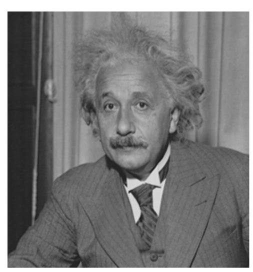
Visual Performance Metrics

- Early work measures the MTF of the eye, but does not provide information about how to correct the optics of the eye to achieve better visual performance.
- Ultimately need the Wavefront Error of the eye to design perfect correction.
- Can measure PSF to indirectly get Wavefront Error, or can measure wavefront error directly.

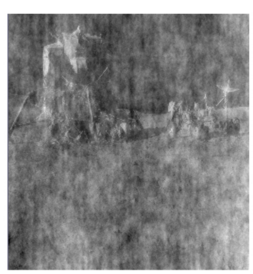
Phase is Important

Apollo Lander



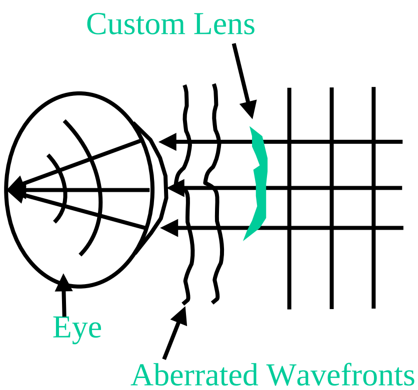
Albert Einstein

Apollo Modulus
+
Einstein Phase



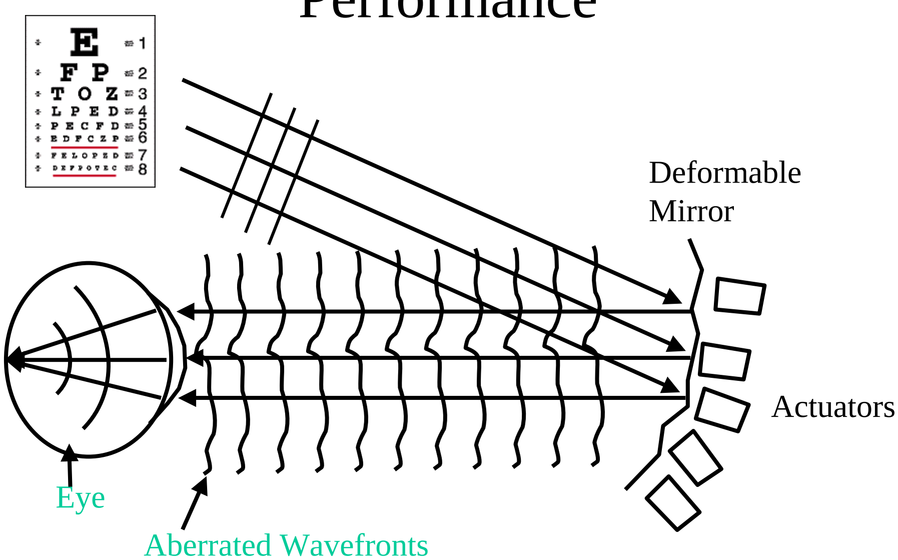
Einstein Modulus
+
Apollo Phase

Diffraction-Limited Eye

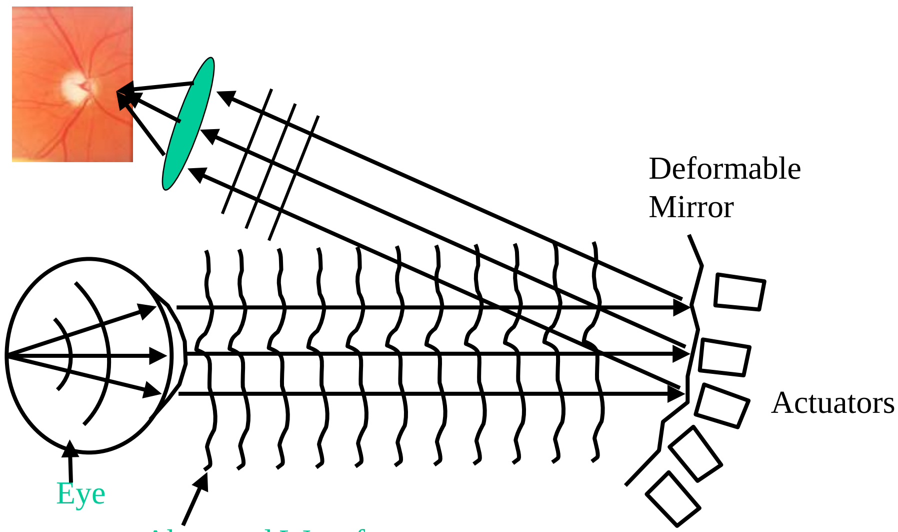


Knowledge of the aberration of the eye allows us to calculate a custom lens, which will compensate for the aberrations of the eye and form a diffraction-limited image on the retina. The results are improved visual acuity and contrast sensitivity.

