INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
I.C.T.P., P.O. BOX 586, 34100 TRIESTE, ITALY, CABLE: CENTRATOM TRIESTE

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Second Winter College on Optics

20 February - 10 March 1995

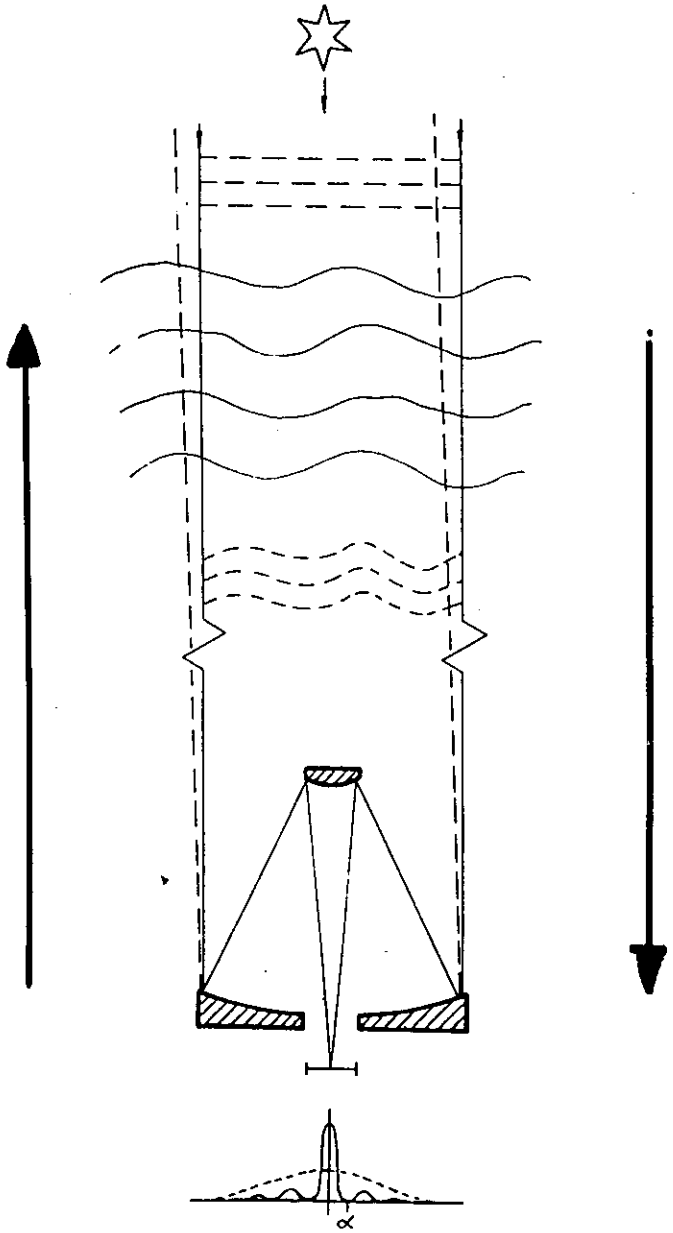
Adaptive Optics

F. Merkle

Carl Zeiss Jena GmbH
Astronomische Technik
Jena, Germany

ADAPTIVE OPTICS
Index

(1)

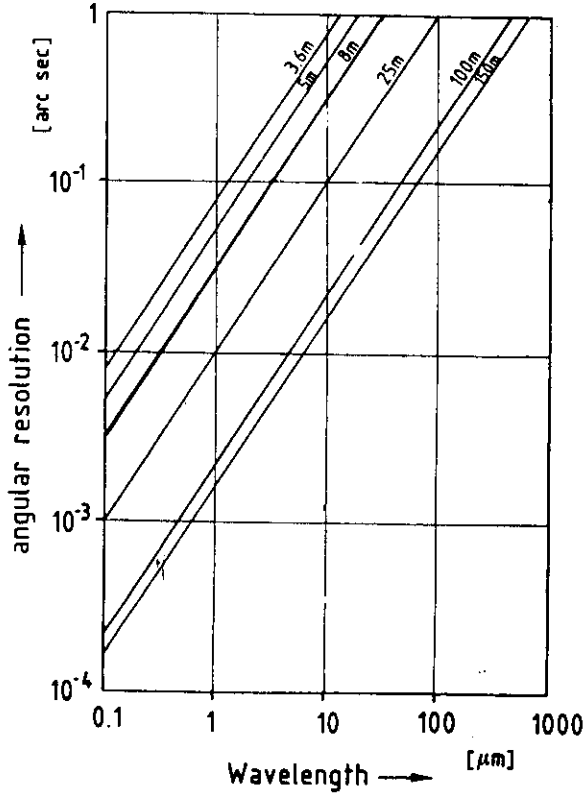


(2)

Angular resolution of an astronomical telescope

$$\Delta\alpha = 1.22\frac{\lambda}{D} \quad (\textit{in Radians})$$

(λ: wavelength, D: telescope diameter)

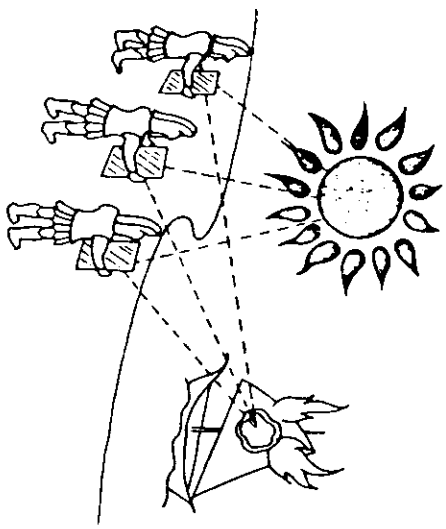


Efficiency of an astronomical telescope:

$$E \propto T \frac{D^2}{r^2}$$

E: Efficiency
T: Transmission of optical system
D: Telescope diameter
r: Radius of telescope point spread function incl. atmosphere

A 8m telescope with an image quality of 0.7 arcsec corresponds to a 3.5 m telescope with 0.3 arcsec image quality!



Archimedes' adaptive optical system using segmented mirror elements.

(5)

Archimedes burning mirror? ——— 212 B.C.

First eyeglasses ——— 1285

Invention of telescope ——— 1606
First reflecting telescope ——— 1663
Isaac Newton's "Optics" ——— 1704
Fizeau Velocity of Light ——— 1849
1864 ——— Maxwell's equations
1888 ——— Hertzian waves
100-inch reflector ——— 1916
1935 ——— Radar experiments
200-inch reflector ——— 1947
Babcock "seeing" compensation ——— 1953
1958 ——— Adaptive antennas
Invention of Laser ——— 1960
Active mirror figure control ——— 1966
Phase conjugate COAT (Rockwell) ——— 1968
Multi-dither COAT (Hughes) ——— 1970
Predetection image compensation (itek) ——— 1973

Next generation telescope ——— ?
Laser fusion ——— ?

(6)

PUBLICATIONS OF THE
ASTRONOMICAL SOCIETY OF THE PACIFIC

Vol. 65 October 1953 No. 386

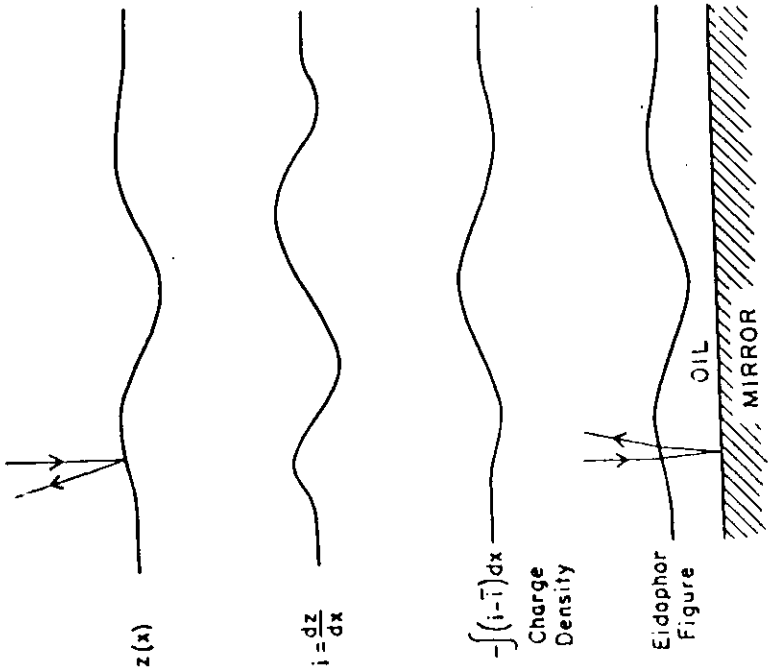
THE POSSIBILITY OF COMPENSATING ASTRONOMICAL SEEING

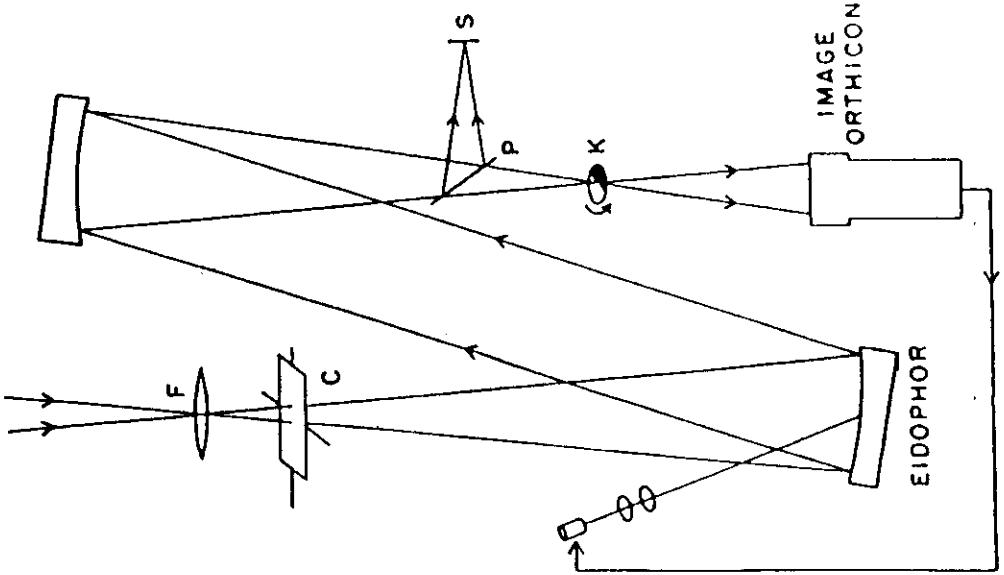
H. W. Babcock

Mount Wilson and Palomar Observatories
Carnegie Institution of Washington
California Institute of Technology

The severe limitations imposed upon nearly all astronomical observations by "seeing"—the effects resulting from passage of light rays through the turbulent atmosphere of the earth—are familiar to every observer. With a small instrument the effect may appear largely as a continual shifting and scintillation of the image of a star, but with a large telescope poor seeing usually manifests itself mainly as an enlargement and blurring of the image. The reason for this difference becomes apparent when one makes a knife-edge test with a large telescope on a bright star. The turbulent elements of the atmosphere appear as shifting dark and bright areas on the image of the objective. In general these turbulent elements or waves have dimensions of the order of a foot or two—small compared to the aperture of a large reflector. Thus the integrated effect of a number of turbulent elements leads to an unsteady enlargement of the image, perhaps with some irregular shifting in position. The seriousness of this is evident when one realizes that ideally the 200-inch Hale telescope is capable of giving diffraction images of stars about $\frac{1}{40}$ of a second of arc in diameter, yet the size of the "seeing image" produced is in the range $\frac{1}{3}$ second to perhaps 5 or 10 seconds, being about 2 seconds in diameter on the average. Only rarely are images as small as $\frac{1}{2}$ second observed, and one may consider himself fortunate to experience one hour out of 1000 of the finest seeing, even at the best locations.

(7)





(8)

Principle of Adaptive Optics

complex phase aberration

$$\Phi(\vec{r},t) - iA(\vec{r},t)$$

image quality: Strehl ratio S

$$S = \frac{peak\ irradiance\ in\ the\ focal\ plan}{peak\ irradiance\ diffraction\ limited}$$

(9) (10)

adaptive correction

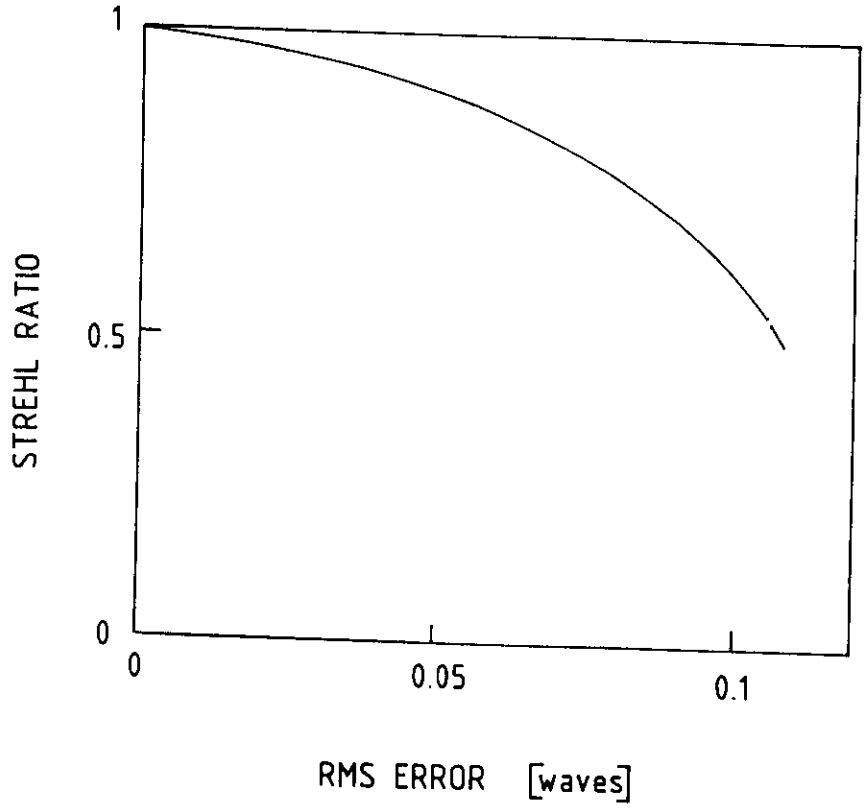
$$-\Phi(\vec{r},t) + i\mu A(\vec{r},t) \quad (11)$$

phase-correction function

$$\Phi(\vec{r},t) = \sum_{n=1}^{N} a_n(t)\, f_n(\vec{r}) \quad (12)$$

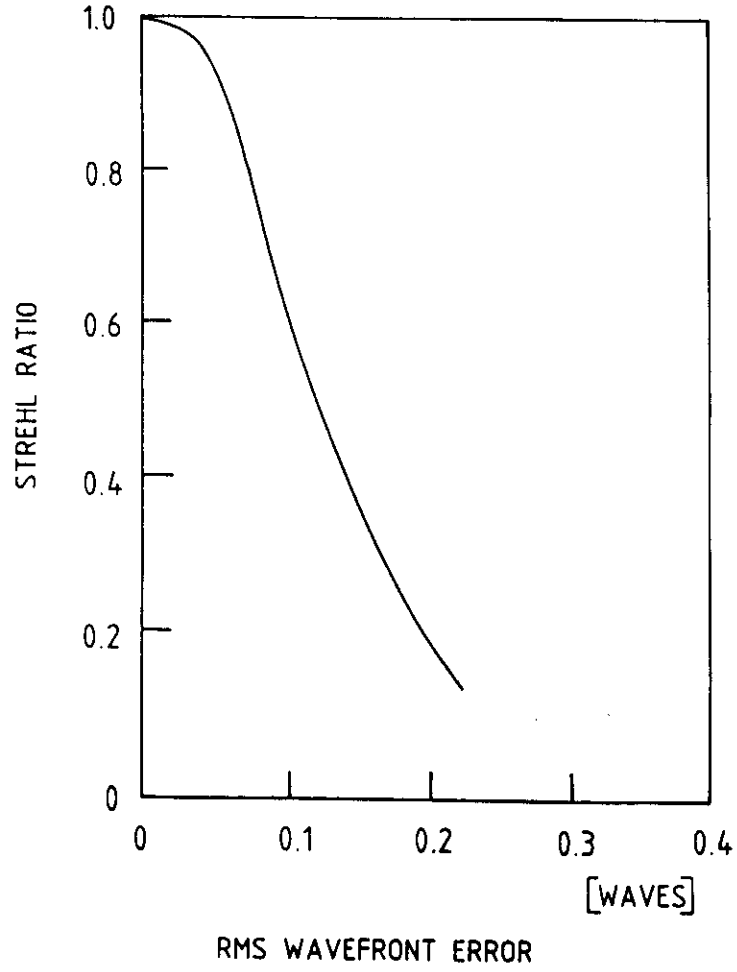
(9)

