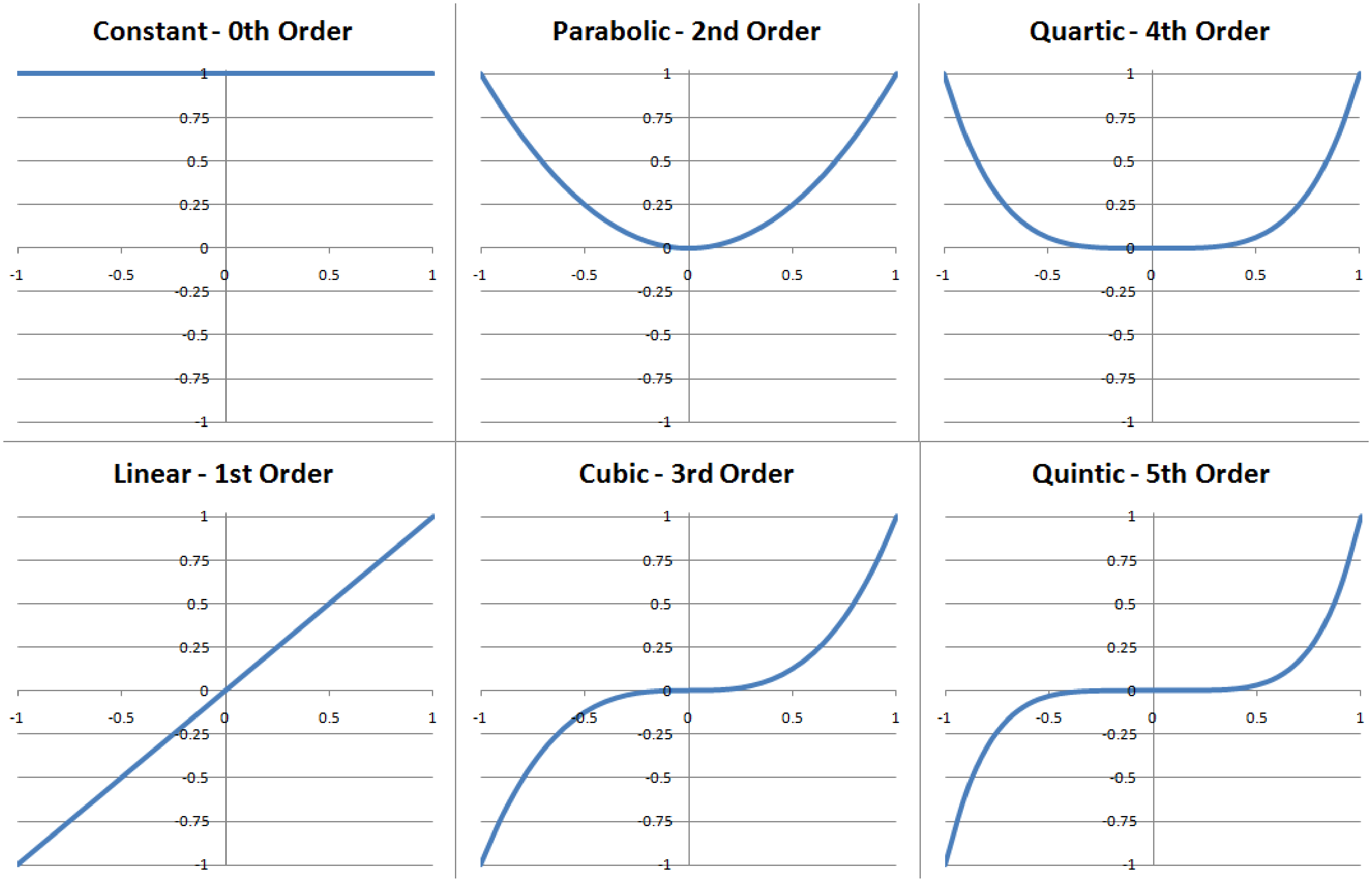
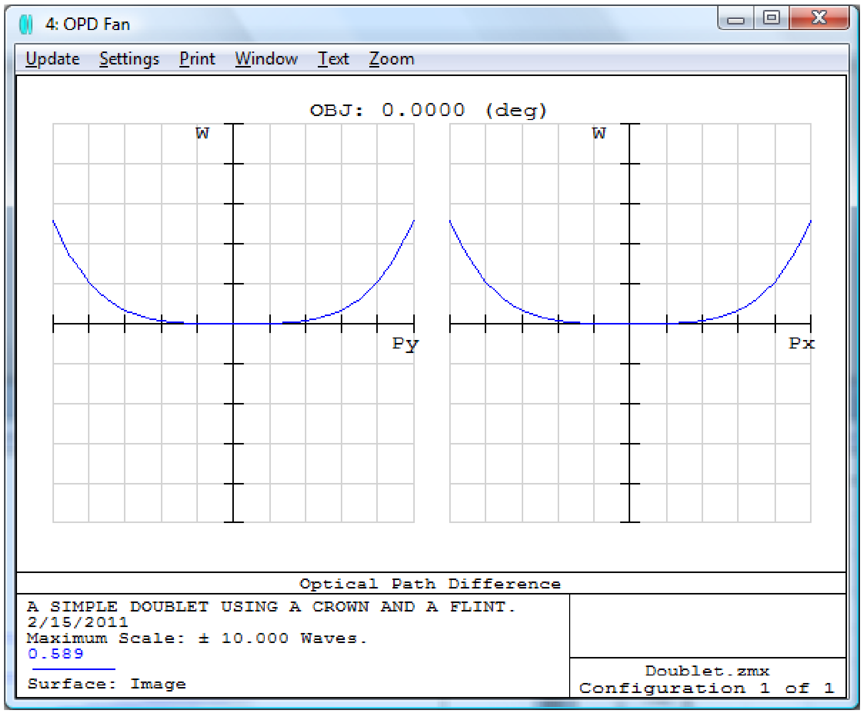
1.5.8 Orders of Polynomials

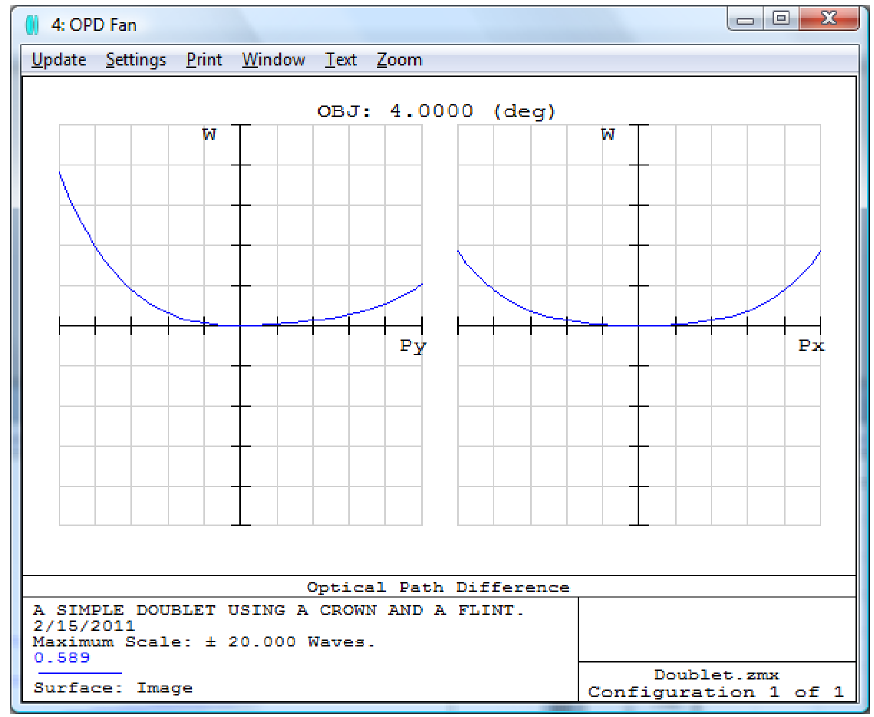


1.5.8 Seidel Aberrations

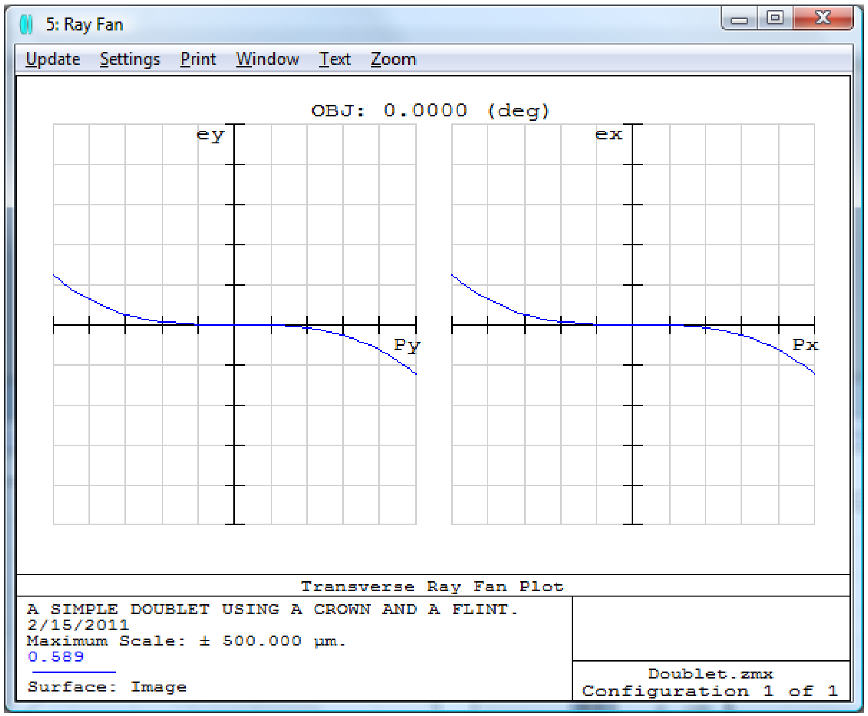
Aberration	$W(0,\rho_y)$	$W(\rho_x,0)$	$\varepsilon_y(0,\rho_y)$	$\varepsilon_x(\rho_x,0)$	h
Tilt	linear	zero	constant	zero	linear
Defocus	parabolic	parabolic	linear	linear	constant
Spherical	quartic	quartic	cubic	cubic	constant
Coma	cubic	parabolic	parabolic	zero	linear
Astigmatism	parabolic	zero	linear	zero	parabolic
Field Curvature	parabolic	parabolic	linear	linear	parabolic
Distortion	linear	zero	constant	zero	cubic