Improvements to Visual Performance

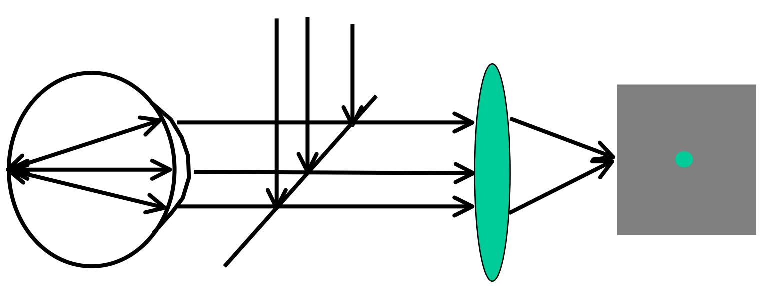


Improvements to Retinal Imaging

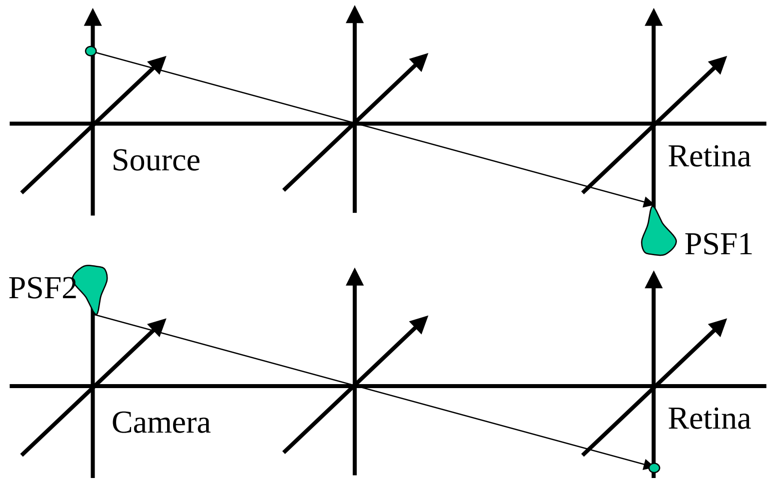


Double-Pass PSF Measurements

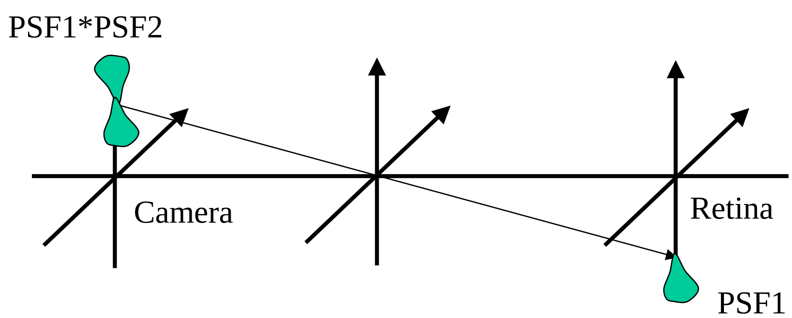
- Aberrations on the way in and aberrations on the way out
- Clipping of tails of PSF and Digitization noise.
- Speckle



Double-Pass PSF



Double-Pass PSF



Double-Pass PSF

Camera records $i(x,y) = PSF1(x,y) * PSF2(x,y)$

From symmetry $i(x,y) = PSF1(x,y) * PSF1(-x,-y)$

In general, need to use deconvolution routines to recover PSF1. Computer intensive and sometimes does not converge.

SPECIAL CASE: $PSF1(x,y) = PSF1(-x,-y)$

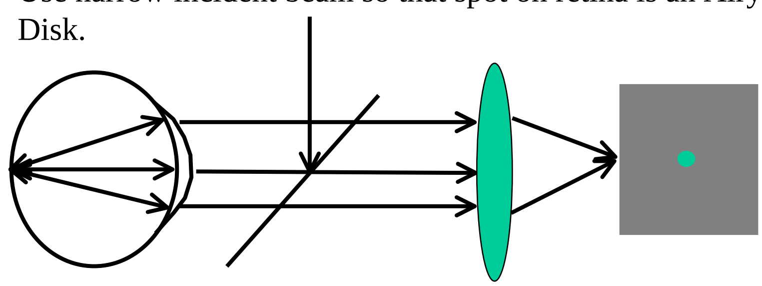
$$i(x,y) = PSF1(x,y) * PSF1(x,y)$$

$$I(\xi,\eta) = OTF^2(\xi,\eta)$$

$$OTF(\xi,\eta) = I(\xi,\eta)^{1/2}$$

Asymmetric Double-Pass PSF

- Use narrow incident beam so that spot on retina is an Airy Disk.

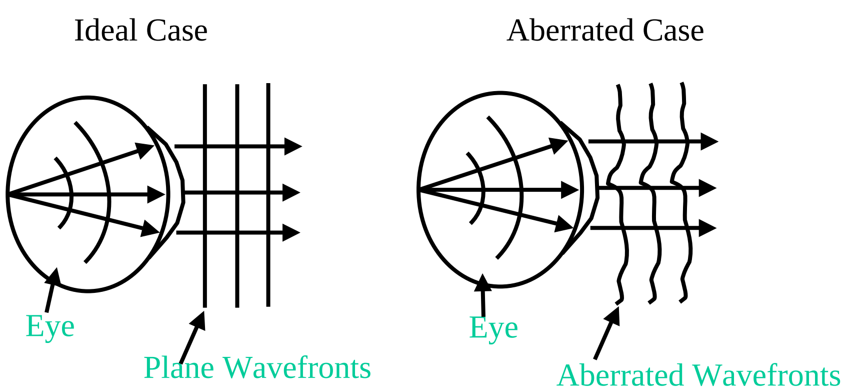


$$OTF(\xi,\eta) = \frac{I(\xi,\eta)}{FT\{\text{Airy Disk}\}}$$

Measurement of Wavefront Error

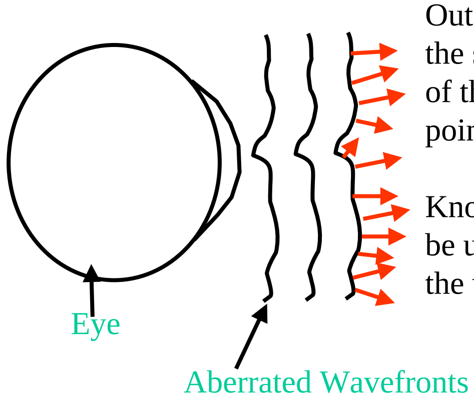
- Different Techniques for Aberration Measurement in the Eye
  - Shack-Hartmann
  - Tscherning
  - Retinal Raytracing
  - Spatially-Resolved Refractometer

Out-going Aberrometry



Wavefront Error - difference between aberrated wave and perfect plane wave.

