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Characterization of adaptive optics mirrors using long trace profilometer

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A Long Trace Profilometer (LTP) was designed and fabricated in-house primarily to measure the profile of long, non-circularly symmetric grazing incidence optics. This system was used to calibrate the tip-tilt and deformable mirrors that we use for our adaptive optics research program. This paper gives optical layout and details of the LTP and the test results of tip-tilt mirror based on piezo-electric actuators and a deformable mirror based on Micro Electro Mechanical System (MEMS) technology.

1. Introduction

The images taken by all earth based big optical telescopes, even if they are optically perfect, cannot achieve their theoretical resolution because of the distortion created by the earth's atmosphere. The resolution of earth-based telescope is same as that of a 10 to 20 cm telescope irrespective of the size of the aperture. The degradation in resolution is more than 50 times for big telescopes. The random refractive-index inhomogeneities in the atmosphere, associated with turbulence, distort the characteristics of light traveling through the atmosphere. The limitation is due to warping of isophase surfaces and to intensity variations across the wave front, which prevents all portion of the optical element from "working together" [1]. Astronomers call this degradation as "seeing effect". Real-time stellar image correction methods, that is also called adaptive optics in a broader sense, removes the wave-front distortion introduced by the earth's atmosphere by means of one or more optical components that are introduced in the light path and which can introduce controllable counter wave-front, which spatially and temporally follows that of atmosphere.

The error in the in-coming wave front can be divided into two groups. The tilt in the wave front and the high frequency corrugation. If the wave front tilt is measured and corrected, than more than 50 % of the error can be removed [2]. Contribution of high frequency errors in the wave front is less. Once the tilt component and the high frequency component are resolved, separate mirrors can be used to compensate them. The optical components used in the present day technology of adaptive optics correction scheme are a tip-tilt mirror to remove the tilts in the wave front and a deformable mirror to generate the conjugate surface of the tilt removed wave front. Tilt mirror is based on a three-actuator piezo-electric tilt platform and the deformable mirror is made by MEMS technology. We are developing a low cost adaptive optics system using the above optical elements. We have developed Shack-Hartmann lenslet array based wave front sensor using CMOS (Complementary Metal Oxide Semiconductor) imager [3] for this purpose and the same is used for evaluating the incoming aberrated wave front

One of the major input for accurate control is to measure how these mirrors function for a given set of control voltages. In other words, these two mirrors have to be calibrated using certain reliable and acceptable procedure. Though Interferometric methods offer a choice, it cannot be used for large surface and tip-tilt errors. A long trace profilometer, in this respect offers a more convenient choice for sufficiently large range and accuracy. We have tested the tip-tilt mirror and deformable mirror with the in-house developed Long Trace Profilometer (LTP). This paper gives details about the principle involved, optical layout and details of the subsystems of LTP. Tests conducted on the

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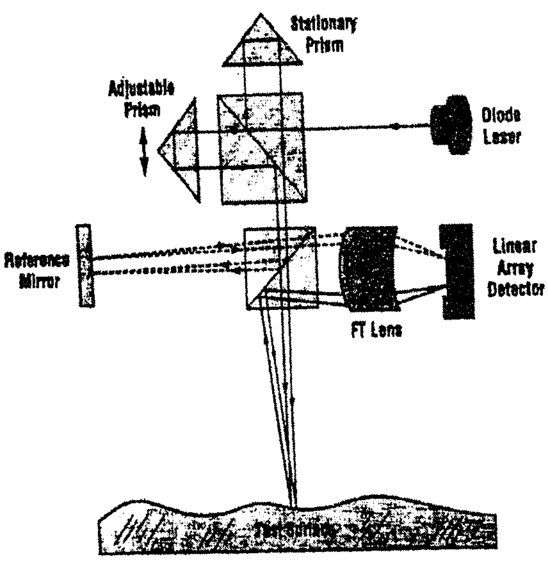

Figure 1: Optical setup of typical LTP.

behavior of the tip-tilt mirror and deformable mirror and the surfaces produced are given. Comparison is made with the results obtained by finite element analysis of the mirror.

2. Long Trace Profilometer (LTP)

The LTP belongs to the class of "slope measuring " interferometer rather than the "height measuring " interferometer. It measures the phase difference between two co-linear probe beams as they move across the surface. It is reasonably insensitive to vibrations which makes it suitable for use in normal laboratory or optical shop environments and becomes a specific choice for the metrology of the long flat and spheroidal mirrors, both during fabrication and post evaluation.

