Ocular Shack-Hartmann sensor resolution

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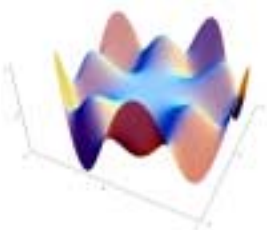
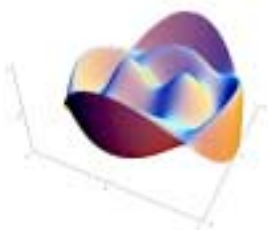


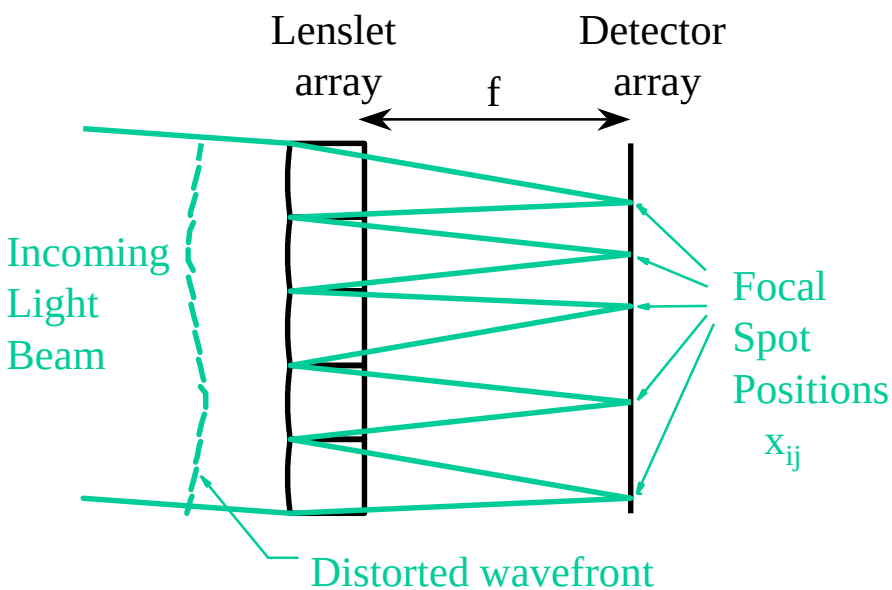
WaveFront SCIENCES
Optics and Instrumentation

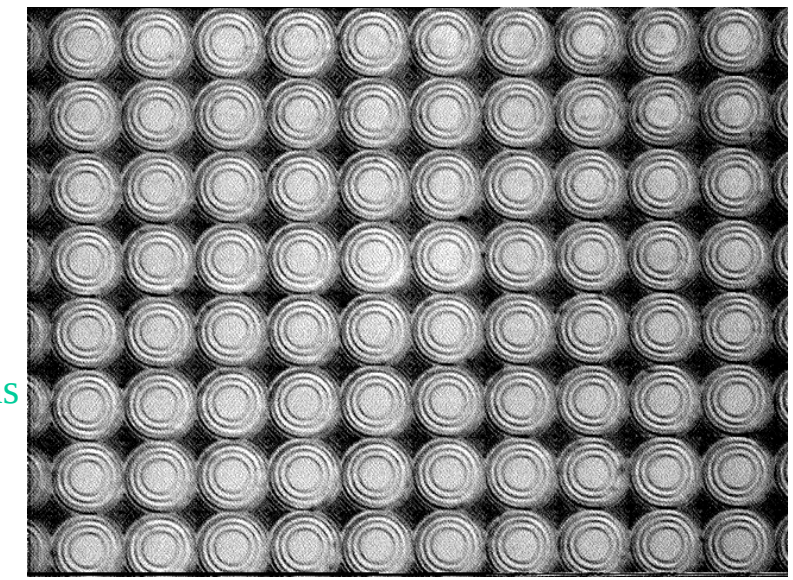


Outline

- Introduction
  - Shack-Hartmann wavefront sensors
  - Performance parameters
  - Reconstructors
- Resolution effects
  - Spot degradation
  - Accuracy
  - Dynamic range
  - Wavefront sampling
- Conclusions

A practical Shack-Hartmann wavefront sensor is based on a microlens array



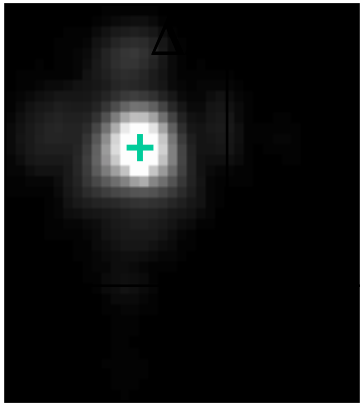


Wavefront Analysis

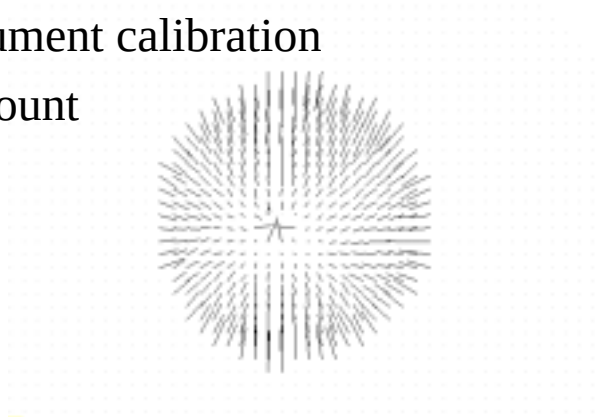
1. Locate position of focal spot x_{ij}
2. Compute wavefront slope $\frac{\hat{x}_{ij} - \hat{x}_{io}}{f} = \left(\frac{\partial \phi_j}{\partial x}\right)_i$
3. Recover wavefront ϕ_j by integrating.

Photomicrograph of discrete level lens array fabricated in fused silica using binary optics technology; lenslets are 250 μm in diameter.

The wavefront analysis process consists of three steps

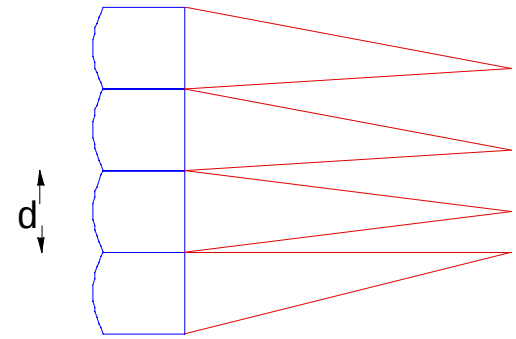


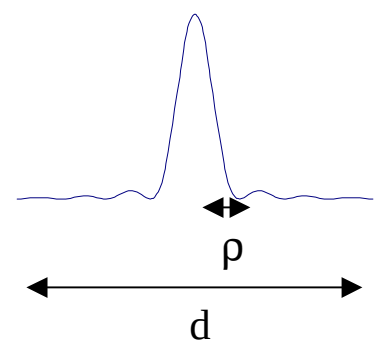
- Find the focal spot centroids
  - Each spot assigned unique Area of Interest (AOI)
  - Typically uses a thresholded centroid algorithm
  - Errors from pixelization, camera noise, and spot Strehl ratio
- Compare to reference to produce slope map
  - Absolute or relative reference acquired during instrument calibration
  - Other instrument calibrations may be taken into account
    - Magnification
    - Telescope focus
- Reconstruct wavefront
  - Zonal: point by point integration of 2D slope map
  - Modal: Fit to polynomials such as Zernike or Taylor



