The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization
IAEA International Atomic Energy Agency

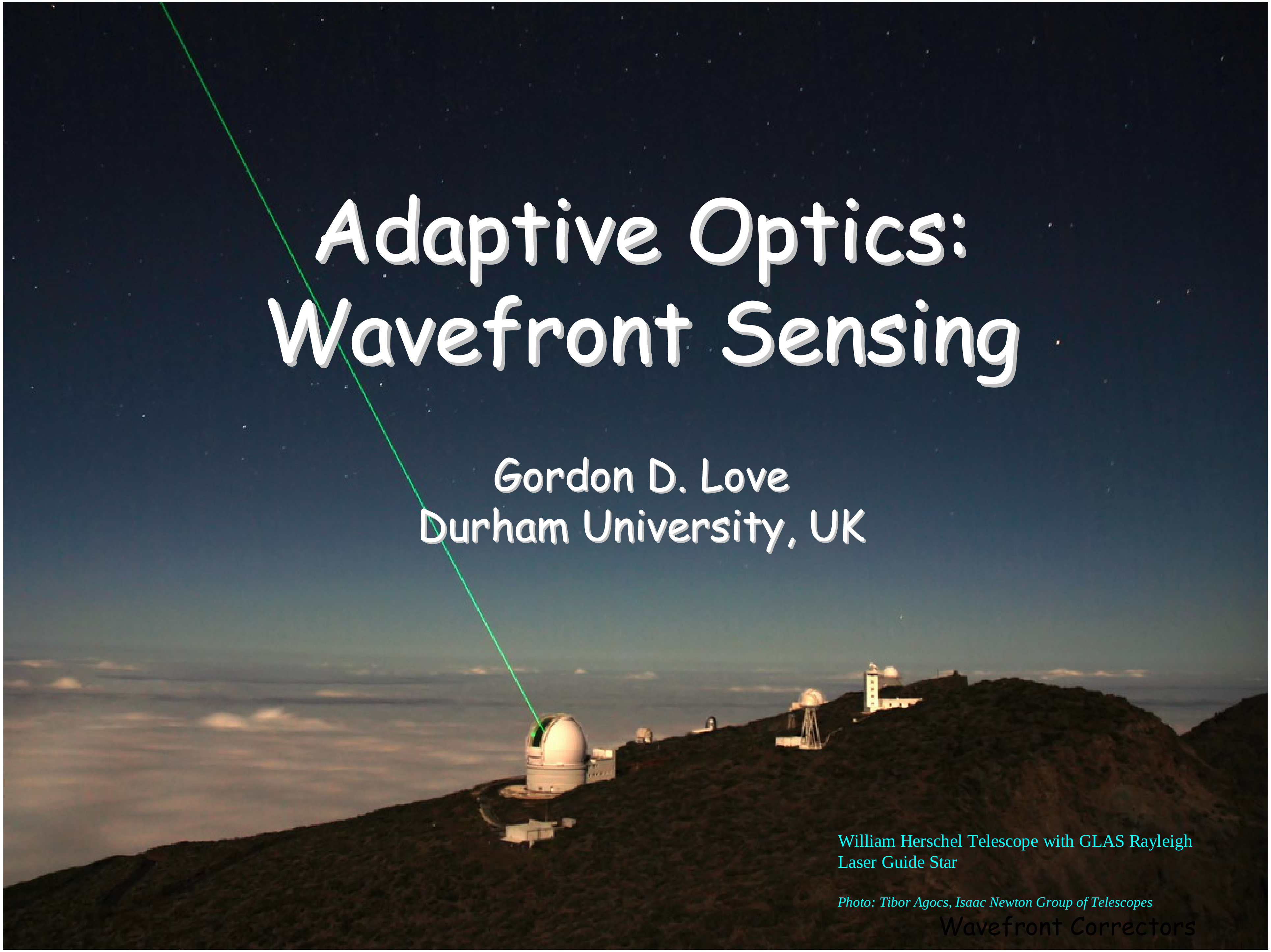
2018-23

Winter College on Optics in Environmental Science

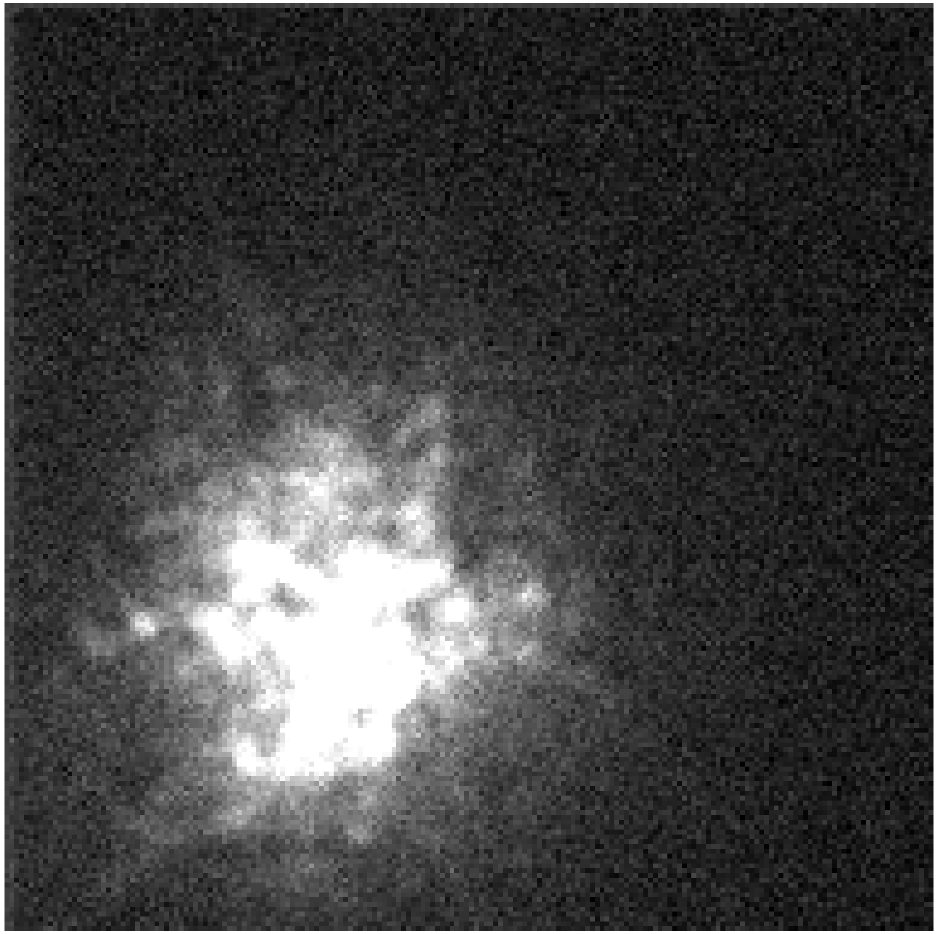
2 - 18 February 2009

Adaptive Optics: Introduction, and Wavefront Correction

Love G.
University of Durham
U.K.


Adaptive Optics:
Wavefront Sensing
Gordon D. Love
Durham University, UK
