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Imaging Through Atmospheric Turbulence

William T. Rhodes

Florida Atlantic University
Boca Raton
USA

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- William T. Rhodes, Ph.D.
- Imaging Technology Center
- Florida Atlantic University, USA

- ICTP Winter College on Optics in Imaging Science, 31 January – 11 February 2011, Trieste, Italy.

The scintillation of the stars

- Ancient man must have asked the question, Why do the stars twinkle (and why do the “wanderers” – the planets – not)?
- This question went unanswered until the early 1700s, at least scientifically. Newton and other telescope users determined that the blurring and the scintillation of star images was caused by atmospheric turbulence.
- Aristotle, Roger Bacon, da Vinci, Kepler attributed the scintillation of stars to an error of human vision.

What occurred in the time between Galileo and Newton?

Galileo: 1609

Newton, ~90 years later

Turbulence Effects Observed

- Galileo’s telescope lenses were of low quality and small diameter. The aberrations produced by the turbulence were probably insignificant compared to those introduced by the lenses.
- Telescope lenses were larger and of better quality in Newton’s time; reflectors eliminated chromatic aberrations, and larger apertures improved resolution, up to a point. For telescope apertures >10cm, however, turbulence limited performance.

Isaac Newton speaking of telescopes and atmospheric turbulence

"…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."

This talk is on reducing the effects of atmospheric turbulence on imaging

- For the past 50 years, scientists and engineers have worked to develop means to improve our ability to view the heavens through the turbulent atmosphere.
- Today, through a combination of techniques, this goal has been largely achieved, with improvements of 100X or better.
- How is this done?

Principal techniques to be discussed:

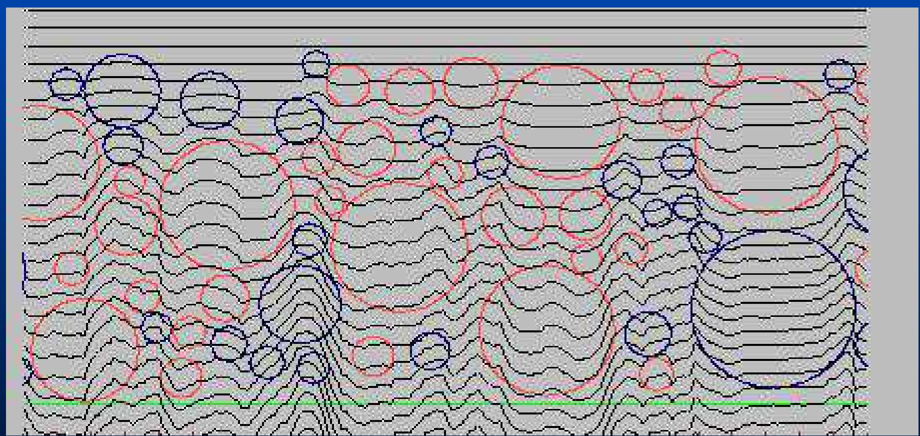
- Lucky imaging
- Adaptive optics and deformable mirrors
- Aperture masking and phase closure
- Speckle interferometry
- Methods for horizontal-path turbulence

Some initial questions

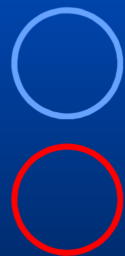
- How does turbulence limit telescope resolution?
- Related question: Why can small-aperture telescopes produce diffraction-limited images but large-aperture telescopes cannot?
- Why do planets not scintillate?

Model of the atmosphere

- Light waves from an astronomical object are distorted as they pass through the atmosphere. The distortion is a consequence of inhomogeneities in the refractive index of the atmosphere, inhomogeneities caused by turbulence. Distorted wavefronts produce low-quality images.



[Roddier 2004]



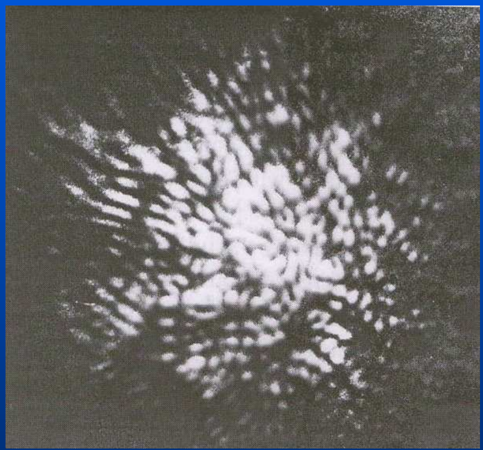
Higher index

Lower index

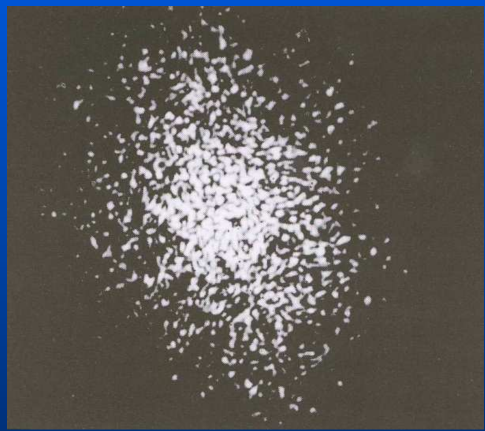
Index inhomogeneities act like positive and negative lenses

Thin random phase screen model

The turbulence is often modeled as though it existed only in a thin layer directly in front of the telescope.



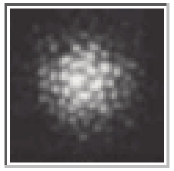
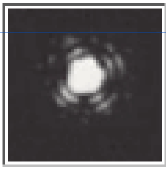
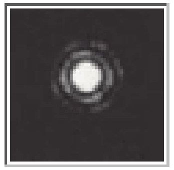
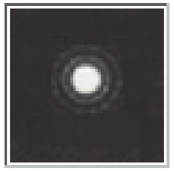
Short-exposure image of star obtained with 5-m telescope.



Laboratory image of point source with polyethylene sheet directly in front of lens.

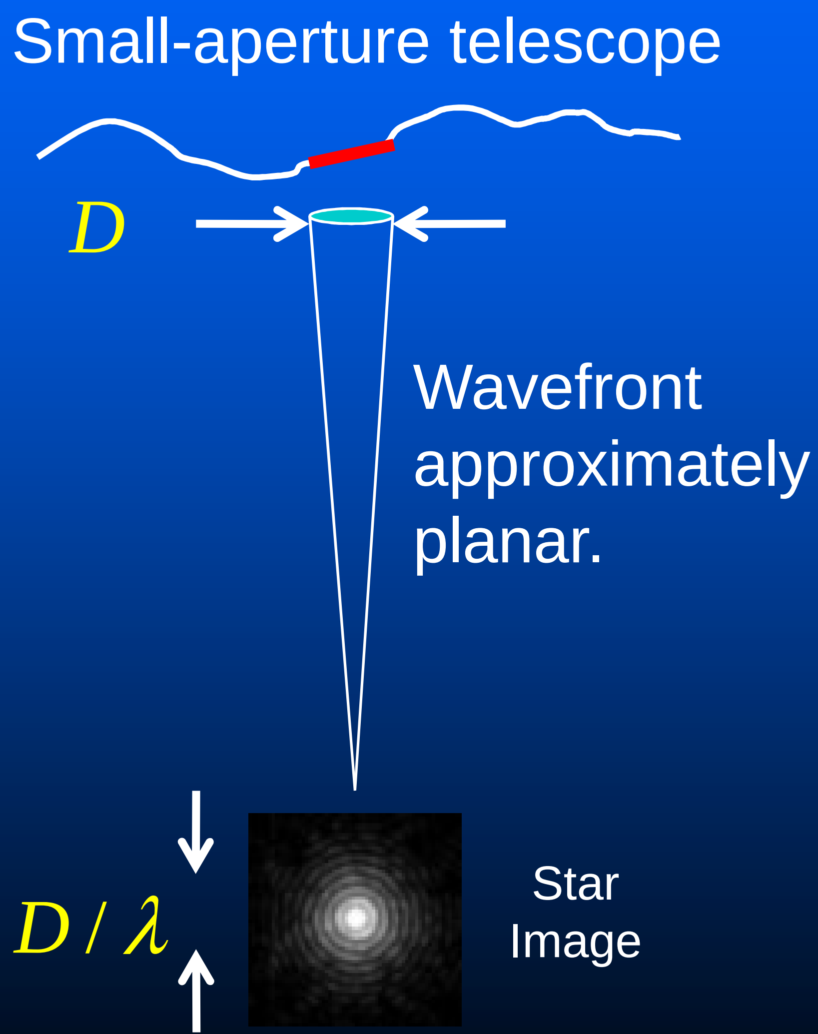
- A better model incorporates two principal layers, one close to ground level, the other in the tropopause, at an altitude of ~10 km.
- The turbulence is dynamic in time. The image of a star obtained with a large-aperture telescope can be observed to “boil” with time.
- Scintillation is associated primarily with the upper layer.