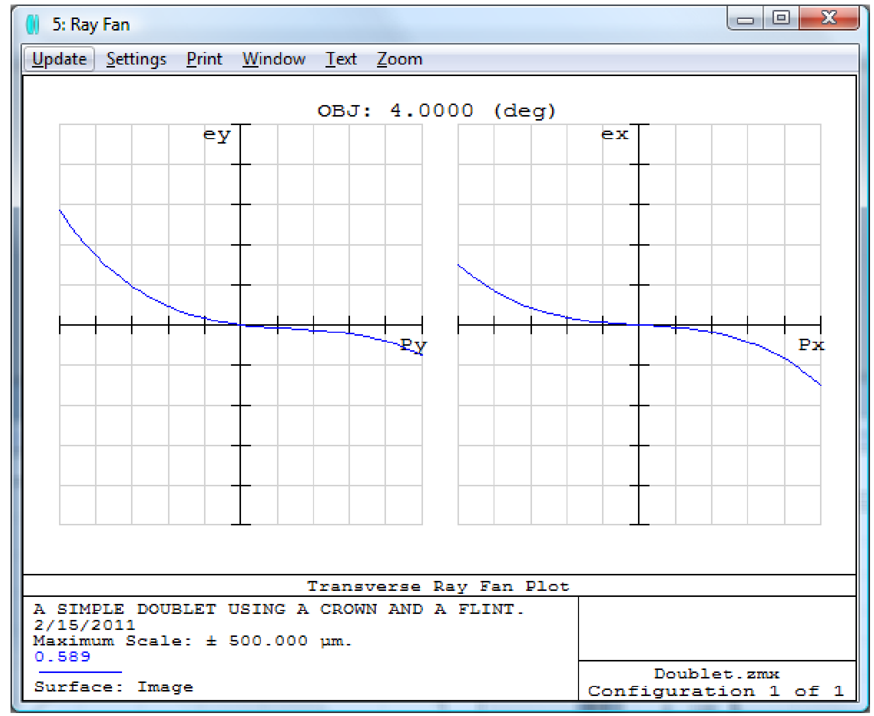
Doublet Wavefront Error





Doublet Transverse Ray Error

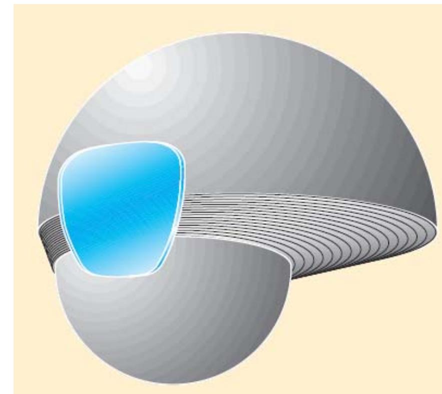




1.5.9.1 Non-Rotationally Symmetric Systems

Edmundoptics.com

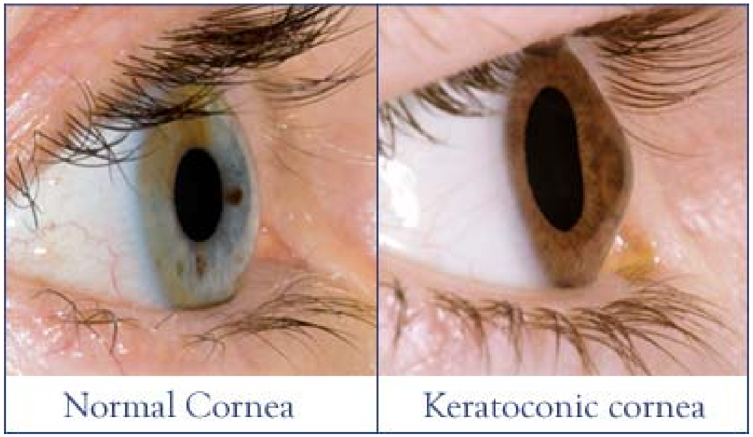
Edmundoptics.com



Essilor

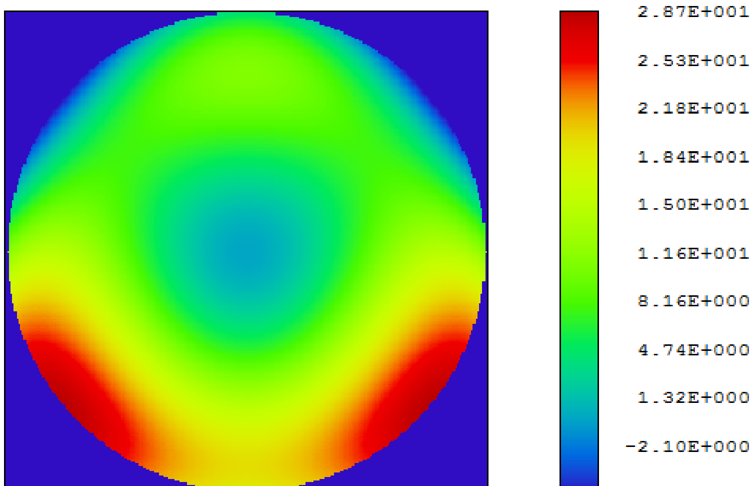
www.davidmullenasc.com

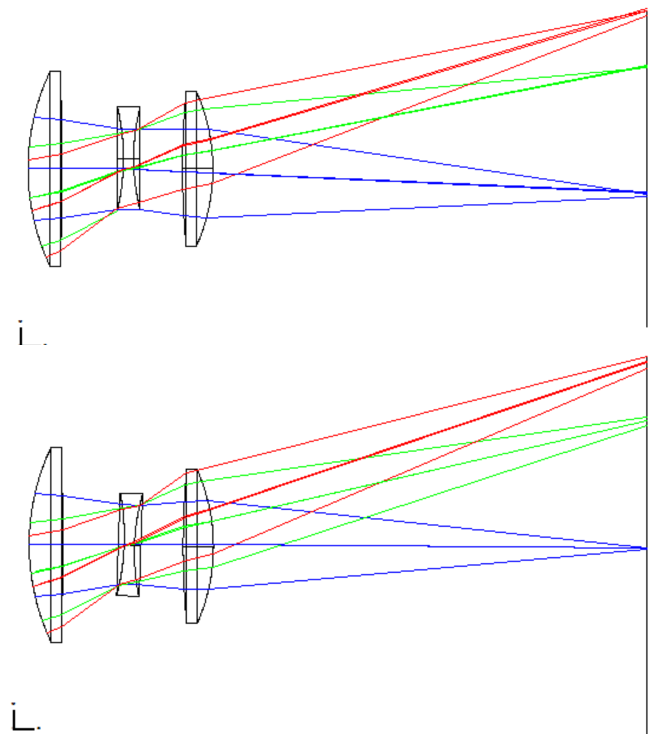
1.5.9.1 Non-Rotationally Symmetric Systems