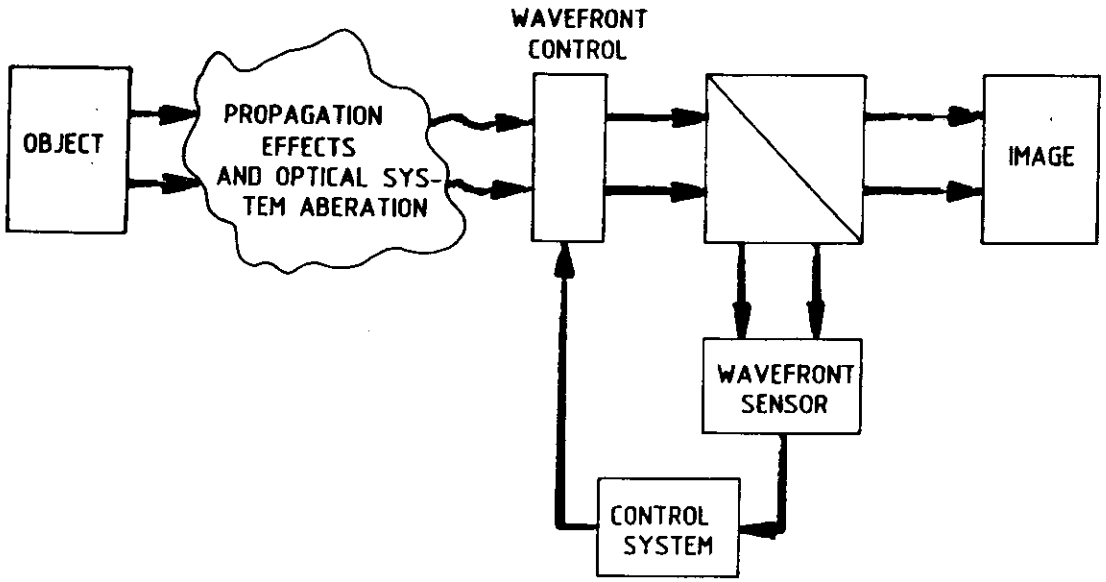
image quality

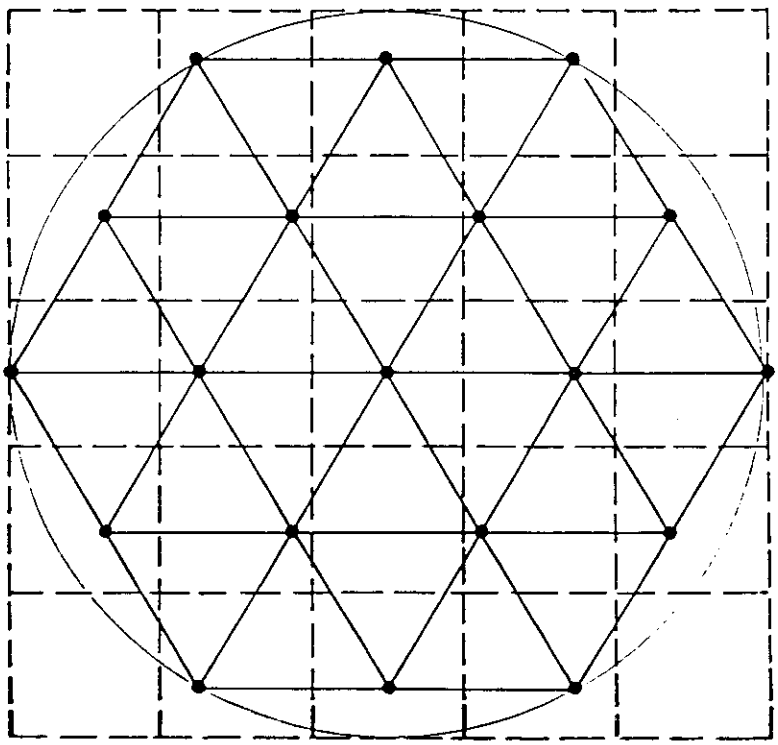


(10)

image quality




WAVEFRONT
CONTROL
OBJECT
PROPAGATION
EFFECTS
AND OPTICAL SYS-
TEM ABERATION
IMAGE
WAVEFRONT
SENSOR
CONTROL
SYSTEM



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seeing conditions

$$r_0 = \left[0.423 k^2 \int_R C_n^2(h)\, dh\right]^{-3/5}$$

14

$$k = 2\frac{\pi}{\lambda}$$

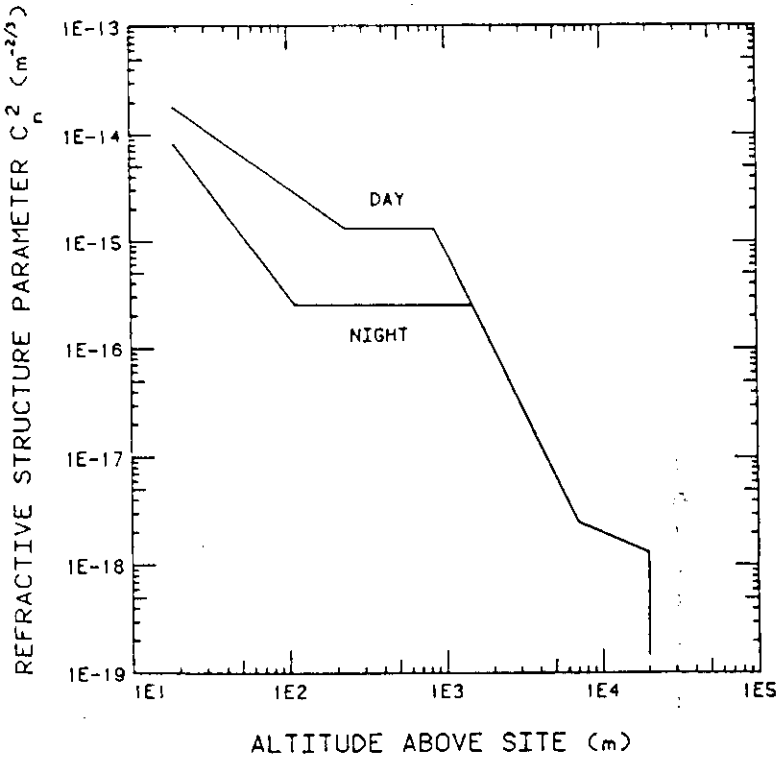
number of subapertures for an ideal adaptive system

$$N = \frac{\left(0.051 k^2\, C_N^2\, R\, D^{5/3}\right)^{6/5}}{\ln(1/S)}$$

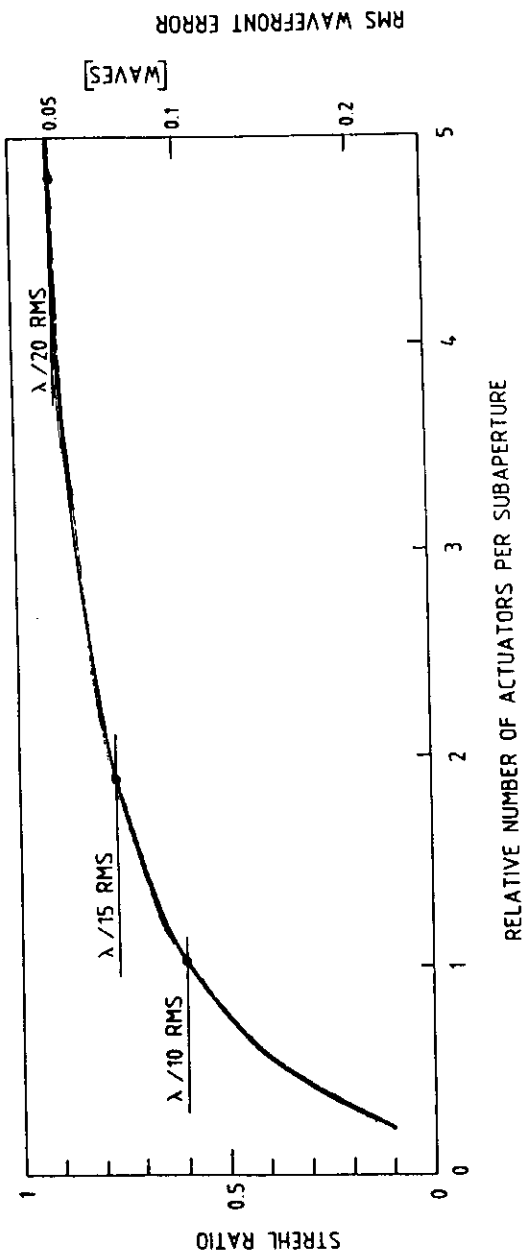
15

$$N \approx \left(\frac{D}{r_0}\right)^2$$

14



15



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life time

$$\tau \simeq \frac{r_0}{\Delta v}$$

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λ	$0.5\mu m$	$2.2\mu m$	$5.0\mu m$	$10\mu m$
r_0	$10cm$	$60cm$	$160cm$	$360cm$
N	6400	180	12	4
τ	$6ms$	$35ms$	$95ms$	$220ms$

isoplanatic angle

$$\Theta = \left[1.45\, k^2 \int_R z^{5/3}\, C_n^2(h)\, dh\right]^{-3/5}$$

typical values

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λ	$0.5\mu m$	$2.2\mu m$	$5.0\mu m$	$10\mu m$
Θ	1.8”	10”	30”	70”

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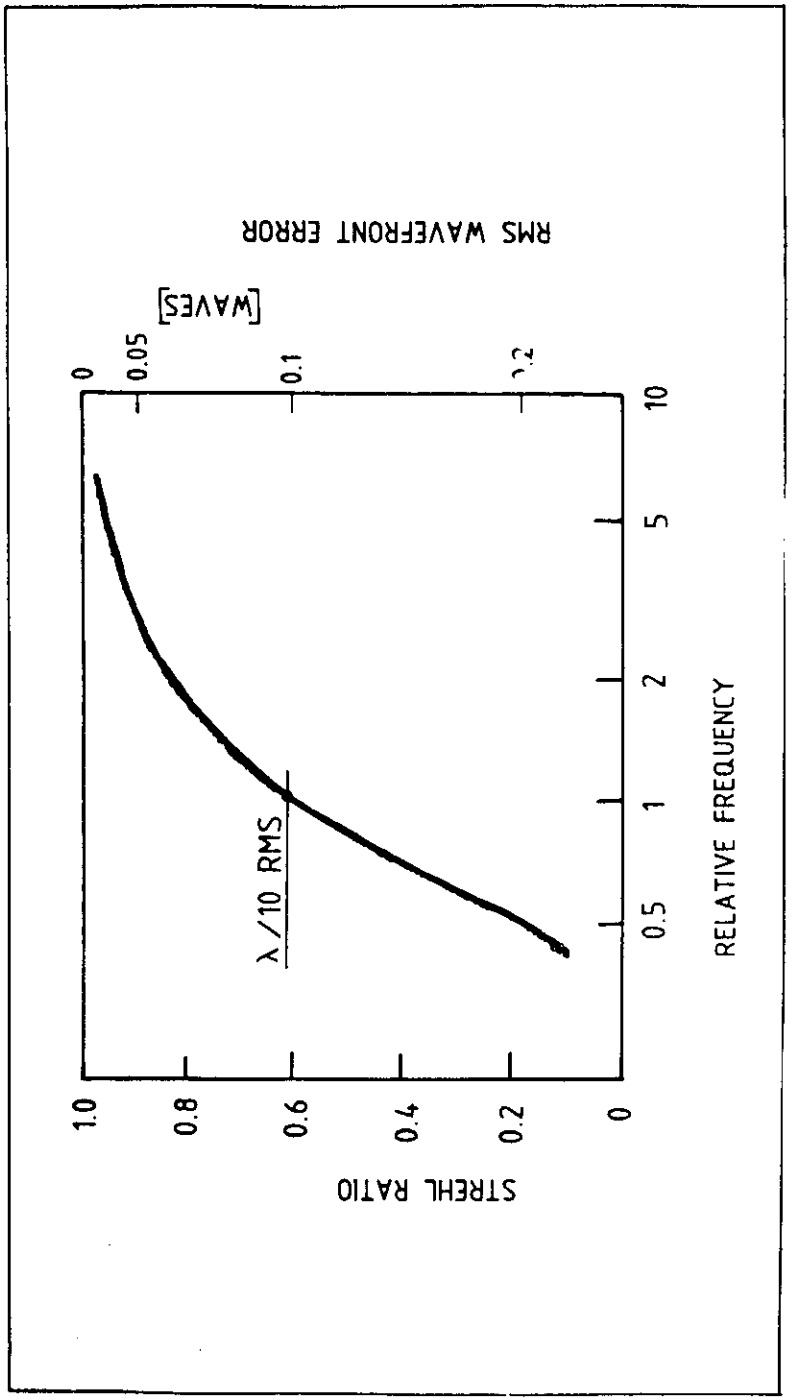
RMS WAVEFRONT ERROR
[WAVES]
0
0.05
0.1
STREHL RATIO
1.0
0.8
0.6
0.4
0.2
0
λ/10 RMS
0.5
1
2
5
10
RELATIVE FREQUENCY

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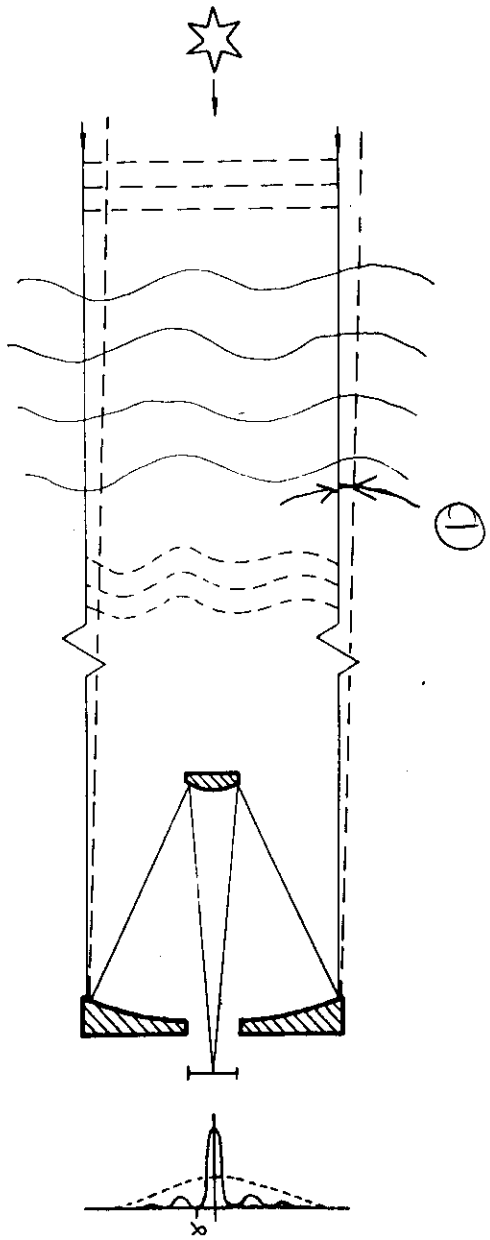
1
α

