Forbidden Pitch or Duty-Free

Revealing the Causes of Across-Pitch Imaging Differences

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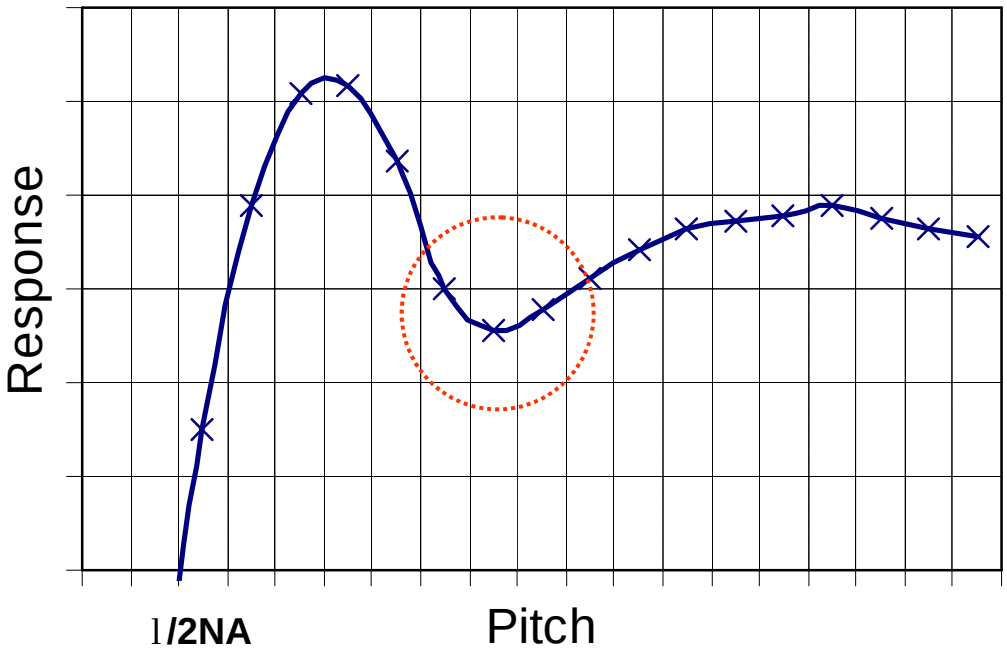
Forbidden or Problematic

Nothing is forbidden $\geq \lambda/2NA$



- Response may be CD, placement error, modulation, NILS, profile, etc.
- "Forbidden" is a message for designers.
- Lithographers don't like to be told what to do.
- Sensitivities should not provide excuses.
- Nothing forbidden > $\lambda/2NA$.

Imaging Situations

1. Binary masking effects
2. Off-axis illumination effects
3. Assist feature effects
4. Contact side-lobes
5. Aberration effects

CD Variation with Pitch
Conventional Binary Masking

CD variation is a consequence of order capture and diffraction energy

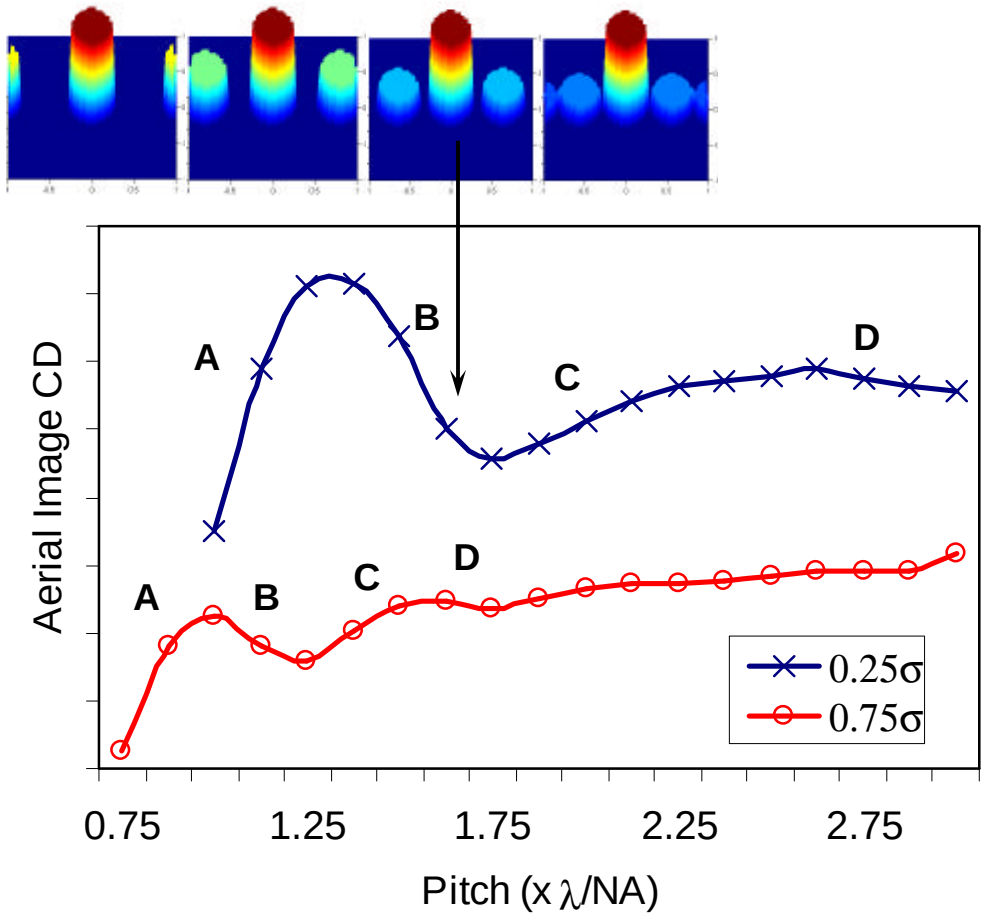
Dominant Effect

A - 1st order capture $\frac{l}{(s+1)NA}$

B - Zero order increase $\frac{l}{(s-1)NA}$

C - 2nd order capture $\frac{2l}{(s+1)NA}$

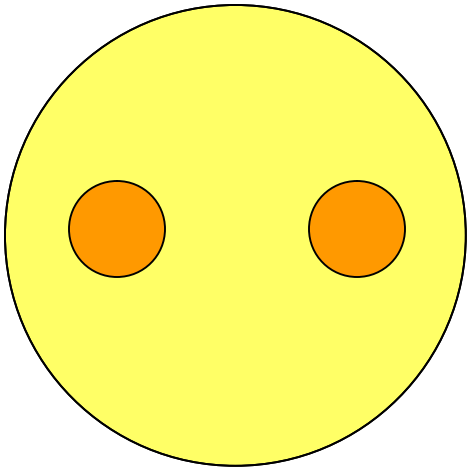
D - Zero order increase $\frac{2l}{(s-1)NA}$

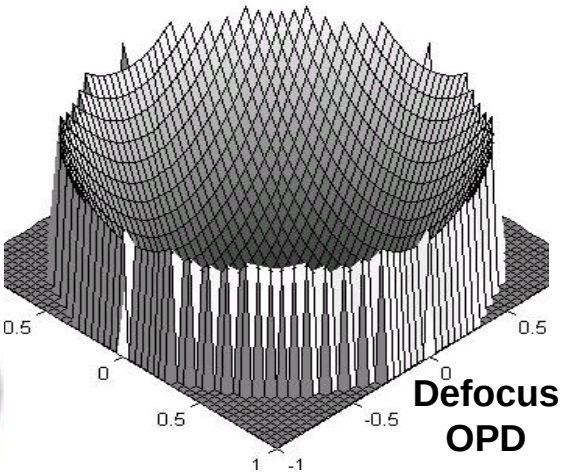


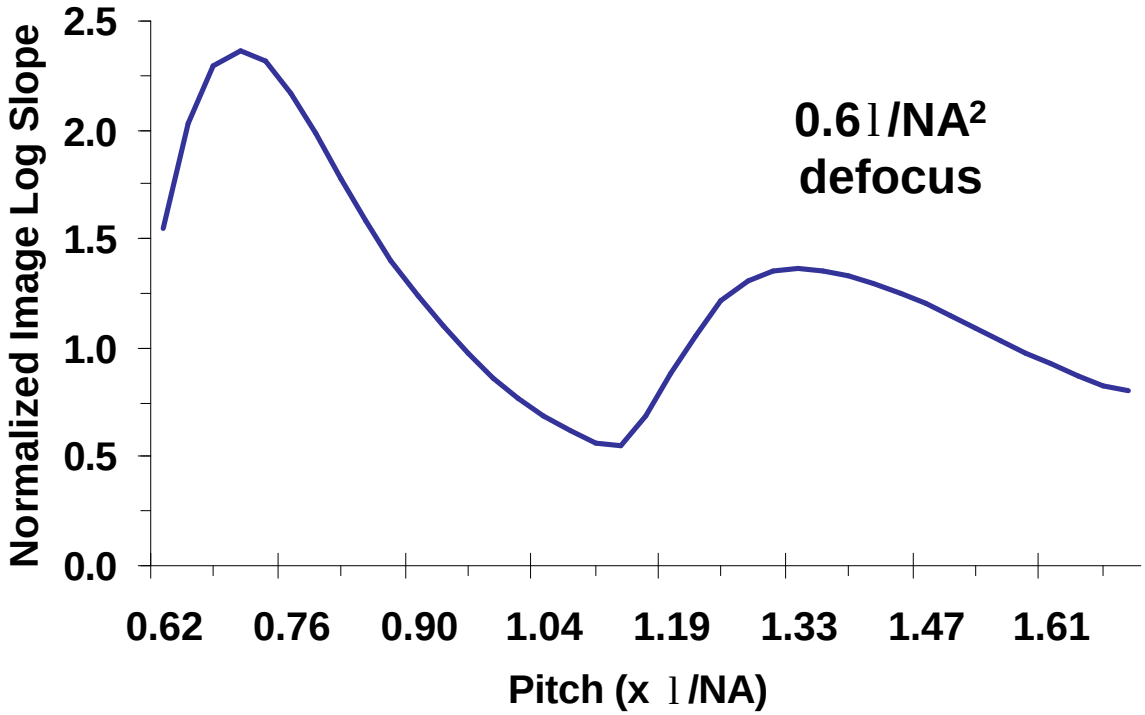
Illumination and Problematic Pitch

OAI for one pitch can be worst case for another

0.7 dipole







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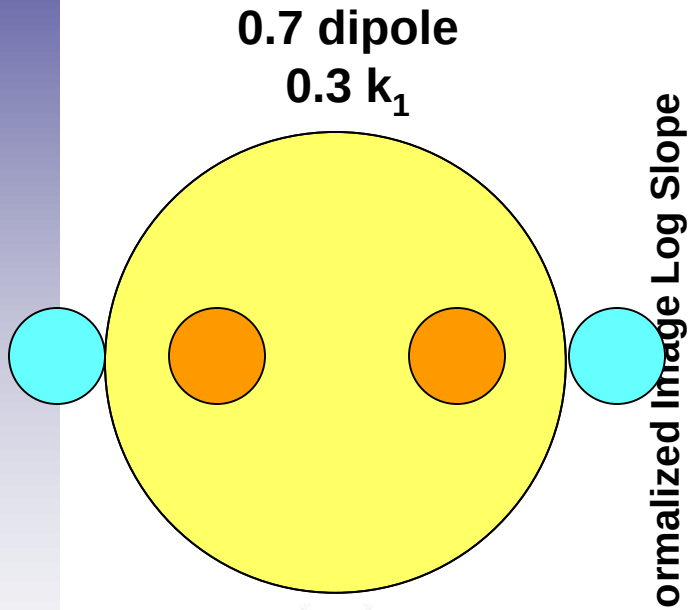

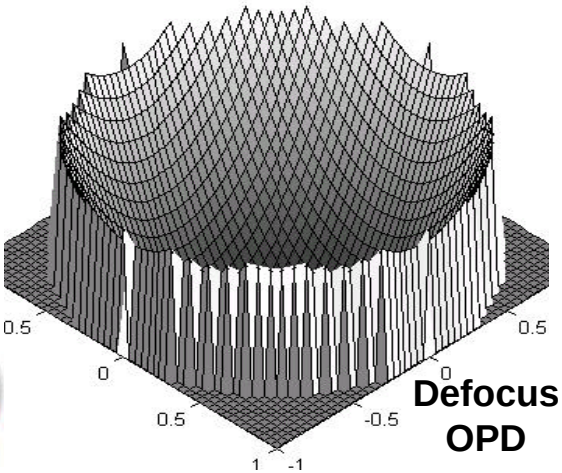

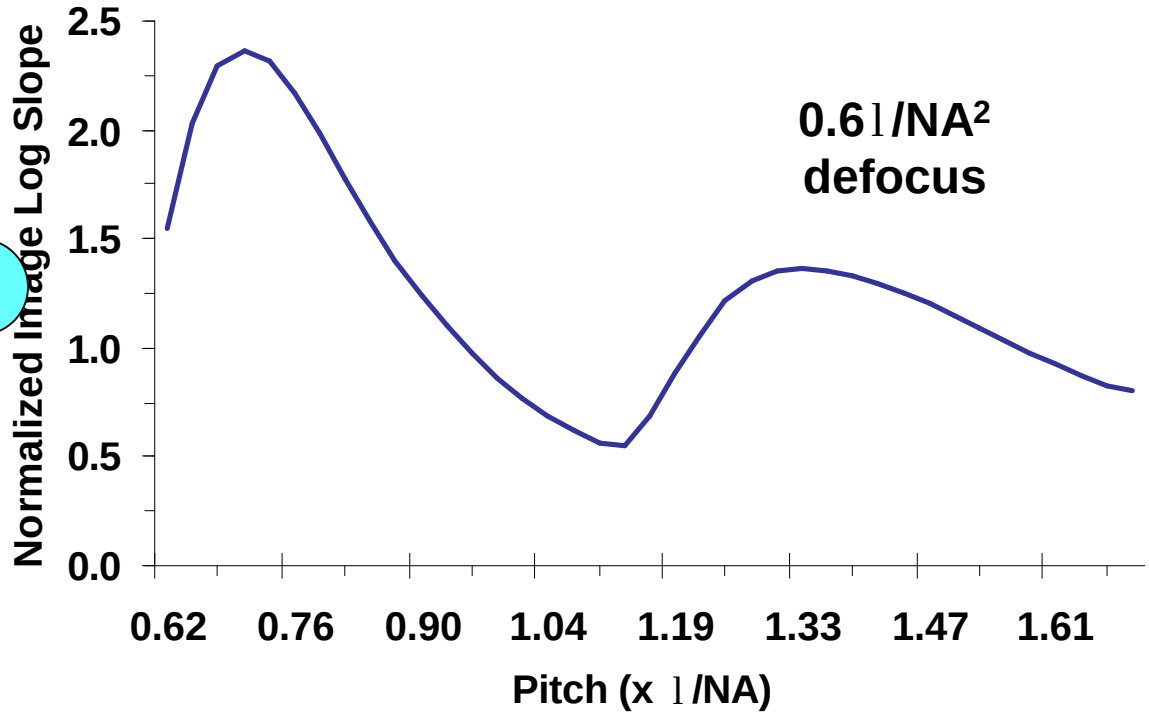

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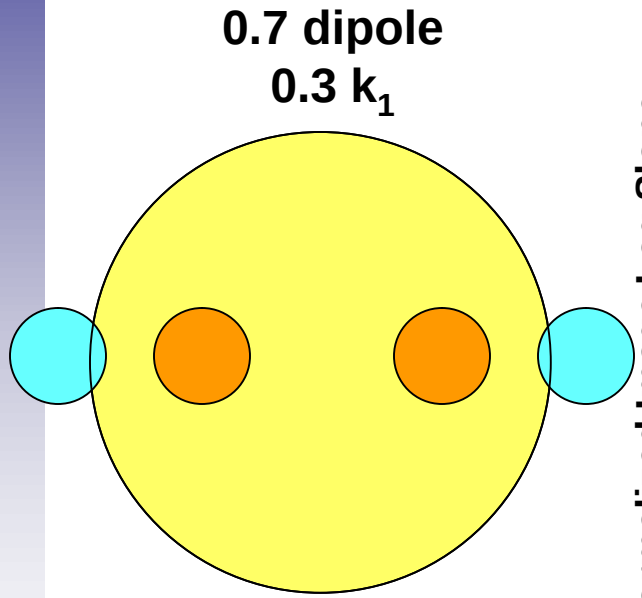
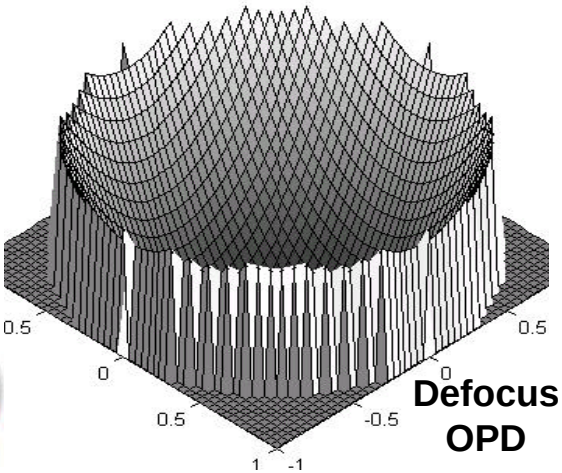
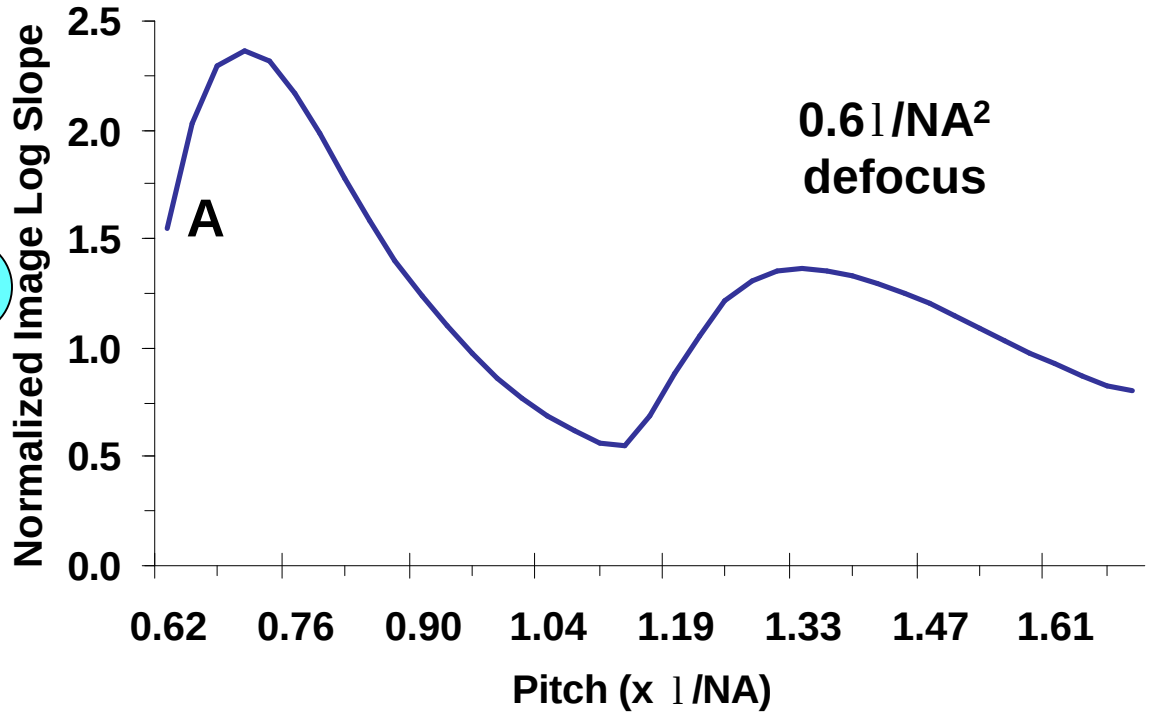


