A new approach to stellar image correction for atmospherically degraded images

V. Chinnappan

Guide: Dr. A. K. Saxena

Electronics Division
Indian Institute of Astrophysics
Photonics Division
Indian Institute of Astrophysics

- Introduction
- Turbulence Theory-as applicable to astronomical seeing
- Seeing measurement at short intervals
- Requirements of real time error measurement & correction system (Adaptive optics)
- Wavefront sensor theory , Design and implementation
- Characterization of Adaptive mirrors
- Control system for Adaptive mirrors
- Lab setup for wavefront measurement and correction system
- Results and Conclusion

- Resolution of an ideal telescope $= 1.22\lambda / D$
- The actual resolving power of the big telescopes of today, even if they are optically perfect, cannot achieve a resolution better than the resolution of 10 to 20 cm diameter telescope, because of the atmosphere.
- Newton said, “If the Theory of making Telescopes could at length be fully brought into Practice, yet there would be certain Bounds beyond which telescopes could not perform. For the Air through which we look upon the Stars, is in a perpetual Tremor…The only Remedy is a most serene and quiet Air, such as may perhaps be found on the tops of the highest Mountains above the grosser Clouds”

- Babcock(1955) was the first to give a schematic idea as how to compensate for the bad seeing. Due to technological limitations of his time, his idea could not be realized in practice.
- Military has similar requirements (Eg. Star war programs) . Most of the technology for real-time image improvement techniques were developed by U.S. military programs.

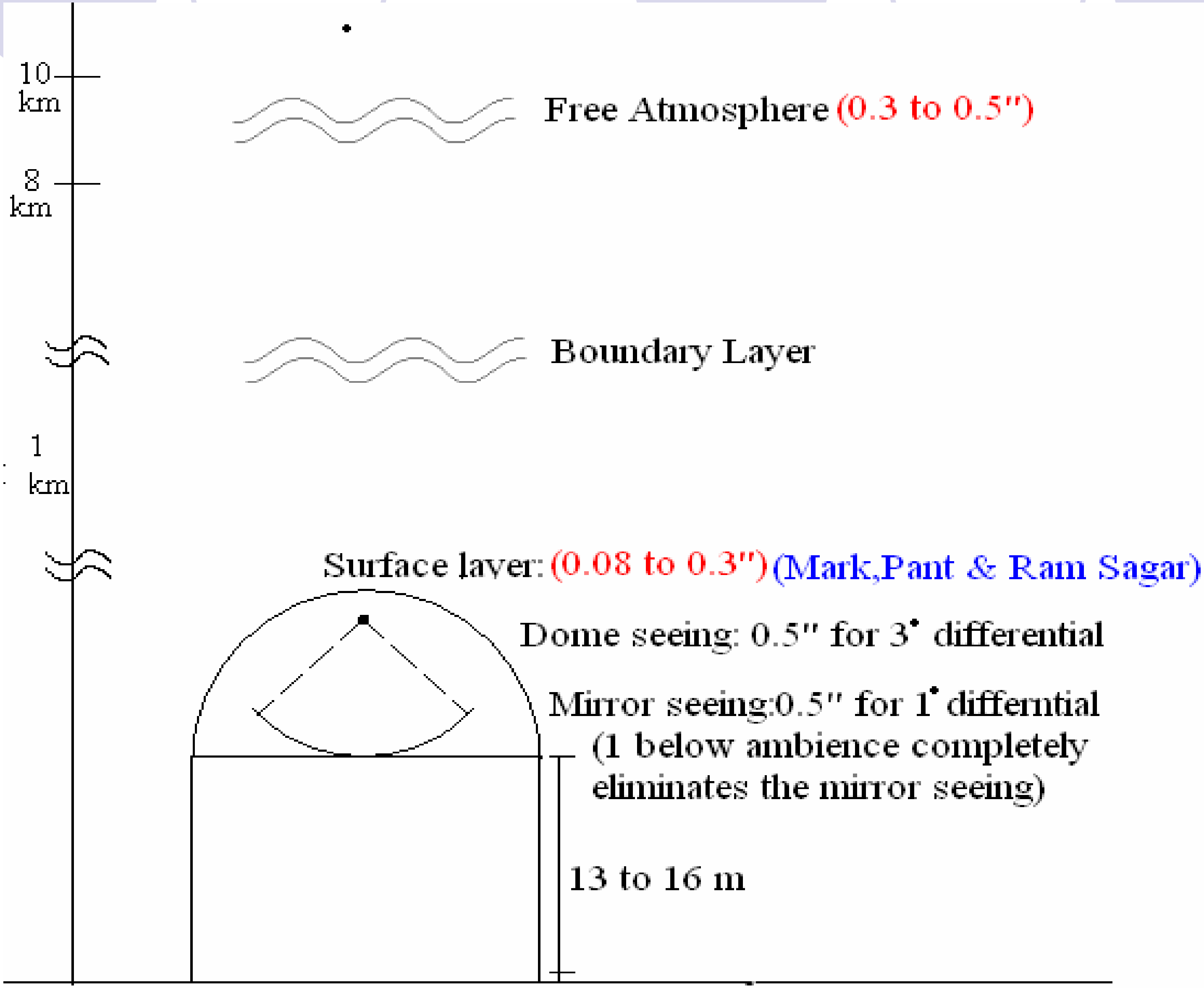
Turbulence Theories

- In a much simplified version, the seeing can be represented by a single parameter called Fried's parameter $r_{0.}$
- $r_0 = (16.7\ \lambda^{-2} \int Cn^2(h)\ d(h)-^{3/5}$
- $\varepsilon_{fwhm}\ =\ 5.25\ \lambda\ -^{1/5}\ (\int Cn^2(h))\ d(h)^{3/5}$

Cn – Refractive index structure function

h - Height

Turbulence Theories



Turbulence Theories

- J.Vernin measured the surface layer contribution alone at a height of 12 m to be 0.08” which is almost negligible
- R.D.Marks measured the contribution of seeing due to different layers on the high Antarctic plateau.The contribution of surface layer was more but the contribution of free atmosphere was 0.23 to 0.26
- Micro-thermal measurement of surface layer seeing at a Himalayan mountain range of India was reported by Pant and Ram Sagar, the contribution of this layer above 13 m is 0.32

Turbulence Theories

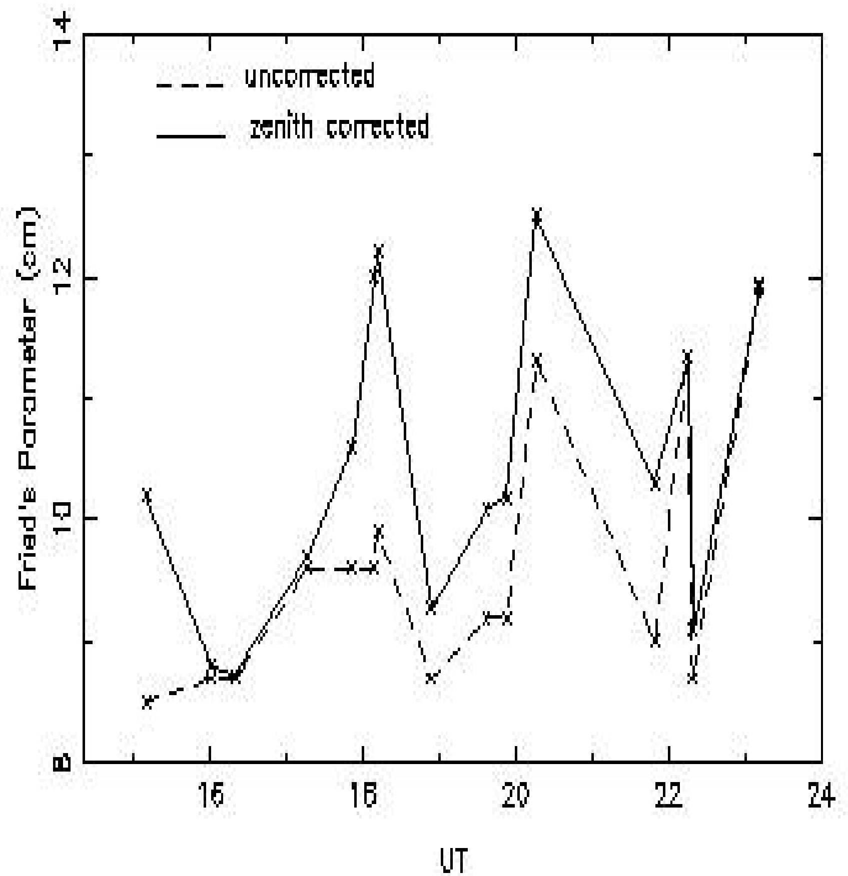
- Conclusion : The contribution of the atmospheric layer at 8 to 12 km height; free atmosphere, is an important contributor .Seeing is about 0.3” to 0.5” at visual wave length.
- It has been customary to build large telescopes to less than diffraction limited standards. Infra-red telescopes can have diffraction limits
- Apparent star diameter is 1 to 50 milli arc-seconds

  (1 milli arc-second=275 billionth of a degree)
- Resolution of telescope with atmosphere $=1.22\ \lambda / r_0$

Typical Values 0.3” to 2” at 500 nm - much better at 2μm

Seeing At Short Intervals

- It was theoretically shown by Fried that short-time exposures in the order of atmospheric coherence time which is in the order of a few tens of milliseconds, where the image motion is frozen, contains higher resolution information
- Night time variations of Fried's parameter at VBT Kavalur .S. K. Saha and V. Chinnappan , Bull. Astron. Soc. India



