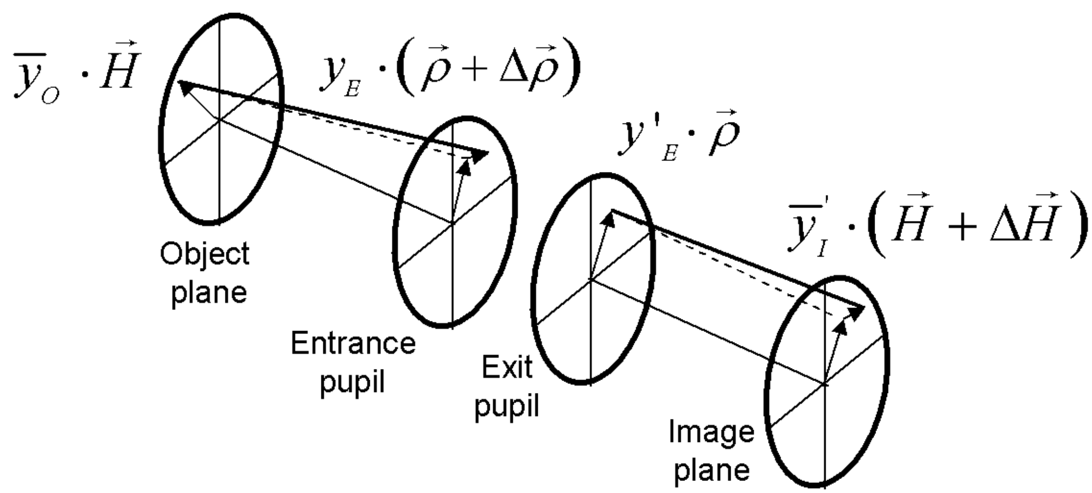
Introduction to aberrations

OPTI 518

Lectures 9



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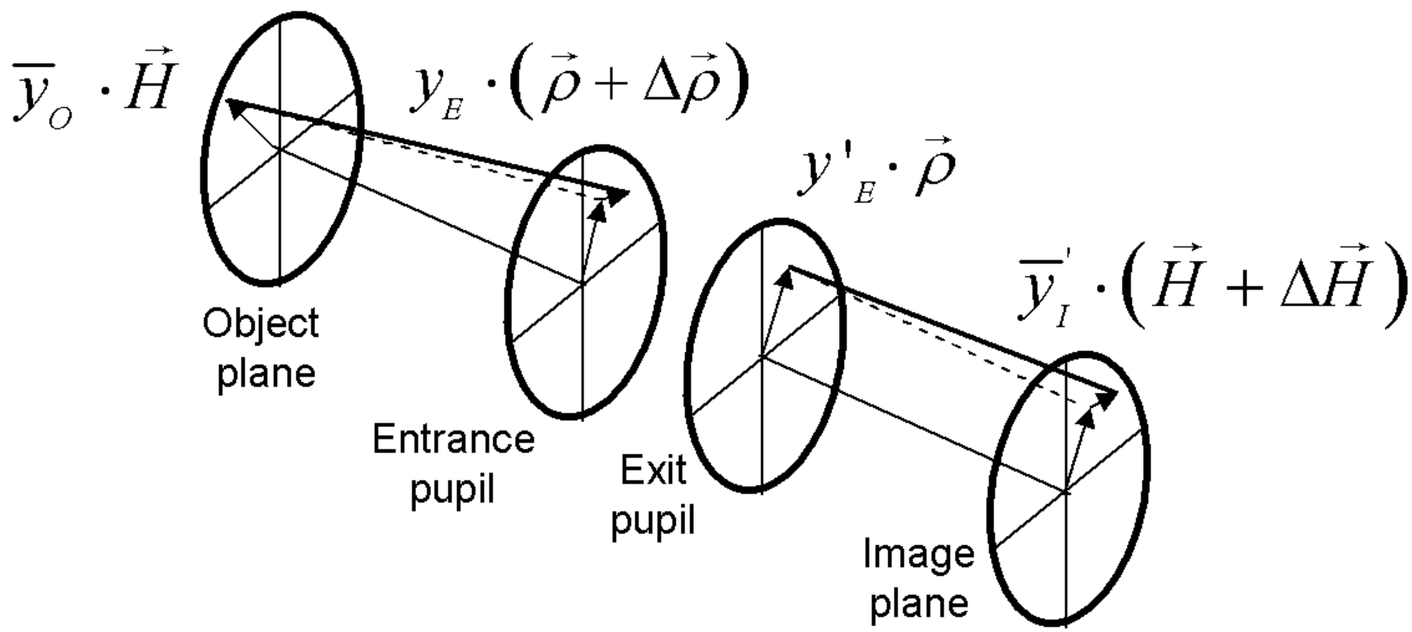
Topics

- Transverse ray aberrations
- RMS spot size
- Spot diagrams
- Ray fans
- Special locations along the spherical aberration caustic

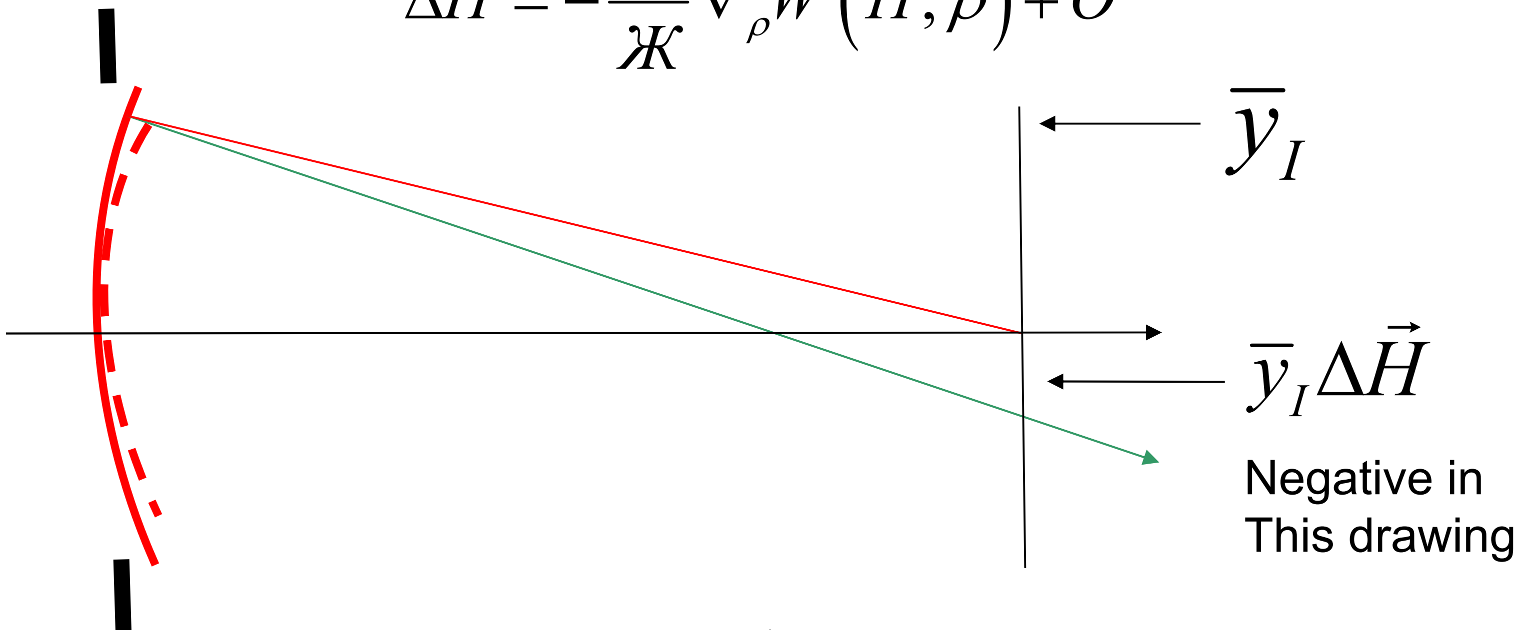
Transverse ray aberration

$$\Delta\vec{H} = -\frac{1}{Ж}\vec{\nabla}_{\rho}W\left(\vec{H},\vec{\rho}\right) + O^{(5)}$$