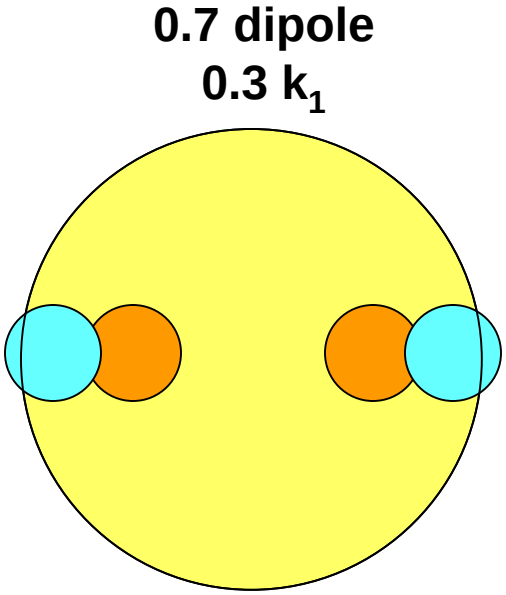


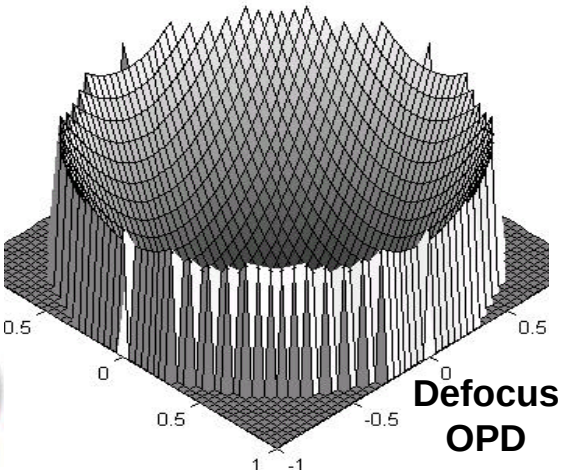


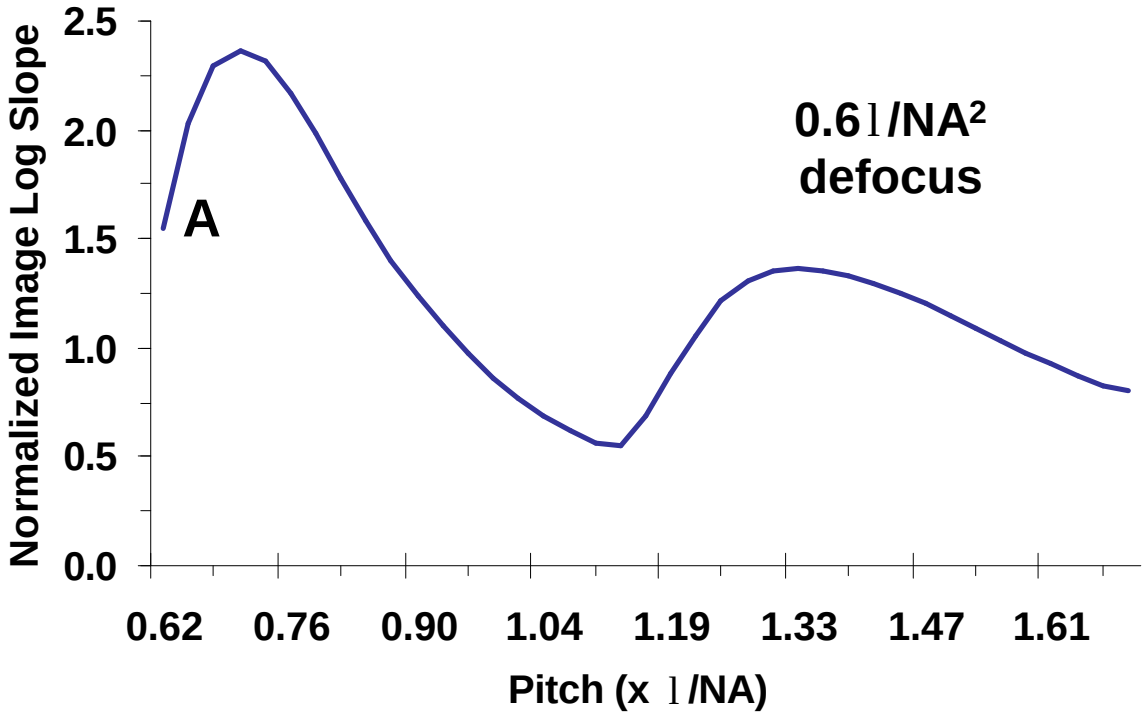
A - 1st order capture

Illumination and Problematic Pitch

OAI for one pitch can be worst case for another





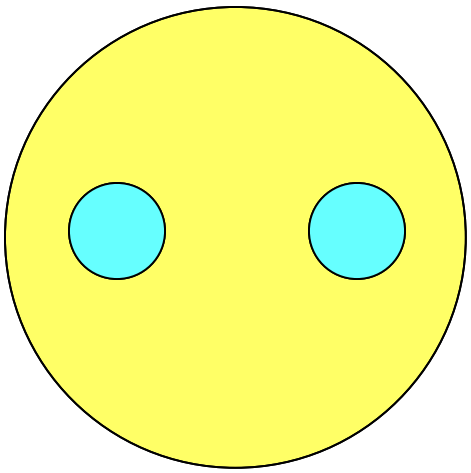


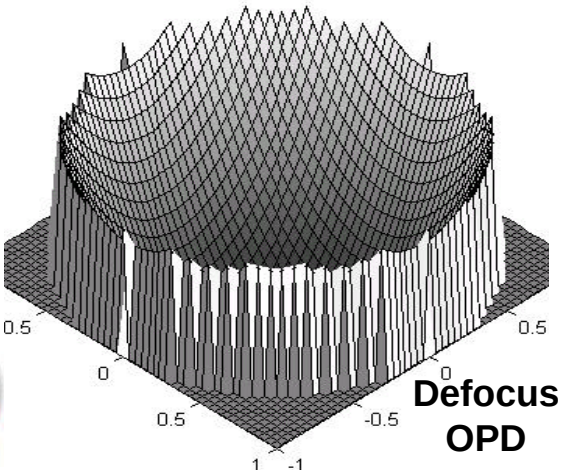
A - 1st order capture

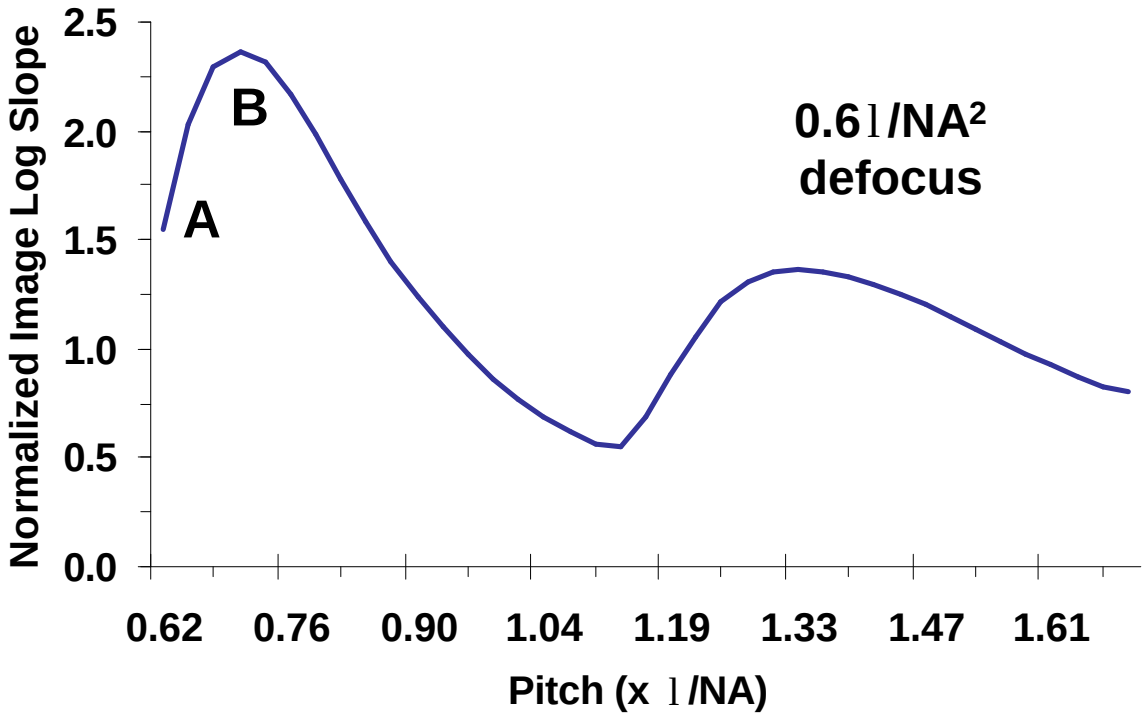
Illumination and Problematic Pitch

OAI for one pitch can be worst case for another

0.7 dipole
0.3 k_1







A - 1st order capture

B – 0th and 1st overlap

Illumination and Problematic Pitch

OAI for one pitch can be worst case for another

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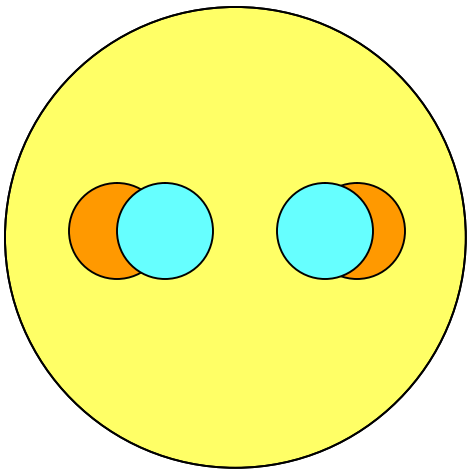
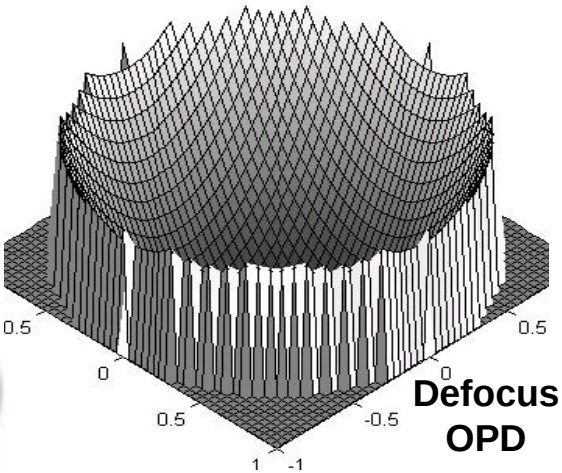
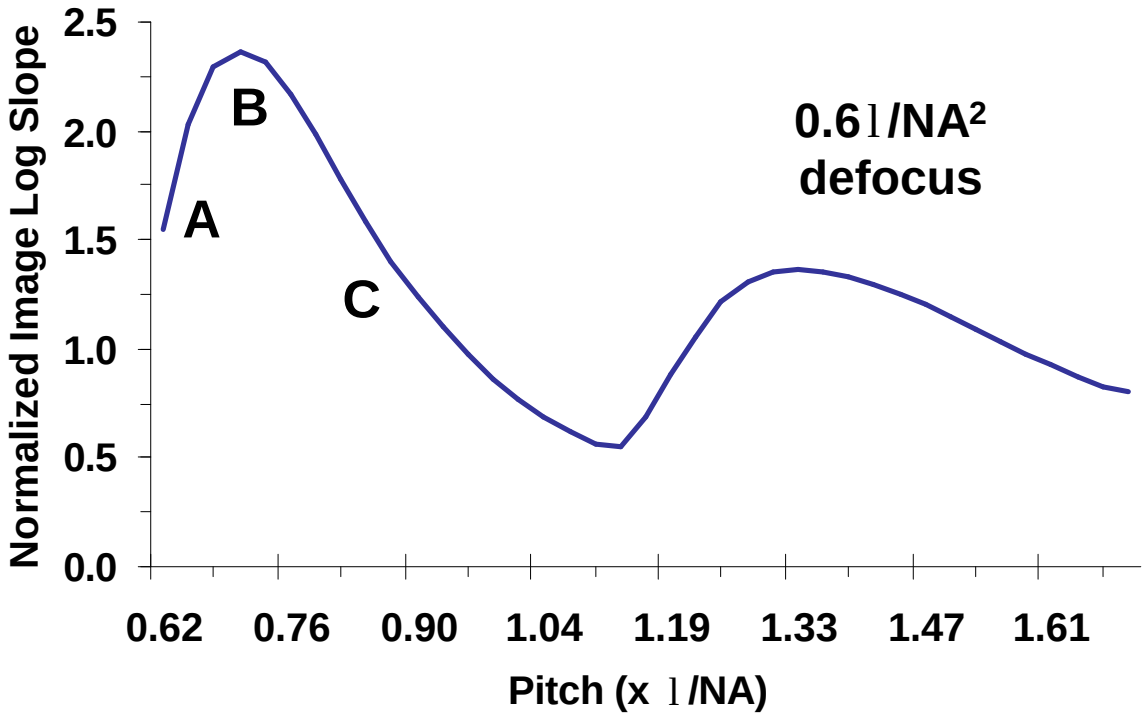