WFS design parameters

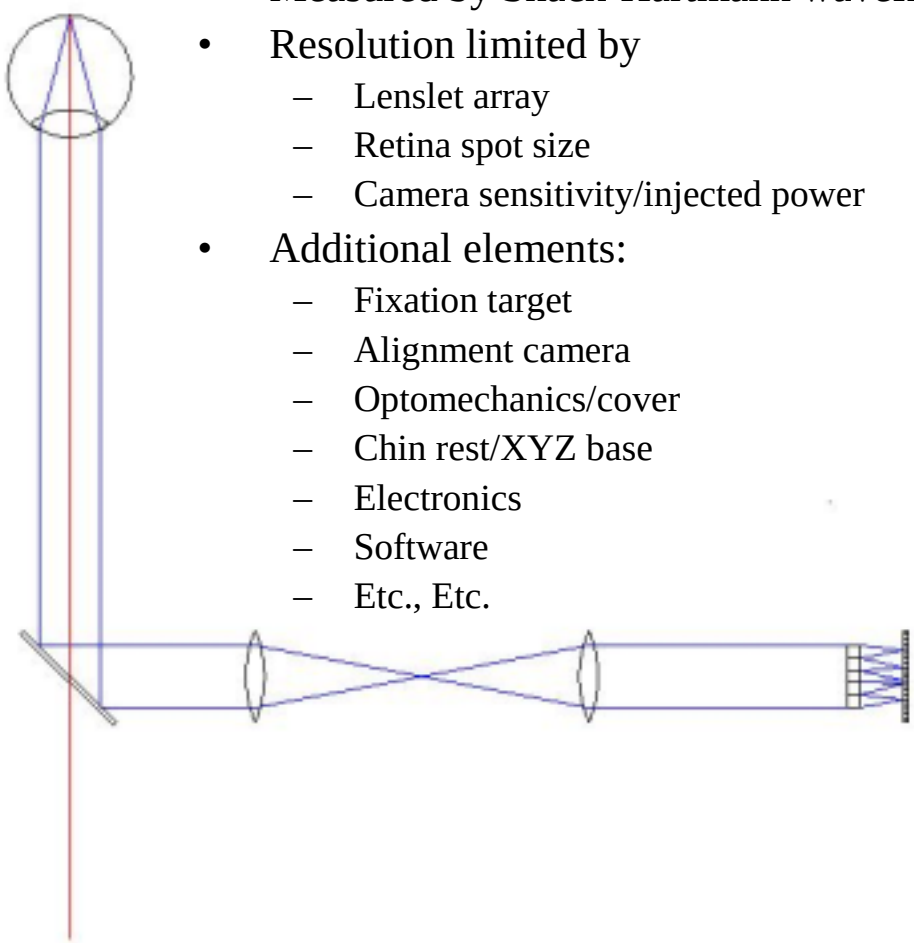
- Lenslet Fresnel number: $N_{Fr} = \dfrac{d^2}{f\lambda}$
- Focal spot size: $\rho = \dfrac{f\lambda}{d}$ or $\rho = \dfrac{d}{N_{Fr}}$
- Angular dynamic range: $\theta_{\max} = \dfrac{d/2 - \rho}{f}$
- Total wavefront dynamic range: $\dfrac{w_{\max}}{\lambda} = \dfrac{N_l N_{Fr}}{4n}$





Ocular SH WFS system

- Guide star system
  - Injected spot
  - Measured scattered light
- Measured by Shack-Hartmann wavefront sensor
- Resolution limited by
  - Lenslet array
  - Retina spot size
  - Camera sensitivity/injected power
- Additional elements:
  - Fixation target
  - Alignment camera
  - Optomechanics/cover
  - Chin rest/XYZ base
  - Electronics
  - Software
  - Etc., Etc.

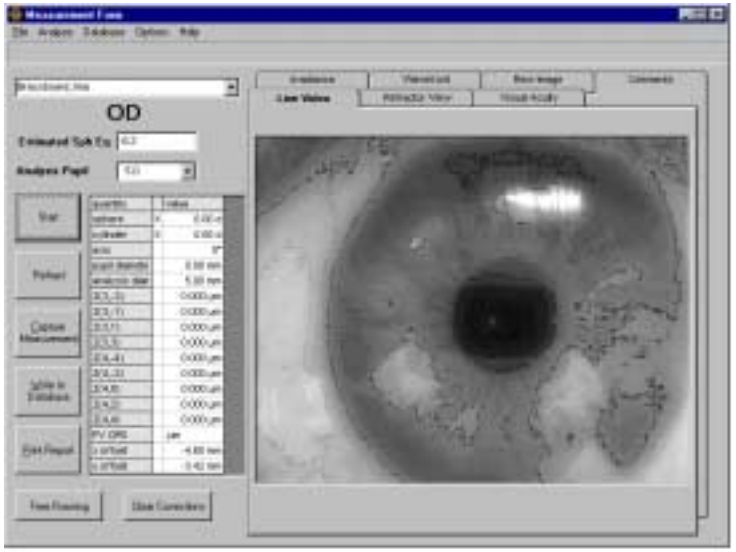


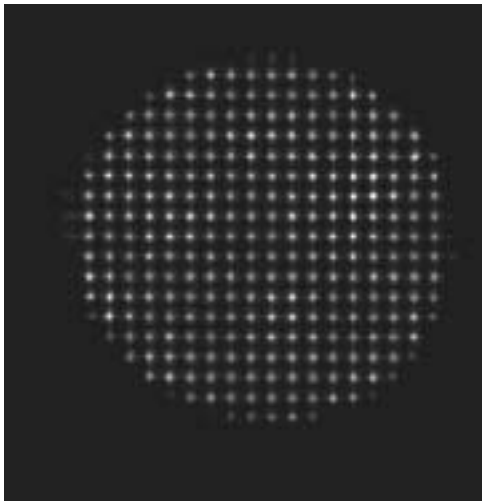
Complete Ophthalmic Analysis System

- Complete system for optical metrology of the eye
- High resolution/high dynamic range wavefront sensor
- Variable position optical system uses active optics to maximize performance
- Experiments with laser vision correction are underway
- The COAS G200 is already a second generation product

COAS Measurement results

- Sphere: -12 to +5 d
- Cyl: 5 d
- Measurement time: 5 sec autorefract, 13 ms measurement
- Zernike polynomial to arbitrary order
- Accuracy: +/- 0.1 diopter