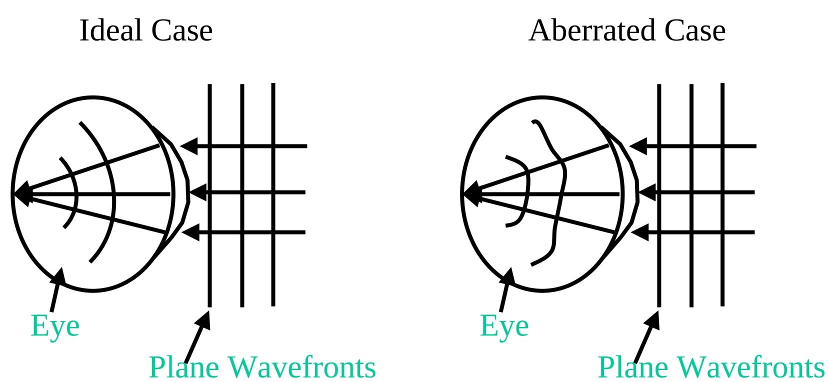
Slope Measurement



Out-going aberrometry measures the slope (or direction of travel) of the wavefront at a series of points.

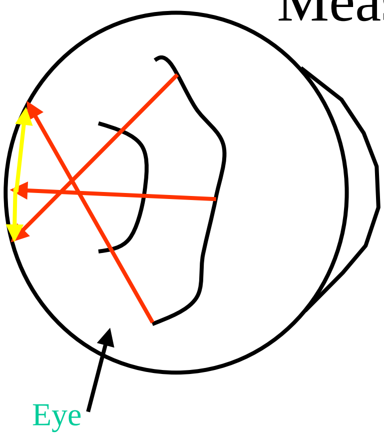
Knowledge of there directions can be used to reconstruct the shape of the wavefront.

In-going Aberrometry



Wavefront Error - difference between aberrated wave and perfect spherical wave.

Transverse Ray Error Measurement



In-going aberrometry measures the transverse ray error (or deviation of the rays from the fovea) of the wavefront at a series of points.

The transverse ray error is proportional to wavefront slope.

Knowledge of there errors can be used to reconstruct the shape of the wavefront.

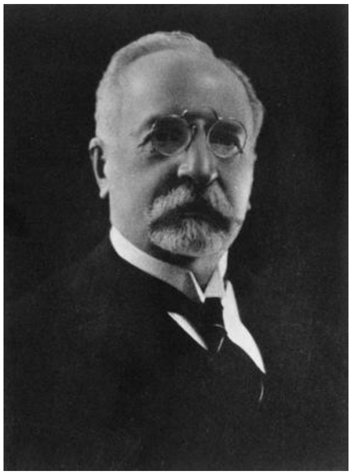
Shack-Hartmann Technique

- Evolution of the Hartmann Screen Test, which was developed to test large telescope optics in the early 1900s.
- Shack modified test in the 1970s by adding lenslet array. The application was to measure atmospheric aberrations.
- Liang applied the technique to the eye in the early 1990s.

- Commercial Devices - VISX, Autonomous, B & L

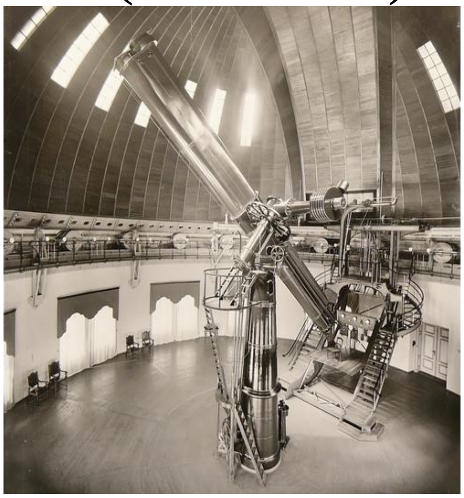
Johannes Hartmann (1865-1936)

- German astrophysicist
- Professor at University in Potsdam
- Potsdam leader in spectroscopy measurement.
- Hartmann demonstrated calcium clouds in Orion.

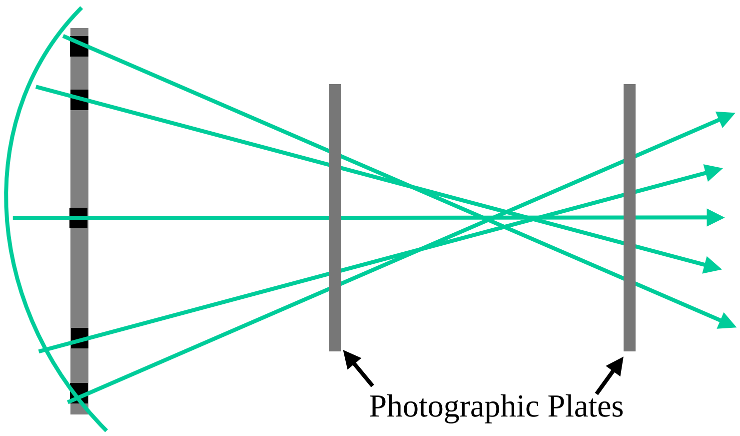


Johannes Hartmann (1865-1936)