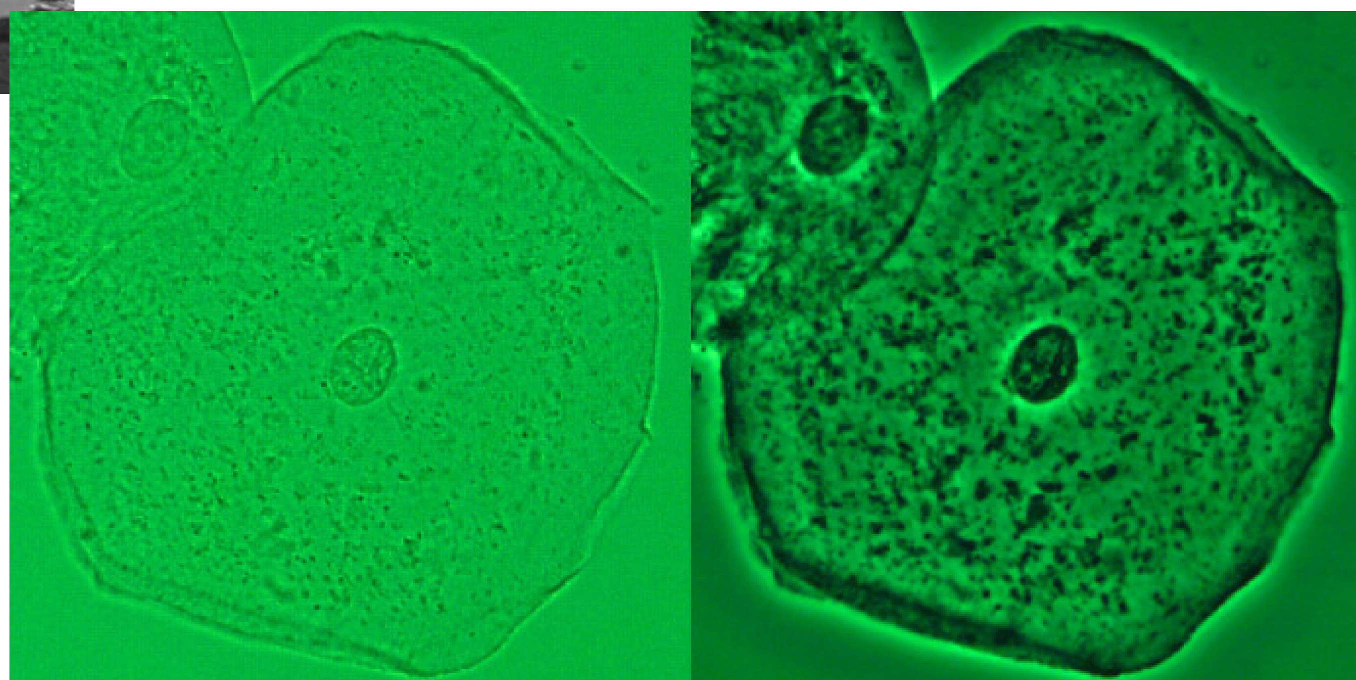
Desmoineseyecare.com

Linhof.de

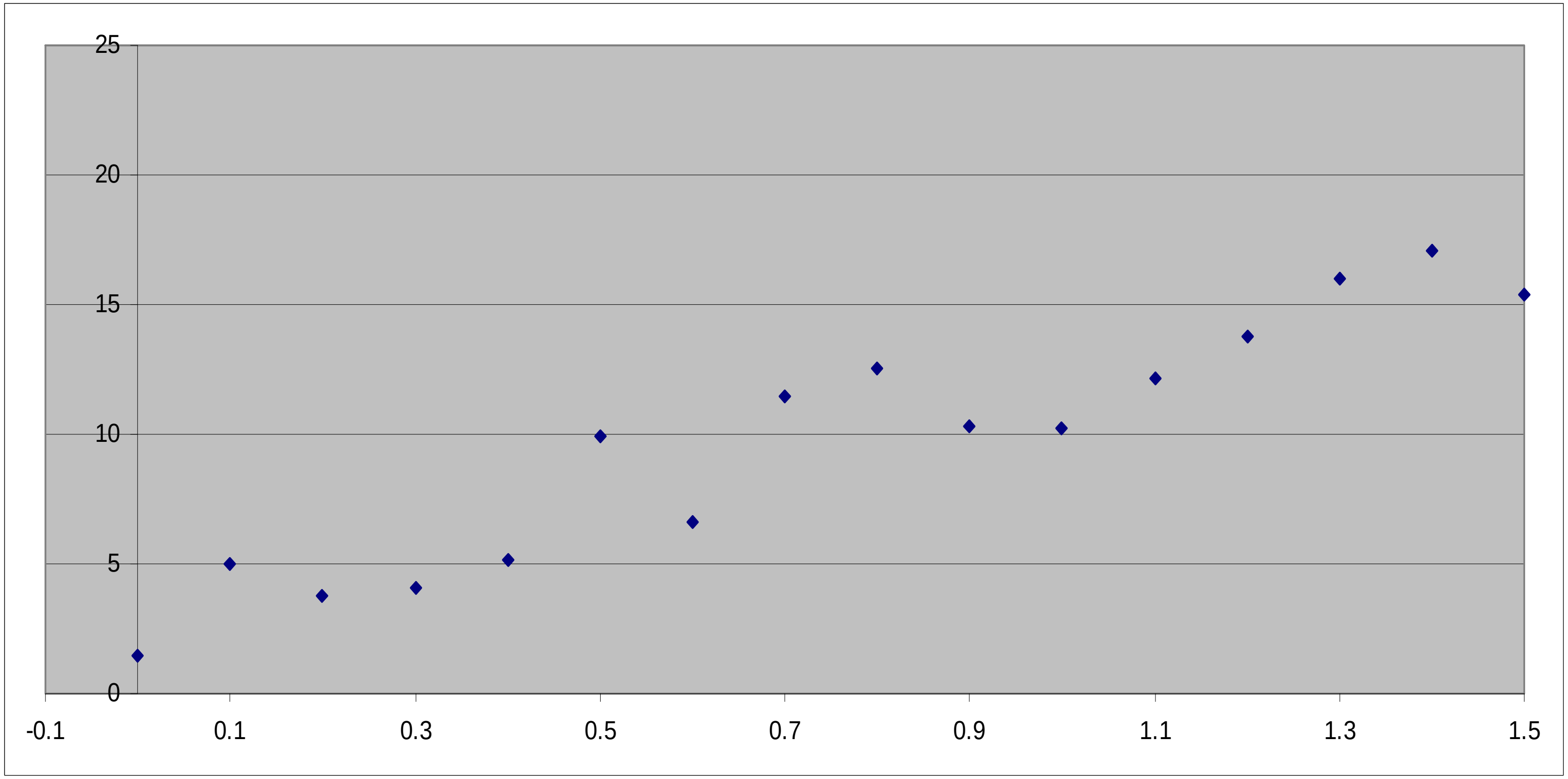




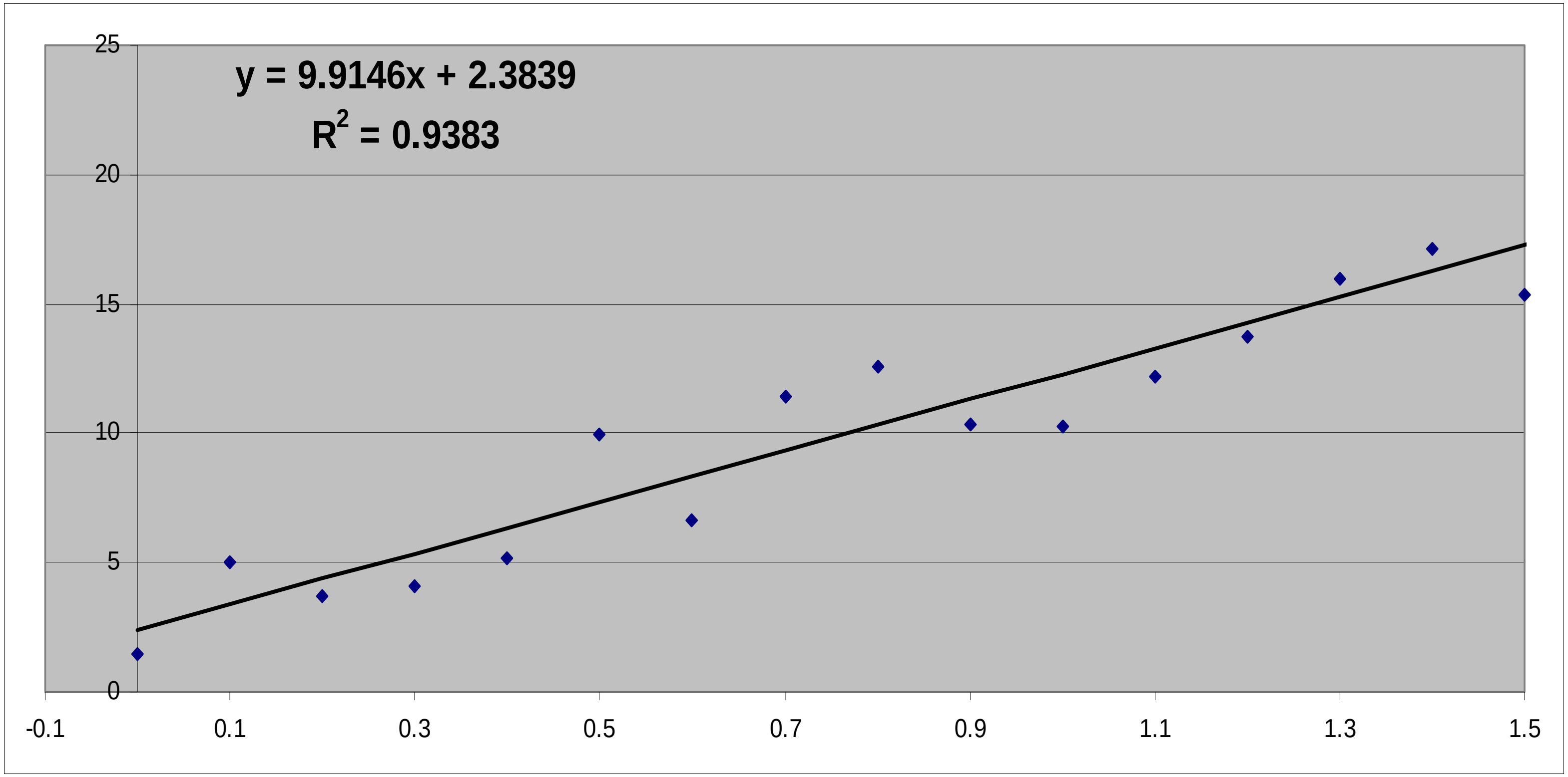
1.5.9.3 Zernike Polynomials



1D Curve Fitting

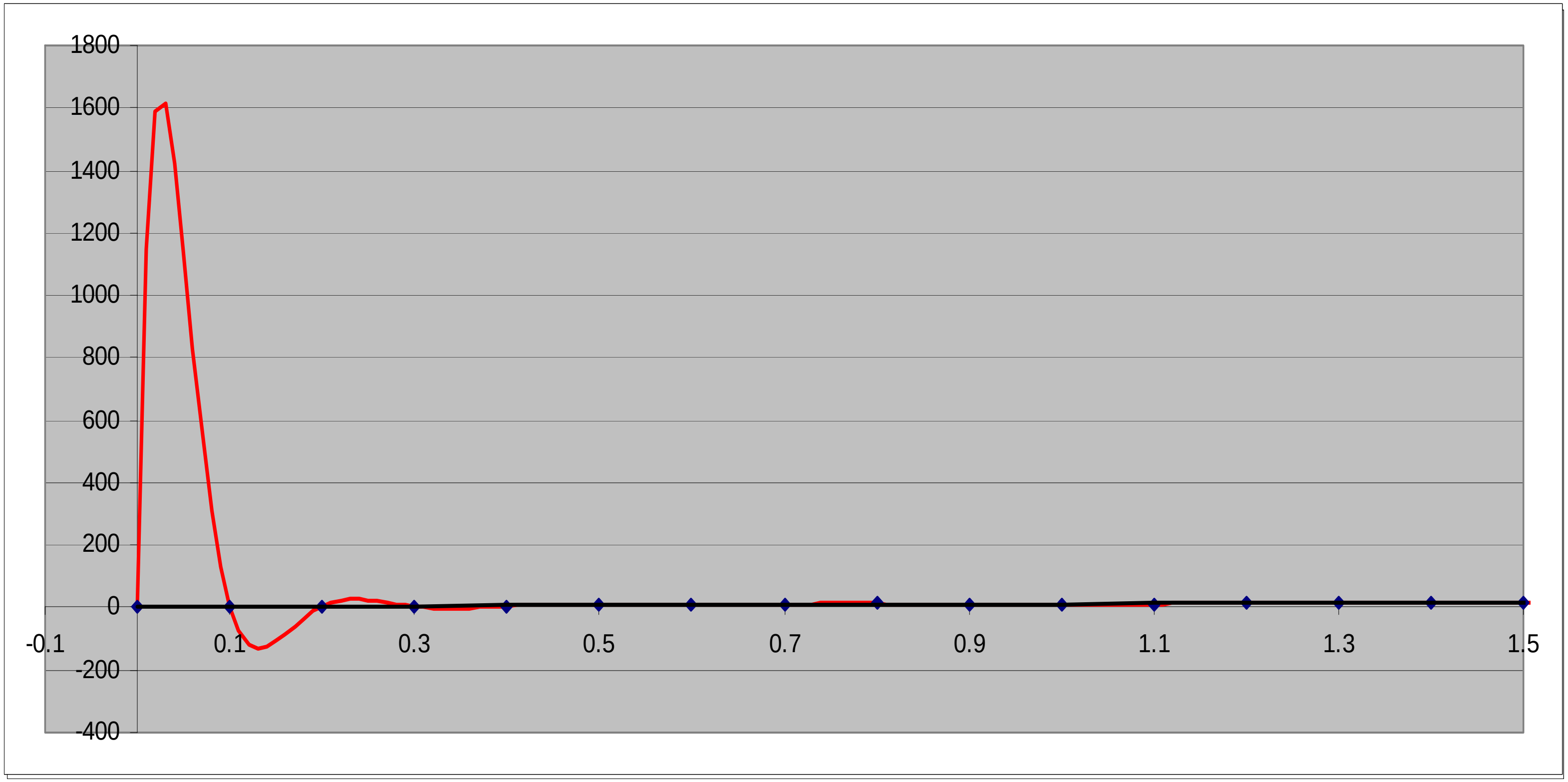


Low-order Polynomial Fit



In this case, the error is the vertical distance between the line and the data point. The sum of the squares of the error is minimized.