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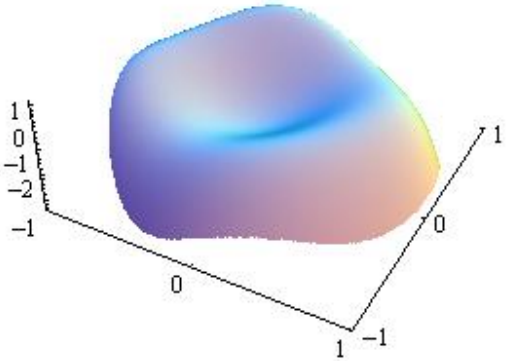
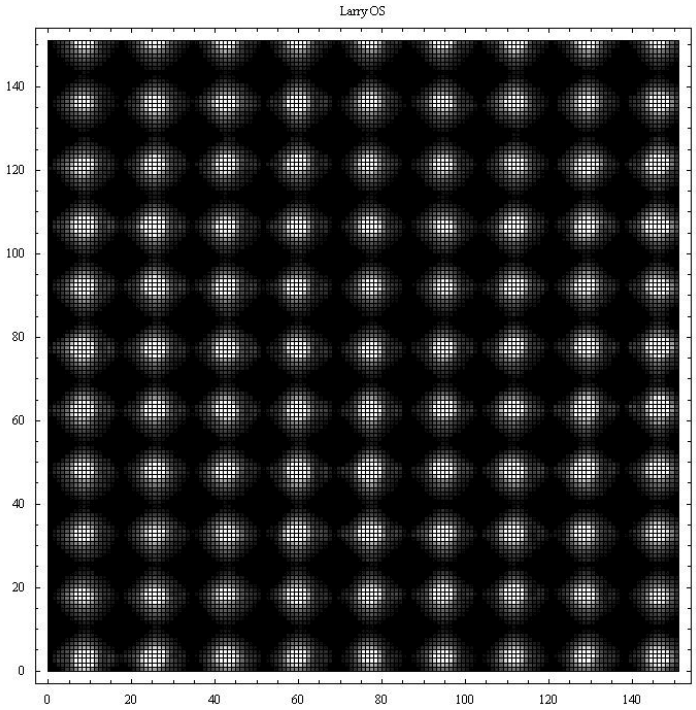
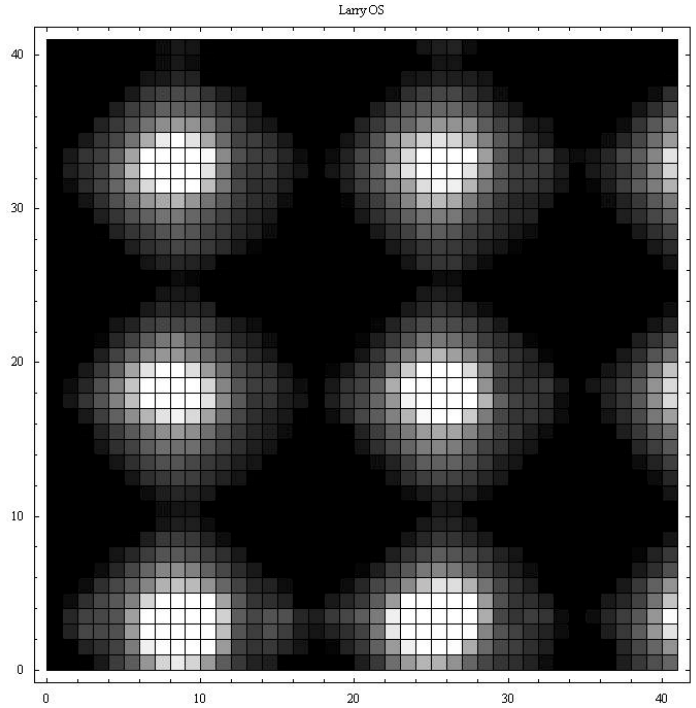


Wavefront sensor image from Human Eye



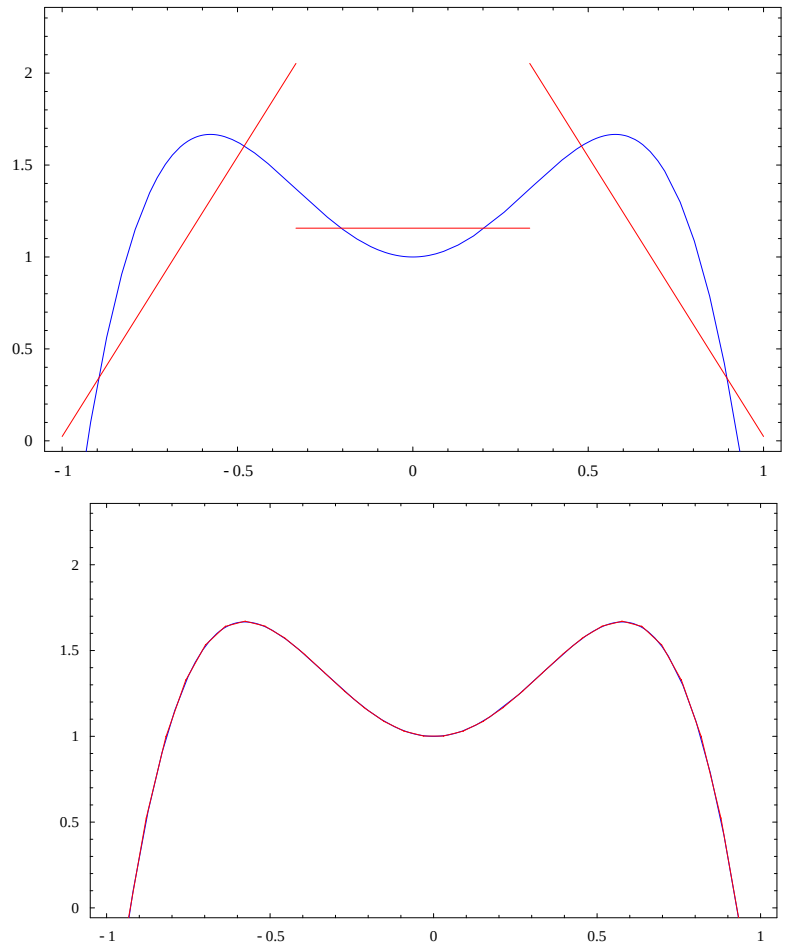


Why does the measurement resolution matter?