Methods Of Image Improvement

- **1. On-line methods**
- **a) Optical Interferometry**

A.A.Michelson, 1920, Astrophysical Journal 51:257

R. Hanbury Brown , J. Davis, L. R. Allen, 1974, MNRAS 167:121

- Stellar Interferometry methods

A. Labeyrie, Annual Rev. Astron. Astrophysics 116:77-102, 197

b) Adaptive Optics

The essential subsystems of an adaptive optics system are

- Wavefront sensing
- Wavefront error computation
- Control of adaptive mirrors

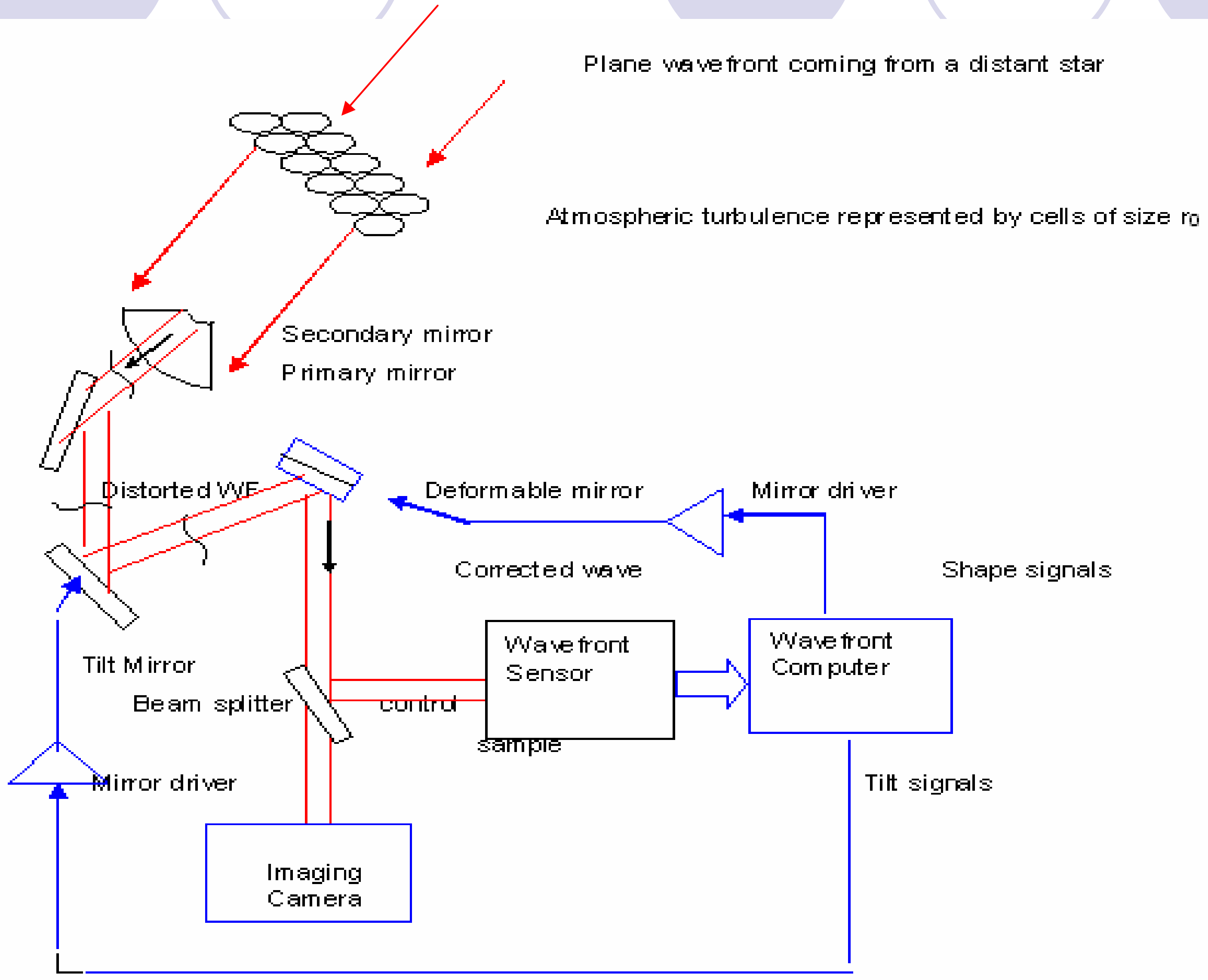
Methods Of Image Improvement

- **2. Offline methods**
- **Speckle Interferometry**
- **Laberie (1971)**

Development of a speckle interferometer and the measurement of Fried's parameter r_0 at the telescope site

S. K. Saha, G. Sudheendra, A. Umesh Chandra, V. Chinnappan, Experimental astronomy 9,39 (1999)

Block Diagram Of Atmospheric Correction System



Wavefront representation with Zernike polynomials

$Z\ j_{even} = [2(n+1)^{1/2} R_n^m(r) \cos m\theta]$ when $m \neq 0$

$Z\ j_{odd} = [2(n+1)^{1/2} R_n^m(r) \sin m\theta]$ when $m \neq 0$

$Z\ j = [(n+1)^{1/2} R_n^m(r) \cos m\theta$ when $m = 0$

Where

$$R_n^m(r) = \sum_{S=0}^{(n-m)/2} \frac{(-1)^s (n-s)!}{s!\,[(n+m)/2 - s]!\,[(n-m)/2 - s]!} r^{n-2s}$$

The values of n and m satisfy the following condition;

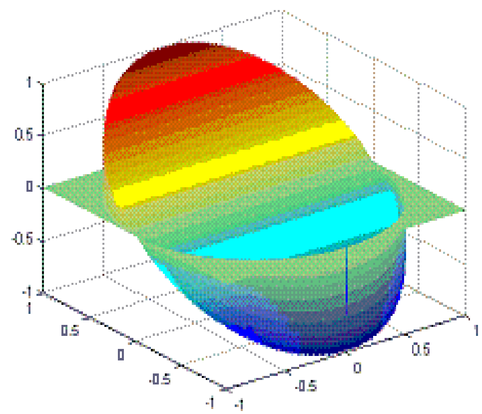
$m \leq n$, and n-m is even. The index j is a mode ordering number derived from m and n. The total number of modes up to a given radial order is

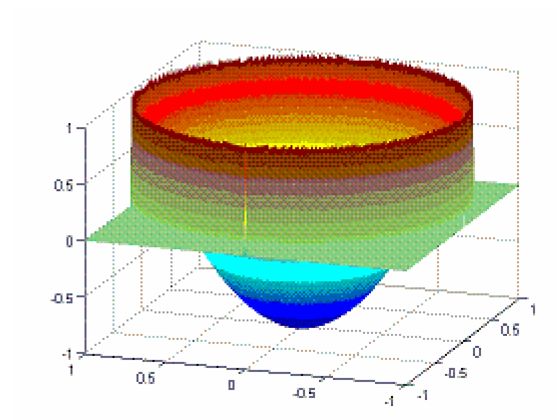
$$j_n = (n+1)(n+2) / 2$$

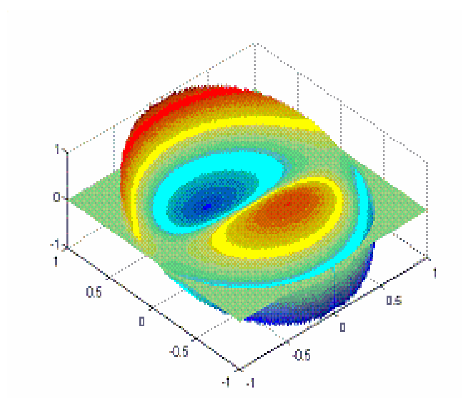
Number of zernike polynomial terms to be used depends on application

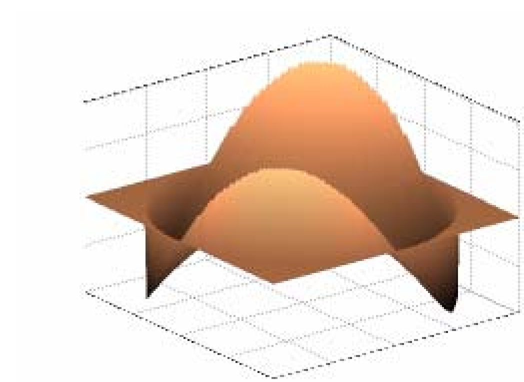
- Roddier has used only two terms (X tilt and Y tilt) alone in a low-order adaptive optics and found good improvement in the image
- Higher order errors have less effect on the image
- Computation of many terms increases the time restricting the speed of correction
- Number of lenslets to be used for wave front sensing depends on the number of terms chosen. Here, 14 Zernike terms are chosen

- w=X*c(1)+Y*c(2)+(X.*Y)*2*c(3)+(1+2*X.^2+2*Y.^2)*c(4)+(Y.^2 -X.^2)*c(5)+(3*X.*Y.^2-X.^3)*c(6)
  +(-2*X+3*X.*Y.^2+3*X.^3)*c(7)
  +(-2*Y+3*Y.^3+3*X.^2.*Y)*c(8)+(Y.^33*X.^2.*Y)*c(9)









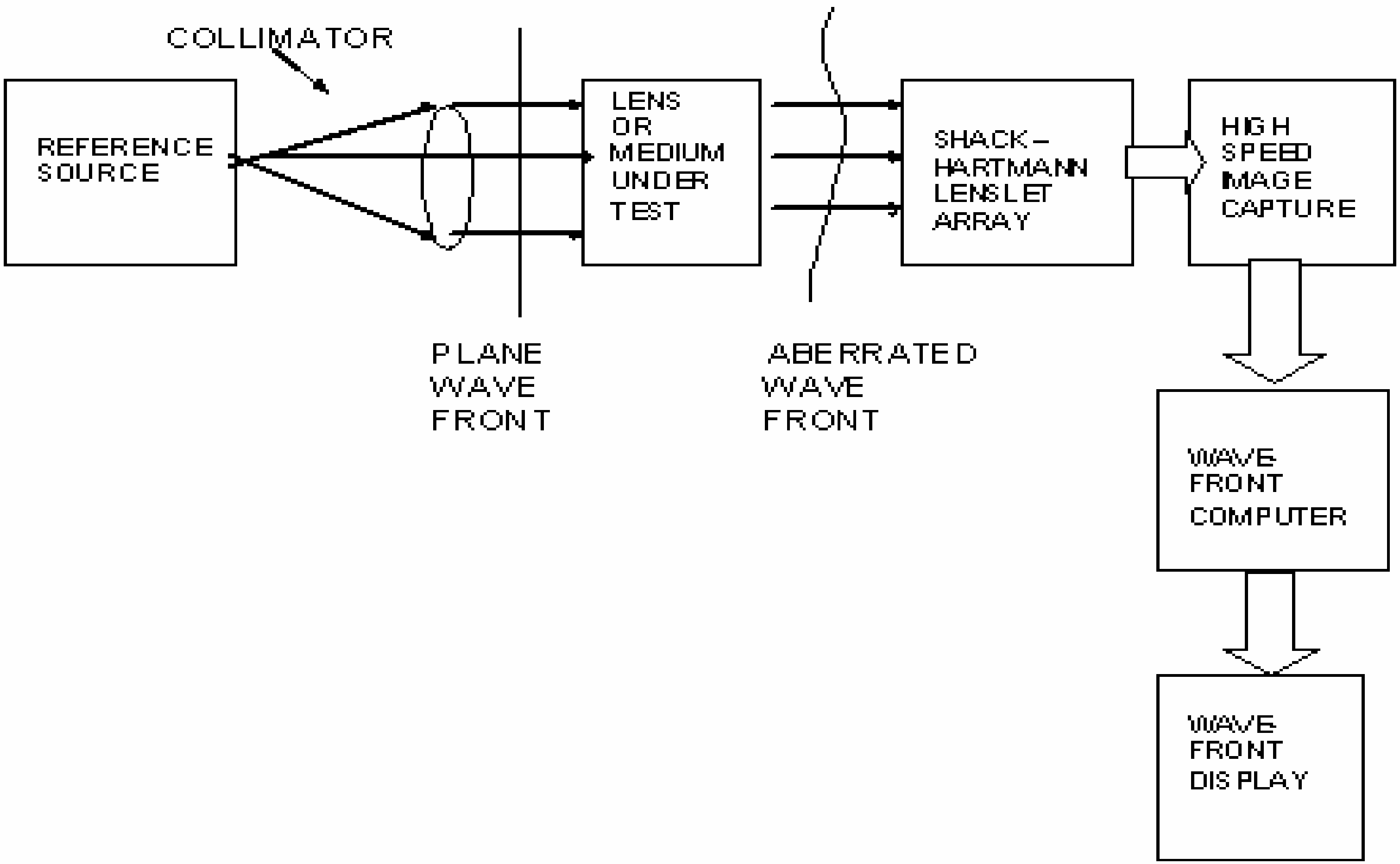
Wavefront sensing

- Shack – Hartmann technique
- Curvature sensing (Roddier Univ. of Hawaai)
- Lateral Shearing Interferometry (Saxsena – IIA)
- Interferometric Hartmann wavefront sensor
- (Univ. of Arizona)
- Pyramid wavefront sensor (Italy)
- Neural network wavefront sensor. (Univ. of Arizona)