The LTP is basically designed and built for absolute figure measurement on large flats, spheres and aspherics upto about 1000 mm in size, particularly for strip mirrors. A typical LTP optical schematic is shown in Figure 1 [4, 5].

Our new system uses lateral Shearing Interferometry principle (Figure 2). It basically consists of laser source, filter (F), Babinet Compensator (B.C), beam splitters (BS1, BS2), Achromats (L1 and L2), Aperture (A) reflecting optics, and the detector based on CCD camera. The surface under test (SUT) is compared with a reference surface in the interferometer and the fringes are captured by the CCD camera system and the surface analysis is done in the computer.

This instrument is capable of measuring profiles of 900mm long mirrors with accuracy of tangent errors ≤ 0.25 arc sec. Figure 3 shows the actual instrument used for the measurement of the tip tilt mirror and adaptive optics mirror that are being used for our adaptive optics experiments.

3. Testing of Tip-Tilt mirror

The tip-tilt mirror system is made up of three piezo-electric actuators located at 120° from each other and a reflecting mirror is pasted on top of the platform to reflect the light. High voltage

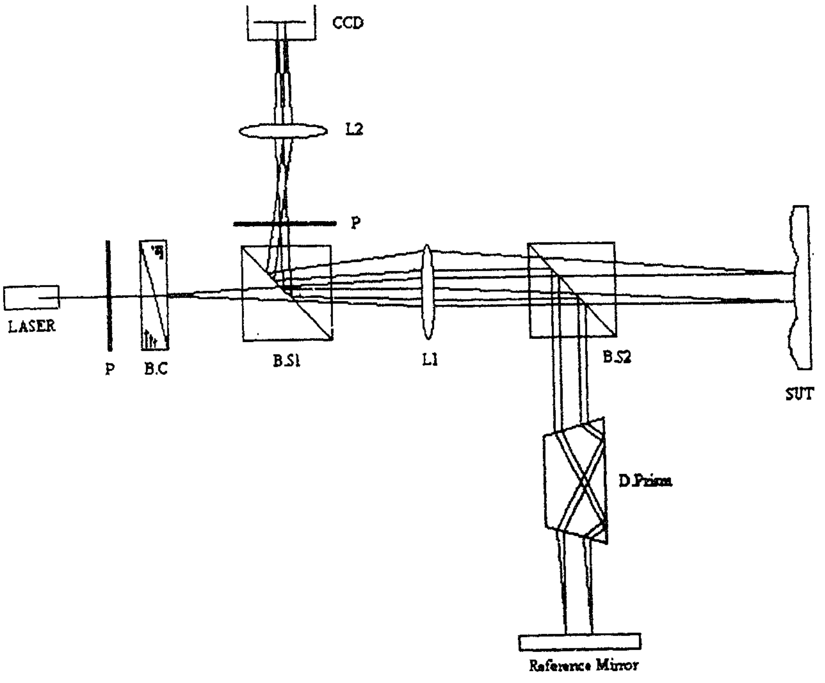

Figure 2: Optical layout of the LTP using shearing interferometer principle.

power amplifiers drive the actuators. We have found that piezos respond even for very small voltage increments thus giving positioning accuracy in nanometer range. The Hysteresis noticed in these actuators can be eliminated by closed loop control with position sensors. We have tested the tip-tilt mirror using LTP by applying voltages from zero volts unto 23 V then started decrementing the voltage back to zero. The reading of the maximum of the central fringe is noted.

Figure 4 is a plot of maximum fringe position with voltage applied to one of the piezo actuator for an input signal varying from zero to ten volts and back to zero volts. The measurement accurately shows the hysteresis present in all the piezo actuators.

3.1 Working of Deformable mirror

The flexible membrane mirror is formed by low-stress nitride membrane suspended on the edge of a window, etched into a silicon die. Aluminium coating is given on top of this to give reflectivity. This die is mounted on a printed circuit board with spacer in between in which hexogen shaped patterns are etched. Figure 5 gives the configuration of the 37 actuators used for the deformable mirror. The same set up was used to test this. The deformable mirror poses special problem for control. If one actuator is energized, not only the surface in front of this actuator is being pulled, but nearby surface is also influenced by it. This influence function is to be determined fcr effective control of such mirrors.