- Spot degradation
  - For larger lenslets, the wavefront aberration across the lenslet may be significant
  - With aberration, the focal spots are degraded
  - Poor focal spots lead to inaccurate measurements, or perhaps no measurement at all
  - This ultimately limits the dynamic range
  - Smaller lenslets intercept a smaller portion of the wavefront aberration
- Dynamic range
  - Depends on number of lenslets, and lenslet Fresnel number
  - Larger lenslets have reduced response for rapidly varying aberrations
- Accuracy
  - Each slope measurement determined from small, high quality focal spot
  - More points in reconstructor lead to higher accuracy for each term
  - Rapidly varying features may be accurately measured

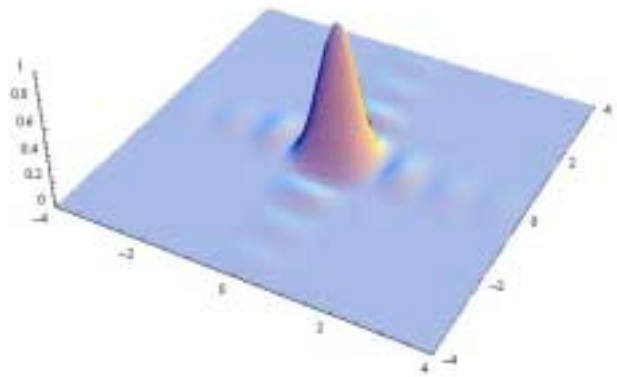
The SHWFS wavefront is a piecewise linear approximation

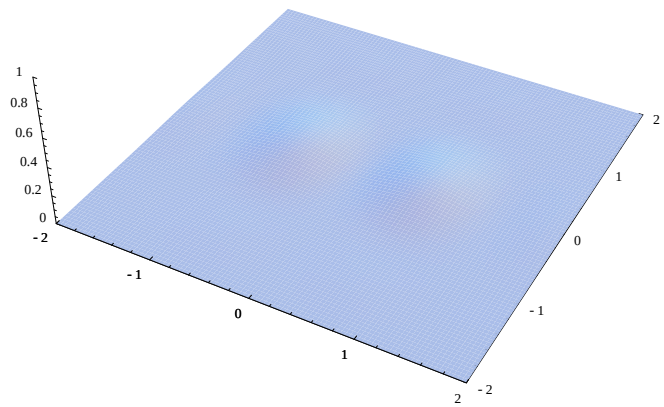
- Shack-Hartmann sensors measure only average tilt
- Focal spot irradiance distribution depends upon total incident wavefront
- Low resolution SHWFS measurements tend to UNDERPREDICT the actual wavefront
- Residual WFE error is the RMS difference between the linear approximation and the actual wavefront



Focal spot degradation

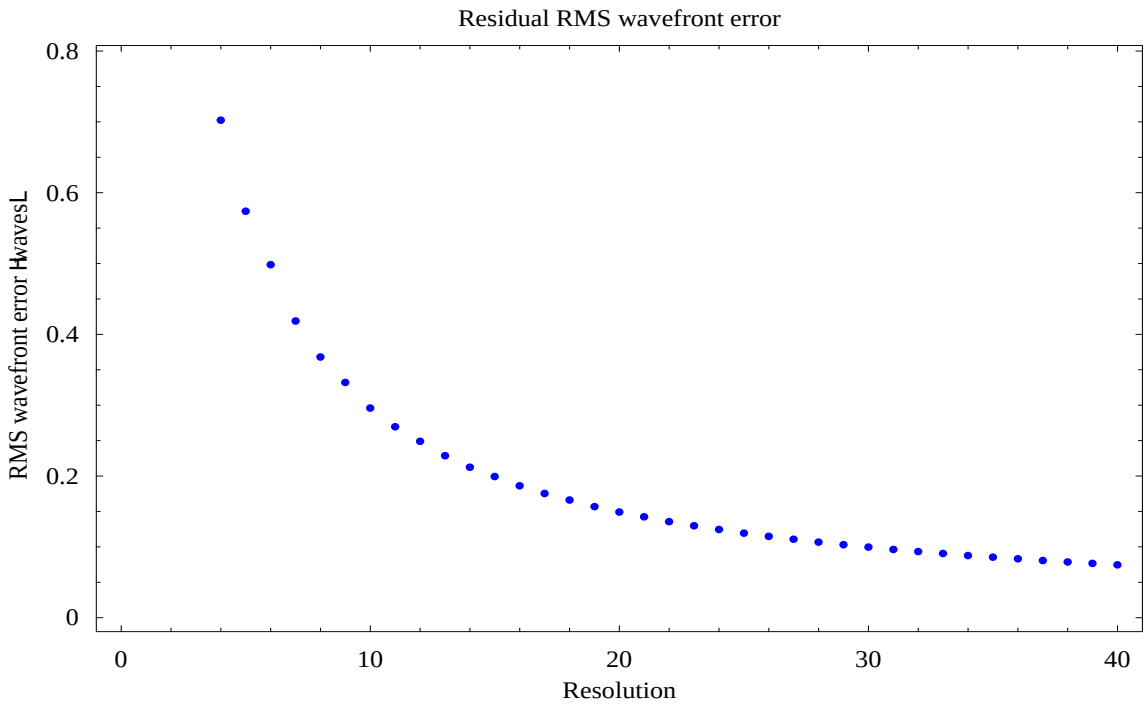
- Small lenslets
  - Sample small portion of the wavefront
  - Sampled wavefront matches well to linear approximation
- Large lenslets
  - May have large residual wavefront error
  - Reduced Strehl may affect centroid location





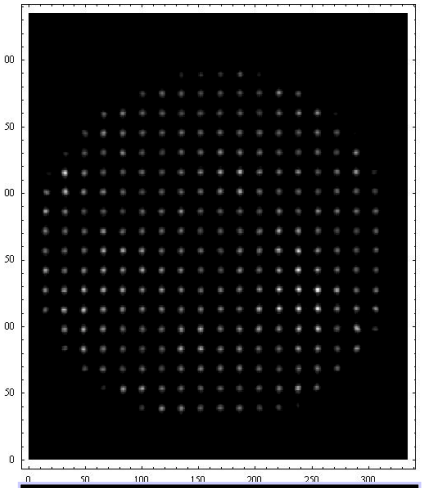
Residual wavefront error depends strongly on resolution

- Linear approximation fit error
- In practice, this fit error reduces the lenslet Strehl ratio

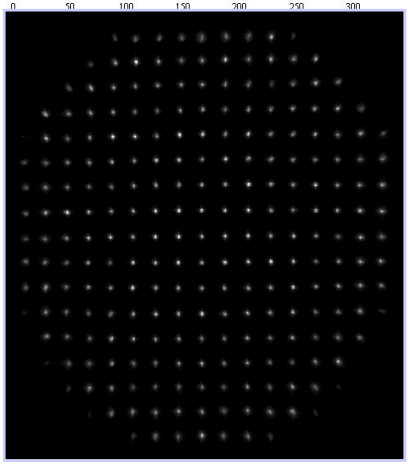


Excellent images can be obtained from a normal eye

- Good focal spots can usually be obtained even at low resolution
- Focus/cylinder result in pattern spread
- Higher order terms usually have limited wavefront error