19

degrees of freedom

$$\sim \left(\frac{D}{r_0}\right)^2$$

$$\sim \lambda^{-12/5}$$

$$\sim (\cos\gamma)^{-6/5}$$

wavefront correction range

$$\sim \frac{(D/r_0)^{5/6}}{\lambda}$$

$$\boxed{\sim \lambda^0}$$

$$\sim (\cos\gamma)^{-1/2}$$

temporal frequency

$$\sim r_0^{-1}$$

$$\sim \lambda^{-6/5}$$

$$\sim (\cos\gamma)^{-3/5}$$

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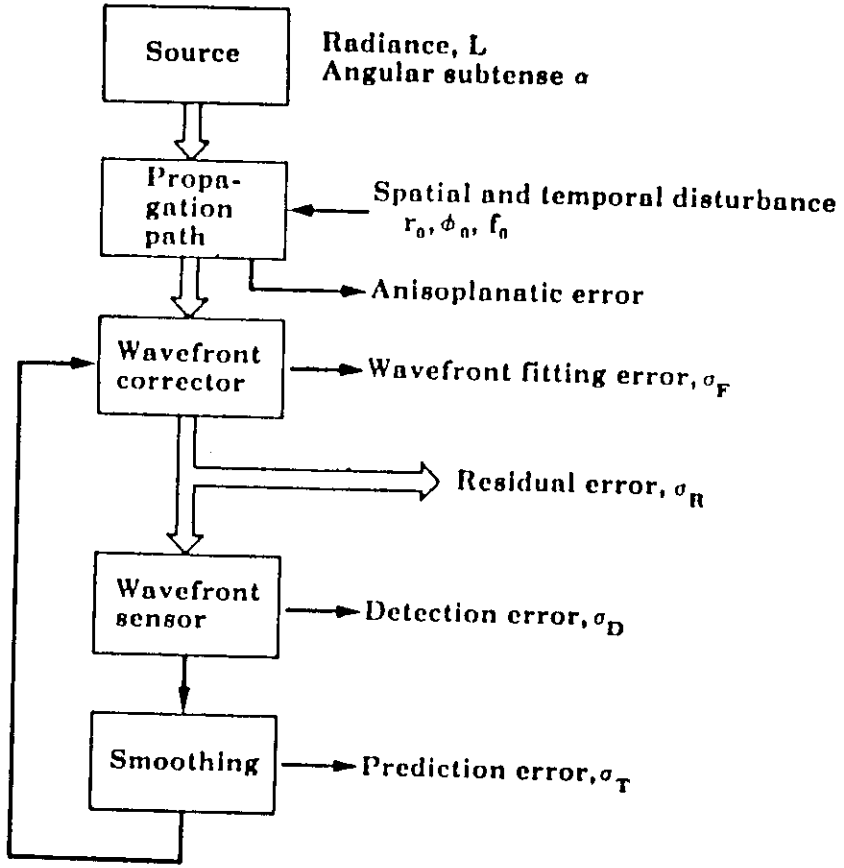
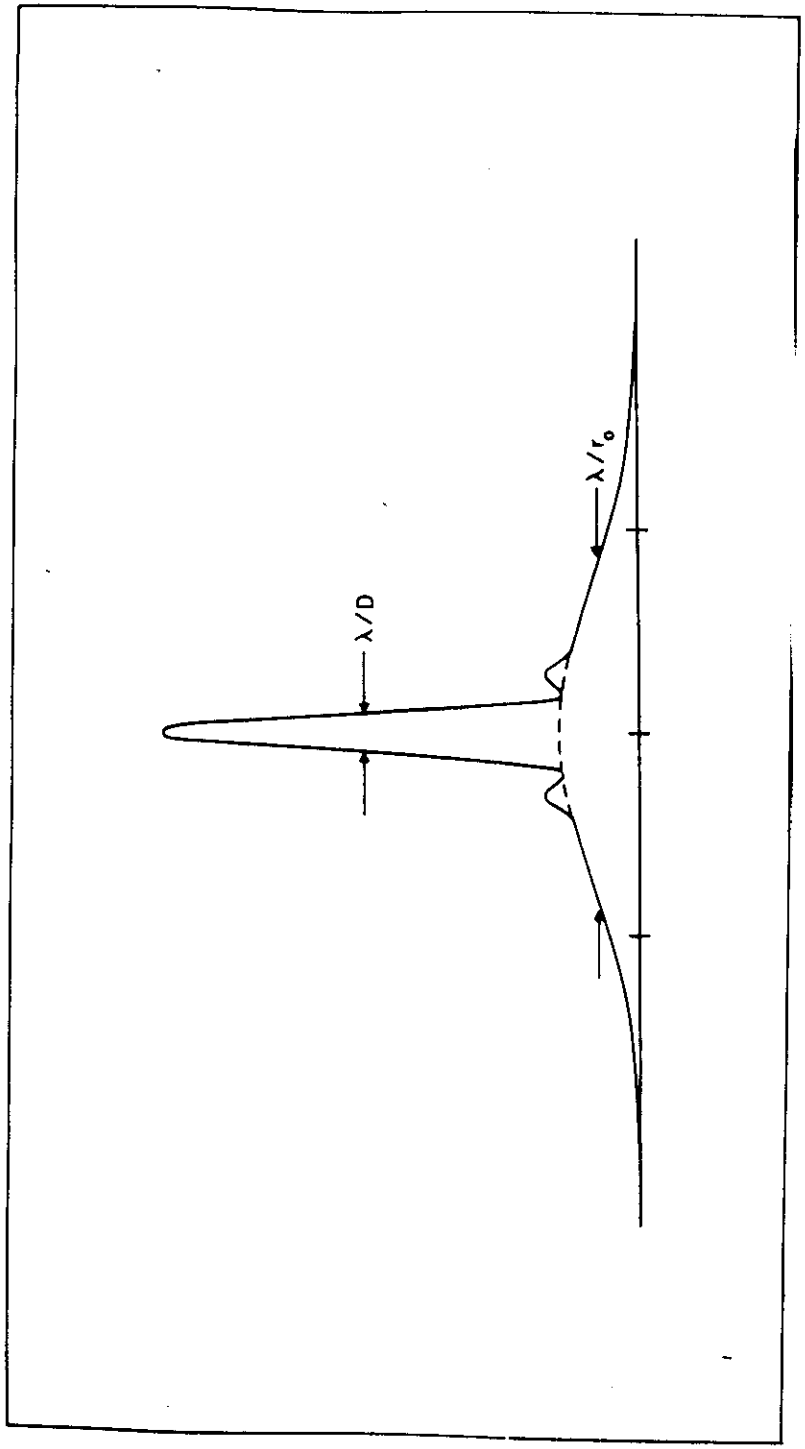
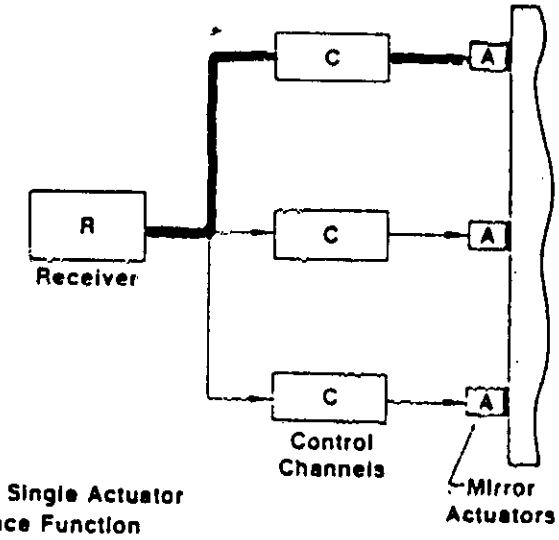
Performance of an Adaptive System



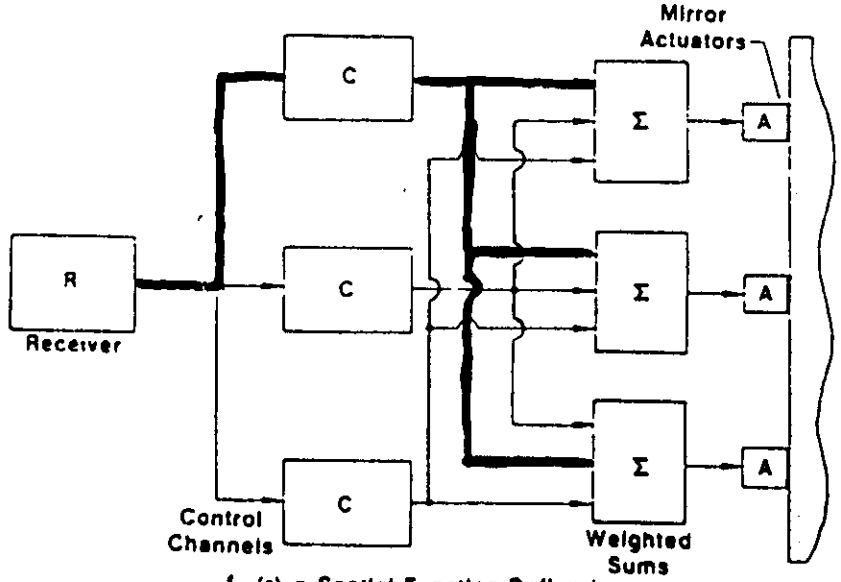
21



22



$f_n(\underline{r})$ = Single Actuator Influence Function



$f_n(\underline{r})$ = Spatial Function Defined Over Entire Aperture

(23)

Modal control concept

quasi-Zernike polynomial

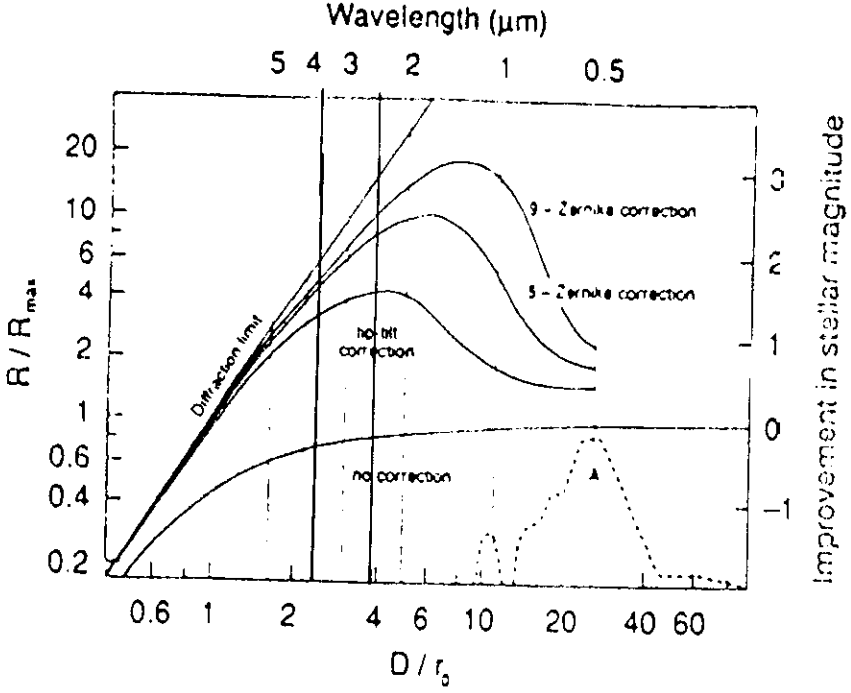
$$W = k \cdot r^m \cdot cos\,(n\Phi + q\Theta)$$

W =	a	constant
	$+br^1cos(\Phi + \Theta_1)$	lateral focus (tilt)
	$+cr^2cos$	longitudinal focus
	$+dr^3cos(\Phi + \Theta_1)$	decentering coma
	$+egr^4$	3. order sperical aberration
	$+fr^6$	5. order sperical aberration
	$+gr^2cos(2\Phi + \Theta_2)$	3. order astigmatism
	$+hr^5cos(3\Phi + \Theta_3)$	triangular coma
	$+ir^2cos(4\Phi + \Theta_4)$	quadratic astigmatism
	$+\cdots$	$\cdots$

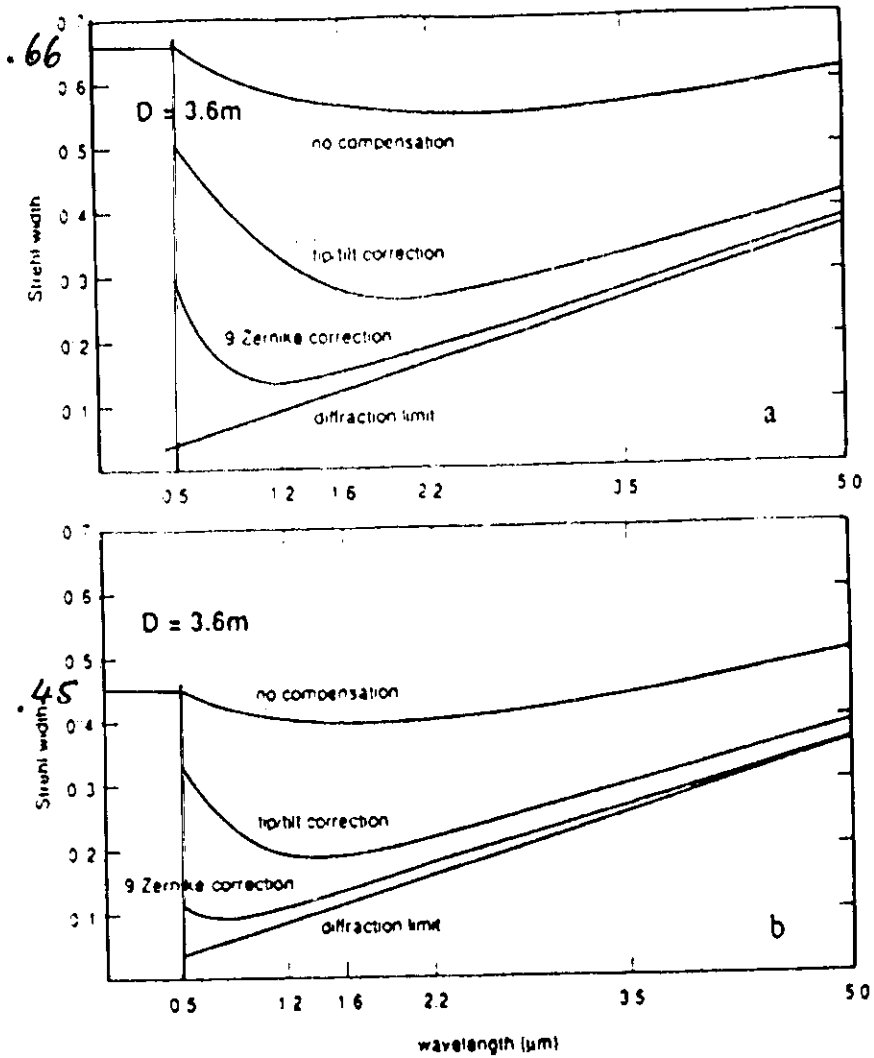
(24)

Low Order Zernike Aberrations

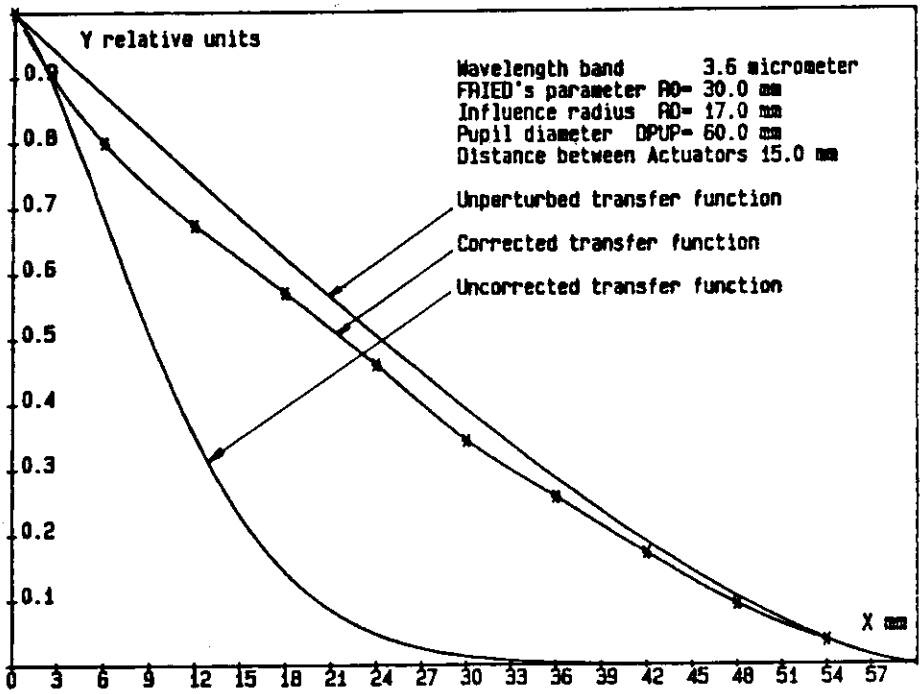
Radial degree (n)	Azimuthal frequency (m) 0	1	2	3
0	Z_1 Piston			
1		Z_2, Z_3 Tip-tilt		
2	Z_4 Defocus		Z_5, Z_6 Astigmatism	
3		Z_7, Z_8 Coma		Z_9, Z_{10} Triangular coma
4	Z_{11} Spherical aber.		Z_{12}, Z_{13}	

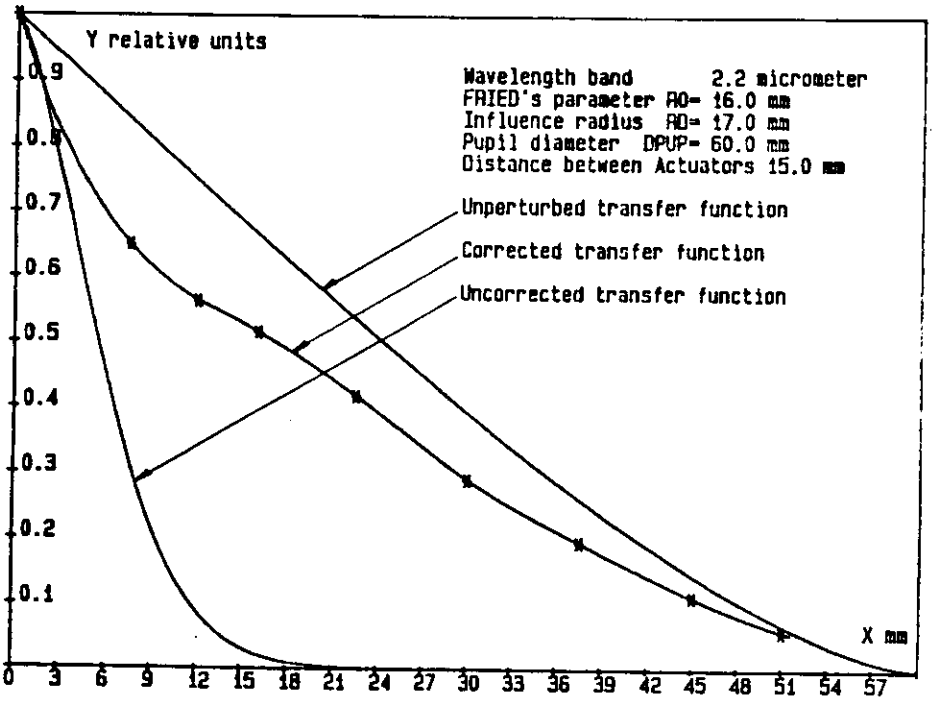


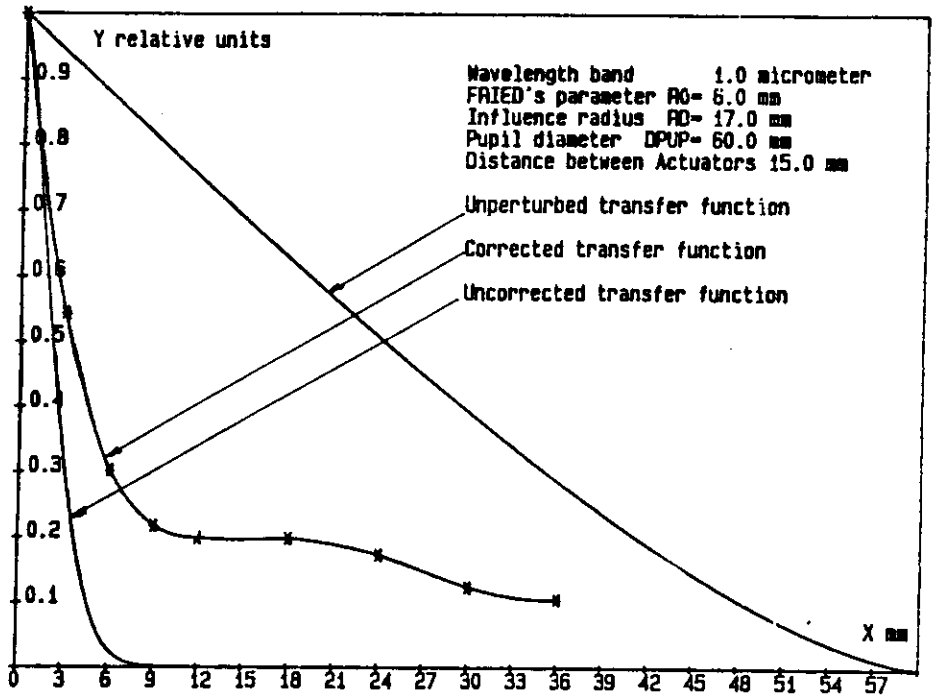
Theoretical curves showing the normalized Strehl resolution R/R_{max} as a function of D/r_0, the ratio of the telescope diameter over Fried's seeing parameter. R/R_{max} is the stellar image central intensity normalized to unity for an infinitely large uncompensated telescope. Curves are for several degrees of compensation. The vertical scale on the right side gives the improvement over the uncompensated case in stellar magnitude. The upper scale indicates the wavelength dependence of D/r_0. It is set for D = 3.6 m (CFHT) and a seeing value of r_0 = 14.4 cm at 0.5 μm and it can be moved horizontally according to seeing conditions. For example, if r_0 = 36 cm at 0.5 μm (which occasionally occurs) then the wavelength scale is shifted to the left with 0.5 μm set to D/r_0 = 10. The dotted curve in the lower right corner shows a statistical distribution of D/r_0 observed at 0.5 μm at the CFHT and it can be moved horizontally to show the statistical distribution of D/r_0 at a different wavelength as pointed by the arrow.