4. Measurement of surfaces generated by MEMS based 37-channel membrane mirror by LTP.

The deformation at a given point on the mirror surface depends on all actuator signals. The center-

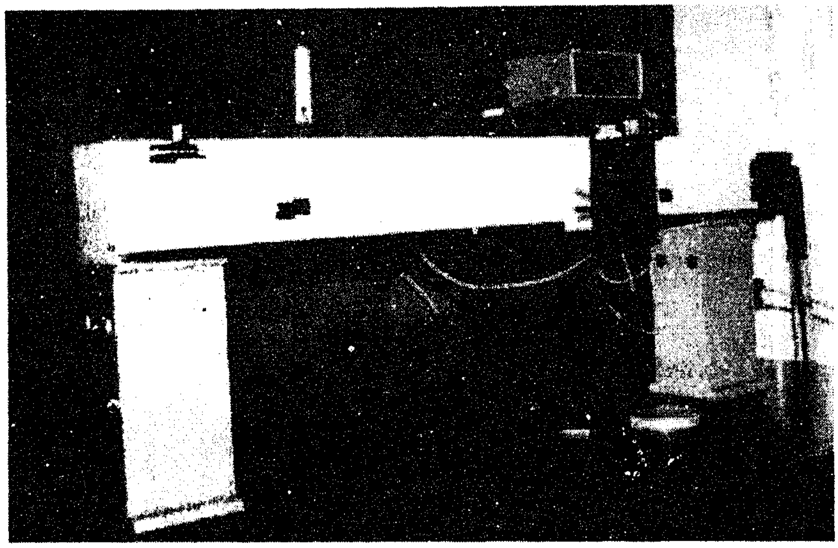

Figure 3: Long Trace Profilometer setup in the laboratory

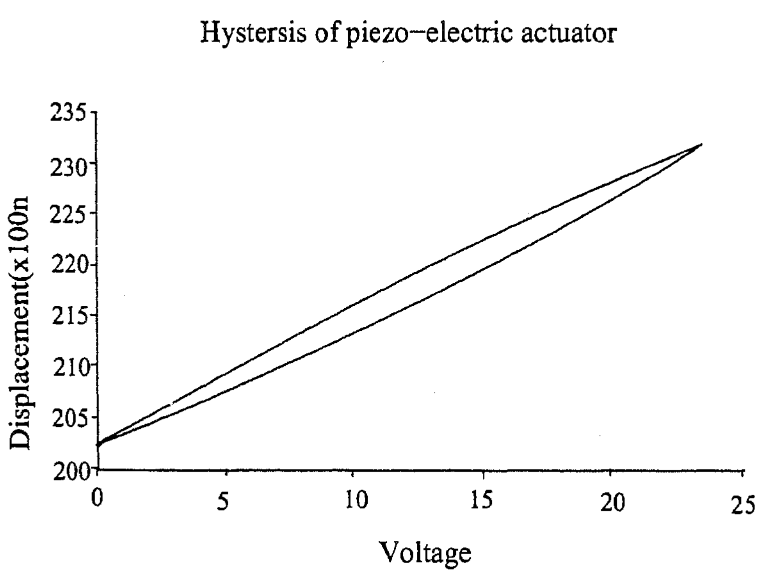

Figure 4: Hysteresis of one of the actuator measured with LTP

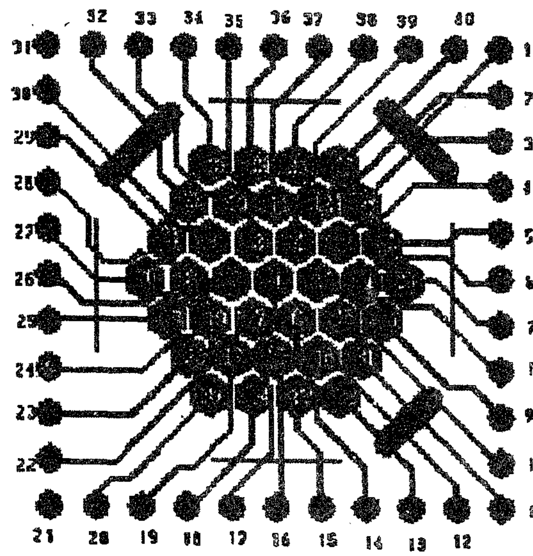

Figure 5: 37-channel OKO MMDM actuator layout

to-center actuator distance is 1.75 mm while actuator structure is located within a 12 mm diameter equivalent circle under the mirror membrane. Each actuator is a hexogen of 1.5 mm size [6]. The central hexogen actuator is surrounded by other actuators in three rings with 6, 13 and 17 actuators.

