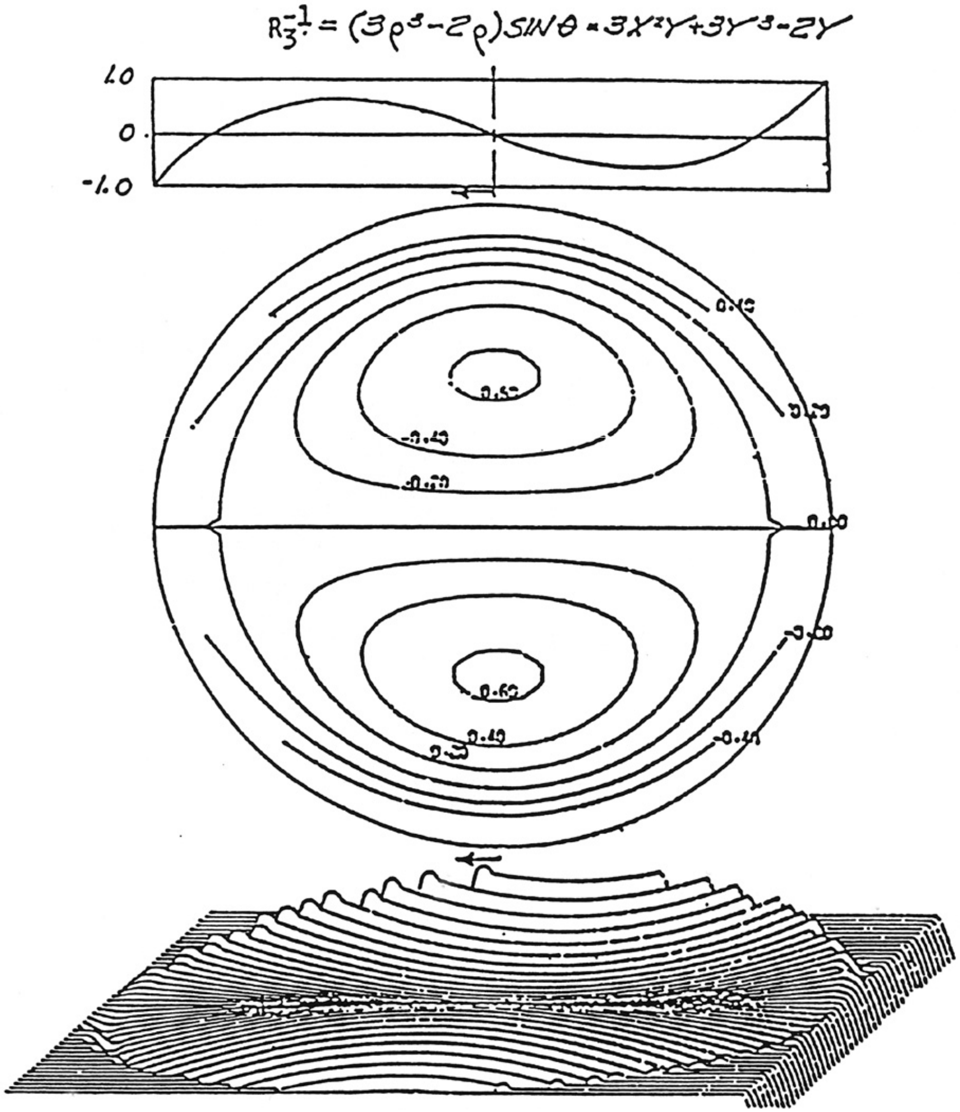
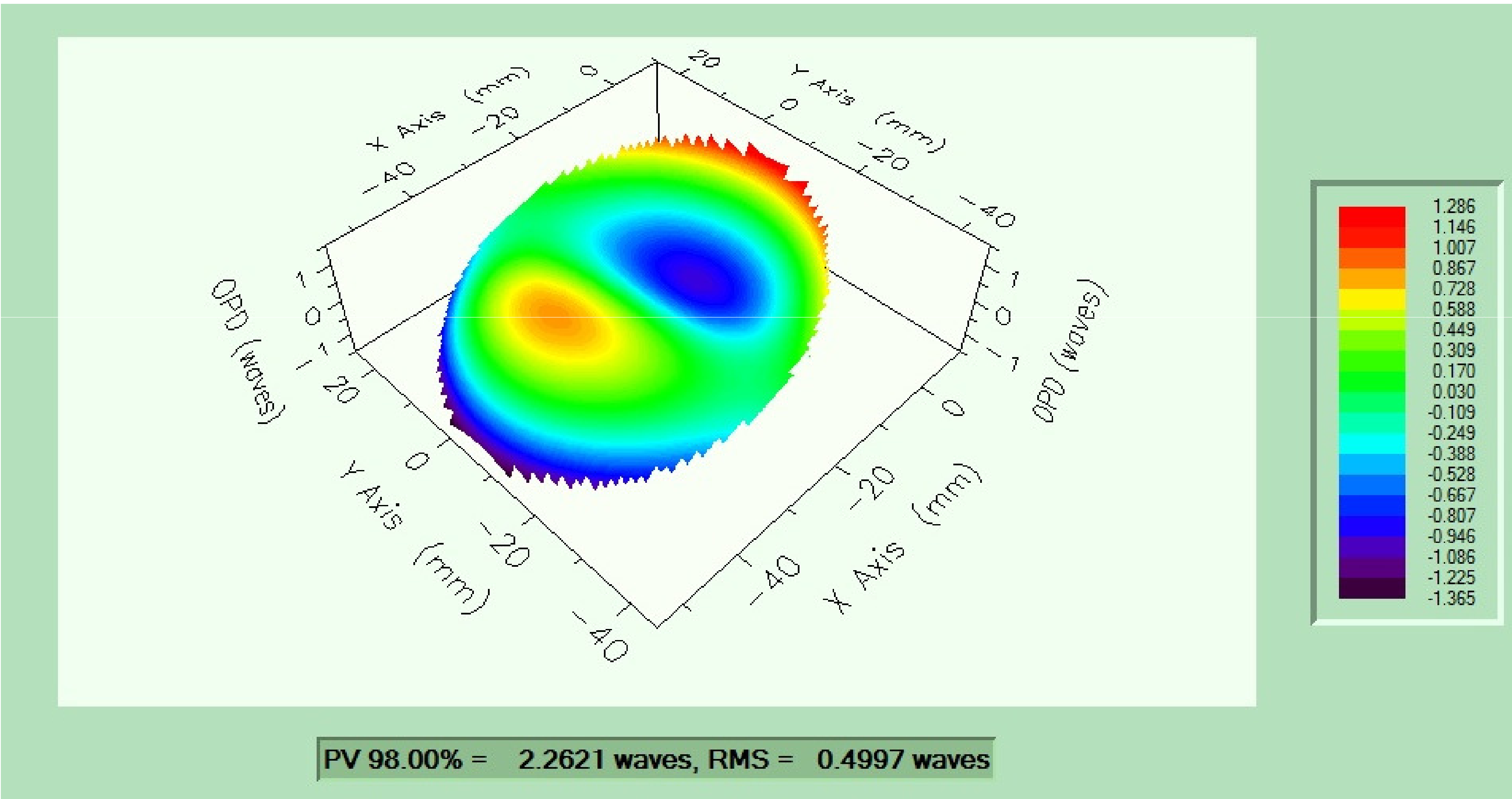
Coma

- Coma is THE misalignment error -- it is nearly always introduced by non-rotationally symmetric misalignment errors
- Mathematically:
  - $W = W_{131} = a_{131} H \rho^3 \cos\theta$
  - Linear with field
  - Non-rotationally symmetric due to $\cos\theta$ term
- Interferometrically:
  - Fairly complex: "D" shaped, "S" shaped, or "Pincushion" contours, depending on the amount and direction of tilt and focus
- Star Test
  - Classic comet shaped image (from whence coma is named)
  - Since the eye can distinguish asymmetries easily, small amounts ($\lambda/10$ or less) can be detected

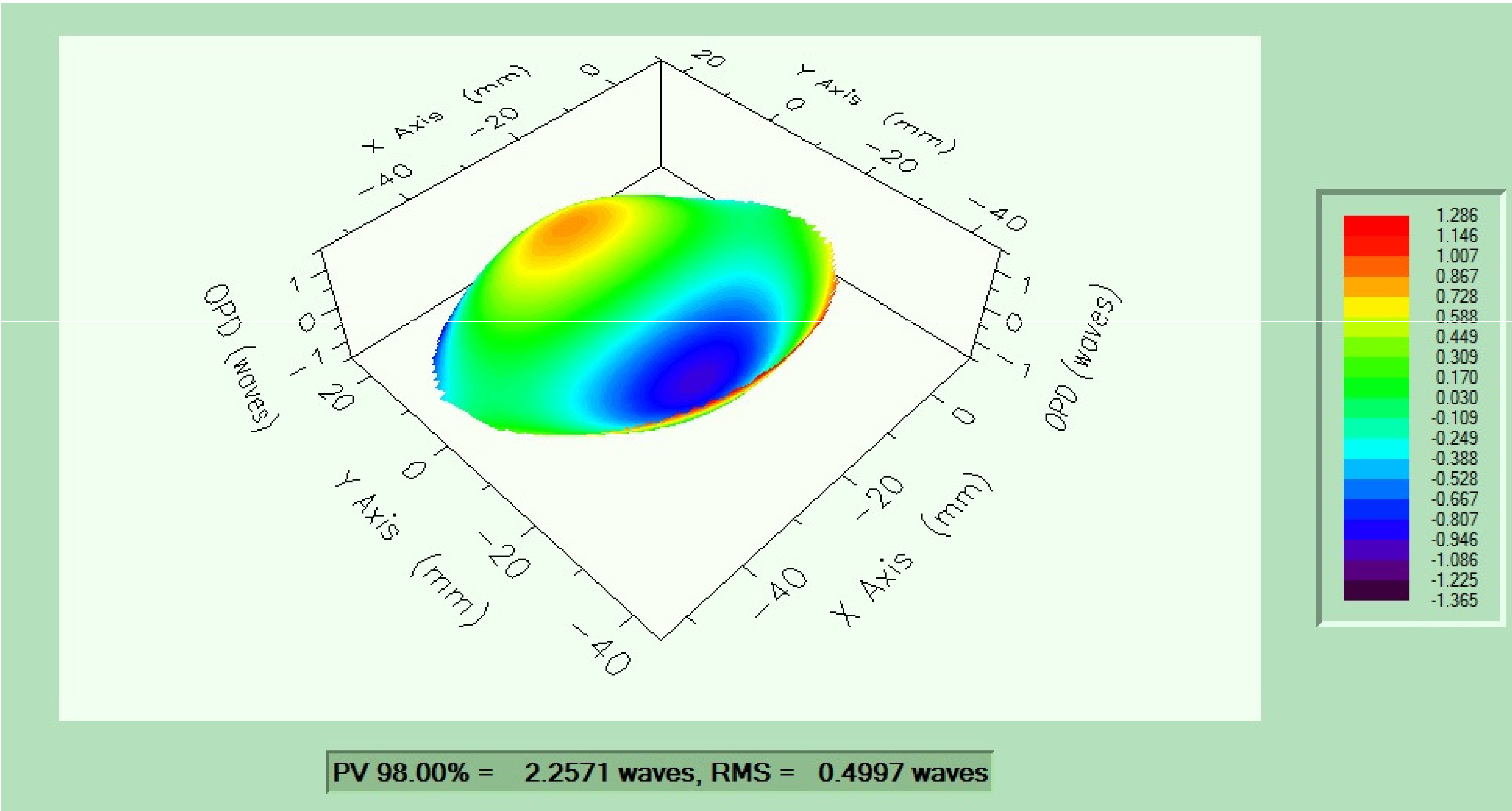
Coma (Best Tilt)