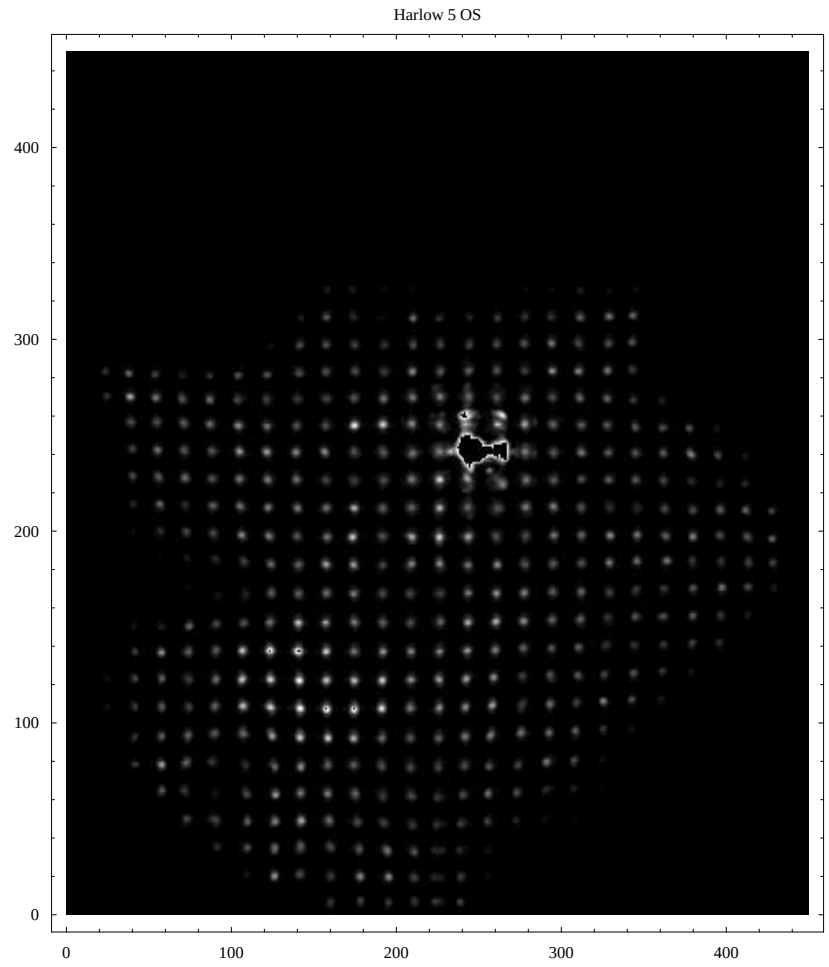
- 210 μm resolution
- 44 X 33 samples
- 3.8 mm pupil
- 25 μW input power



- 400 μm resolution
- 18 x 18 samples
- 6.8 mm pupil
- 6 μW input power
- Salmon et al, JOSA A 1998

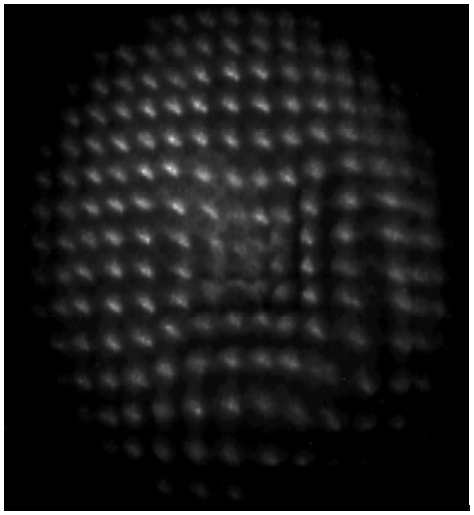
With high resolution, good focal spots are obtained even from a badly damaged eye

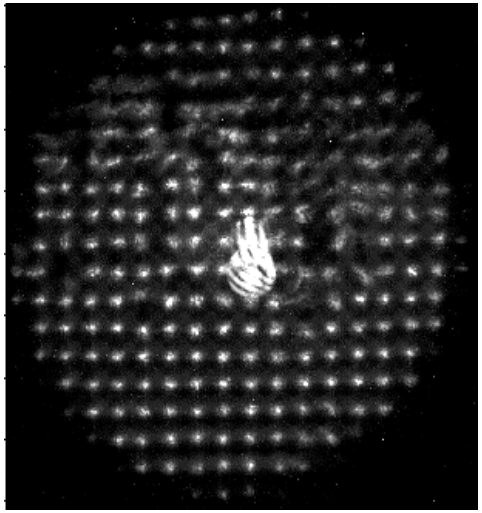
- 210 μm resolution
- RK patient with poor correction
- Damaged regions scatter light badly
- Patient has poor BCVA



However, with lower resolution, the focal spots are degraded

- 400 μm lenslets
- 6.5 mm pupil
- 16 X 16 samples
- Poor focal spots are difficult to locate
- Blurry, fuzzy spots give inaccurate results
- Strehl reduction reduces signal to noise





You *do* need more incident power with more focal spots

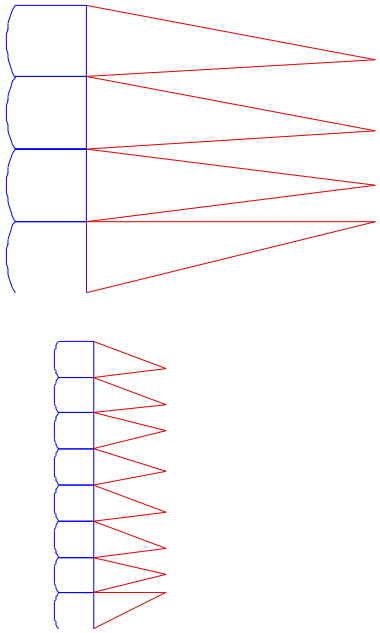
- Scattered light is collected by smaller area lenslets
- Spot size should be similar for good accuracy
- Improved Strehl keeps light level high even for aberrated systems
- Near IR measurement improves patient comfort
- Extremely accurate lenslet array with 100% fill factor maximizes the efficiency

Resolution (7 mm pupil)	**Focal spots**	**Lenslet area** (μm)	**Power** (μW)
33 X 33	800	210 X 210	22
18 X 18	254	400 X 400	6
10 X 10	78	700 X 700	2

But not much!

With higher resolution, you get better dynamic range AND accuracy

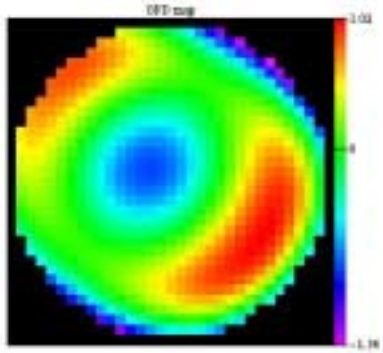
- Dynamic range
  - For smaller lenslets, the focal length is shorter for the same spot size
    - Larger angular dynamic range per lenslet
  - More focal spots divide the aberration into smaller samples
    - Spots are unlikely to collide with neighbor because they measure similar wavefronts
- Accuracy
  - Strehl ratio is high, even for aberrated pupils
  - Uniform brightness gives better centroids
  - Short focal length is less important than centroid estimation error
  - Larger number of samples approximate wavefront better
  - Reconstructor error is reduced



There are two basic types of reconstructor

- Modal
  - Fits to polynomials
  - Typically Zernikes
  - Polynomials have optical meanings
  - Quantitative understanding of results
  - Expansion yields point by point wavefront map
  - Interpolation functions in place