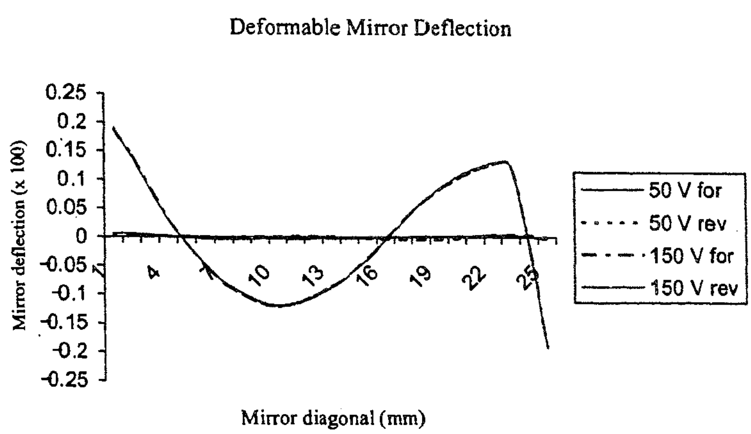

Figure 6: Mirror profile for forward and reverse direction voltages: No hysteresis is seen

As the LTP can measure the profile only in a straight line, we have placed the mirror under LTP such that the laser beam passes through the center of the mirror and the graphs shown is the profile of the mirror for a line passing through the diagonal. The mirror is rotated about its optical axis to measure deformation in the other axis. These values are used for the generation of three dimensional figures. Voltages for all the 37 channels were produced by 37 DACs and the signals were then connected to high voltage amplifiers. The actuators can be given a maximum of 220V. To find out whether any hysteresis present in the mirror, experiment was conducted by applying 50V and increasing to 150V and the experiment was repeated by reducing the voltage from 150 to 50 V. Figure 6 shows the response of the mirror for 150V applied in the forward and reverse direction and the profile of the two curves matches very well showing that the mirror did not have any hysteresis.