Amateur Astronomer "Seeing" Scale

Rating	Scale	Image	Arc-seconds	Description
bad	I		> 4"	Boiling image without any sign of diffraction pattern.
poor	II		~ 3.0-4."	Important eddy streams in the central disc. Missing or partly missing diffraction rings.
average	III		~ 1.0-2.0"	Central disc deformations. Broken diffraction rings.
good	IV		~ 0.4-0.9"	Light undulations across diffraction rings.
excellent	V		< 0.4"	Perfect motionless diffraction pattern.

http://calgary.rasc.ca/seeing.htm

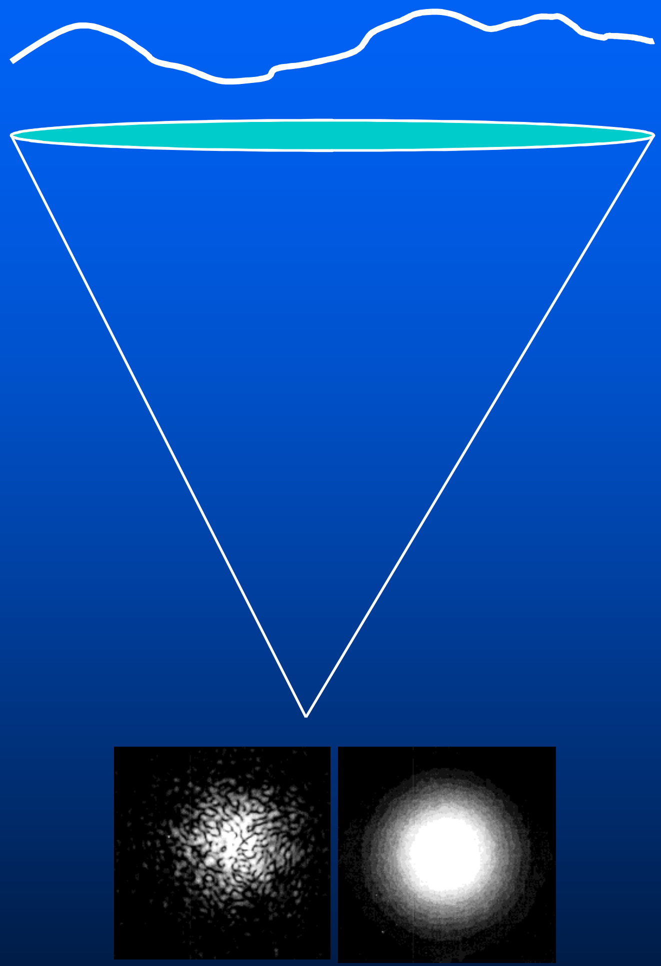
Effect of Telescope Size



With a small-aperture (<10 cm) telescope, a star image – the point spread function – is essentially diffraction limited. It moves about in time, but through distances small compared with its width.

Across the small aperture, the distorted wavefront from a star is essentially planar.

Large-aperture telescope



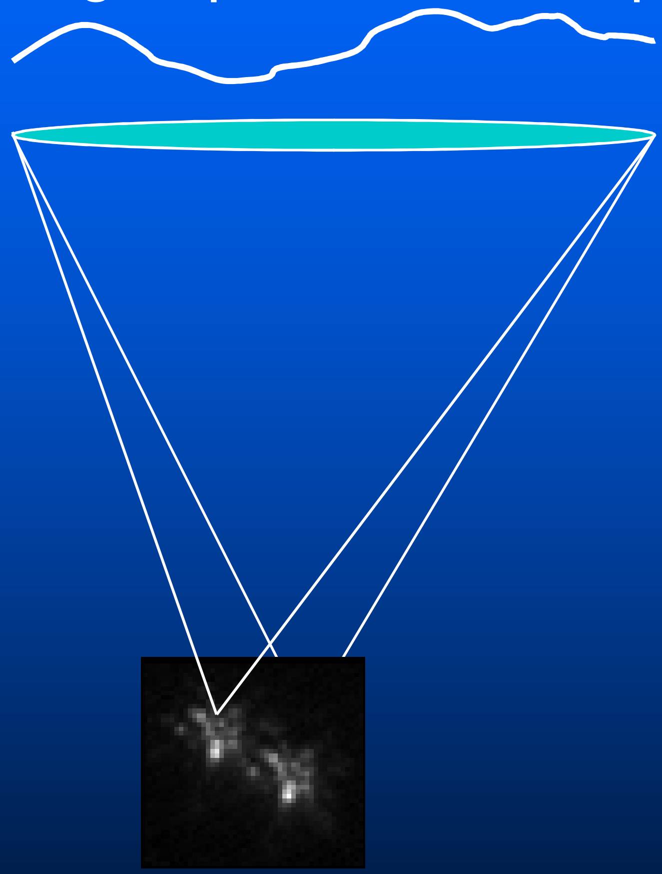
Short Exposure | Long Exposure

With a large-aperture telescope, the star image has a speckle-like distribution. This distribution “boils” with time, producing in the time average a point spread function no smaller than that obtained with a 10 cm aperture.

Temporal frequency bandwidth: Between 100 and 1000 Hz.

The isoplanatic patch

Large-aperture telescope

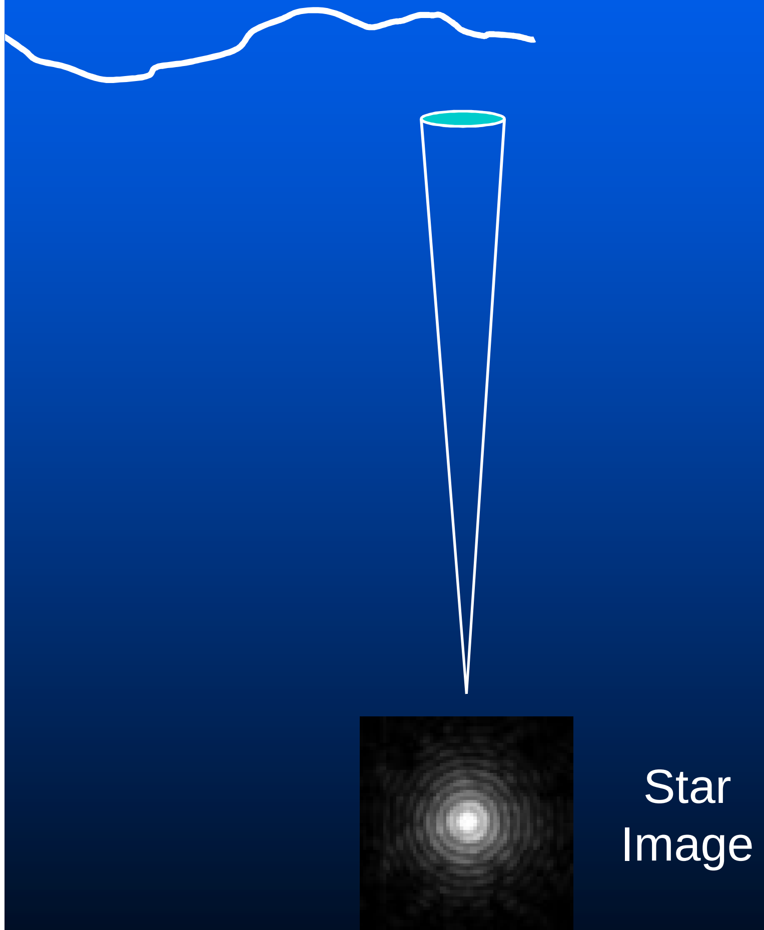


Typical isoplanatic patch size: 1-5 arcsec

If two stars are close together, their short-exposure images are essentially the same.

If their angular separation is large, the images differ because the light from the stars passes through different turbulence cells.

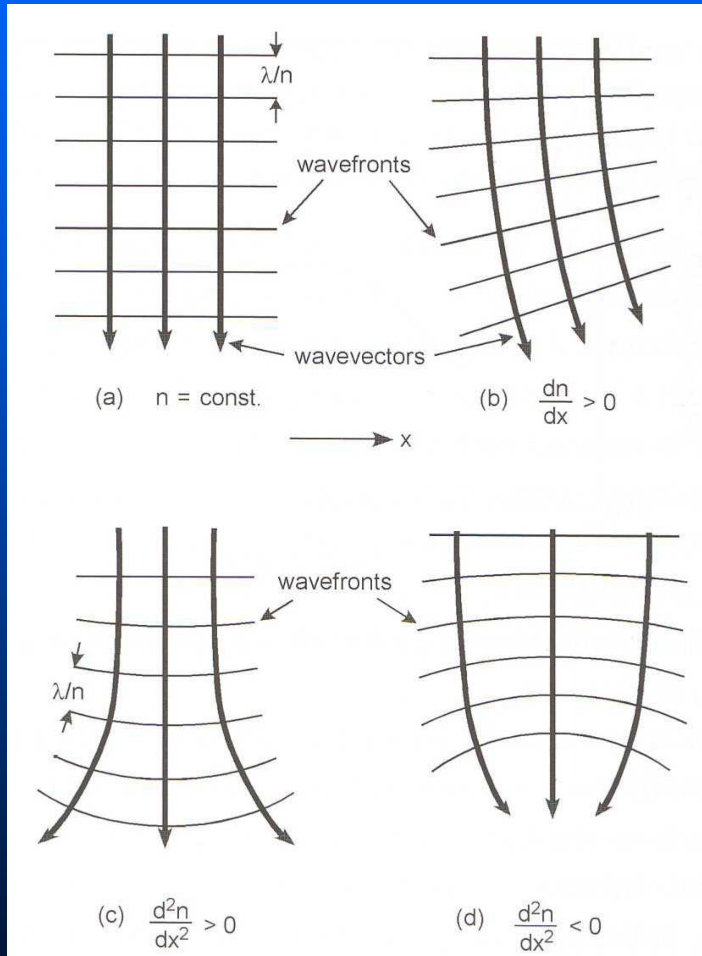
Frozen-Turbulence Model



The turbulence structure changes very little as it moves in front of the telescope at local wind speed.