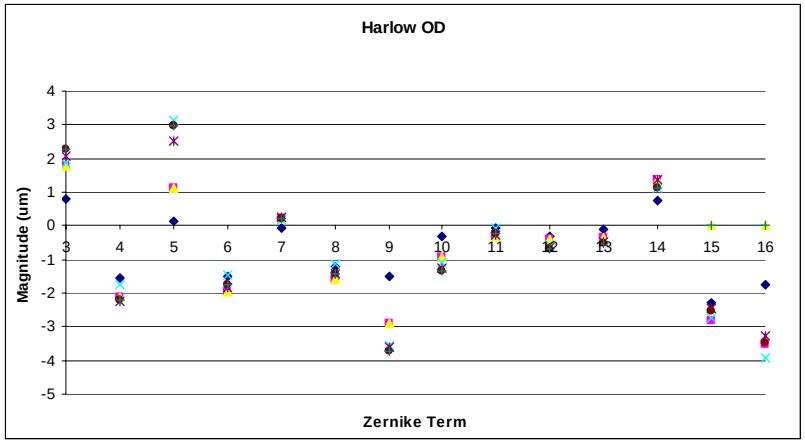
Z_4^{-4} Z_4^{-2} Z_4^{0} Z_4^{2} Z_4^{4}

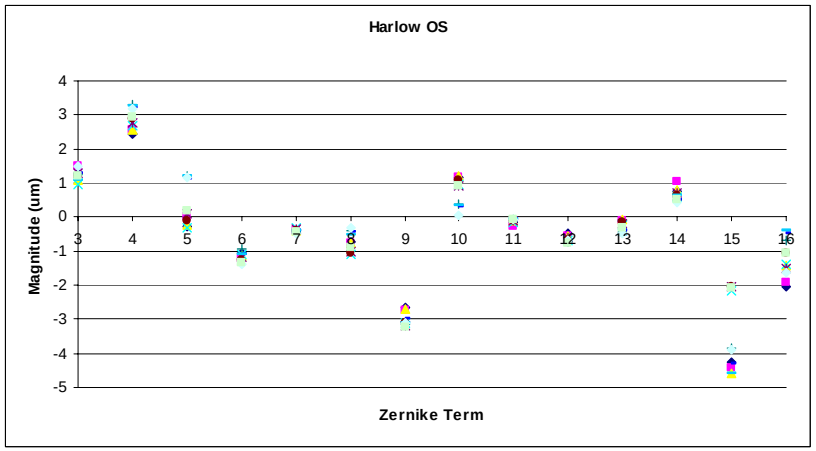


- Zonal
  - Numerical integration of slope grid
  - Yields point by point phase
  - Further fitting needed to produce sphere, cylinder, coma or other terms
  - Produces high spatial frequency results

Zernike polynomials allow quantitative display of the data

- RK patient
- 4th Order Zernike reconstructor
- High RMS values and odd mix of higher orders
- 4th order fit does not really resolve wavefront

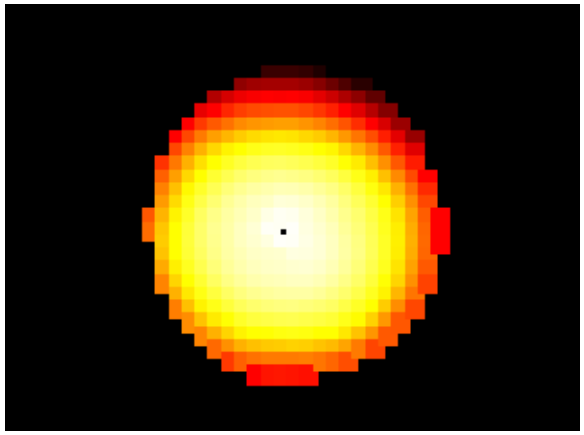




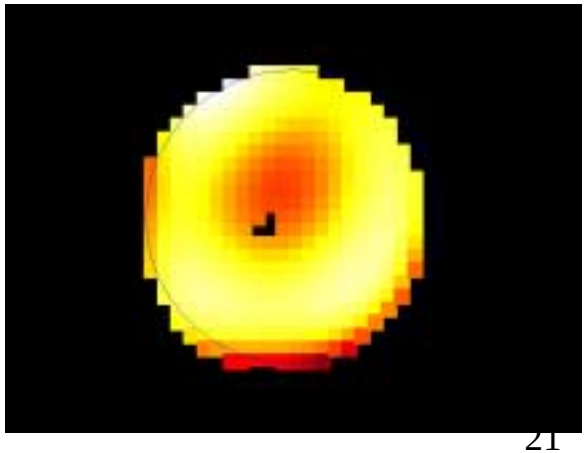
For a normal eye, high resolution may not be needed

- Normal eye
- Low higher order terms
- Small pupil
- Zonal and Modal produce similar results

Total wavefront: P-V 16.3 μm

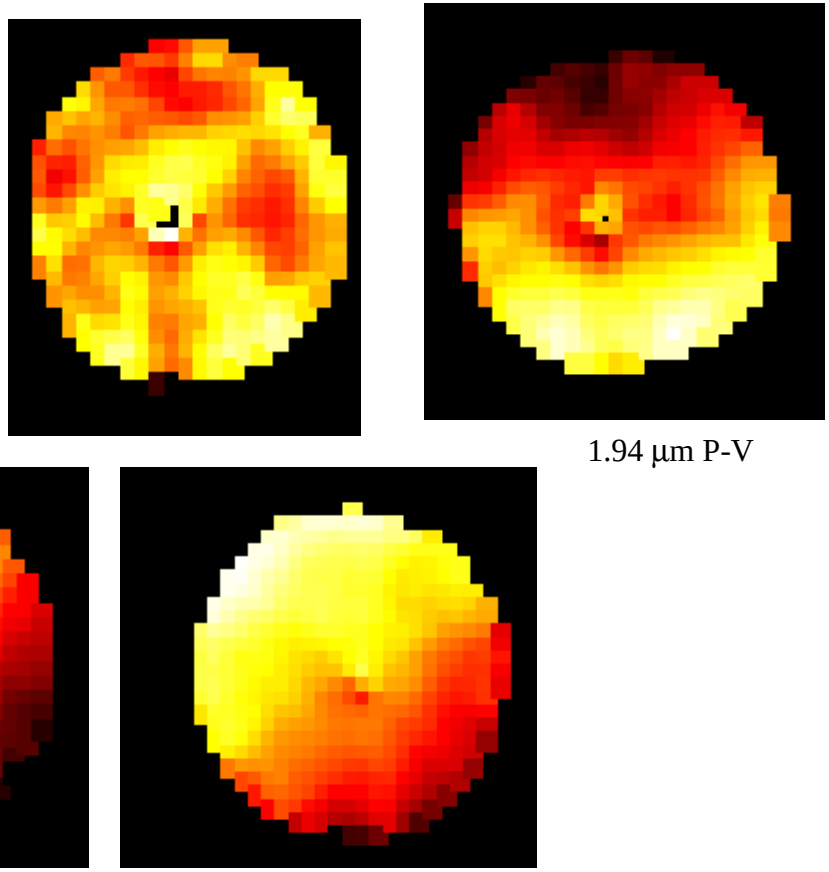


Total wavefront: P-V 1.04 μm



Unless you're interested in the detailed structure

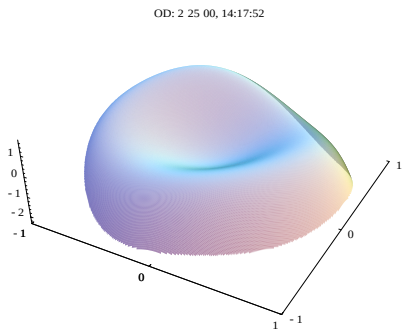
- Tear film
- Scratches
- Edema
- Unusual structures

