DOING PHYSICS WITH PYTHON

COMPUTATIONAL OPTICS

RS1 DIFFRACTION INTEGRAL

CIRCULAR APERTURE

FOCUSED BEAM

SPHERICAL ABERRATION

Ian Cooper

Please email me any corrections, comments, suggestions or additions: **matlabvisualphysics@gmail.com**

DOWNLOAD DIRECTORIES FOR PYTHON CODE

[Google drive]

[GitHub]

emRSFBXY.py

Calculation of the radiant flux density (irradiance) in a plane perpendicular to the optical axis for the radiant flux of convergent beam emitted from a circular aperture.

emFBZX.py

Calculation of the irradiance in the meridional (ZX plane) for the radiant flux of convergent beam emitted from a circular aperture.

emRSFBZ.py

Calculation of the radiant flux density (irradiance) along the optical axis for the radiant flux of convergent beams emitted from a circular aperture.

Warning: The results of the integration may look OK but they may not be accurate if you have used insufficient number of partitions for the aperture space and observation space. It is best to check the convergence of the results as the number partitions is increased. Note: as the number of partitions increases, the calculation time **rapidly** increases.

It is necessary to modify the Python Codes and comment or uncomment lines of code to run the simulations with different input and output parameters, and for different aperture functions.

Link: essential reference

RS1 diffraction integral: Focused beam from a circular aperture

SPHERICAL ABERRATION

Spherical aberration is an optical defect where light rays passing through the periphery of a lens or mirror are not focused at the same point as those passing through the centre. This causes a blurring or distortion of the image, especially at the edges of the field of view. Spherical aberration primarily arises from the spherical shape of the lens as light rays entering the lens at the edge are refracted more than those entering near the centre, leading to different focal points. This results in a blurry or distorted image, particularly at the edges of the field of view, thus there is a reduction in image sharpness and contrast, making images appear fuzzy or out of focus.

Reducing the aperture radius reduces the angle of incidence and can minimize spherical aberration, but this also increases the depth of field.

Aberrations are due to a distortion of the wave front and the aberrations can be described by an aberration function Φ that produces a change in phase of $\exp(ik\Phi)$. For spherical aberration, the **aberration** function is

$$\Phi = -\pi \rho^4$$

where ρ is the radial distance from the centre of the aperture.

RQ = (XQ**2 + YQ**2)**0.5 $\rightarrow \rho$

Simulation: Axial irradiance

Figure 1 shows the axial irradiance patterns for the circular aperture with zero spherical aberration.

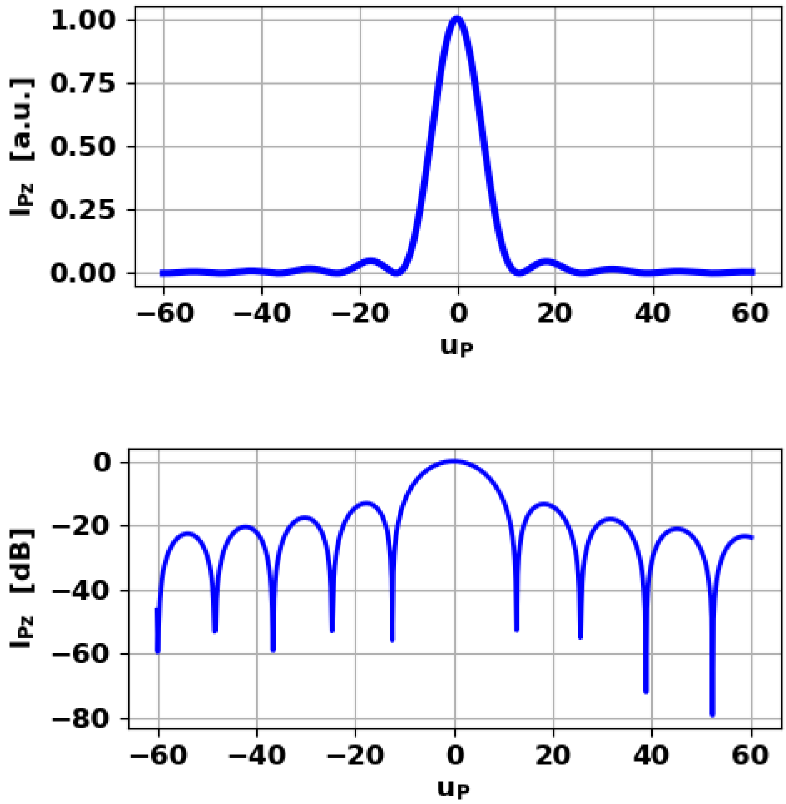


Fig. 1. Axial irradiance near the focal point with no spherical aberration.