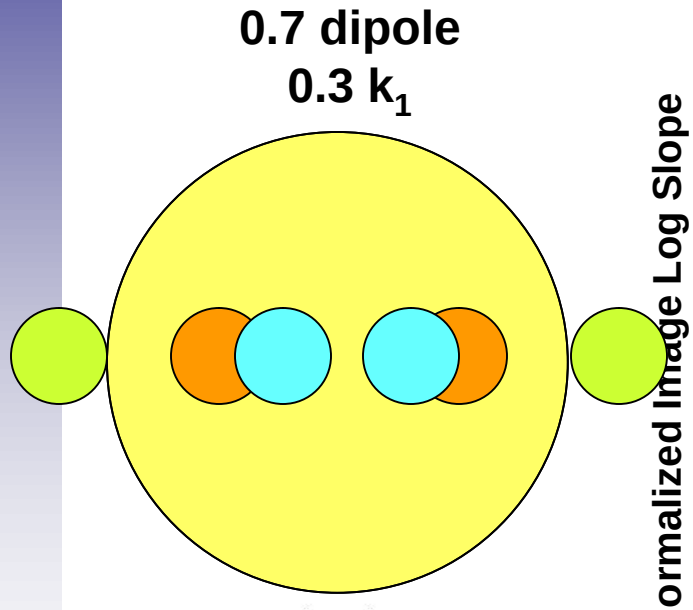
A - 1st order capture

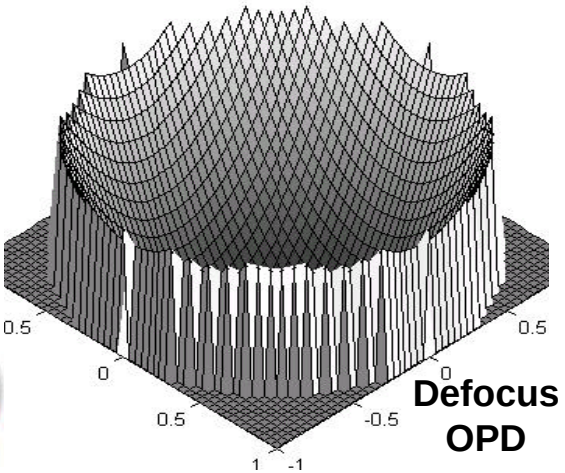
B – 0th and 1st overlap

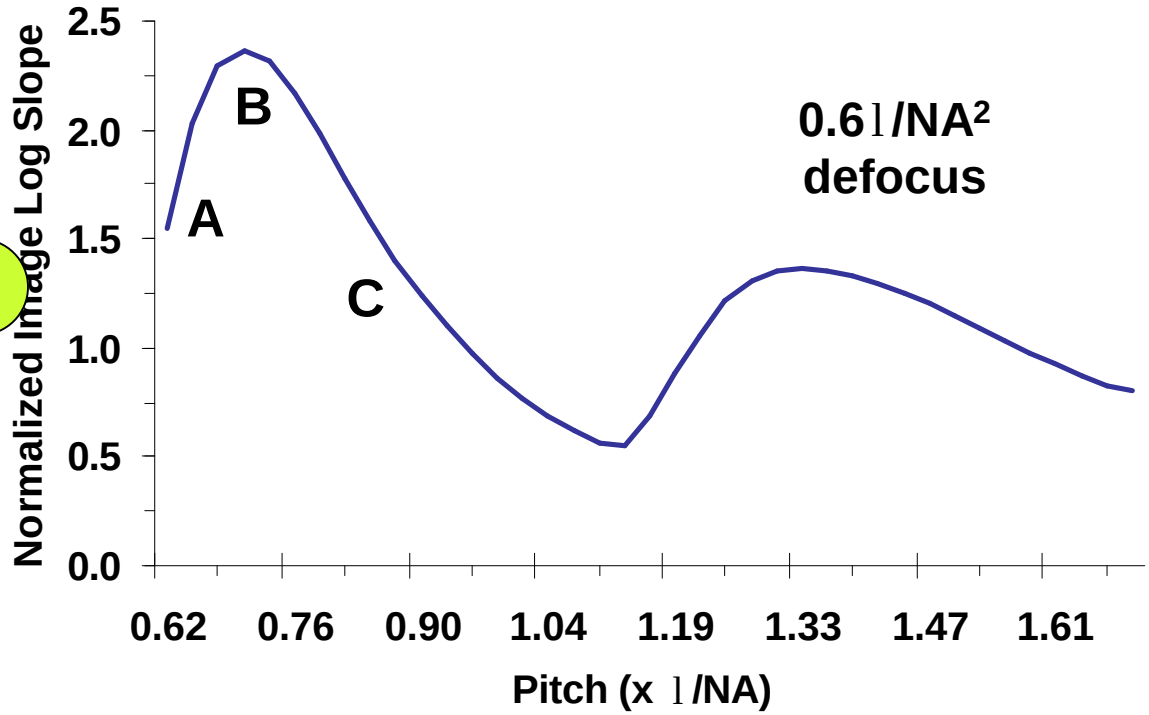
C – 1st into center

Illumination and Problematic Pitch

OAI for one pitch can be worst case for another







A - 1st order capture

B – 0th and 1st overlap

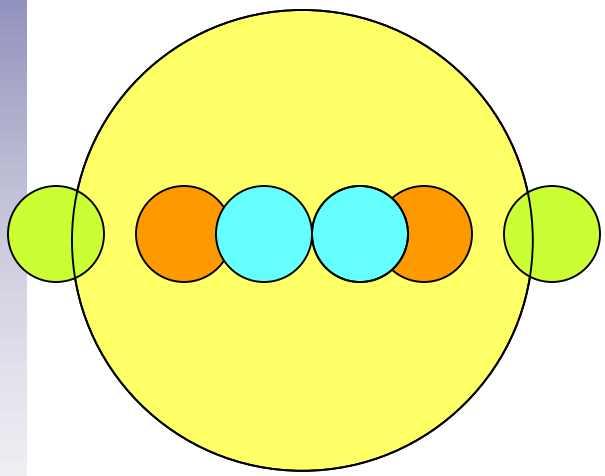
C – 1st into center

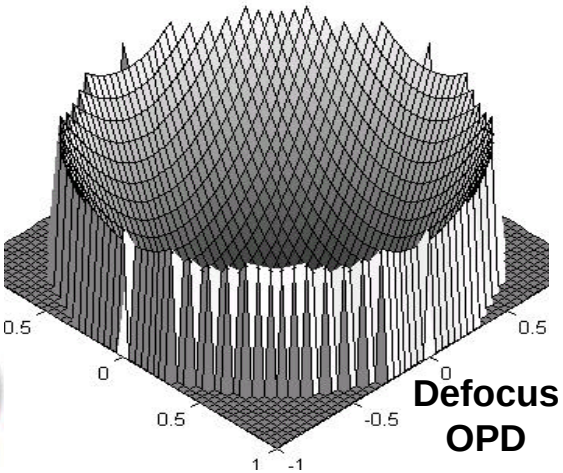
D – 2nd order capture

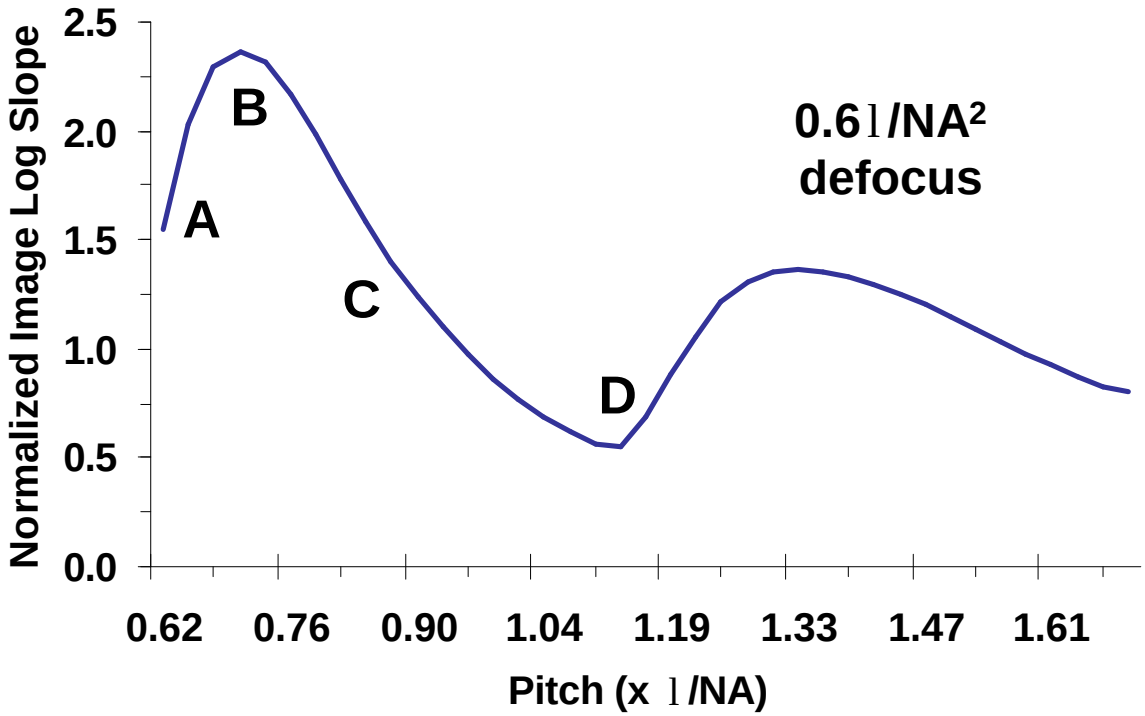
Illumination and Problematic Pitch

OAI for one pitch can be worst case for another

0.7 dipole
0.3 k_1







A - 1st order capture

B – 0th and 1st overlap

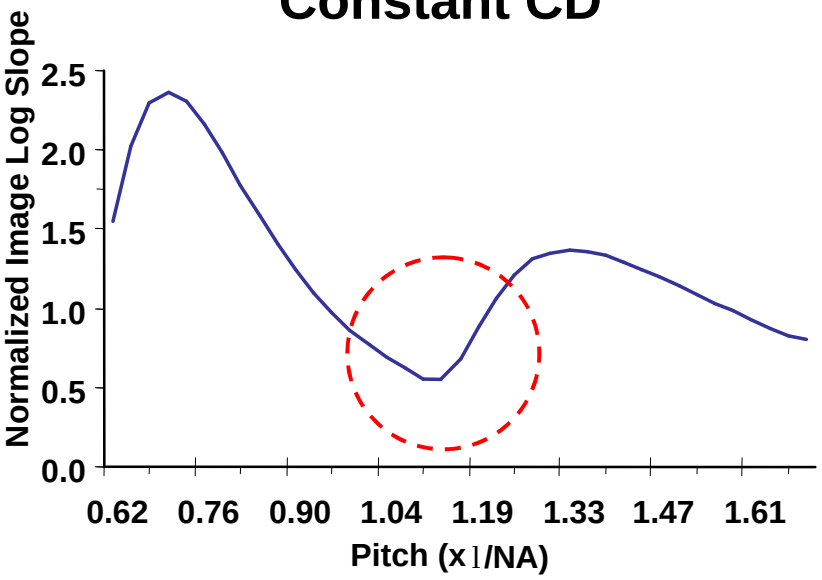
C – 1st into center

D – 2nd order capture

Illumination and Problematic Pitch

The second order effect

Increasing pitch
Constant CD



Increasing pitch
1:1 ratio

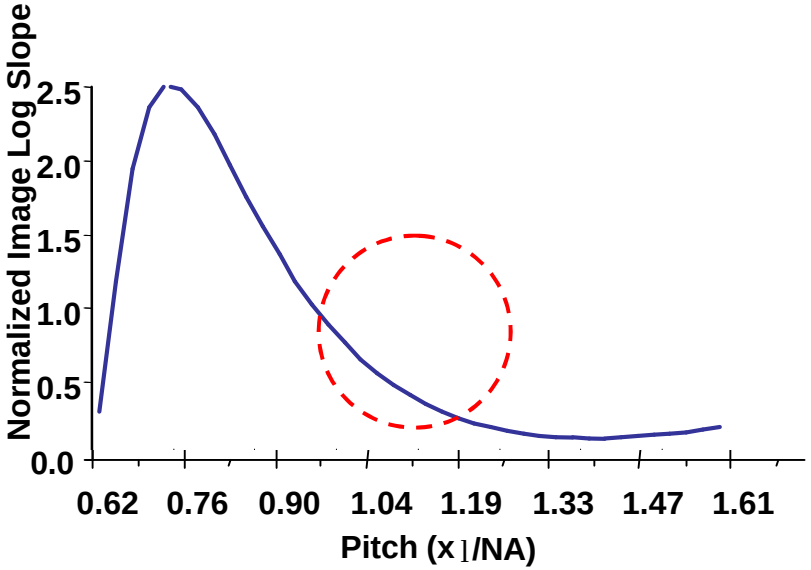
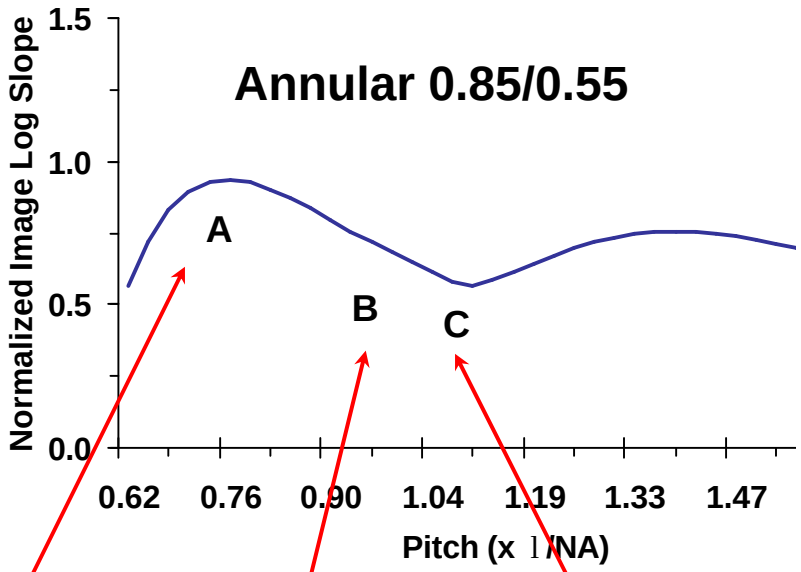
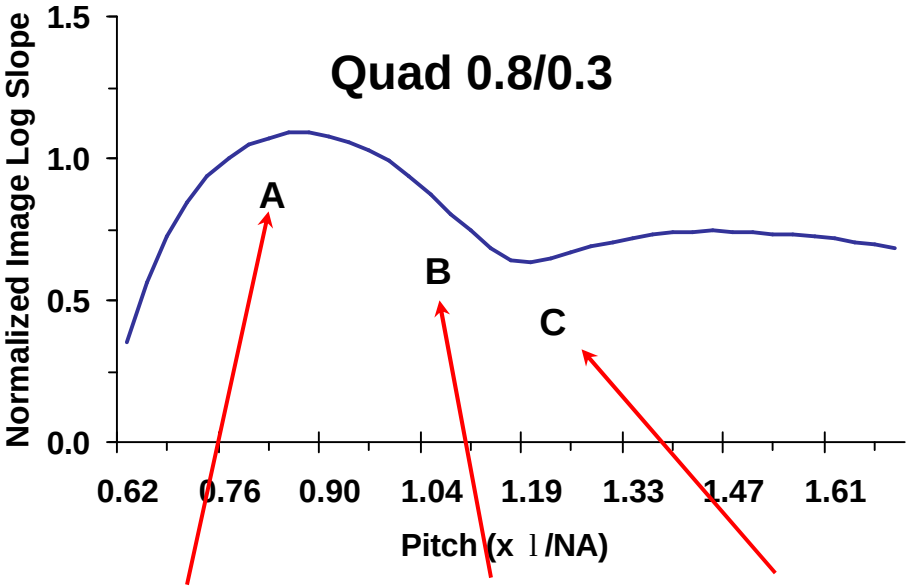


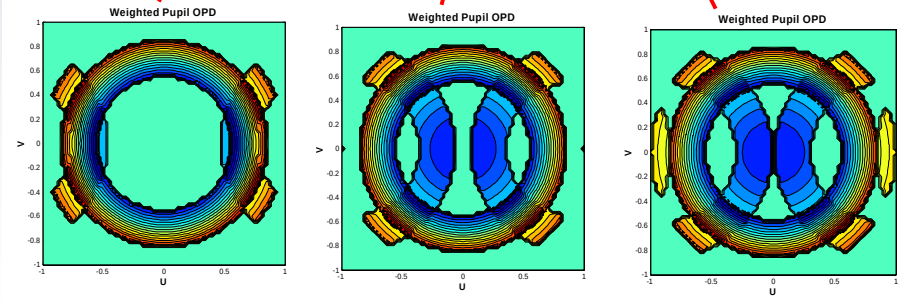
Image quality continues to decrease until the 3rd order is collected.

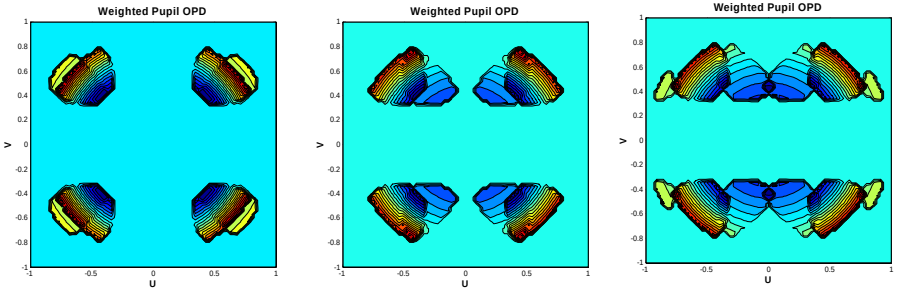
Illumination and Problematic Pitch

Annular and Quadrupole Illumination









A – 0th and 1st overlap

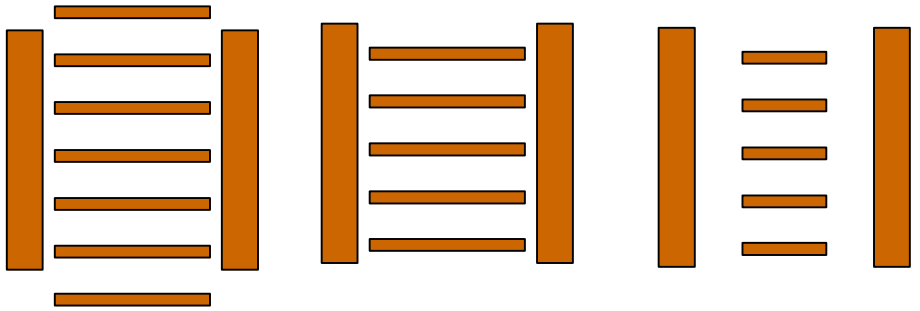
B – 1st into center

C – 2nd order capture

Assist Feature OPC

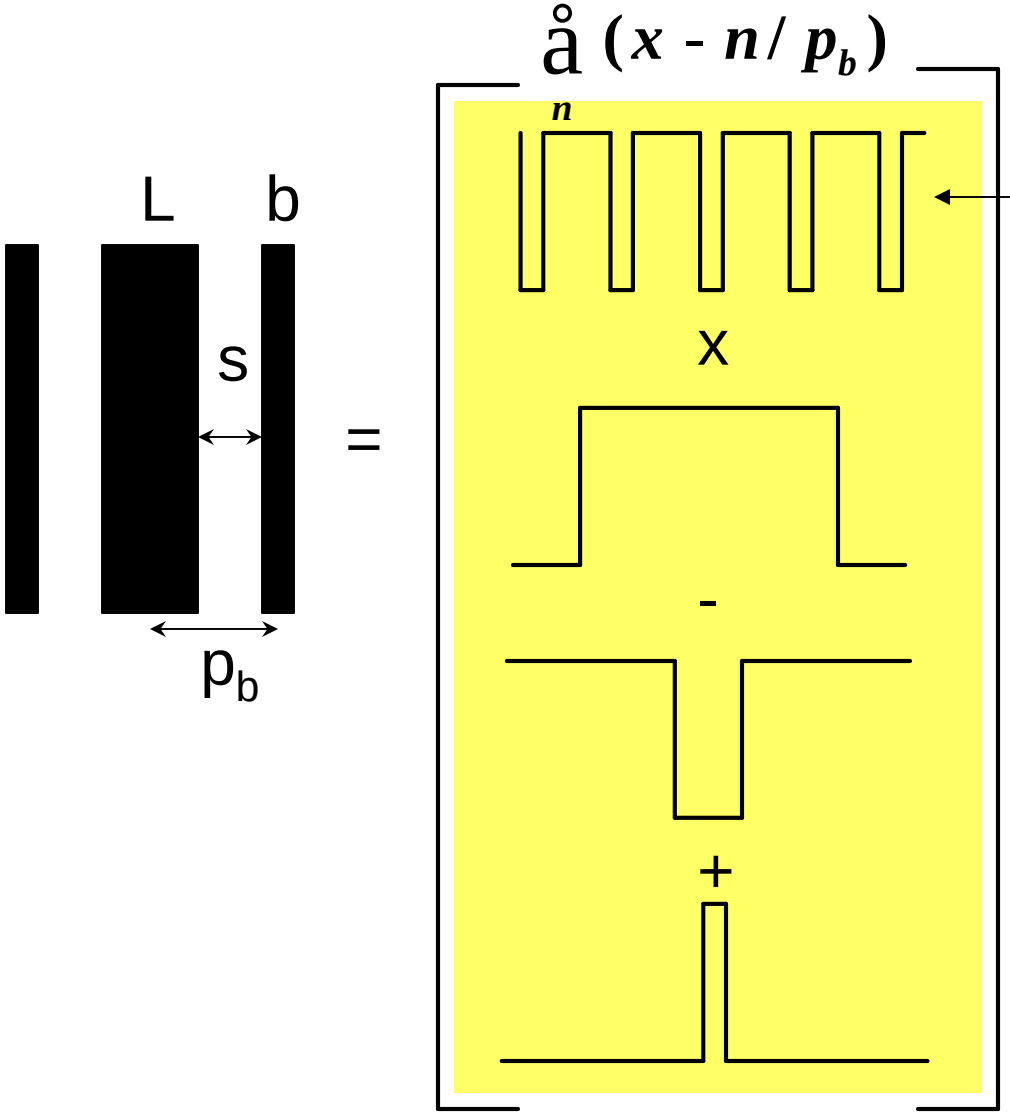
- Assist features are subjected to the same illumination considerations as main feature.
- Assist features will print at problematic pitch harmonics
- Orientation of bars can help, especially with OAI.

No problematic pitch with dipole.



One pair of bars

Consideration of main feature and bar pitch



Fundamental pitch of the bars

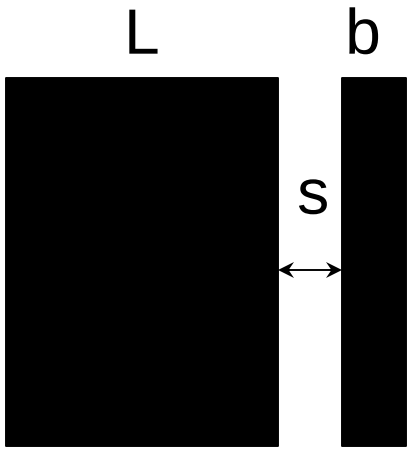
$* \sum_n (x - n/p_L)$

Pitch of the main feature

Bar printability is sensitive to illumination

The (bar + space) effect only

Is there a "hidden frequency"?



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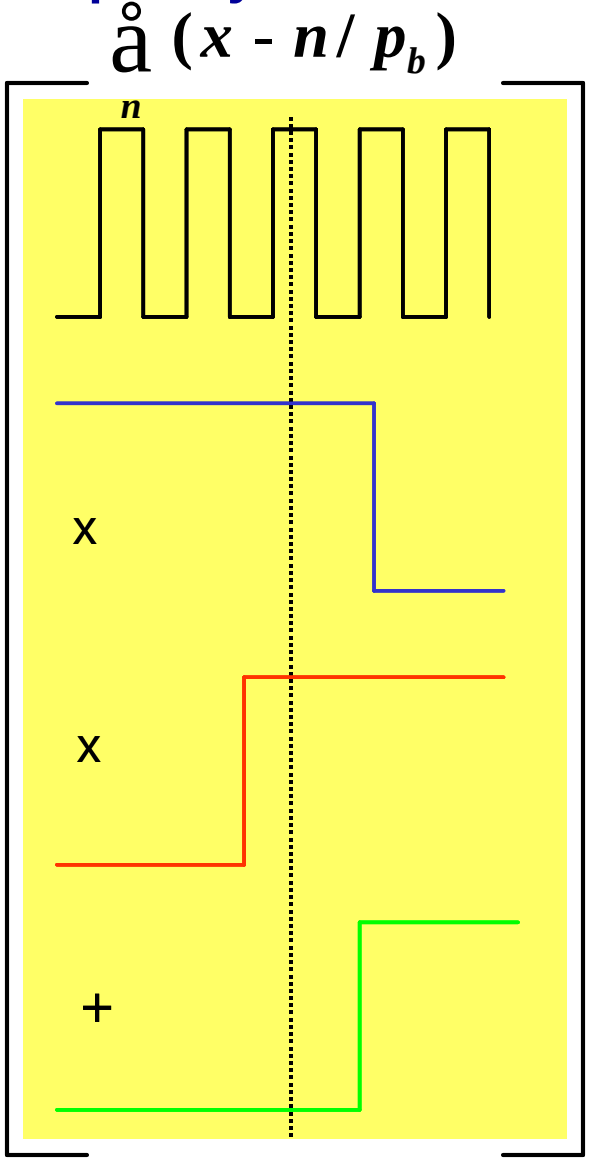
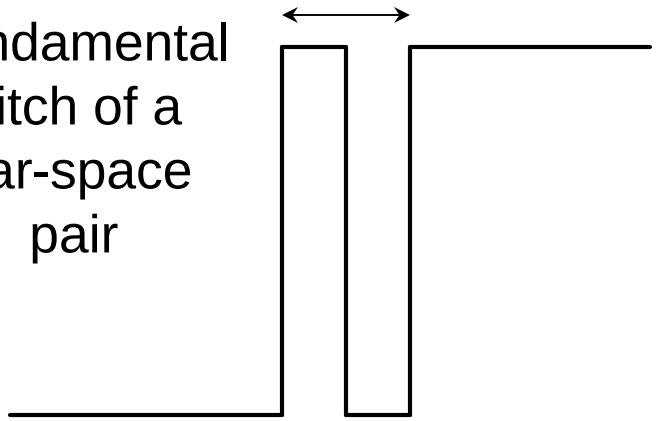


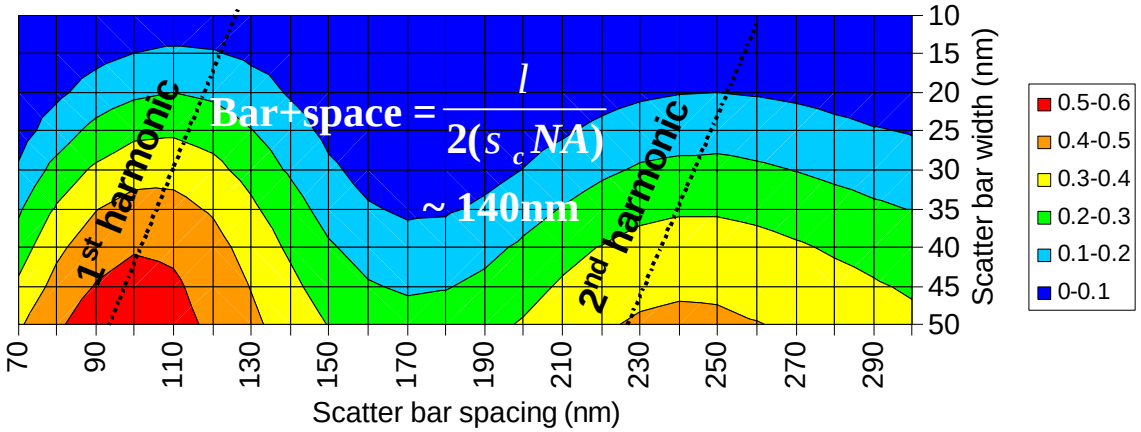
Fundamental pitch of a bar-space pair



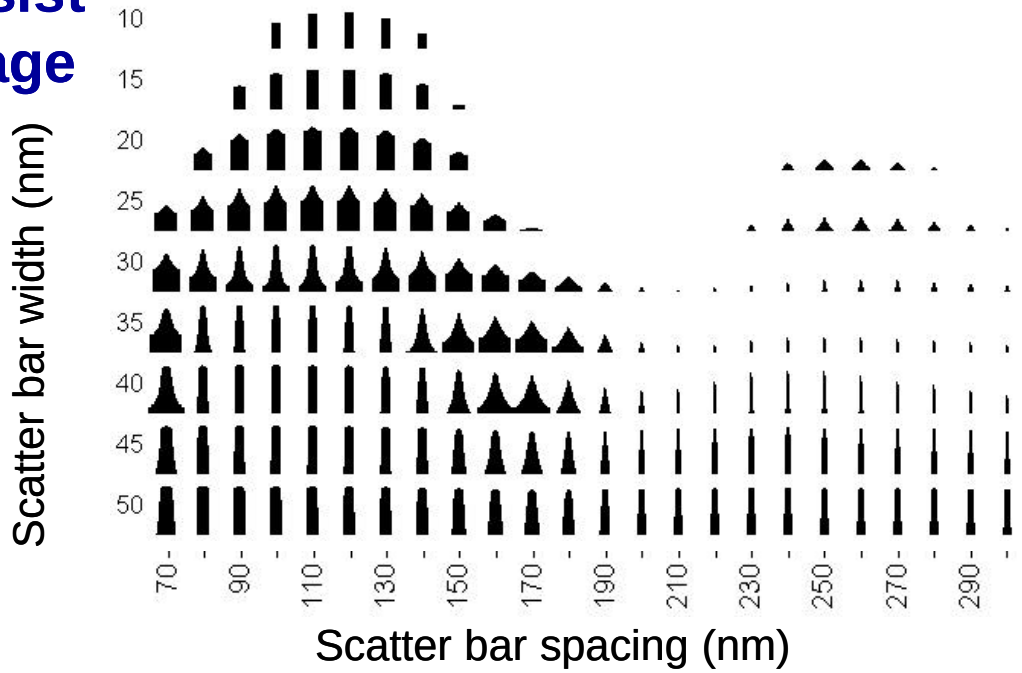
Printability of (bar + space) combinations