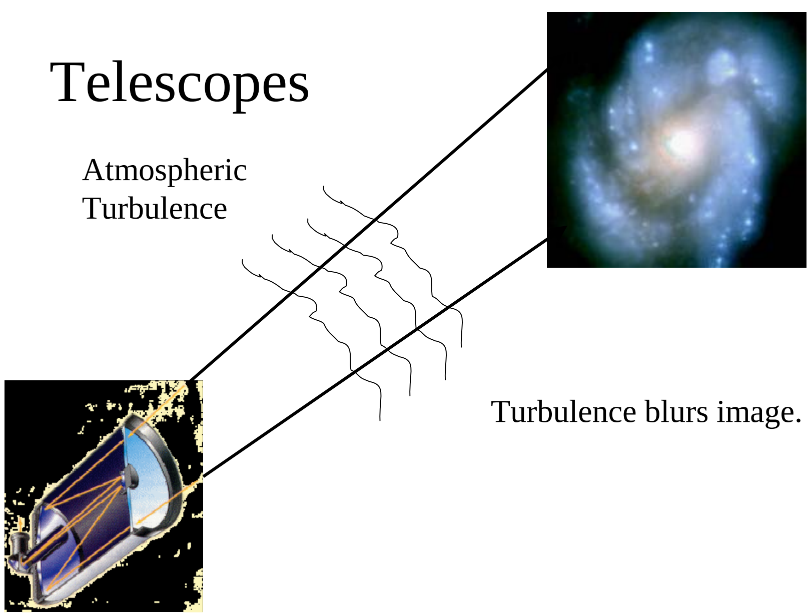
- 80 cm refracting telescope came on-line ~1902.
- Optics were poor and the telescope was unusable.
- Hartmann developed his now famous screen test to determine cause of problems.
- Primary was reworked as a result of his efforts and the telescope became usable.



Hartmann Screen Test

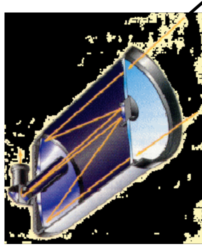


Telescopes



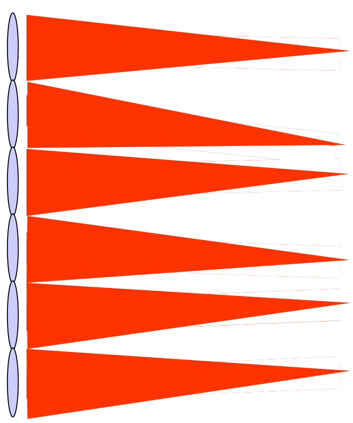
Telescopes

Wavefront Sensor measures error due to turbulence



Knowledge of the atmospheric aberrations allows for the correction of these errors.

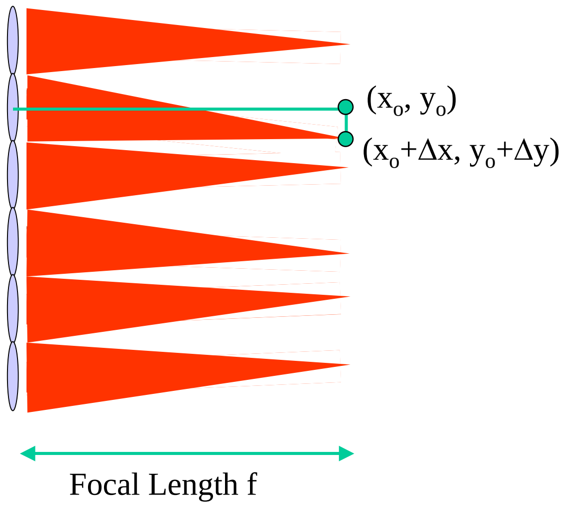
Shack’s Solution



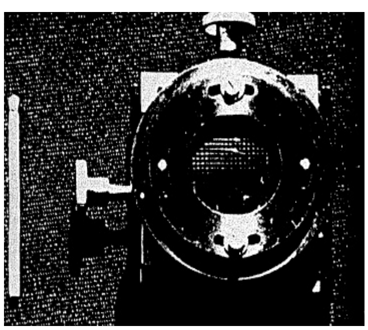
Spot Movement

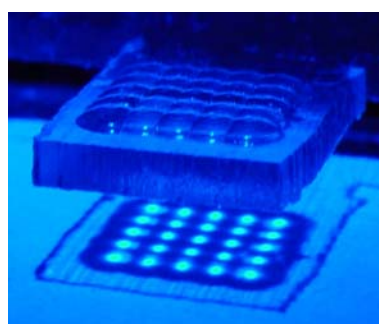
$$\Delta x = -f\,\frac{\partial W(x_o, y_o)}{\partial x}$$

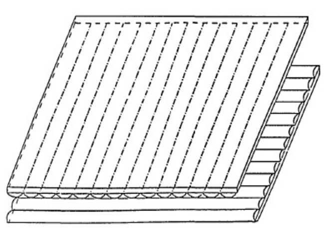
$$\Delta y = -f\,\frac{\partial W(x_o, y_o)}{\partial y}$$

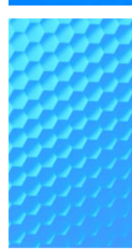


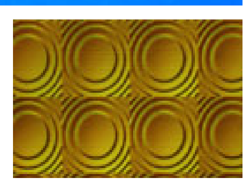
Lenslet Array



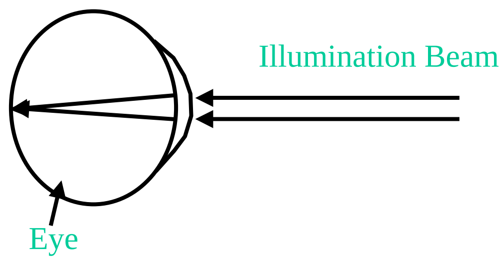






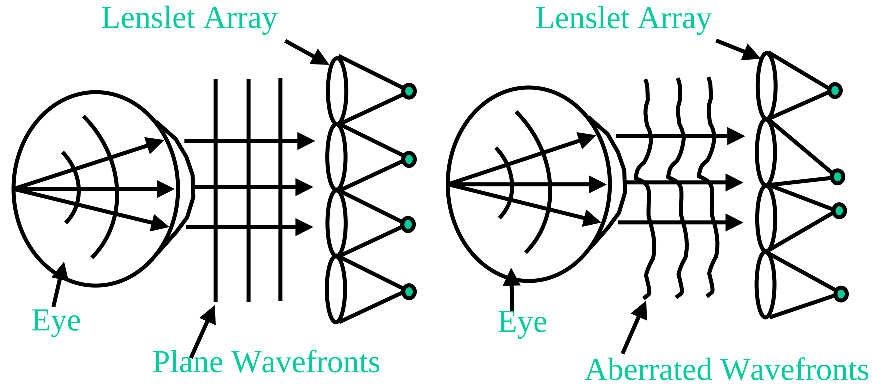


Shack-Hartmann Wavefront Sensor



A narrow illumination beam goes into the eye and focuses to a diffraction-limited point on the retina. The light scatters of the retina and back out of the eye.