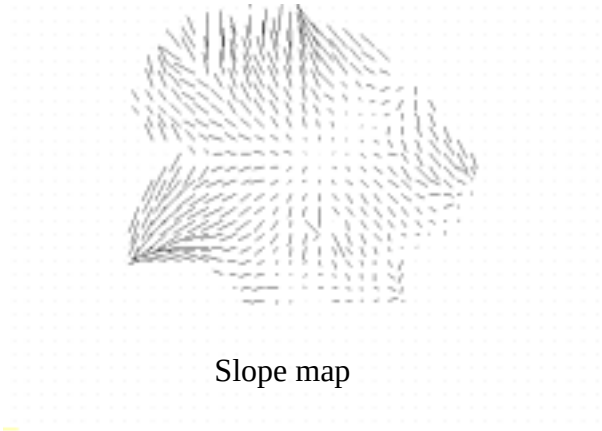


Various wavefront maps with 4th order terms removed

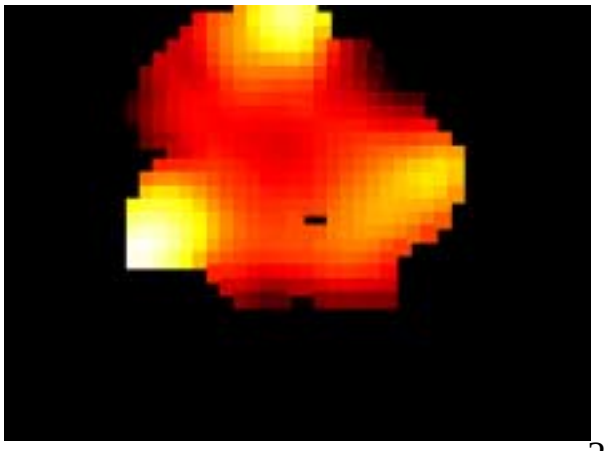
There are also many “abnormal” eyes

- RK patients
- Large pupils
- LASIK
- PRK
- Damaged
- Wrinkled flap
- Scratched/edema
- Dry eye
- Kerataconus





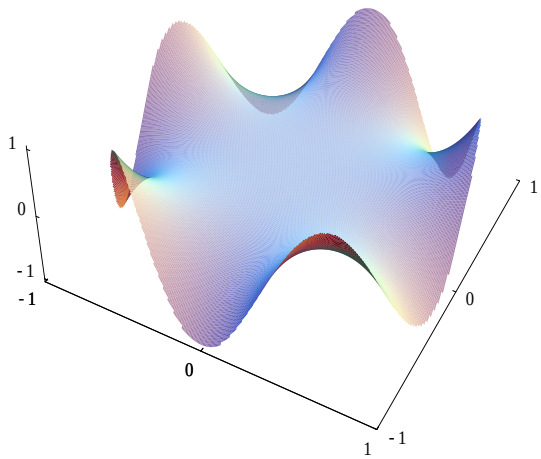
Slope map

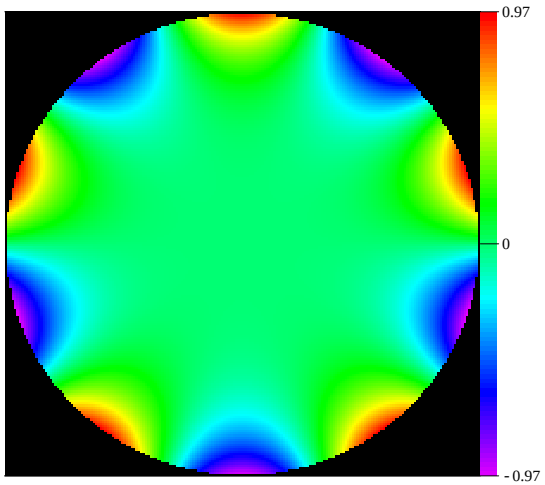


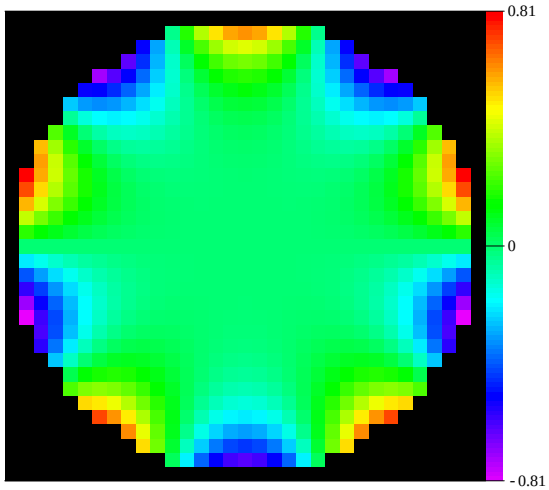
Wavefront map (sph/cyl subtracted)

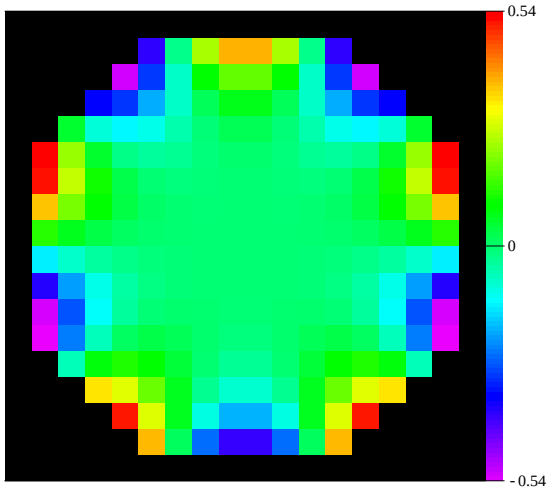
A pure Zernike viewed at different resolutions

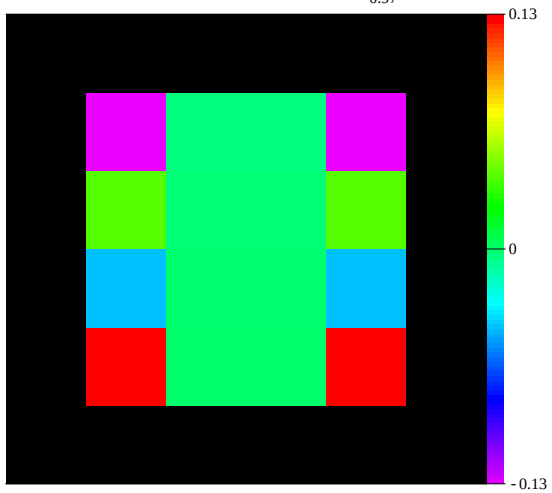
- “Simulated” RK patient
- “Perfect” reconstruction