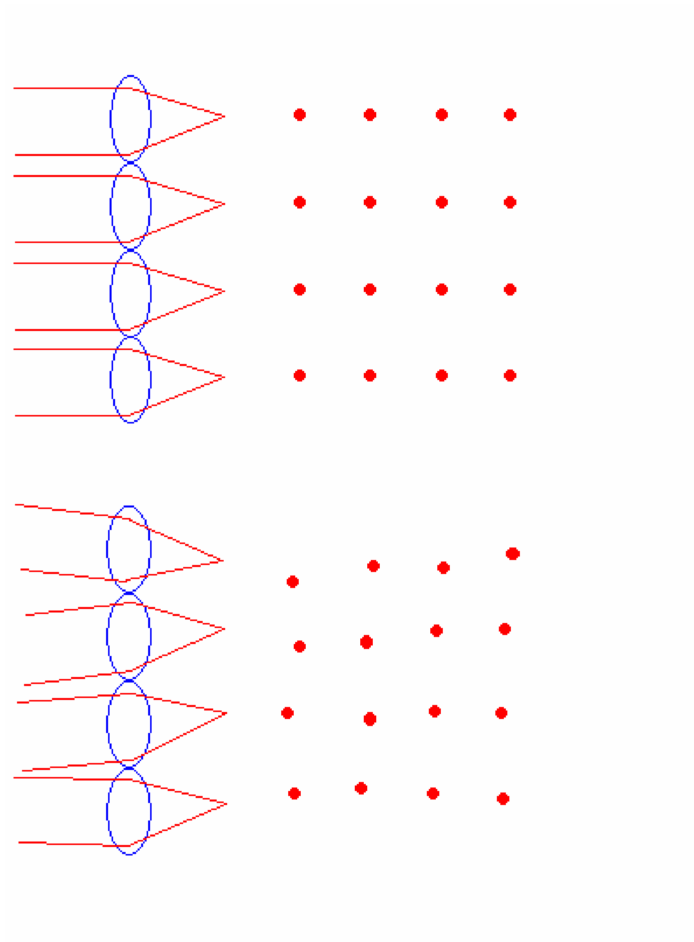
The new Low Cost Approach

- Fast CCD cameras are expensive So newly developed low cost CMOS imagers are chosen for experimentation
- Mirrors fabricated with IC technology costs much less ($ 2000) compared to old piezo based mirror ($ 40000) for 37 actuators. Electronic controls costs comparable to mirror cost. Hence MEMS mirrors are chosen
- PC costs have come down with increasing MFLOPS. PC is chosen for measurement and control instead of dedicated parallel processors and DSPs

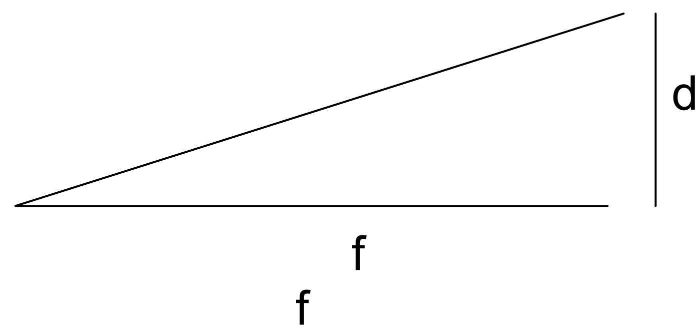
Shack – Hartmann technique



Shack – Hartmann technique



- Total no of lenslets:69*69
- Lenslet size:300 μm
- Focal length:41 mm
- Thickness:1 mm
- Size:25*25 mm
- Material: Glass

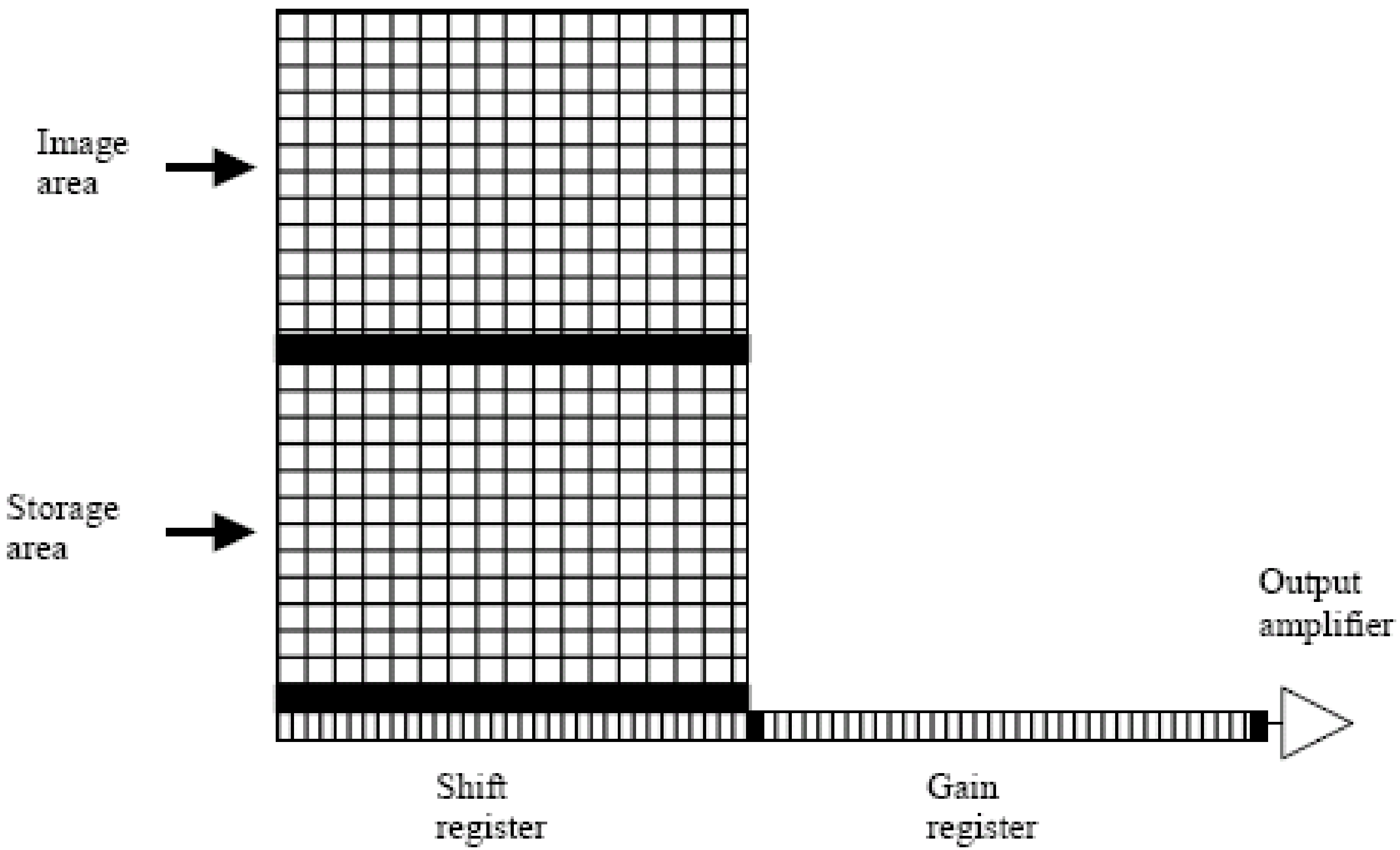


CMOS Based Imaging Sensor

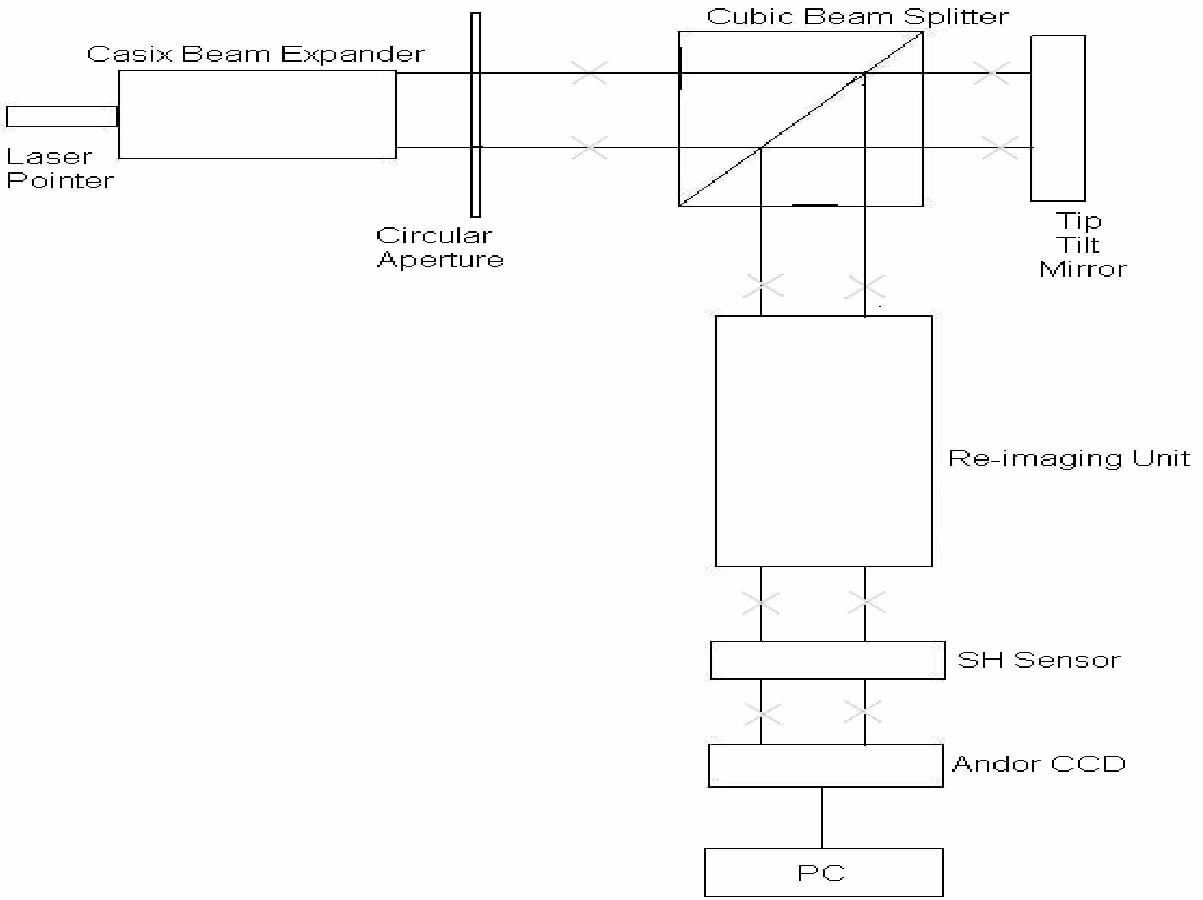
- Parallel and random sensor access
- CMOS fabrication technology
- Camera on a chip
- Active pixel sensor
- On-chip multiple A/D converter
- Non-integrating type pixel
- 6.4 * 6.4 mm optical area
- Reference current source for calibration
- 15 % pixel is light sensitive

Schematic of low light level CCD

Major improvement after 30 years



SH Lenslet Based Wavefront Sensor



Shack-Hartmann Wavefront Sensor

The algorithm or steps to reconstruct the wavefront is given below.

- Step 1: Grab the reference image from Shack-Hartmann sensor.
- Step 2: Calculate the centroid positions of focal spots of reference image.
- Step 3: Grab the aberrated image from Shack-Hartmann sensor.
- Step 4: Calculate the centroid positions of focal spots of the aberrated image.
- Step 5: Calculate the difference of the centroid positions of reference image and those of aberrated image. These differences represent average wavefront slope values at each sub aperture. Arrange these differences in a matrix [S].