Coma (X Coma – Cos(0°)



Coma (Y Coma – Cos(90°))



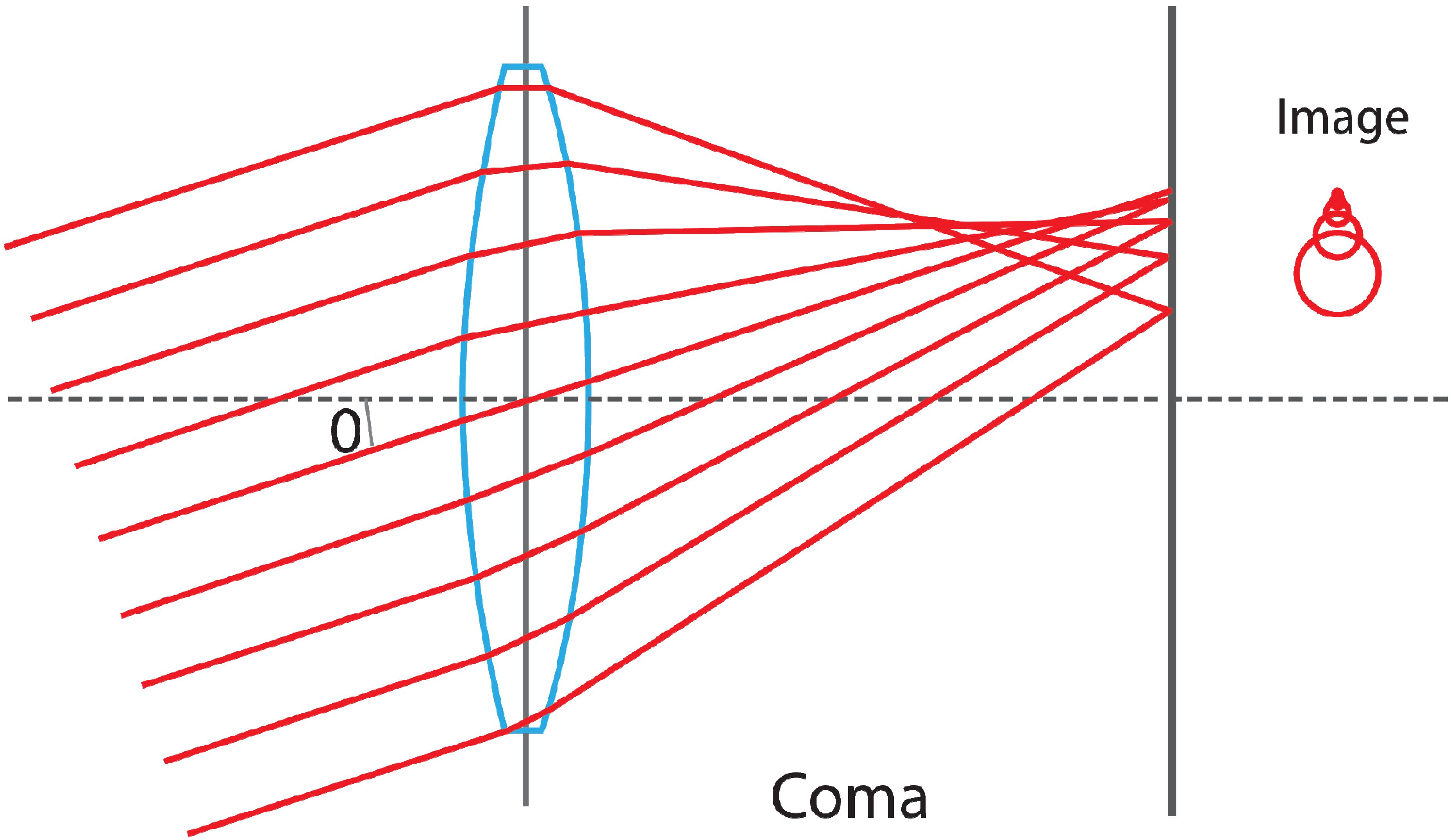
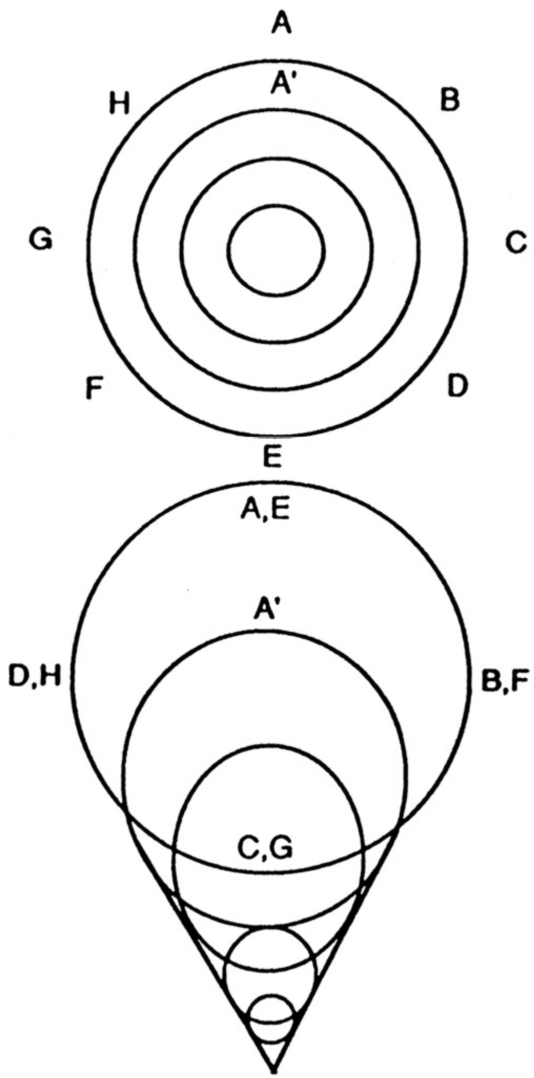


Image
θ
Coma

Coma



Location of points and zones

Comatic image showing location of above points

Interesting Facts

1. Angular rotation, ω, of a point in the pupil is 2ω in the image

2. For 3rd order coma, envelope is a "V" with a 60º angle

3. Circles in image often represent zones on the optics. An alignment trick is to defocus image, make rings concentric, and refocus

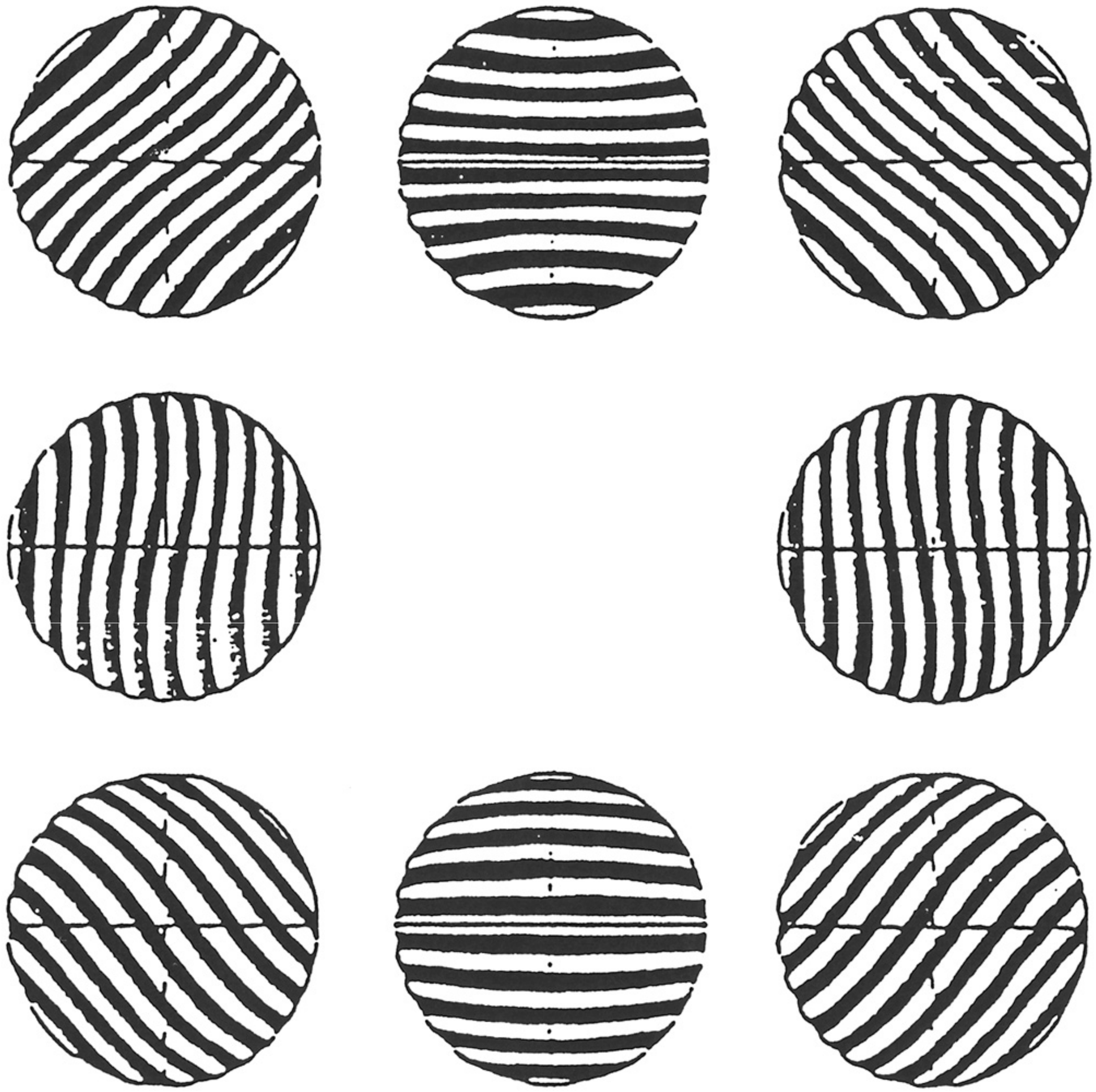
Small Amounts of Coma

- Diffraction blur dominates
- Lopsided energy distribution in rings is easy to detect*
- When defocused, asymmetric diffraction rings are present