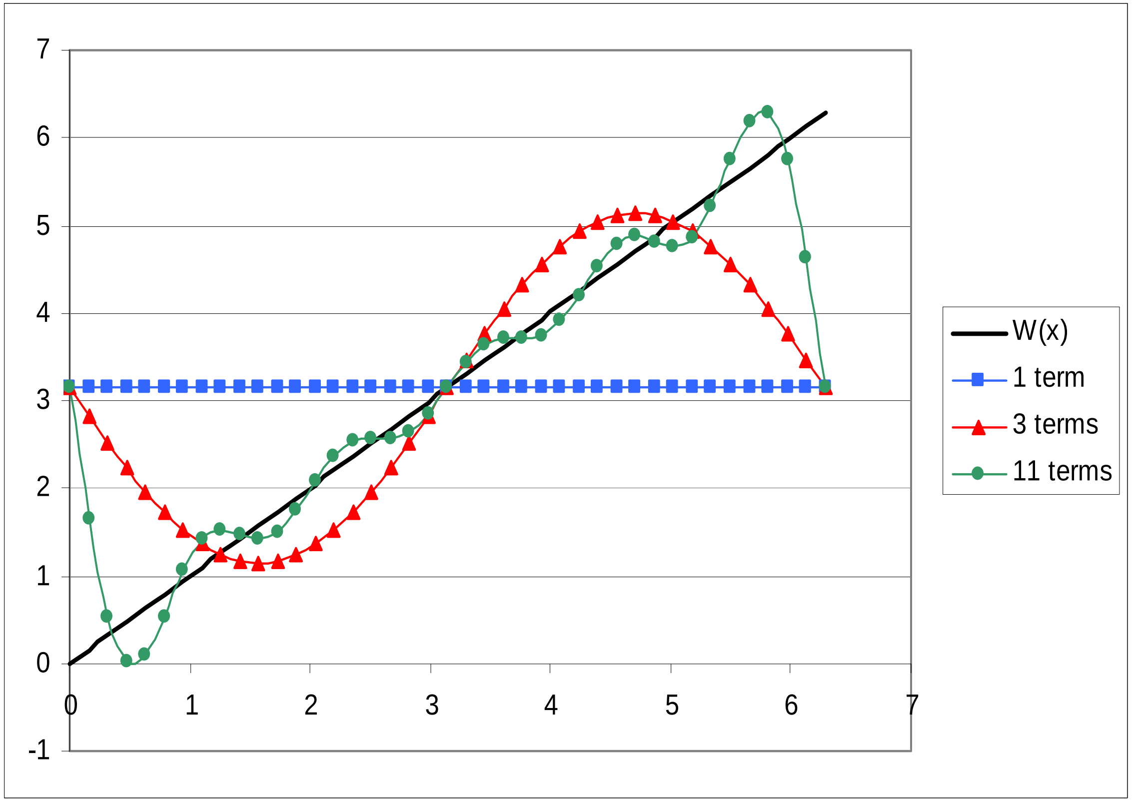
High-order Polynomial Fit



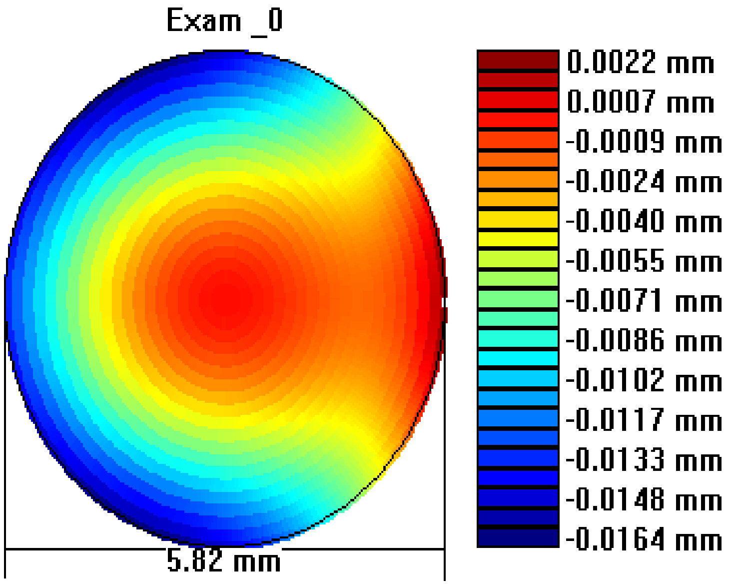
$$y = a_0 + a_1x + a_2x^2 + \ldots\ a_{16}x^{16}$$

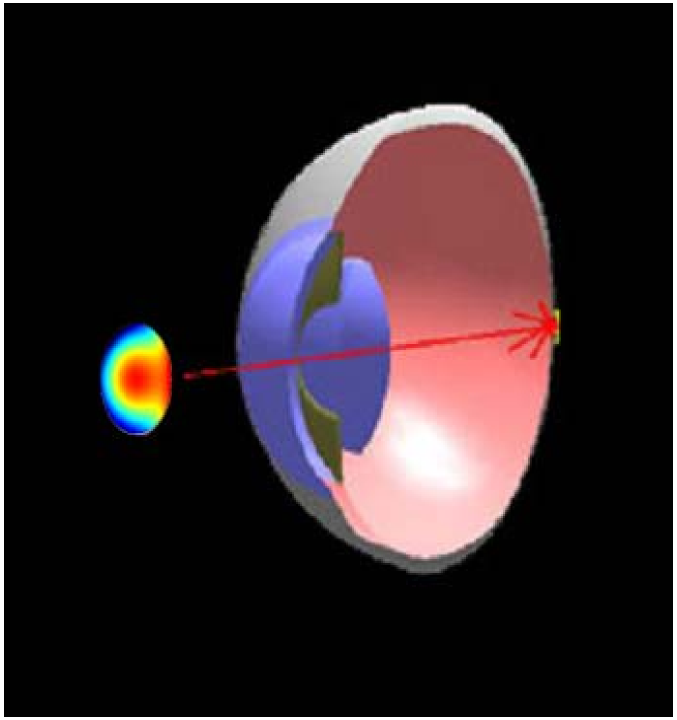
Fit to W(x) = x

j	a_j
0	π
1	-2
2	0
3	-1
4	0
5	-0.6666
6	0
7	-0.5
8	0
9	-0.4
10	0



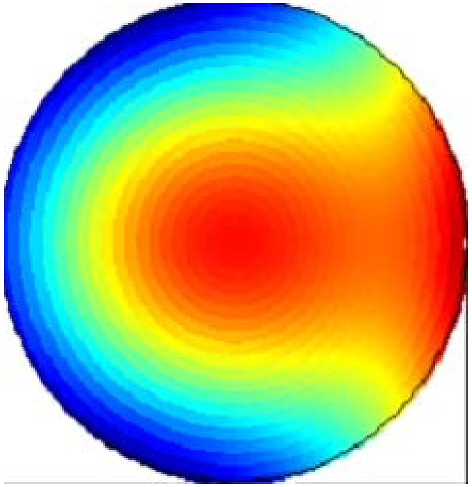
Extension to Two Dimensions





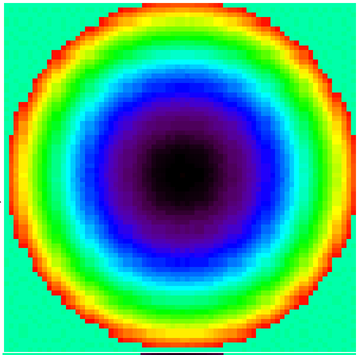
In many cases, wavefronts take on a complex shape defined over a circular region and we wish to fit this surface to a series of simpler components.