William Herschel Telescope with GLAS Rayleigh Laser Guide Star
Photo: Tibor Agocs, Isaac Newton Group of Telescopes
Wavefront Correctors

Atmospheric Seeing



ICSTM, 1995, Betelgeuse, 30ms exposures, 689nm

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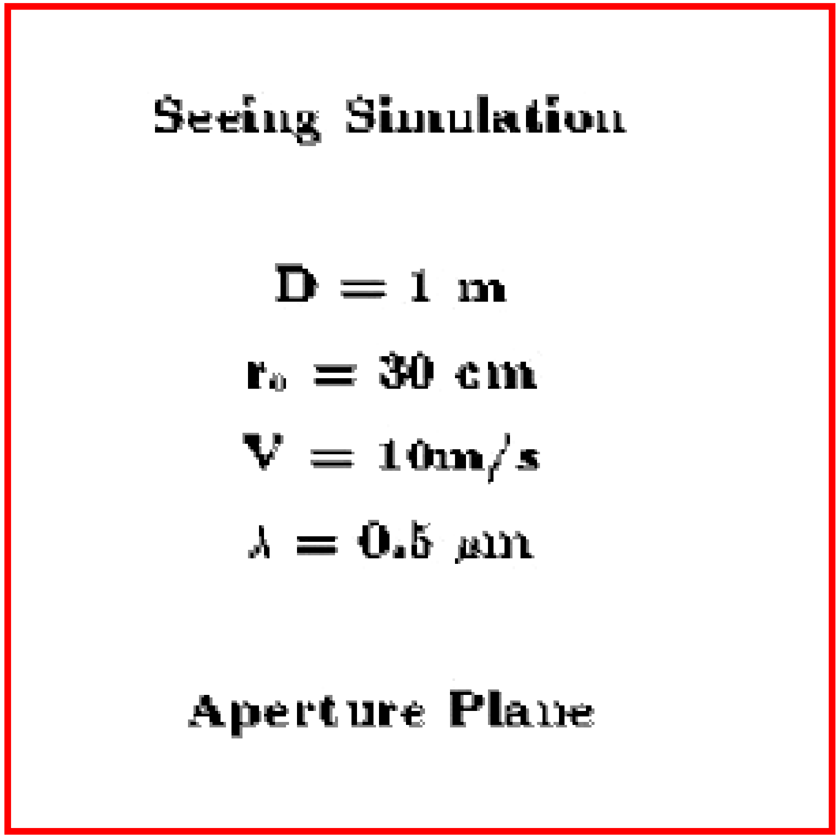
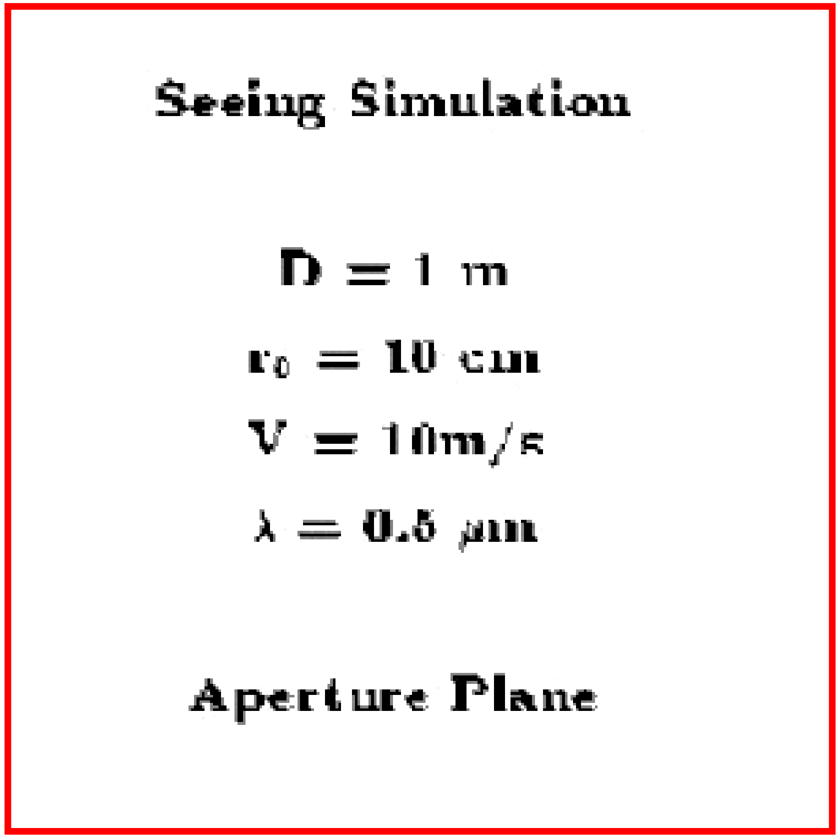
Seeing Simulation: Wavefronts





(Courtesy of Georgia State University www.chara.gsu.edu/Resources/gallery.html)