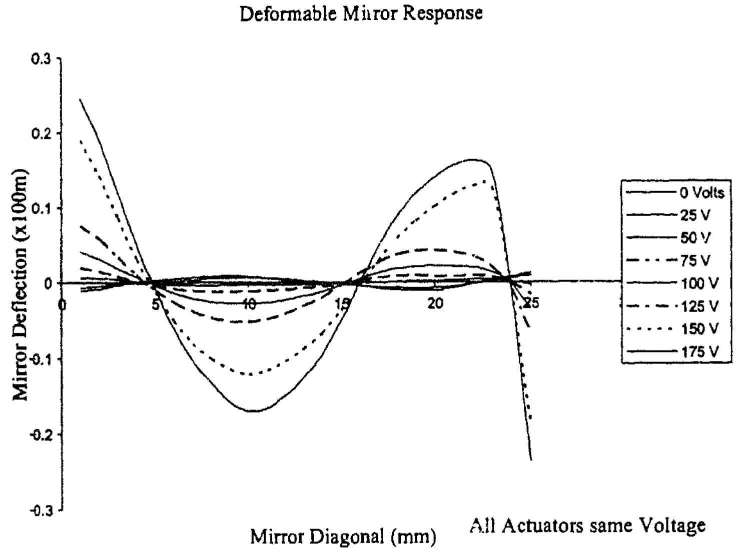

Figure 7: Surfaces created by the mirror for different voltages

It is found that when the actuator voltages were off, the initial mirror surface was not flat (Figure 7: 0 volt). When 50 V were applied to all actuators, we can see the tendency of the mirror surface to become flat (Figure 7: 50 V). We have seen earlier that voltage of 51.4 V to all actuators gives a flat surface. This measurement was done using Zygo interferometer by applying varying voltages to the actuator and observing the null fringe. This was again validated by the LTP measurement. Figure 8a shows the three dimensional (3-D) view of the mirror surface for 50 V and Figure 8d shows the two-dimensional (2-D) profile of the surface. We have applied increasing voltages in increments of 25 V and measured the profiles, which are shown in fig. 7 in different line style. From these curves, it can be seen that the useful area of the mirror to generate surfaces, depending on the voltages applied, is about 11 mm out of the mirror size of 15 mm. The concave surface generated by the mirror deepens as the voltage is increased. Figure 8b shows the 3-D view of the mirror which is a good parabola when 175 V was applied to all the 37 actuators. Figure 8e shows the line profile for 175 V. As the positions of the actuators are approximately circularly symmetric with respect to central actuator, the mirror influence function can be calculated from the above data when same voltage is applied to all the actuators. Figure 8f shows the shape of the mirror when the central actuator (actuator 1) and actuators in the second and third rings (actuators 8 to 37) were given 50V (which generates flat surface of the mirror) and actuators in the first ring (actuators 2 to 7) were given 100 V. We can see a small convex surface at the position of the first actuator. When the first actuator alone was given 50V while rest of the actuators are given 100 V, a flat surface at the position of the first actuator was also seen. The above experiment shows that the mirror is capable of generating flat, concave, convex and other complicated surfaces. Table 1 lists the voltages given to the actuators and corresponding figure numbers.

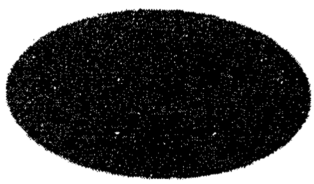

Fig 8 a

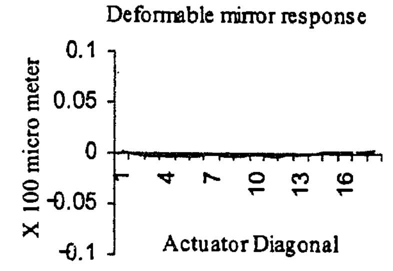

Fig 8 d

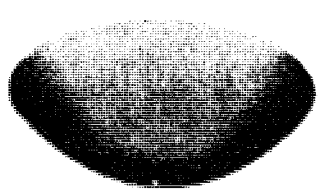

Fig. 8 b

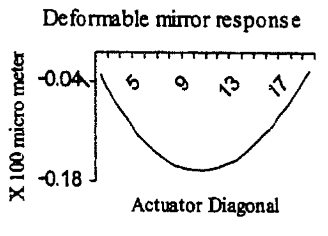

Fig. 8 e

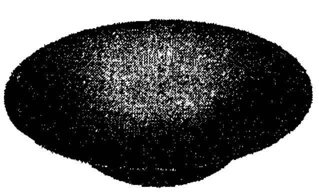

Fig. 8 c

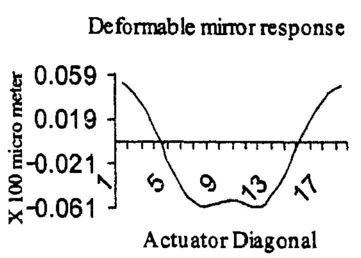

Fig. 8 f

3-D slant view of adaptive mirror

Plot of Distance Vs depth

Figure 8: Three dimensional view and Two dimensional cross-section of the mirror surface

Table I
Lists the voltages applied to the actuators and corresponding Figure numbers

	Actuator number Voltage	Figure No	Legend
1	All actuators 0	7	0 V
2	All actuators 25	7	25V
3	All actuator 50	7	50V
4	All actuators 75	7	75 V
5	All actuators 100	7	100 V
6	All actuators 125	7	125 V
7	All actuators 150	7	150 V
8	All actuators 175	7,8b,e	175 V
9	All actuators 50	6	50 V For
10	All actuators 50	6	50 V Rev
11	All actuators 150	6	150 V For
12	All actuators 150	6	150 V Rev
13	Actuator1 50 Actuators 2 to 7 100 Actuators 8 to 37 50	8 c, f	

5. Finite element analysis of the mirror

We have done finite element analysis of the membrane mirror [7] to find out the mirror influence function. Figure 9 gives the shape of the mirror when the central actuator and actuator in the first, second and third ring is applied unit force. The depths of the mirror surface vary, maximum being below the central actuator which is at position 4. We can see that for the same force, the maximum depth given by the mirror reduces as the ring approaches the edge.