Transverse ray aberration

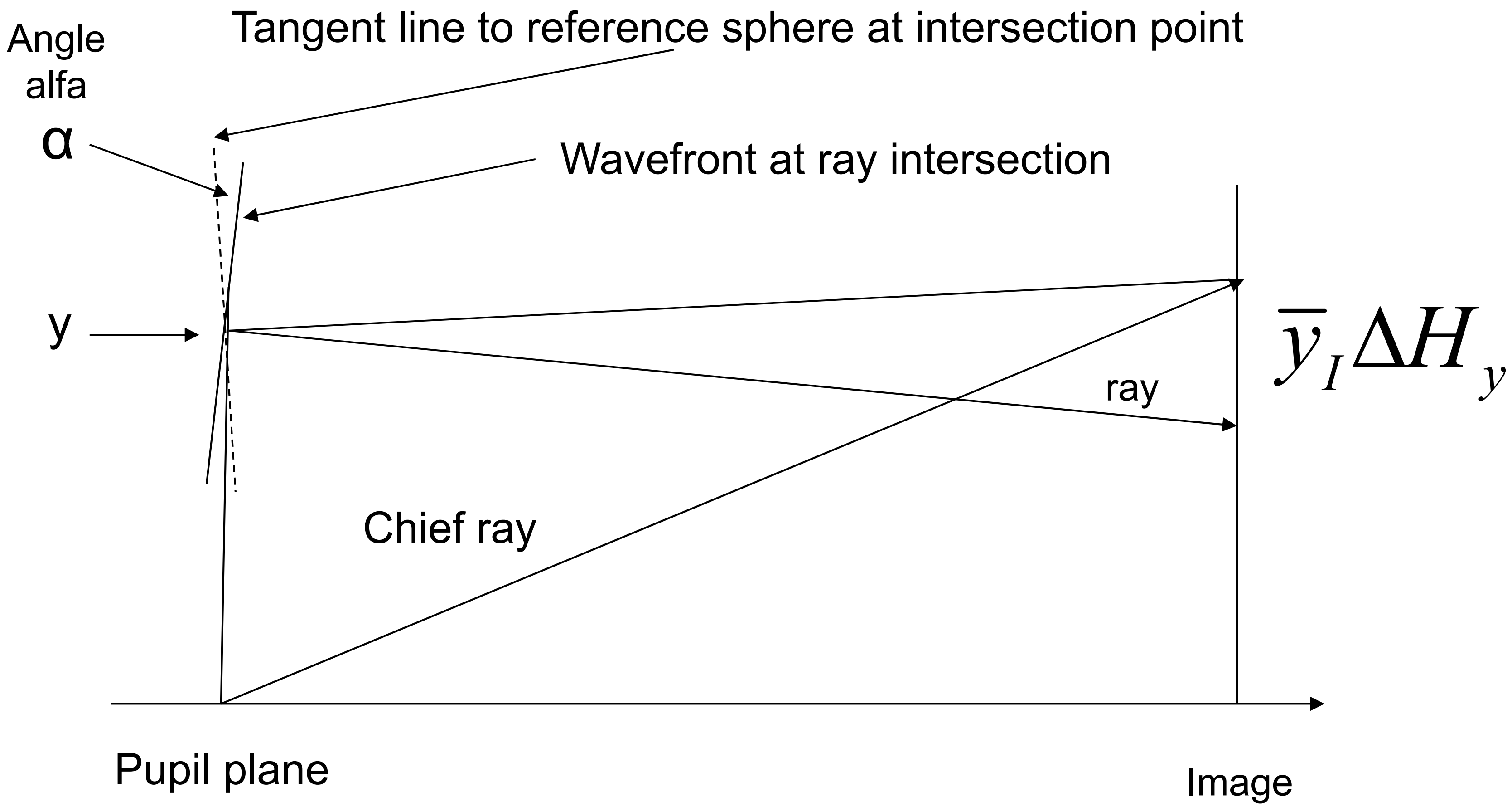
$$\Delta\vec{H} = -\frac{1}{Ж}\vec{\nabla}_{\rho}W\left(\vec{H},\vec{\rho}\right) + O^{(5)}$$



$$\vec{\varepsilon} = \bar{y}_I\Delta\vec{H} = \frac{1}{n'u'}\vec{\nabla}_{\rho}W\left(\vec{H},\vec{\rho}\right)$$

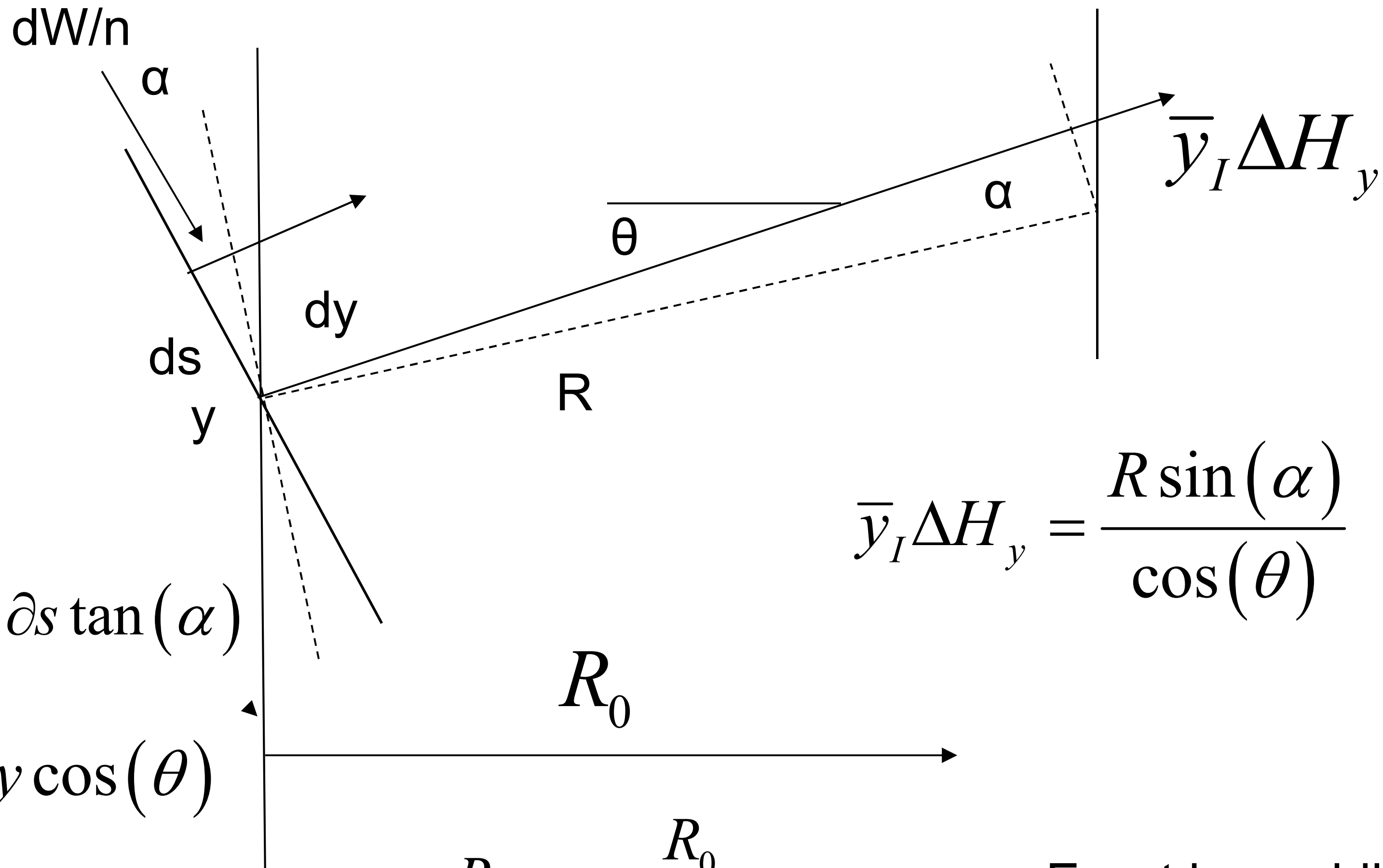
$\bar{y}_I$ Is the chief ray height at the image plane

Derivation



We exactly know where the real ray intersects the exit pupil plane as we have selected it with the tip of the aperture vector

Derivation



$$\frac{\partial W}{n} = \partial s \tan(\alpha)$$

$$\partial s = \partial y \cos(\theta)$$

$$\bar{y}_I \Delta H_y = \frac{R \sin(\alpha)}{\cos(\theta)}$$

$$R = \frac{R_0}{\cos(\theta - \alpha)}$$

Exact in meridional plane

Derivation

$$\frac{1}{n}\frac{\partial W}{\partial y} = \frac{\cos^3(\theta)}{R_0}\left(1-\tan(\alpha)\tan(\theta)\right)\bar{y}_I \Delta H_y$$

$$= \frac{\cos^3(\theta)}{R_0}\bar{y}_I \Delta H_y + O^{(7)} = \frac{1}{R_0}\bar{y}_I \Delta H_y + O^{(5)}$$

Derivation to 2D

$$\frac{1}{n}\frac{y}{u}\frac{\partial W}{\partial y} = \frac{1}{nu}\frac{\partial W}{\partial \rho_y} = \bar{y}_I \Delta H_y + O^{(5)}$$

$$\frac{-1}{Ж}\frac{\partial W}{\partial \rho_y} = \Delta H_y + O^{(5)}$$

$$\frac{-1}{Ж}\frac{\partial W}{\partial \rho_x} = \Delta H_x + O^{(5)}$$

$$\frac{-1}{Ж}\vec{\nabla}_\rho W = \Delta\vec{H} + O^{(5)}$$

Key relationship between wave and transverse aberrations

Example

$$\vec{\varepsilon} = \bar{y}_I \Delta \vec{H} = \frac{1}{n'u'} \vec{\nabla}_\rho W\left(\vec{H}, \vec{\rho}\right)$$

$$= \frac{1}{n'u'} \vec{\nabla}_\rho W_{040} \left(\vec{\rho} \cdot \vec{\rho}\right)^2$$

$$= \frac{4}{n'u'} W_{040} \left(\vec{\rho} \cdot \vec{\rho}\right) \vec{\rho}$$

$$= \frac{4}{n'u'} W_{040} \rho^2 \left(\rho_h \vec{h} + \rho_i \vec{i}\right)$$

$\vec{i}$ $\vec{h}$ are orthogonal unit vectors

Gradient operator

$$\vec{\nabla}_{\rho}\left(\rho^{2}\right)=\vec{\nabla}_{\rho}\left(\rho_{h}^{2}+\rho_{i}^{2}\right)=\frac{\partial\left(\rho_{h}^{2}+\rho_{i}^{2}\right)}{\partial\rho_{h}}\vec{h}+\frac{\partial\left(\rho_{h}^{2}+\rho_{i}^{2}\right)}{\partial\rho_{i}}\vec{i}$$