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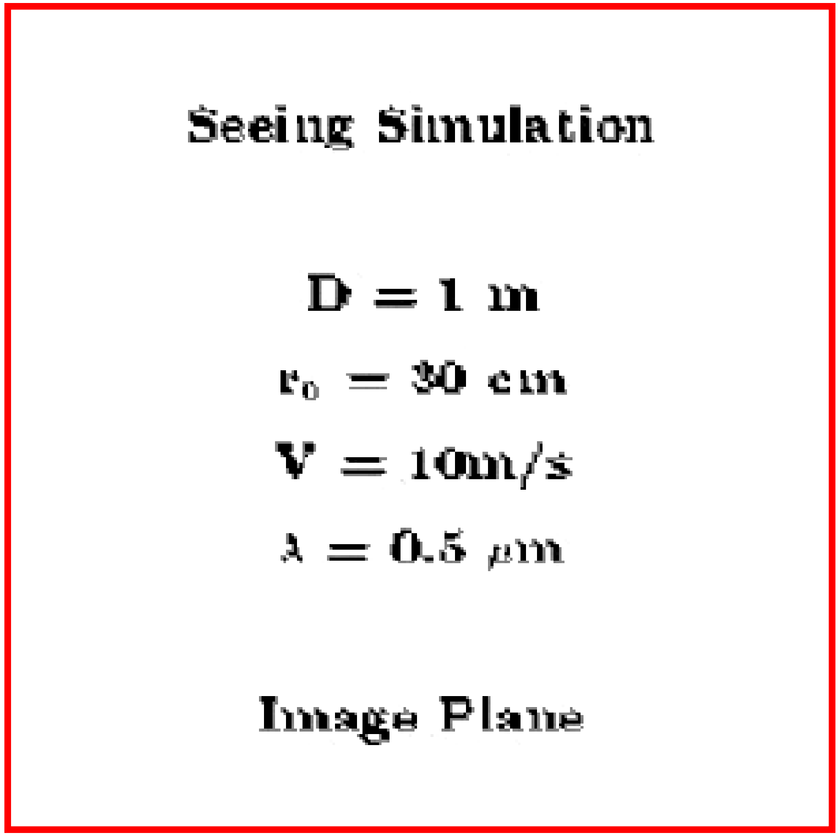
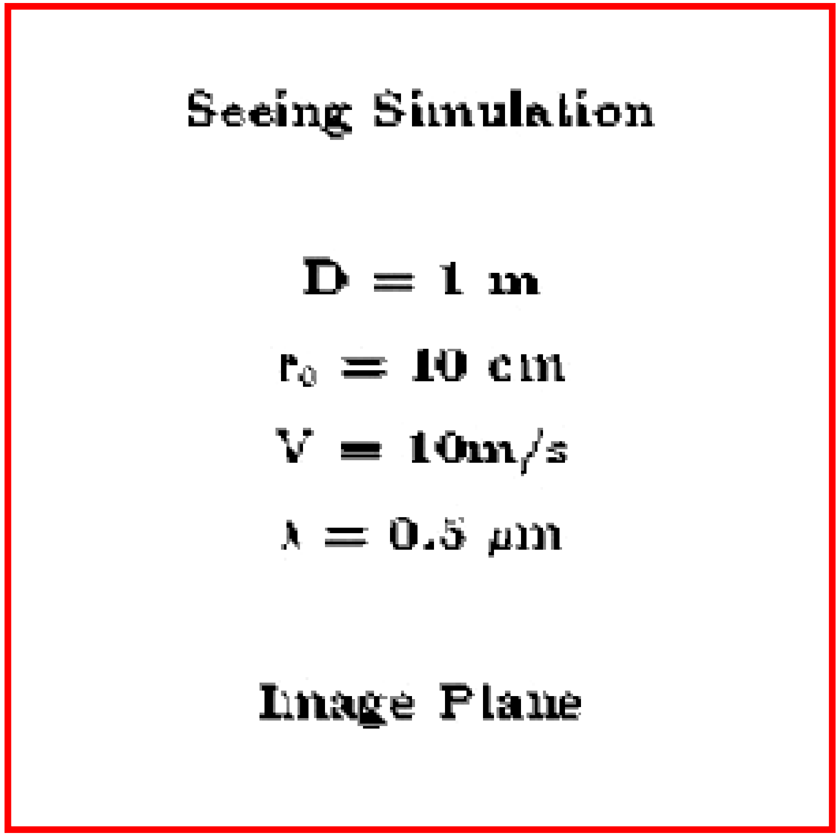
Seeing Simulation: Effect on Image



$D/r_0 \sim 4$ - image dominated by tip/tilt



$D/r_0 > 4$ - image dominated by speckle

(Courtesy of Georgia State University www.chara.gsu.edu/Resources/gallery.html)

Wavefront Sensing I Overview

- Shack Hartmann WFS
- Curvature Sensing

} Most commonly used techniques

- Interferometry
- Phase Retrieval Methods
- Image Quality Metrics

} Used relatively infrequently

- Modal WFS
- Pyramid WFS
- Hybrid Curv. & Grad. WFS

} Newer techniques

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Why is wavefront sensing not simple?

Classic Problem in Physics called the Inverse Problem

- Given a particular intensity distribution, in the focal plane, what was the distribution of phase, and intensity, in the pupil plane which caused it?

For a point source

$$I(x,y) \sim \left| \Im\left[A(u,v) e^{i\phi(u,v)} \right] \right|^2$$

Where $\Im$ means Fourier Transform.

Given *I(x,y)* it is impossible to unambiguously determine *ϕ(u,v)*.