Simulation parameters:

NQ = 299 NP = 299 nQ = 599 nP = 599

wavelength wL = 500 nm

aperture outside radius a = **10.000 mm**

Source xS = 0.000 m yS = 0.000 m zS = 1.000 m

Focal length f = 1.000 m

Numerical aperture NA = 0.0100 Fresnel number NF = 200.000

The irradiance pattern is slightly asymmetrical about the focal point as indicated below. The axial optical coordinates u_P for the minima in the axial irradiance are (error ± 0.1):

-59.9 -48.4 -36.6 -24.7 -12.4 12.7 25.6 38.9 52.4

Figure 2 shows the axial irradiance when there is spherical aberration applied to the aperture electric field for the same parameters as given for figure 1.

```
phi = -pi*RQ**4
T = exp(ik*phi)
EQ = T*EQ
```

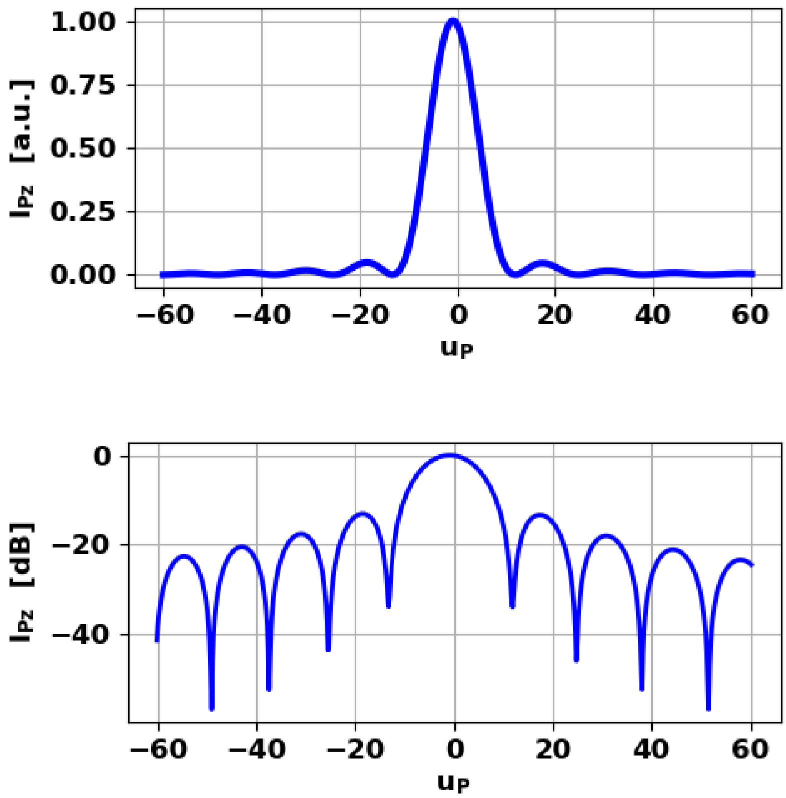


Fig. 2. Axial irradiance near the focal point with spherical aberration. The peak occurs at $u_P = -0.8$.

The axial irradiance is asymmetrical about the focal point. The axial optical coordinates u_P for the minima in the axial irradiance are (error ± 0.1):

-49.0 -37.4 -25.5 -13.2 11.9 24.8 38.1 51.5

Figure 3 shows the axial irradiance when the radius of the aperture is increased from **0.01 m** to **0.02 m**. All the other simulations parameters are unchanged. The axial irradiance is now very different from the patterns shown in figures 2 and 3. The is no distinctive first zero in the axial irradiance pattern.