The mirror shape shows a sharp depression. Figure 7 shows the shape of the mirror as measured by the LTP which gives a smooth surface. It can be seen that the measurement given by LTP matches very well to the physical nature of the silicon membrane mirror, hence the mirror influence function derived from the measurements with LTP is more realistic which will enable accurate control of the membrane mirror.

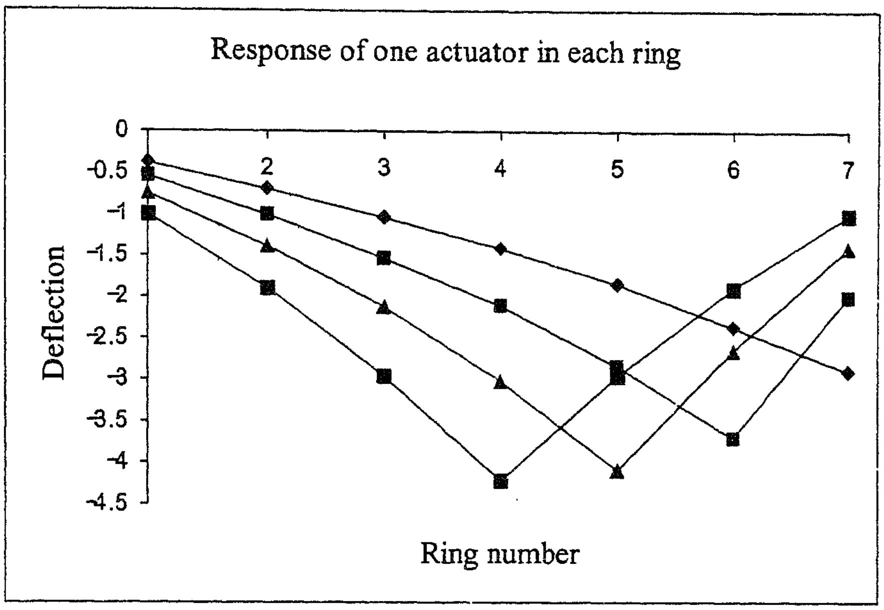

Figure 9: Response of the actuator in the center, 1st, 2nd, 3rd and forth ring

6. Conclusion

The aim of this experiment is to calibrate and check the performance of control mirrors used in our adaptive optics research work. While flat and concave mirror surfaces with less sagita can be easily measured with interferometers available with us, deep surfaces generate by the adaptive mirror produces hundreds of fringes which the interferometer could not handle. Finite element analysis is purely a theoretical approach and the results largely depend on the various mechanical and electrical parameters of the mirror system given as input for analysis. We were in need of a direct measurement of the complicated surfaces generated by the adaptive mirror. The LTP provided very handy method to measure the surface profiles in a very accurate manner.

It is seen from the above data and graphs that the LTP is capable of giving very accurate measurement of profiles of complicated optical surfaces. From the study of the behavior of the tip-tilt and deformable mirrors, it is clearly seen that LTP facilitates an accurate and suitable means of characterizing the adaptive optics mirrors. The instrument's range and sensitivity is good enough to measure unconventional optical surfaces and the size of the optics is also not a constraint. Influence function, which is required for control of the adaptive mirror, can thus be experimentally determined for these mirrors with much ease. In conclusion, we have seen from the graphs presented above that the piezo actuator is having hysteresis and suitable counter-measure is required to compensate hysteresis produced in the control system of the tip-tilt mirror system. As for as the deformable mirror is concerned, it is found that when power is not applied to the actuators, the surface is not flat and has small aberrations. It is also seen that this error could be easily removed and made to a flat the surface by applying suitable voltages to all the actuators. It is seen from the LTP measurements that both concave and convex surfaces of suitable curvature and flat surfaces can be generated easily by applying appropriate control voltages to selective actuators. The mirror can produce surfaces with smooth profiles. The curves produced from the finite element analysis gives very sharp edges and the mirror surface looks like 'V'. The material of the mirror is a membrane made out of silicon nitride and production of sharp edges like the one seen in 'V' shape cannot be produced in a silicon mirror. The footprints of the actuator can be clearly seen in Figure 8 c where as the FEM analysis did not show the footprints of the actuator. LTP directly measures the surface profiles generated by the MEMS mirror to a good accuracy. This also proves that the newly built LTP is indeed suitable to measure profiles of mirrors with odd shapes to a very good accuracy.

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