Wavefront Fitting

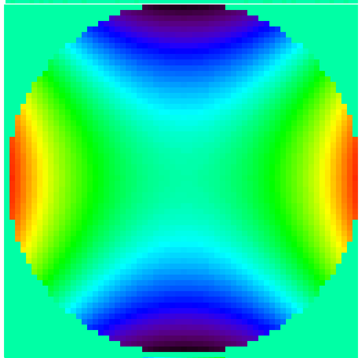


=

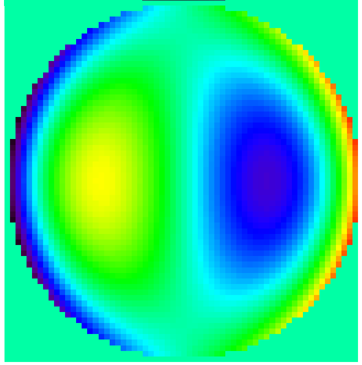
-0.003 x



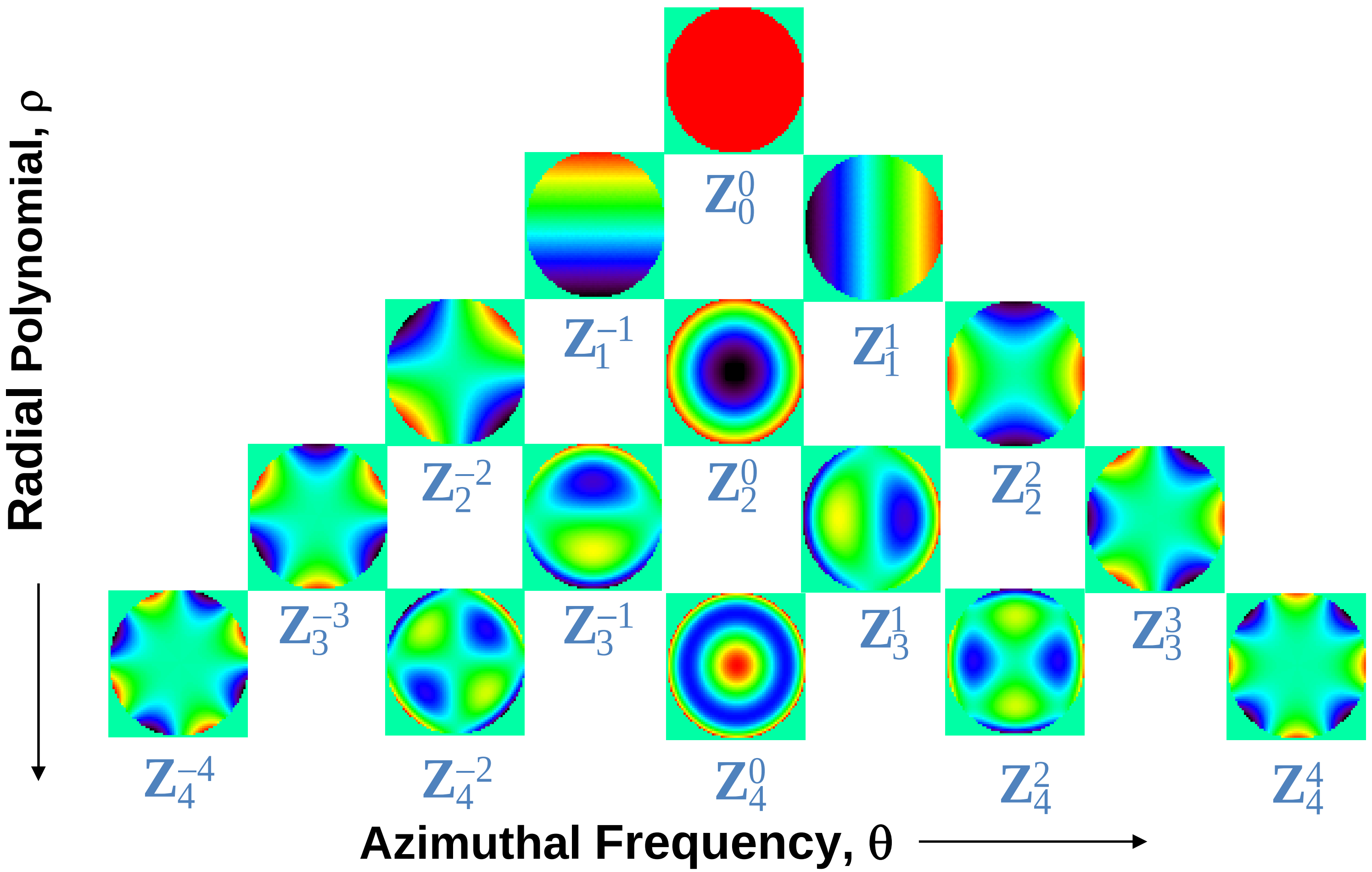
+ 0.002 x



+ 0.001 x



Zernike Polynomials

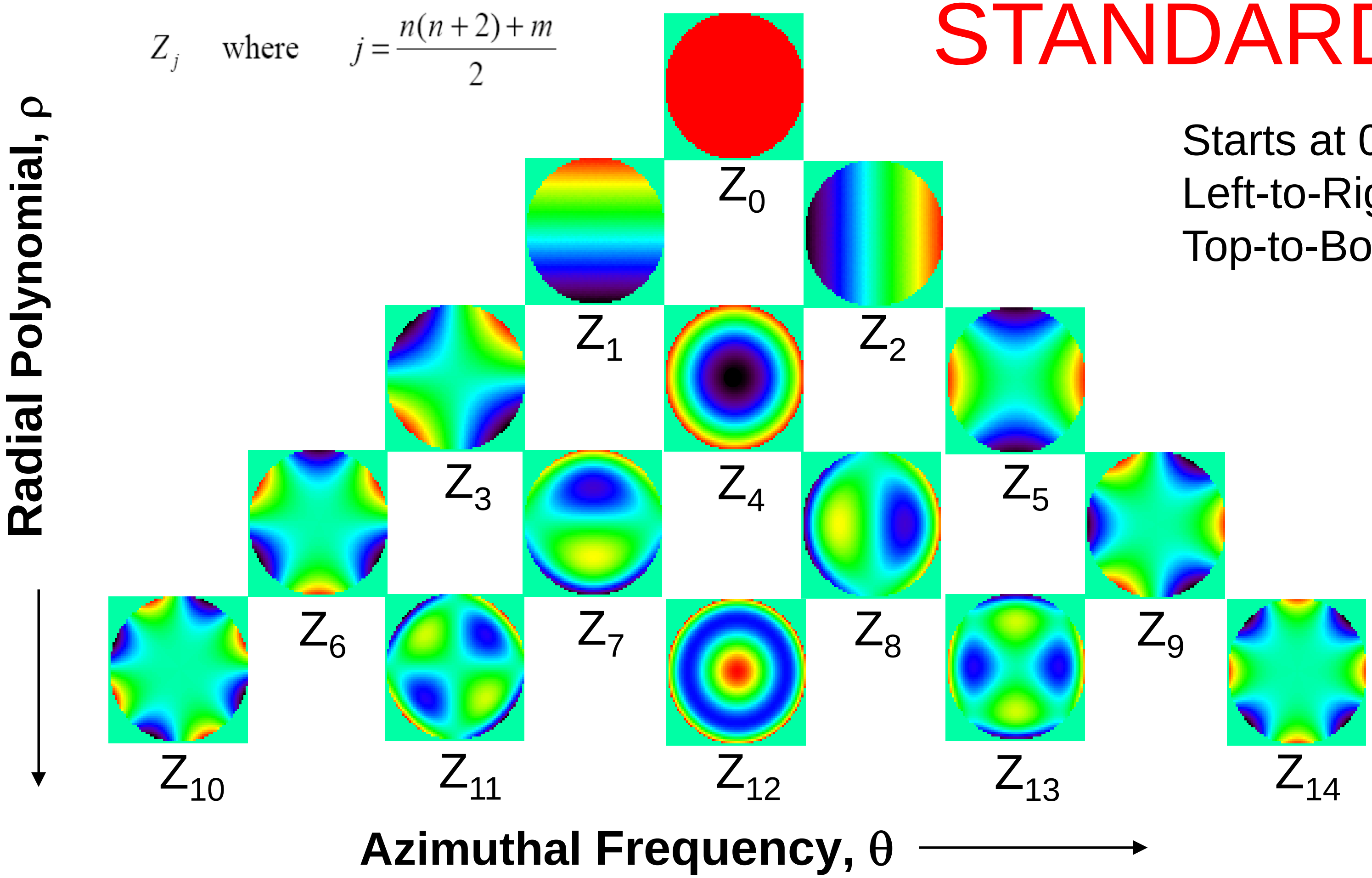


Zernike Polynomials - Single Index

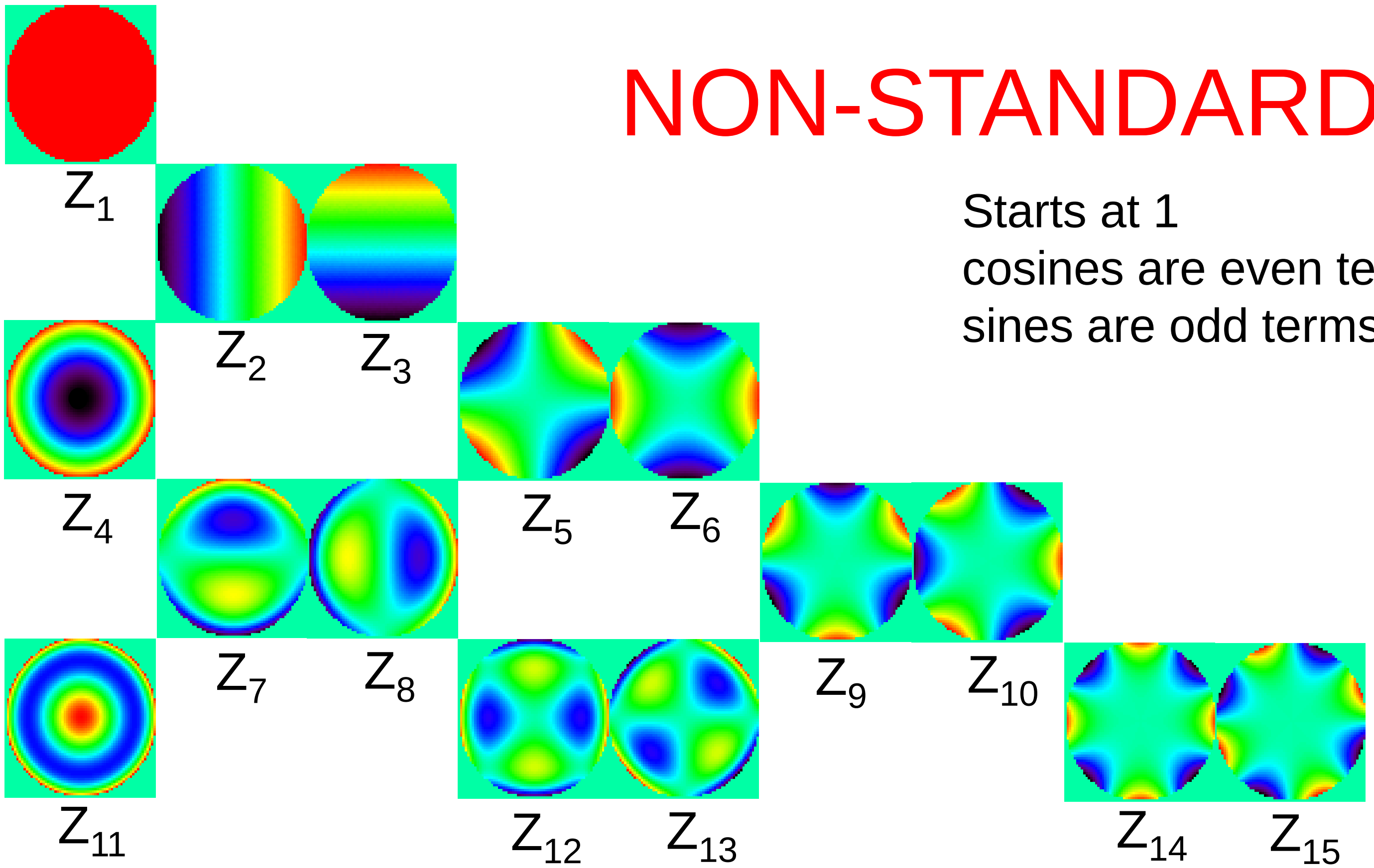
ANSI STANDARD

Z_j where $j = \frac{n(n+2)+m}{2}$

Starts at 0
Left-to-Right
Top-to-Bottom



Other Single Index Schemes



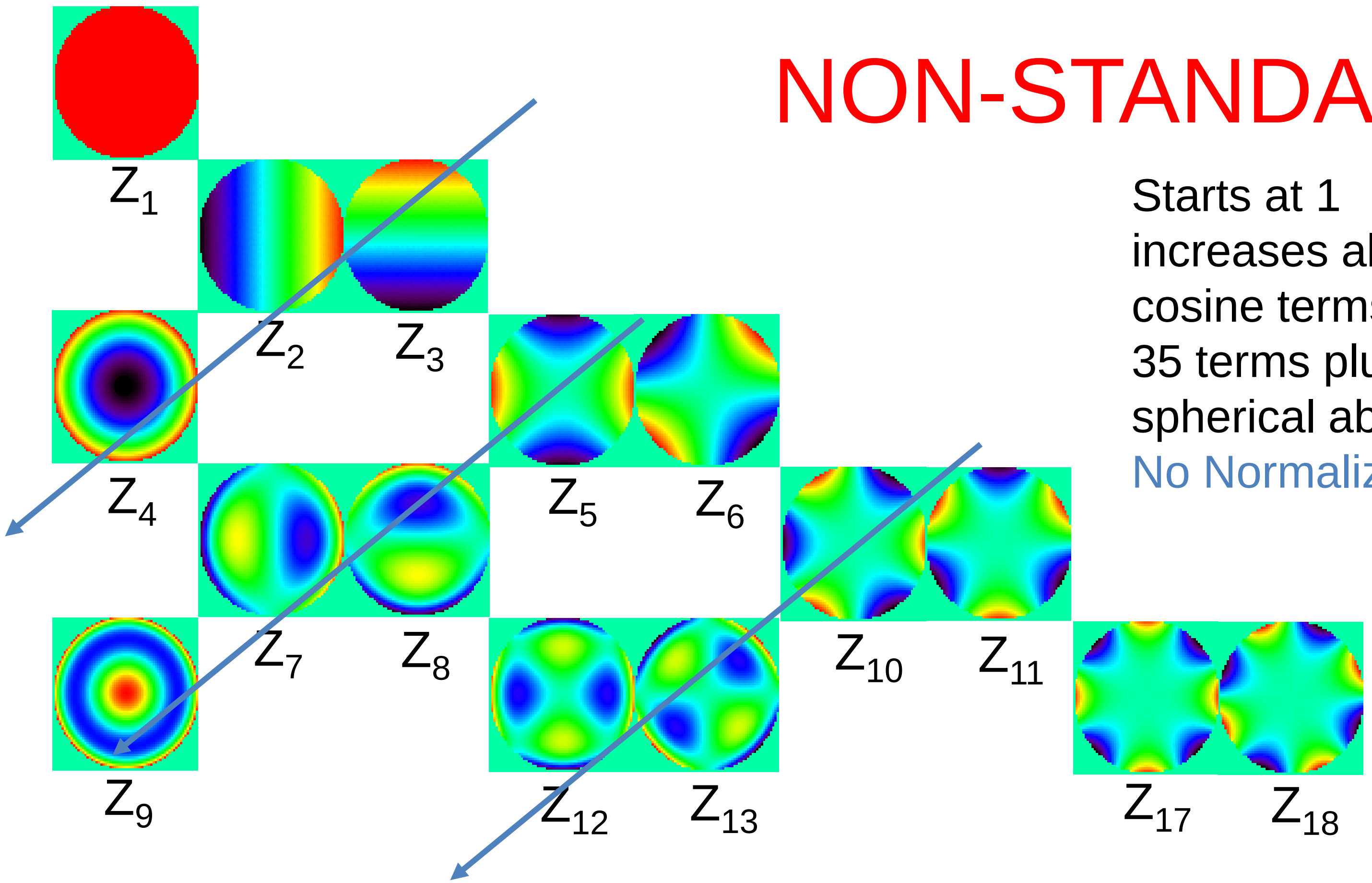
NON-STANDARD

Starts at 1
cosines are even terms
sines are odd terms

Noll, RJ. Zernike polynomials and atmospheric turbulence. J Opt Soc Am 66; 207-211 (1976).