Scintillation

Scintillation is a result of turbulence in a high layer of the atmosphere, which causes focusing or defocusing of the light rays.



Dynamics of Turbulence:

Source: Lucky Imaging Web Site

The evolution of the turbulence is illustrated by a video of the pupil plane of a large-aperture telescope.

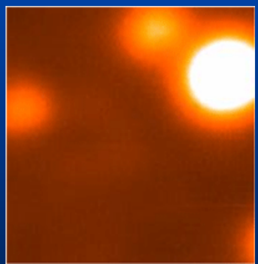
The dynamic patterns are sometimes referred to as stellar shadow bands

Some Current Problems

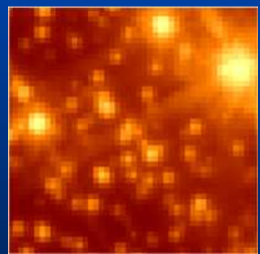
- Modeling inhomogeneous and nonisotropic turbulence
- Numerical models

Method 1: Lucky Imaging

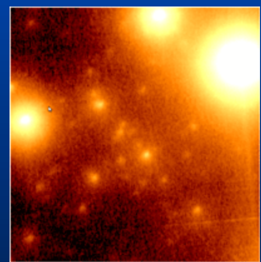
- In a video sequence of short-exposure images, some images—the “lucky” images—are better than others. These images are combined to produce a composite that is much better than any single image. Images sharper than from the space-based Hubble telescope have been obtained by this method..



Palomar 200”



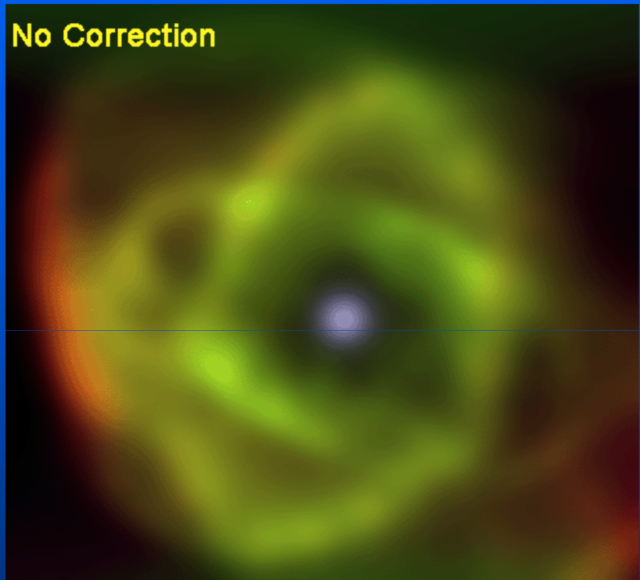
Hubble telescope

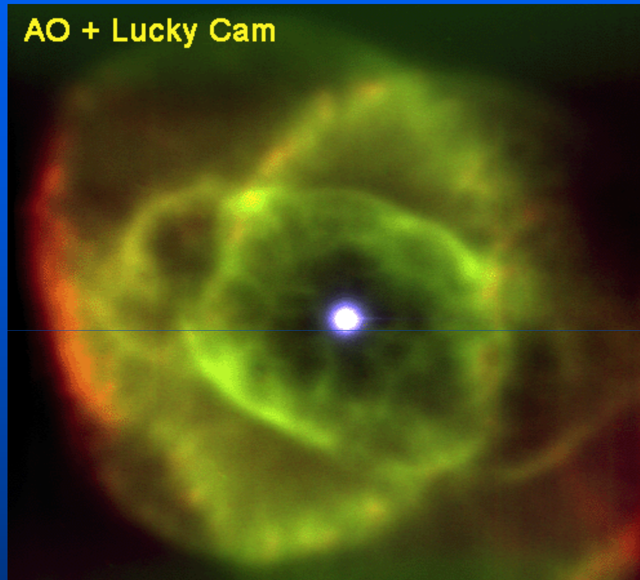


Palomar 200” with lucky imaging

From the Lucky Imaging Web Site

Example





The Cat’s Eye nebula.The individual frames of the video sequence must “freeze” the turbulence, i.e., they must have a duration of ~10 msec or less. Sensitivity is thus low.

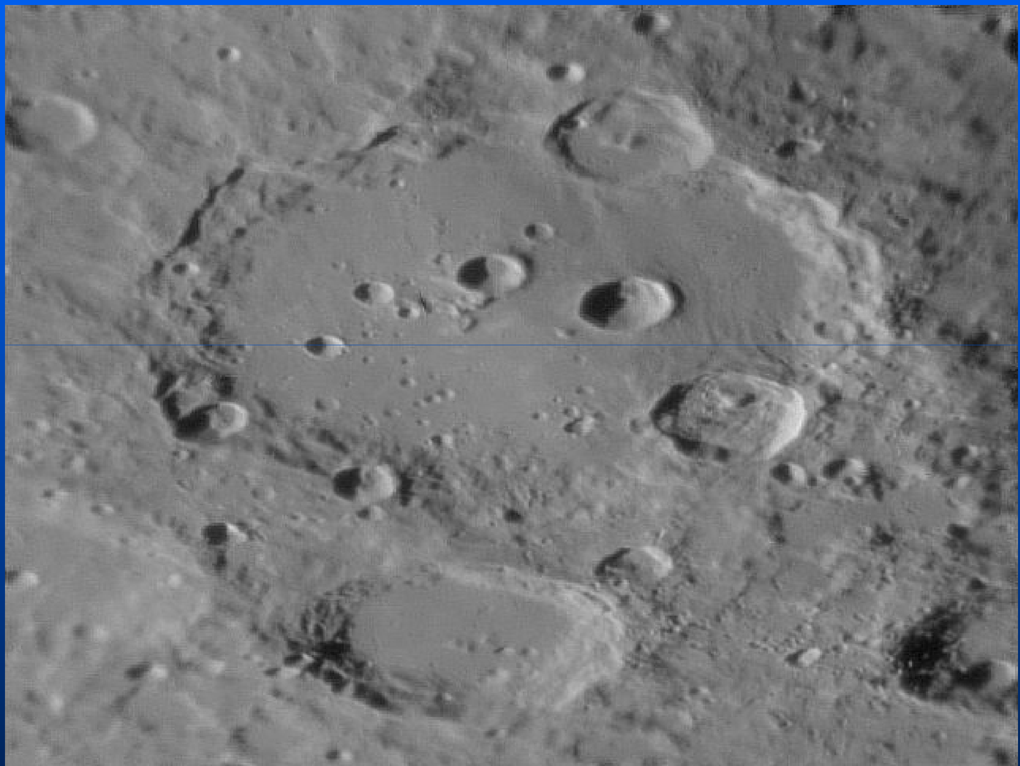
Amateur Lucky Imaging

Part of original motion picture film strip

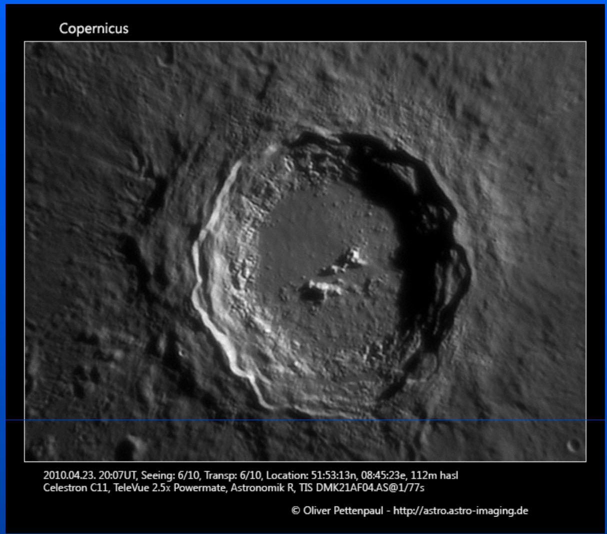
Result of processing with Registax Version 4 free software package