193nm/0.8NA/0.65-0.95 annular/ 70nm semi-iso CD

Aerial Image Contrast



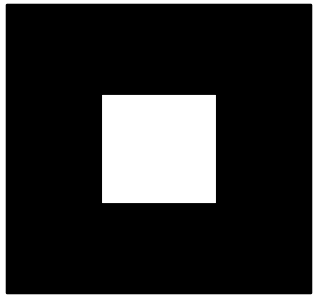
Resist Image



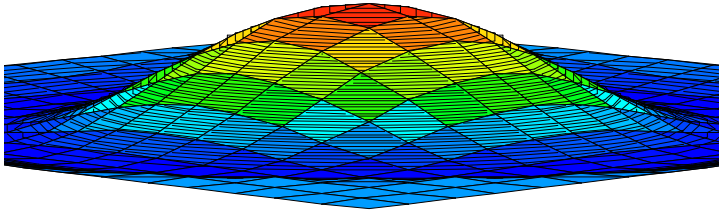
Contacts and Sidelobes

The Contact Misconception

Drawn contact



Diffraction



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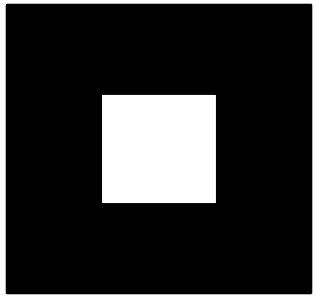
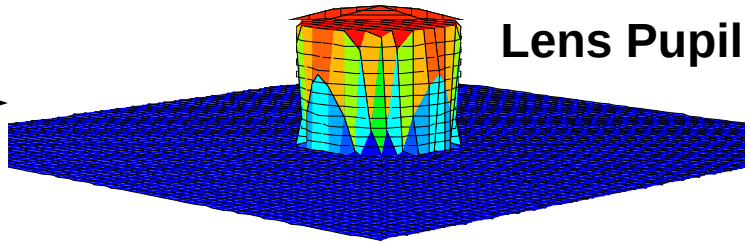
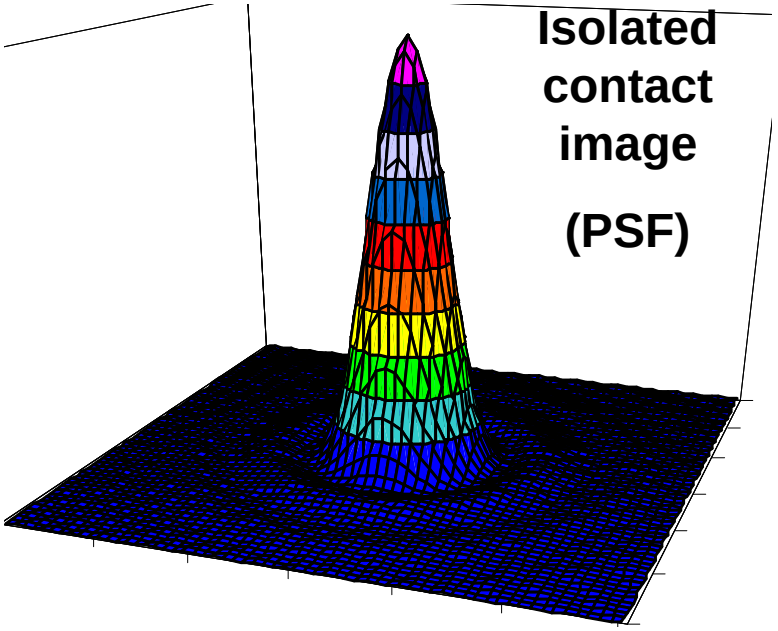


Diffraction



Lens Pupil



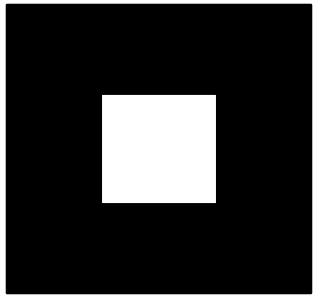
Isolated contact image

(PSF)

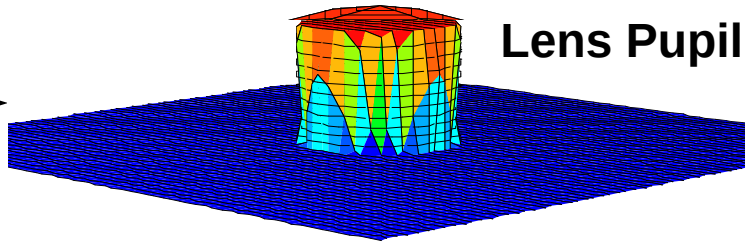
Contacts and Sidelobes

The Contact Misconception

Drawn contact



Diffraction

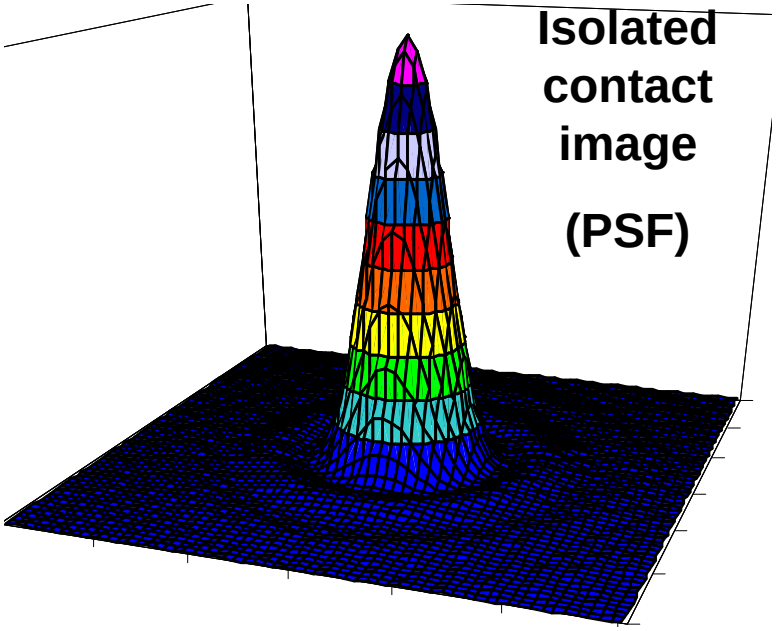


Lens Pupil

The Contact Reality

1. Besinc^2 lobes only for isolated contacts.

2. "Gibb's Phenomenon" only for Fourier Series with orders > 1.

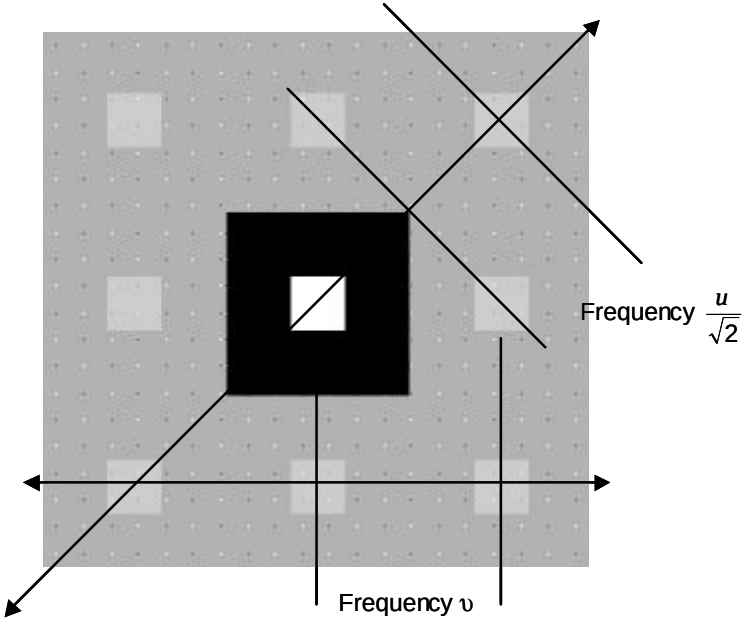


Isolated contact image

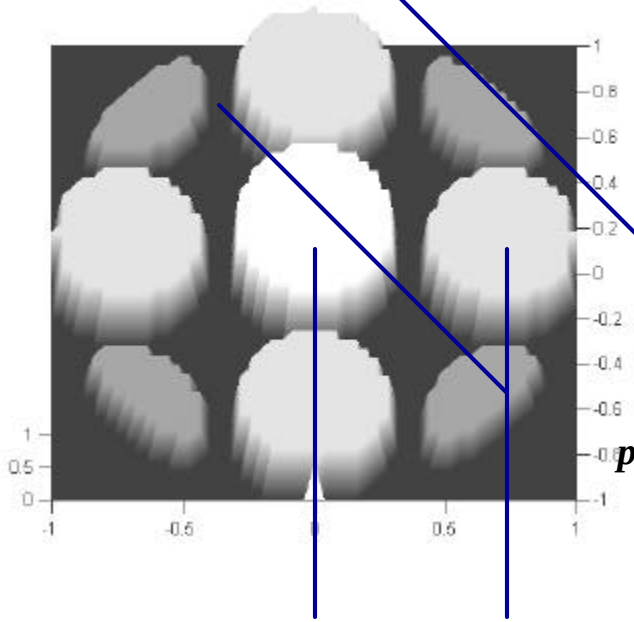
(PSF)

Contact Frequency and Sidelobes

Contacts have a density



Diffraction energy in Pupil



Diagonal Frequency Lost when

$$p < \frac{\sqrt{2}\,l}{(s+1)NA}$$

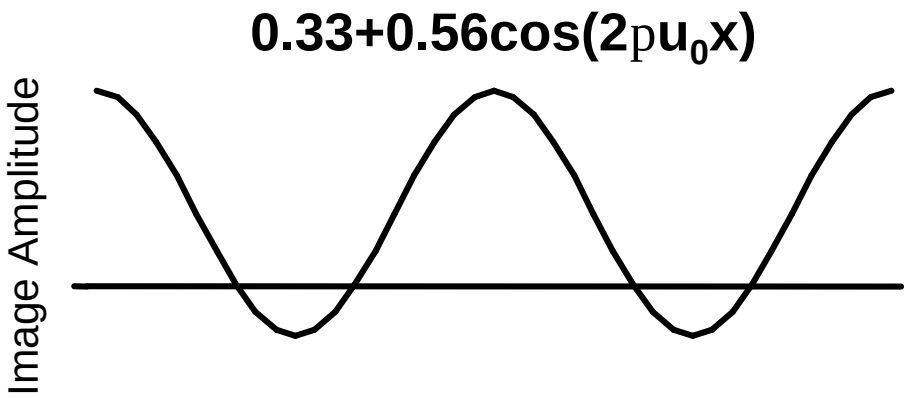
X Frequency

$$|\text{Mag.}|_{\text{zero order}} = (s/p)$$

$$|\text{Mag.}|_{\text{first order}} = \left|\left(\frac{s}{p}\right)\text{sinc}\left(\frac{s}{p}\right)\right|$$

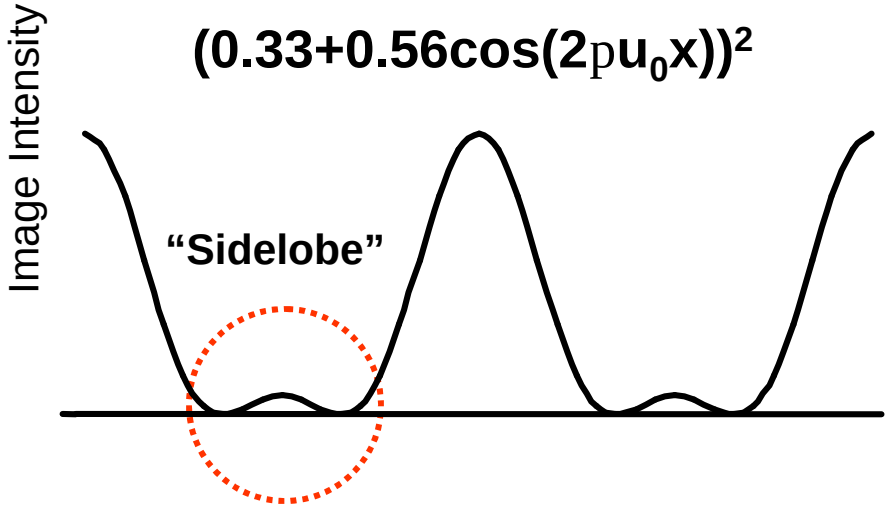
Coherent 1:2 Contact Image

Capture of 0, +/- 1 orders – biased cosine



Contact Image =

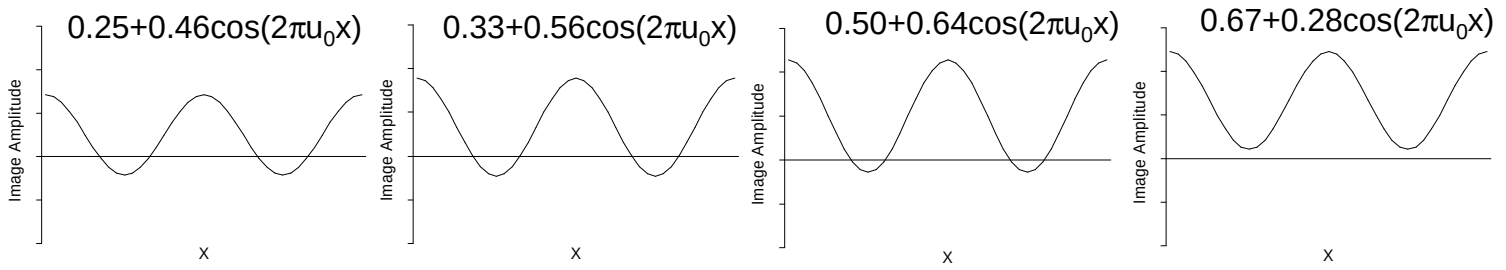
|zero order + first order cosine|²



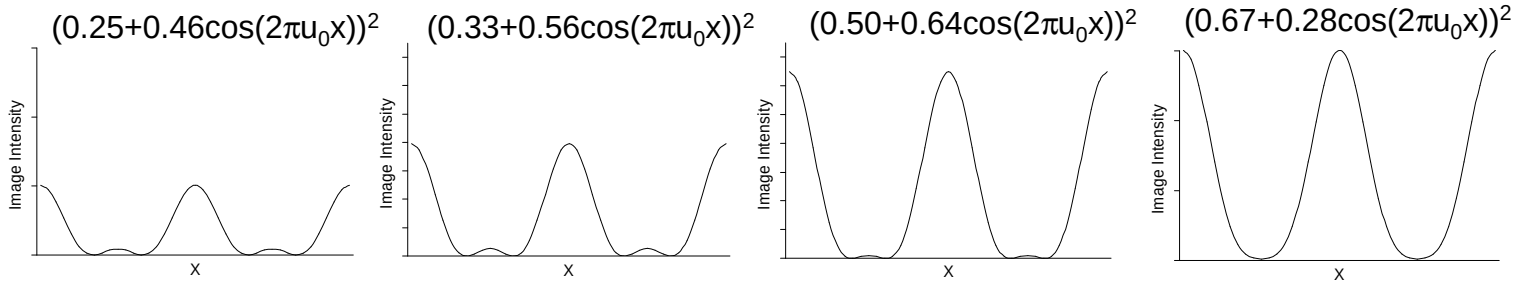
Images with decreasing pitch

1:3 contacts **1:2 contacts** **1:1 contacts** **2:1 contacts**

Amplitude



Intensity

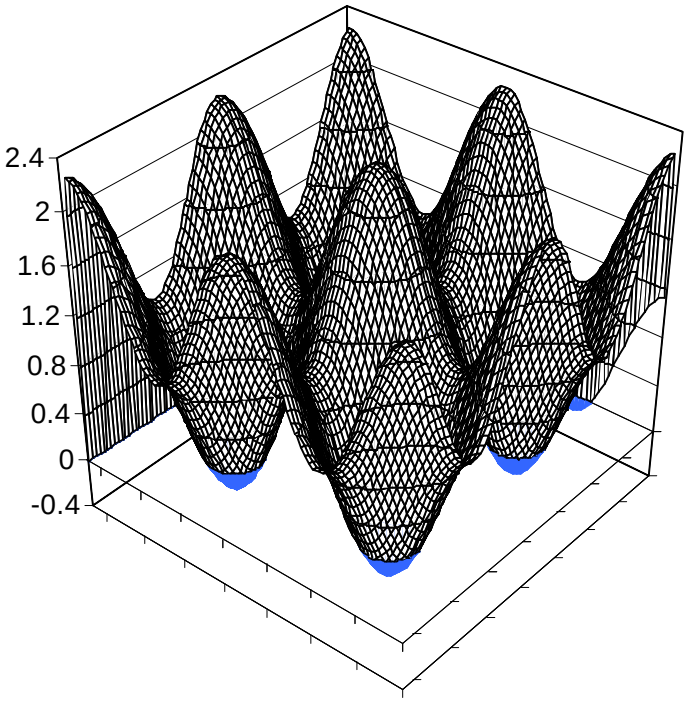


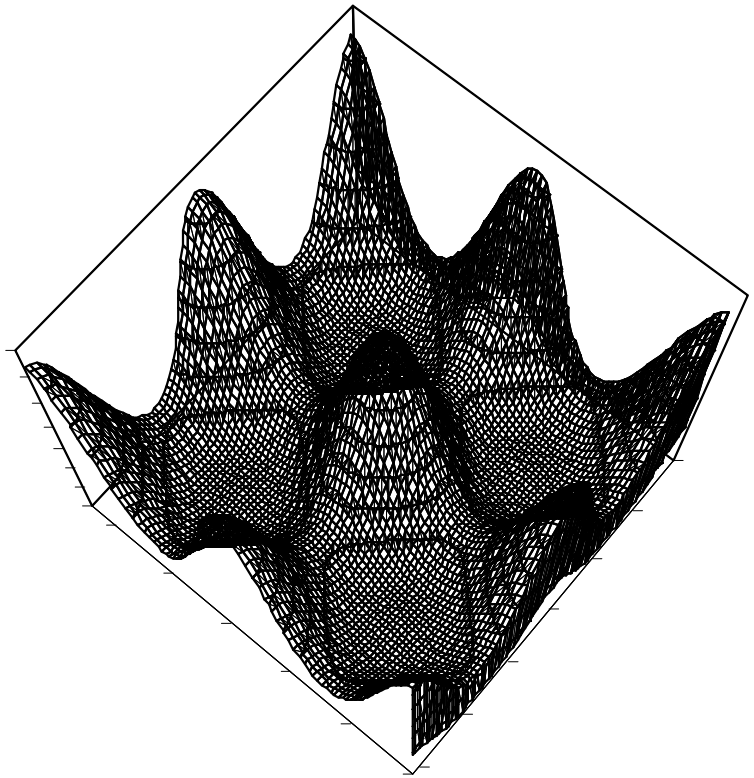
Both lobes of the 1st order cosine may print!