Also Mahajan and Zemax “Standard Zernike Coefficients”

Other Single Index Schemes



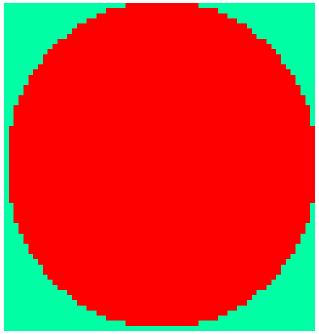
NON-STANDARD

Starts at 1
increases along diagonal
cosine terms first
35 terms plus two extra
spherical aberration terms.
No Normalization!!!

Zemax “Zernike Fringe Coefficients”

Also, Air Force or University of Arizona

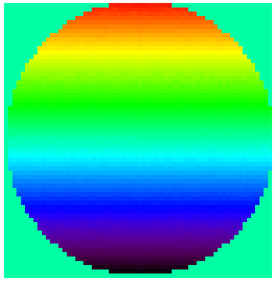
Zeroth Order Zernike Polynomials



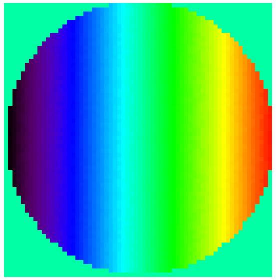
Z_0^0

This term is called Piston and is usually ignored. The surface is constant over the entire circle, so no error or variance exists.

First Order Zernike Polynomials



$$Z_1^{-1}$$



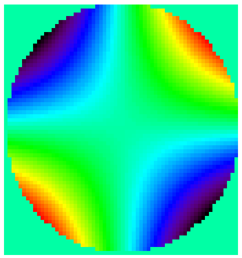
$$Z_1^1$$

These terms represent a tilt in the wavefront.

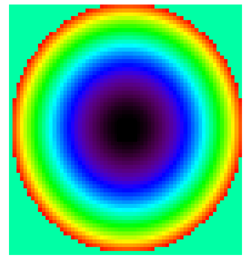
Combining these terms results in a general equation for a plane, thus by changing the coefficients, a plane at any orientation can be created. This rotation of the pattern is true for the sine/cosine pairs of Zernikes

$$a_{1-1}Z_1^{-1}(\rho,\theta)+a_{11}Z_1^1(\rho,\theta)$$
$$=a_{1-1}\rho\sin\theta+a_{11}\rho\cos\theta$$
$$=a_{1-1}\frac{y}{r_{max}}+a_{11}\frac{x}{r_{max}}$$

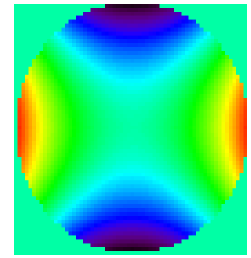
Second Order Zernike Polynomials



Z_2^{-2}



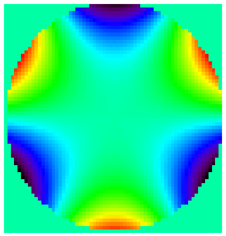
Z_2^{0}



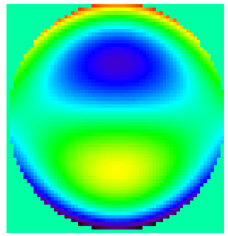
Z_2^{2}

Z(2,0) is a paraboloid, so it represents defocus. Z(2,2) and Z(2,-2) are saddle shaped surfaces rotated 45 degrees to one another. Much like tilt, appropriate weighting of these two terms can create a saddle shape rotated through any angle.

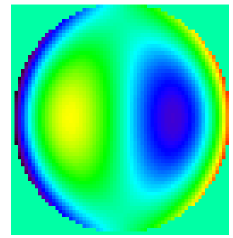
Third Order Zernike Polynomials



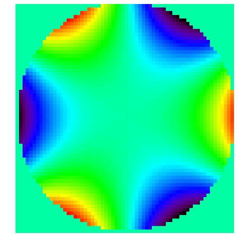
$\mathbf{Z}_3^{-3}$



$\mathbf{Z}_3^{-1}$



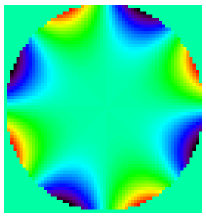
$\mathbf{Z}_3^{1}$



$\mathbf{Z}_3^{3}$

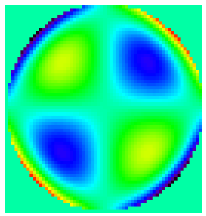
The inner two terms are coma and the outer two terms are trefoil.
These terms represent asymmetric.

Fourth Order Zernike Polynomials



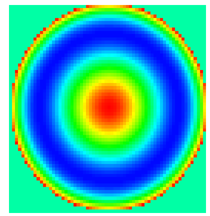
Z_4^{-4}

Quadroil



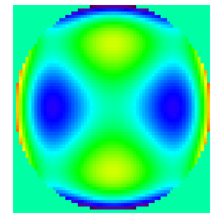
Z_4^{-2}

4th order Astigmatism



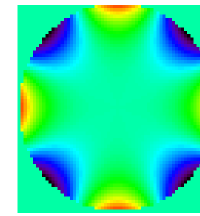
Z_4^{0}

Spherical Aberration



Z_4^{2}

4th order Astigmatism

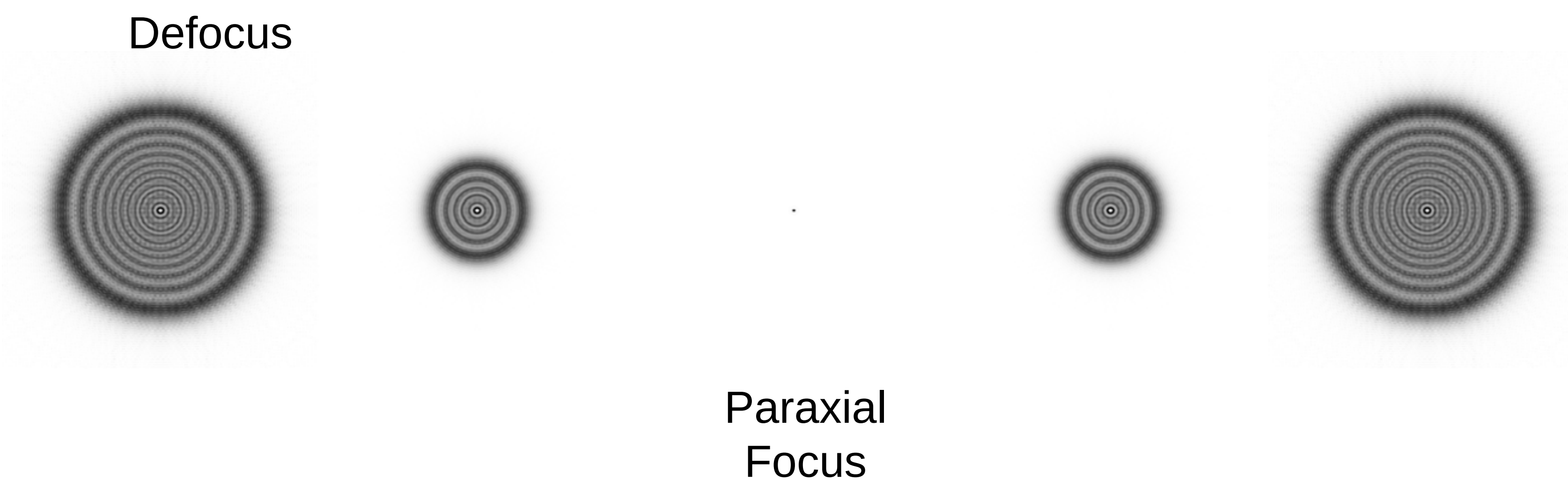


Z_4^{4}

Quadroil

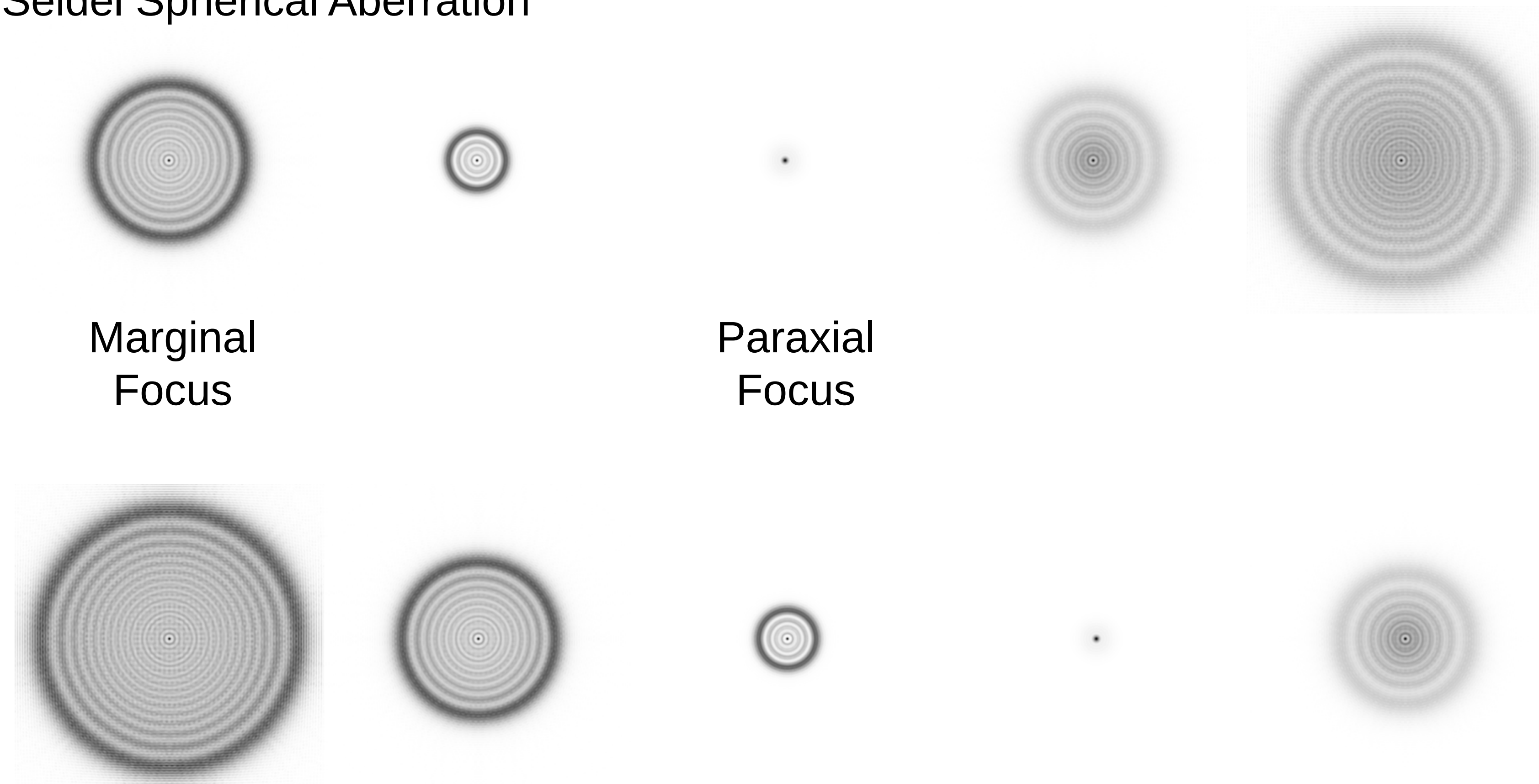
These terms represent more complex shapes of the wavefront.