Conclusions

- High resolution ocular wavefront sensing is a desirable and practical solution
  - High Strehl ratio spots, even with aberrated systems
  - Safe, comfortable power levels maintained
- Larger aberrations may be measured, more accurately
  - Better focal spots
  - Larger dynamic range and accuracy
  - Reduced fitting error
- Fine detail allows observation of important phenomena

WFS Precision

- Zero Tilt Centroid Estimation Error

$$\sigma_{j,0}{}^2 = \frac{\sum_{i=1}^{N}\left(\rho_i - \rho_i^{REF}\right)^2}{N} \qquad \bar{\sigma}_0 = \frac{\sum_{j=1}^{M}\sigma_{j,0}}{M}$$

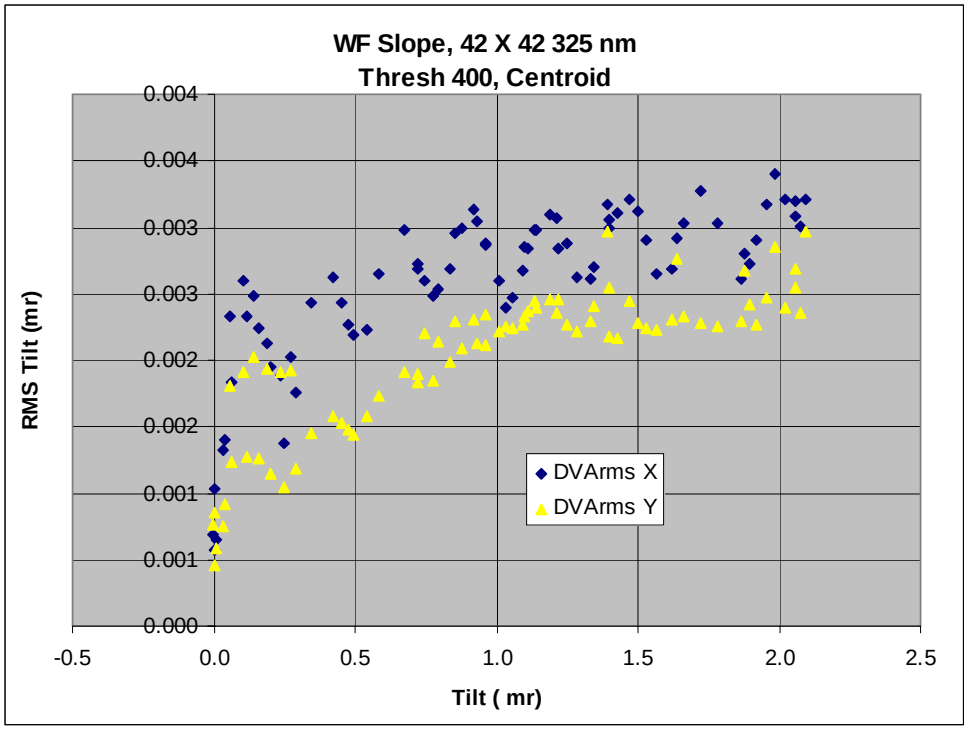
- Tilt precision:

$$\theta_{RMS} = \frac{\bar{\sigma}_0}{f}$$

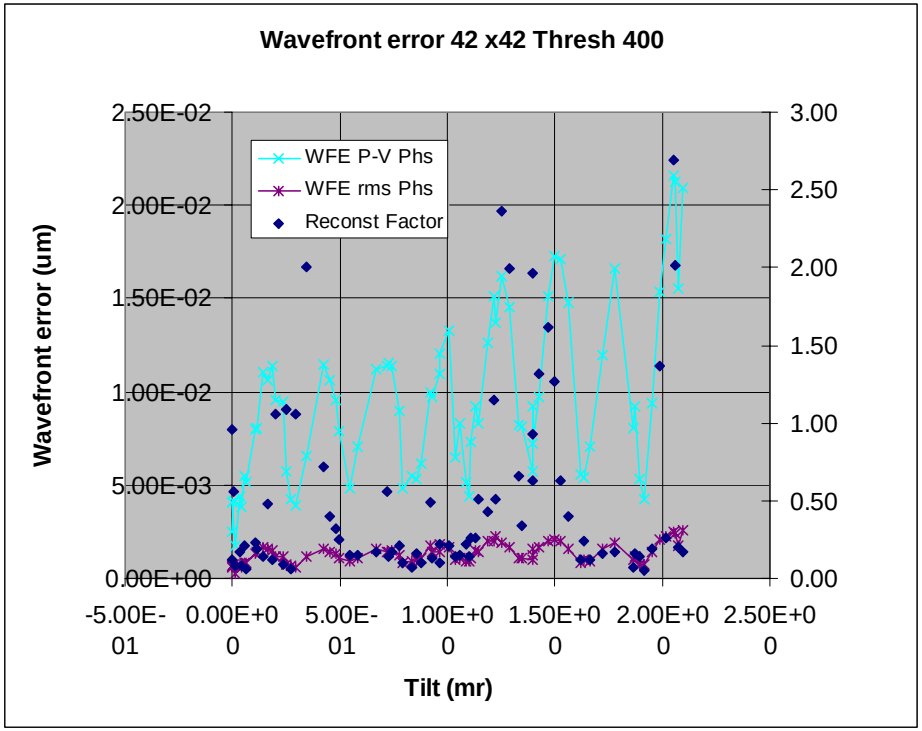
- Wavefront precision (RMS)
  - Per lenslet $w_0^l = \theta_{RMS} \cdot d$
  - Total across aperture $w_0^{Tot} = K_R w_0^l$

WFS Accuracy

- Pixelization Error
  - Threshold dependent
  - Depends strongly on pixels/focal spot
  - Is sometimes limiting performance metric
  - Pixelization factor Kp



WFS Accuracy, cont…



- Wavefront error
  - PV
  - RMS
- Reconstructor factor K_p depends on type and options for reconstructor
- Total wavefront error is given by:

$$w_{RMS} = K_r \cdot K_p \theta_{RMS} \cdot d$$

Typical WFS design process

- Specify key design parameters
  - Lenslet size in pixels
  - Lenslet Fresnel number
  - Total size of array
- Estimate performance parameters
  - Angular dynamic range, θ_{max}
  - Total wavefront dynamic range (*n=1, 2*)
  - Precision:
    - Scale σ_0 from measurements to new design point
    - Compute θ_{rms}, and $w_{rms,l}$
  - Accuracy
    - Compute $W_{rms,tot}$ using K_p and K_r

Measuring WFS performance

- Precision
  - 100 Frame statistical average of focal spots
  - Average RMS Tilt values produce θ_{rms}
  - $\overline{\sigma}_0 = \theta_{rms} f$
- Accuracy
  - Vary tilt, focus or other parameter
  - Measure residual WFE
- Dynamic range
  - Increase tilt while monitoring spot centroid
  - Dynamic range exceeded when non-linearity is induced