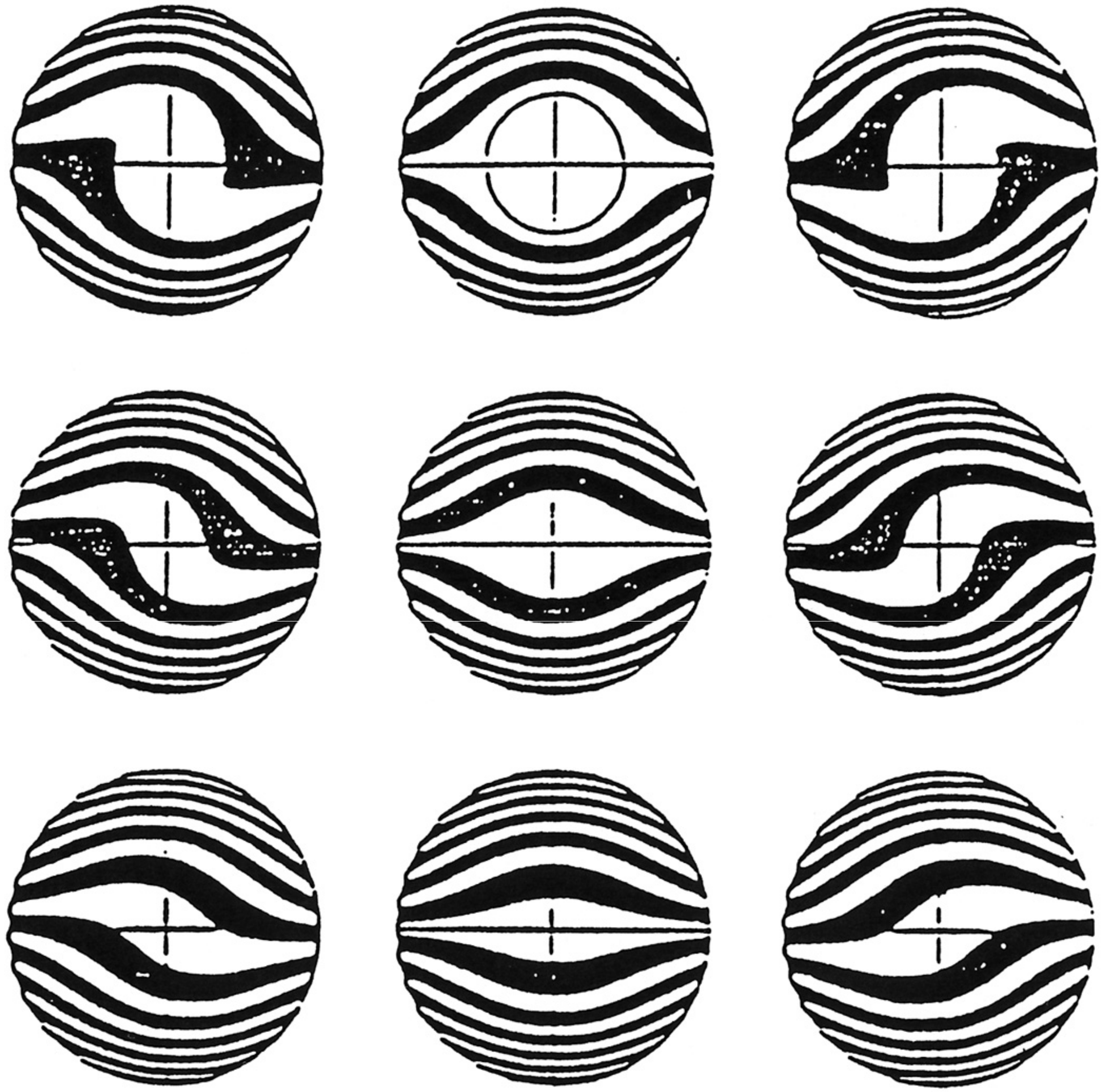
*However, as coma is further reduced, the asymmetry is difficult to detect because it gets lost in the intensity of the central core of the Airy disk. Another technique is thus required.

Large Amounts of Coma

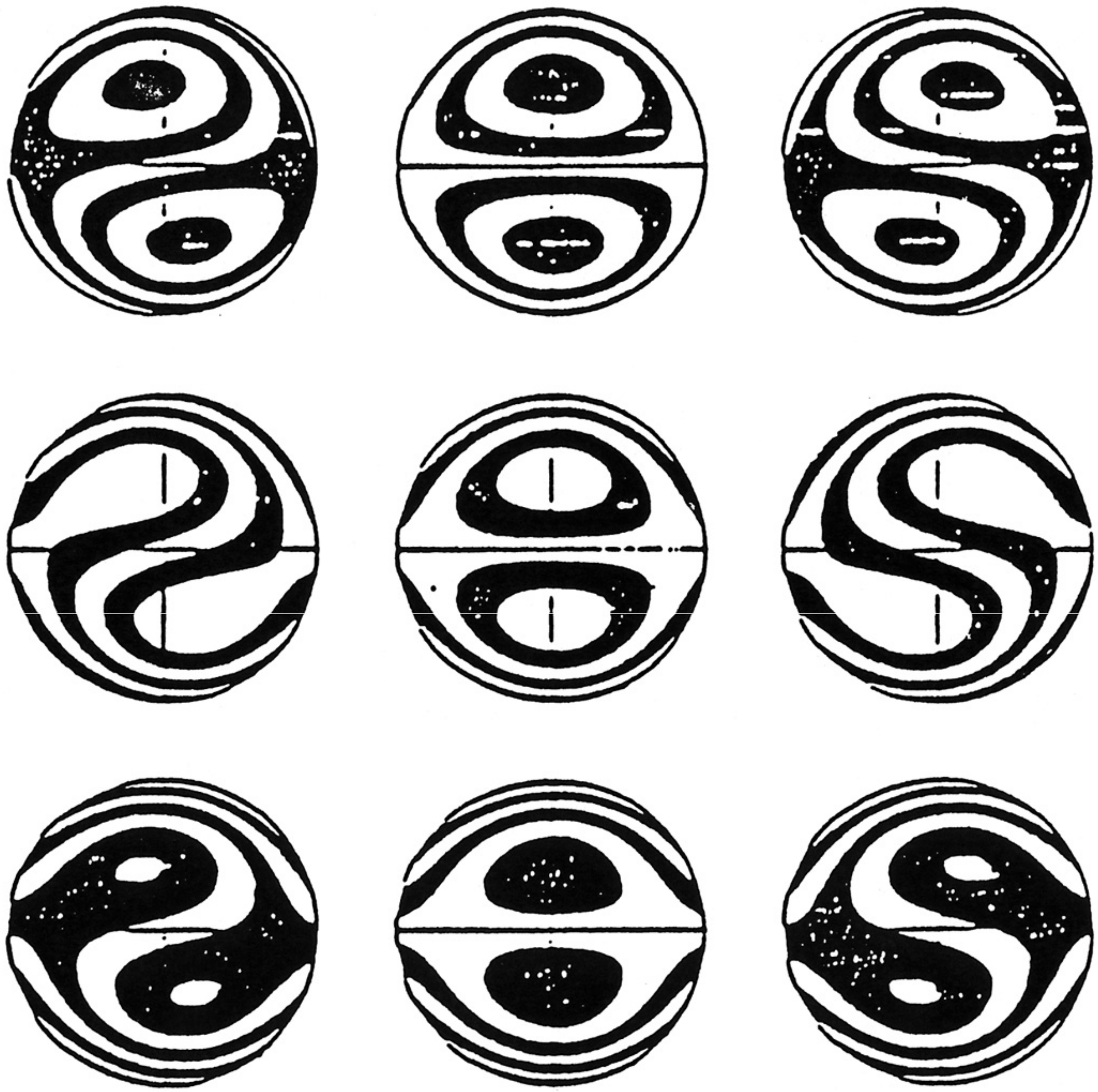
- Looks like a comet
- Apex angle = 60º
- Tip corresponds to paraxial focus
- Geometric blur dominates diffraction blur