Contacts on 2D

X/Y Sum of Biased Cosines

1:1



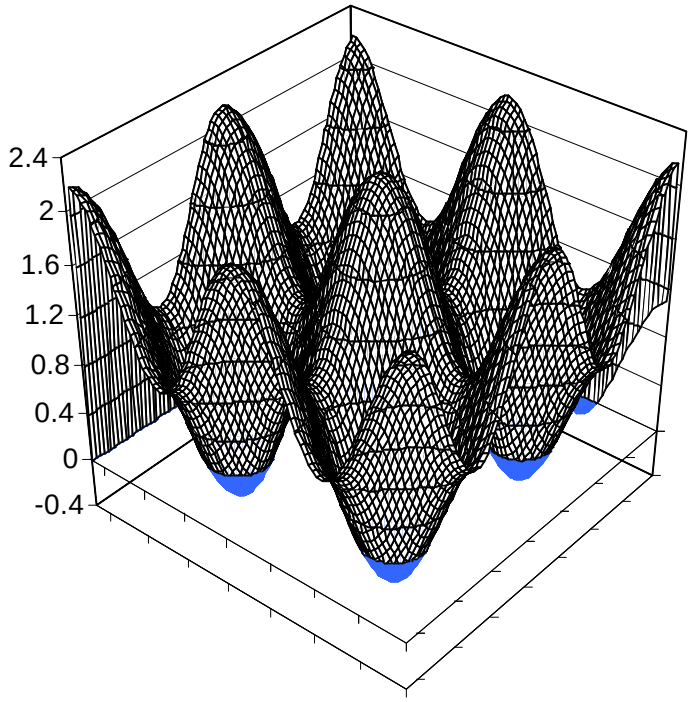


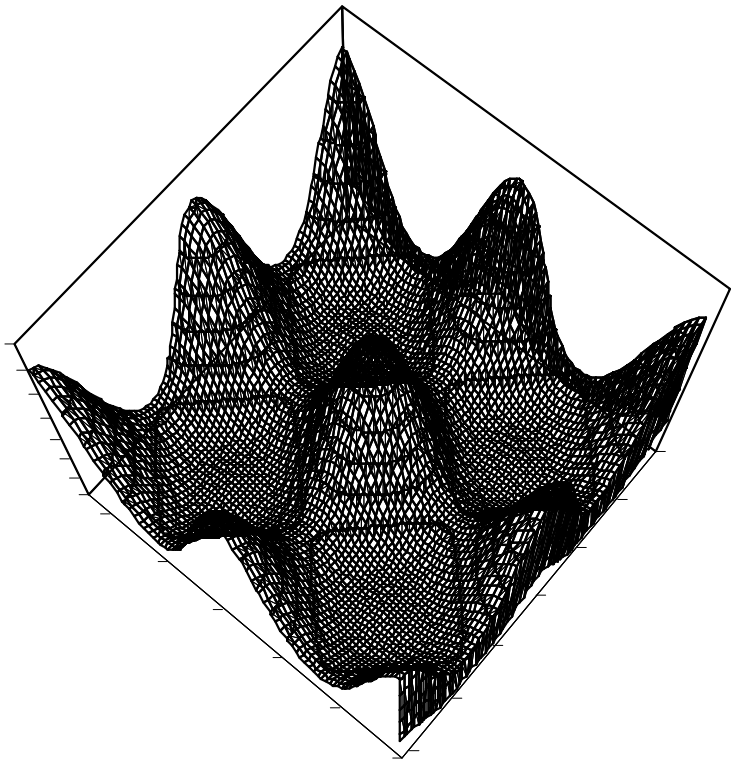
Amplitude **Intensity**

Contacts on 2D

X/Y Sum of Biased Cosines

1:1.2



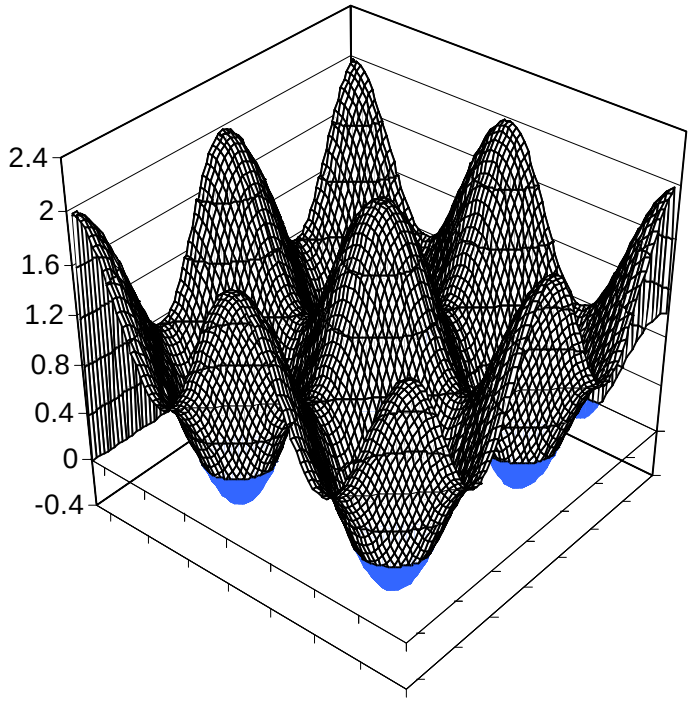


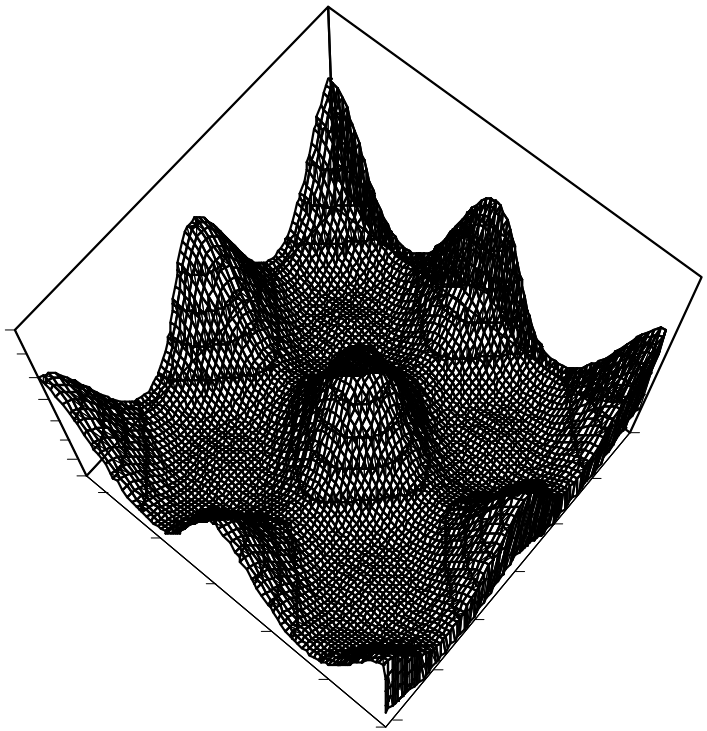
Amplitude **Intensity**

Contacts on 2D

X/Y Sum of Biased Cosines

1:1.5



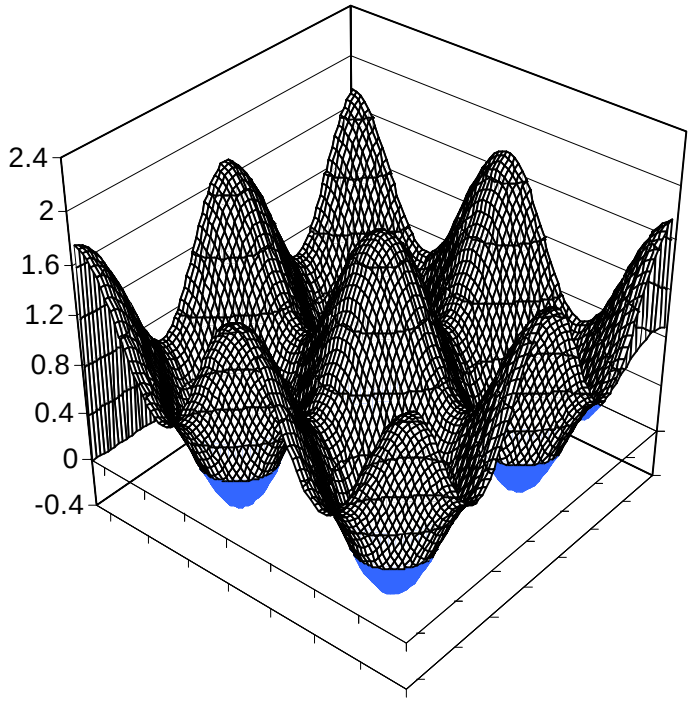


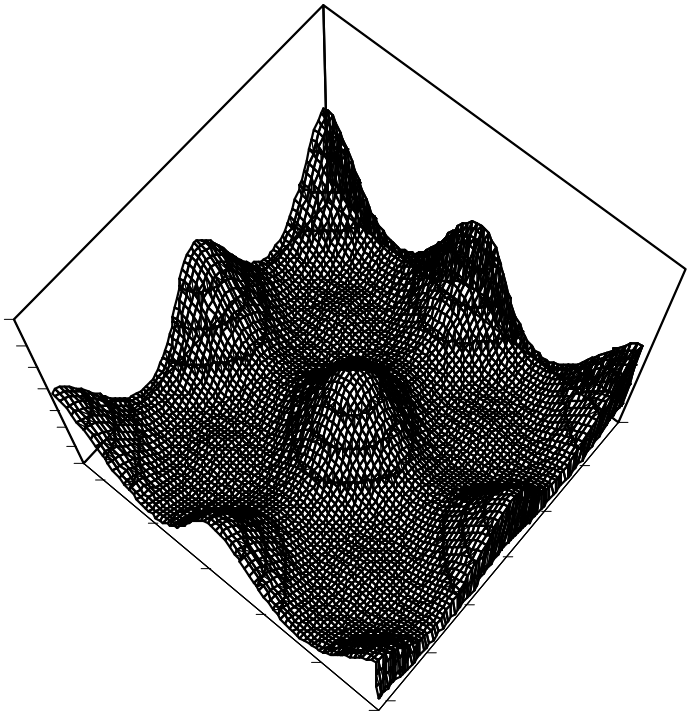
Amplitude **Intensity**

Contacts on 2D

X/Y Sum of Biased Cosines

1:2



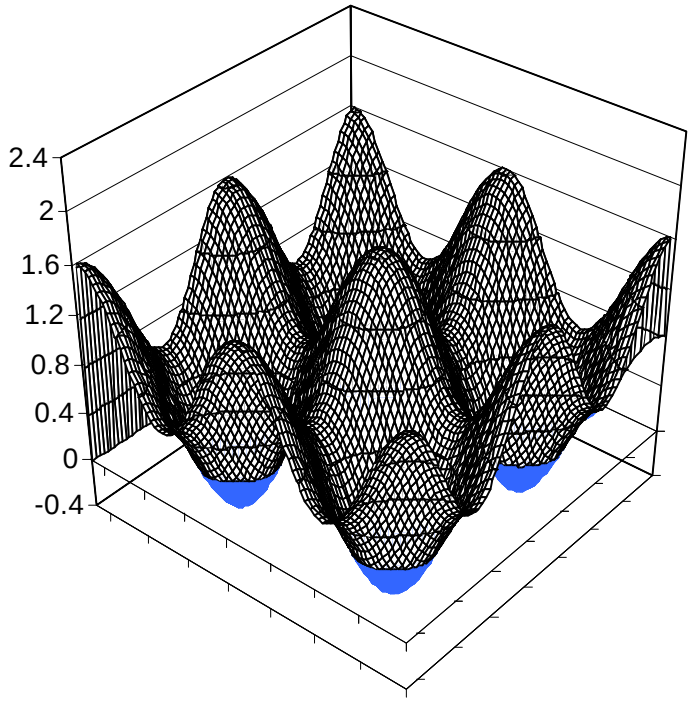


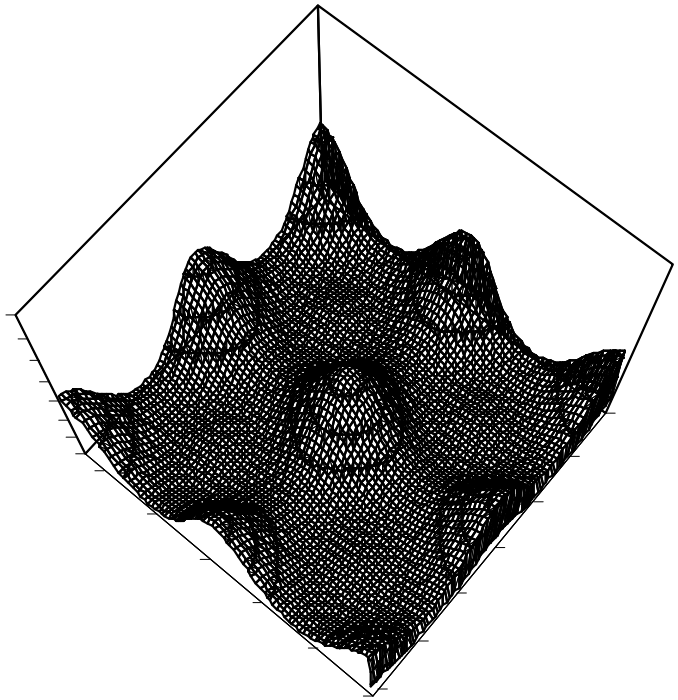
Amplitude **Intensity**

Contacts on 2D

X/Y Sum of Biased Cosines

1:2.5



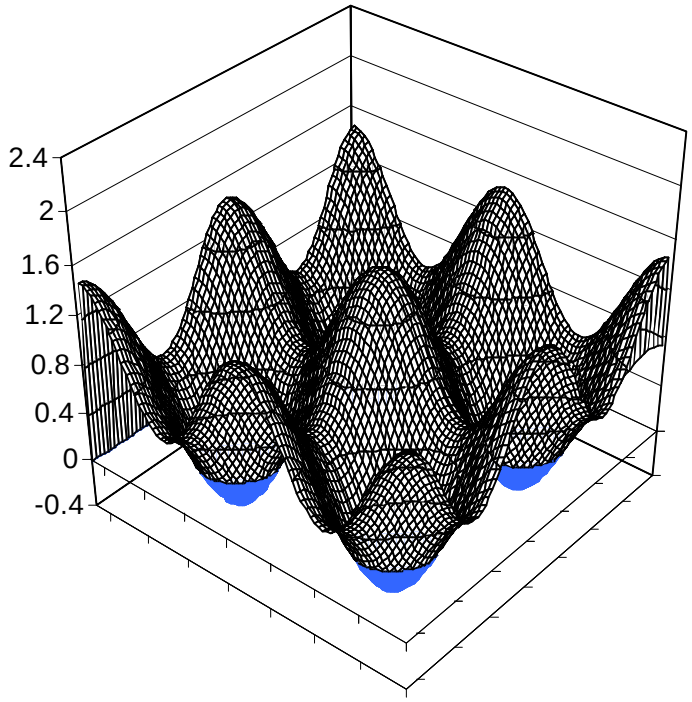


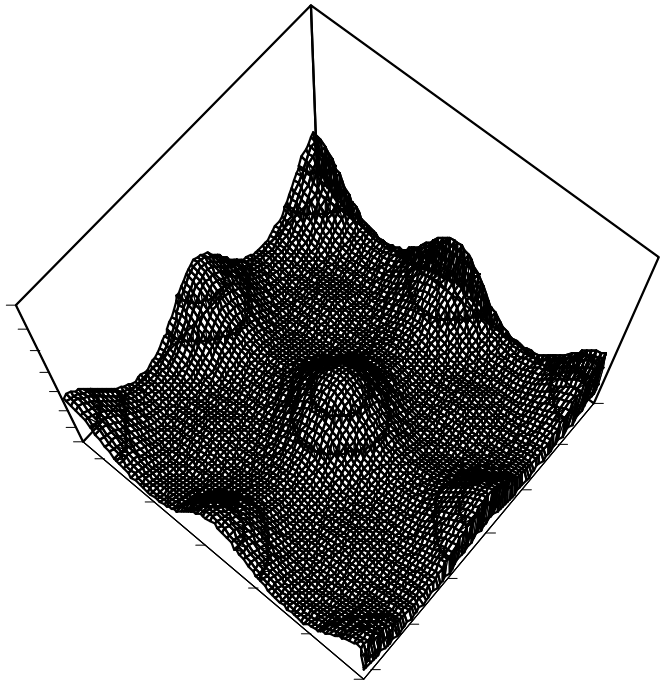
Amplitude **Intensity**

Contacts on 2D

X/Y Sum of Biased Cosines

1:3

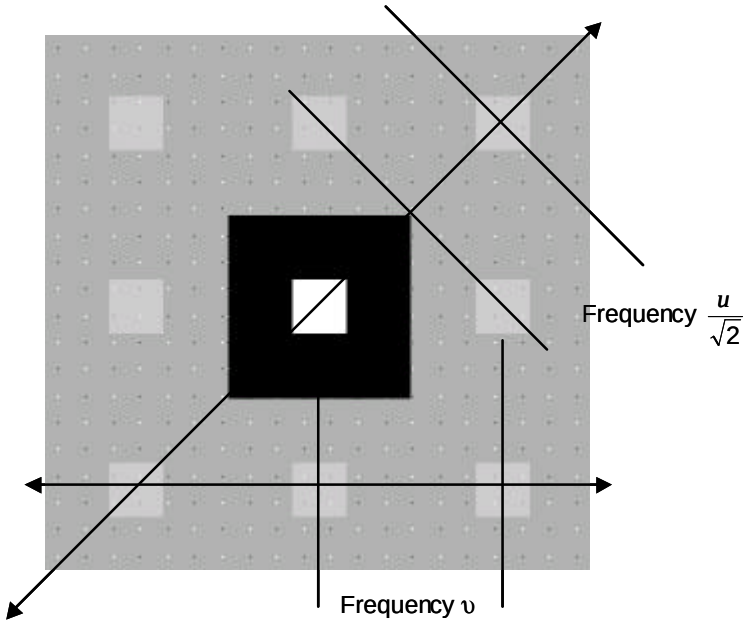




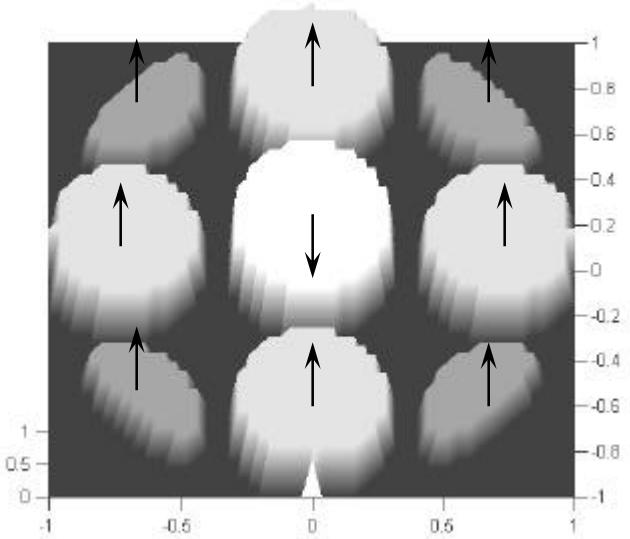
Amplitude **Intensity**

Orders for APSM

APSM p PS at T > 0



Diffraction energy for APSM



$$|\text{Mag.}|_{\text{zero order}} = [1+\sqrt{T}](s/p) - \sqrt{T}$$

Zero order decrease

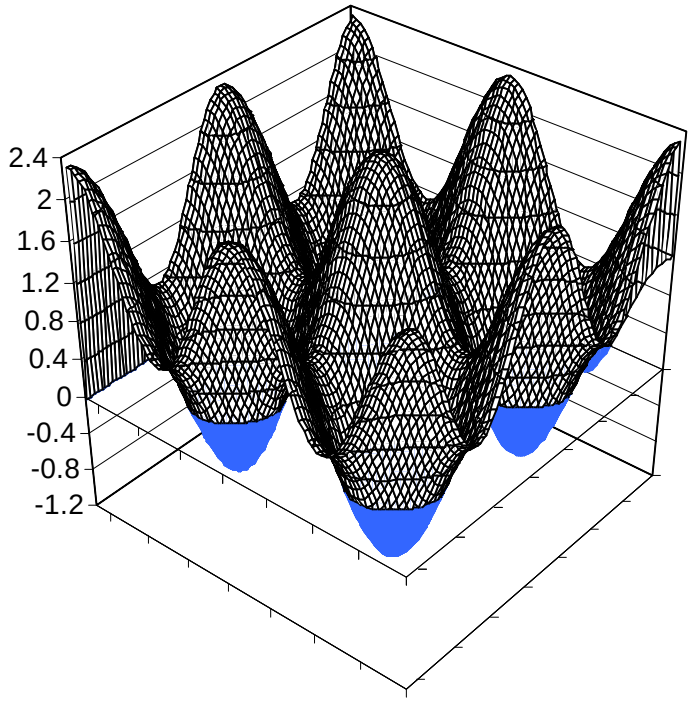
$$|\text{Mag.}|_{\text{first order}} = [1+\sqrt{T}]\left|\left(\frac{s}{p}\right)\text{sinc}\left(\frac{s}{p}\right)\right|$$