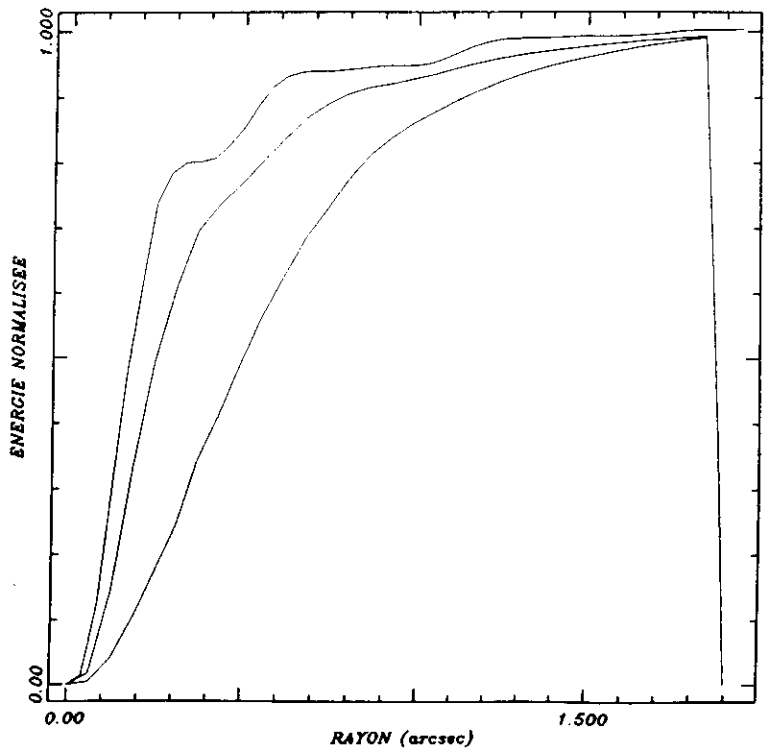
Calculated Strehl width as a function of wavelength for a 3.6-m telescope with various degrees of compensation. The uncompensated Strehl width at 0.5 μm is assumed to be 0.66 arc second (a) or 0.45 arc second (b).


Y relative units
Wavelength band 3.6 micrometer
FRIED's parameter RO= 30.0 mm
Influence radius RO= 17.0 mm
Pupil diameter DPUP= 60.0 mm
Distance between Actuators 15.0 mm
Unperturbed transfer function
Corrected transfer function
Uncorrected transfer function
X mm
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0 3 6 9 12 15 18 21 24 27 30 33 36 39 42 45 48 51 54 57


Y relative units
Wavelength band 2.2 micrometer
FRIED's parameter RO= 16.0 mm
Influence radius RO= 17.0 mm
Pupil diameter DPUP= 60.0 mm
Distance between Actuators 15.0 mm
Unperturbed transfer function
Corrected transfer function
Uncorrected transfer function
X mm
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0 3 6 9 12 15 18 21 24 27 30 33 36 39 42 45 48 51 54 57



ENERGIE ENCERCLE



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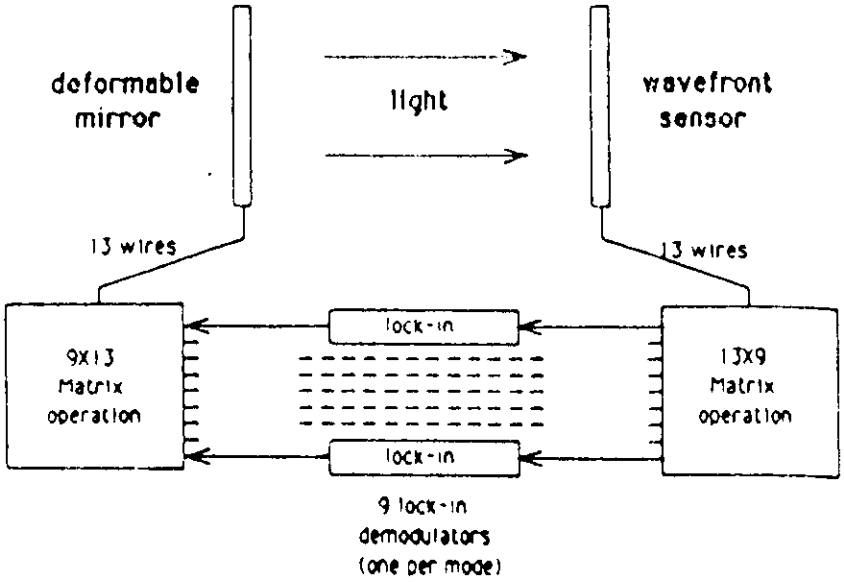
deformable mirror
light
wavefront sensor
13 wires
13 wires
lock-in
lock-in
9X13 Matrix operation
13X9 Matrix operation
9 lock-in demodulators (one per mode)

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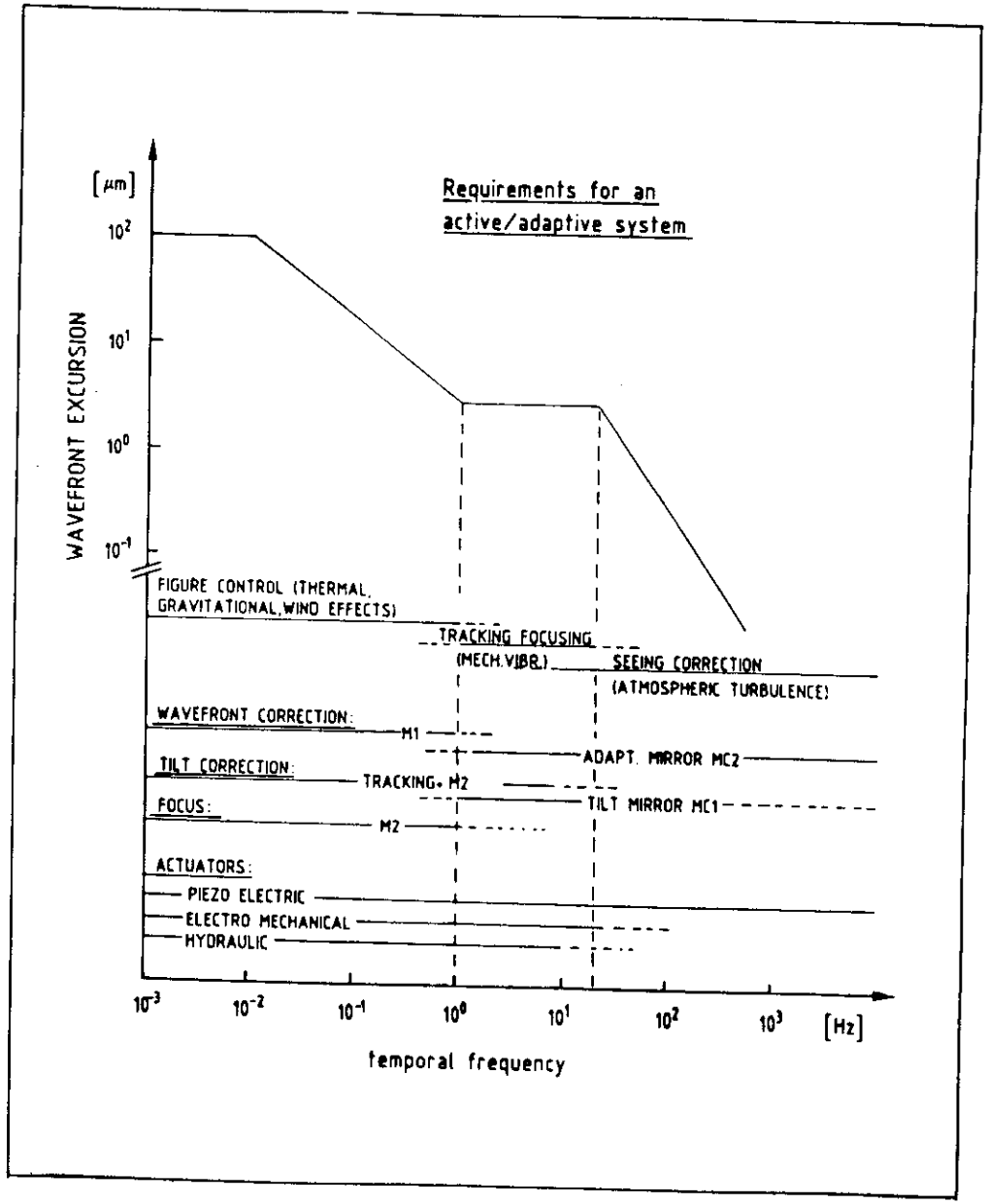
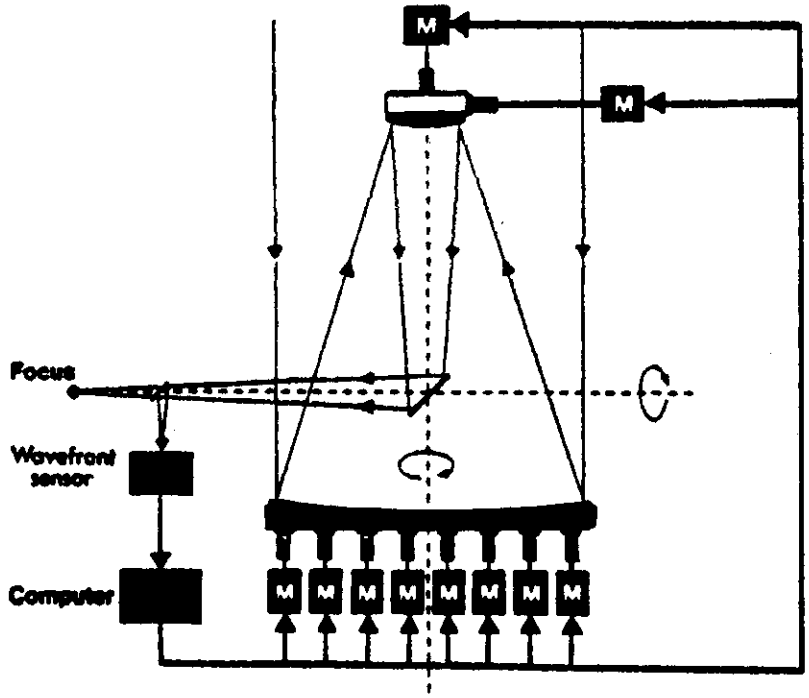

Requirements for an active/adaptive system
[μm]
WAVEFRONT EXCURSION
10^2
10^1
10^0
10^{-1}
FIGURE CONTROL (THERMAL, GRAVITATIONAL, WIND EFFECTS)
TRACKING FOCUSING (MECH. VIBR.)
SEEING CORRECTION (ATMOSPHERIC TURBULENCE)
WAVEFRONT CORRECTION:
M1
ADAPT. MIRROR MC2
TILT CORRECTION:
TRACKING M2
TILT MIRROR MC1
FOCUS:
M2
ACTUATORS:
PIEZO ELECTRIC
ELECTRO MECHANICAL
HYDRAULIC
10^{-3}
10^{-2}
10^{-1}
10^0
10^1
10^2
10^3
[Hz]
temporal frequency

33



PRINCIPLE OF THE ESO ACTIVE OPTICS SCHEME

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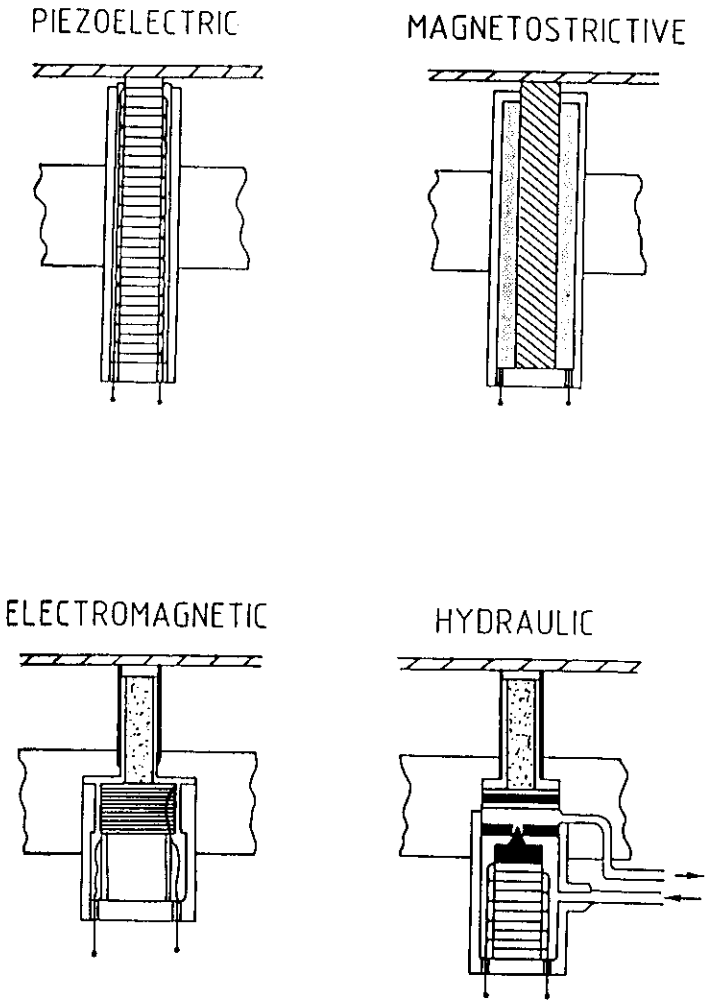
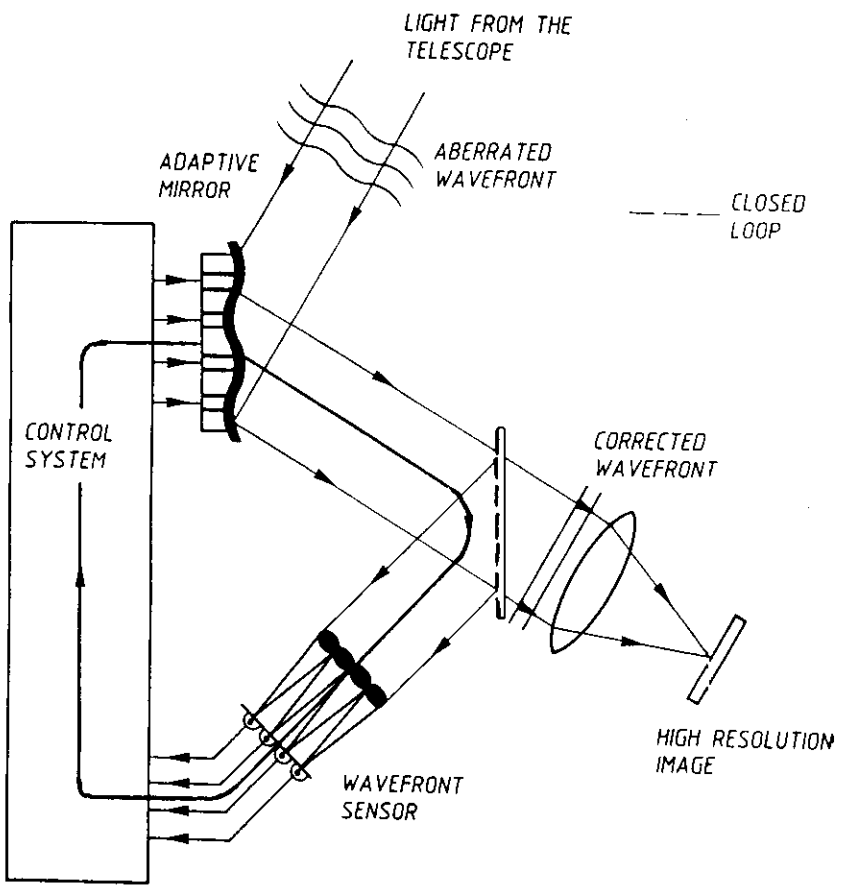


ACTUATORS

FOR DEFORMABLE MIRRORS

Principle of Adaptive Optics



Wavefront Correction Device

- Segmented mirrors
  - Piston only
  - Piston and tilt
- Continous thin-plate mirrors
  - Discrete position actuators
  - Discrete force actuators
  - Bending moment actuators
- Monolithic mirrors
- Membrane or pellicle mirrors.

