Code to produce wavefront aberrations

```
5580. if(a=0,5) then print,"waves of spherical aberration" print,aa,",waves of spherical aberration" print,aw,",waves of paraxial apsiciamization" print,ae,",waves of 3rd order astigmatism" print,av,",waves of coma" print,aw,",waves of field curvature" print,aa,=aa(aw) print,ae,=ae(aw) if ag(a)=0 then begin print,"Use 2-D complex array for pupil plane wavefront" & return endif
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```

Diffraction Limited Wavefronts at Exit Pupil
And Interfered with on-axis wave

Wavefronts at exit pupil of imaging system

Waverfronts interfered with on-axis wavefronts show linear tilt
Diffraction Limited
Peak: \( jinc(0)^2 = 0.616 \)

Spherical Aberration: \(.25\) wave
Strehl Ratio \(\approx 0.78\)

Spherical Aberration: \(.5\) wave
Strehl Ratio \(\approx 0.4\)

Spherical Aberration: \(1\) wave
Strehl Ratio \(\approx 0.09\)
MisFocus: 1 wave
Strehl Ratio ≈ 0.05

1 wave MisFocus partially compensates 1 wave Spherical: Strehl Ratio ≈ 0.94

Spherical Aberration OTF plots from literature
Field Curvature

Field curvature even for thin lens. Sag:

$$\Delta \approx \frac{h^2\theta^2}{2f}$$

Radius of curvature ($h' \approx t_1 \theta$)

$$\rho = \frac{h^2}{2\Delta} \approx f$$

For $j$ surfaces with flat object $\rho_0 = \infty$, Image curvature given by Petzval sum

$$\frac{1}{\rho_j+1} = -n_{j+1} \sum_{i=0}^{j} \frac{(n_{i+1} - n_i)C_{i+1}}{n_{i+1}P_i+k_i}$$

Curved Sensors to Compensate Field Curvature

Sony’s new bent stressed curved CMOS chip

Kepler Space Telescope Focal Plane Mosaic

Curvature of Field: 1/4 wave
Diffraction limited on-axis, misfocused off-axis

Curvature of Field: 1/2 wave
Diffraction limited on-axis, misfocused off-axis
Curvature of Field: 1 wave
√2 wave along diagonal

Coma: .25 wave

Coma: .5 wave

Coma: 1 wave
Coma: 2 wave

Coma: 4 wave

Coma OTF plots from literature

Astigmatism from Cylindrical lens or laser diode: .2 wave
Astigmatism from Cylindrical lens or laser diode: \(0.5\) wave

OTF on axis, mid field, and full field

1/2 Wave Cylindrical Astigmatism compensated by 1/2 wave misfocus

OTF on axis, mid field, and full field

1/2 Wave Cylindrical Astigmatism compensated by -1/2 wave misfocus

OTF on axis, mid field, and full field
1 Wave Cylindrical Astigmatism compensated by 1 wave misfocus

OTF on axis mid field and full field

Wave Shape = 0.00 + 0.00j
Wave Astigmatism = 1.00 + 0.00j
Wave Phase = 0.00
Wave Magnitude = 1.00
Field curvature = 0.00

What is Astigmatism?

no astigmatism sagittal focus tangential focus

Geometry of Astigmatism

Circle of least Confusion Sagittal Focus Tangential Focus Paraxial Focal Plane

Tangential Fan Sagittal Fan

Off-axis rays launched in tangential fan (in plane off off-axis point) or sagittal fan (perpendicular plane) come to focus in different curved focal surfaces.
Tangential focus where tangential features have highest resolution.
Sagittal focus where radial features have highest resolution.
All focal surfaces converge on axis to the paraxial focus.
Astigmatism and Moving the Focal Plane

Astigmatism: Varying Focal Planes

- At Paraxial focus, any orientation is in focus, but as we move off-axis lines misfocus
  - Sagittal and Tangential features go out of focus at different rates, first T then S
- Misfocused \((d = 1.5\text{mm})\) brings sagittal (radial) features into focus at field edge
  - on axis not too blurry, but tangential features still blurry at field edge
- Misfocused by \(3 \times (d = 4.5\text{mm})\) brings tangential features into focus at field edge
  - on axis totally out of focus and sagittal (eg radial) features blurry

Curved Focal planes, Astigmatism and Petzval surface: Placement of flat CCD

Focal length and field curvature can vary with wavelength

Tangential and Sagittal focal surfaces \((T - P) = 3(S - P) \Rightarrow (T - S) = 2(S - P)\)

- Uncompensated
- No Astigmatism
- No Field Curvature
- Negative Petzval for flat average \(T + S\)
- With balanced 4th order Field Curvature

3rd order Astigmatism: .25 wave

3rd order Astigmatism: .5 wave
1/2 wave 3rd order Astigmatism with 1/4 wave curvature of field

OTF on axis, mid field, and full field

Waves Sphere = 0.0040000
Waves Astigmatism = 0.0040000
Waves Cylinder = 0.00
Waves Field = 0.00
Field Curvature = 0.25

1/2 wave 3rd order Astigmatism and with 1/2 wave curvature of field

Imaging with 1 wave 3rd order Astigmatism

Test target image with 1 wave astigmatism, 1/2 wave field curvature

1/2 wave 3rd order Astigmatism with 1/2 wave curvature of field

OTF on axis, mid field, and full field

Waves Sphere = 0.0040000
Waves Astigmatism = 0.0040000
Waves Cylinder = 0.00
Waves Field = 0.00
Field Curvature = 0.25

Scalar Wave Eqn in 1+1D expanded as envelope and carrier

\[(\nabla^2 + k_0^2)E = 0\]

with \[E = E(x, z)e^{i\alpha z}\]

\[
\frac{\partial^2 E}{\partial x^2} + \frac{\partial^2 E}{\partial z^2} + k_0^2 = 0 = e^{i2k_0 z} \left[ \frac{\partial^2 E}{\partial x^2} + i2k_0 \frac{\partial E}{\partial z} - k_0^2 + \frac{\partial^2 E}{\partial z^2} + k_0^2 \right] = 0
\]

leads to evolution eqn

\[i2k_0 \frac{\partial E}{\partial x} + \frac{\partial E}{\partial z} = 0\]

If we have a sampled representation of the transverse field \(E(x) \rightarrow E_n\) we will need to evaluate derivatives along \(x\) to advance the field along \(z\).

Which side should we take difference on right or left?

\[
\frac{dE}{dt} = E_{n+1} - E_n \Rightarrow \delta_x
\]

\[
\frac{dE}{dt} = E_n - E_{n-1} \Rightarrow \delta_x
\]

simple, but not very accurate. Errors build up with the number of numerical integrations.