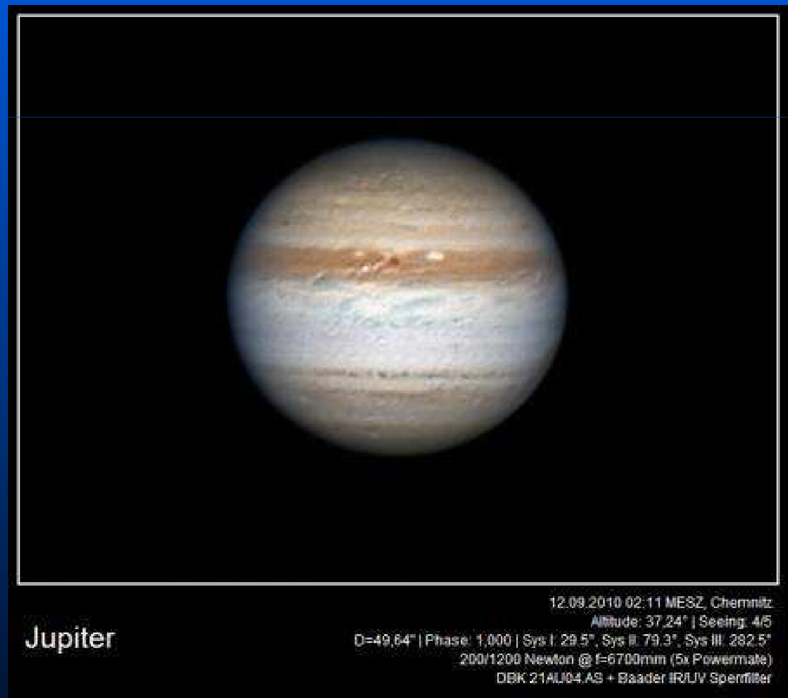
Source: Lucky Imaging Web Page

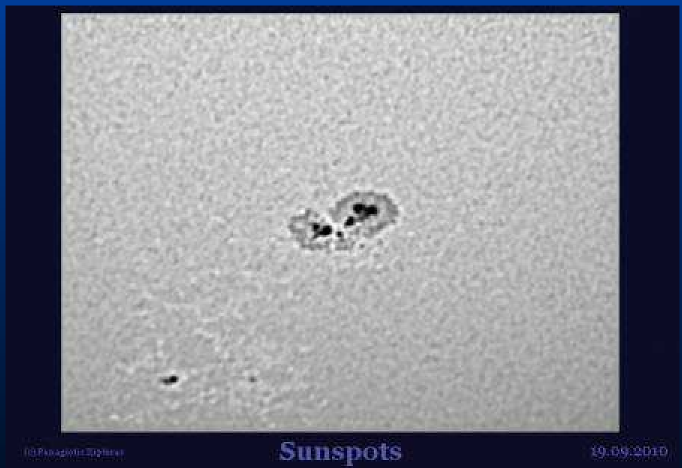
Result of lucky imaging



Other Amateur Results



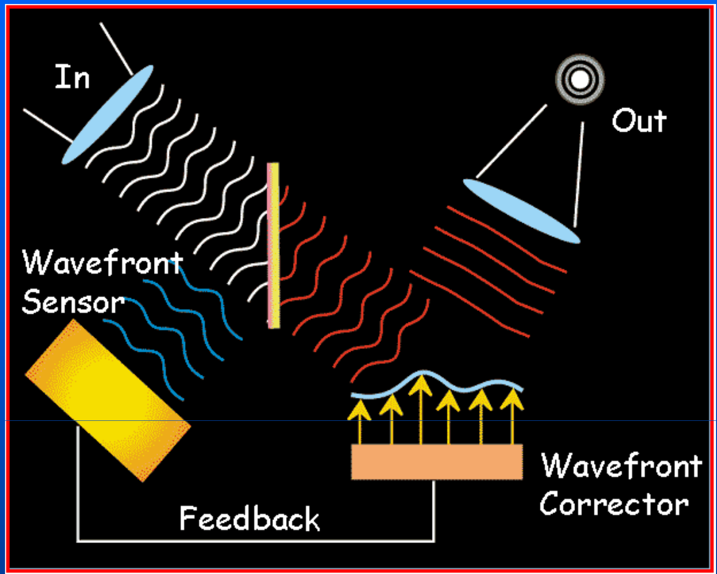


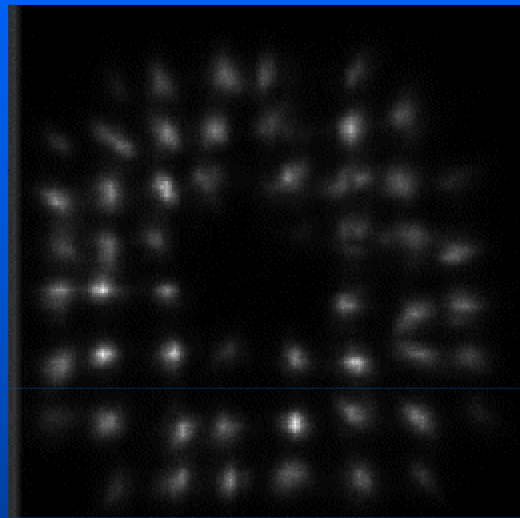


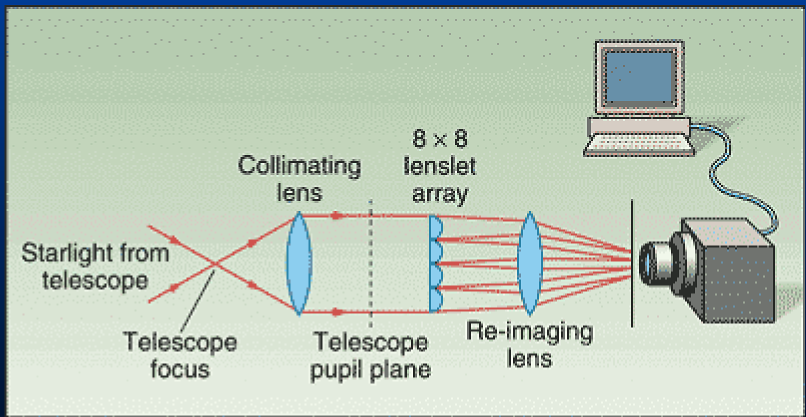
Current Problems

- Optimizing the selection of the lucky images.
- Space variance: How best to put together lucky pieces of a large image.

Method 2: Adaptive Optics

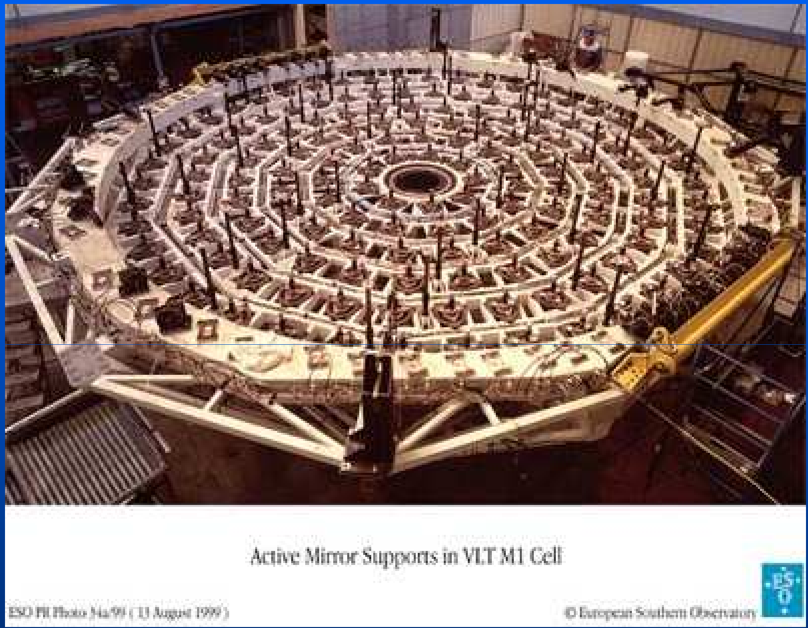




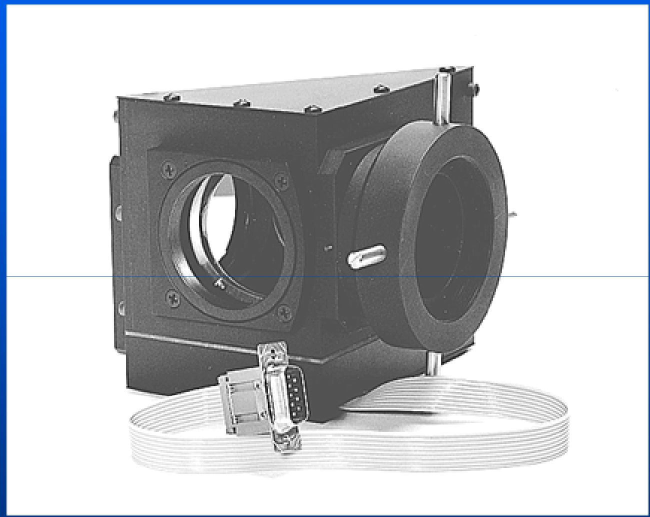


Tip-tilt correction functions well at ~15 Hz.