Shack-Hartmann Wavefront Sensor

- Step 6: Normalize the reference plane centroids such that all spots come inside the unit circle
- Step 7: Calculate derivative of Zernike polynomial, of required degree N, w.r.t. x and y, at M reference spots inside the unit circle. Arrange these values in a matrix Z of size 2xMxN.
- Step 8: Fit this matrix [Z] and slope value matrix [S] in to polynomial by least square fitting method, i.e.,

$$[Z][A] = [S]$$

- Step 9: Find the coefficients Ai of Zernike polynomial by matrix inversion, i.e.,

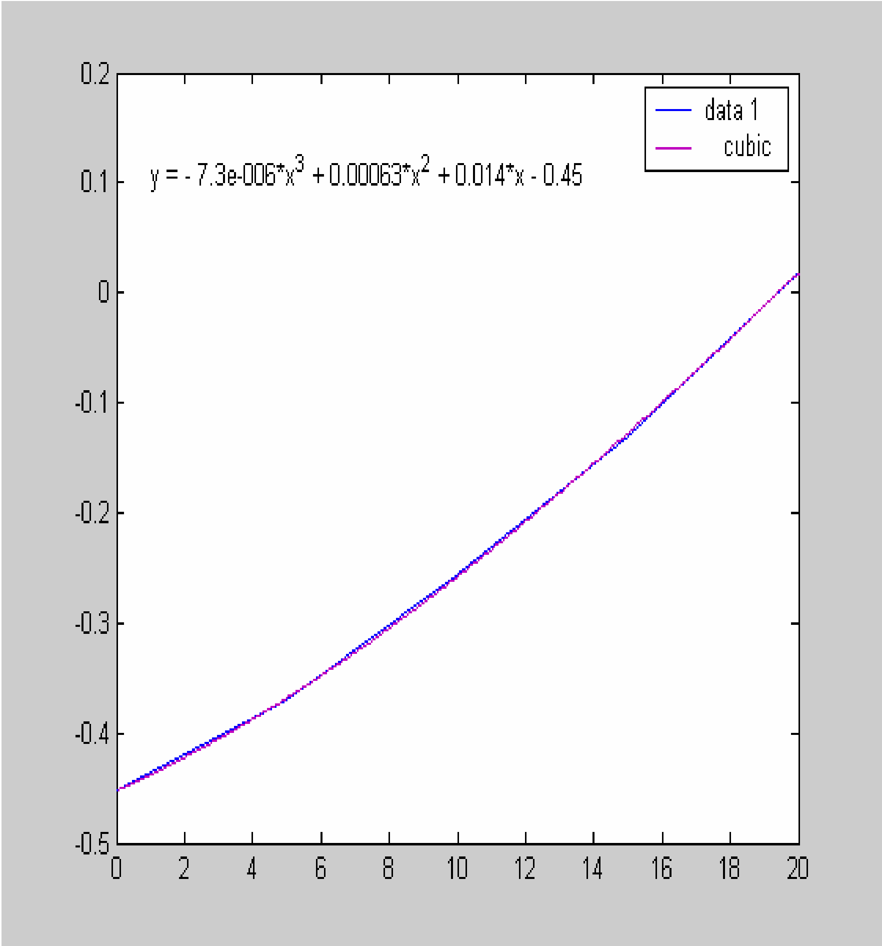
$$[A] = [Z]^{-1} [S].$$

- Step10: Reconstruct the wavefront using these coefficients and display wavefront.

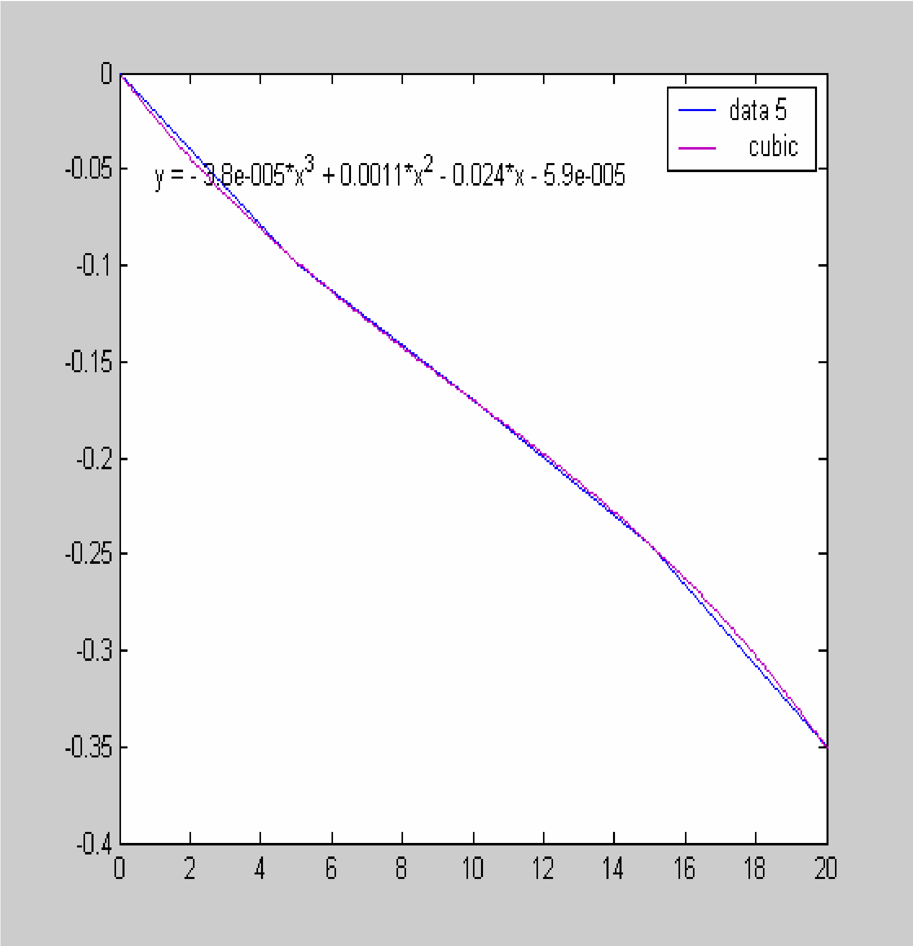
V. Chinnappan, A.K.Saxena et al. ASI meeting, Thiruvananthapuram(2003)

s	s	a=0,b=0,c=0	X= 0 Y= 0	Reference image
s	u	a=15,b=0,c=0	Y= 0.2746 X= 0.0085	Tilt in y
s	v	a=20,b=0,c=0	Y= 0.432 X= 0.0105	Tilt in y increases
s	w	a=20,b=5,c=0	X= -0.1307 Y= 0.4192	Tilt in x and y
s	x	a=20,b=10,c=0	X= -0.1813 Y= 0.4127	“
s	y	a=20,b=15,c=0	X= -0.396 Y=0.3224	“
s	z	a=20,b=20,c=0	X= -0.5499 Y= 0.3610	“
s	i	a=20,b=20,c=5	X= -0.4148 Y= 0.3104	“
s	j	a=20,b=20,c=10	X= -0.3436 Y= 0.1750	
s	k	a=20,b=20,c=15	X= -0.1818 Y= 0.0745	
s	l	a=20,b=20,c=20	X=-0.0092 Y= 0.0183	Equivalent to reference image
s	m	a=15,b=20,c=20	X= -0.0066 Y= -0.1297	Y tilt in negative dir
s	n	a=10,b=20,c=20	X= -0.0398 Y= -0.2552	“
s	o	a=5, b=20,c=20	X= -0.0444 Y= -0.3704	“
s	p	a=0, b=20, c=20	X=-0.0764 Y= -0.4521	“