$$=2\left(\rho_{h}\vec{h}+\rho_{i}\vec{i}\right)=2\vec{\rho}$$

$$\vec{\nabla}_{\rho}\left(\vec{\rho}\cdot\vec{\rho}\right)=2\vec{\rho}$$

$$\vec{\nabla}_{\rho}\left(\vec{H}\cdot\vec{\rho}\right)=\vec{H}$$

$$\vec{H}\cdot\vec{\rho}=H_{h}\rho_{h}+H_{i}\rho_{i}$$

Normalized mean square spot size and RMS spot size

$$\overline{\left|\Delta\vec{H}\right|^2} = \frac{1}{Ж^2}\overline{\left|\vec{\nabla}_\rho W\left(\vec{H},\vec{\rho}\right)\right|^2} = \frac{1}{Ж^2}\frac{1}{\pi}\int_0^{2\pi}\int_0^1 \left|\vec{\nabla}_\rho W\left(\vec{H},\vec{\rho}\right)\right|^2 \rho d\rho d\phi$$

$$RMS = \left|\bar{y}_I\right|\sqrt{\overline{\left|\Delta\vec{H}\right|^2}}$$

RMS spot size is an image quality criteria

Spherical aberration and defocus

$$\bar{y}_I \Delta\vec{H} = \frac{1}{n'u'} \vec{\nabla}_\rho W\left(\vec{H},\vec{\rho}\right)$$

$$= \frac{1}{n'u'} \vec{\nabla}_\rho \left(W_{040}\left(\vec{\rho}\cdot\vec{\rho}\right)^2 + W_{020}\left(\vec{\rho}\cdot\vec{\rho}\right)\right)$$

$$= \frac{1}{n'u'} \left(4W_{040}\left(\vec{\rho}\cdot\vec{\rho}\right)\vec{\rho} + 2W_{020}\vec{\rho}\right)$$

$$\Delta\vec{H}\cdot\Delta\vec{H} = \frac{1}{\text{Ж}^2}\left|\vec{\nabla}_\rho W\left(\vec{H},\vec{\rho}\right)\right|^2 = \frac{1}{\text{Ж}^2}\left|\left(4W_{040}\left(\vec{\rho}\cdot\vec{\rho}\right)\vec{\rho} + 2W_{020}\vec{\rho}\right)\right|^2$$

$$= \frac{1}{\text{Ж}^2}\left(16W_{040}^2\left(\vec{\rho}\cdot\vec{\rho}\right)^3 + 16W_{040}W_{020}\left(\vec{\rho}\cdot\vec{\rho}\right)^4 + 4W_{020}^2\left(\vec{\rho}\cdot\vec{\rho}\right)\right)$$

Spherical aberration and defocus

$$\overline{\left|\Delta\vec{H}\right|}^2 = \frac{1}{Ж^2}\frac{1}{\pi}\int_0^{2\pi}\int_0^1\left(16W_{040}^2\rho^6 + 16W_{040}W_{020}\rho^4 + 4W_{020}^2\rho^2\right)\rho d\rho d\phi$$

$$= \frac{2}{Ж^2}\left(\frac{16}{8}W_{040}^2 + \frac{16}{6}W_{040}W_{020} + \frac{4}{4}W_{020}^2\right)$$

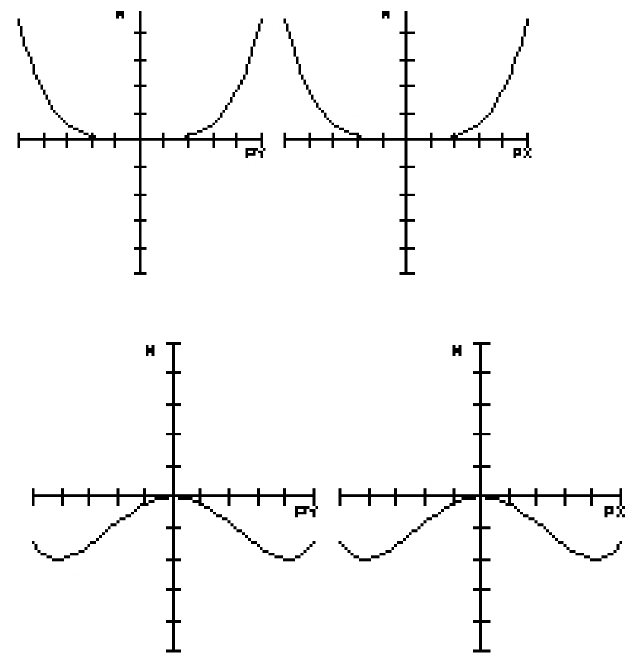
$$= \frac{1}{Ж^2}\left(4W_{040}^2 + \frac{16}{3}W_{040}W_{020} + 2W_{020}^2\right)$$

$$= \frac{1}{Ж^2}\left(2\left(W_{020} + \frac{4}{3}W_{040}\right)^2 + \frac{4}{9}W_{040}^2\right)$$

"Best focus"

Minimum rms spot when:

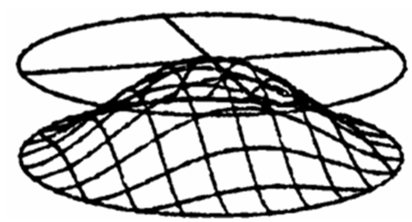
$$W_{020} = -\frac{4}{3} W_{040}$$

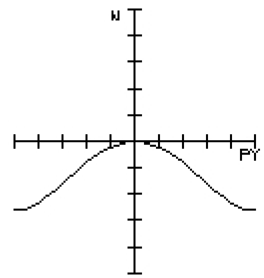


Normalized RMS spot size

$$\sqrt{\overline{\left|\Delta \vec{H}\right|^2}} = \frac{1}{\text{Ж}} \frac{2}{3} W_{040}$$

Marginal focus





$$\bar{y}_I \Delta\vec{H} = \frac{1}{n'u'}\vec{\nabla}_\rho W\left(\vec{H},\vec{\rho}\right)$$

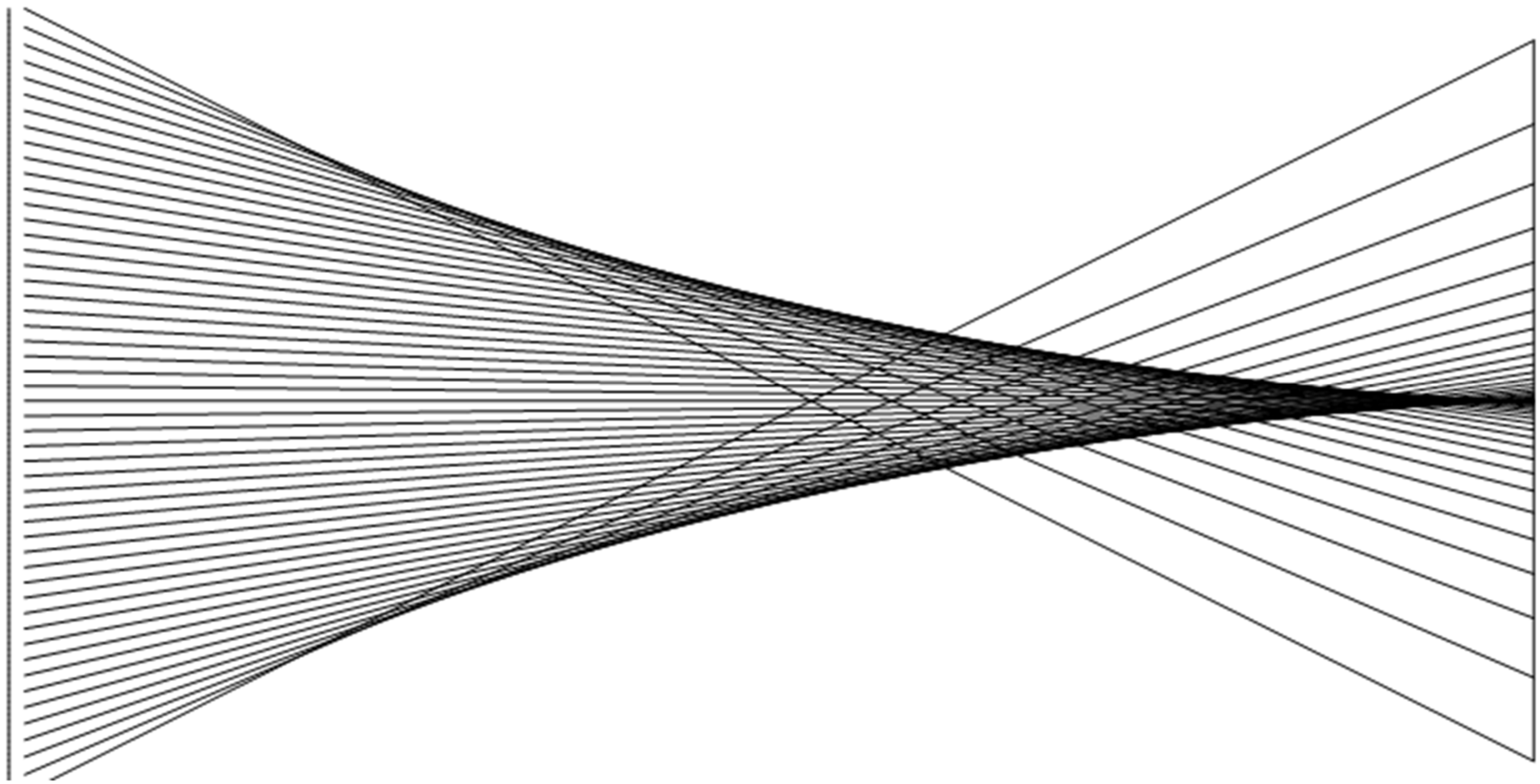
$$= \frac{1}{n'u'}\vec{\nabla}_\rho \left(W_{040}\left(\vec{\rho}\cdot\vec{\rho}\right)^2 + W_{020}\left(\vec{\rho}\cdot\vec{\rho}\right)\right)$$

$$= \frac{1}{n'u'}\left(4W_{040}\left(\vec{\rho}\cdot\vec{\rho}\right)\vec{\rho} + 2W_{020}\vec{\rho}\right)$$