Twyman-Green Interferograms, small coma, large tilt

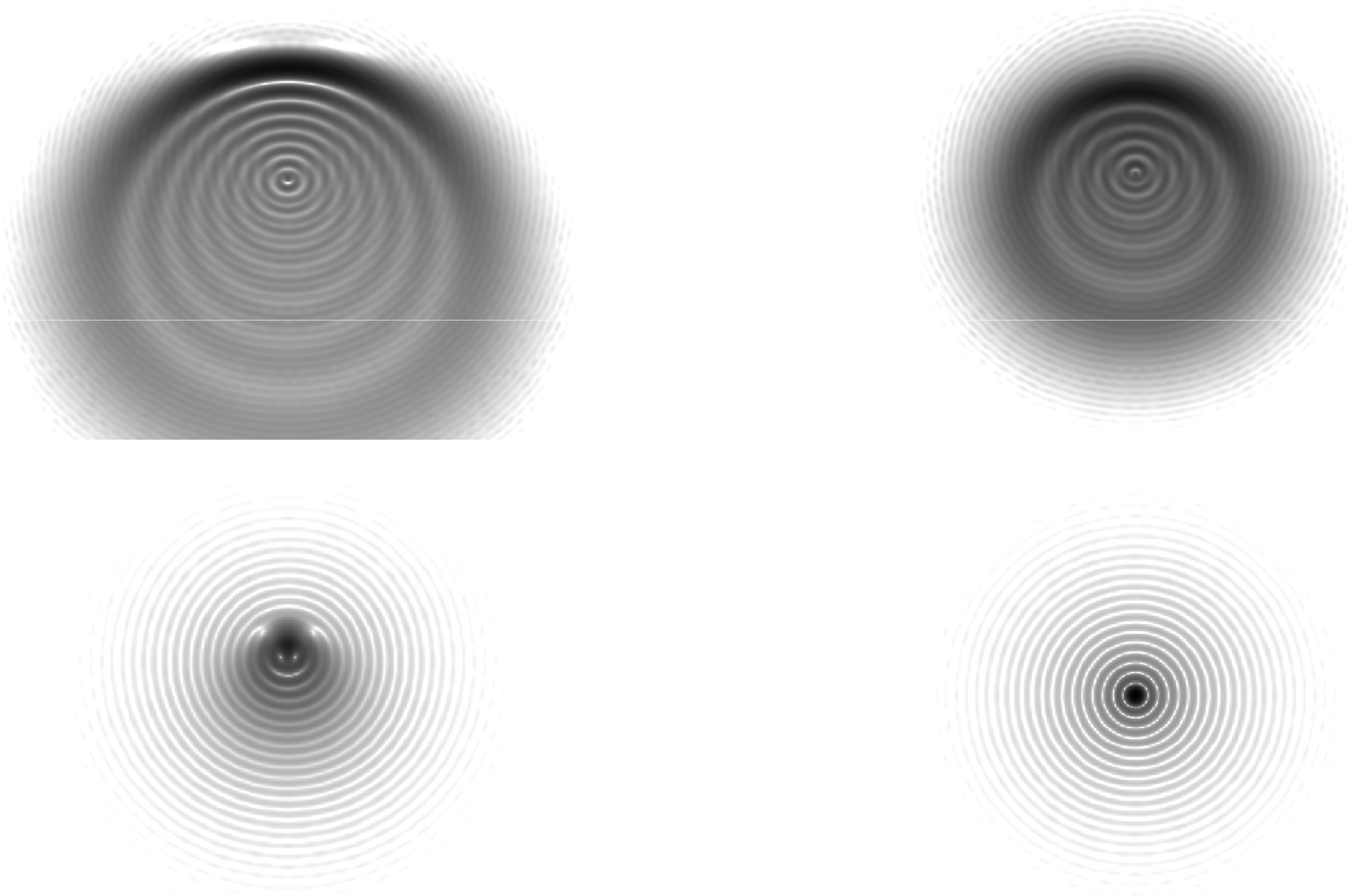


Twyman-Green Interferograms, large coma, small tilt



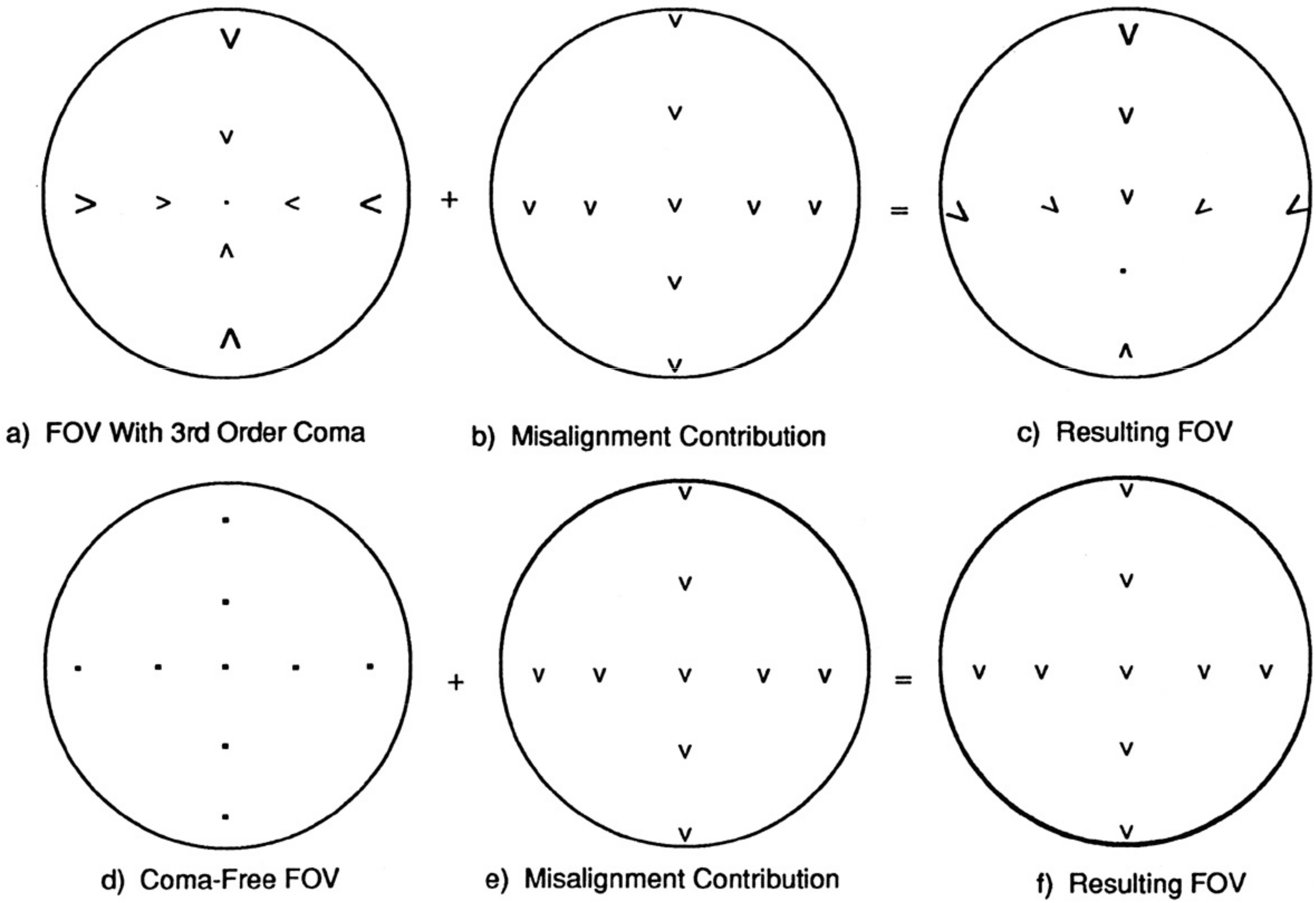
Twyman-Green Interferograms, large coma, small tilt