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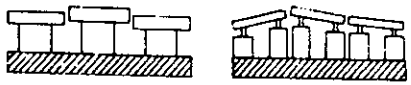
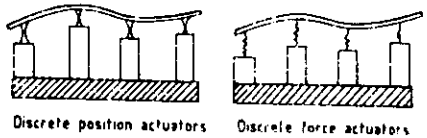
Wavefront Correction Device

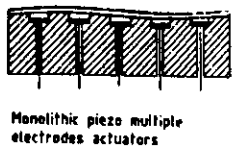
- Segmented mirrors



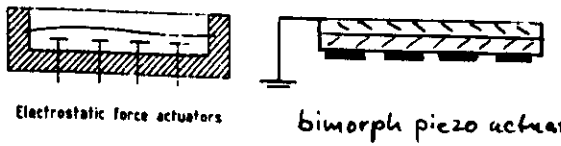
- Continuous thin-plate mirrors



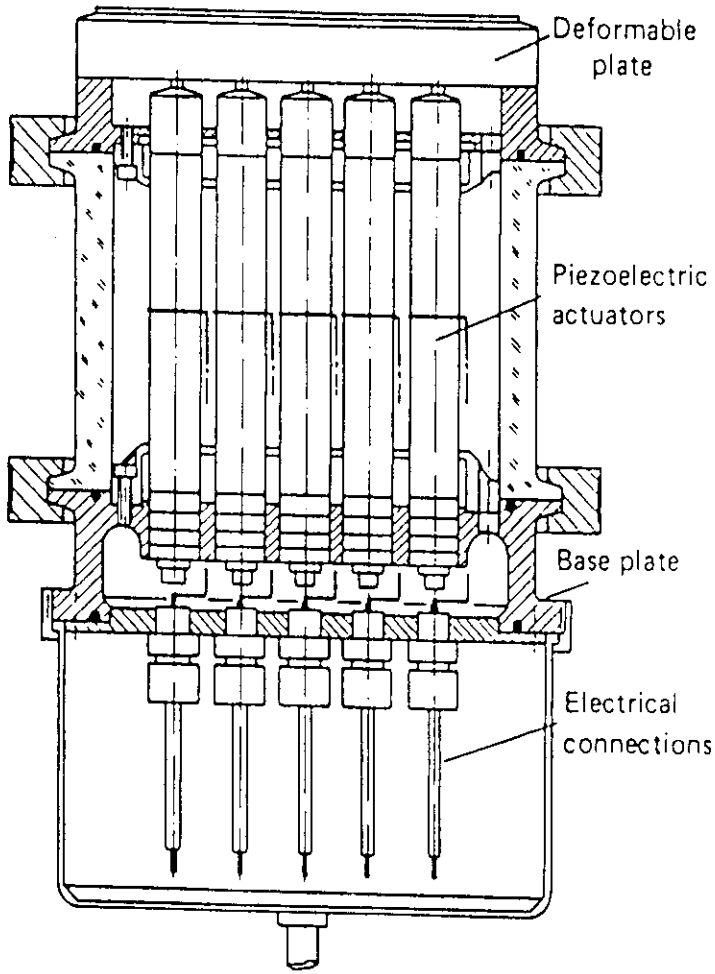
- Monolithic mirrors



- Membrane or pellicle mirrors.



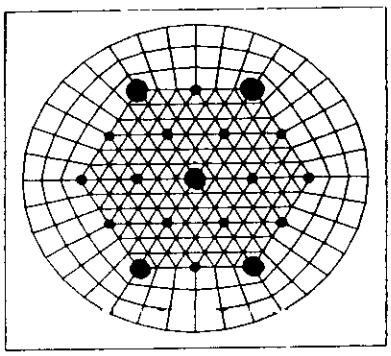
(38)



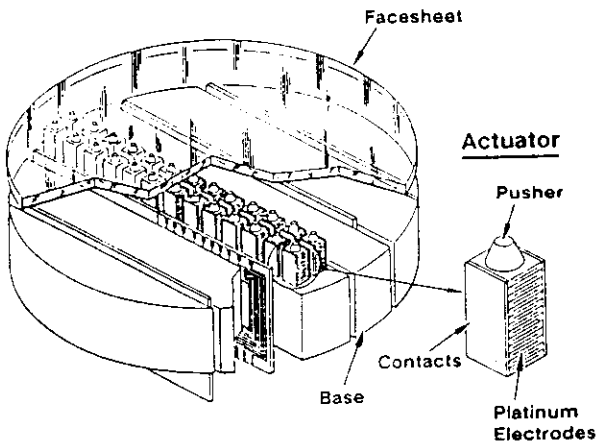
ADAPTIVE MIRROR
19 ACTUATORS
CGE-LABORATOIRES DE MARCOUSSIS

ADAPTIVE OPTICS
PROTOTYPE SYSTEM

VLT



LOW-VOLTAGE ELECTRODISTORTIVE MIRROR



Concept sketch

Size	1 to 8 in. diameter
No. of elements	>241 (typical)
Mirror thickness	0.050 in. (typical)
Sensitivity	12 Å/V
Surface flatness	λ/20 P-V at 0.6 μm
Max. operating voltage	±150 V
Frequency range	DC to 1 kHz
Capacitance	2.0 μF (stacked)
Stroke	±2.0 μm (typical)

Typical characteristics

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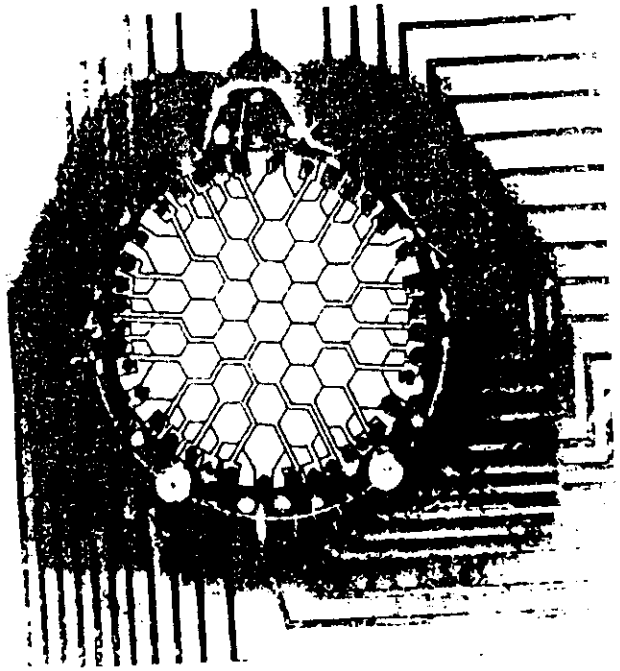
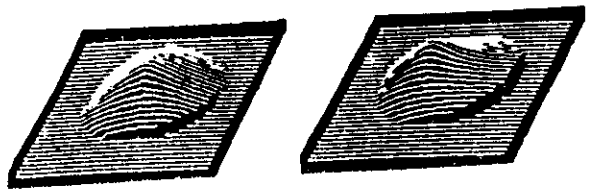
Deformable Mirrors DS 89/161/333 for astronomical use

turbulence compensation in the visible and IR wavelength range up to 400 Hz

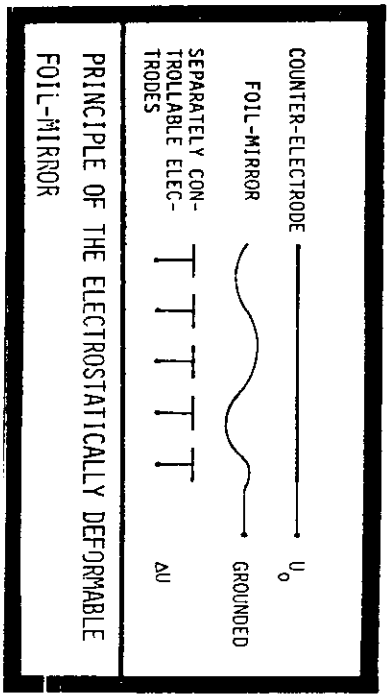
ZEISS

42





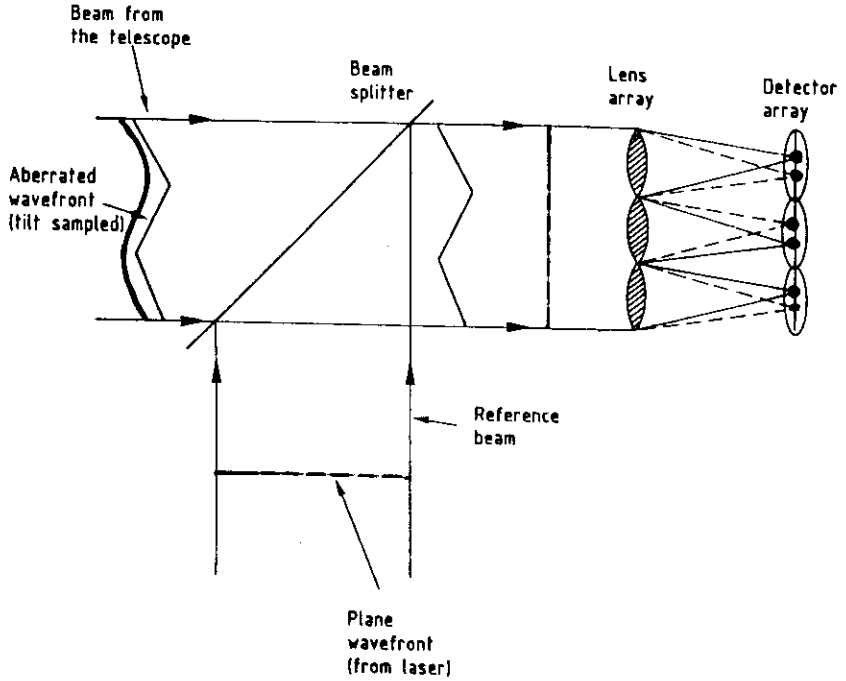
Back side view of a 37-actuator bimorph mirror made by Fred Forbes at NOAO (Fred Forbes et al. 1989). It shows the control electrodes. Underneath is the mirror figure response obtained with a Zygo interferometer when exciting either the central electrode (left) or an adjacent electrode (right). Figure 13 shows the curvature sensor signal in both cases. Edge control has not been implemented yet.



Wavefront Sensor

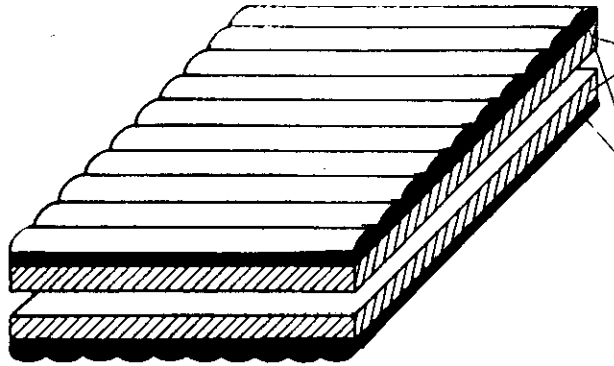
1. Measurements can be made on the intensity distribution of the image produced by the entire wavefront.
2. A reference wavefront of the same or slightly different wavelength combined with the wavefront to be measured to produce interference fringes.
3. The wavefront slope of small zones of the wavefront may be measured. This can be achieved by using a shearing interferometer or the Hartmann test.
4. Curvature sensor

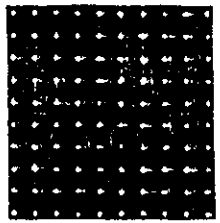
45



SHACK - HARTMANN SENSOR

46



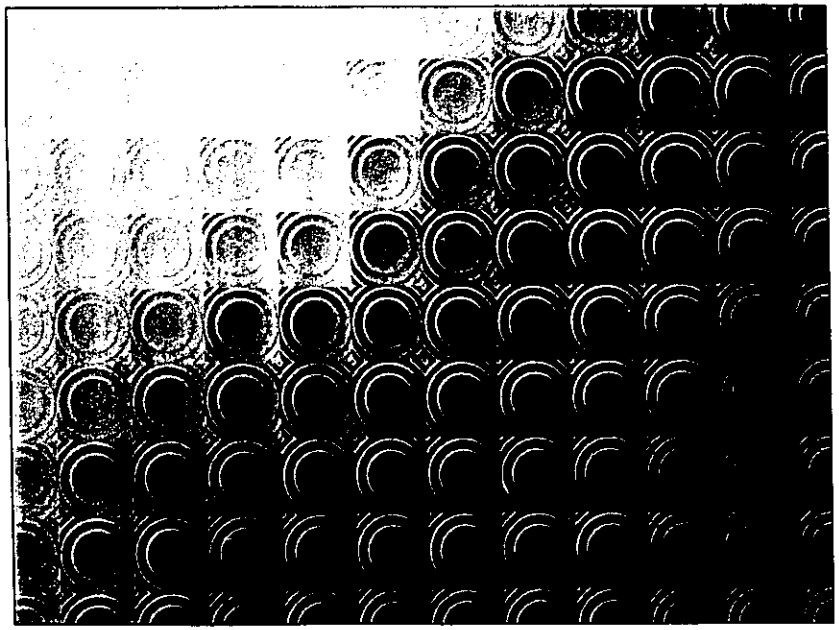


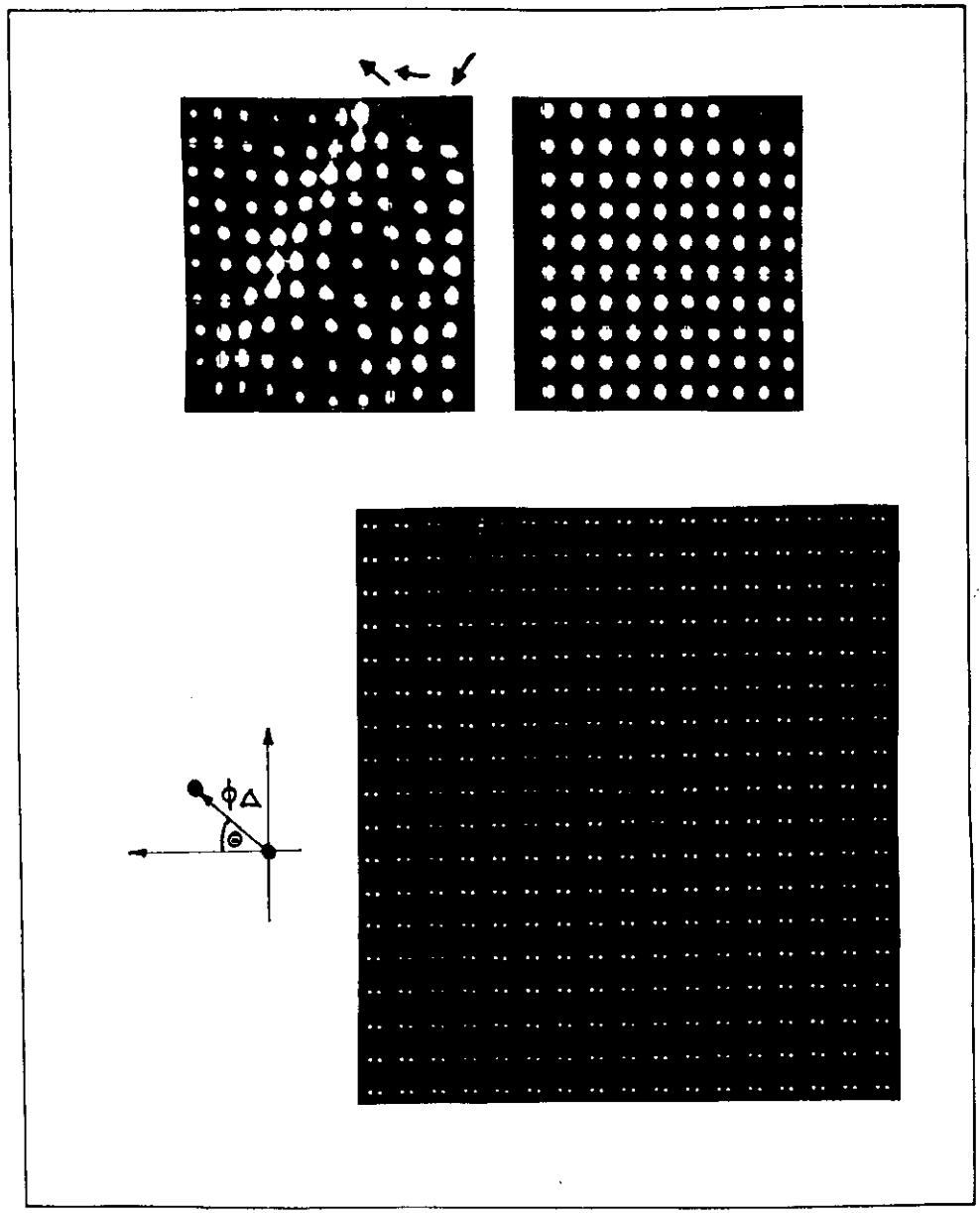
TYPICAL FOCUS PATTERN

Mikrolinsenarray

Daten und Vorteile

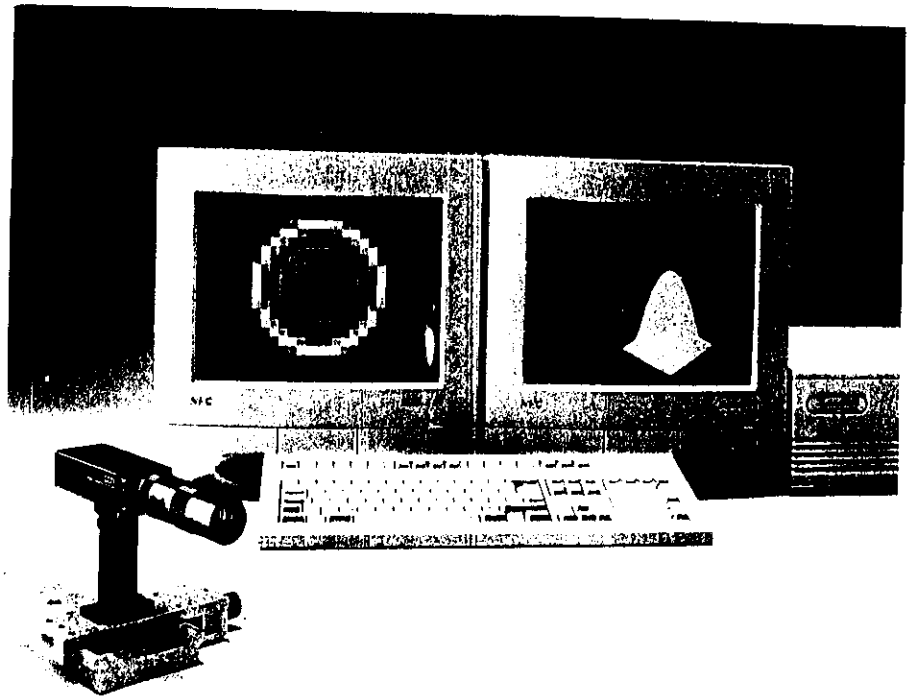
- Linsenzahl 16x16
- Brennweite 40mm
- Apertur 352μm^2 $(32\ pixel)^2$
- Kein Justageaufwand
- Keine Zwickelverluste