Marginal focus is at:

$$W_{020} = -2W_{040}$$

Ray caustic for spherical aberration



Caustic ~ burning

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Special locations along the ray caustic

$$W_{020} = -W_{040}$$

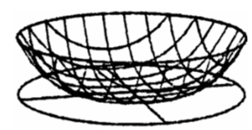
Minimum wavefront variance

$$W_{020} = -\frac{4}{3}W_{040}$$

Minimum rms spot size

$$W_{020} = -\frac{3}{2}W_{040}$$

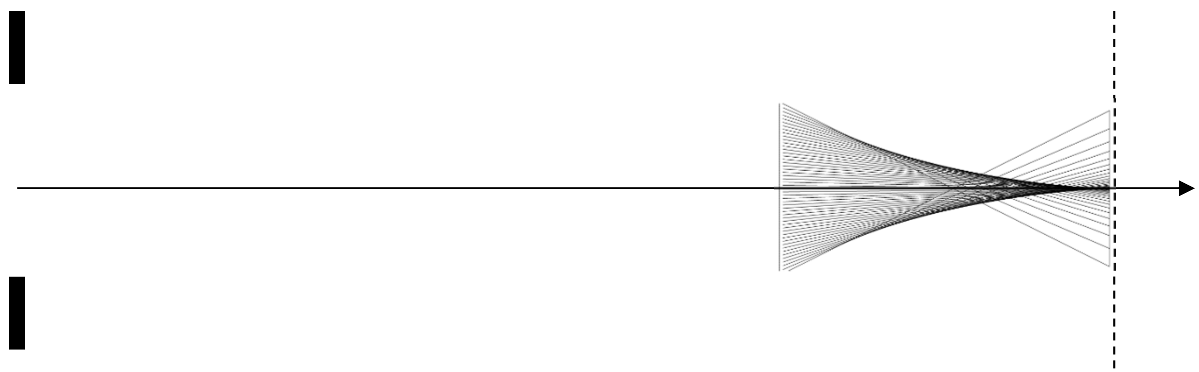
Minimum circle



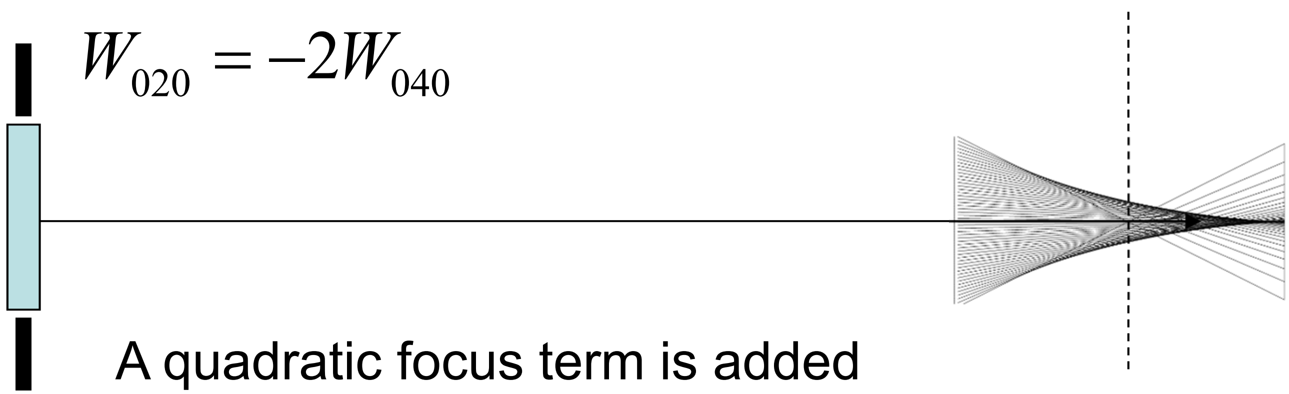
$$W_{020} = -2W_{040}$$

Marginal focus

Focus view

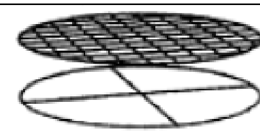
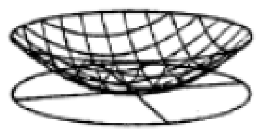
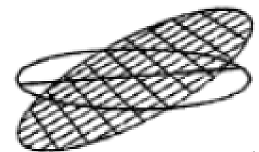
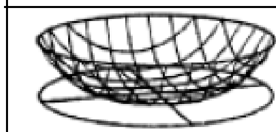
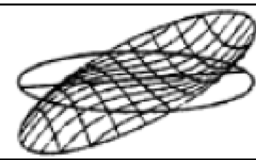
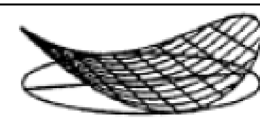
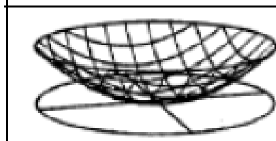
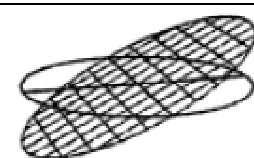
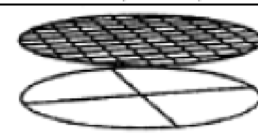


$$W_{020} = -2W_{040}$$



A quadratic focus term is added at exit pupil to move the caustic in relation to the ideal image plane

Wave deformation shapes

Wave aberration shapes		
Zero-order		
		
W_{000}		
Second-order		
		
$W_{020}(\vec{\rho}\cdot\vec{\rho})$	$W_{111}(\vec{H}\cdot\vec{\rho})$	$W_{200}(\vec{H}\cdot\vec{H})$
Fourth-order		
		
$W_{040}(\vec{\rho}\cdot\vec{\rho})^2$	$W_{131}(\vec{H}\cdot\vec{\rho})(\vec{\rho}\cdot\vec{\rho})$	$W_{222}(\vec{H}\cdot\vec{\rho})^2$
		
$W_{220}(\vec{H}\cdot\vec{H})(\vec{\rho}\cdot\vec{\rho})$	$W_{311}(\vec{H}\cdot\vec{H})(\vec{H}\cdot\vec{\rho})$	$W_{400}(\vec{H}\cdot\vec{H})^2$