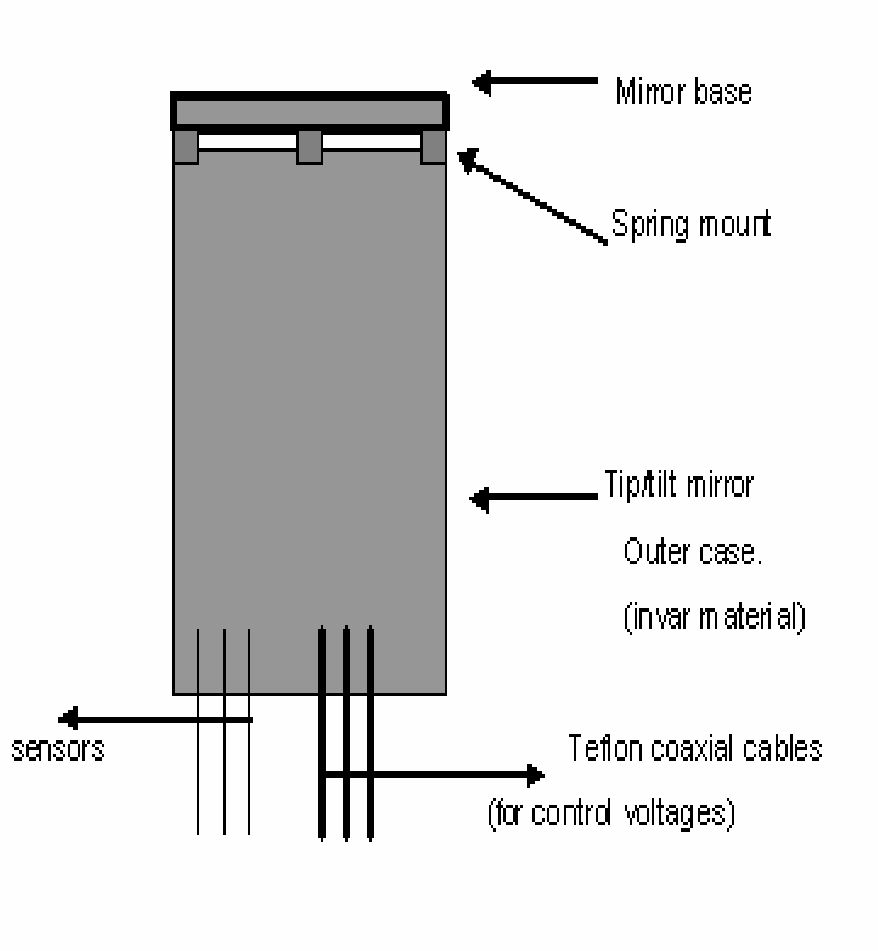
CMOS Imager



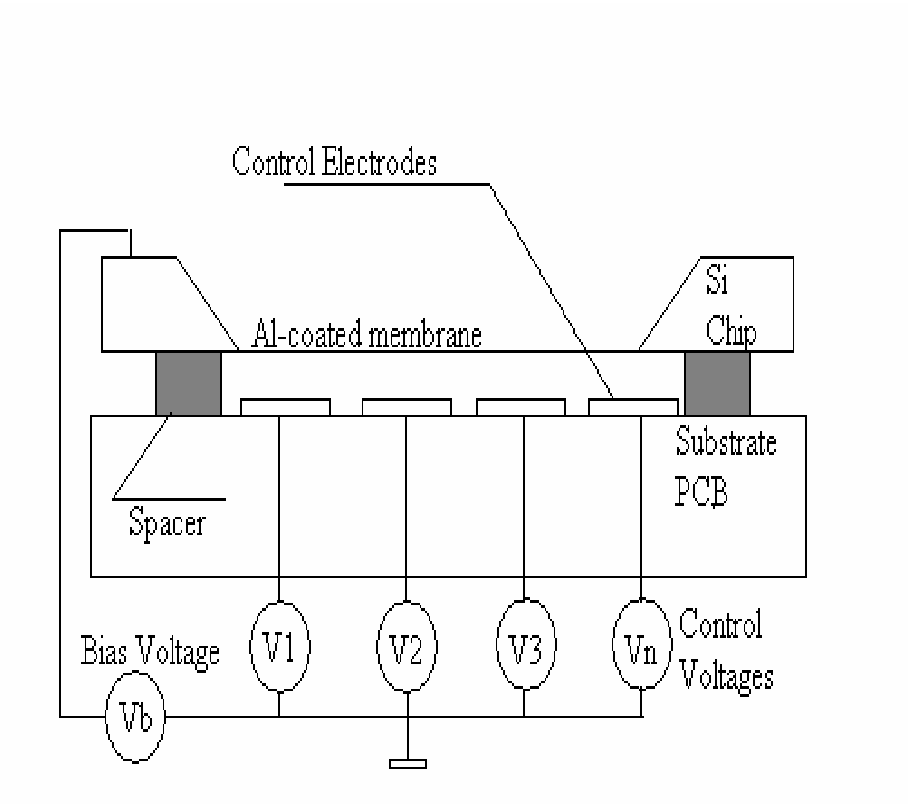
LLLCCD



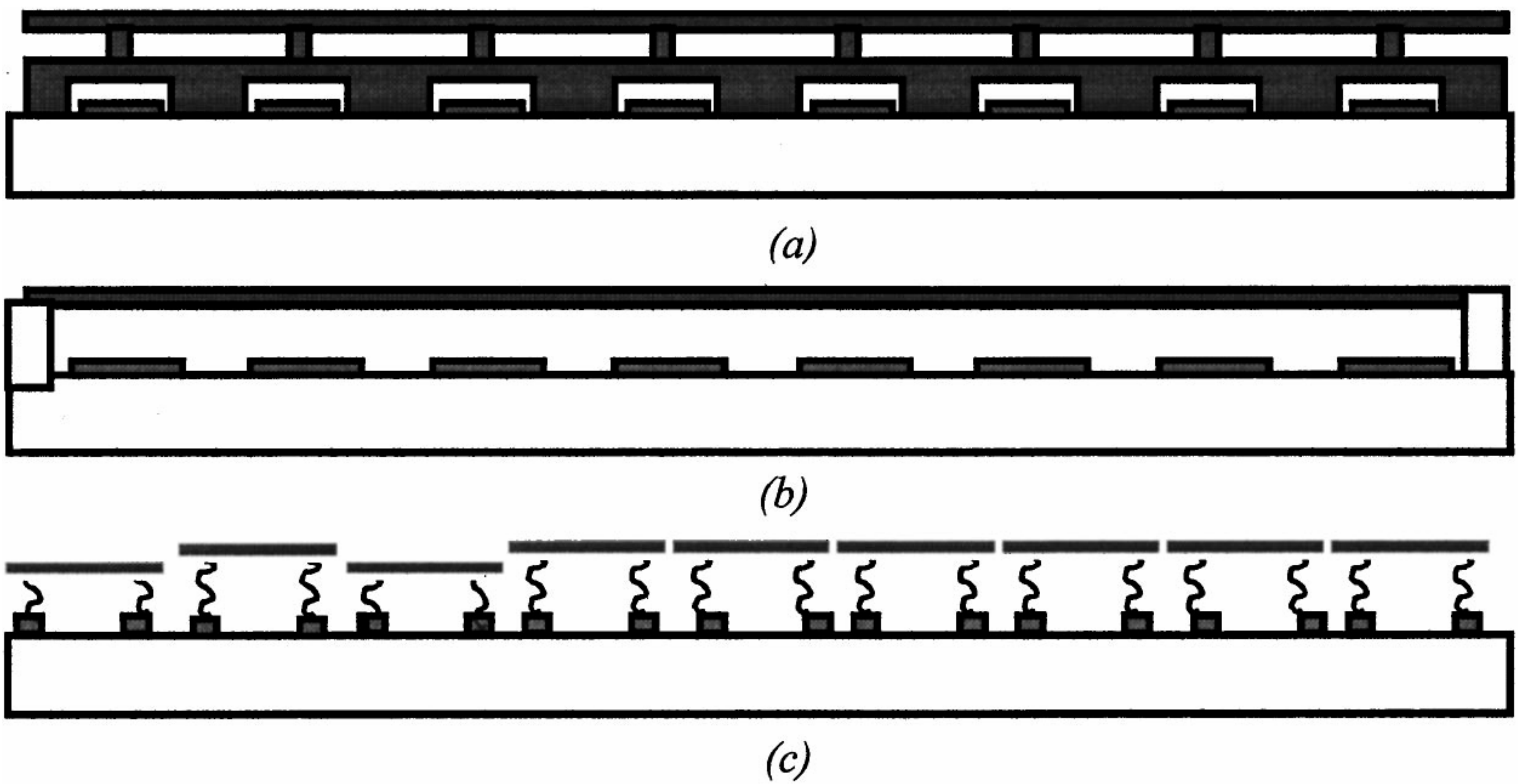
Piezo-electric Actuator



MEOMS Mirror



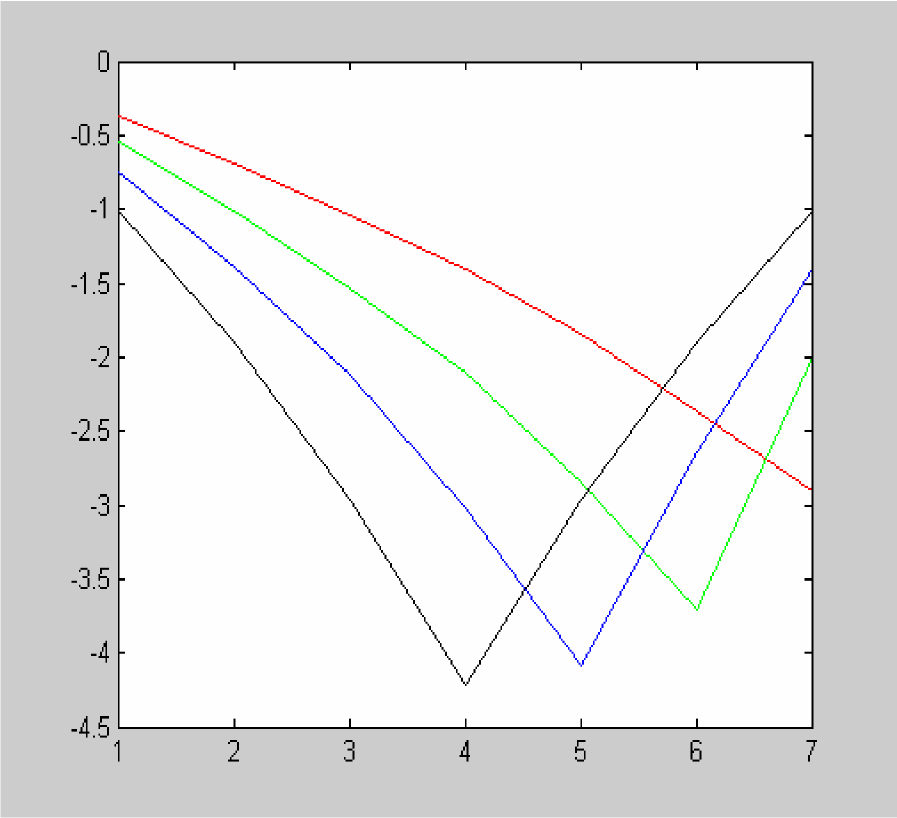
Adaptive Mirror Types

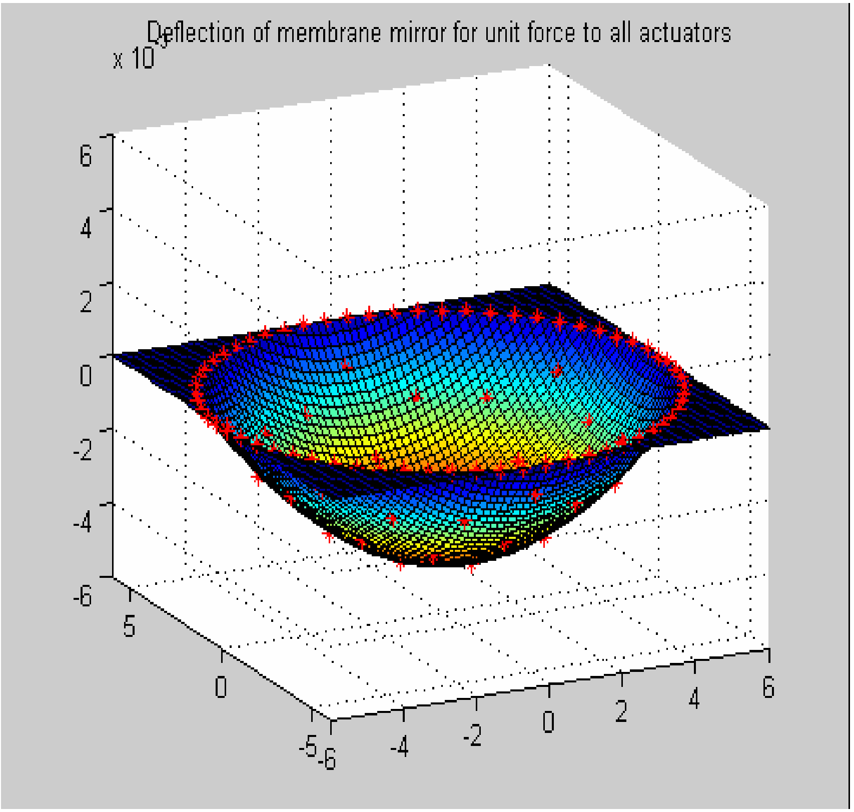


a) Boston University DM b) Delft University DM c) AFIT DM

Finite Element Analysis of deformable mirror

(Report: Central Manufacturing Technology Institute (CMTI, Bangalore))



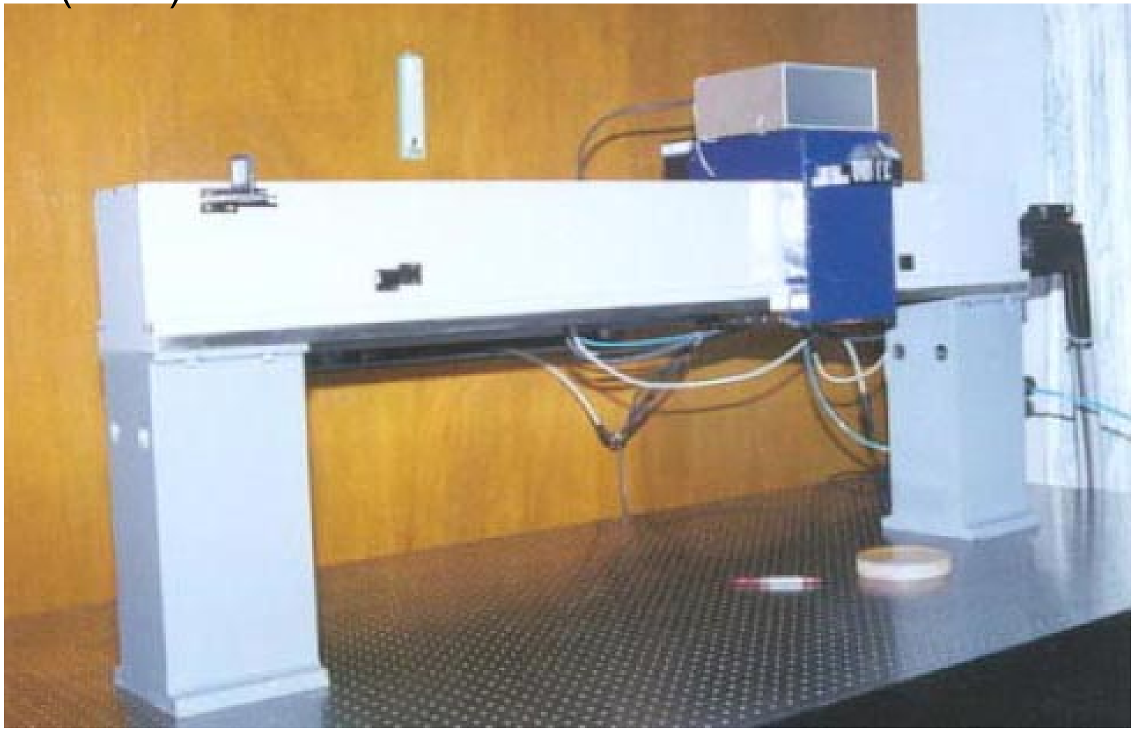


Long Trace Profilometer

A.K Saxena,V.C.Sahni et al.