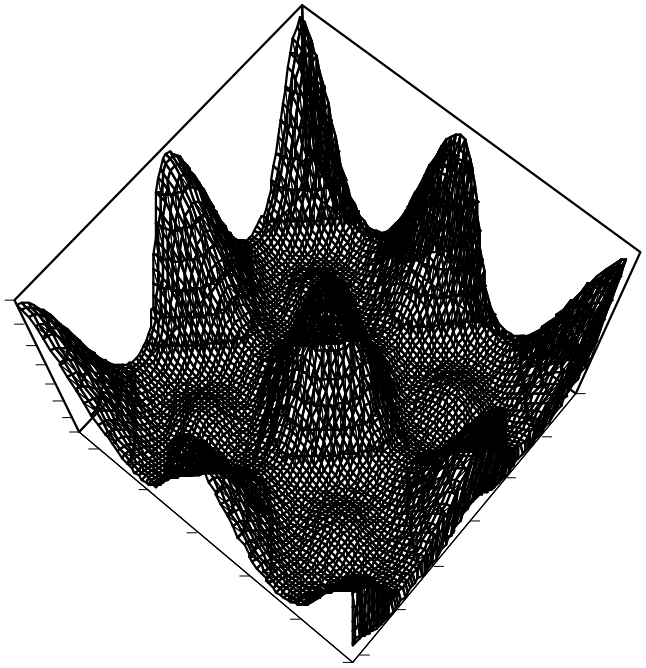
First order increase

Contacts on 2D – 6% APSM

X/Y Sum of Biased Cosines

1:1



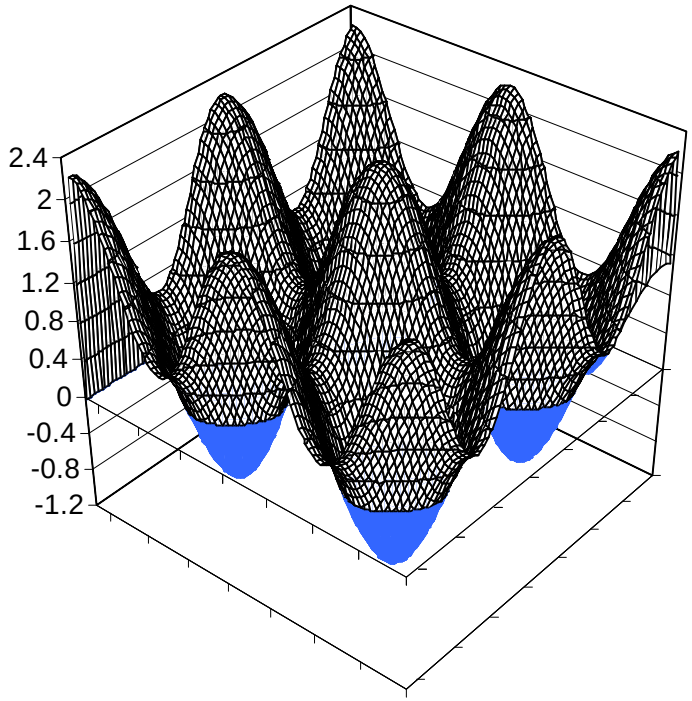


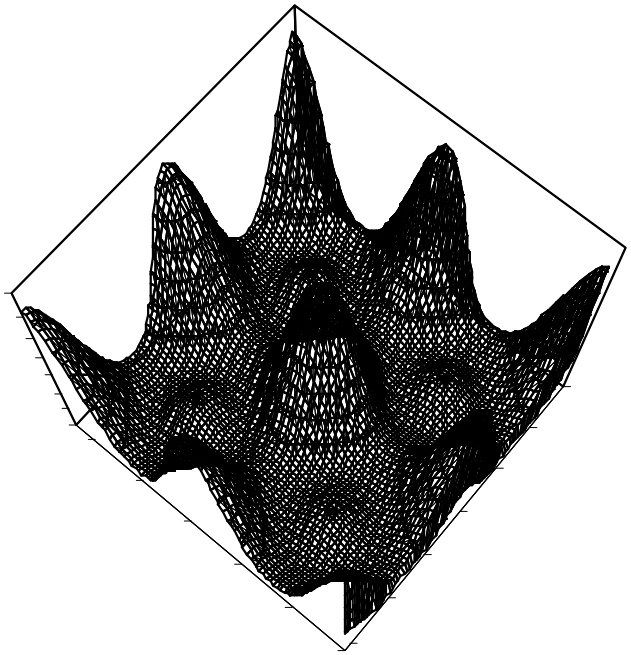
Amplitude **Intensity**

Contacts on 2D – 6% APSM

X/Y Sum of Biased Cosines

1:1.2



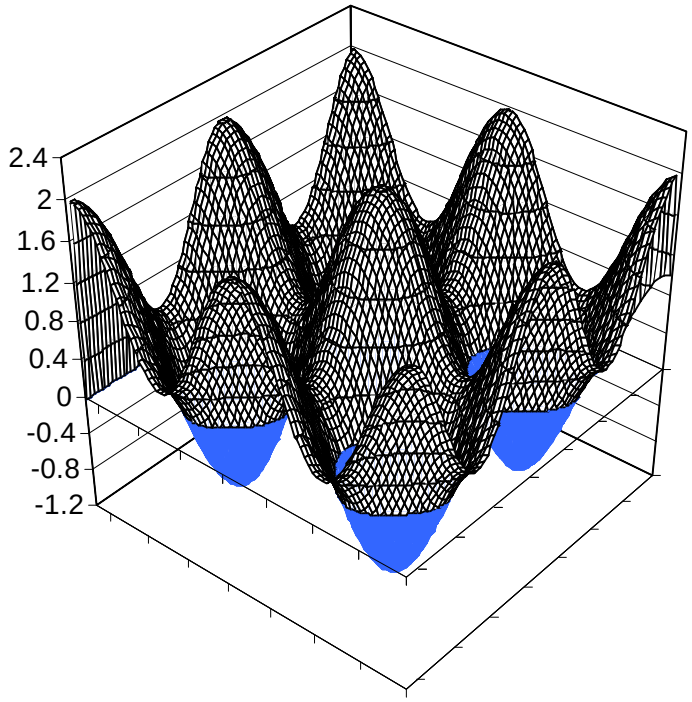


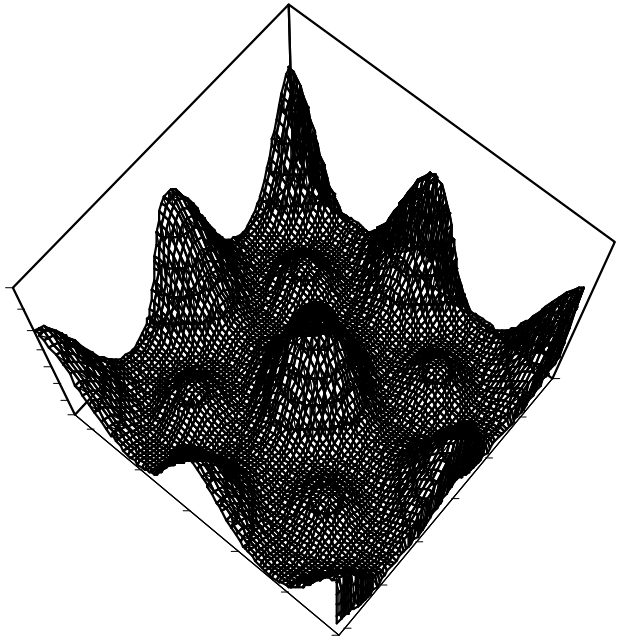
Amplitude **Intensity**

Contacts on 2D – 6% APSM

X/Y Sum of Biased Cosines

1:1.5



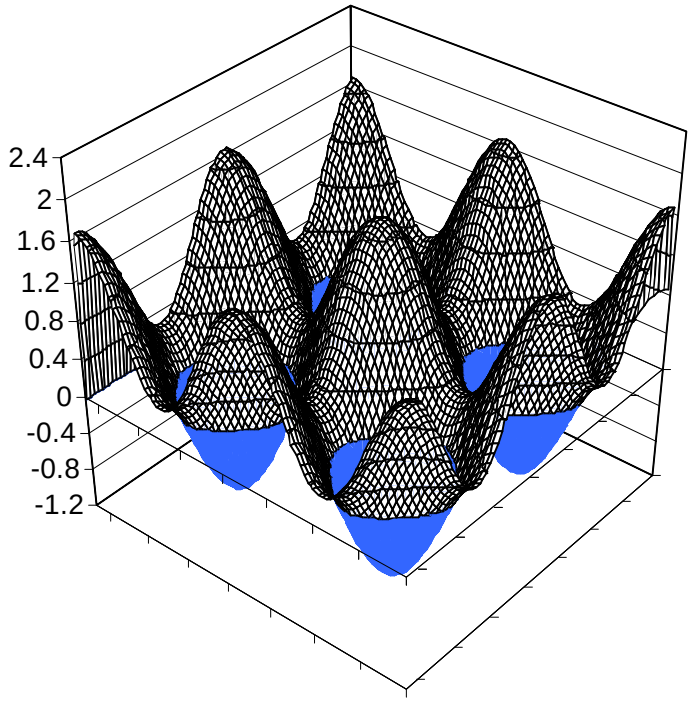


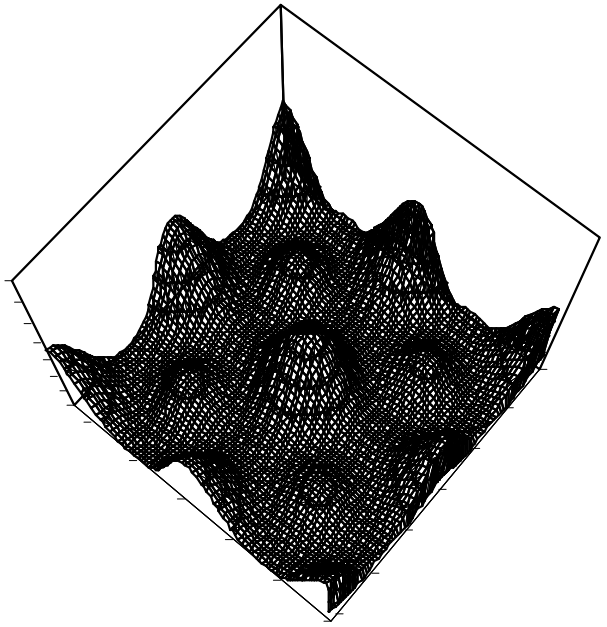
Amplitude **Intensity**

Contacts on 2D – 6% APSM

X/Y Sum of Biased Cosines

1:2



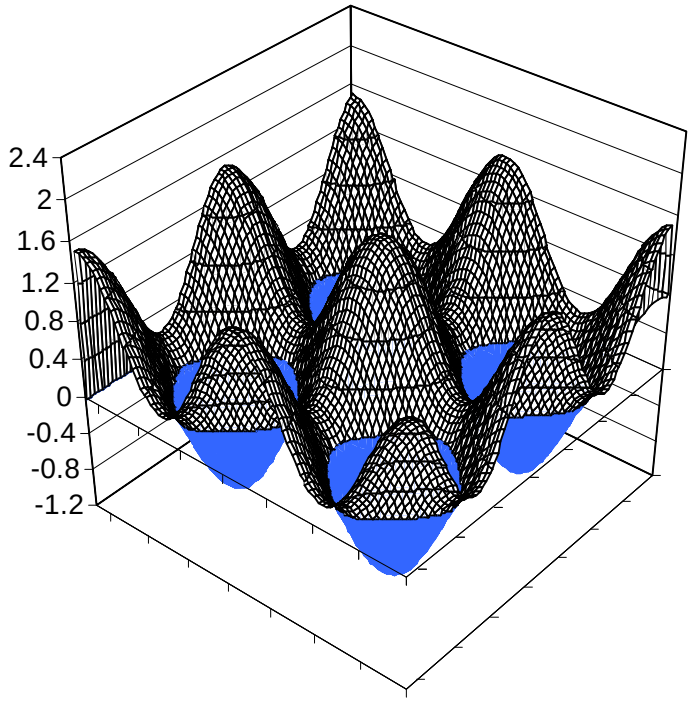


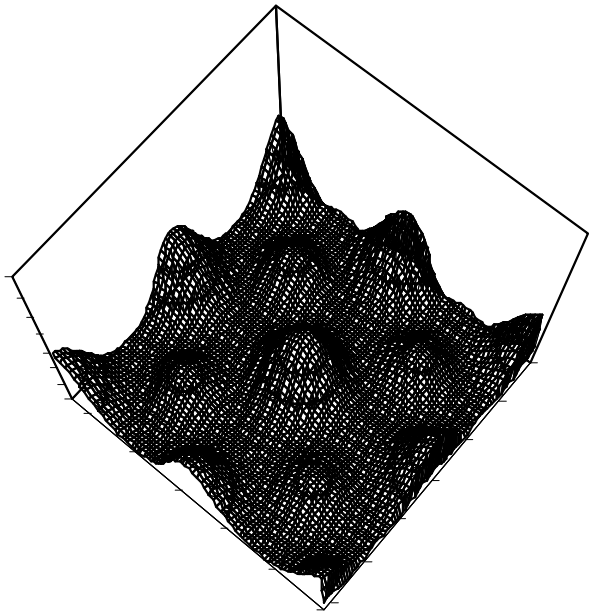
Amplitude **Intensity**

Contacts on 2D – 6% APSM

X/Y Sum of Biased Cosines

1:2.5



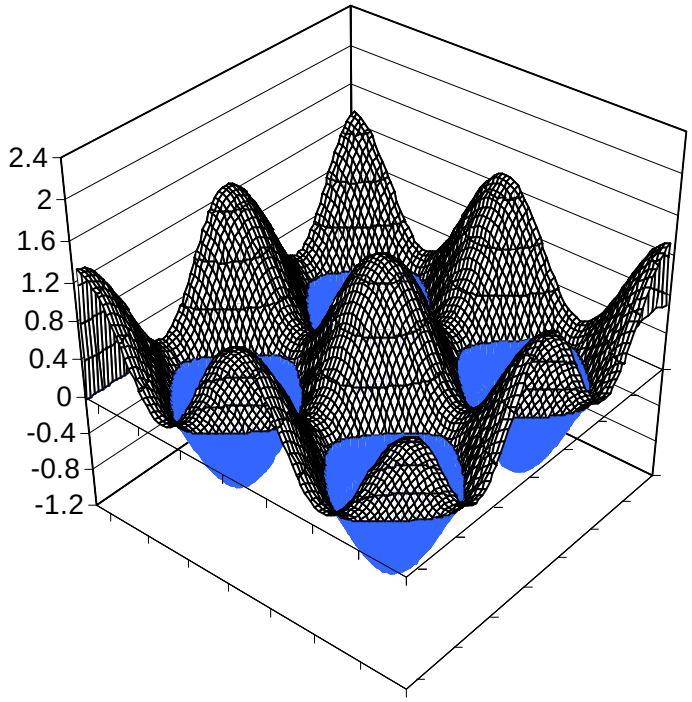


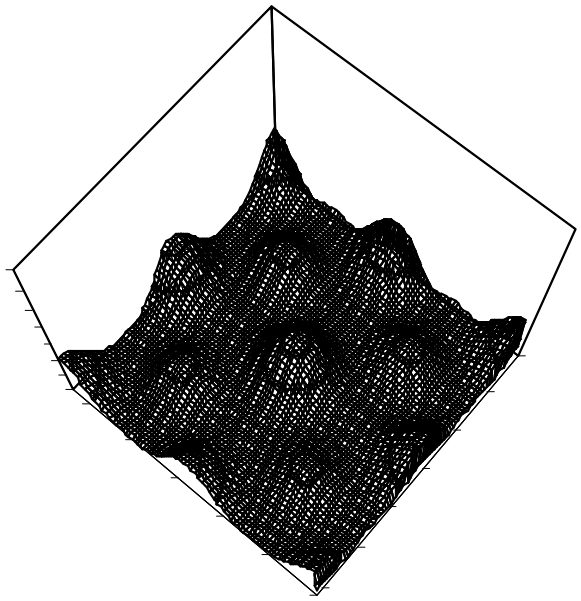
Amplitude **Intensity**

Contacts on 2D – 6% APSM

X/Y Sum of Biased Cosines

1:3



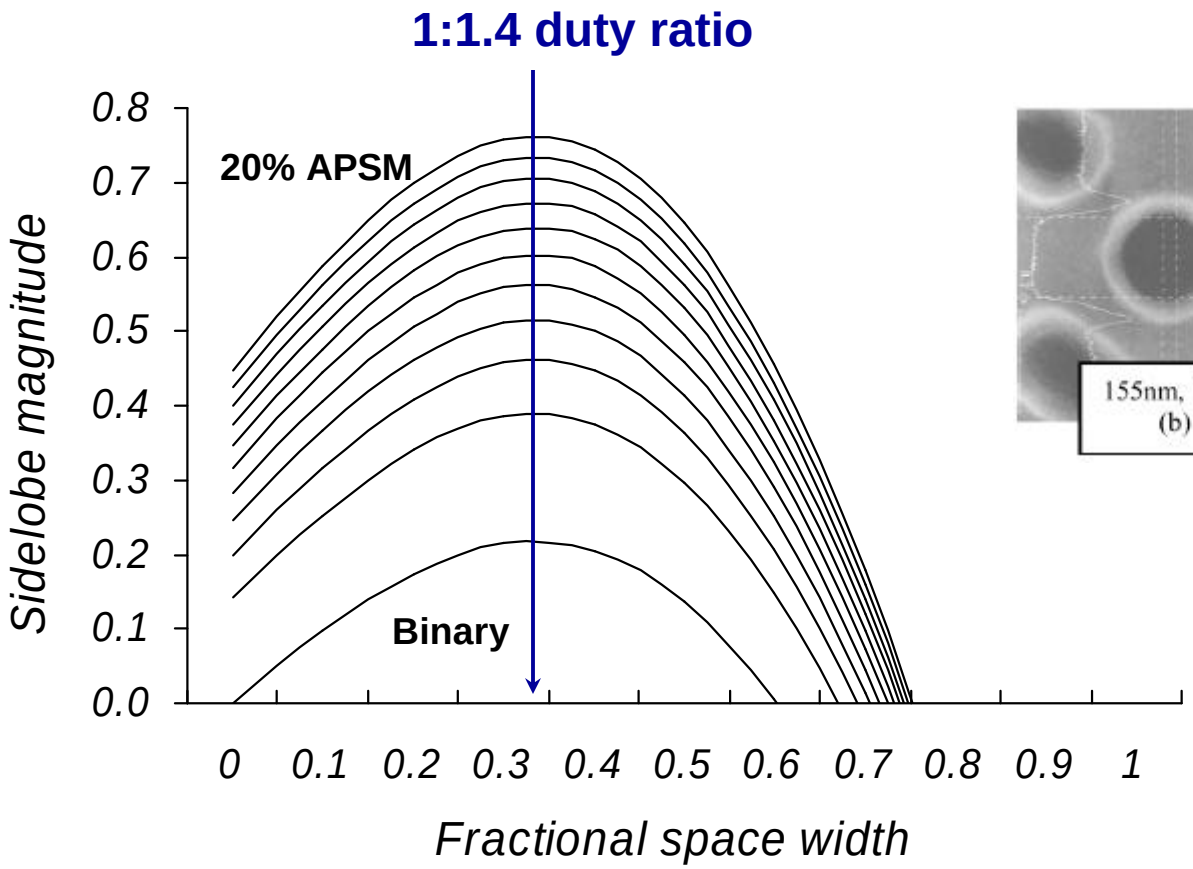


Amplitude **Intensity**

Worst Case Pitch for Sidelobes

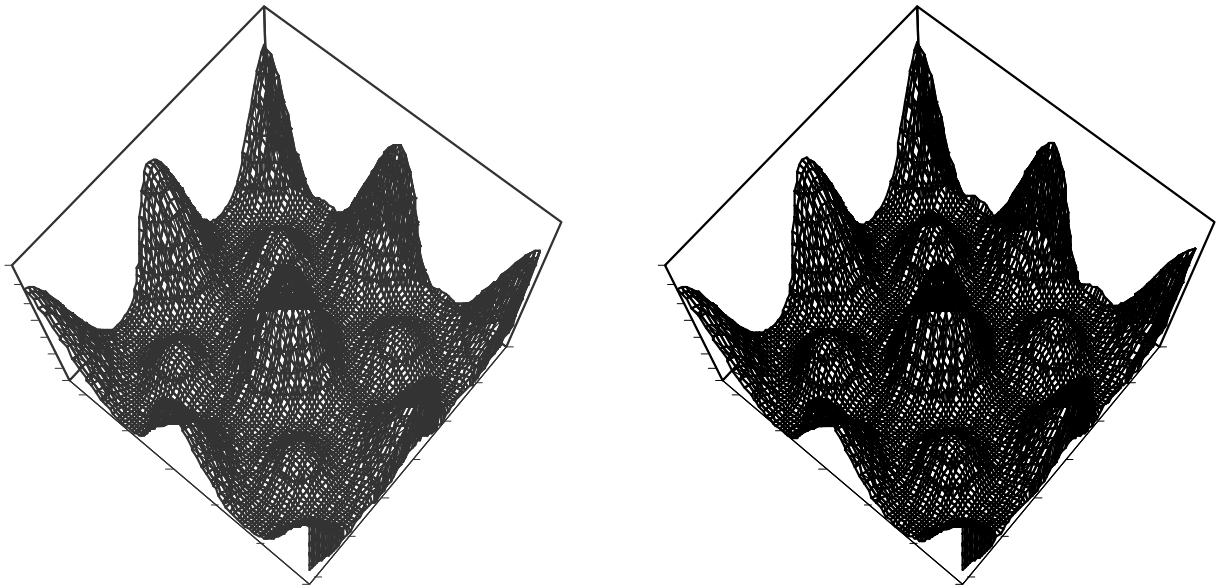
Problems when:

$(2 \times |Mag|_{first} - |Mag|_{zero}) >$ Resist amplitude threshold



Sing et al, Proc. SPIE 4691.