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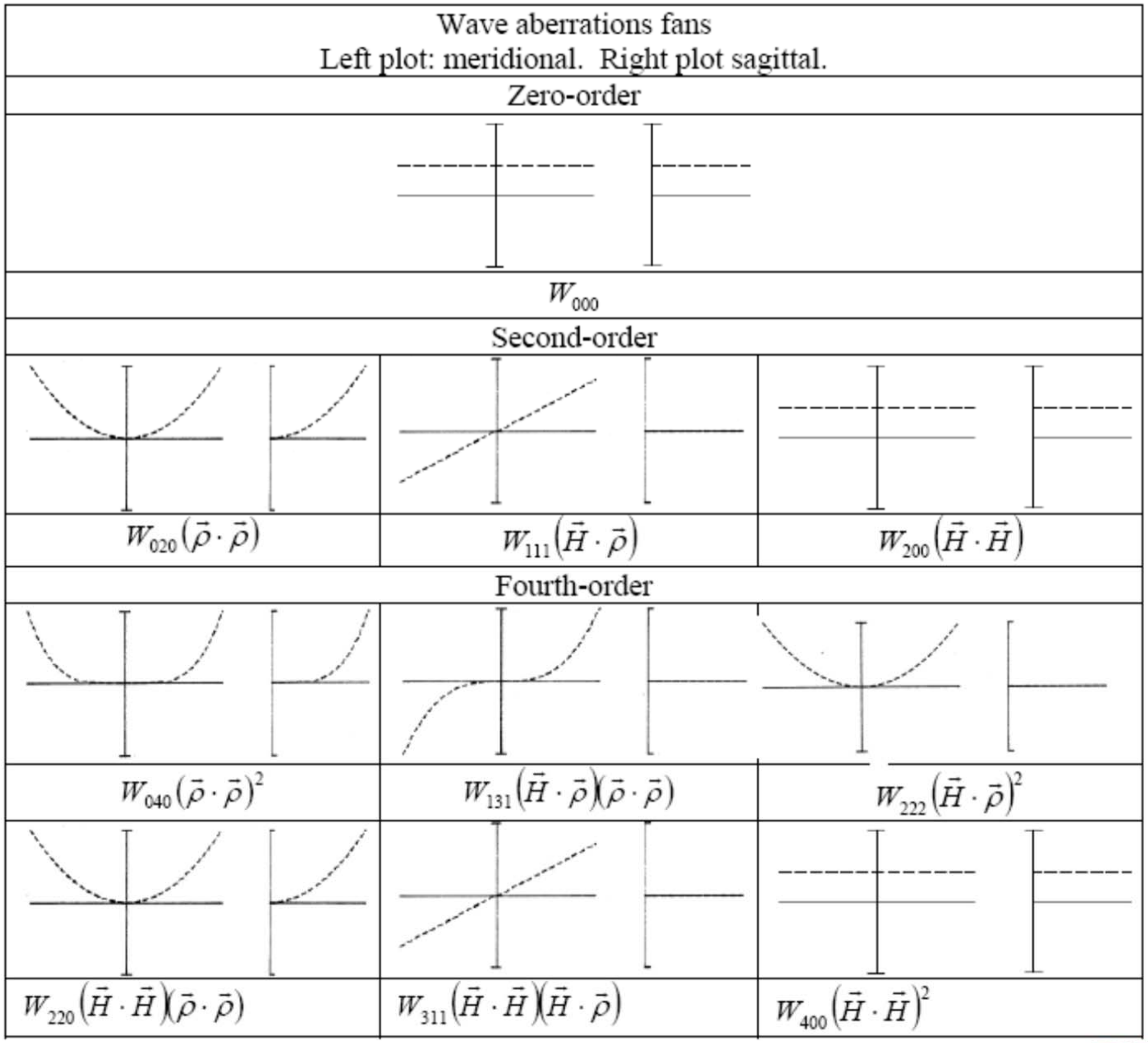
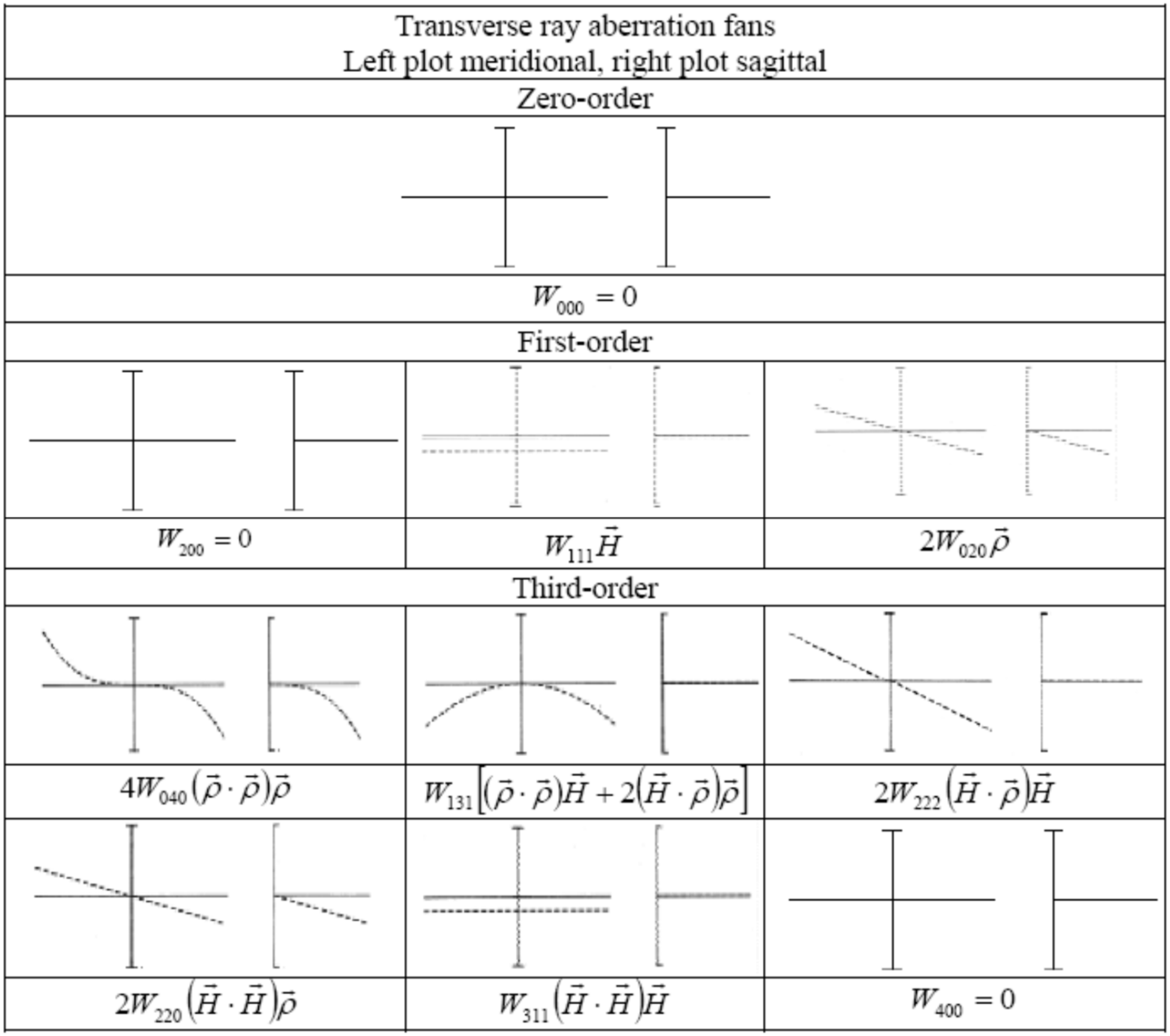
Notes

- Pure terms
- Fourth-order terms
- Actually they are a mixture including higher order.
- Need to learn them to recognize dominant aberrations
- Preferred in waves

Wave fans

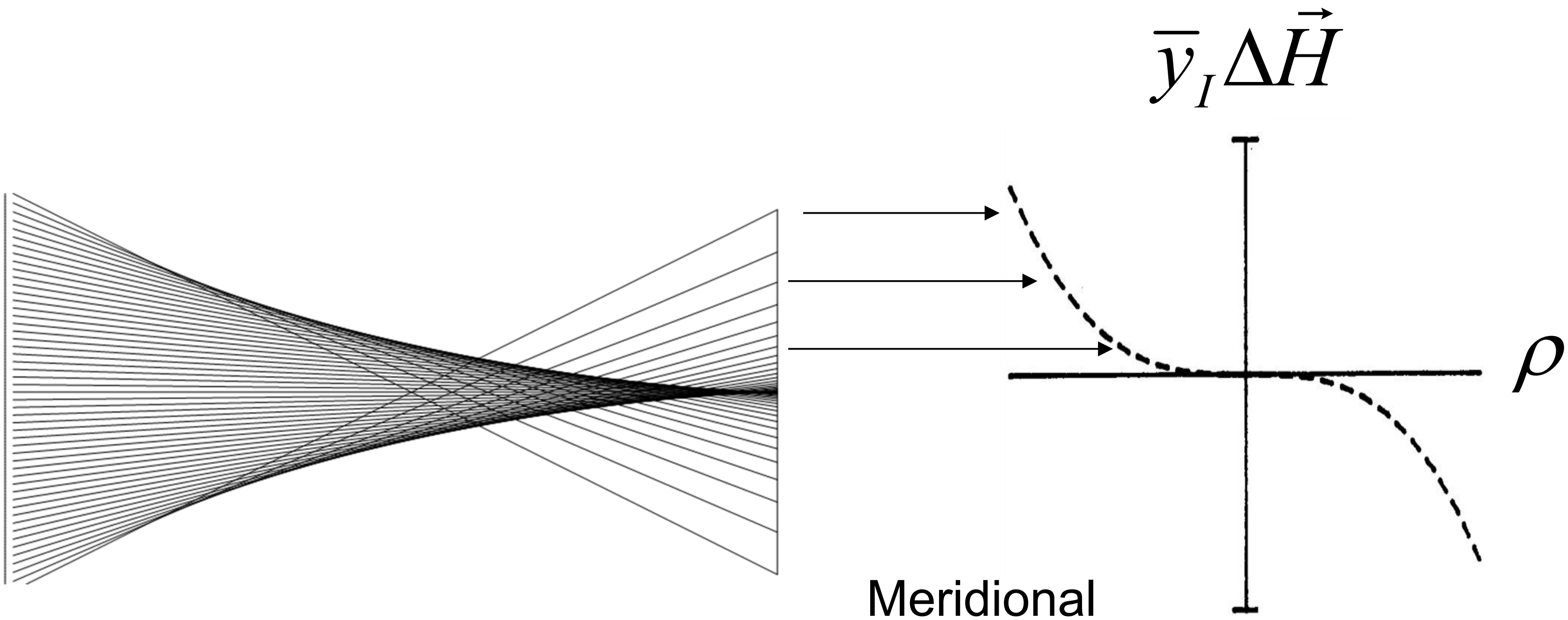

Wave aberrations fans
Left plot: meridional. Right plot sagittal.
Zero-order
W_{000}
Second-order
$W_{020}(\vec{\rho}\cdot\vec{\rho})$
$W_{111}(\vec{H}\cdot\vec{\rho})$
$W_{200}(\vec{H}\cdot\vec{H})$
Fourth-order
$W_{040}(\vec{\rho}\cdot\vec{\rho})^2$
$W_{131}(\vec{H}\cdot\vec{\rho})(\vec{\rho}\cdot\vec{\rho})$
$W_{222}(\vec{H}\cdot\vec{\rho})^2$
$W_{220}(\vec{H}\cdot\vec{H})(\vec{\rho}\cdot\vec{\rho})$
$W_{311}(\vec{H}\cdot\vec{H})(\vec{H}\cdot\vec{\rho})$
$W_{400}(\vec{H}\cdot\vec{H})^2$