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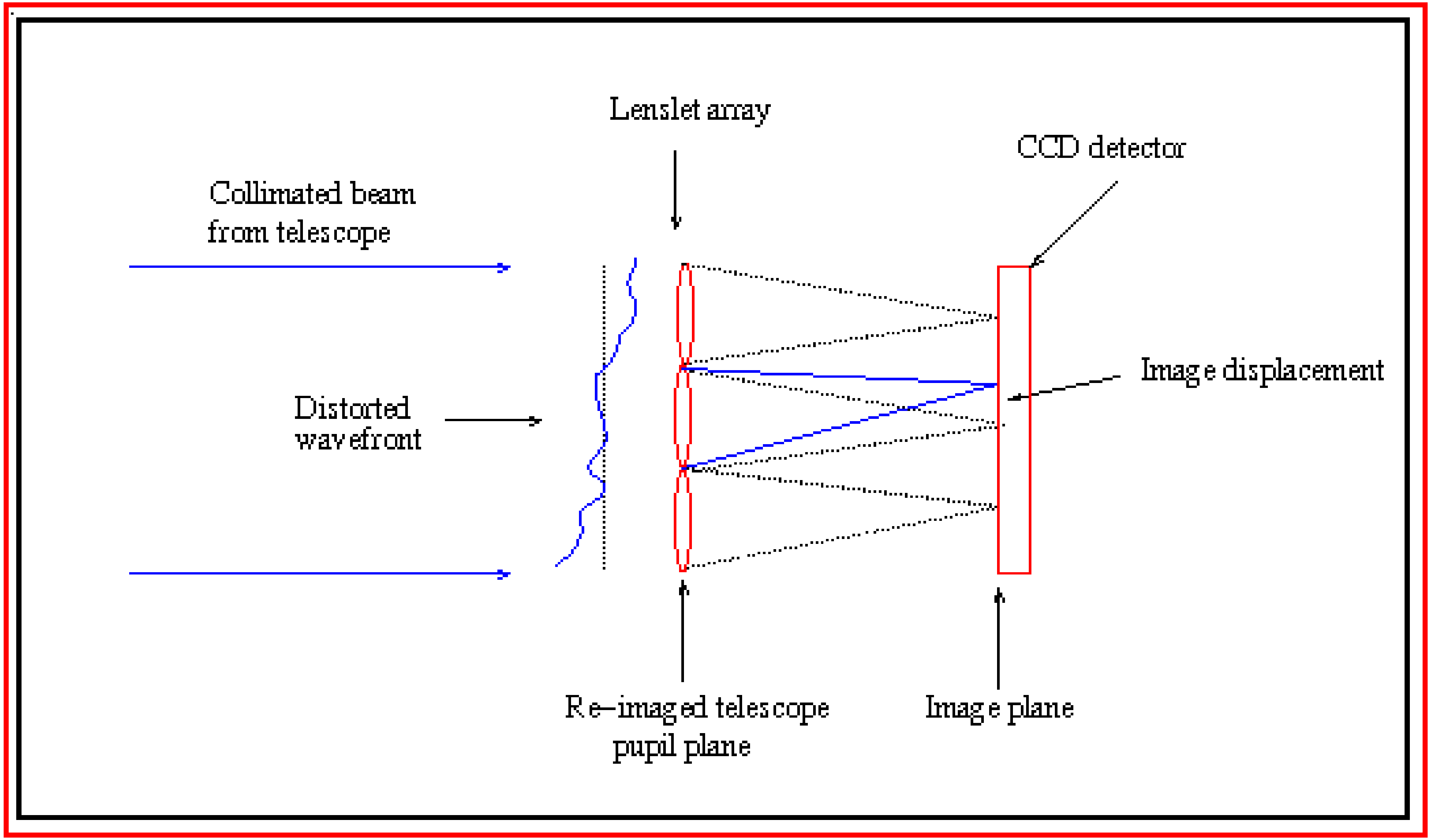
Shack Hartmann WFS



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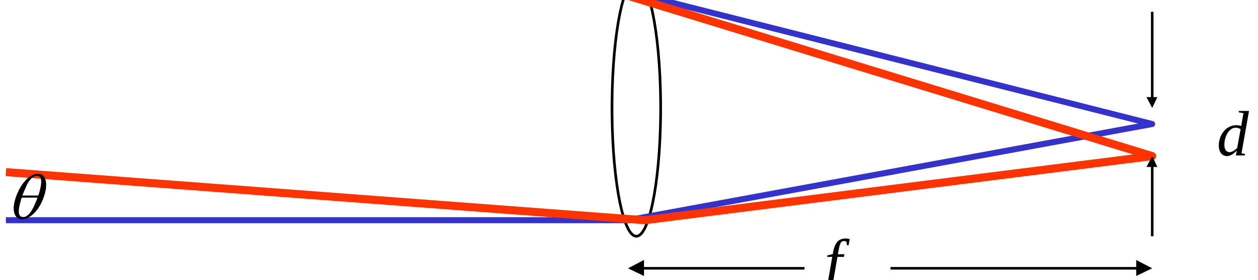
Shack Hartmann WFS
Displacement Measurements

A Shack Hartmann WFS measures the local wavefront slope, or gradient. The data consists of a series of *x* and *y* slope measurements for each lenslet.

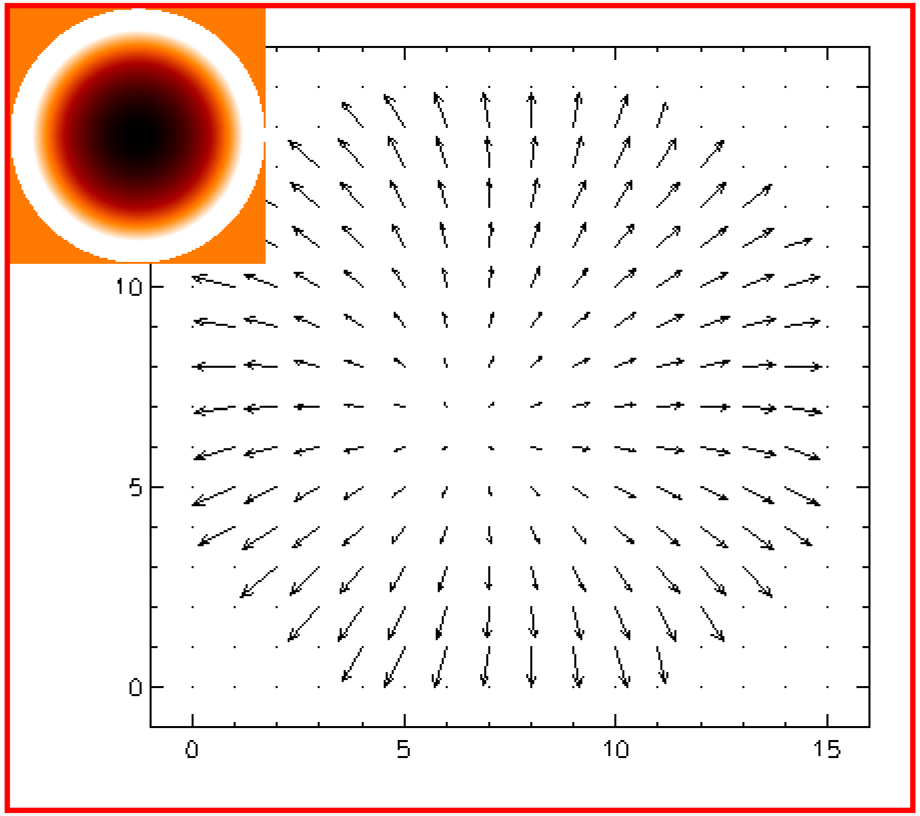
If a wavefront is tilted by an angle θ, then the image moves by a distance