Defocus coma, remove some coma, re-focus, remove some more



Ruda Cardinal

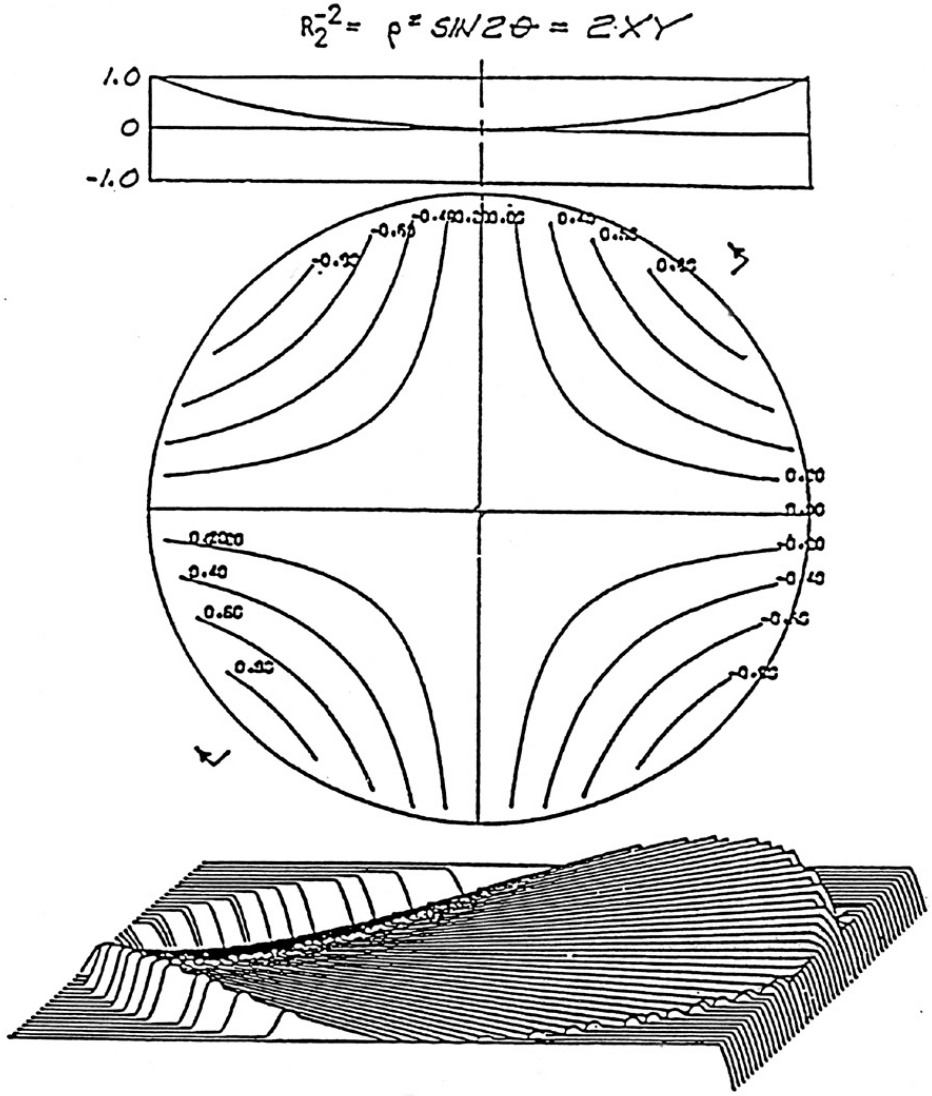
Field Coma and Misalignment



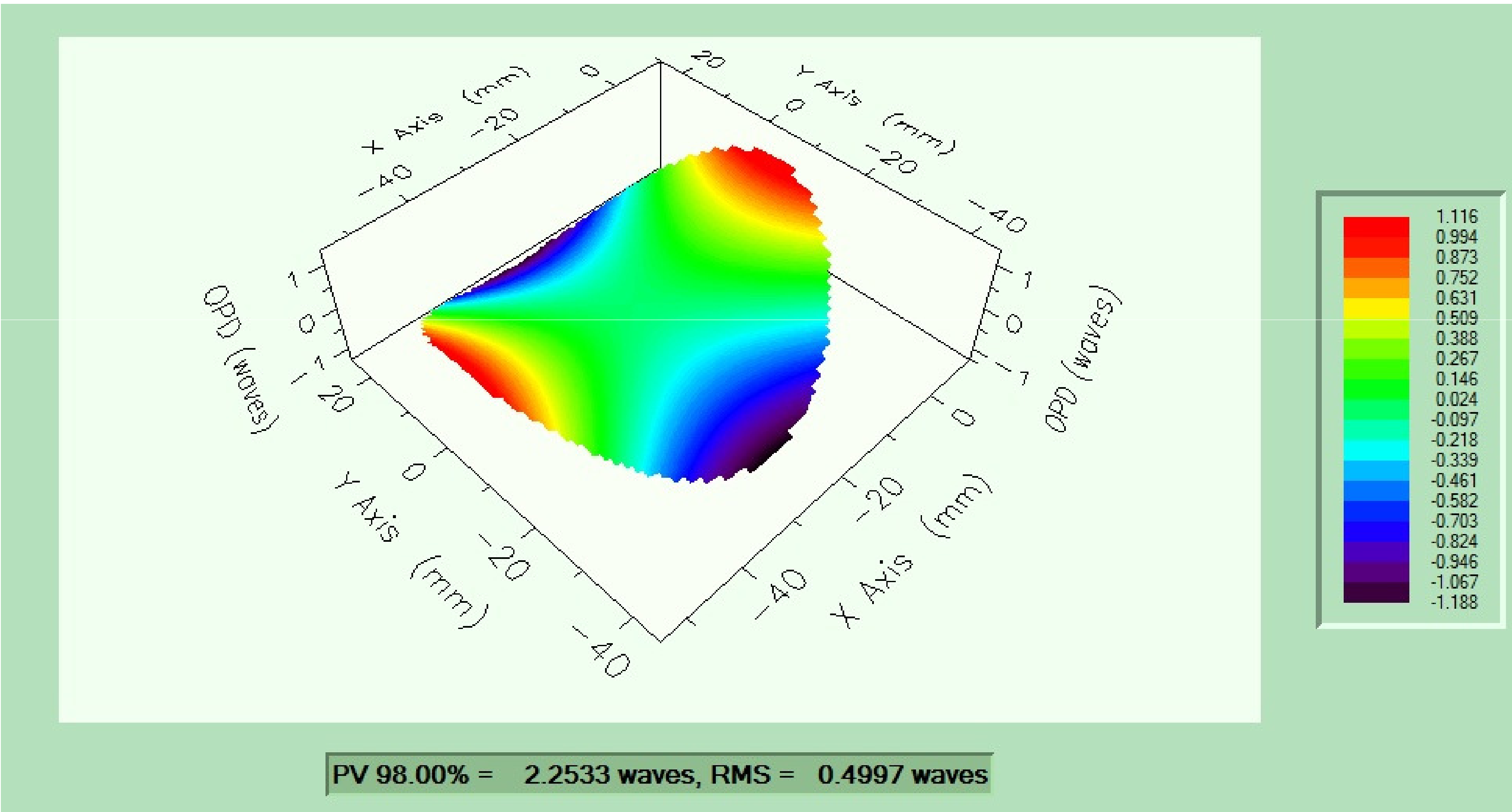
Astigmatism

- Astigmatism is of secondary importance to coma as a misalignment aberration However, it's on-axis presence can indicate misalignment and also:
  - Gravity Sag, Mounting Stress, Polishing Error, etc.
- Mathematically:
  - $W = W_{222} = a_{222}H^2\rho^2\cos^2\theta$
  - Think of astigmatism as a type of defocus which grows quadratically with field of view, and has different values in the x-z and y-z planes
  - Also $\Delta f = \pm 8\lambda a_{222}F\#^2$!!
- Interferometrically:
  - Also fairly complex: "Saddle", "Cylinder", or "Fan" contours depending on the amount and direction of tilt and focus. Bull's eye fringes give the most insight into amount and direction of astigmatism
- Star Test
  - Classic sagittal and tangential line foci
  - $\lambda/20$ easy to detect

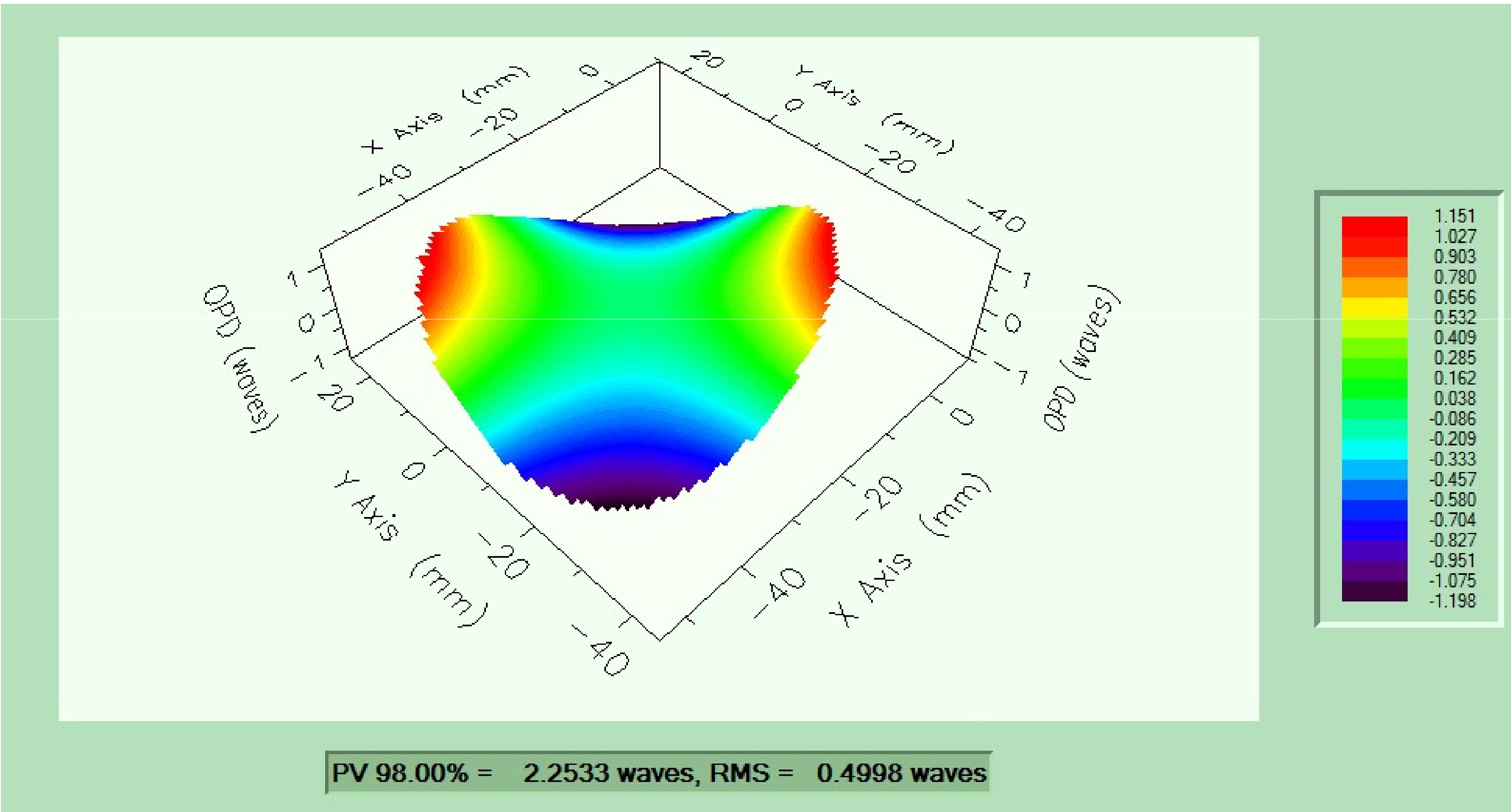
Medial Astigmatism



Medial Astigmatism (Astigmatism)