(49)

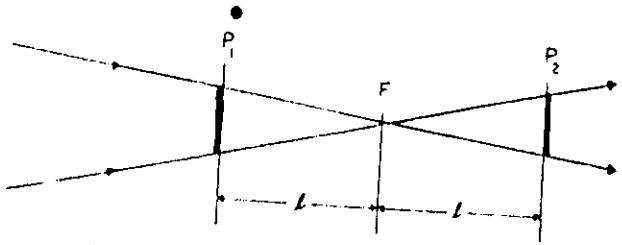
Der Wellenfrontsensor Detect 16 für Labor und Praxis



Wellenfrontbestimmung
durch Gradientenfeldmessung

ZEISS

(50)

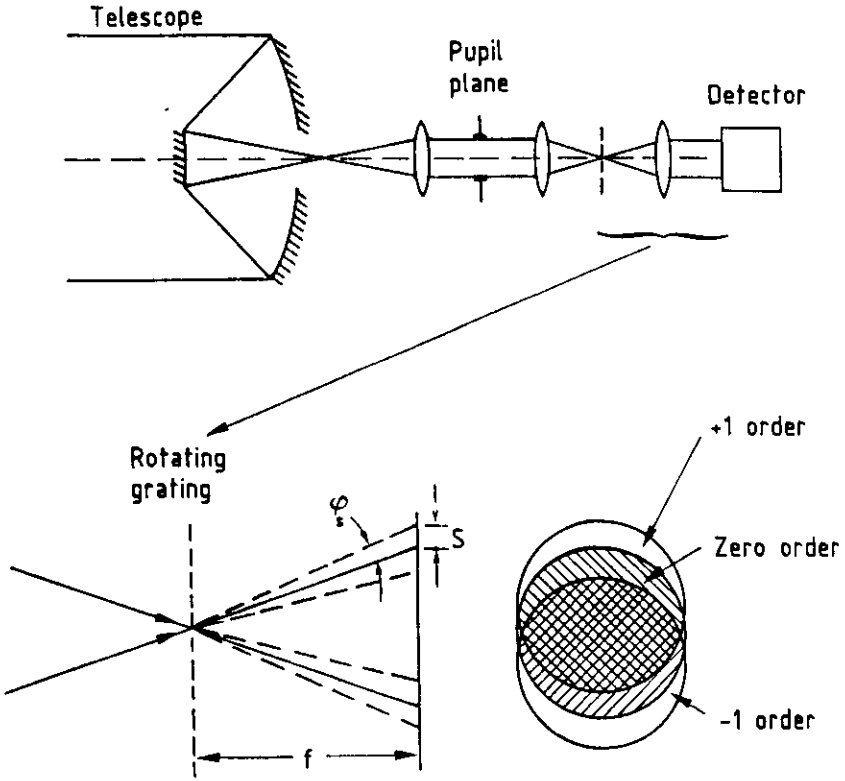


Curvature sensing consists of taking the difference between the illuminations observed in two planes such as P_1 and P_2 at a distance ℓ from the telescope focal plane F.

Examples of curvature signals obtained by taking the difference between symmetrically defocused images recorded on a CCD camera (Roddier et al. 1987). The deformable bimorph mirror shown in Figure 10 was used to deform a plane wavefront. A single electrode was excited in each case, the central electrode (left) or an adjacent electrode (right).

(51)

Shearing-Interferometer



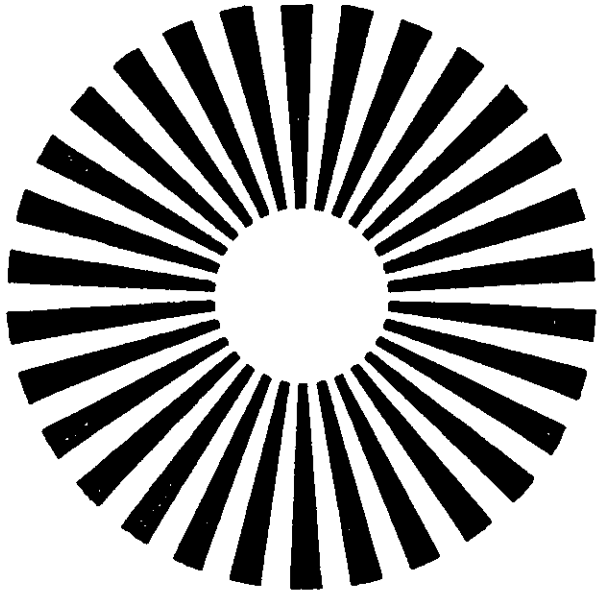
ESO

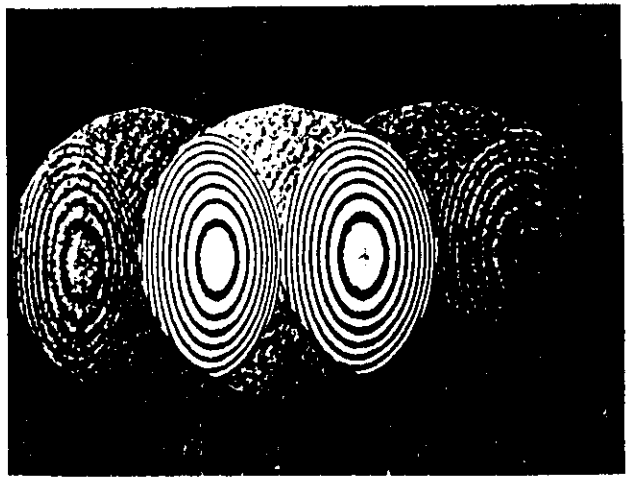
Elements of an Adaptive System

VLT

(52)

Shearing-Interferometer





QUANTUM EFFICIENCY OF CCD IMAGERS

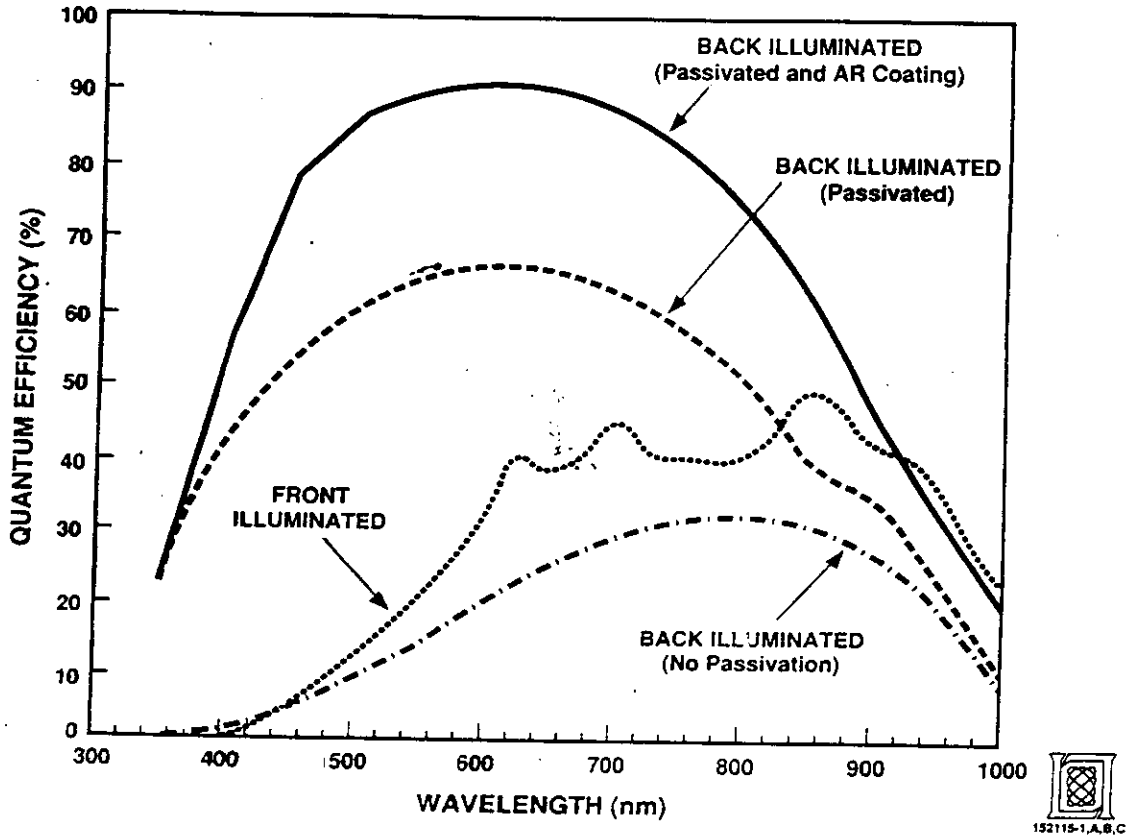
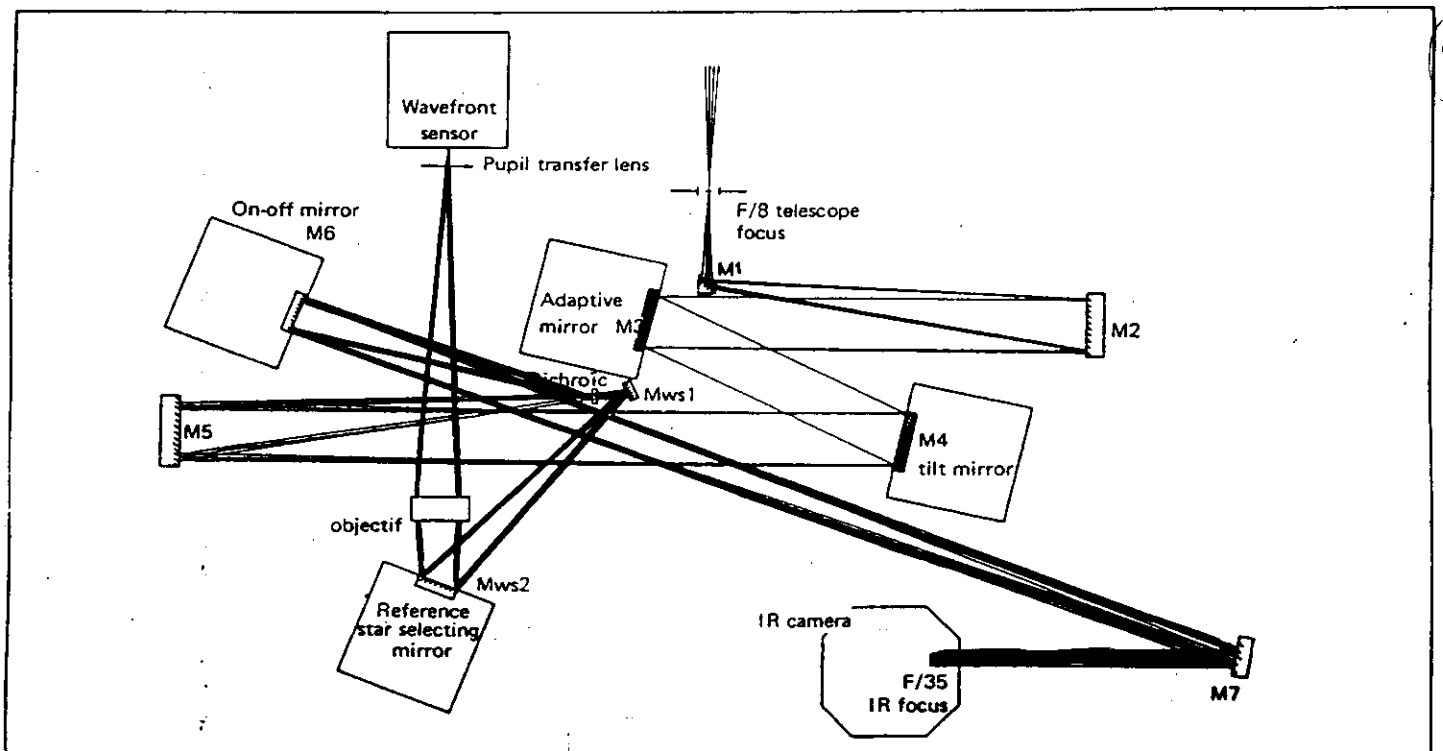
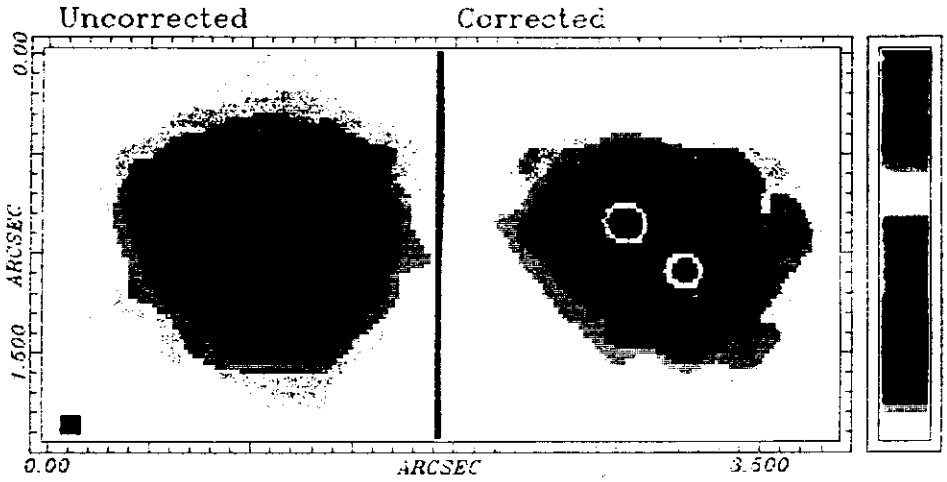


Figure 2



ADAPTIVE OPTICS PROTOTYPE SYSTEM

HR6658. Separation 0.36 arcsec. L Band.