Adaptive Optics Mirrors

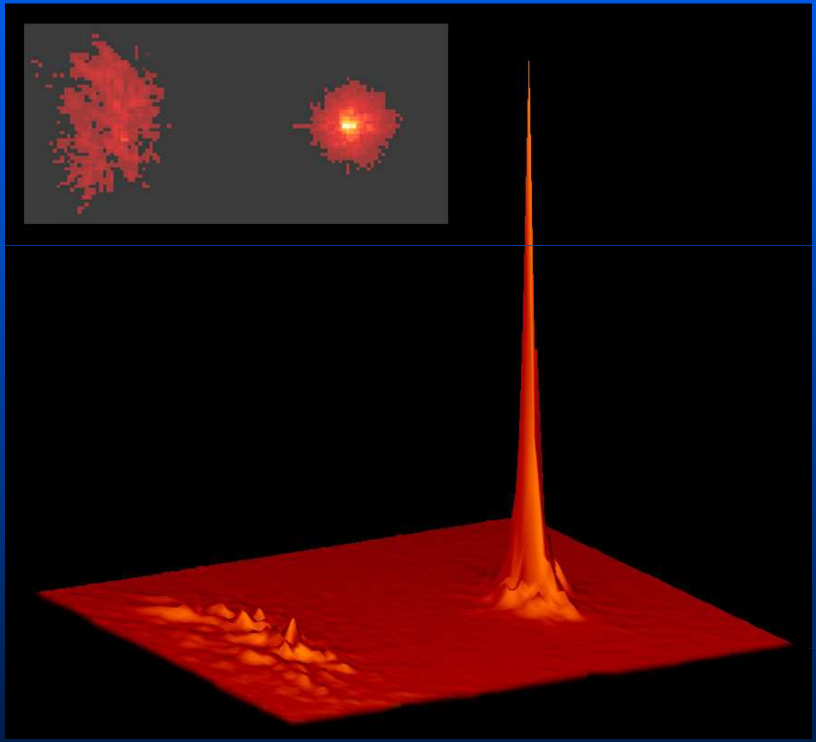


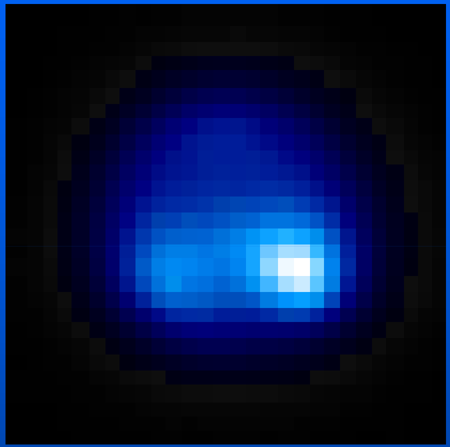
Mirror segment actuators, 150 in number.

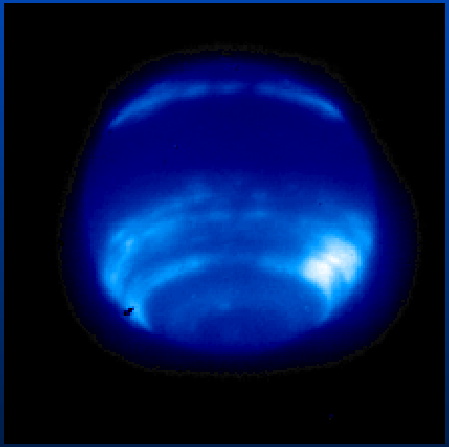


100 Hz tip-tilt AO corrector available to amateurs [sbig.com].

AO Results







Need for a Reference Star

- A reference star in the isoplanatic patch is required to “guide” the control system.
- Sufficiently bright natural stars are often not available.
- Artificial stars are produced by laser beams.

Adaptive Optics: The Next Stage

- 1000-actuator, large bandwidth (>1 kHz), predictive wavefront control system to be installed in 2011 on the Gemini North Planet Imager 8-m telescope in Hawai‘i. An improvement of 100X is expected. Cost: $24M.

Dr. Lisa Poyneer, LLNL, lead engineer

Current Problems

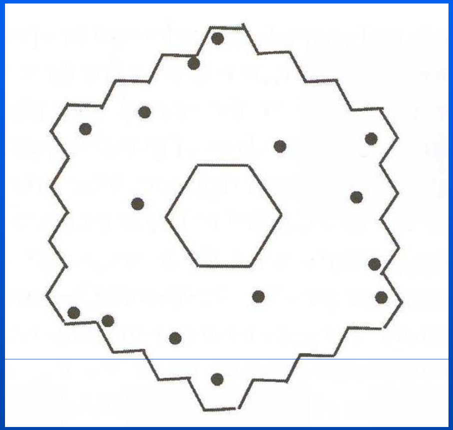
- Control system algorithms
- Modeling of the mirror surface and actuator system
- Tomographic (multilayer) modeling of the atmosphere

Lucky Imaging vs. Adaptive Optics

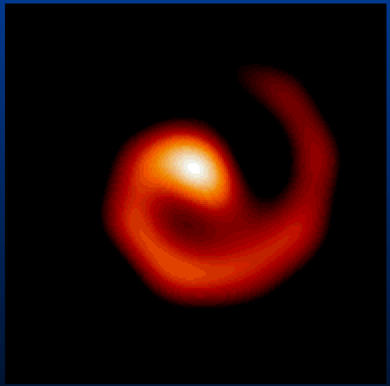
- The mean-size isoplanatic patch at the ESO Paranal telescope is normally only about 2.6 arc seconds, but with lucky imaging it approaches one arc minute.
- The reason: Lucky images are obtained at times when the turbulence energy is primarily in large-scale inhomogeneities.
- However, lucky imaging requires short exposures and, therefore, bright objects.

Method 3: Aperture Masking

Astronomer Peter Tuthill has placed masks similar to the one to the right in the pupil plane of his telescopes to obtain some fantastic high-resolution images.



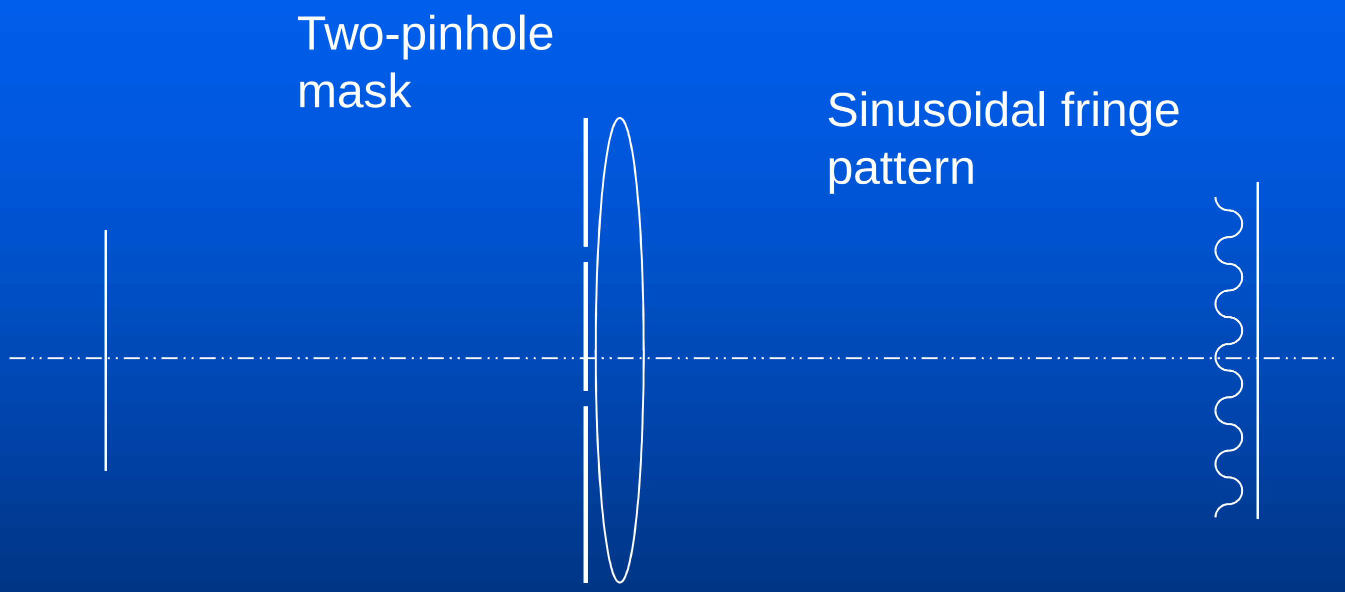
Why the mask?



Eight-month cycle of pinwheel nebula Wolf-Rayet 104

http://www.physics.usyd.edu.au/~gekko/pinwheel.html

Pinhole Masks, Young's Fringes, and Closure Phase



If a 2-pinhole mask is placed in the pupil plane of an imaging system, the result is a set of Young's fringes in the image plane.

Two-pinhole
pupil-plane mask

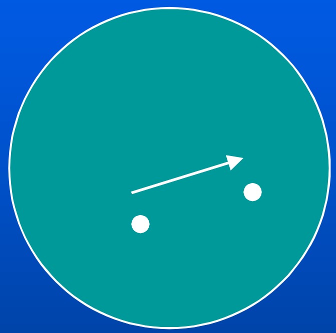
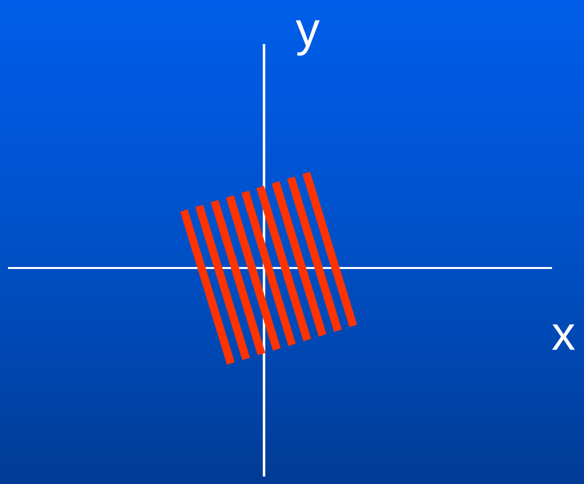