$$d = f \tan\theta \approx f\theta$$

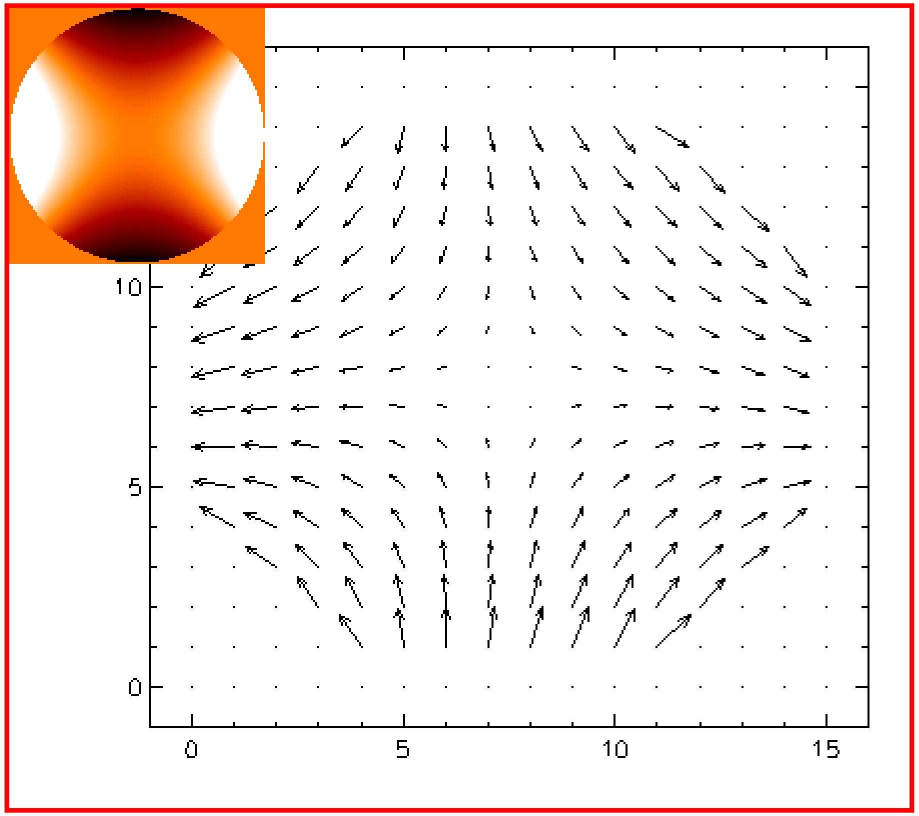


Shack Hartmann WFS
Example spot displacement patterns

Defocus



Astigmatism



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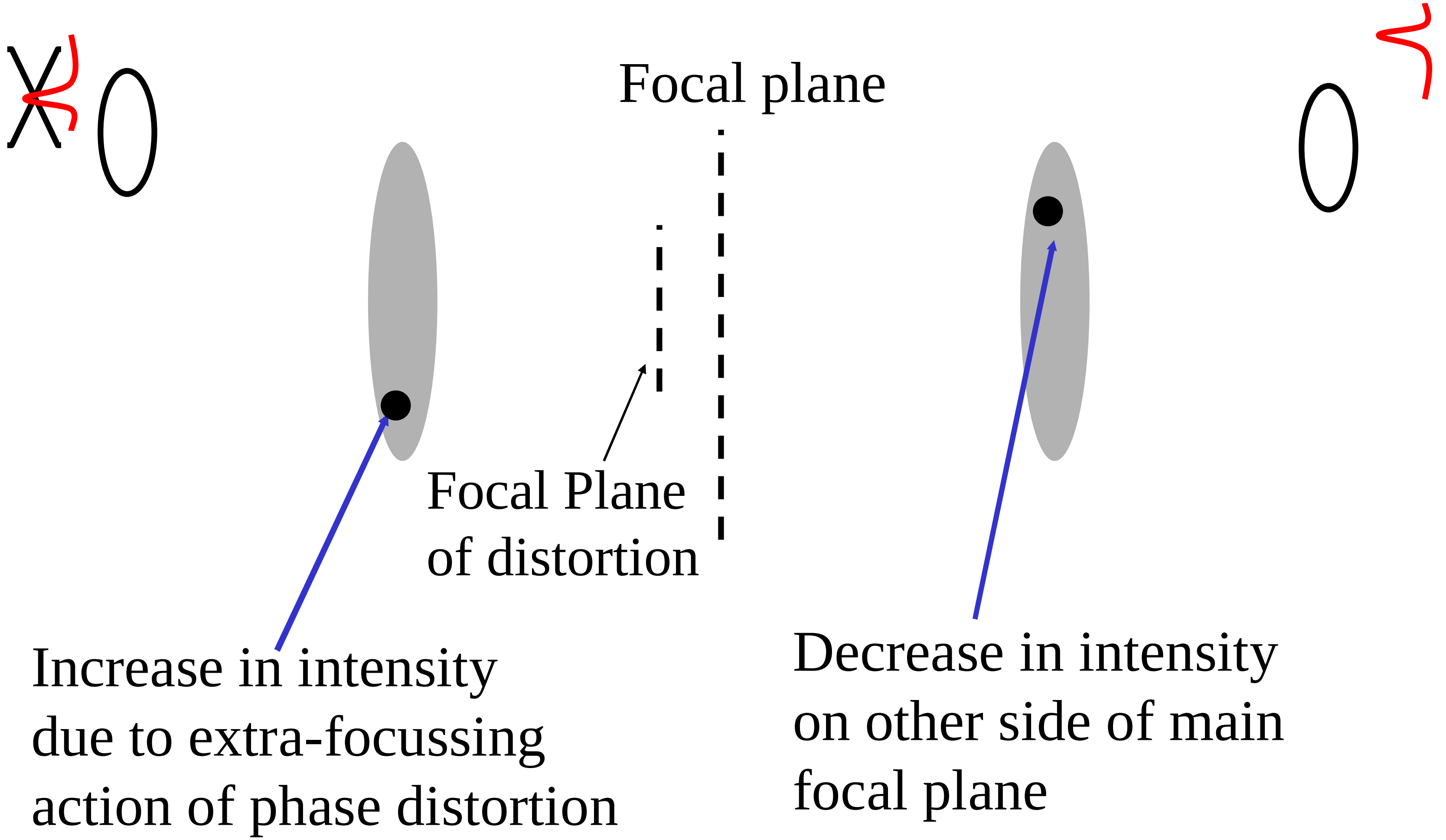
Curvature Sensors
Basic Principle