1.5.10 Through-Focus PSF and the Star Test



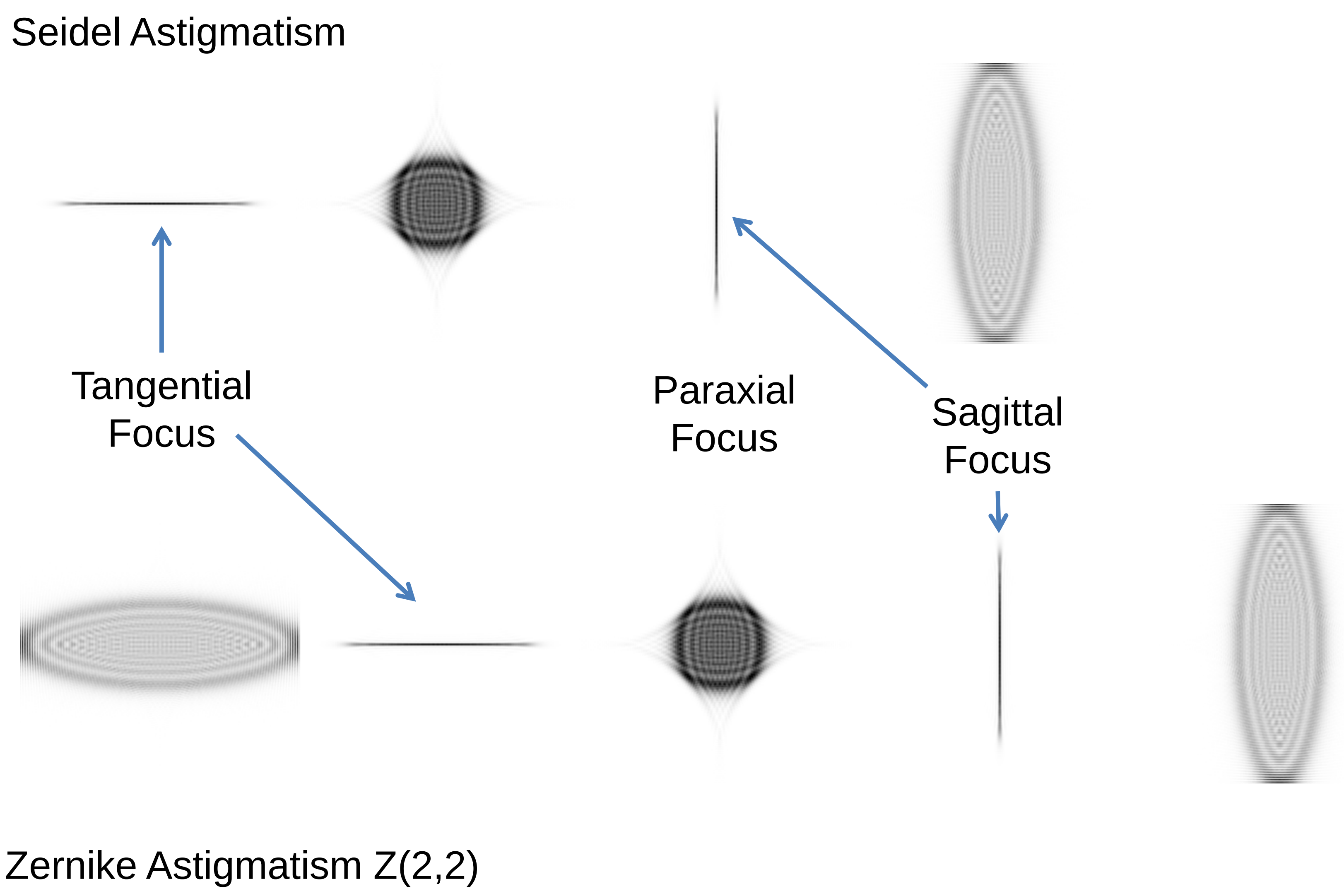
Spherical Aberration

Seidel Spherical Aberration



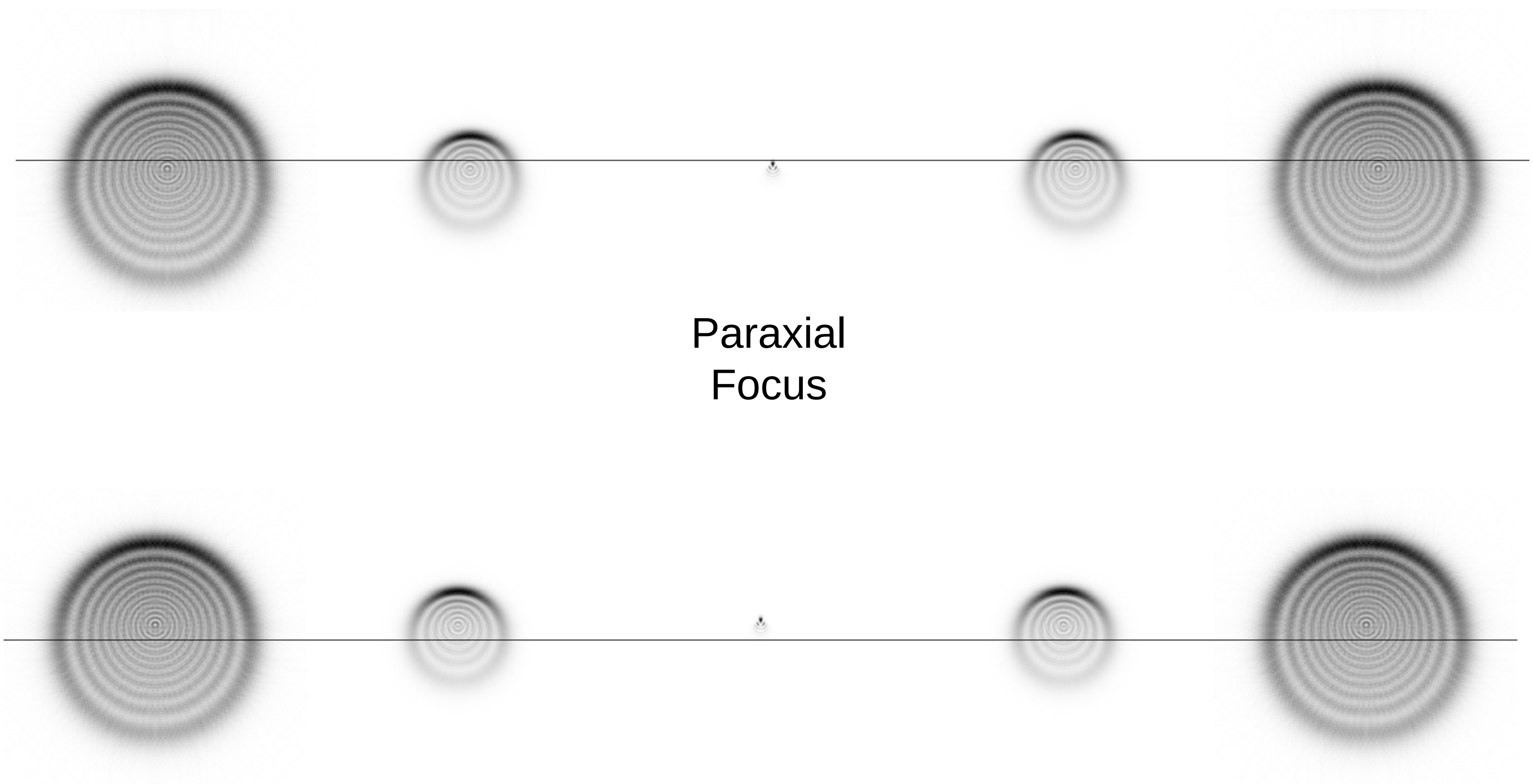
Zernike Spherical Aberration Z(4,0)

Astigmatism



Coma

Seidel Coma

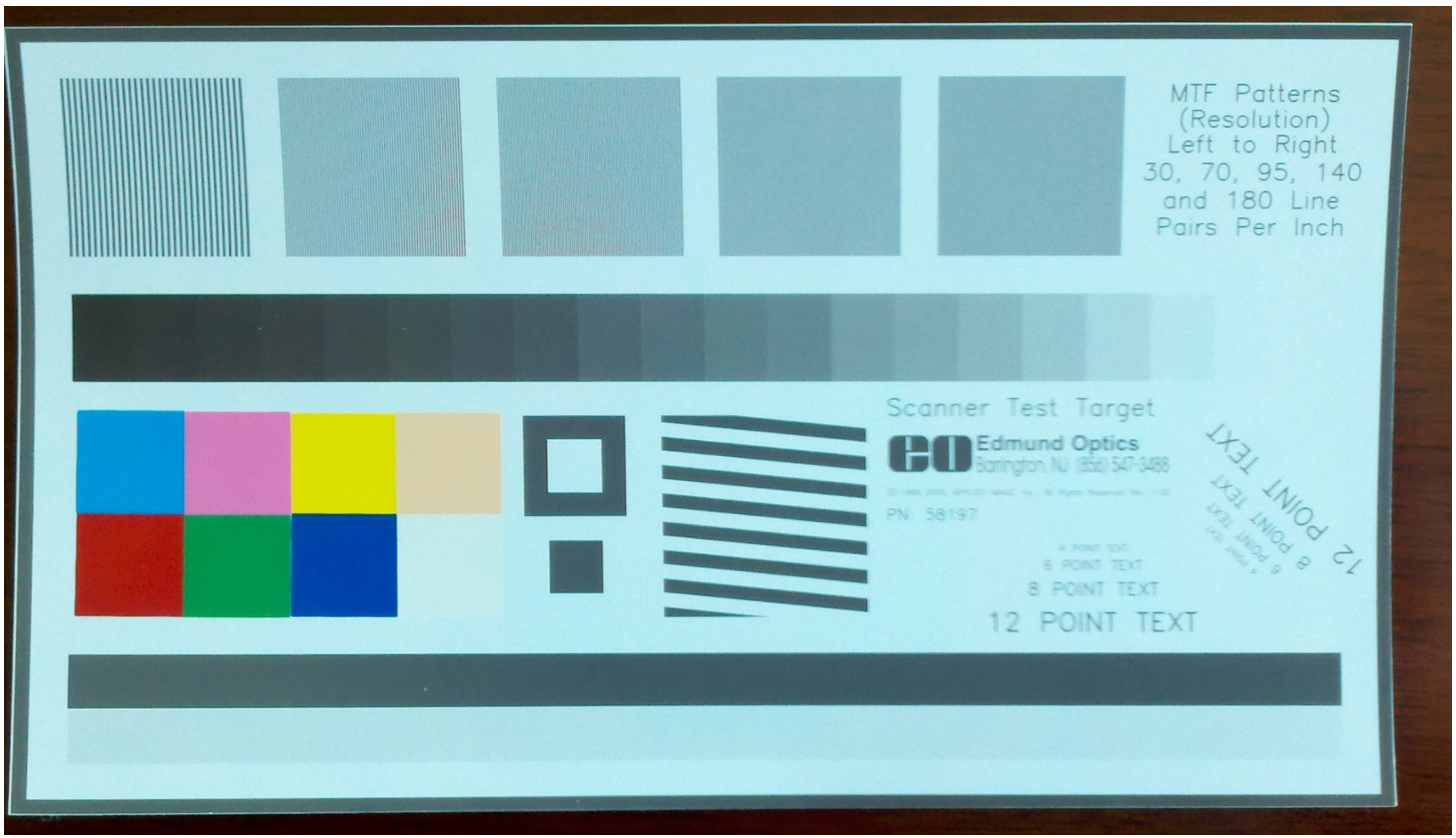


Zernike Coma Z(3,-1)