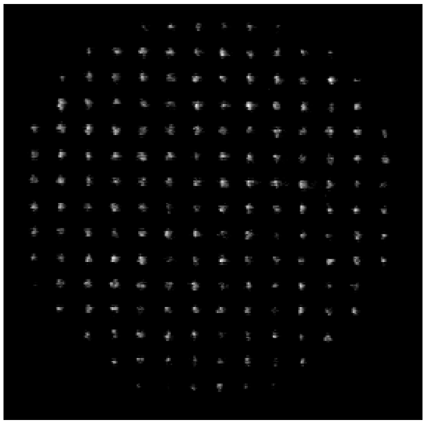
Shack-Hartmann Wavefront Sensor



Perfect wavefronts give a uniform grid of points, whereas aberrated wavefronts distort the grid pattern.

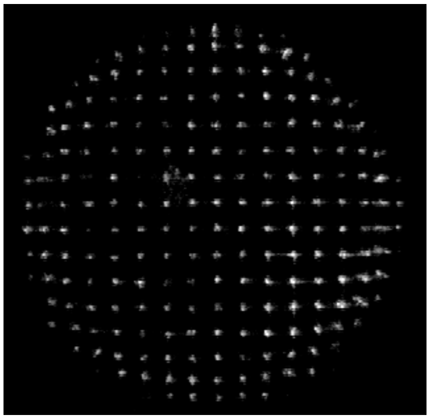
Example Images

No Refractive Surgery



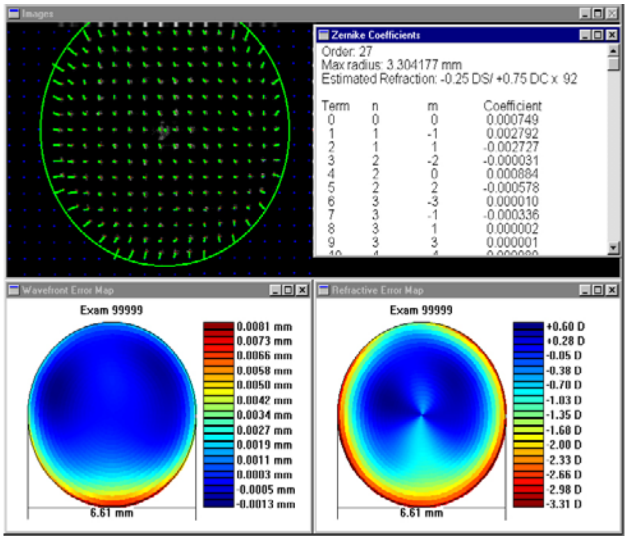
Low Aberrations

Post-LASIK with VISX Star S2



High Aberrations

Wavefront Reconstruction



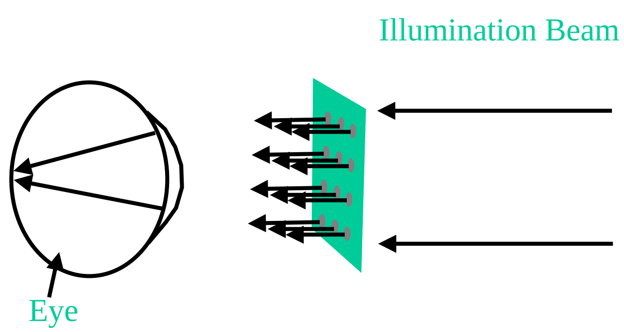
PSF

Tscherning Technique

- Tscherning developed a subjective technique in the late 1800s.
- Equivalent to a Hartmann Screen Test for the eye.
- Howland and Howland modified test in the 1980s and made it an objective measurement.
- University of Dresden built modern system.

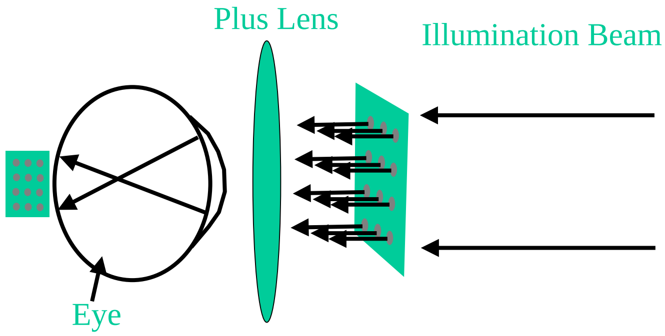
- Commercial Devices - Wavelight

Tscherning Wavefront Sensor



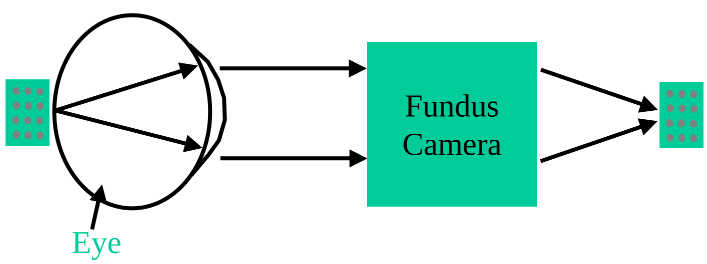
A collimated illumination beam goes through a dot pattern mask.