Second International Workshop On Metrology for X-ray optics

Grenoble,France(2004)

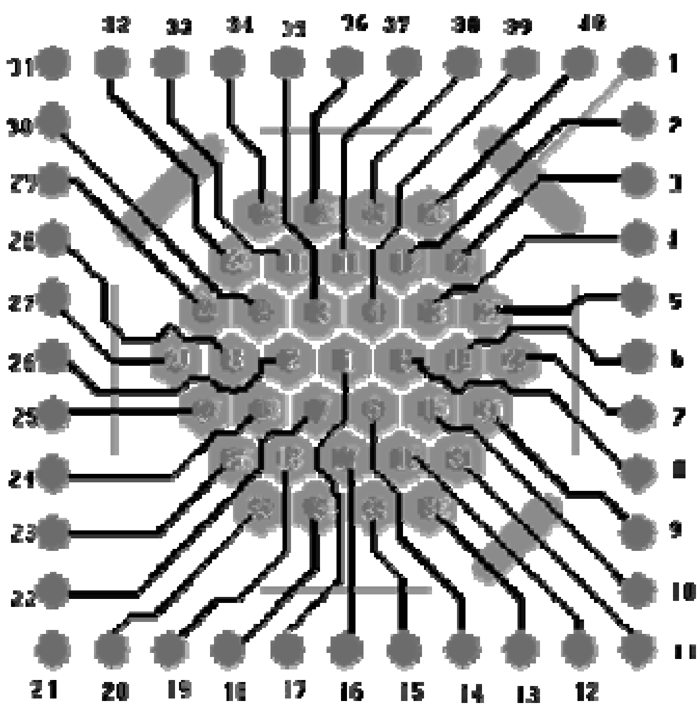


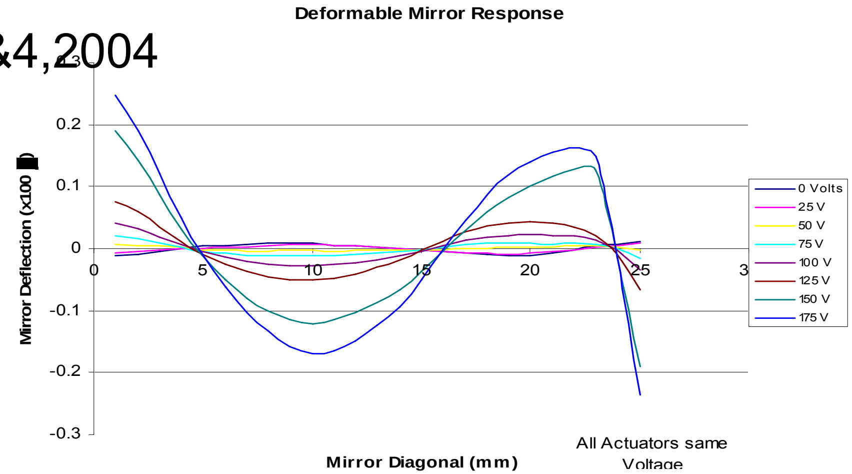
37 Actuator Layout

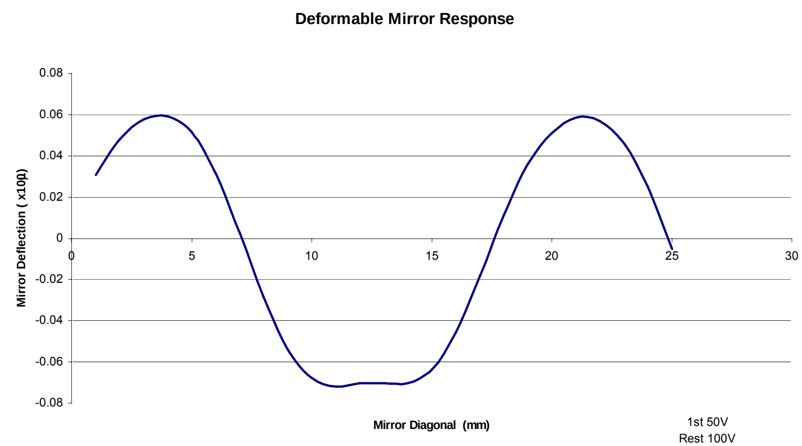
A.K .Saxena, V. Chinnappan, Ismail Jabilulla