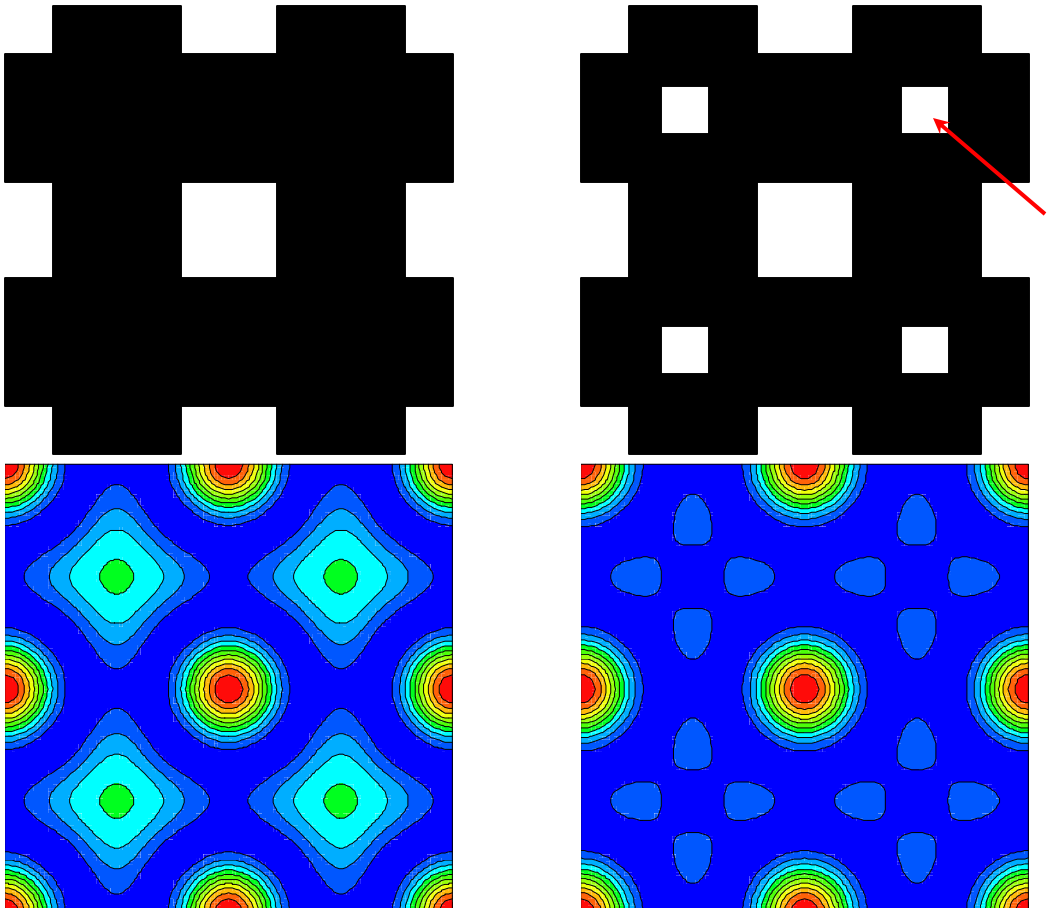
1:1.4 Contacts with 10% and 20% APSM



Result of zero and first orders only.

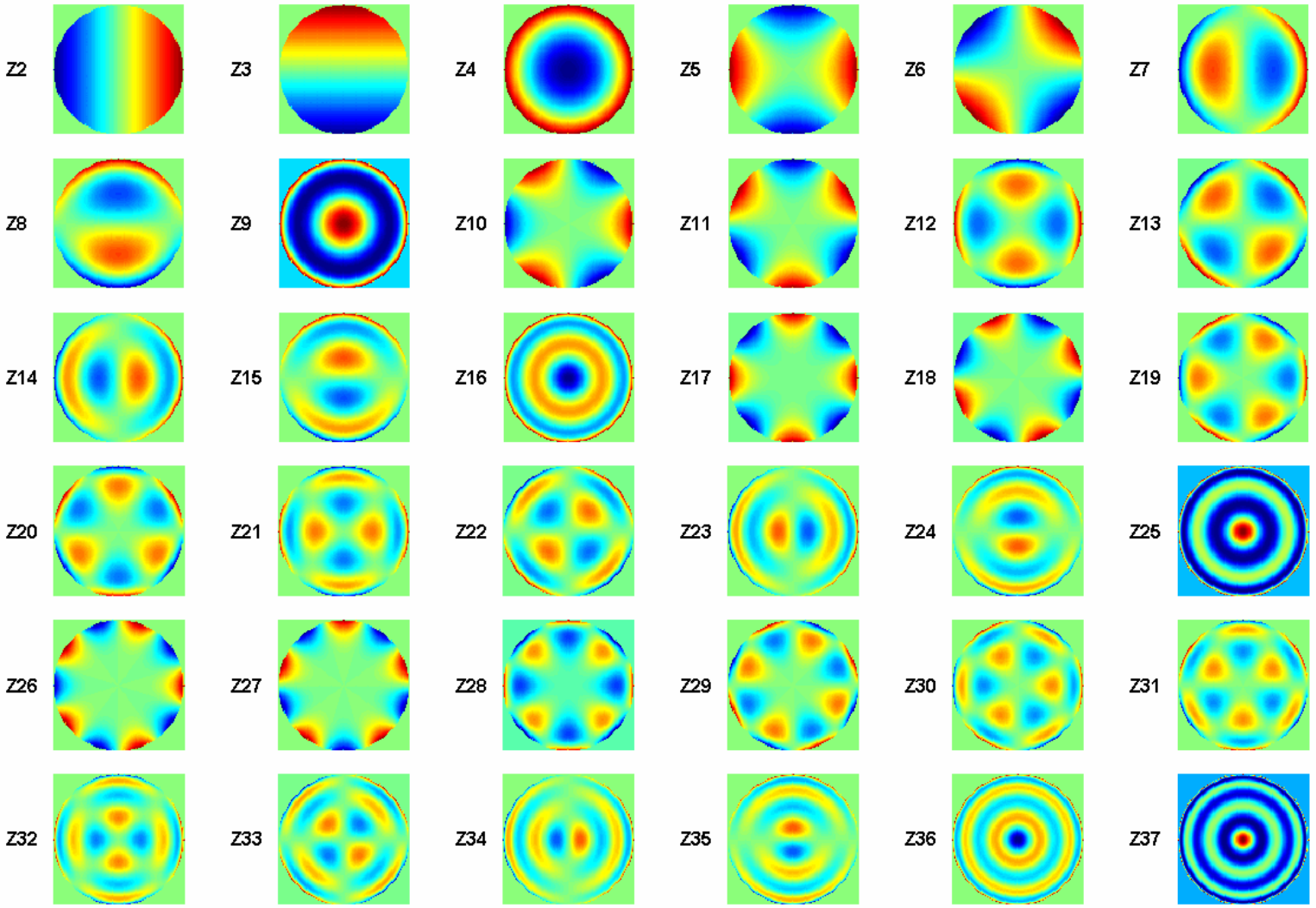
Anti-sidelobe OPC

1:1.4 contacts, 10% APSM

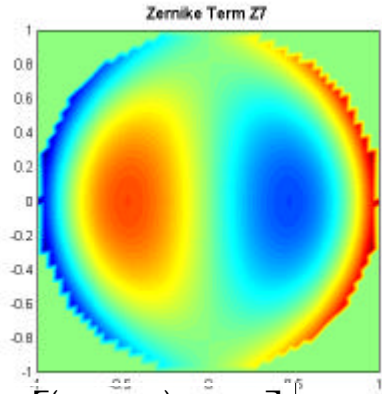


Clear anti-sidelobe

Pitch Sensitivities to Aberration

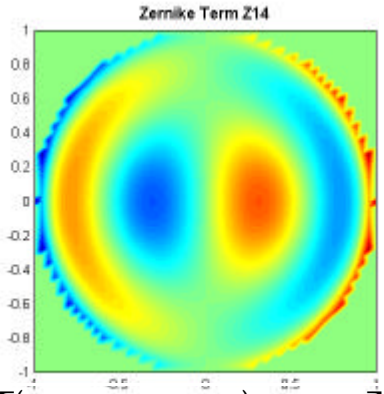


Coma hot spots



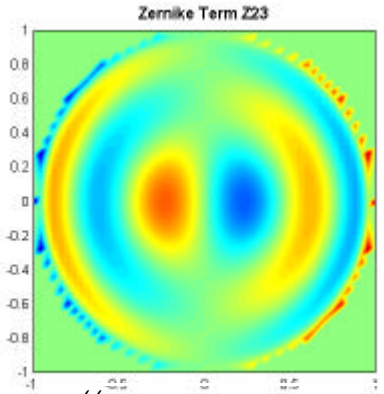
$$\frac{d}{dr}\left[\left(3r^3 - 2r\right)\cos(\theta)\right]\Big| = 0$$

Radius = +/- 0.46



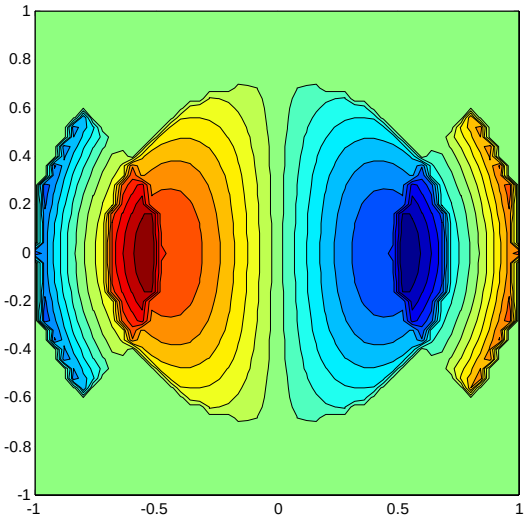
$$\frac{d}{dr}\left[\left(10r^5 - 12r^3 + 3r\right)\cdot\cos(q)\right]\Big| = 0$$

Radius = +/-0.31

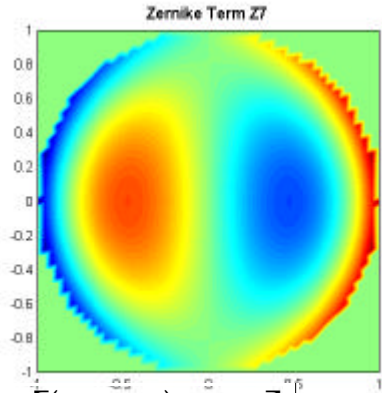


$$\frac{d}{dr}\left(\left(35r^7 - 60r^5 + 30r^3 - 4r\right)\right)\Big| = 0$$

Radius = +/-0.23

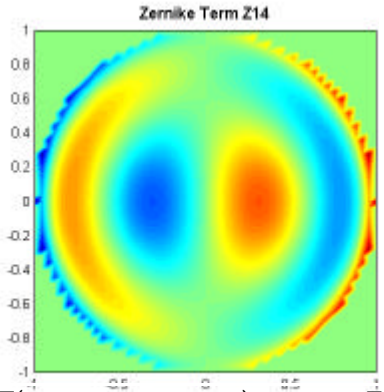


Coma hot spots



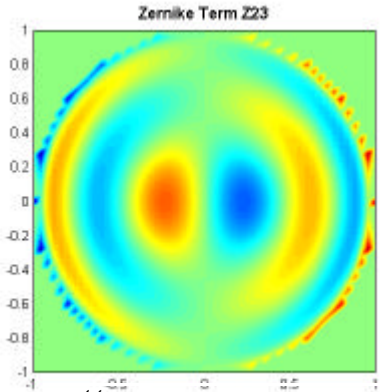
$$\frac{d}{dr}\left[\left(3r^3 - 2r\right)\cos(\theta)\right] = 0$$

Radius = +/- 0.46



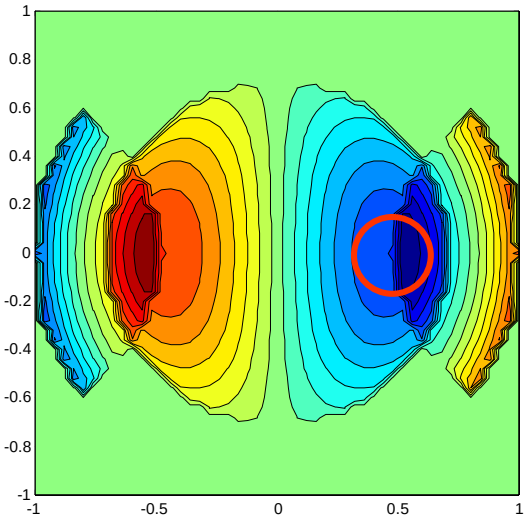
$$\frac{d}{dr}\left[\left(10r^5 - 12r^3 + 3r\right)\cdot\cos(q)\right] = 0$$

Radius = +/-0.31

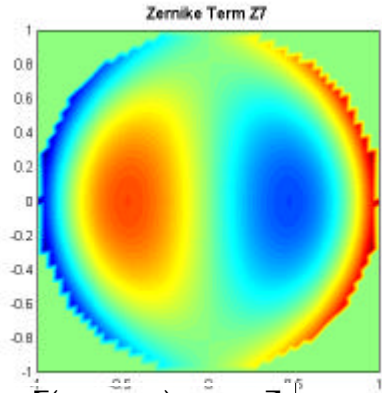


$$\frac{d}{dr}\left(\left(35r^7 - 60r^5 + 30r^3 - 4r\right)\right) = 0$$

Radius = +/-0.23

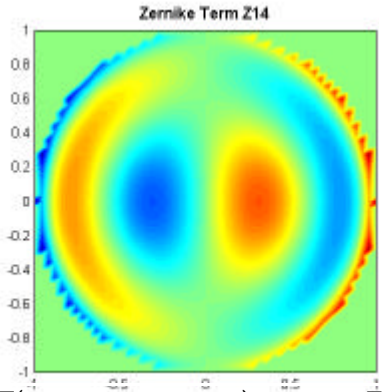


Coma hot spots



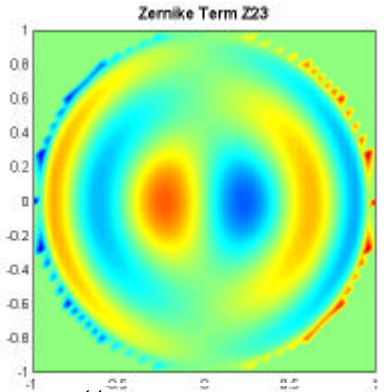
$$\frac{d}{dr}\left[\left(3r^3 - 2r\right)\cos(\theta)\right]\Big| = 0$$

Radius = +/- 0.46



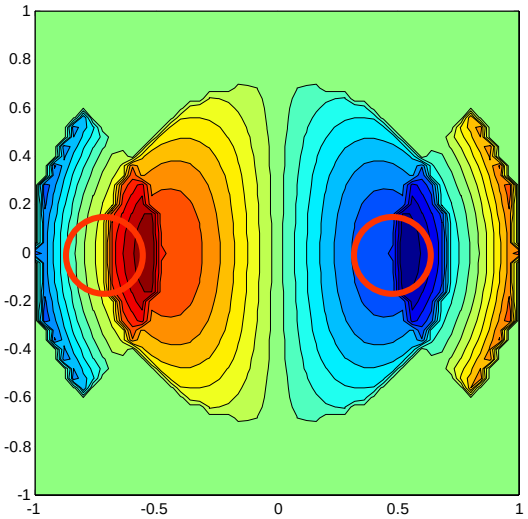
$$\frac{d}{dr}\left[\left(10r^5 - 12r^3 + 3r\right)\cdot\cos(q)\right]\Big| = 0$$

Radius = +/-0.31

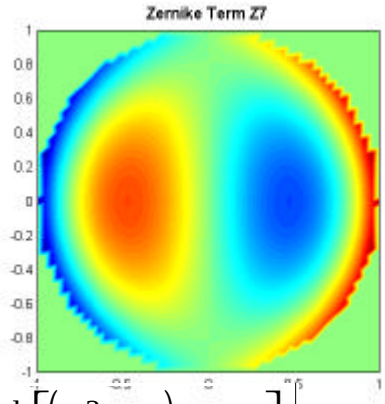


$$\frac{d}{dr}\left(\left(35r^7 - 60r^5 + 30r^3 - 4r\right)\right)\Big| = 0$$

Radius = +/-0.23

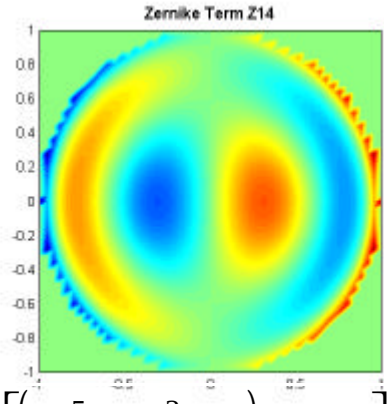


Coma hot spots



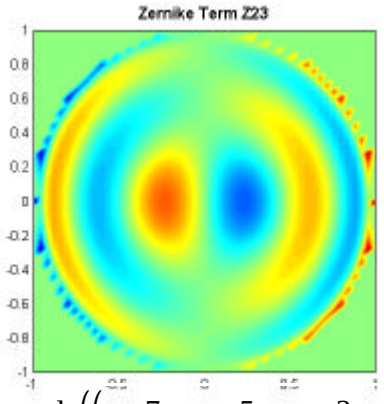
$$\frac{d}{dr}\left[\left(3r^3 - 2r\right)\cos(\theta)\right] = 0$$

Radius = +/- 0.46



$$\frac{d}{dr}\left[\left(10r^5 - 12r^3 + 3r\right)\cdot\cos(q)\right] = 0$$

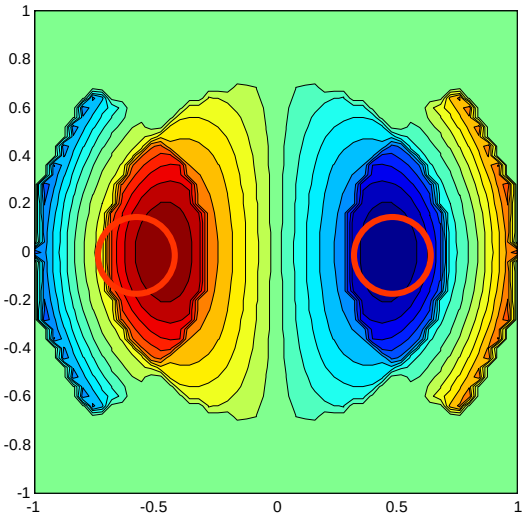
Radius = +/-0.31



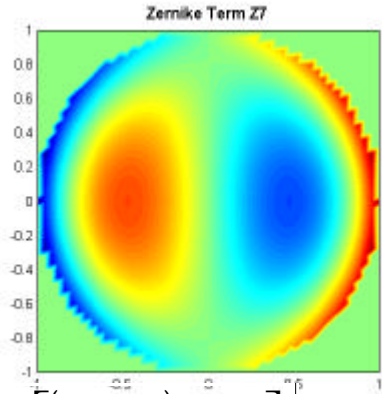
$$\frac{d}{dr}\left(\left(35r^7 - 60r^5 + 30r^3 - 4r\right)\right) = 0$$

Radius = +/-0.23

Increasing Pitch

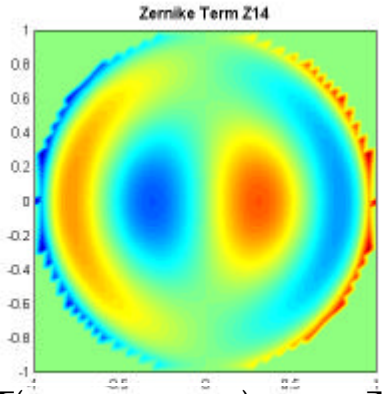


Coma hot spots



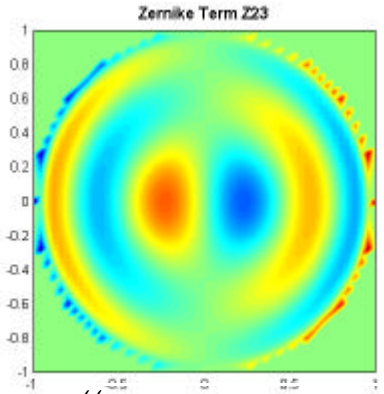
$$\frac{d}{dr}\left[\left(3r^3 - 2r\right)\cos(\theta)\right] = 0$$

Radius = +/- 0.46



$$\frac{d}{dr}\left[\left(10r^5 - 12r^3 + 3r\right)\cdot\cos(q)\right] = 0$$

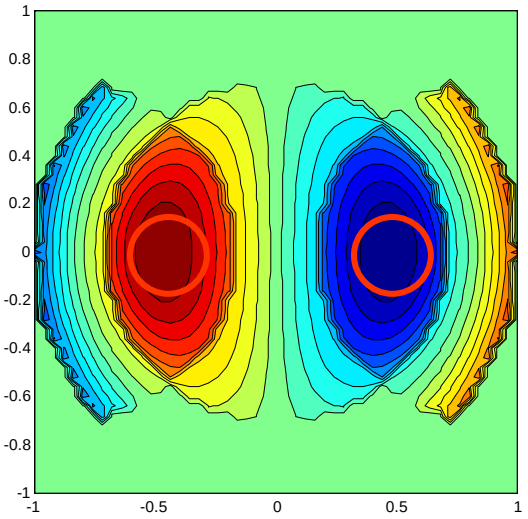
Radius = +/-0.31



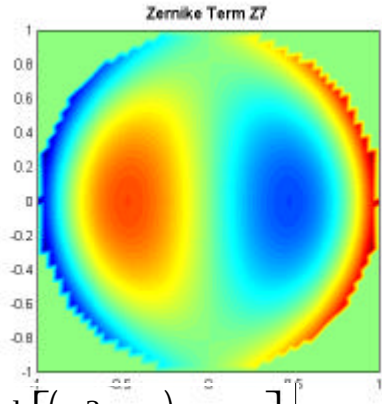
$$\frac{d}{dr}\left(\left(35r^7 - 60r^5 + 30r^3 - 4r\right)\right) = 0$$