Tscherning Wavefront Sensor



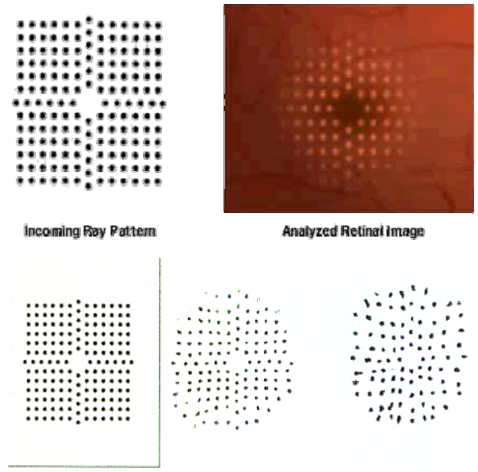
Adding an aberroscope lens of appropriate power causes “shadow” of mask to be cast onto the retina

Tscherning Wavefront Sensor



A fundus camera is used to photograph the retinal pattern. Perfect wavefronts give a uniform grid of points, whereas aberrated wavefronts distort the grid pattern.

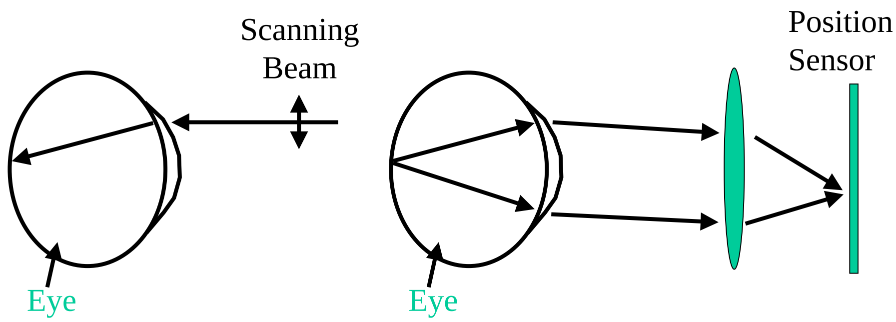
Example Images



Retinal Raytracing Technique

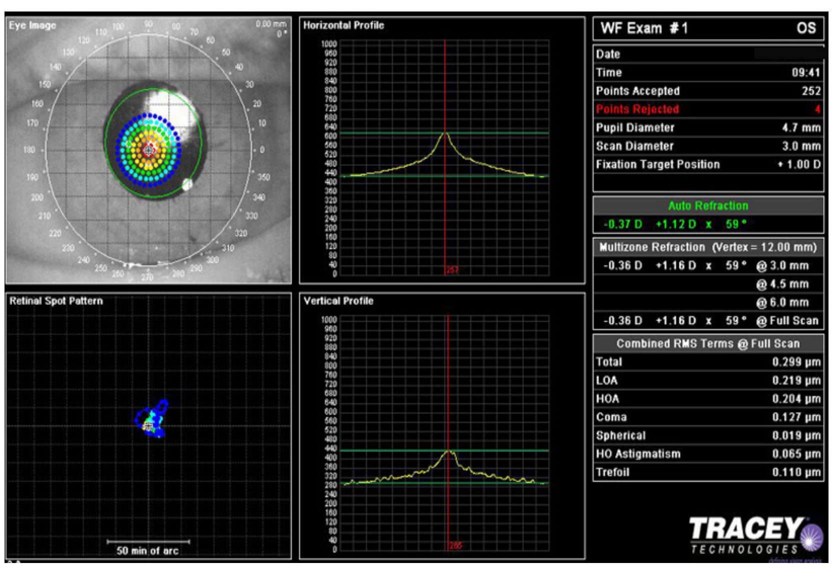
- Modification of the Tscherning technique. Repeated measurement of a single scanning beam instead of multiple beams simultaneously.
- Molebny developed modern device.
- Commercial Devices - Tracey

Retinal Raytracing



In-going beam is scanned around pupil. The position of the point on the retina is recorded with a position sensor.

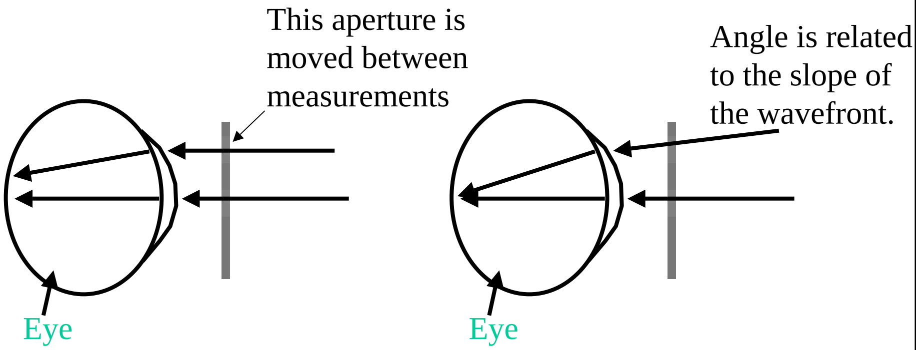
Retinal Raytracing



Spatially-Resolved Refractometer Technique

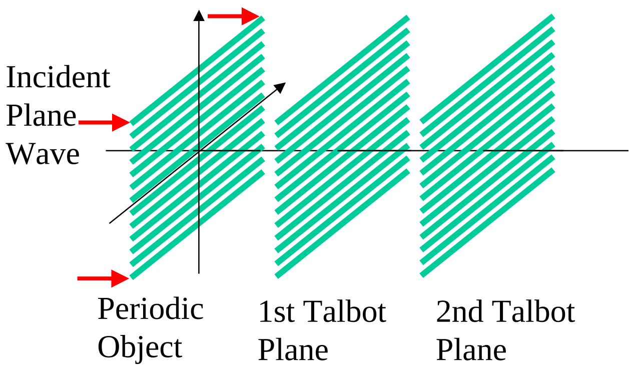
- Psychophysical test to determine aberrations of the eye. Repeated measurements at different pupil locations.
- Smirnov used technique in 1961.
- Webb built modern system in early 1990s.
- Commercial Devices - Emory University?