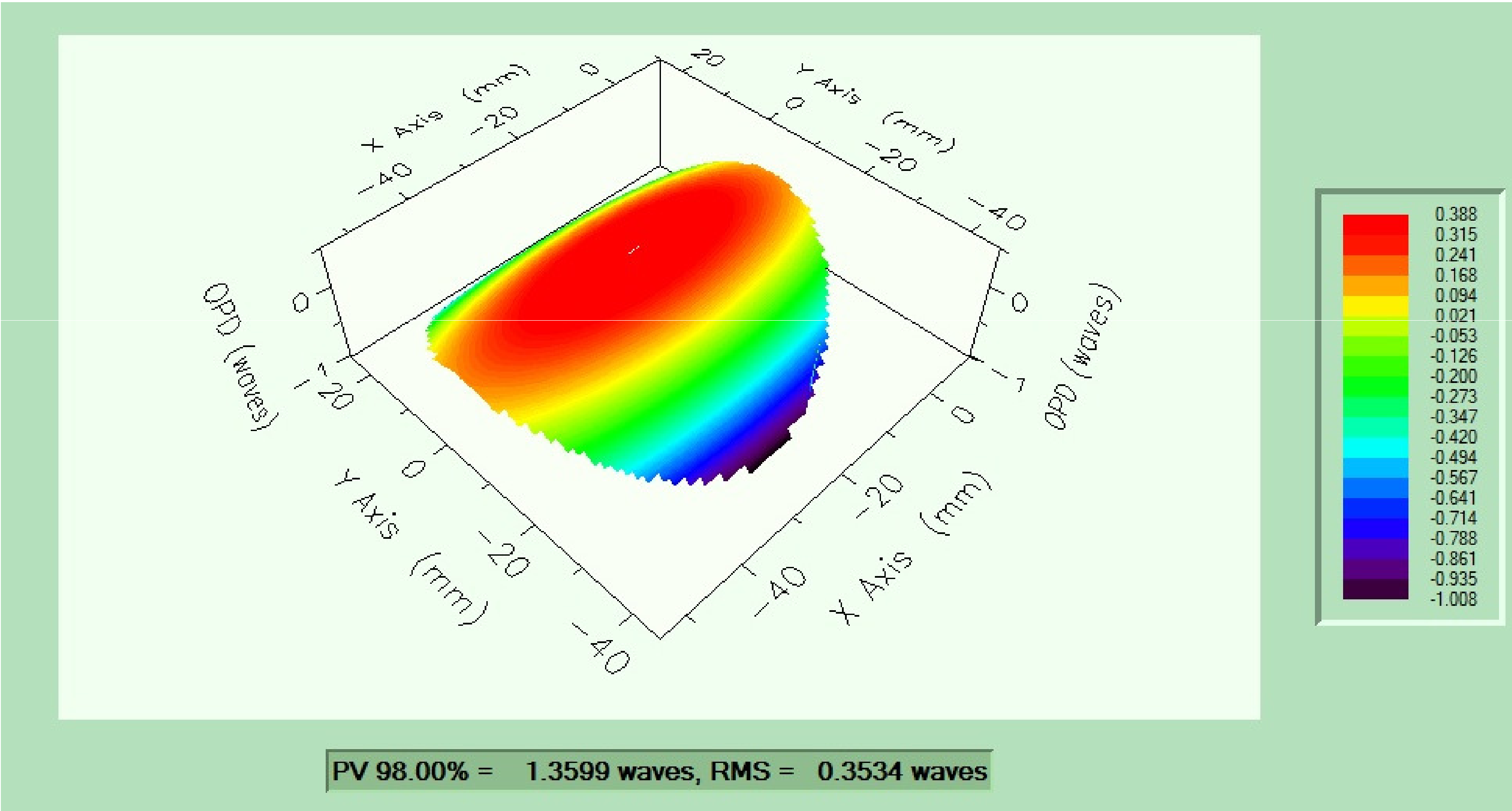


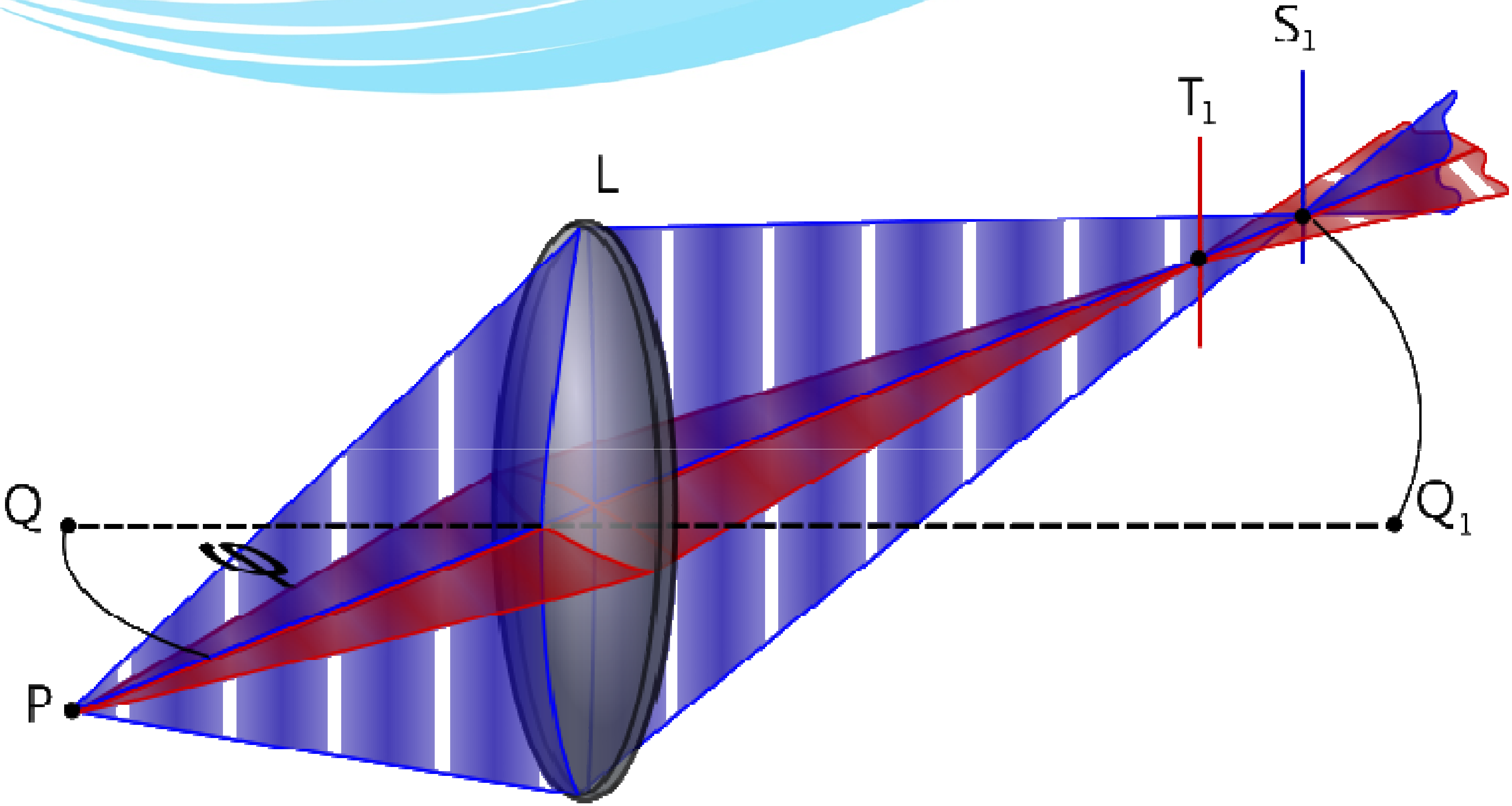
Medial Astigmatism (XY Astigmatism)



RUDA CARDINAL

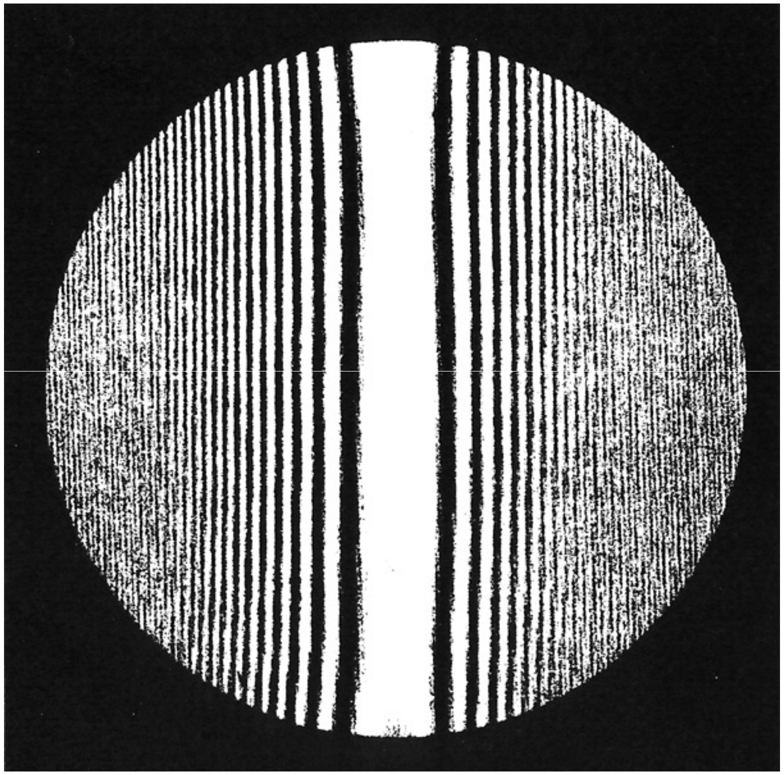
Medial Astigmatism (X Astig, Y Focus)





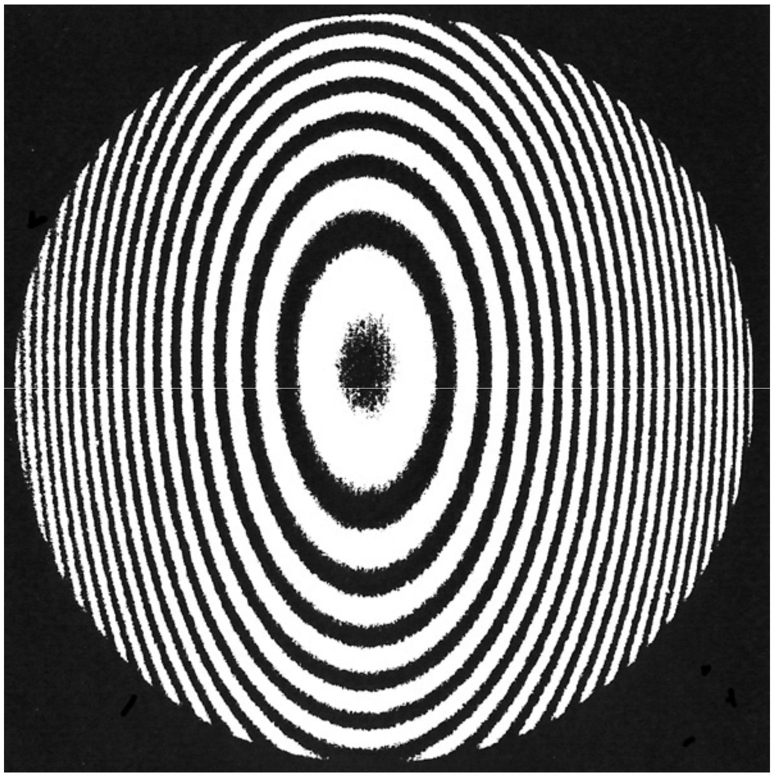
(Wikipedia figure)