Radius = +/-0.23

Increasing Pitch

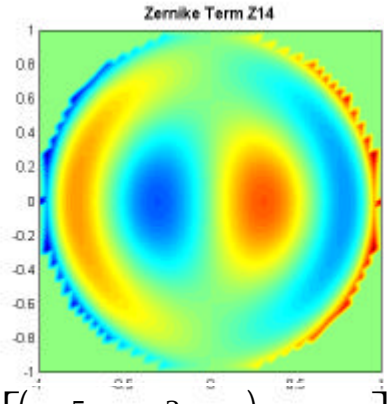


Coma hot spots



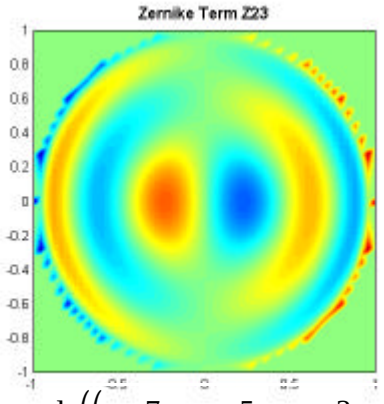
$$\frac{d}{dr}\left[\left(3r^3 - 2r\right)\cos(\theta)\right] = 0$$

Radius = +/- 0.46



$$\frac{d}{dr}\left[\left(10r^5 - 12r^3 + 3r\right)\cdot\cos(q)\right] = 0$$

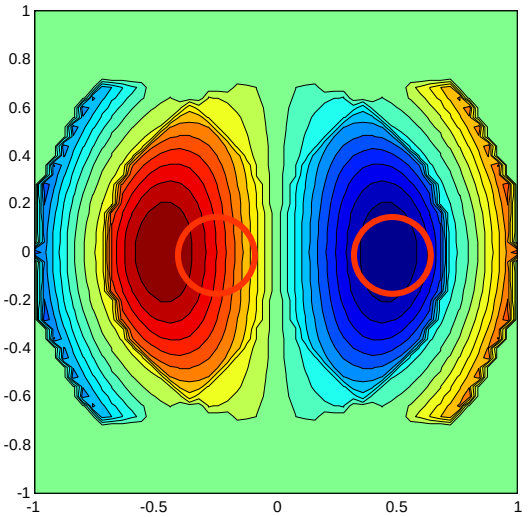
Radius = +/-0.31



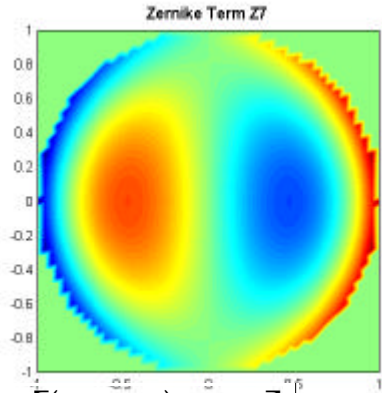
$$\frac{d}{dr}\left(\left(35r^7 - 60r^5 + 30r^3 - 4r\right)\right) = 0$$

Radius = +/-0.23

Increasing Pitch

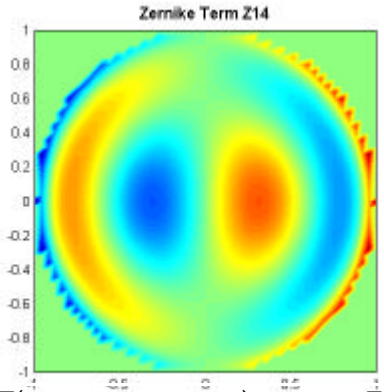


Coma hot spots



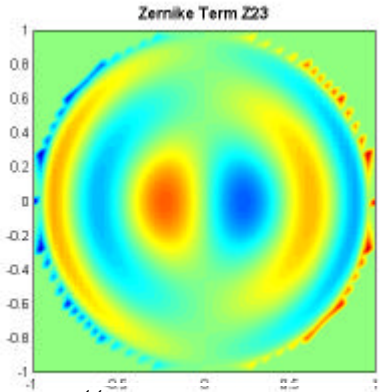
$$\frac{d}{dr}\left[\left(3r^3 - 2r\right)\cos(\theta)\right] = 0$$

Radius = +/- 0.46



$$\frac{d}{dr}\left[\left(10r^5 - 12r^3 + 3r\right)\cdot\cos(q)\right] = 0$$

Radius = +/-0.31



$$\frac{d}{dr}\left(\left(35r^7 - 60r^5 + 30r^3 - 4r\right)\right) = 0$$

Radius = +/-0.23

Increasing Pitch

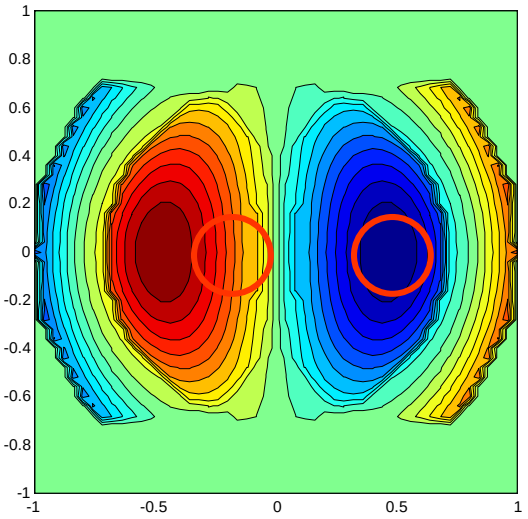
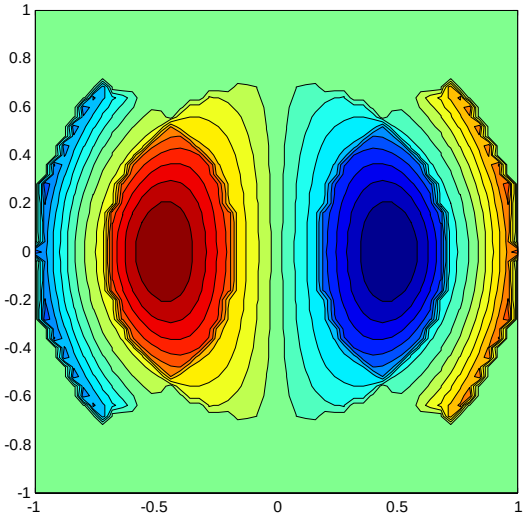


Image Placement Error with Coma



Dominant Effect

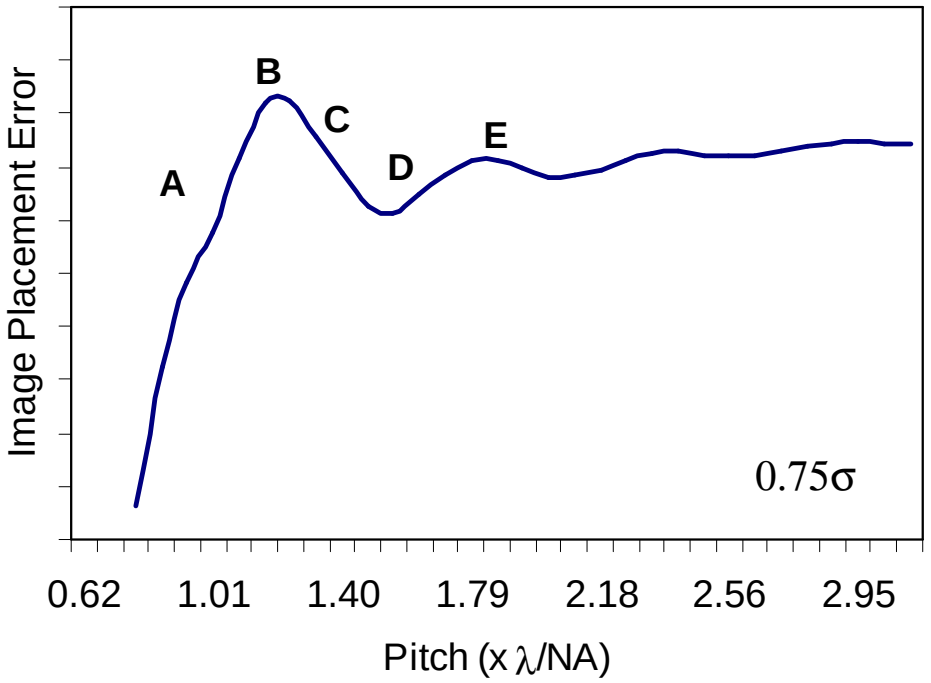
A - 1st order to coma max

B - 1st order at coma max

C - 1st order to center

D - 2nd order to coma max

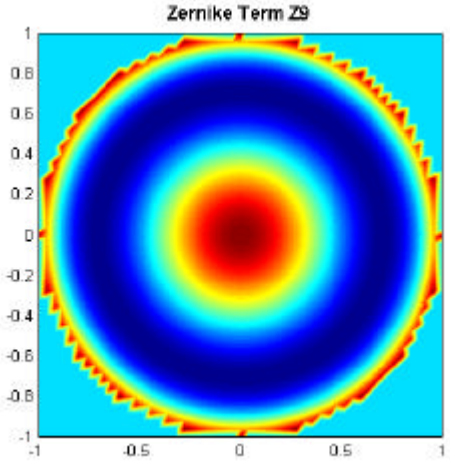
E – 2nd order at coma max



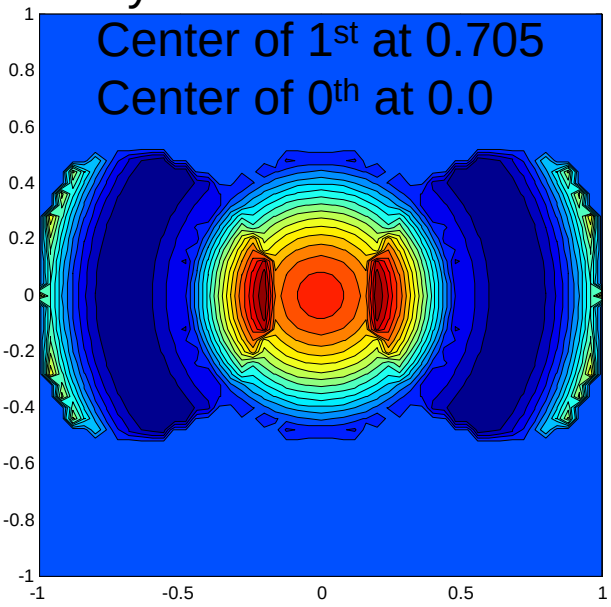
Spherical hot spots

$$\frac{d}{dr}\left[\left(6 \cdot r^4 - 6 \cdot r^2\right) + 1\right] = 0$$

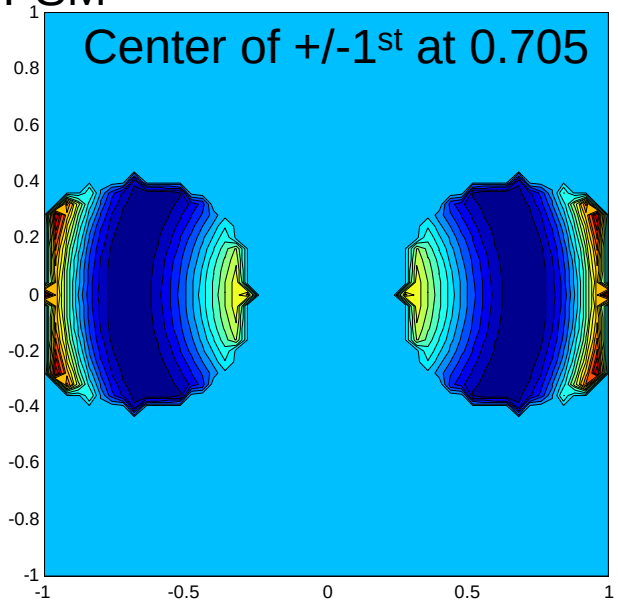
Radius = 0.705



Binary



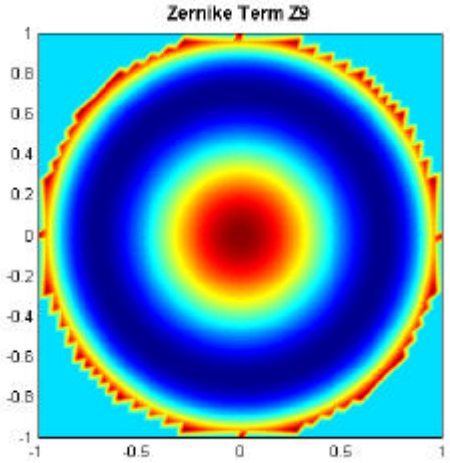
PSM



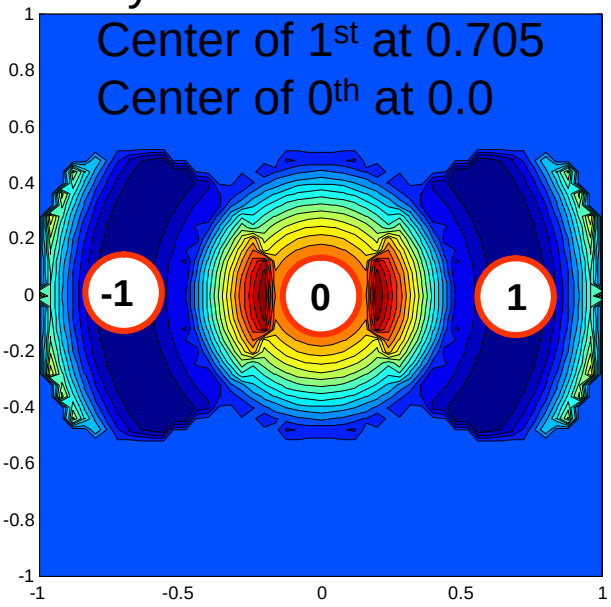
Spherical hot spots

$$\frac{d}{dr}\left[\left(6 \cdot r^4 - 6 \cdot r^2\right) + 1\right] = 0$$

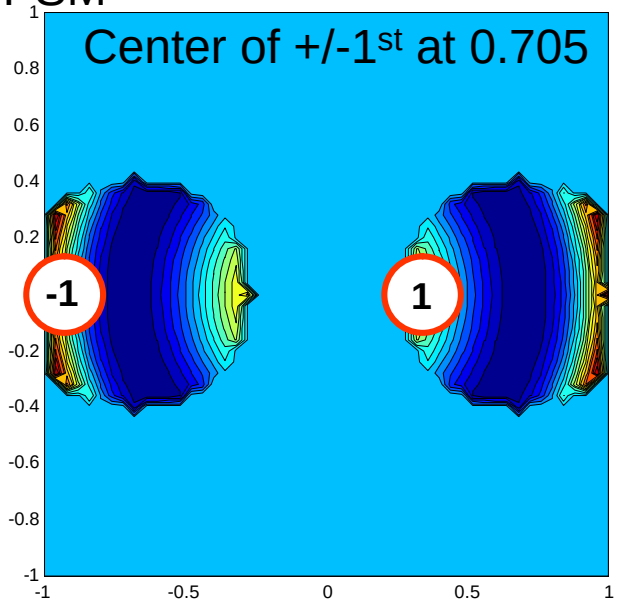
Radius = 0.705



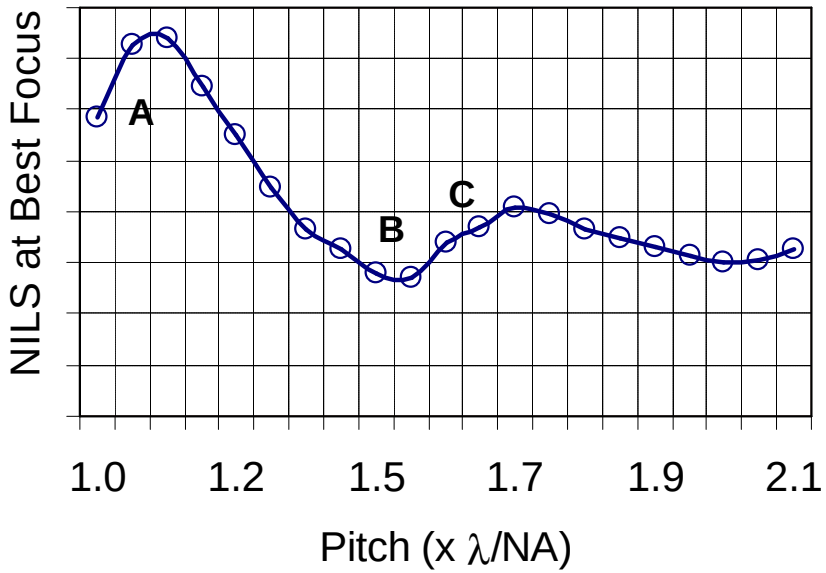
Binary



PSM



Spherical hot spots

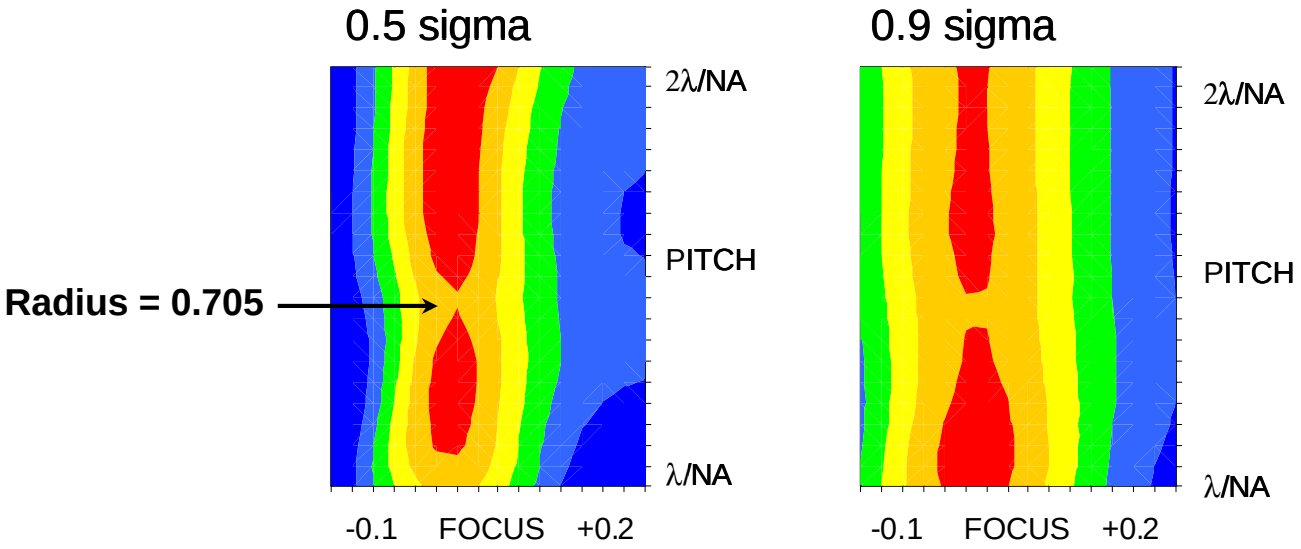


Dominant Effect

A – 1st order collection

B - 1st order at spherical max

C – 2nd order collection



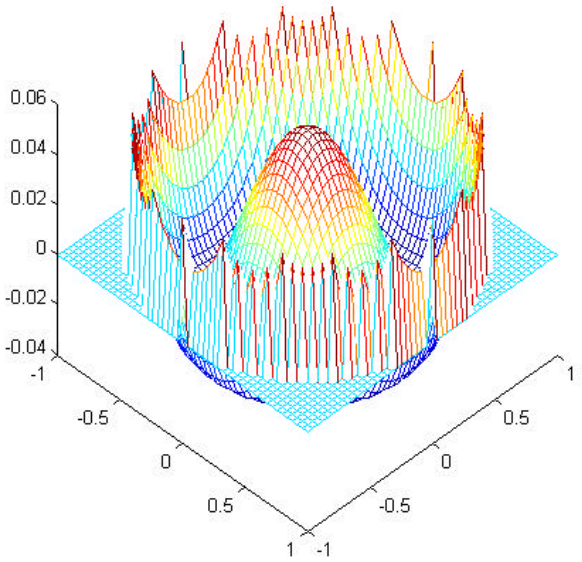
Summary

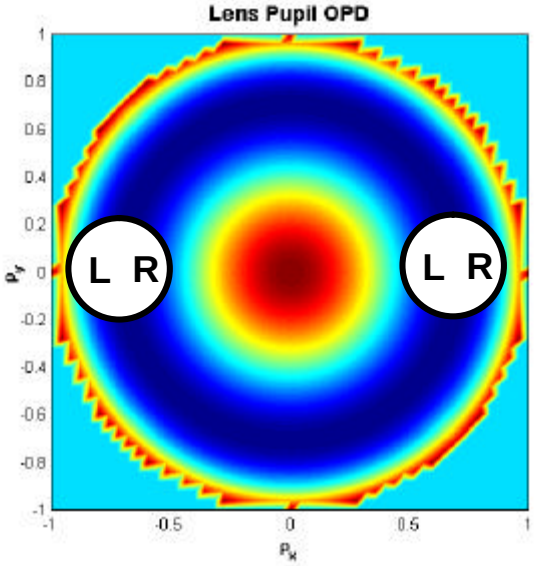
- Binary pitch follows $\frac{m\,l}{(s \pm 1)NA}$

- OAI pitch follows $\frac{m\,l}{R(s_c + s_r + 1)NA}$

- Assist features have pitch and (bar + space) sensitivity
- Contact side-lobes are a primary order effect
- Aberration sensitivity follows derivative of aberration

Phase Shift Mask and Spherical





ALT PSM, 0.85NA, 0.2W spherical

0.2 sigma

0.4 sigma

0.6 sigma