Characterization of AO mirrors using LTP

Asian Journal Of Physics,Vol 13, No 3&4,2004



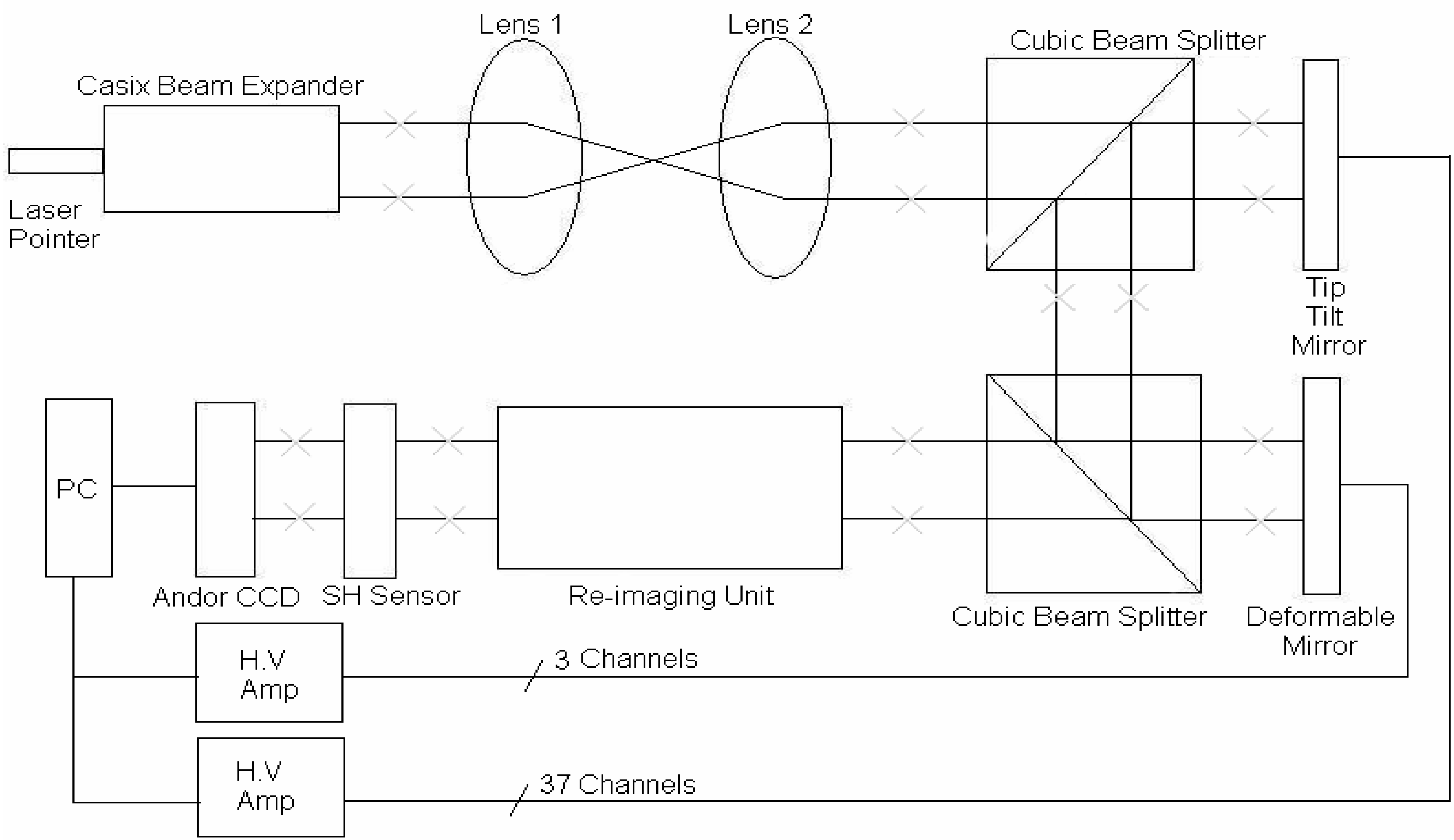




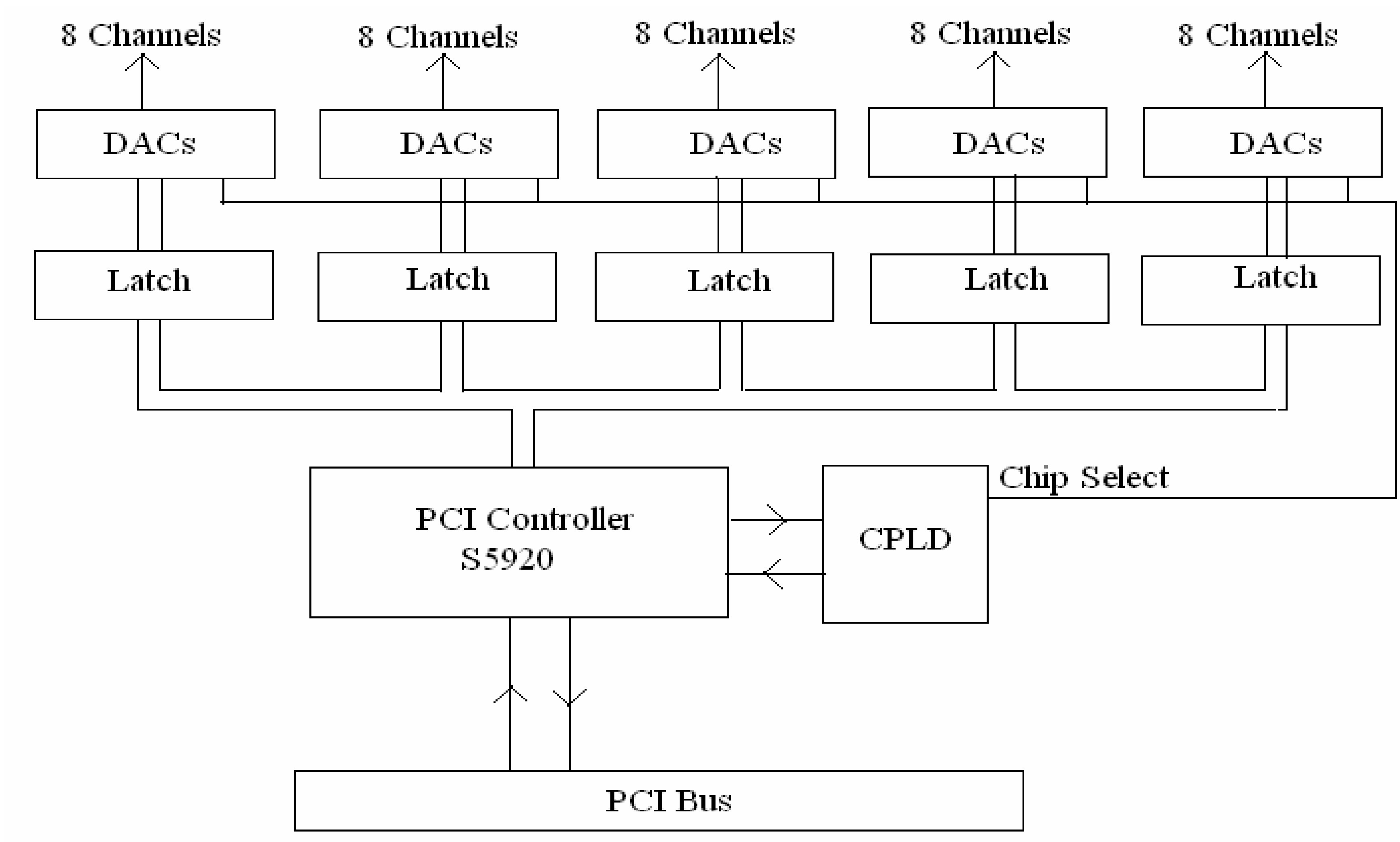
Wavefront Correction Experiment

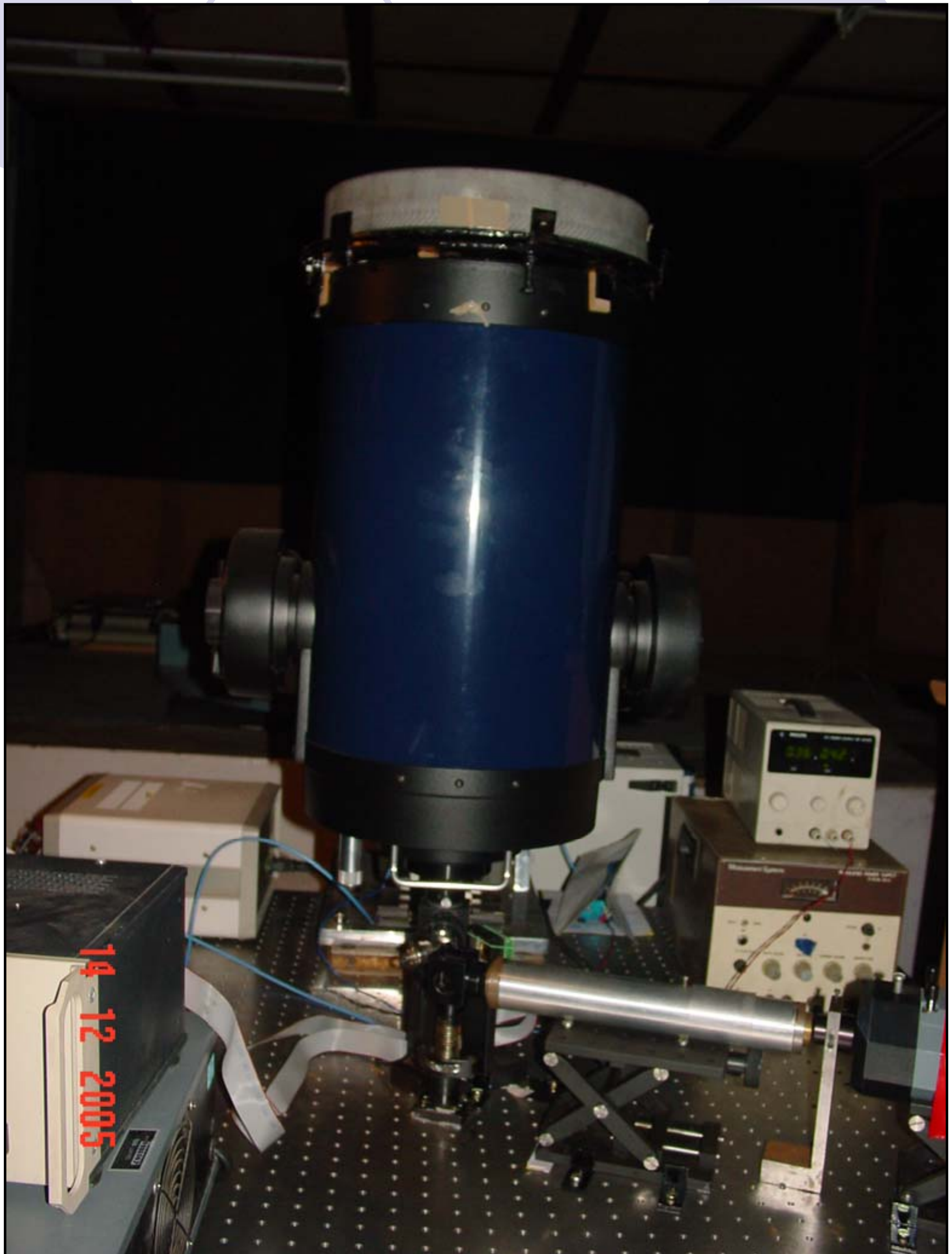
Proceedings of SPIE , Vol 4417,2001,56

V. Chinnappan, A.K. Saxena, A. Sreenivasan

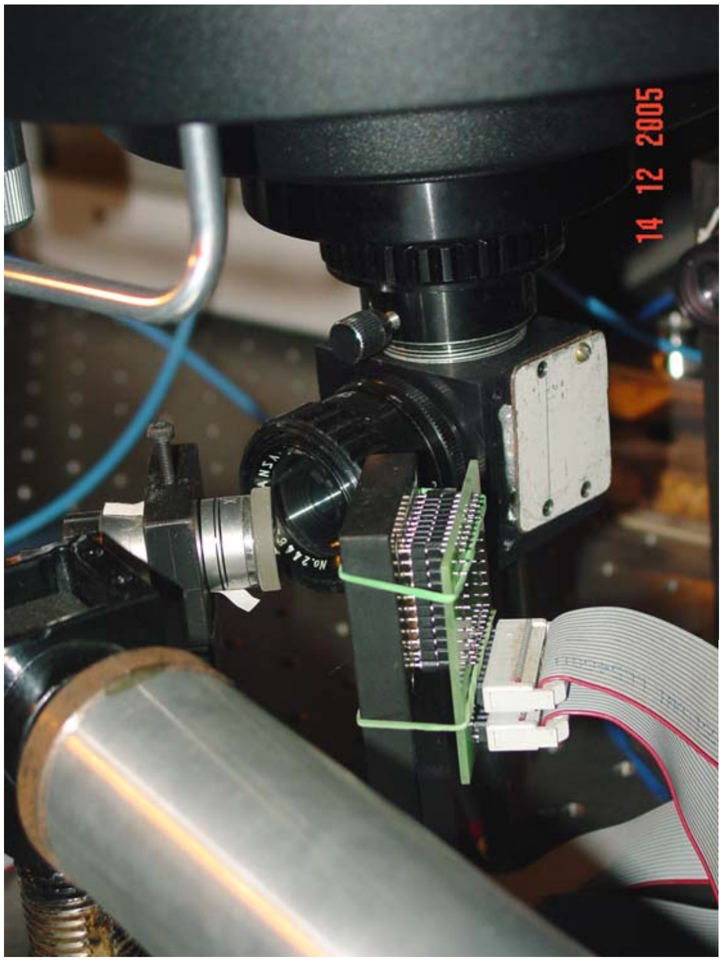


32 bit PCI Bus Interface-40 Channel DACs

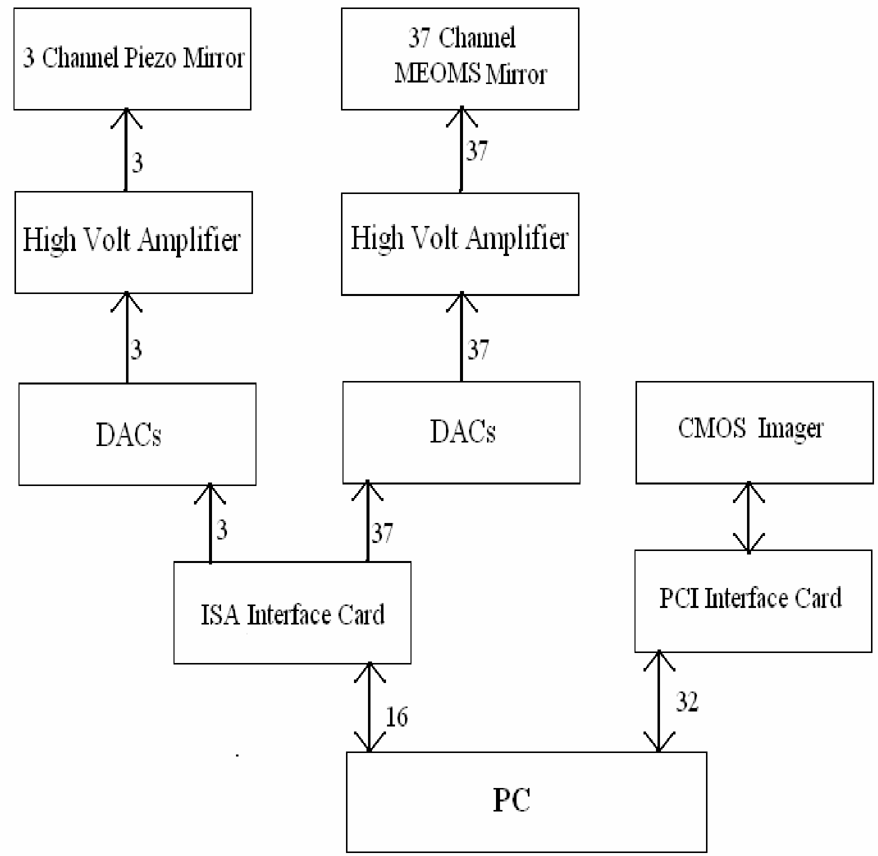



14 12 2005

Experimental Setup



Electronic Control



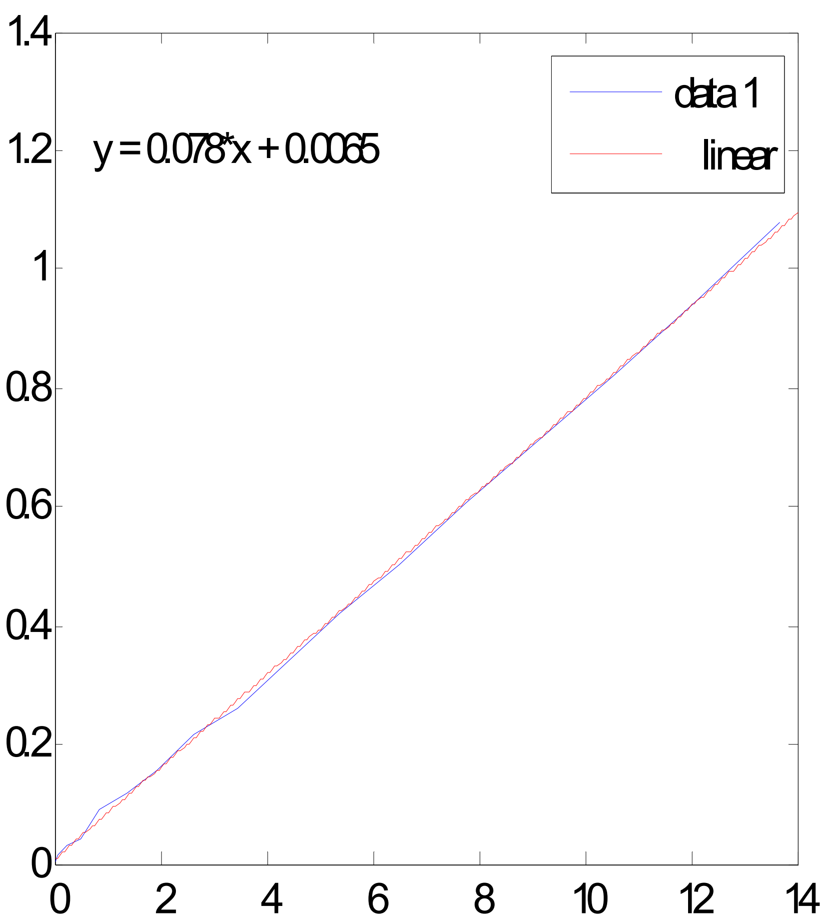
Adaptive Mirror Control

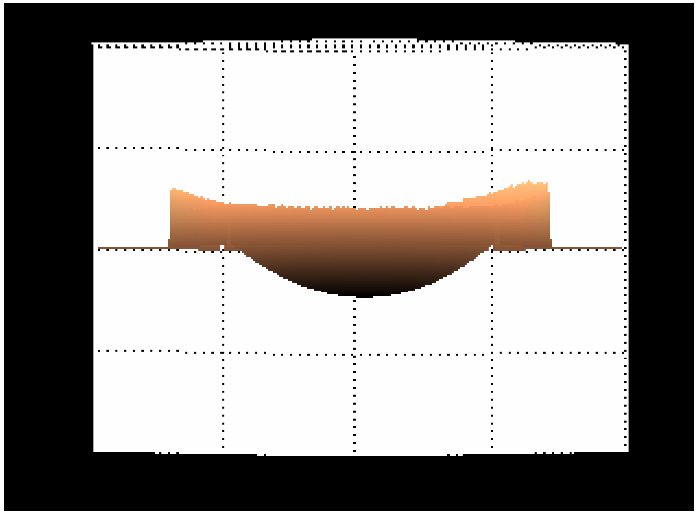
DAC V	Z1 Y tilt	Z2 X tilt	Z3 Astigmat	Z4 Defocus	Z5 Astig (90)
0.237	-0.0707	0.0775	0.0021	-0.0016	0.0045
0.469	-0.0699	0.0648	0.0060	0.00057	0.0044
0.932	-0.0912		0.0026	0.0085	0.0055
1.005				0.0131	
1.164				0.0191	
1.236				0.0205	
1.395				0.0281	
1.858				0.0531	
2.321				0.0816	
2.785				0.1257	
3.248				0.1277	
3.697				0.1301	