Spatially-Resolved Refractometry



Subject views two beams simultaneously and adjusts the angle of one beam fuse the retinal spots. Test is repeated for multiple pupil locations.

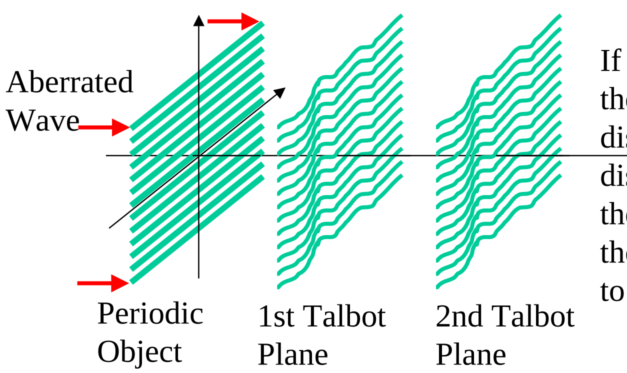
Talbot Imaging



Talbot imaging is a diffraction phenomenon that occurs with periodic objects. Perfect replicas of the object appear at fixed distances called Talbot planes. The location of the Talbot planes depends on the period of the object and the wavelength of light.

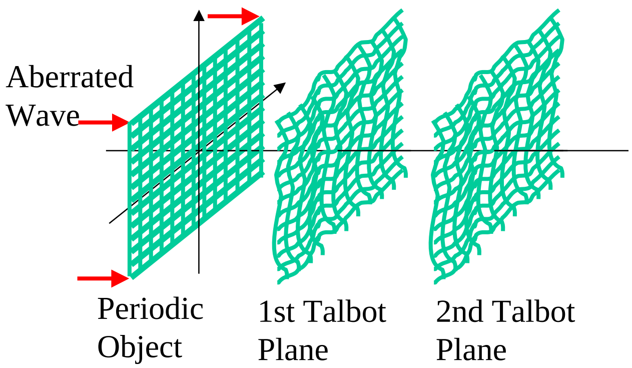
Talbot Notes

Aberrations



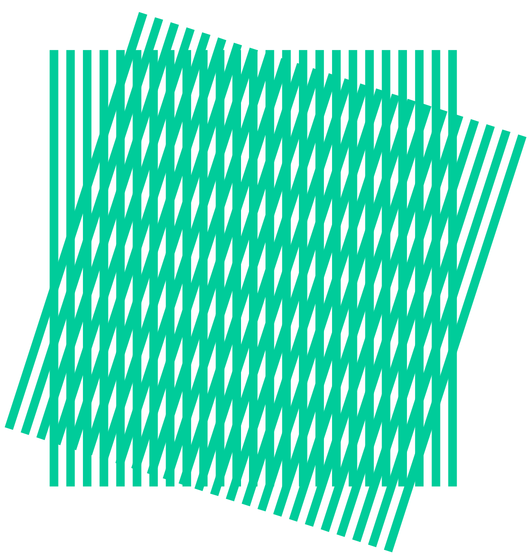
If aberrations are present, the Talbot images are distorted. The amount of distortion depends upon the wavefront slope in the direction perpendicular to the bars of the object.

Aberrations



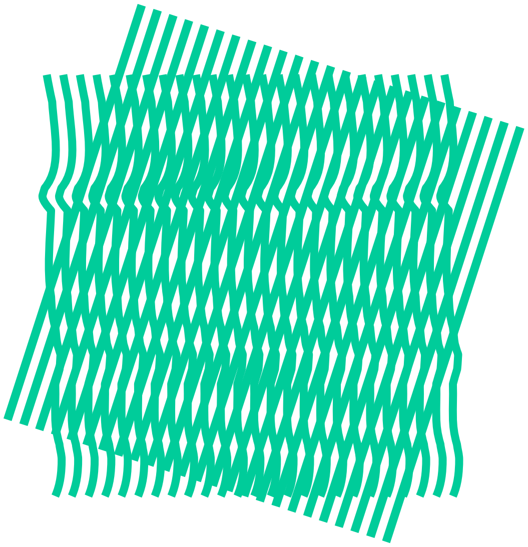
Crossed-gratings can be used to recover the wavefront slope in two orthogonal directions.

Moire Effect



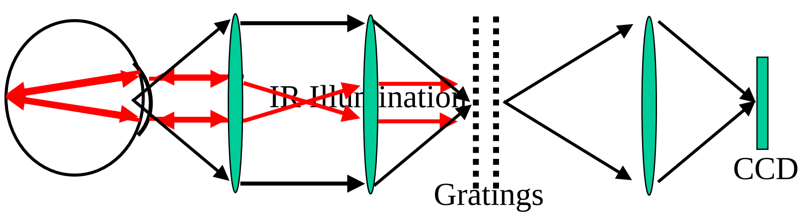
For large grating periods, the distorted Talbot images can be captured & analyzed easily. To increase resolution, however, finer grating periods can be used and a second grating is placed at one of the Talbot planes and rotated slightly.