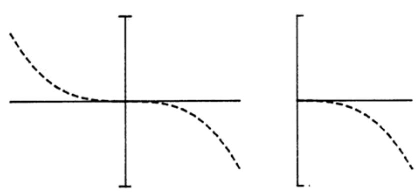
Ray fans

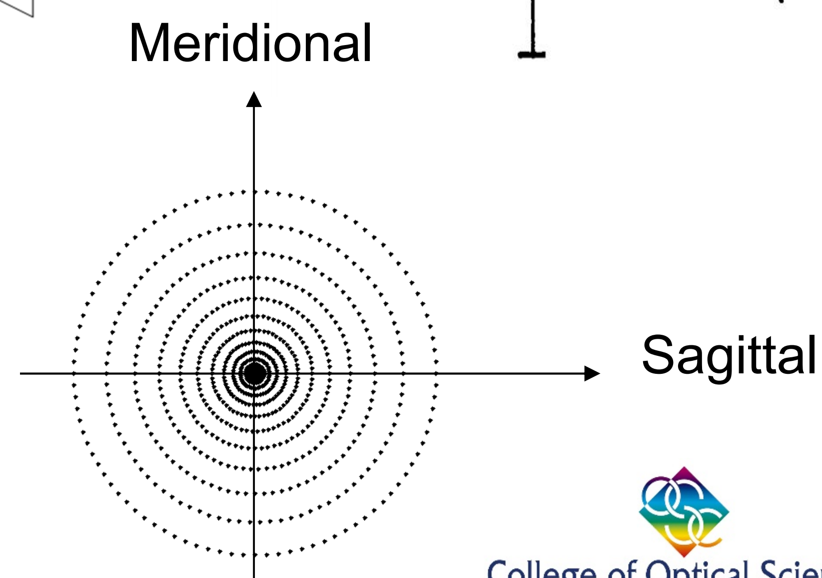


Transverse ray aberration fans
Left plot meridional, right plot sagittal
Zero-order
$W_{000} = 0$
First-order
$W_{200} = 0$
$W_{111}\vec{H}$
$2W_{020}\vec{\rho}$
Third-order
$4W_{040}(\vec{\rho}\cdot\vec{\rho})\vec{\rho}$
$W_{131}\left[(\vec{\rho}\cdot\vec{\rho})\vec{H} + 2(\vec{H}\cdot\vec{\rho})\vec{\rho}\right]$
$2W_{222}(\vec{H}\cdot\vec{\rho})\vec{H}$
$2W_{220}(\vec{H}\cdot\vec{H})\vec{\rho}$
$W_{311}(\vec{H}\cdot\vec{H})\vec{H}$
$W_{400} = 0$

Spherical aberration







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Transverse ray aberrations

$$\vec{\nabla}_{\rho} W = \sum_{j,m,n} W_{k,l,m} \left(\vec{H} \cdot \vec{H}\right)^{j} \left[(\vec{\rho} \cdot \vec{\rho})^{n} \vec{\nabla}_{\rho} \left(\vec{H} \cdot \vec{\rho}\right)^{m} + \left(\vec{H} \cdot \vec{\rho}\right)^{m} \vec{\nabla}_{\rho} (\vec{\rho} \cdot \vec{\rho})^{n} \right] =$$

$$= \sum_{j,m,n} W_{k,l,m} \left(\vec{H} \cdot \vec{H}\right)^{j} \left[m\left(\vec{H} \cdot \vec{\rho}\right)^{m-1} (\vec{\rho} \cdot \vec{\rho})^{n} \vec{\nabla}_{\rho} \left(\vec{H} \cdot \vec{\rho}\right) + n\left(\vec{H} \cdot \vec{\rho}\right)^{m} (\vec{\rho} \cdot \vec{\rho})^{n-1} \vec{\nabla}_{\rho} (\vec{\rho} \cdot \vec{\rho}) \right] =$$

$$= \sum_{j,m,n} W_{k,l,m} \left(\vec{H} \cdot \vec{H}\right)^{j} \left[m\left(\vec{H} \cdot \vec{\rho}\right)^{m-1} (\vec{\rho} \cdot \vec{\rho})^{n} \vec{H} + 2n\left(\vec{H} \cdot \vec{\rho}\right)^{m} (\vec{\rho} \cdot \vec{\rho})^{n-1} \vec{\rho} \right]$$

The gradient of the wavefront has two component vectors; one in the direction of the field vector and another in the direction of the aperture vector. Note that the transverse ray aberrations have one algebraic order less than the wavefront aberrations.

Transverse ray aberrations

Transverse ray aberrations	
Aberration name/order	Vector form
Zero order	
Uniform piston	0
First order	Gaussian
Quadratic piston	0
Magnification	$W_{111}\vec{H}$
Focus	$2W_{020}\vec{\rho}$
Third order	Seidel
Spherical aberration	$4W_{040}(\vec{\rho}\cdot\vec{\rho})\vec{\rho}$
Coma	$W_{131}\left[(\vec{\rho}\cdot\vec{\rho})\vec{H}+2(\vec{H}\cdot\vec{\rho})\vec{\rho}\right]$
Astigmatism	$2W_{222}(\vec{H}\cdot\vec{\rho})\vec{H}$
Field curvature	$2W_{220}(\vec{H}\cdot\vec{H})\vec{\rho}$
Distortion	$W_{311}(\vec{H}\cdot\vec{H})\vec{H}$
Quartic piston	0

Piston terms do not contribute transverse ray aberration

Components

In order to calculate and plot the components of the transverse ray aberrations we write the field and aperture vectors as,

$$\vec{H} = H\vec{h}$$

$$\vec{\rho} = \rho\vec{g}$$

where $\vec{h}$ is a unit vector in the direction of $\vec{H}$ and $\vec{g}$ is a unit vector in the direction of $\vec{\rho}$. The magnitudes H and ρ have ranges $0 \le H \le 1$ and $0 \le \rho \le 1$. The transverse ray aberration vector $\bar{y}_I \Delta\vec{H}$ can be written as,

$$\bar{y}_I \Delta\vec{H} = A\vec{h} + B\vec{g}$$

Components

$$A=\frac{1}{n'u'}\sum_{j,m,m}W_{k,l,m}\left[m\left(\vec{H}\cdot\vec{H}\right)^{j}\left(\vec{H}\cdot\vec{\rho}\right)^{m-1}\left(\vec{\rho}\cdot\vec{\rho}\right)^{n}\right]H=$$

$$=\frac{1}{n'u'}\sum_{j,m,m}W_{k,l,m}H^{k}\rho^{l-1}\left[m\cos^{m-1}(\phi)\right]$$

,

$$B=\frac{1}{n'u'}\sum_{j,m,m}W_{k,l,m}\left[2n\left(\vec{H}\cdot\vec{H}\right)^{j}\left(\vec{H}\cdot\vec{\rho}\right)^{m}\left(\vec{\rho}\cdot\vec{\rho}\right)^{n-1}\right]\rho=$$

$$=\frac{1}{n'u'}\sum_{j,m,m}W_{k,l,m}H^{k}\rho^{l-1}\left[(l-m)\cos^{m}(\phi)\right]$$

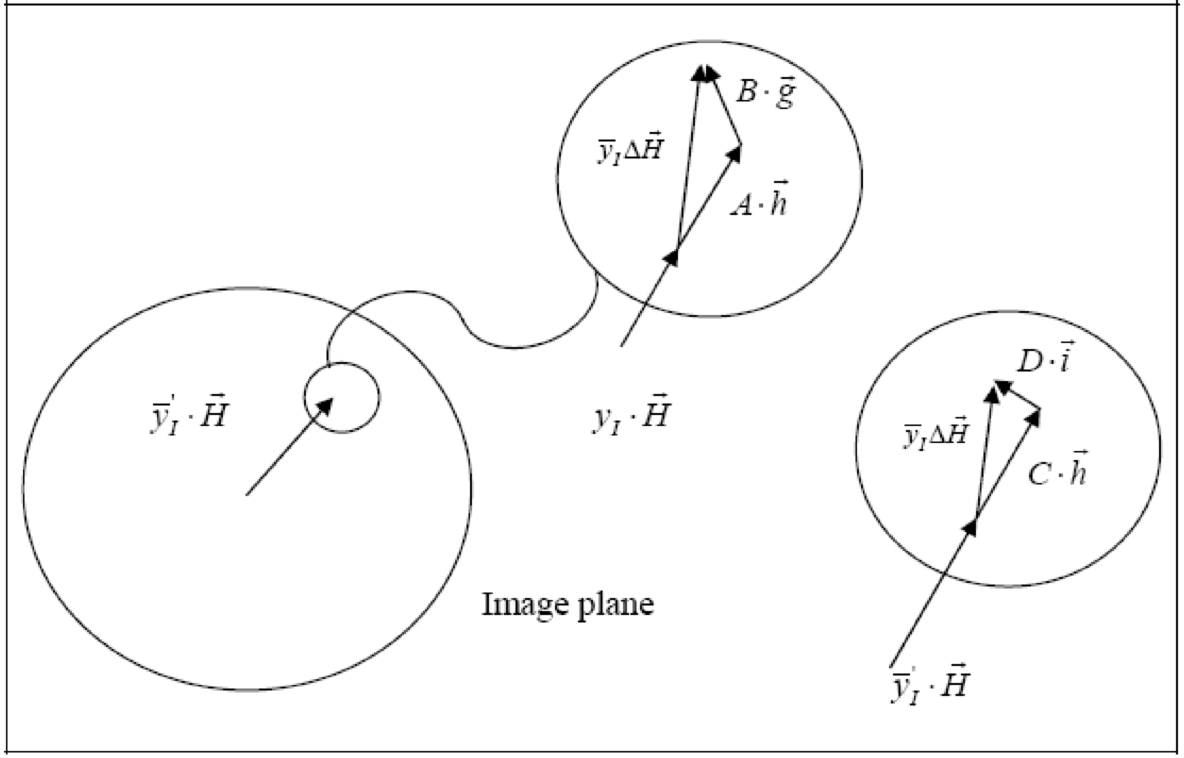
$$k=2j+m \qquad l=2n+m$$

The components of $\overline{y}_I \Delta \vec{H}$

$$\overline{y}_I \Delta \vec{H} = A\vec{h} + B\vec{g}$$

$$\overline{y}_I \Delta \vec{H} = C\vec{h} + D\vec{i} = \left(A + B\cos(\varphi)\right)\vec{h} + \left(B\sin(\varphi)\right)\vec{i}$$

The components $A \cdot \vec{h}$ and $B \cdot \vec{g}$, and the orthogonal components $C \cdot \vec{h}$ and $D \cdot \vec{i}$ of the vector $\overline{y}_I \Delta \vec{H}$.