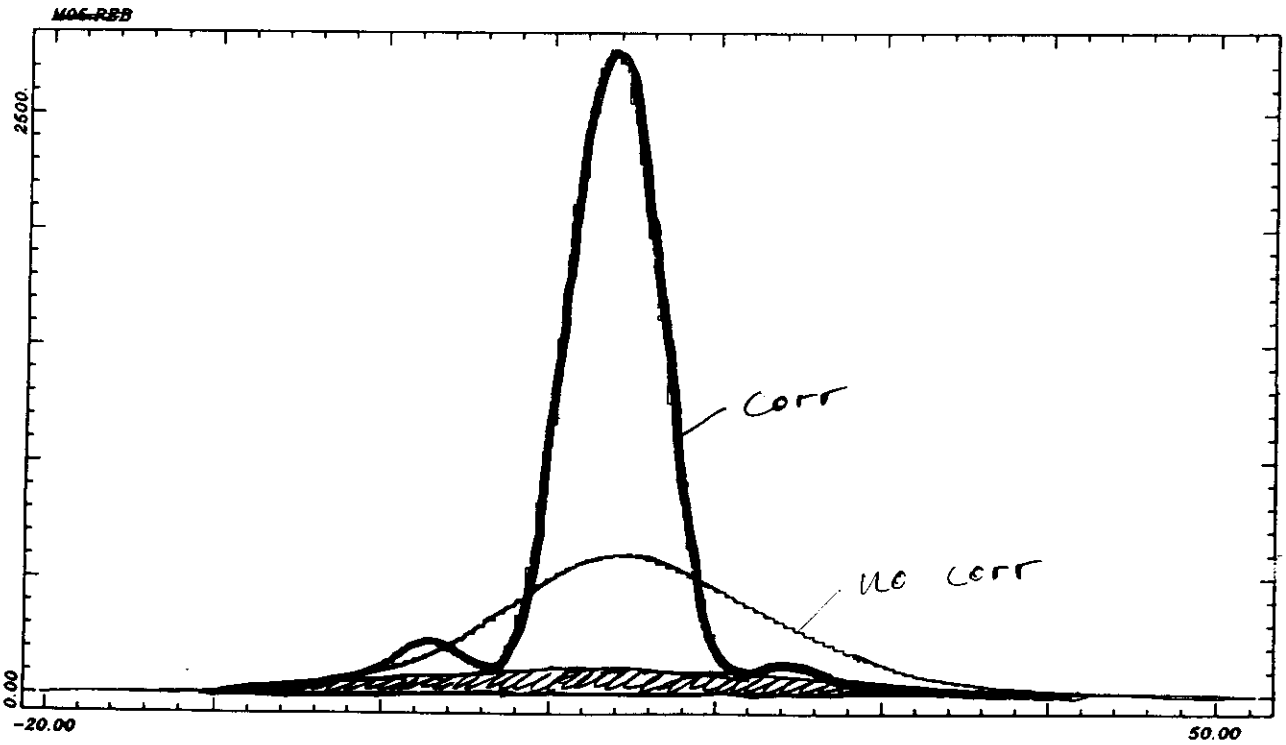
COME-ON ESO 3.6m APR 90

3.6 m telescope

1.68 μm

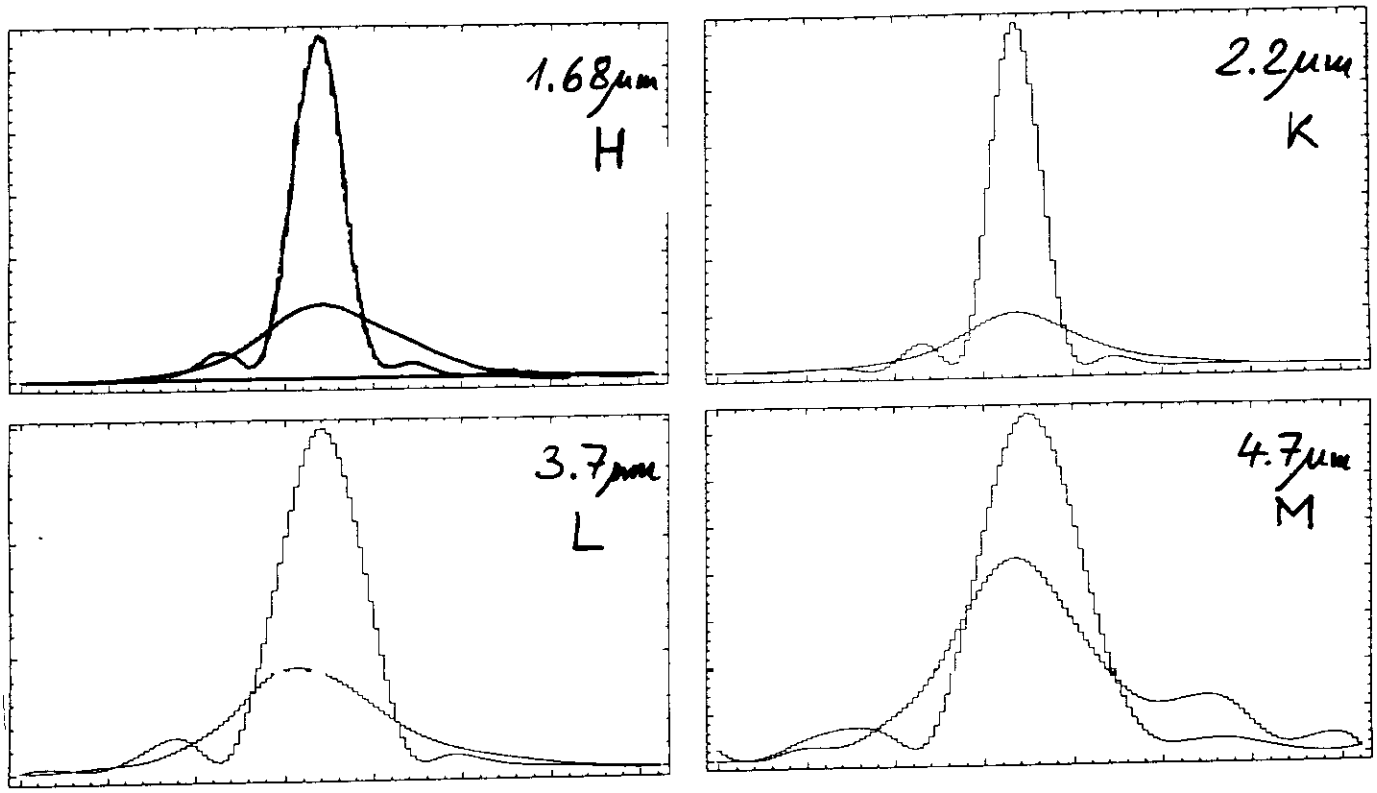
Zeta Cyg. H

Zeta Cyg

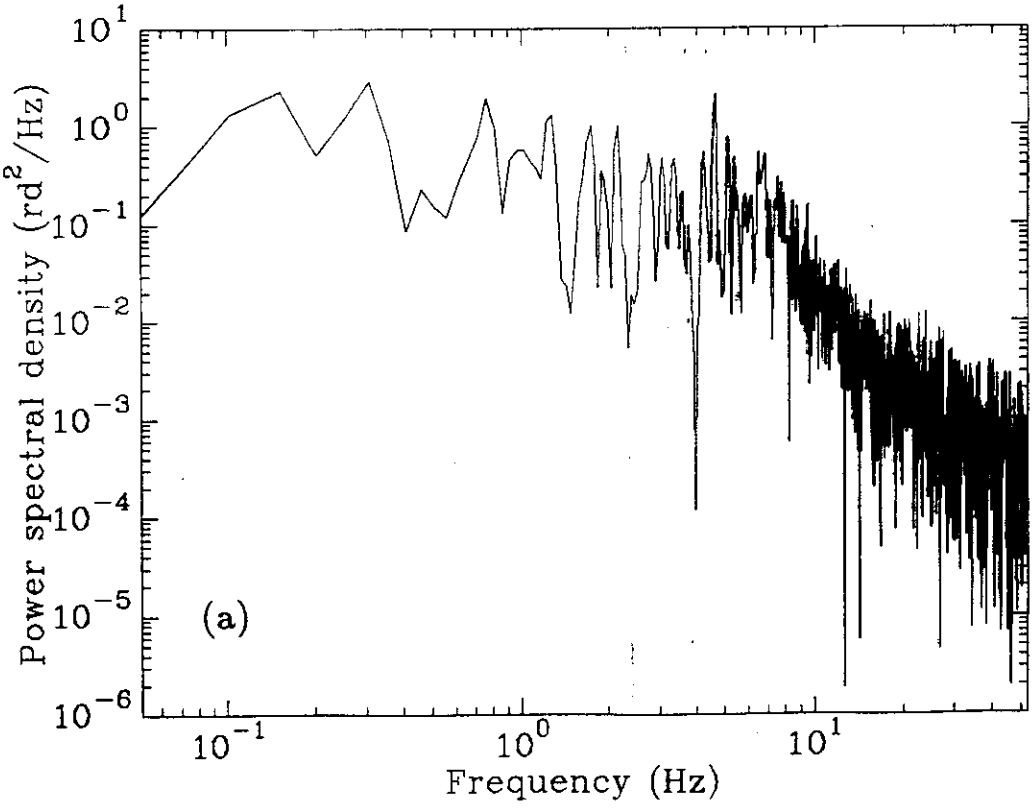


(57)

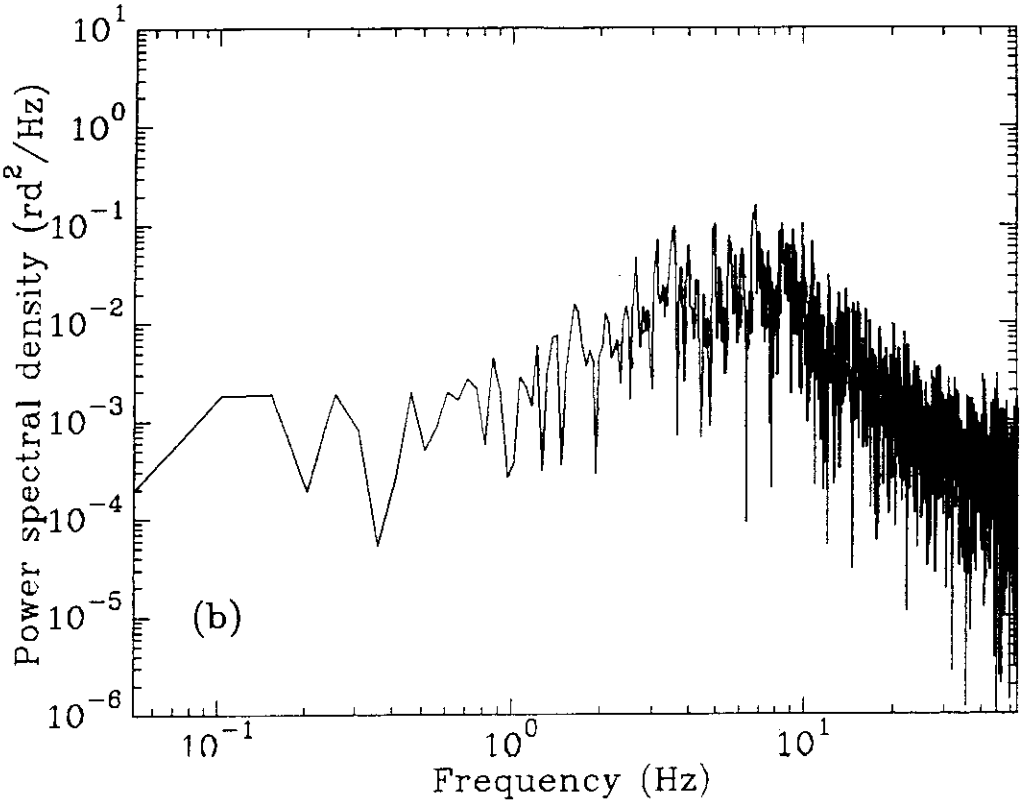
1.52-m.



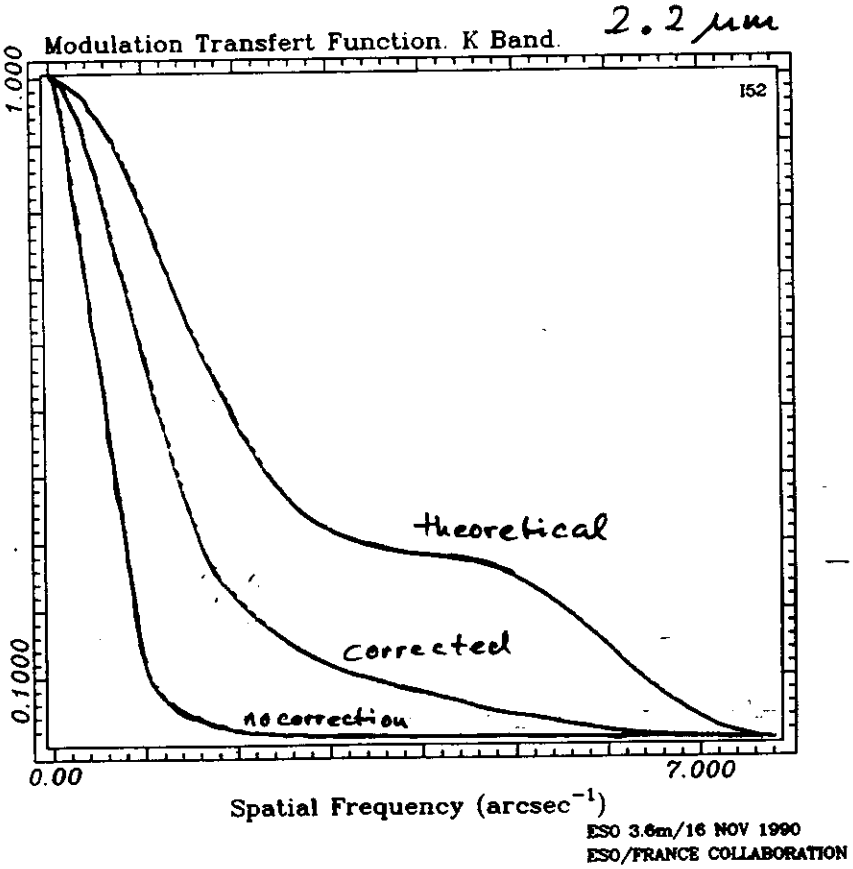
(58)



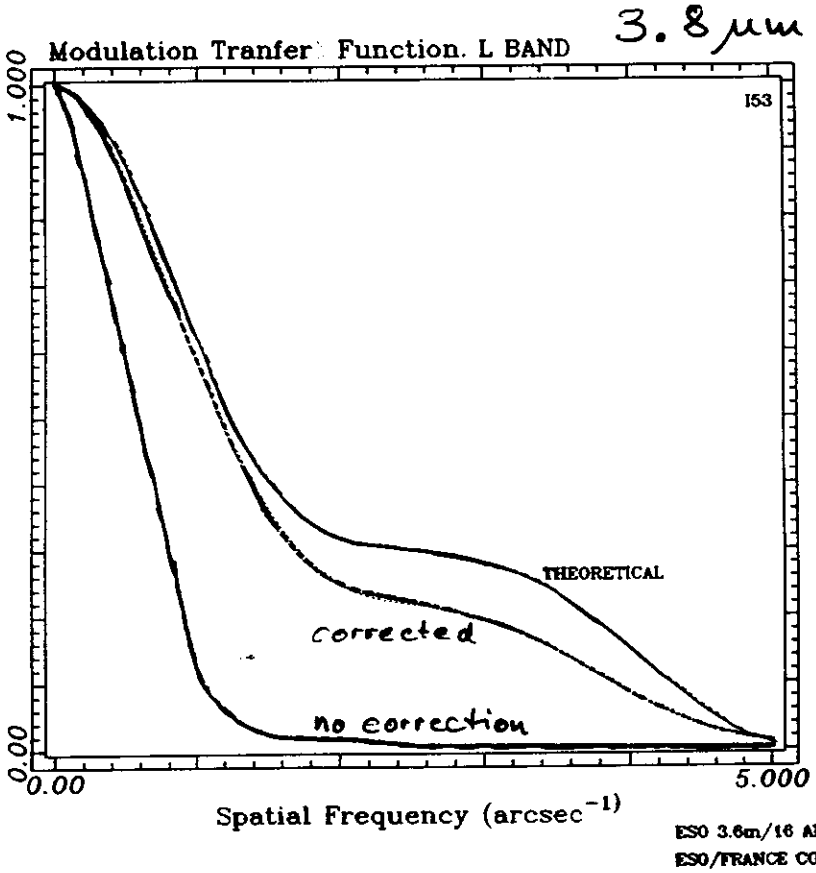
Zernike Coefficient a_4 (defocus


Power spectral density (rd^2/Hz)
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
(b)
10^{-1}
10^0
10^1
Frequency (Hz)

MTF


Modulation Transfert Function. K Band.
2.2 μm
152
1.000
0.1000
0.00
7.000
theoretical
corrected
no correction
Spatial Frequency (arcsec^{-1})
ESO 3.6m/16 NOV 1990
ESO/FRANCE COLLABORATION

MTF



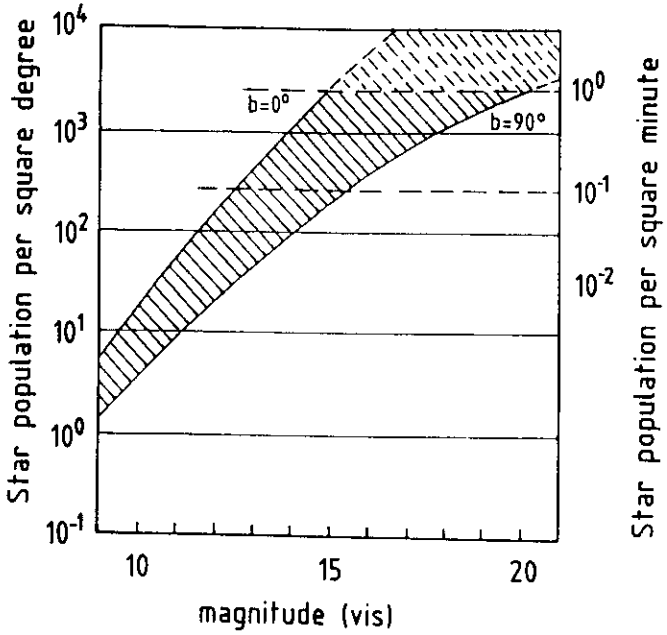
Performance of Come-On Adaptive Optics System on ESO 3.6-m Telescope

Band	Wavelength, m	Corrected Strehl	FWHM, arc-sec	S/N Gain Over Uncorrected System
H	1.68	0.1	0.24	7
K	2.23	0.28	0.18	12
L	3.87	0.7	0.23	7

91050-T3

(63)

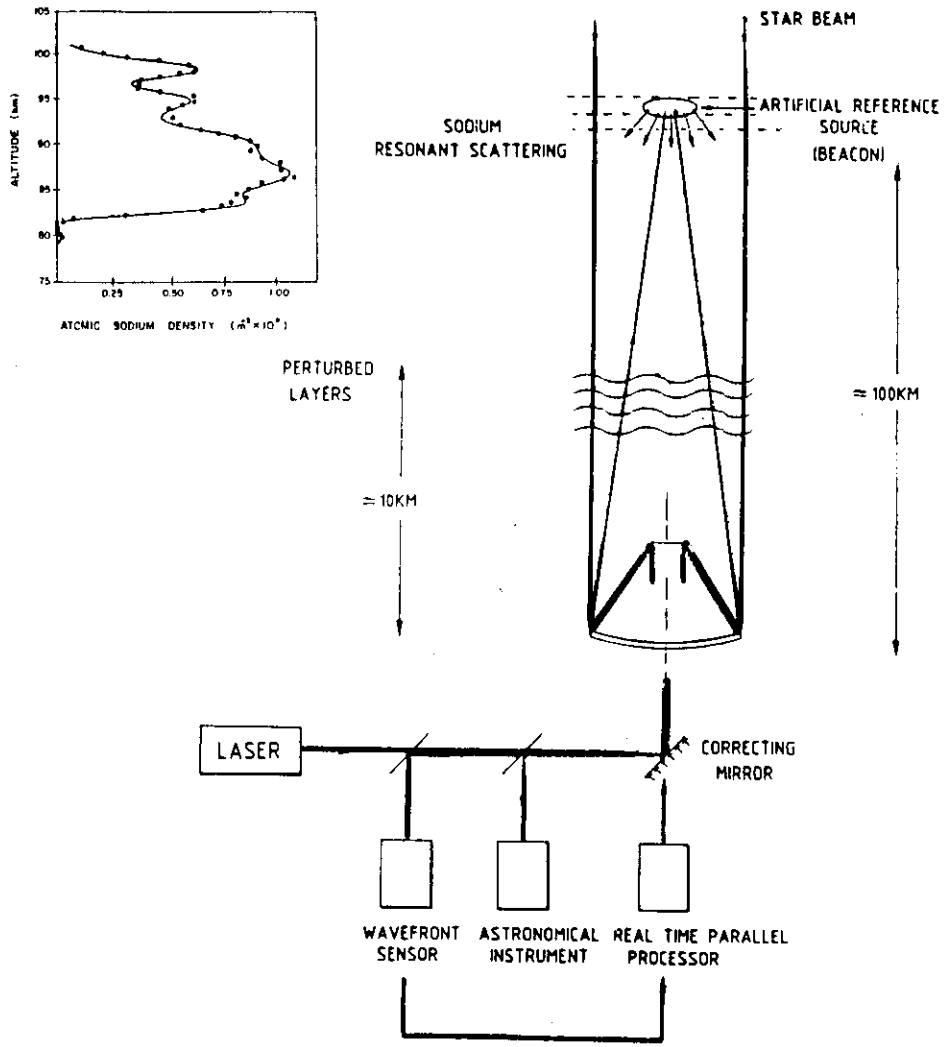
Requirements for Adaptive Correction in Astronomy