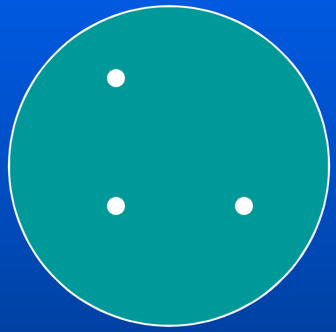
Image plane fringes



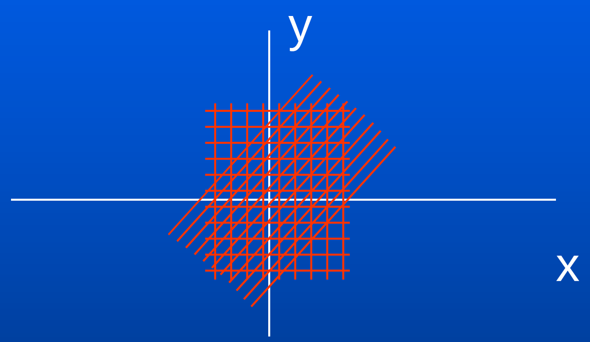
vector separation = $\vec{S}$

fringe frequency = $\vec{S} / \lambda d$

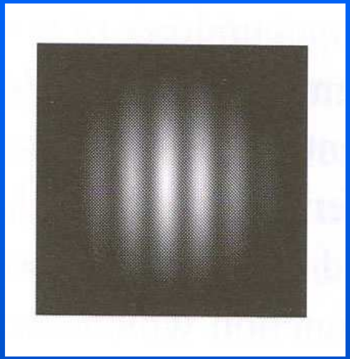
Adding Pinholes…



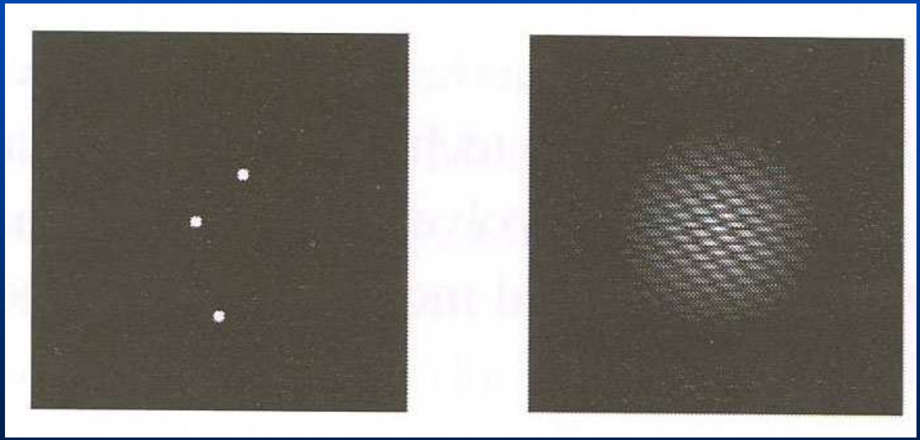
adds image plane fringes



These sinusoidal fringe patterns are essentially spatial frequency (Fourier) components of the image distribution.



Fringes from single pair of pinholes.



Fringes from three pinholes (non-repeated spacings)

Pupil Mask

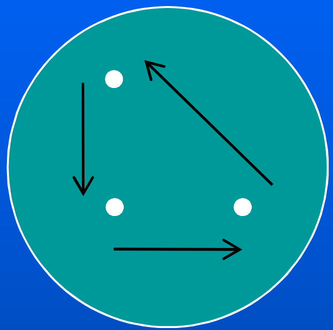
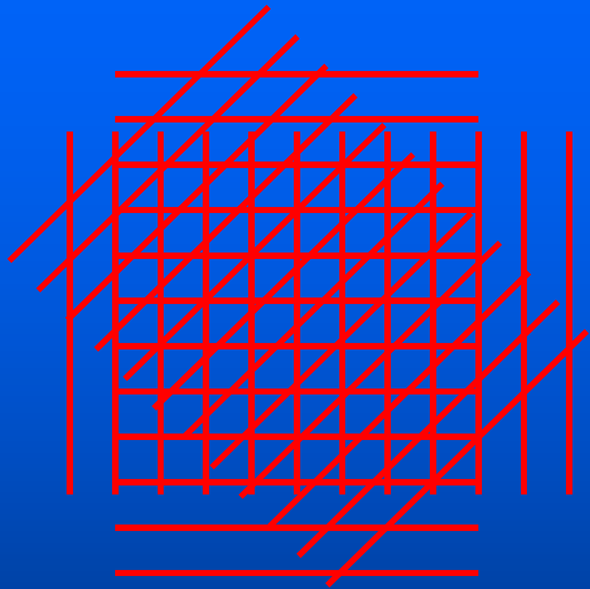
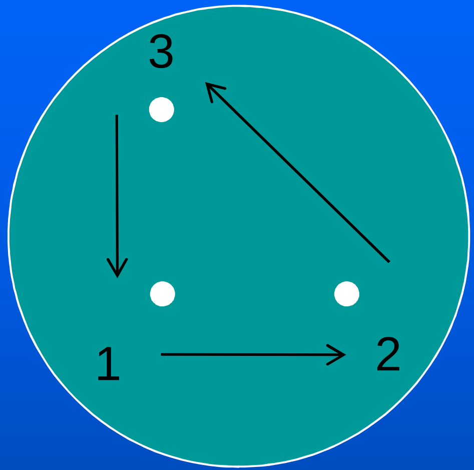


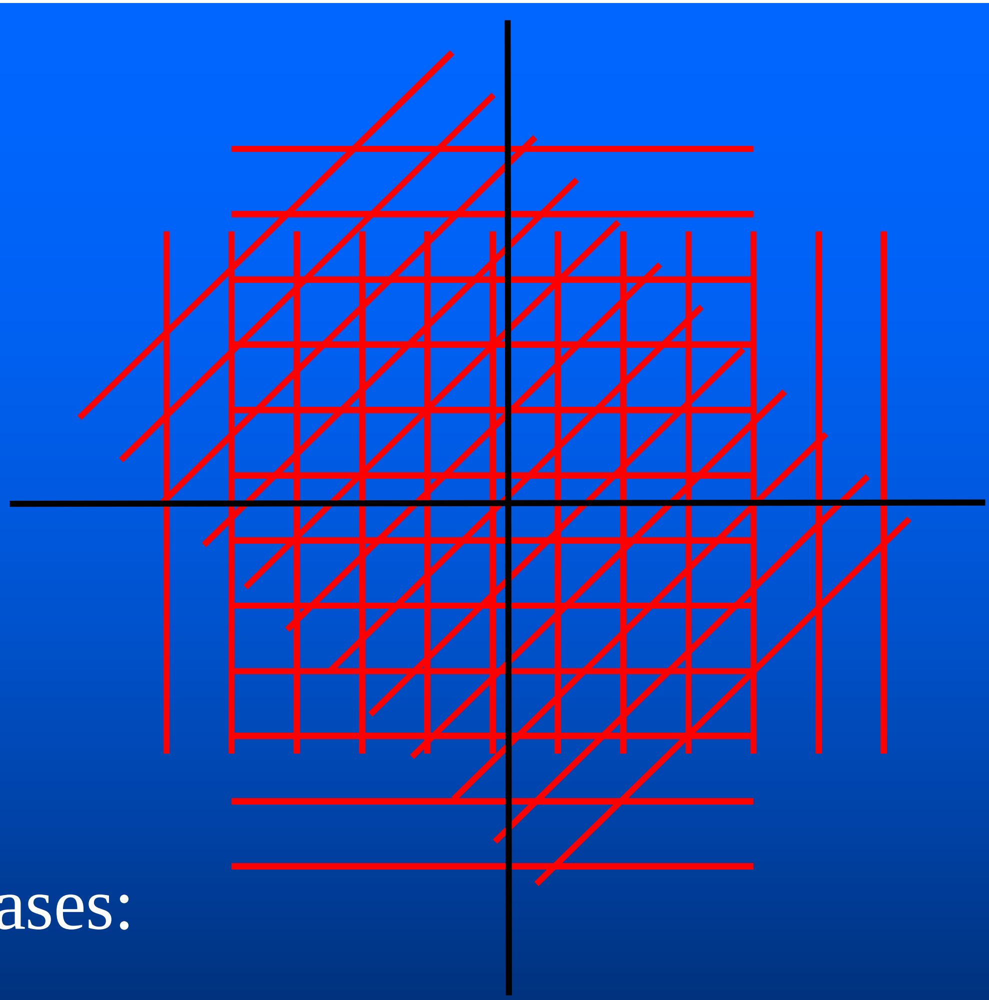
Image plane fringes



Two pinholes produce a single fringe set.

Add a pinhole and two additional fringe sets result.