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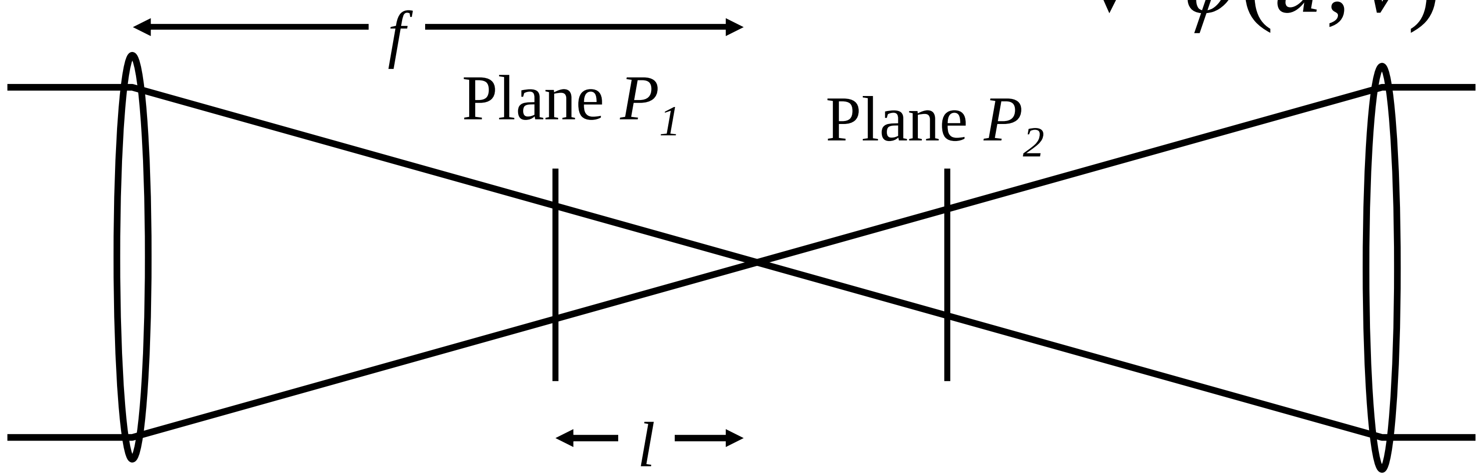
Curvature Sensors Measurements

- Curvature sensing involves recording the intensity of the beam in 2 planes on either side of the focus.
- The difference in intensities is proportional to the wavefront curvature $\nabla^2\phi(u,v)$



Curvature Sensors
Transport of Intensity Equation

The transport of intensity equation governs how the field propagates from one plane to another. For a wave described by

$$\nabla = \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y} \right)$$

$$U(x,y,z) = \sqrt{I(x,y,z)}\, \exp\big(ikW(x,y,z)\big)$$

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}$$

Then

$$\nabla . I \nabla . W + I \nabla^2 W + \frac{\partial I}{\partial z} = 0$$

Generally significant only at pupil edge

Curvature

Measurement

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Curvature Sensors Measurements

$$\frac{I_1(\underline{r}) - I_2(\underline{r})}{I_1(\underline{r}) + I_2(\underline{r})} = \frac{f(f-l)}{l}\left[\frac{\partial W}{\partial n}\delta_c - \nabla^2 W\right]$$

Roddier, Appl. Opt. **27**(7):1223 (1988)

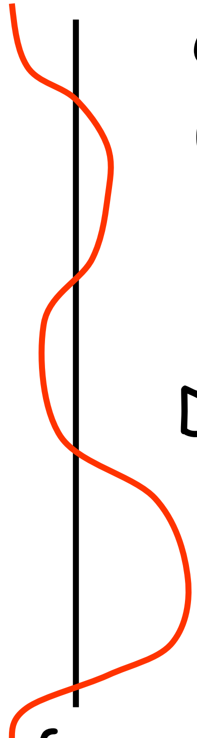
δ_c a unit impulse function around the edge of the pupil

I.e. curvature sensing involves solving Laplace's equation with the Neumann boundary conditions.

f = focal length and *l* = displacement of planes from the focus

Interferometry
Basic Concept

Distorted Wavefront



Constructive Interference

$$(W_{distorted} - W_{plane}) = n\lambda$$

Destructive Interference

$$(W_{distorted} - W_{plane}) = (n+1)\lambda$$

+ Reference Plane Wavefront

Seeing Simulation

D = 1 m

r_0 = 10 cm

V = 10 m/s

λ = 0.5 μm

Aperture Plane Fringes

(Courtesy of Georgia State University)