Moire Effect

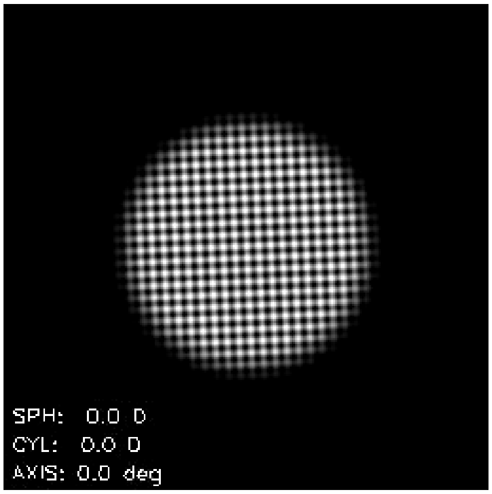


The superposition of the distorted Talbot image and the second grating gives a Moire pattern. The shape of the Moire pattern is again related to the slope of the wavefront.

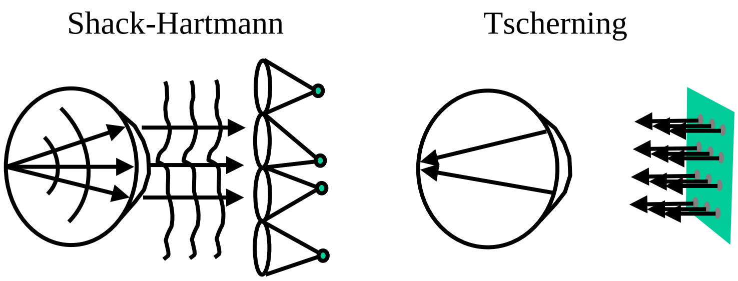
Ocular Wavefront Sensing



Simulation



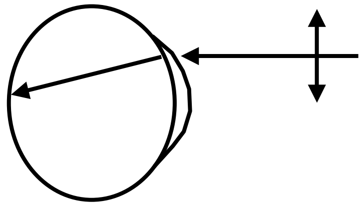
Measurements in Parallel



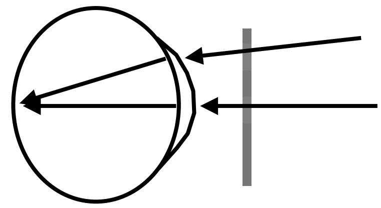
The number of points measured in the pupil depends on the spacing between the apertures. There exists a size limitation on how closely spaced these can be and still have the device resolve individual spots. Also, lenslet fabrication cost increases as they are made smaller.

Measurements in Series

Retinal Raytracing



Spatially-Resolved Refractometer



The number of points measured in the pupil can in theory be increased to any limit. The tradeoff for increased spatial resolution of these systems is an increase in measurement time.

The Talbot Effect

Jim Schwiegerling, PhD
February 20, 2006

The Talbot effect is a self-imaging phenomenon where the diffraction pattern from a periodic structure reforms a copy of the structure at downstream planes. The effect can be derived from the Fresnel diffraction integral.

If (x,y) are the transverse coordinates in the plane of the periodic structure and (x',y') are the transverse coordinates at a plane a distance z from the periodic structure, then the electric field in the (x',y') plane is given by

$$E(x',y') = \frac{\exp[ikz]}{i\lambda z}\exp\left[\frac{i\pi}{\lambda z}\left(x'^2+y'^2\right)\right]\Im\left\{E(x,y)\exp\left[\frac{i\pi}{\lambda z}\left(x^2+y^2\right)\right]\right\} \quad (1)$$

where $\Im\{\ \}$ is the Fourier transform with respect to the variables $\xi = x' / \lambda z$ and $\eta = y' / \lambda z$. For convenience, the following constant can be defined

$$A = \frac{\exp[ikz]}{i\lambda z}\exp\left[\frac{i\pi}{\lambda z}\left(x'^2+y'^2\right)\right] \qquad (2)$$

If E(x,y) is a periodic function with period L, then it can be represented by a Fourier series such that

$$E(x,y) = \sum_{n=-\infty}^{\infty} a_n \exp\left[\frac{i2\pi nx}{L}\right] \quad (3)$$

$$a_n = \frac{1}{L}\int_{-L/2}^{L/2} E(x,y)\exp\left[\frac{-i2\pi nx}{L}\right]dx \quad (4)$$

Substituting equation (3) into equation (1) gives

$$E(x',y') = A\sum a_n \Im\left\{\exp\left[\frac{i2\pi nx}{L}\right]\exp\left[\frac{i\pi}{\lambda z}\left(x^2+y^2\right)\right]\right\} \qquad (5)$$

Let $b^2 = i\lambda z$ and use the properties of Fourier transform of products being equal to a convolution of the individual Fourier transforms to get

$$E(x',y') = A\sum a_n\left[\Im\left\{\exp\left[\frac{i2\pi nx}{L}\right]\right\} * \Im\left\{\exp\left[\frac{-\pi}{b^2}\left(x^2+y^2\right)\right]\right\}\right] \qquad (6)$$

Transforming gives

$$E(x',y') = b^2 A \sum a_n \left[\left(\delta\left(\xi - \frac{n}{L} \right) \delta(\eta) \right) * \exp\left[-\pi b^2 \left(\xi^2 + \eta^2 \right) \right] \right] \qquad (7)$$

Carrying out the convolution gives

$$E(x',y') = b^2 A \sum a_n \exp\left[-i\pi\lambda z \left(\left(\xi - \frac{n}{L} \right)^2 + \eta^2 \right) \right] \qquad (8)$$

Simplifying gives

$$E(x',y') = e[ikz] \sum a_n \exp\left[\frac{i2\pi nx'}{L} \right] \exp\left[\frac{-i\pi\lambda z n^2}{L^2} \right] \qquad (9)$$

Note that except for a phase term that is constant over the (x’,y’) plane, equation (9) is identical to equation (3) when

$$\exp\left[\frac{-i\pi\lambda z n^2}{L^2} \right] = 1 \qquad (10)$$

The condition in equation (10) is only satisfied when

$$\frac{\lambda z}{L^2} = 2m, \text{ m integer} \qquad (11)$$

Consequently, the Talbot planes or the planes where the object is reproduced are located at

$$z_m = \frac{2mL^2}{\lambda} \qquad (12)$$