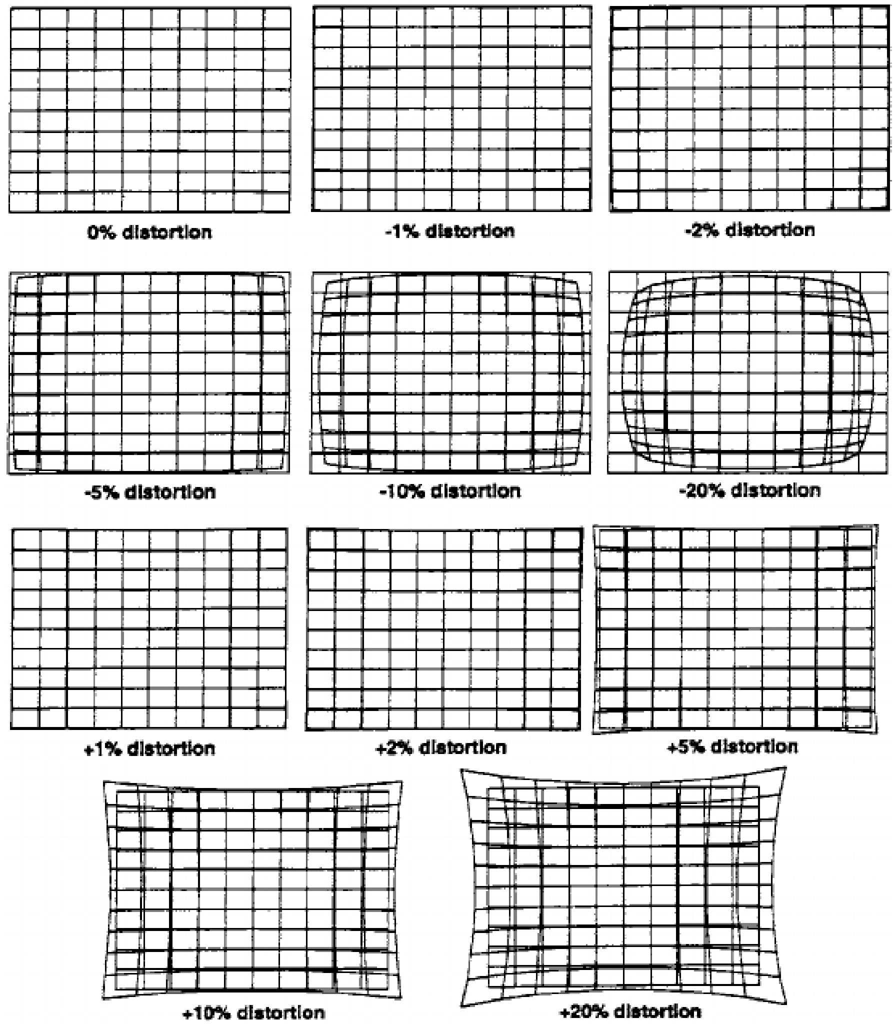
1.5.11 Barrel Distortion

www.recipester.org

Pincushion Distortion



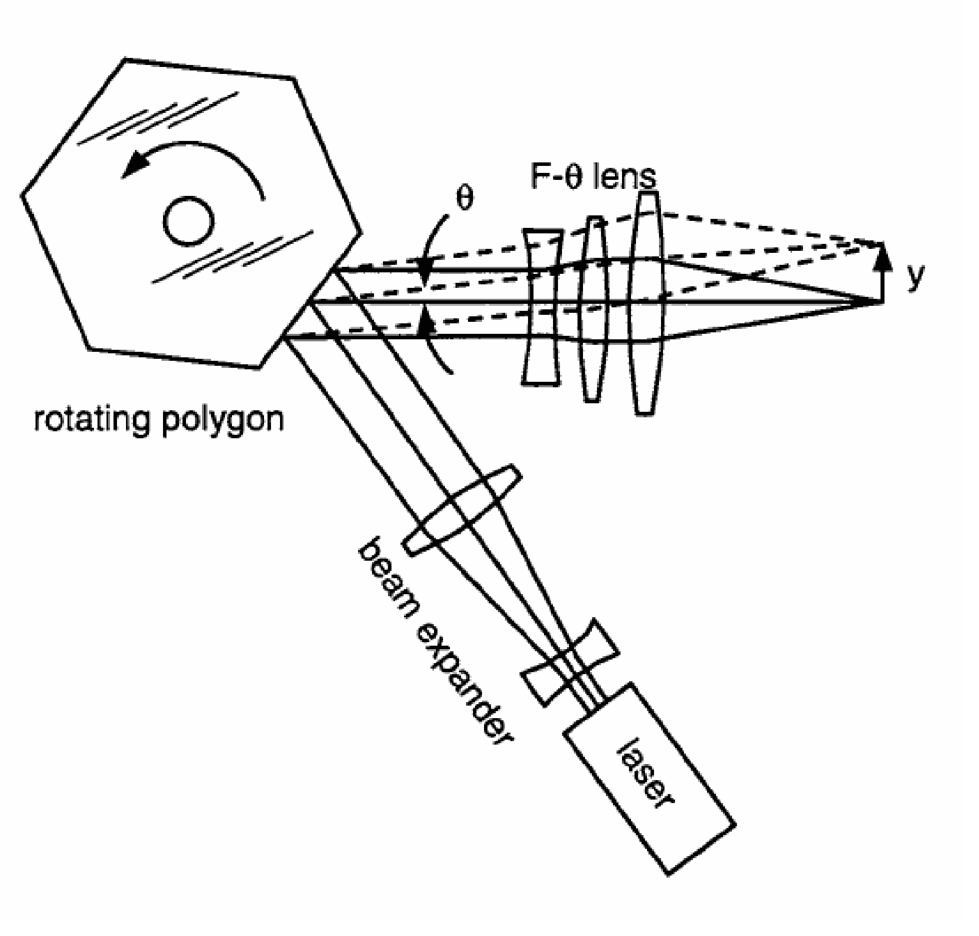
Percent Distortion



Fischer, Optical System Design

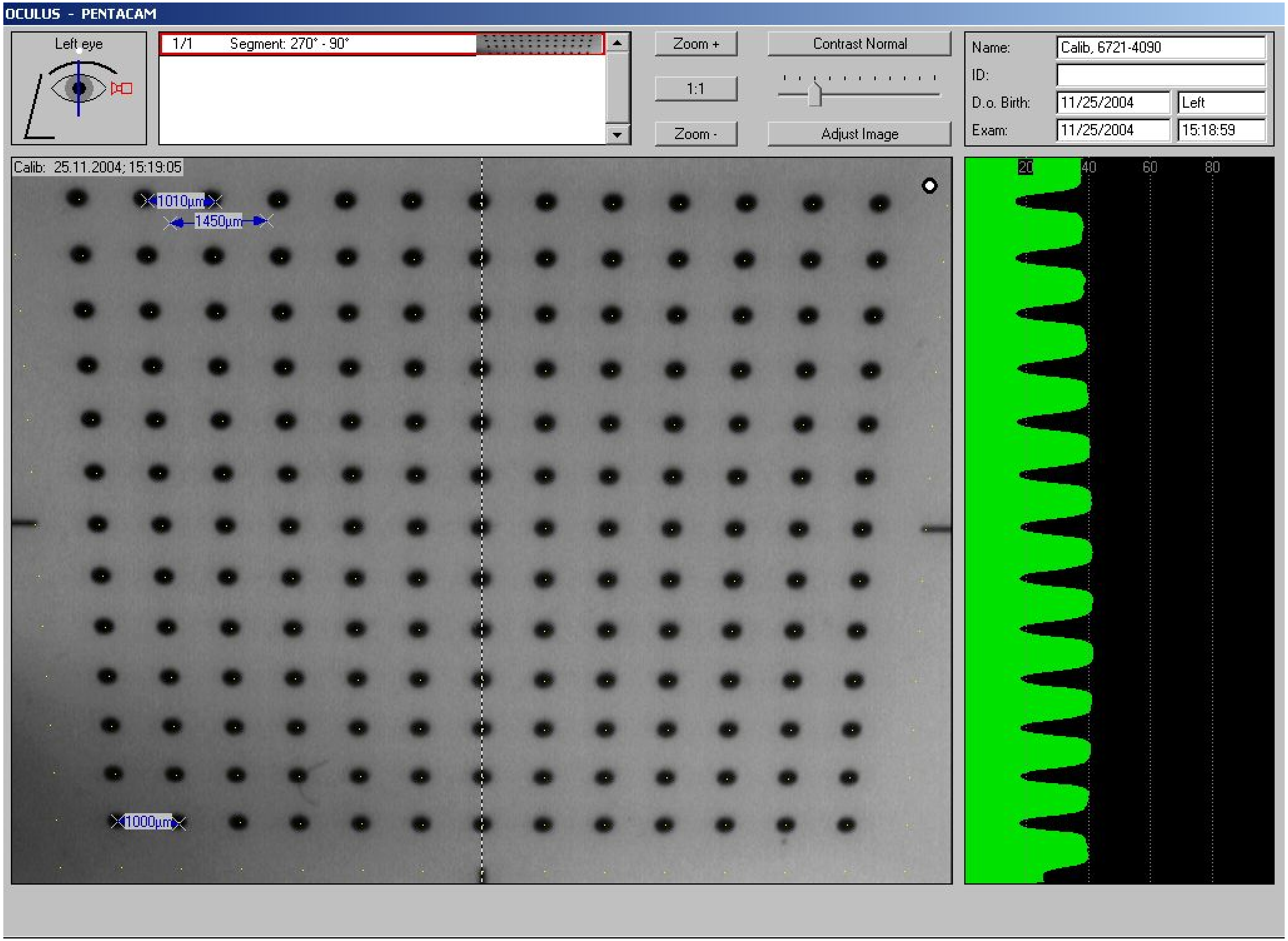
Anamorphic Distortion

F-θ Lens



Fischer, Optical System Design

Keystone Distortion



Keystone Correction

www.lonestardigital.com/perspective_correction.htm

Scheimpflug Imaging

http://users.gsinet.net/pjwhite/tilt-shift.htm