Cylindrical Wavefront

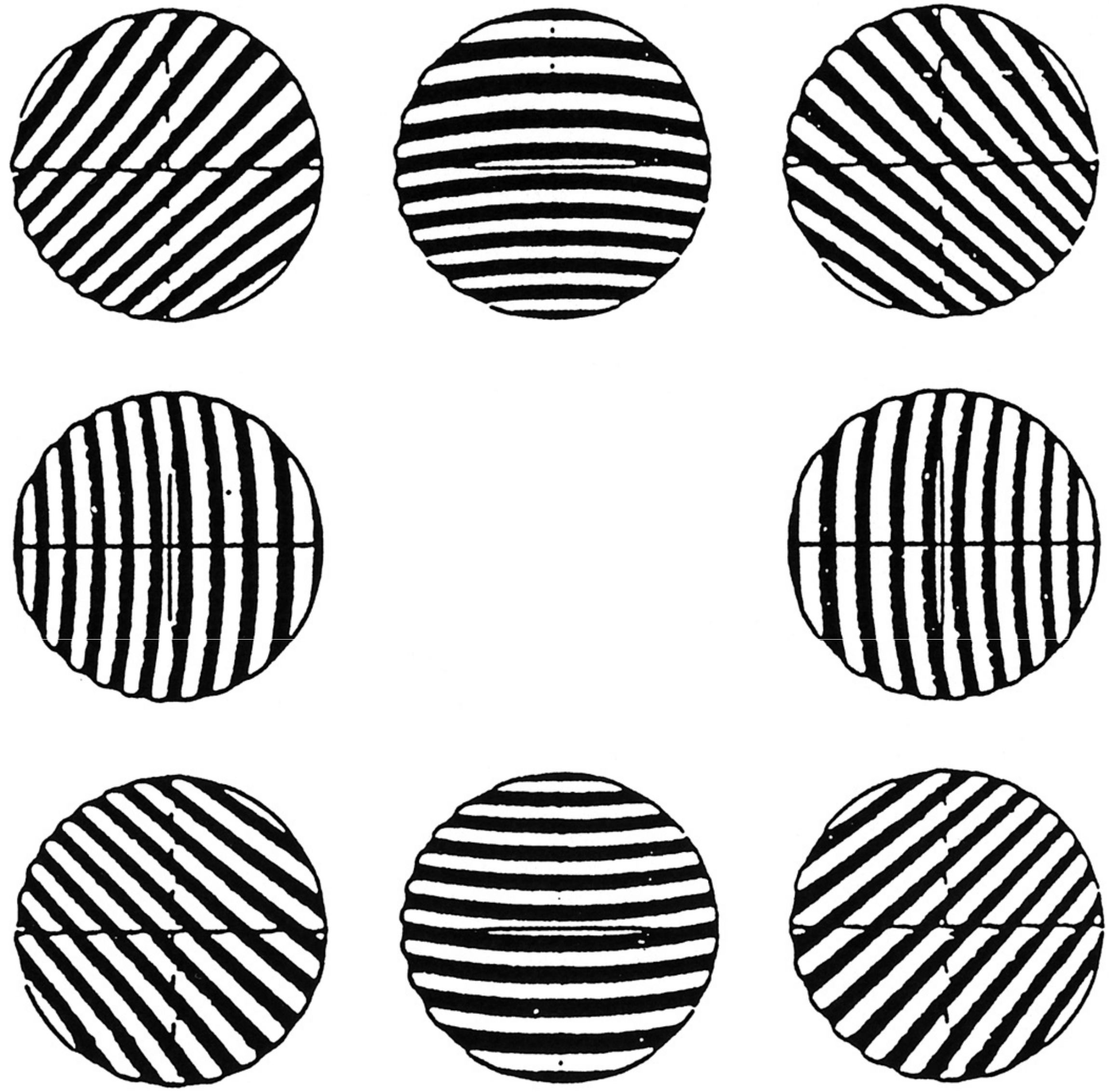


- Astigmatism observed at one of the foci

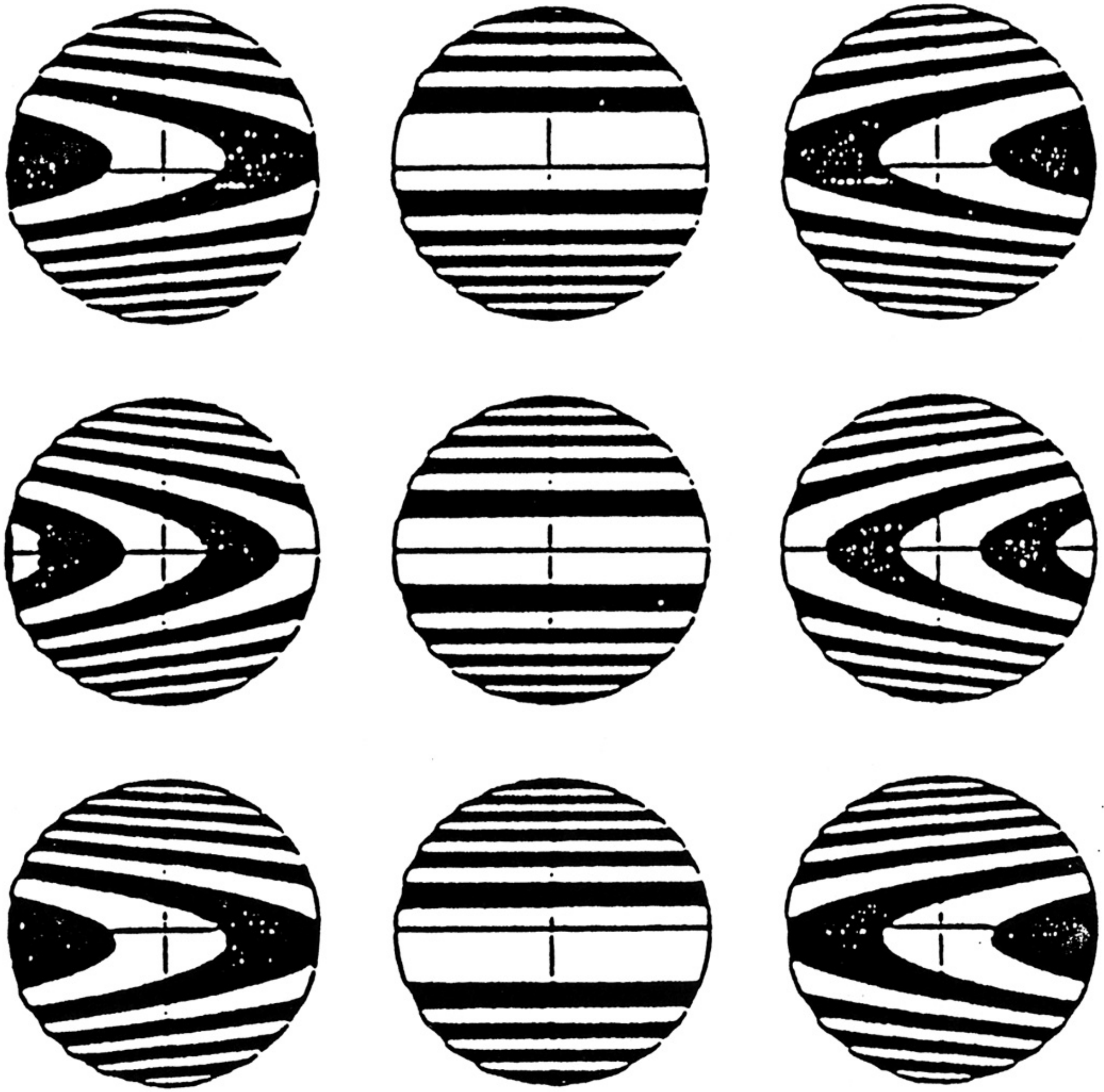
Bull's Eye with Astigmatism



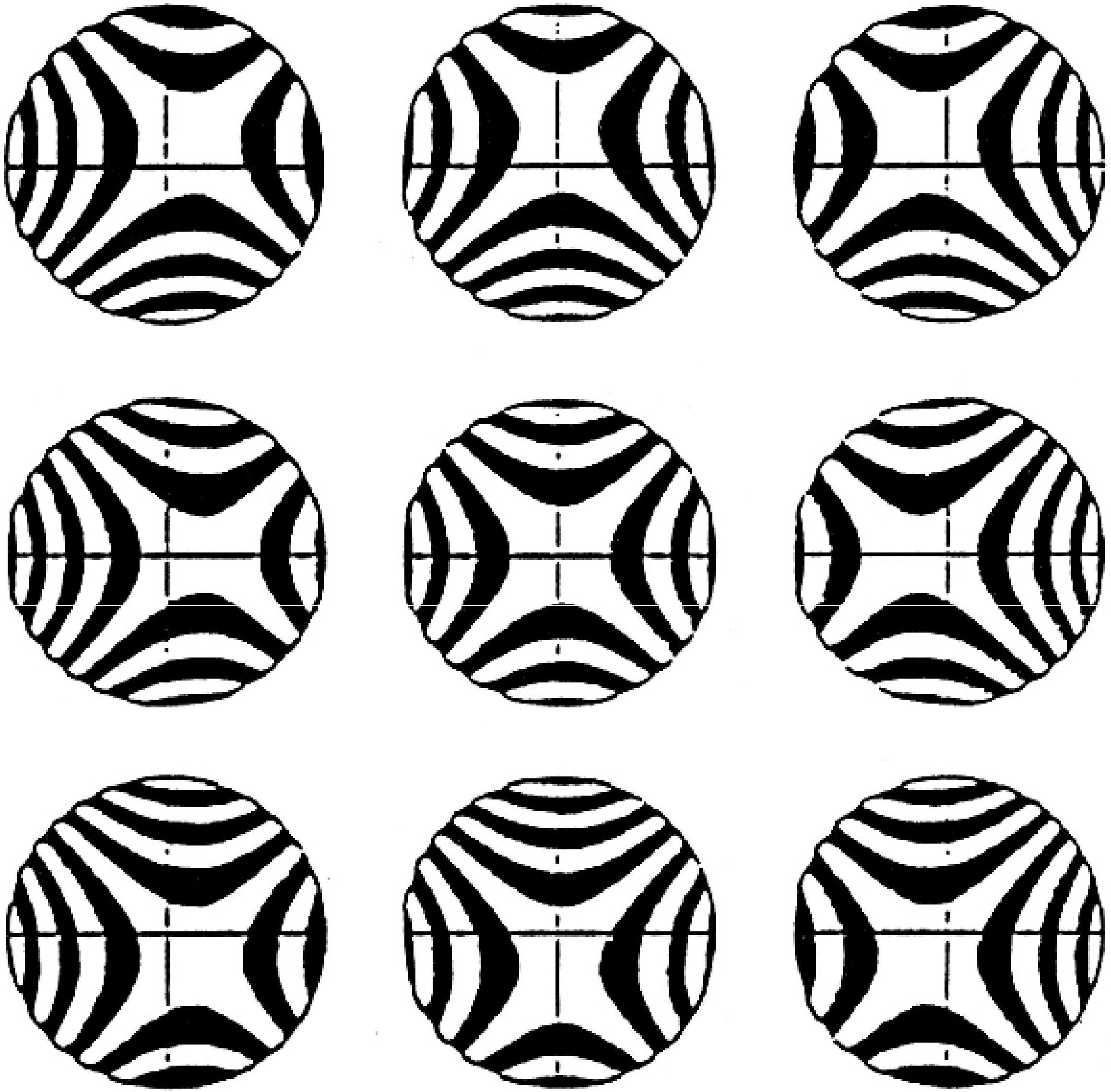
- When astigmatism is suspected, go way out of focus. Elliptical fringes result
- Orientation of axes are astigmatic axes
- Difference in # fringes is value of astigmatism (here 18-6 = 12 waves)



Twyman-Green Interferograms, small astigmatism, medial focus

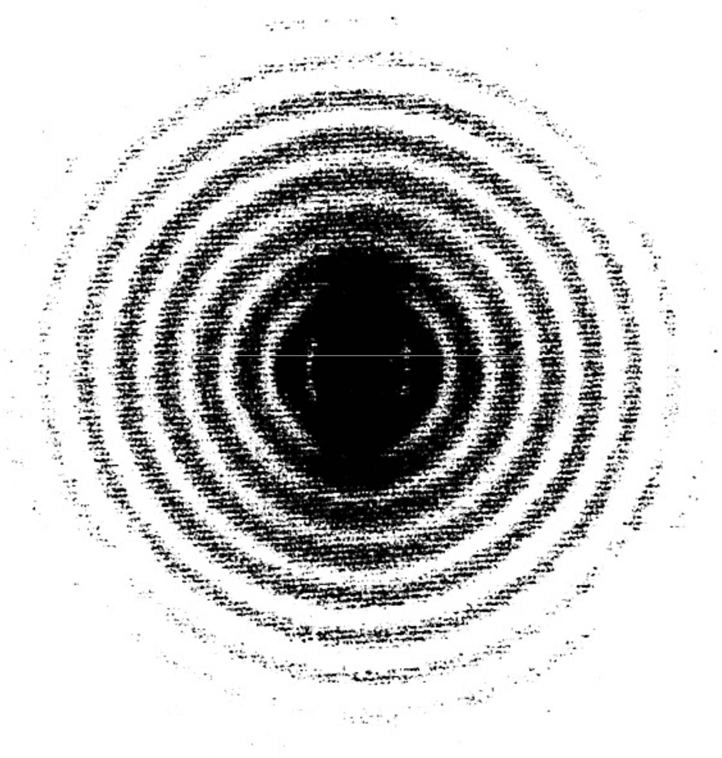


Twyman-Green Interferograms, large astigmatism, sagittal focus, small tilt



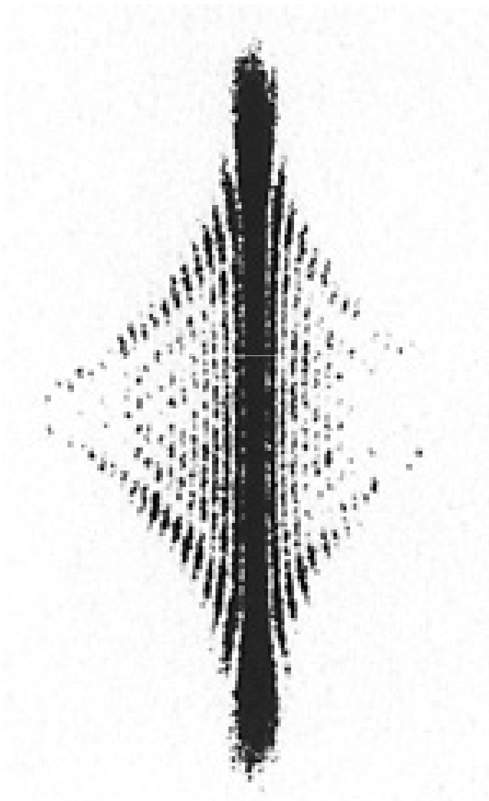
Twyman-Green Interferograms, large astigmatism, medial focus, small tilt