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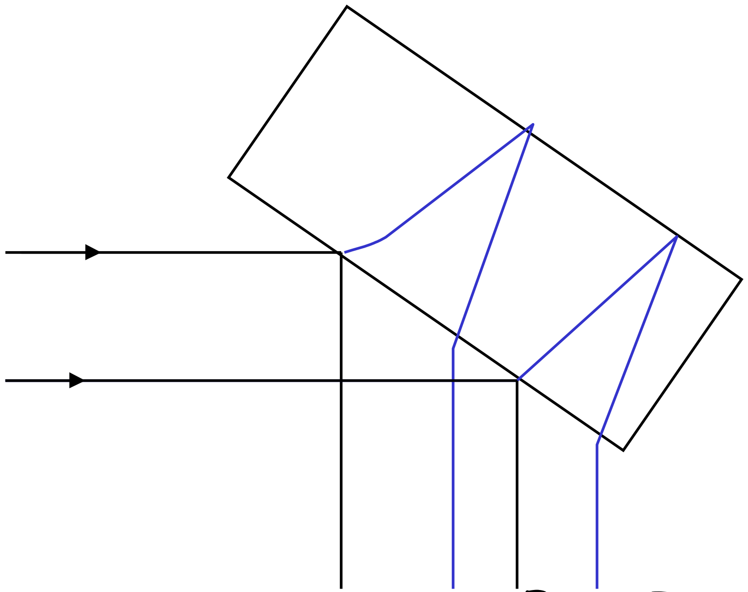
Interferometry

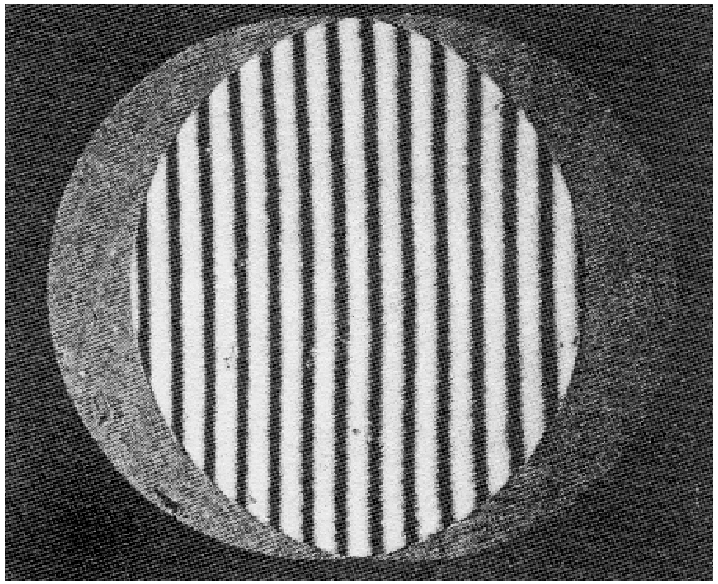
It is difficult to produce a flat reference wavefront (at least for measuring atmospheric turbulence), so interferometers that have been used in AO have had to generate their own reference wavefront.

- Shearing Interferometer
- Smartt Interferometer
- For non-atmospheric turbulence AO, then one could use a conventional Michelson, or similar, interferometer.

Interferometry: Shearing Interferometry

- No reference arm is (usually) available, hence use shearing interferometer.
- E.g. lateral shearing interferometer





From: Intro. To Wavefront Sensors. J.M.Geary SPIE Press

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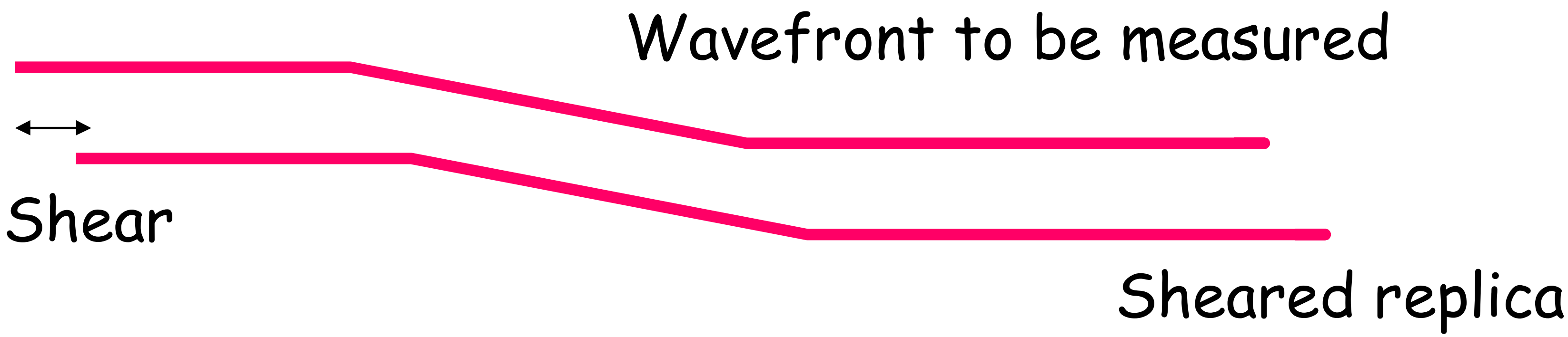
Interferometry:
Shearing Interferometry



Interferometry measures phase difference

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos(\phi_1 - \phi_2)$$

If we plot $\phi_1 - \phi_2$ we get the following

Hence the shearing interferometer is a gradient detector

Maui Space Surveillance System

Durham University

Phase Retrieval: The Gerchberg-Saxton Algorithm

- The Gerchberg-Saxton Algorithm is an iterative computational technique used to determine the phase distortion that produced a particular PSF (Image of a point source).
- It uses knowledge of…
  - The intensity distribution in the image plane (PSF)
  - The intensity distribution in the aperture (or pupil) plane (usually a top-hat function).