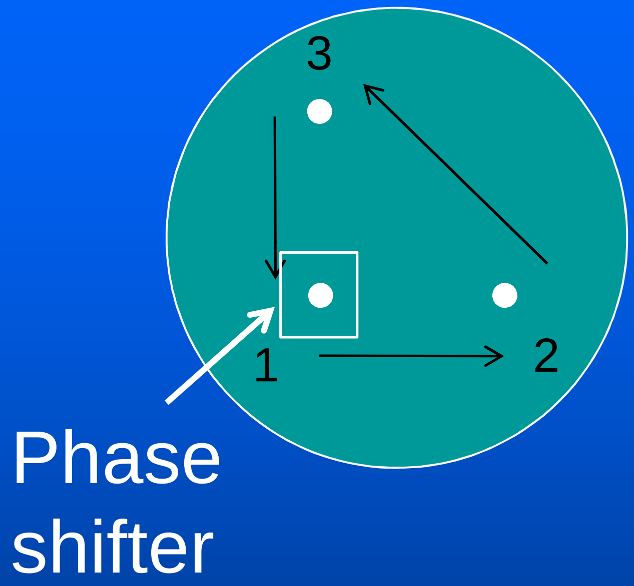


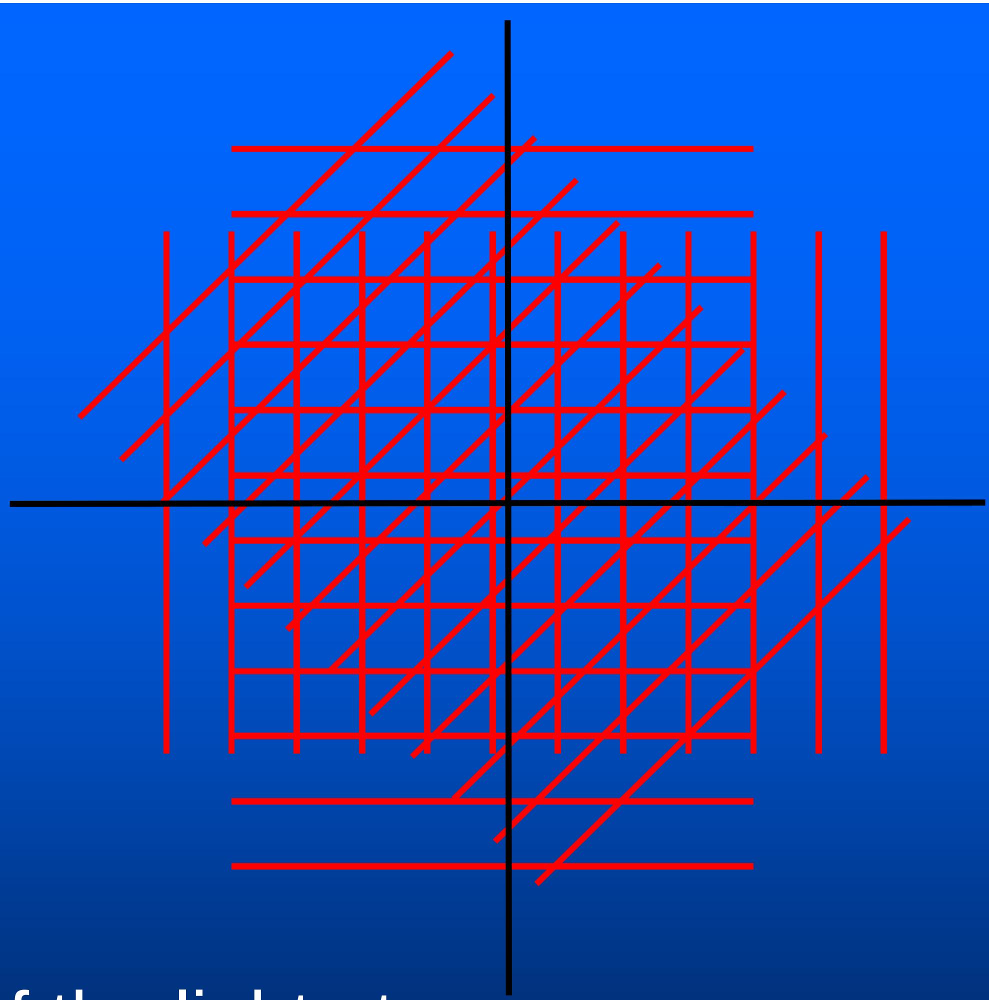
Measure the fringe phases:

$$\psi_{12}, \psi_{23}, \psi_{31}$$

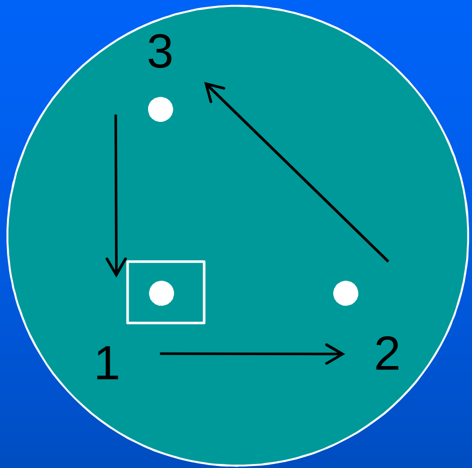
Calculate the sum around the triangle--the closure phase:

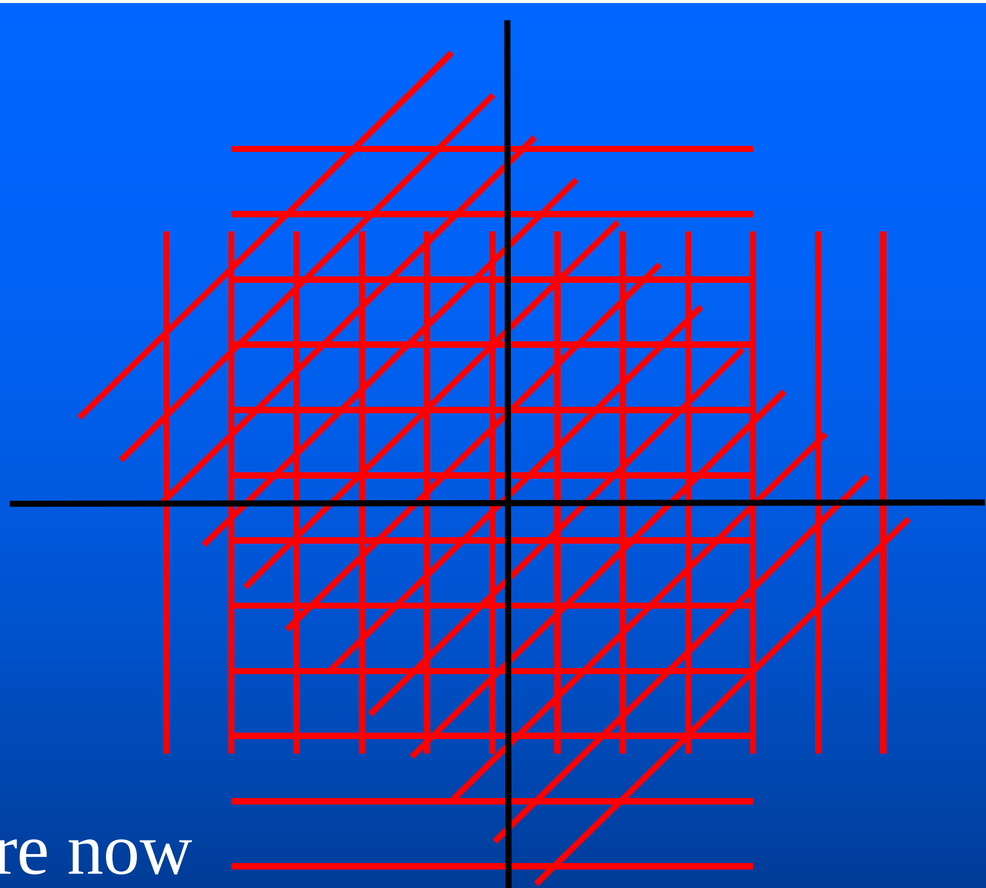
$$C_{123} = \psi_{12} + \psi_{23} + \psi_{31}$$





A shift in the phase of the light at pinhole 1—the result of the turbulence—causes fringes (1,2) and (3,1) to shift .