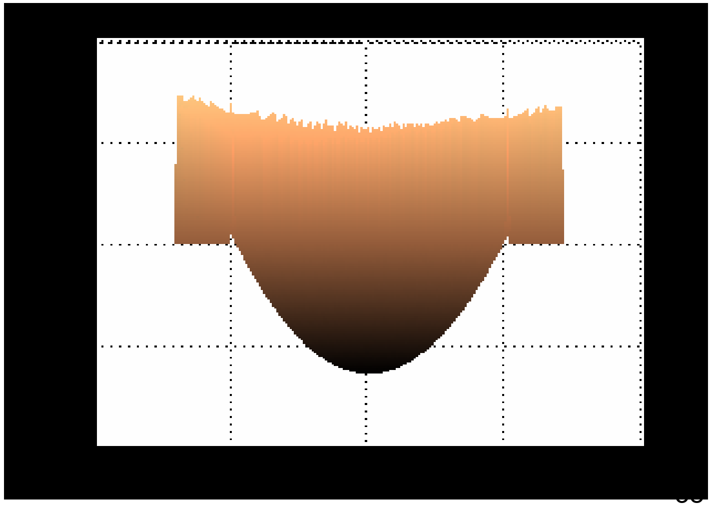
Adaptive Mirror Control

DAC V	Z6 Triang. Astig	Z7 3rd coma	Z8 Y Coma	Z9 Astig
0.237	0.000037	0.0012	0.0021	0.0001
0.469	0.000259	0.0013	0.0016	-0.0011
0.932	0.0017	0.0008	0.0021	0.00001

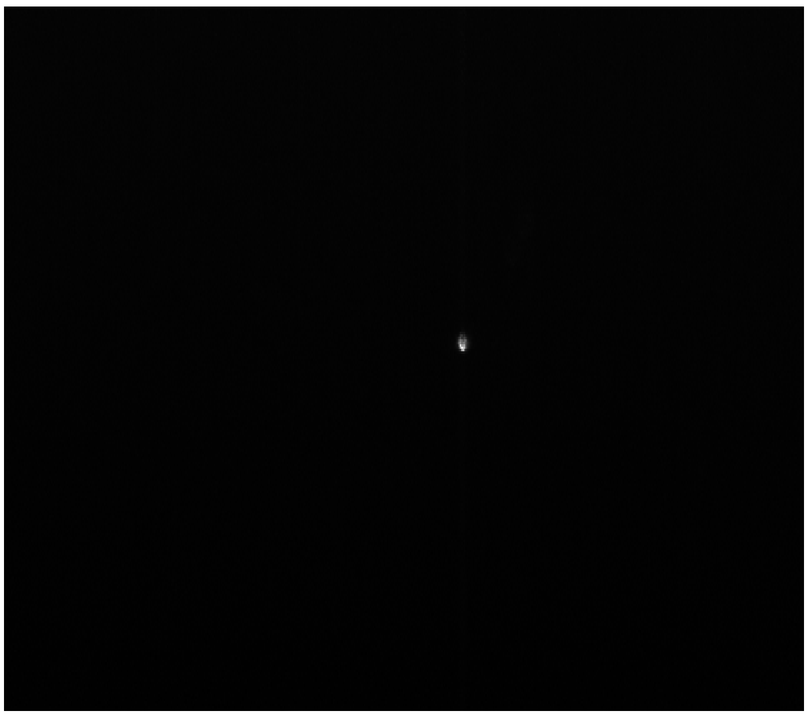
Zernike Coefficient vs. V^2



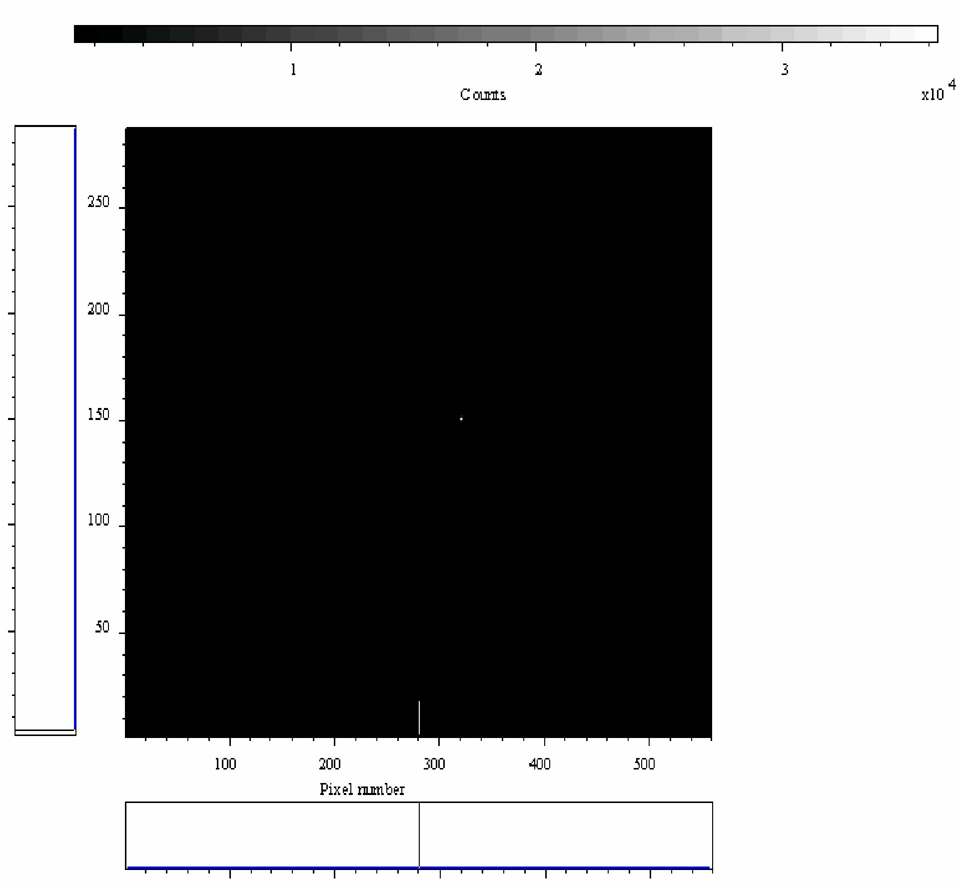




Uncorrected Image



Corrected Image

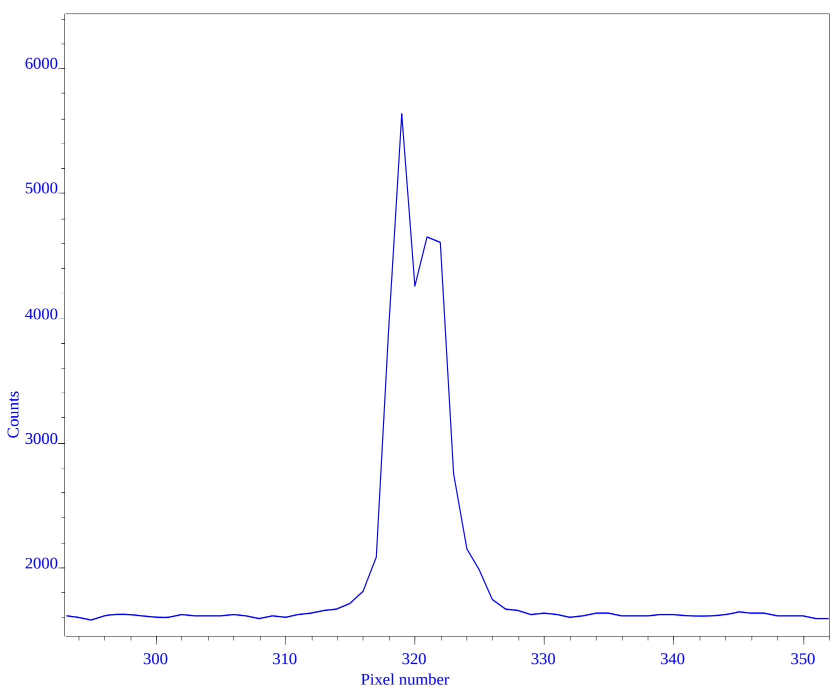


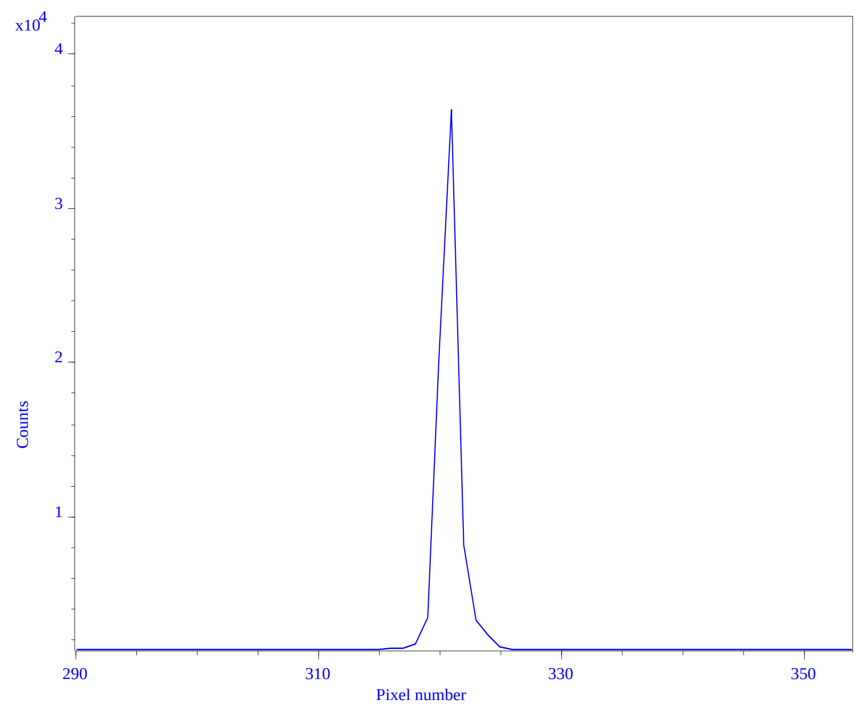
FWHM 6.4 Pixels

3.5 Pixels

Max Count:5610

Max Count:36500





Conclusion

Major contributor for seeing is at a height of 8 to 10 km - 0.3” to 0.5”

- Correction time required is 10 to 20 msec at V band, more at IR
- CMOS imager used in ROI can meet speed requirements but is very noisy. Algorithms were developed to get results with noise. It can be used for bright sources only (No on-chip integration)
- Low light level CCD matches the requirements, but speed improvement with software is required
- Tilt mirror has hysterisis. We have measured the hysterisis and it is used in control for compensation
- Adaptive mirror creates smooth bends suitable for low order aberration correction
- We have shown a sharpened image where intensity is increased many times and the FWHM has reduced to nearly half.

Restoration

Restoration attempts to reconstruct or recover an image that has been degraded by using prior knowledge of degraded phenomenon

- Model re-degradation
- Apply the inverse process
- Spatial domain, Frequency domain

  g (x,y) = H [f x,y) +η(x,y)]

  Degraded image - H:degraded function

  η(x,y):noise function

  g(x,y)=h(x,y) * f(x,y)+ η(x,y)

  PSF * convolution
- Convolution in spatial domain and multiplication in frequency domain constitute a fourier transform pair

- Freq. Domain representation: G(u,v)= H(u,v)+ f(u,v)+ N(u,v)

  (capital letters are fourier transforms)
- Simulate no behaviour and effects of noise is central to image restoration
- When no information is available about PSF, we can resort to blind documentation