Orthogonal Components

$$\overline{y}_I \Delta\vec{H} = C\vec{h} + D\vec{i} = \left(A + B\cos(\varphi)\right)\vec{h} + \left(B\sin(\varphi)\right)\vec{i}$$

$\vec{i}$ is a unit vector orthogonal to $\vec{h}$

$$C = \frac{1}{n'u'}\sum_{j,m,m} W_{k,l,m} H^k \rho^{l-1}\left[m\cos^{m-1}(\phi) + (l-m)\cos^m(\phi)\cos(\phi)\right]$$

$$D = \frac{1}{n'u'}\sum_{j,m,m} W_{k,l,m} H^k \rho^{l-1}\left[(l-m)\cos^m(\phi)\sin(\phi)\right]$$

$$k = 2j + m \qquad l = 2n + m$$

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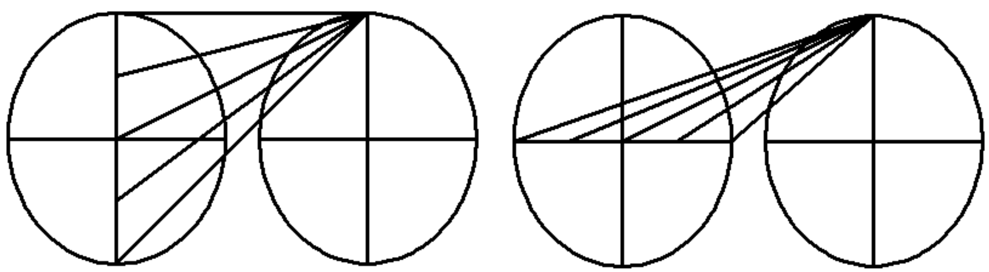
Choice of ray fan plots

For historical reasons plots of ray intercepts at the observation plane, of rays in the meridional plane and in the sagittal plane, are usually produced. Since there is symmetry only one half of the sagittal rays intercepts may be plotted.



$$(\phi = 0) \qquad (\phi = 90)$$

Meridional rays

$$C = \frac{1}{n'u'}\sum_{j,m,m} W_{k,l,m} H^k \rho^{l-1}\left[m\cos^{m-1}(\phi) + (l-m)\cos^m(\phi)\cos(\phi)\right]$$

$$D = \frac{1}{n'u'}\sum_{j,m,m} W_{k,l,m} H^k \rho^{l-1}\left[(l-m)\cos^m(\phi)\sin(\phi)\right]$$

For the meridional rays the intercept is given by, $(\phi = 0)$

,

$$C = \frac{1}{n'u'}\sum_{j,m,n} W_{k,l,m} H^k \left(l\rho^{l-1}\right)$$

$$D = 0$$

$$l = 2n + m$$
$$k = 2j + m$$

Since $D = 0$

the meridional ray intercepts remain in the meridional plane.

Sagittal rays

$$(\phi = 90)$$

According to the integer m the sagittal ray intercepts are given by,

$$C = \frac{1}{n'u'} \sum_{j,1,n} W_{k,l,1} H^k \left(\rho^{l-1}\right) \qquad m = 1$$

$$C = 0 \qquad m \neq 1$$

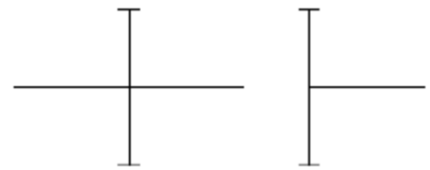
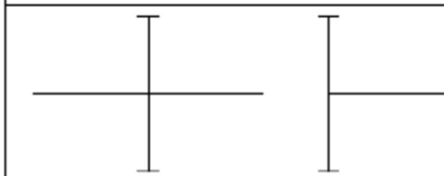
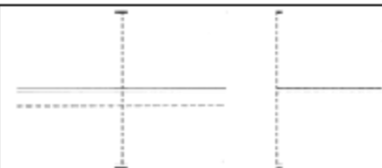
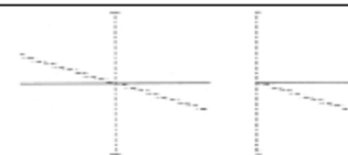
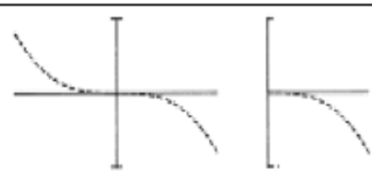
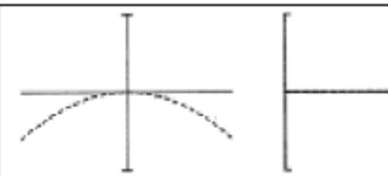
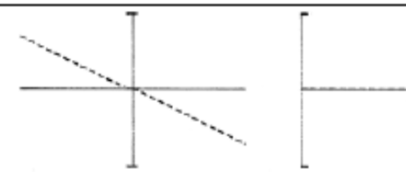
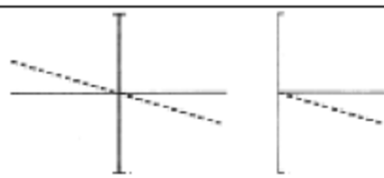
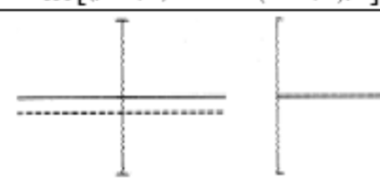
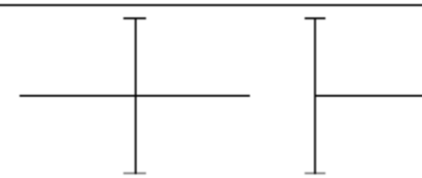
$$D = \frac{1}{n'u'} \sum_{j,0,n} W_{k,l,0} H^k \left(l\rho^{l-1}\right) \qquad m = 0$$

$$D = 0 \qquad m \neq 0$$

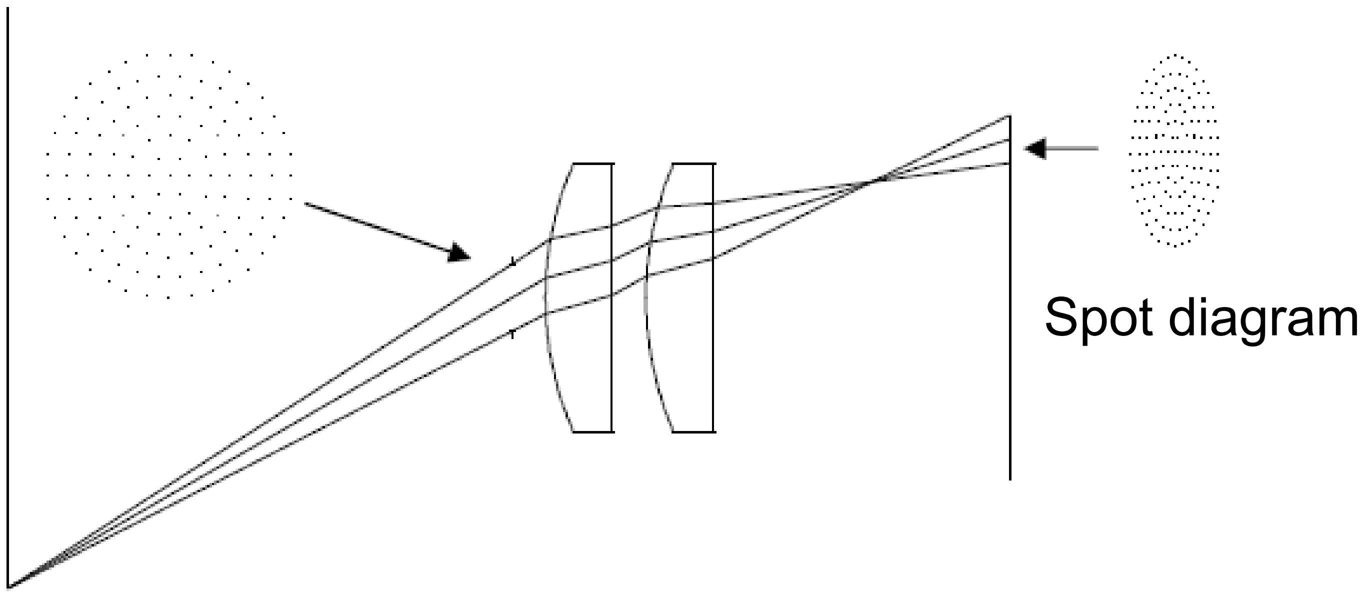
Summary

Transverse ray aberrations scalar components				
Aberration	A	B	C	D
W_{000}	0	0	0	0
$W_{200}(\vec{H}\cdot\vec{H})$	0	0	0	0
$W_{111}(\vec{H}\cdot\vec{\rho})$	H	0	H	0
$W_{020}(\vec{\rho}\cdot\vec{\rho})$	0	2ρ	$2\rho\cos(\phi)$	$2\rho\sin(\phi)$
$W_{040}(\vec{\rho}\cdot\vec{\rho})^2$	0	$4\rho^3$	$4\rho^3\cos(\phi)$	$4\rho^3\sin(\phi)$
$W_{131}(\vec{H}\cdot\vec{\rho})(\vec{\rho}\cdot\vec{\rho})$	$H\rho^2$	$2H\rho^2\cos(\phi)$	$H\rho^2(1+2\cos^2(\phi))$	$2H\rho^2\sin(\phi)\cos(\phi)$
$W_{222}(\vec{H}\cdot\vec{\rho})^2$	$2H\rho^2\cos(\phi)$	0	$2H\rho^2\cos(\phi)$	0
$W_{220}(\vec{H}\cdot\vec{H})(\vec{\rho}\cdot\vec{\rho})$	0	$2H\rho^2$	$2H\rho^2\cos(\phi)$	$2H\rho^2\sin(\phi)$
$W_{311}(\vec{H}\cdot\vec{H})(\vec{H}\cdot\vec{\rho})$	H^3	0	H^3	0
$W_{400}(\vec{H}\cdot\vec{H})^2$	0	0	0	0