R. Gerchberg & W. Saxton. Optik, **34**, 275 (1971)

Phase Retrieval:
The Gerchberg-Saxton Algorithm

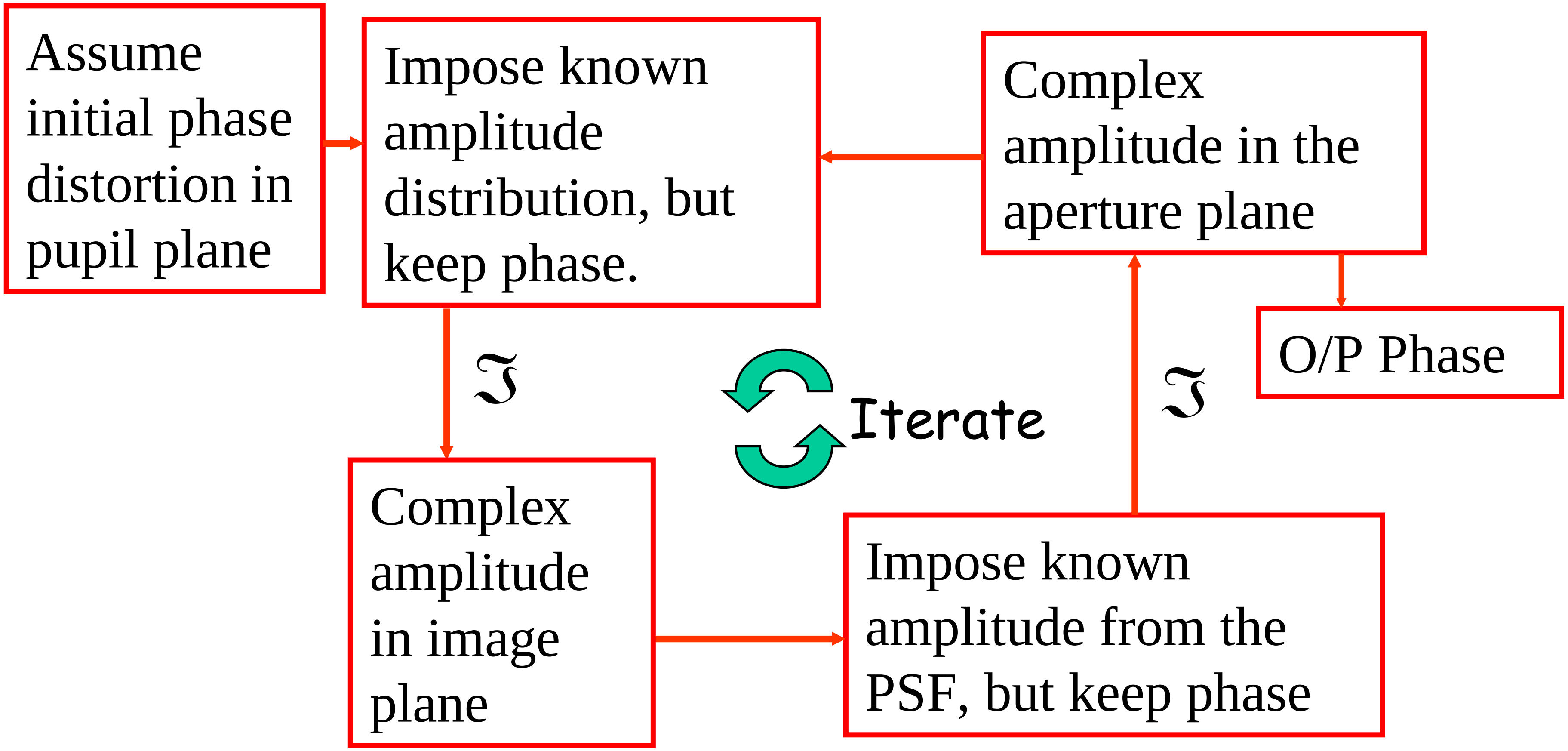


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Image Quality Metrics

1. Record distorted image
2. Measure "quality" of the image (called image metric).
3. Adjust wavefront corrector
4. Re-measure the image quality to determine whether it has improved.
5. Iterate

Example metrics....

$$M = \int Mask(u).I(u)du$$

$$M = \int I^2(u)du$$

Pros: No optics
Cons: Slow

Wavefront Sensors
Summary

- Shack Hartmann wavefront sensing
  - wavefront gradient determination by measuring displacements of sub-images from a lens array
- Curvature Sensing
  - wavefront Laplacian determination by measuring changes in the beam intensity as it propagates
- Interferometry
  - wavefront (gradient) determination by interfering the wavefront to be tested with a reference wavefront
- Phase retrieval:
  - wavefront determination from the actual image data.
- Image Quality Metric Assessment
  - optimisation method using image data

Wavefront Sensors II

Detectors & Technology

Gordon D. Love

Durham University

Overview

- Fundamental Requirements of a WFS
- Fundamental Limitations on WFSing
- Detectors for WFSing
- Commercially available WFSs
- Comparison of different WFS types
- Practical issues of dividing the light between the WFS and WFC

Fundamental Requirements of a WFS

1. The WFS must be able to measure the wavefront to sufficiently high quality (typically $\lambda/10$)
2. The WFS must be able to operate on faint objects.
3. The WFS must, in general, be able to work with broadband sources.
4. It is desirable for the WFS to operate using extended sources.

Wavefront Sensing Fundamental Limitations

- For astronomy, the wavefront sensor camera needs to be…
  - high sensitivity
  - high frame rate
  - low noise
- For non-astronomical applications, the criterion can sometimes be relaxed, because of the relatively large amount of light available. This is not always the case, however, e.g. ophthalmic imaging.

Shack Hartmann WFS
Signal/noise calculations

Better adaptive correction

↓

More information about the atmosphere is needed

↓

More Photons are needed

↓

Brighter Guide Star is needed

↓

Less sky coverage is achieved

Shack Hartmann WFS Signal/noise calculations

Should the WFS always be used in closed loop?

In general, yes.

- The spots are stationary when the loop is closed
- Therefore WFS only needs a restricted dynamic range.
- Reduces number of pixels needed, and therefore can improve signal/noise.

Electronic offsets are sometime used to account for static aberrations in the optics. If this is so, care must be taken if using a quad-cell arrangement, since the spots may not be centrally placed on the array.

Conclusions

- Wavefront sensing is a critical part of an adaptive optics system.
- Wavefront sensing and testing is critical in optics in general. Interferometry is generally the tool of choice here.