimorph mirror in future. By adjusting the position of L4 in the optical set-up one can incorporate few more sub-apertures for sampling the wavefront.

6. References


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