Transverse ray aberration fans

Transverse ray aberration fans Left plot meridional, right plot sagittal		
Zero-order		
		
$W_{000} = 0$		
First-order		
		
$W_{200} = 0$	$W_{111}\vec{H}$	$2W_{020}\vec{\rho}$
Third-order		
		
$4W_{040}(\vec{\rho}\cdot\vec{\rho})\vec{\rho}$	$W_{131}\left[(\vec{\rho}\cdot\vec{\rho})\vec{H}+2(\vec{H}\cdot\vec{\rho})\vec{\rho}\right]$	$2W_{222}(\vec{H}\cdot\vec{\rho})\vec{H}$
		
$2W_{220}(\vec{H}\cdot\vec{H})\vec{\rho}$	$W_{311}(\vec{H}\cdot\vec{H})\vec{H}$	$W_{400} = 0$

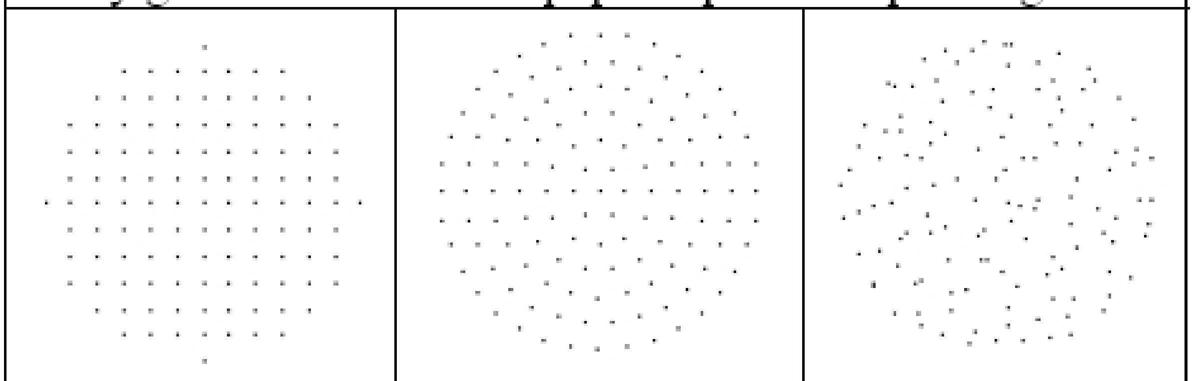
Concept of spot diagram



A grid of points is defined at the entrance or exit pupil of an optical system and rays are traced from the object point through the grid points, through the observation plane. The rays intersections form a spot diagram.

Ray grids

Ray grids at the entrance pupil to produce spot diagrams



Square	Hexapolar	Dithered

Located at the entrance or exit pupil plane

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Spot diagrams for spherical aberration, coma, and astigmatism

What are the symmetries?

Prof. Jose Sasian
OPTI 518

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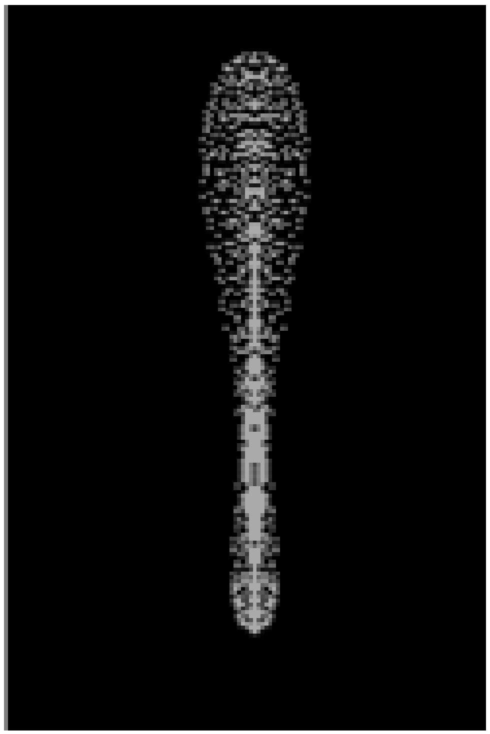
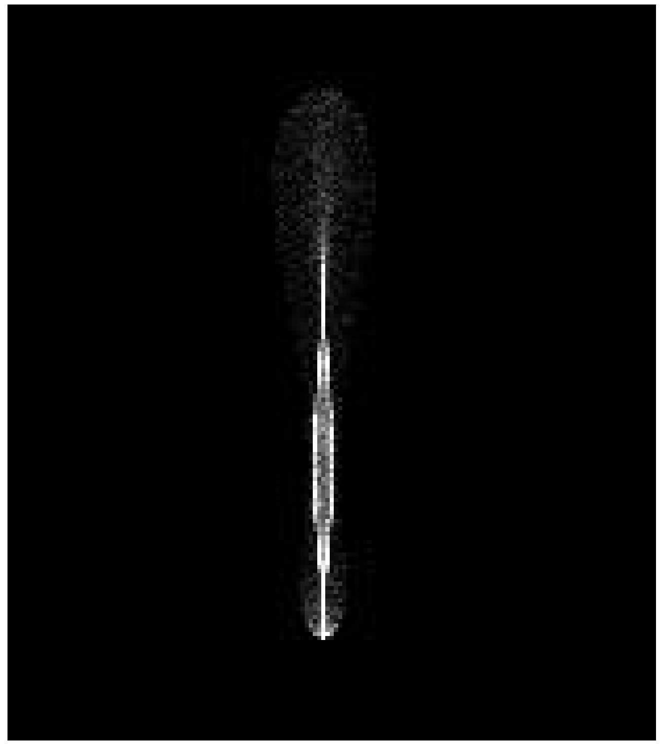
The University of Arizona®

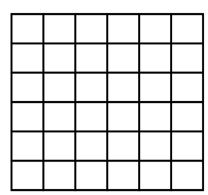
Binning and counting spots



Spot diagram



Binning and counting



Diffraction based

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RMS Spot size

$$RMS = \left|\bar{y}_I\right|\sqrt{\overline{\left|\Delta\vec{H}\right|^2}}$$

$$\overline{\left|\Delta\vec{H}\right|^2} = \frac{1}{Ж^2}\overline{\left|\vec{\nabla}_\rho W\left(\vec{H},\vec{\rho}\right)\right|^2} = \frac{1}{Ж^2}\frac{1}{\pi}\int_0^{2\pi}\int_0^1\left|\vec{\nabla}_\rho W\left(\vec{H},\vec{\rho}\right)\right|^2\rho d\rho d\phi$$

$$W\left(\vec{H},\vec{\rho}\right)= W_{040}\left(\vec{\rho}\cdot\vec{\rho}\right)^2 + W_{131}\left(\vec{H}\cdot\vec{\rho}\right)\left(\vec{\rho}\cdot\vec{\rho}\right) + W_{222}\left(\vec{H}\cdot\vec{\rho}\right)^2$$
$$+W_{220}\left(\vec{H}\cdot\vec{H}\right)\left(\vec{\rho}\cdot\vec{\rho}\right) + W_{311}\left(\vec{H}\cdot\vec{H}\right)\left(\vec{H}\cdot\vec{\rho}\right) + W_{400}\left(\vec{H}\cdot\vec{H}\right)^2$$

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RMS Spot size

$$RMS^2 = \bar{y}_I^2 \overline{\left|\Delta\vec{H}\right|^2} = \frac{1}{(n'u')^2}\left(\begin{array}{l} 2\left(W_{020} + \frac{4}{3}W_{040} + (W_{222} + W_{220P})\left(\vec{H}\cdot\vec{H}\right)\right)^2 \\ +\left(W_{131}\vec{H} + W_{311}\left(\vec{H}\cdot\vec{H}\right)\vec{H}\right)^2 \\ +\frac{4}{9}W_{040}^2 + \frac{1}{2}W_{222}^2\left(\vec{H}\cdot\vec{H}\right)^2 + \frac{2}{3}W_{131}^2\left(\vec{H}\cdot\vec{H}\right) \end{array}\right)$$

Summary

- Transverse ray aberration
- Spot diagrams
- Wave fans and ray fans
- Meridional and sagittal planes
- Special locations along the ray caustic
- RMS spot size