Small Astigmatism



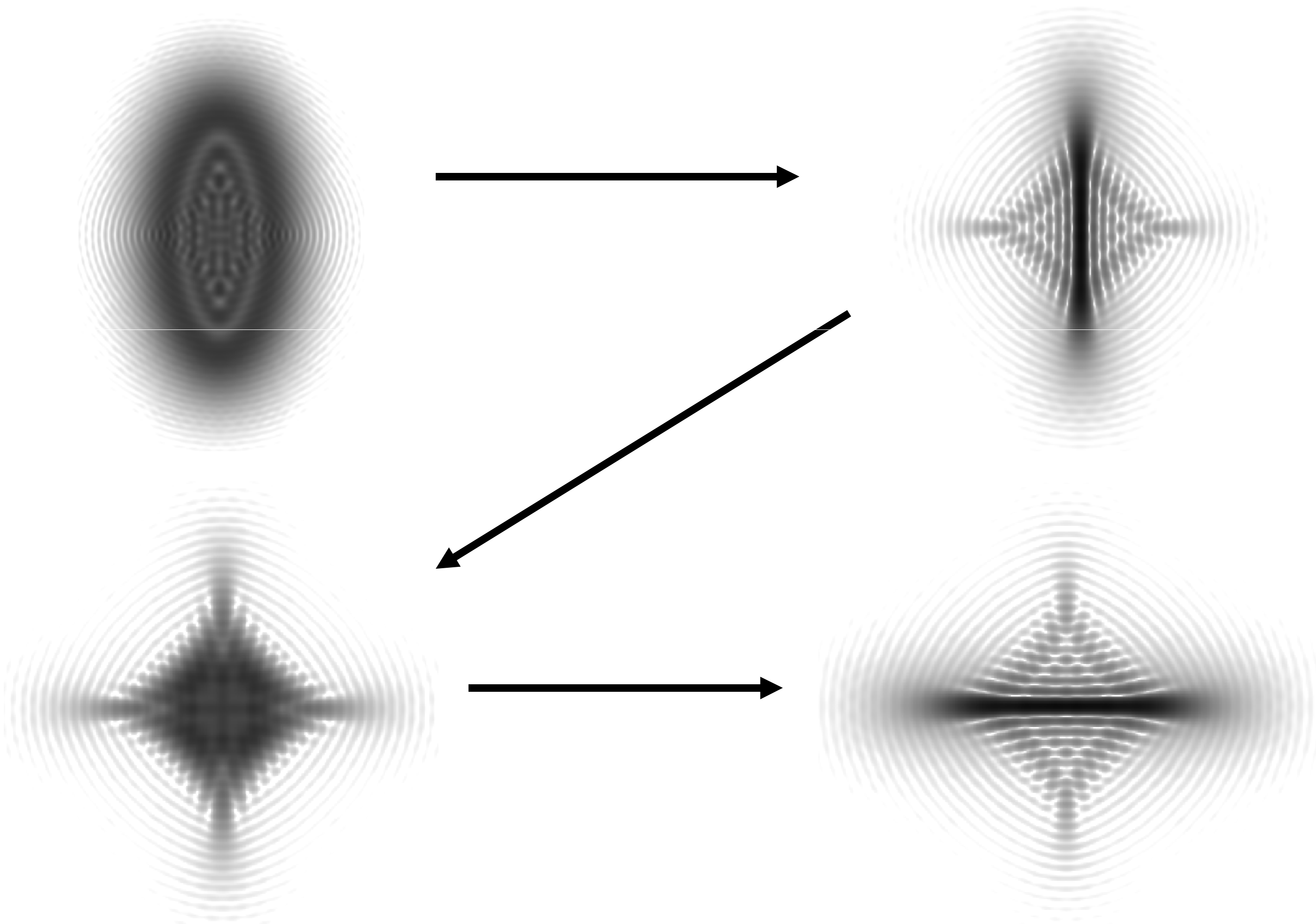
- First sign of astigmatism is an intensity increase along a diameter in the first ring of the Airy disk

Large Astigmatism



- As geometric blur dominates, a line image is formed
- At the other focus, image is rotated 90º

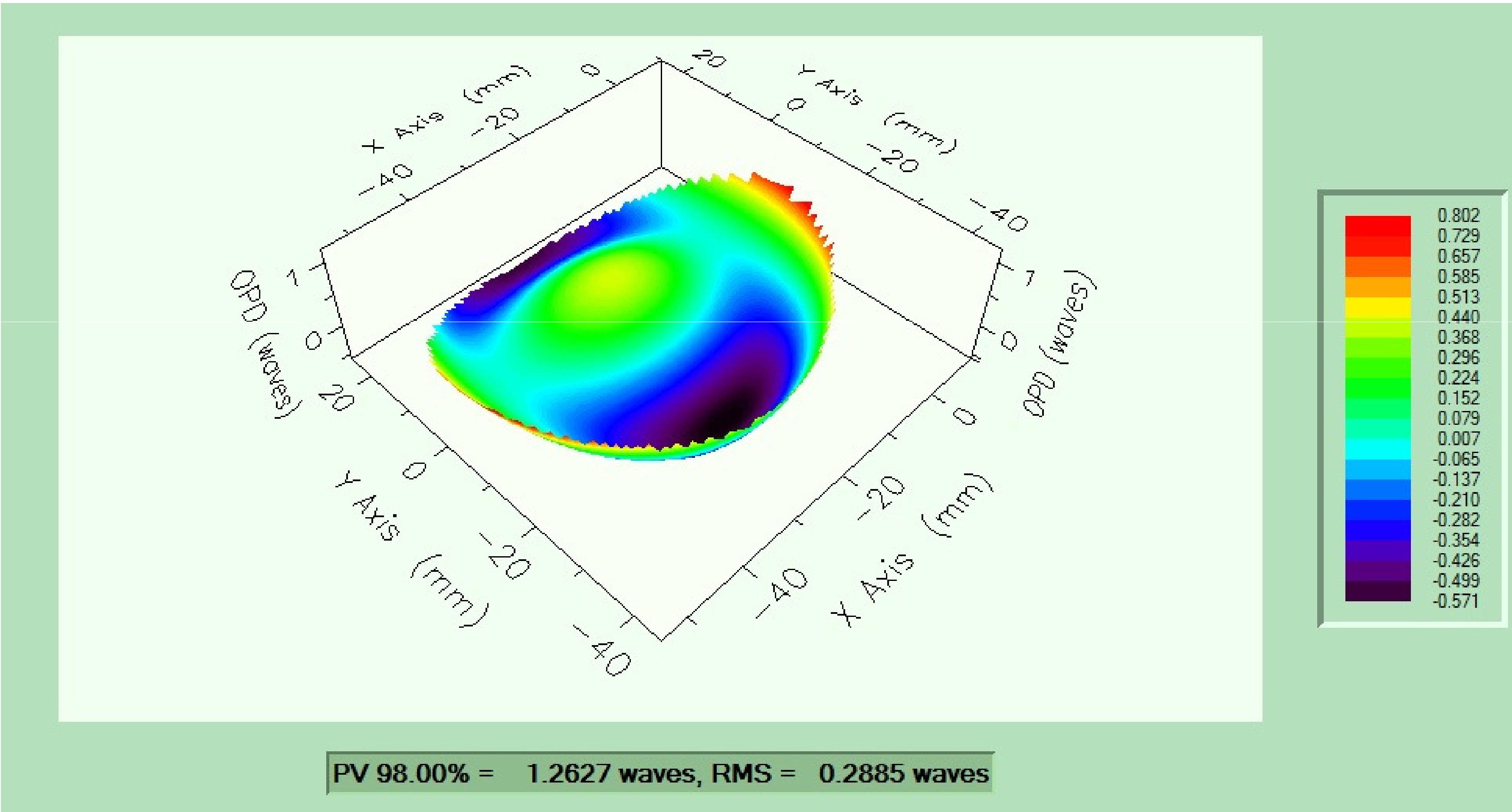
Astigmatism thru focus



Example: Measuring Astigmatism in the Lab

- Problem: You're looking at the on-axis image formed by an F/8 optical system using a HeNe light source. The microscope you're looking through to examine the image is on a linear slide. You view a vertical line image at one focus, and moving the slide 150 microns (approximately 6 mils) you view a horizontal line image.
- How many waves of astigmatism are there?
  - $\Delta f = \pm 8\lambda a_{222} F\#^2$
  - $a_{222} = \pm 0.2315$ waves (0.463 waves from one focus to the other)

Mixture of Aberrations (0.33λ each of S.A., Coma, Astigmatism)



Boresight Error

- Boresight error is the "line-of-sight" error in optical systems
  - It is measured in terms of object space angle
  - It is hard to define because there are so many requirements peculiar to specific systems. Examples are:
    - *Absolute and relative boresight error, static and dynamic error, etc.*
- Mathematically:
  - $W = W_{011} = a_{011}\rho\cos\theta$
  - Tilt of the wavefront causes a displacement of the image, ΔH
  - This is boresight error
  - If the focal length of the optical system is f, then the boresight error is given by $\Delta\theta_B = \Delta H/f$
- Interferometrically:
  - Straight line fringes
- Star Test:
  - Image quality remains the same -- only the image shifts
  - Distortion is like a boresight error that increases as the field of view cubed

Recognition of Causes of Aberrations

Fabrication Errors in Optics

- Central Bumps and Holes
- Zones
- Rolled Edges
- On-Axis Astigmatism
- Erroneous CT measurements
- Wrong material
- Wrong asphere

Misalignment Errors - The Usual

- Focus and Tilt
- Spherical
- Coma
- Astigmatism

Mounting Errors

- On-axis Astigmatism
- 3-Fold Symmetry
- Highly Localized Errors, Bumps, Stress Points

Off-Axis Imagery and Off-Axis Aspherics

- The usual Low-Order Aberrations