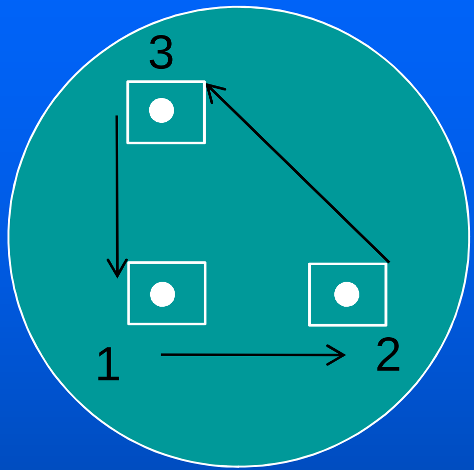
The measured phases are now

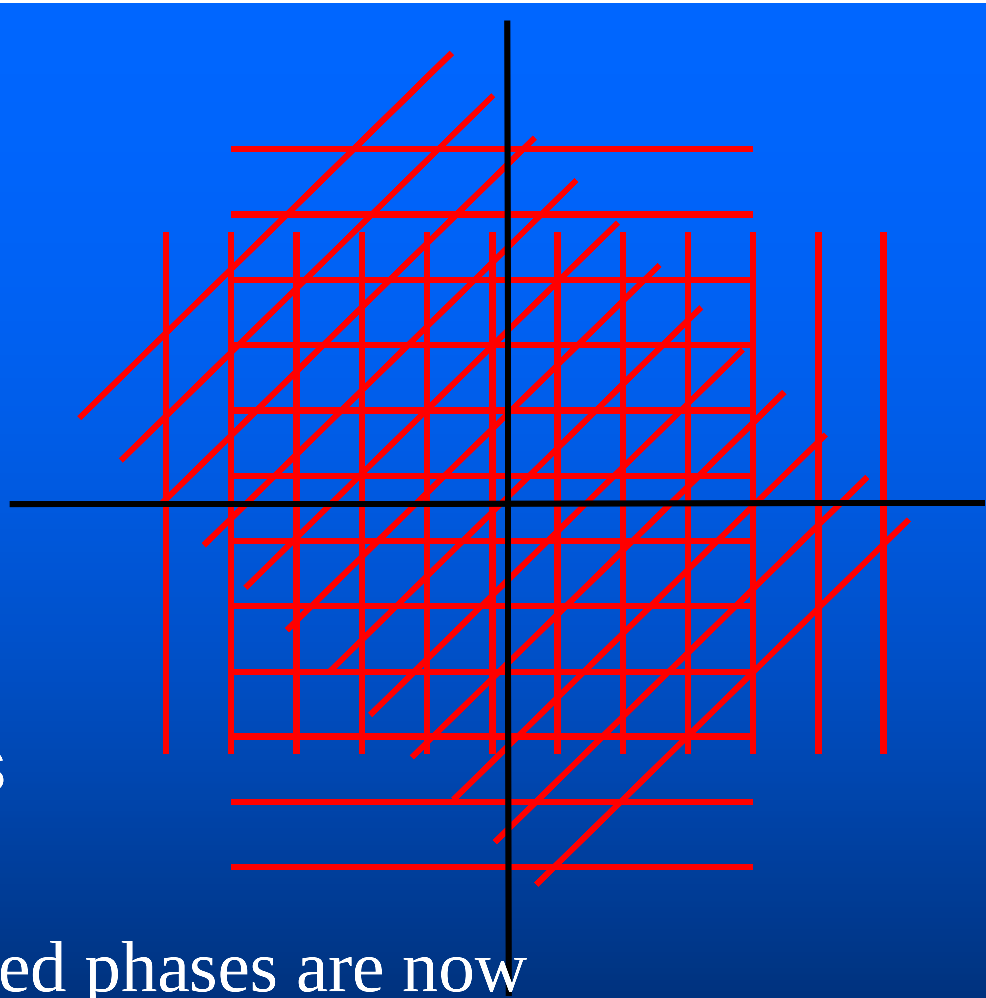
$\psi_{12} + \theta_1, \;\; \psi_{23}, \;$ and $\; \psi_{31} - \theta_1$

Calculate the sum, the closure phase:

$$C_{123} = \left(\psi_{12} + \theta_1\right) + \psi_{23} + \left(\psi_{31} - \theta_1\right) = \psi_{12} + \psi_{23} + \psi_{31}$$

SAME!





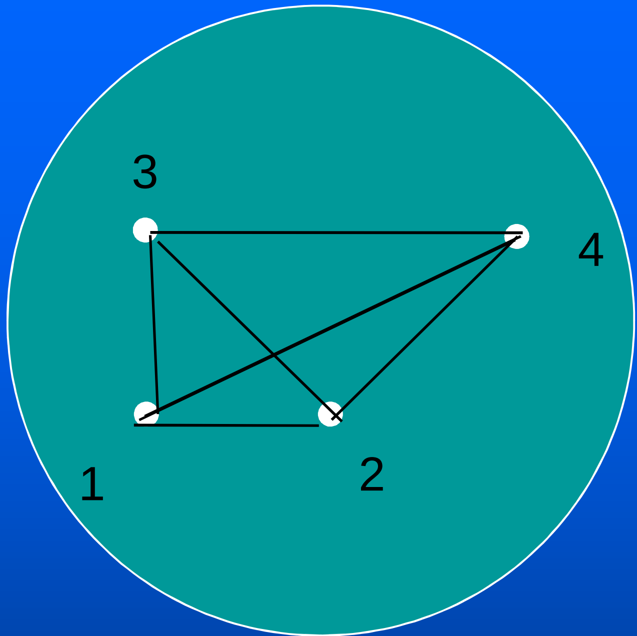
Place phase shifters at all three pinholes.

The measured phases are now

$$\psi_{12} + \theta_1 - \theta_2,\ \ \psi_{23} + \theta_2 - \theta_3,\text{ and }\ \psi_{31} + \theta_3 - \theta_1$$

But the closure phase is again unchanged:

$$C_{123} = \psi_{12} + \psi_{23} + \psi_{31}$$



There are now six unknown phases:

$$\psi_{12}, \psi_{13}, \psi_{14}, \psi_{23}, \psi_{24}, \psi_{34}$$

Four closure phases can be calculated:

$$C_{123} = \psi_{12} + \psi_{23} + \psi_{31}$$

$$C_{124} = \psi_{12} + \psi_{24} + \psi_{41}$$

$$C_{134} = \psi_{13} + \psi_{34} + \psi_{41}$$

$$C_{234} = \psi_{23} + \psi_{34} + \psi_{42}$$

In general we can calculate N-2 equations in N unknowns. However, we can set the origin of the coordinate system such that two of the unknowns are made to equal zero!

- Exploitation of the closure phase principle, first proposed in the radio astronomy community by Jennison in 1958, has played an exceptionally important role in reducing the effects of turbulence during the past 50 years.
- The method requires short-exposure images, and, therefore, bright objects.

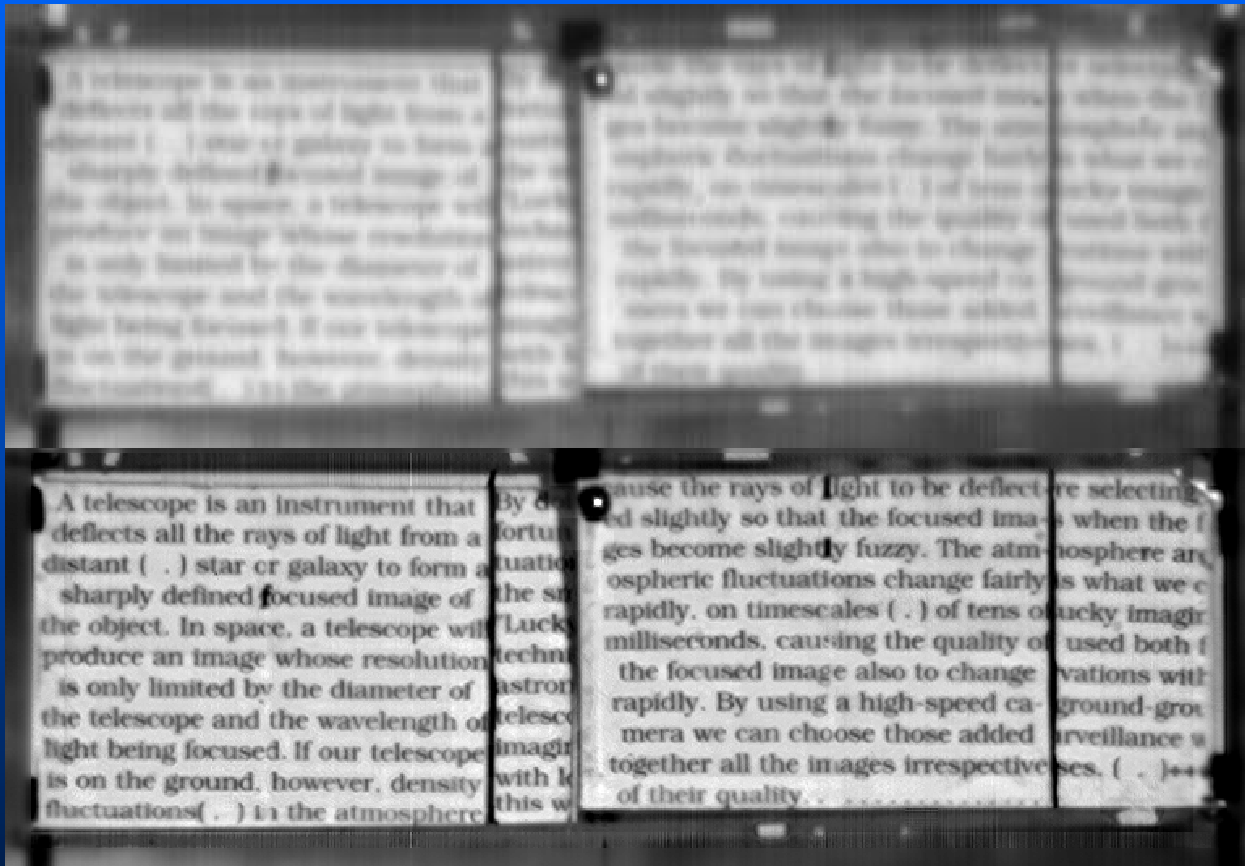
Horizontal-Path Turbulence

A more challenging problem

- Thin random phase screen model inadequate
- Stronger turbulence
- Smaller isoplanatic patch

- Lucky imaging has some success
- Fourier-domain imaging offers a different solution

Horizontal-Path Lucky Imaging



Results achieved over ~40m path.

http://www.ast.cam.ac.uk/~optics/Lucky_Web_Site/LI_Ground_Surveillance.htm

Final Comments

- Turbulence degrades images formed in water, too.
- The turbulence is of the long-path type—the thin phase screen model is not applicable—and solutions to the problem are more difficult to find.
- This is also an active area of research.

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