λ	$0.5\mu m$	$2.2\mu m$	$5.0\mu m$	$10\mu m$
r_0	$10cm$	$60cm$	$160cm$	$360cm$
m_{lim}	7	13	15.5	17
C_P	$\simeq 0\%$	0.1%	30%	100%
C_E	$\simeq 0\%$	0.3%	100%	100%

(64)

Schematics of the laser probing principle



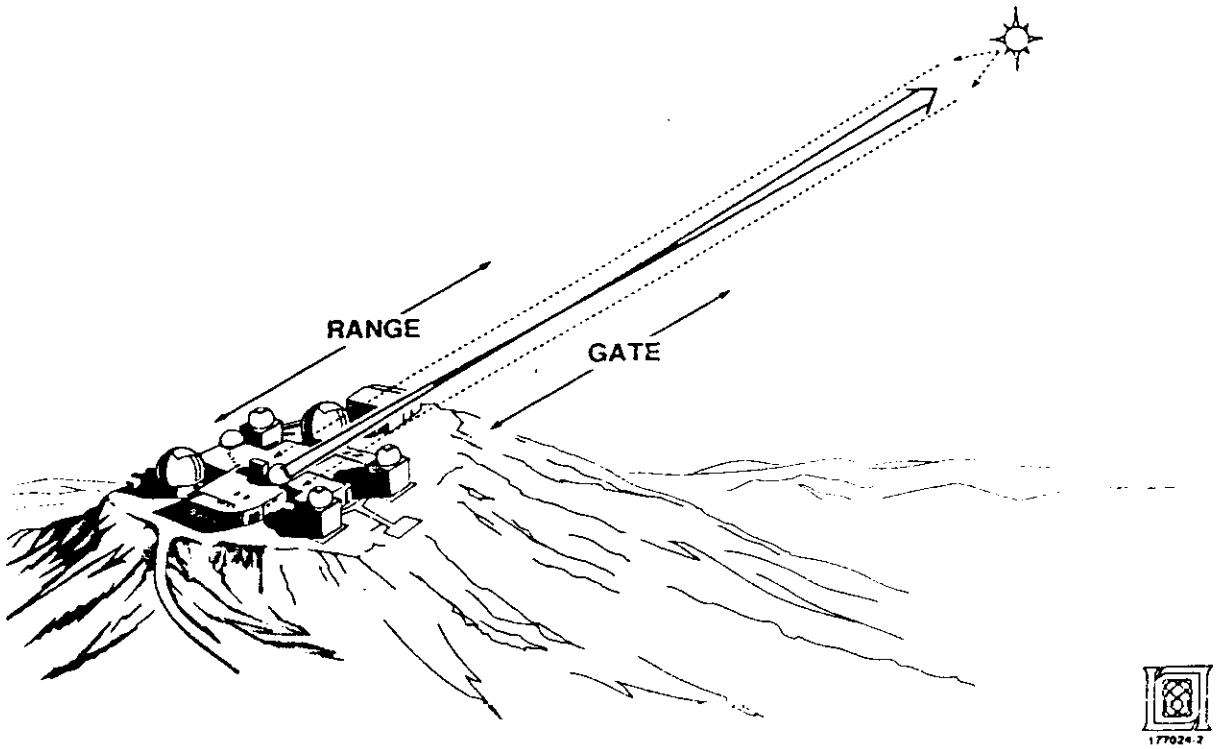
ESO

Adaptive Optics in Astronomy

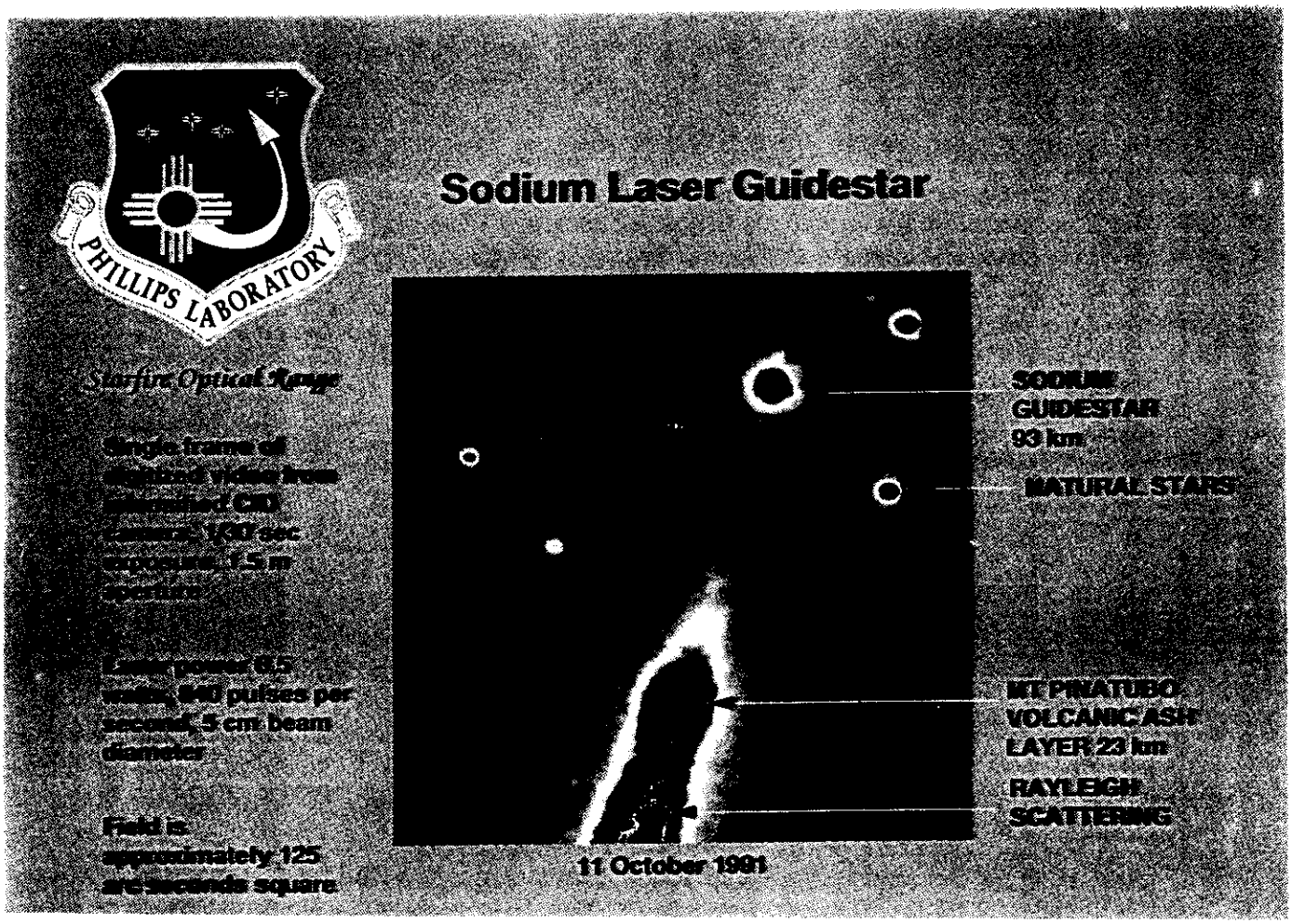
VLT

65

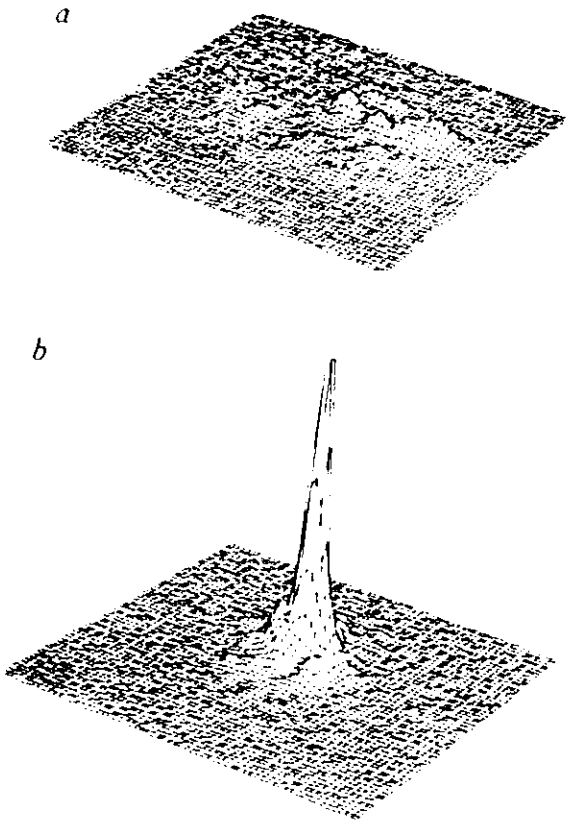
GEOMETRY FOR SYNTHETIC BEACON EXPERIMENT



66



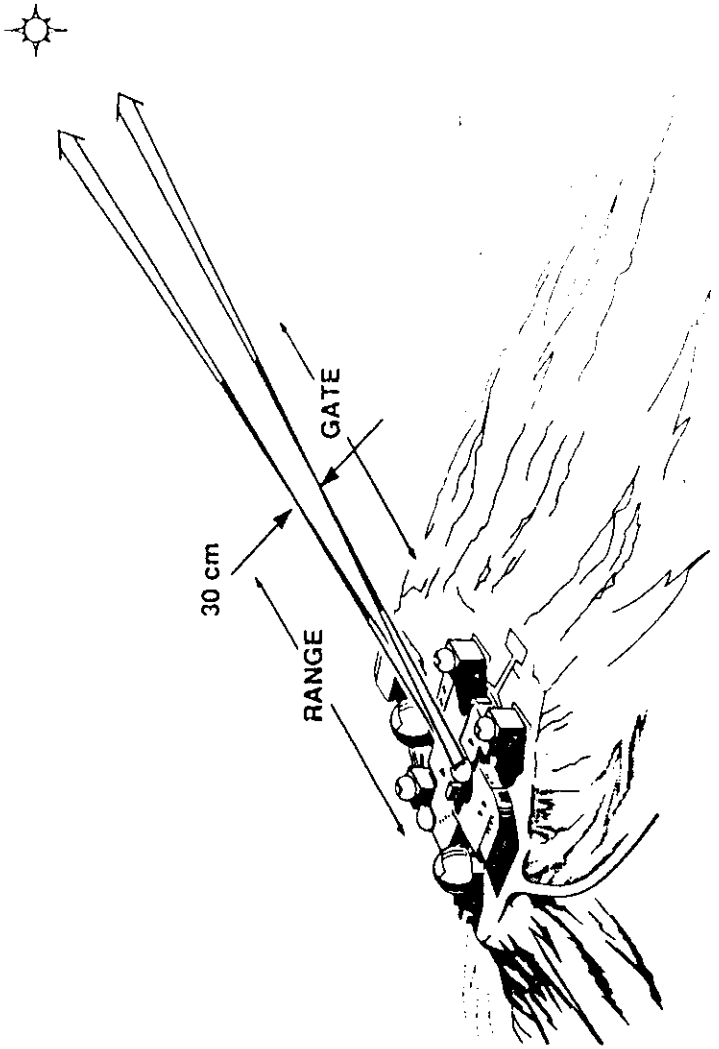
(67)

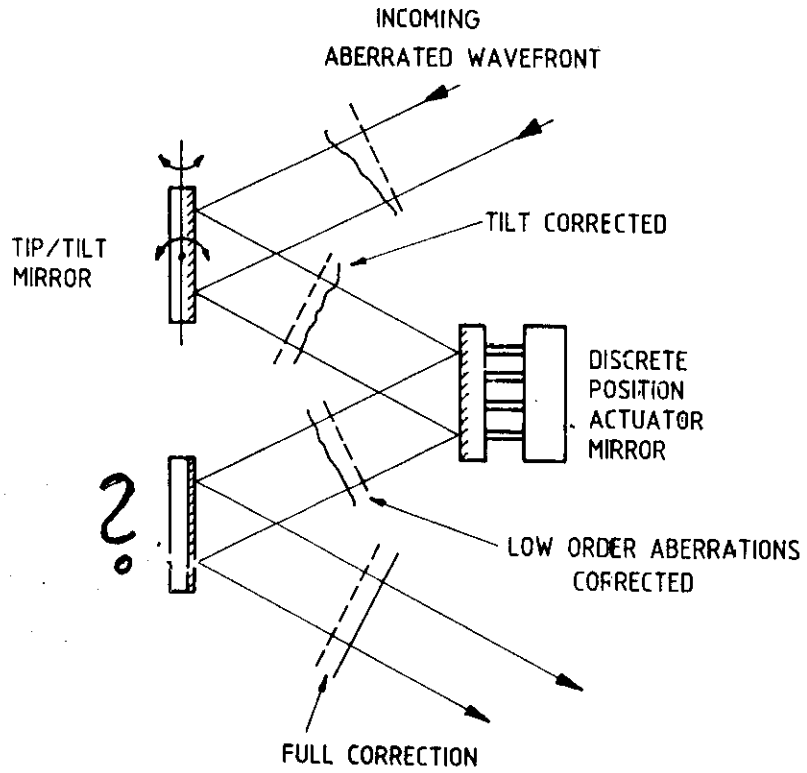


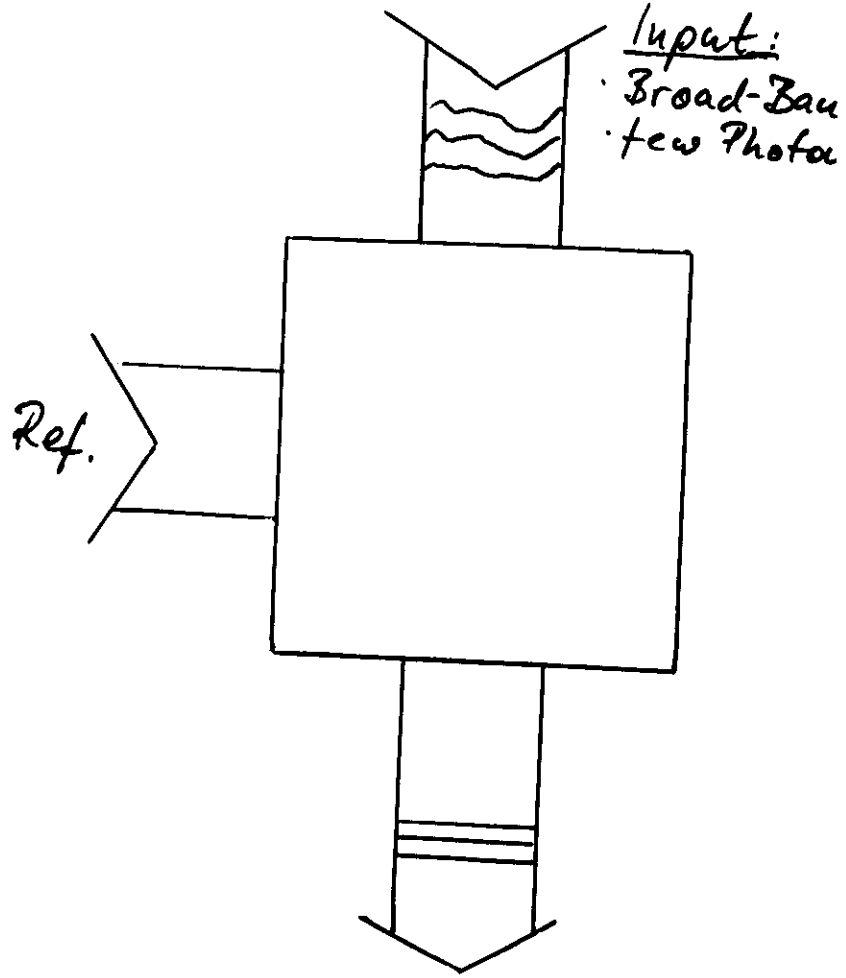
Images of Procyon at a zenith angle of 20° taken with a 64 × 64 CCD camera. *a*, Uncompensated star image. *b*, Compensated star image; Strehl ratio is 0.46. CCD camera field of view is 19 μrad. Synthetic beacon at 6 km, length 1.5 km. $r_0 = 10$ cm.

(68)

TWO-BEACON STITCHING EXPERIMENT




INCOMING
ABERRATED WAVEFRONT
TIP/TILT
MIRROR
TILT CORRECTED
DISCRETE
POSITION
ACTUATOR
MIRROR
2.
LOW ORDER ABERRATIONS
CORRECTED
FULL CORRECTION
reference wavefront
observed wavefront


Input:
Broad-Ban
few Photo
Ref.

ZEISS

Potential Applications for Adaptive Optics:

- Astronomical Observations and Remote Sensing
- Laser Beam Shaping for Instustrial Applications
- Medical Optics (Ophthalmology)
- Synchrotron Beam Lines
- ?

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