The axial irradiance is very asymmetrical about the focal point. The axial optical coordinates u_P for the minima in the axial irradiance are (error ± 0.1):

-49.8 -37.6 -25.1 -0.2 12.5 25.2 37.9 50.7

aperture outside radius a = 20.000 mm

Numerical aperture NA = 0.0200

Fresnel number NF = 800.000

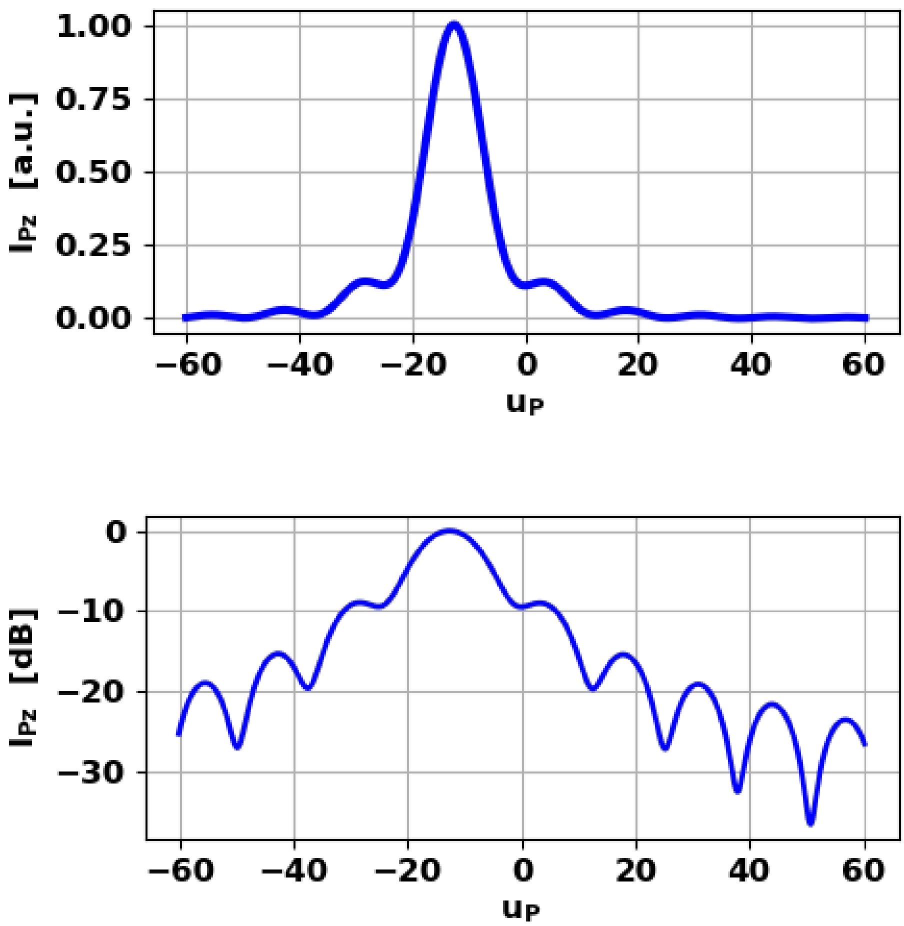


Fig. 3. Axial irradiance near the focal point with spherical aberration. The peak occurs at $u_P = -12.6$.

Simulation: radial irradiance in XY focal plane

Figures 4 and 5 show the radial irradiance patterns in the XY focal plane. For the smaller aperture, ***a* = 0.01 m**, the radial irradiance patterns are almost identical. However, when the aperture radius is ***a* = 0.02 m**, the pattern is very different and is dominant by a large focal bright spot. This is due to the shift in the maximum irradiance towards the aperture and not at the focal distance *f* = 1.00 m. So, an image would be blurred and not in the focal plane.

Fig. 4A. Radial irradiance: zero spherical aberration.
a = 10.0 mm NA = 0.01
NF = 200

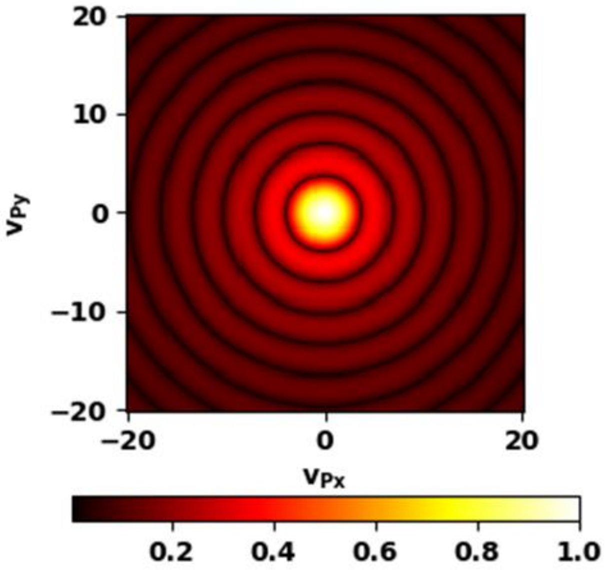


Fig 4B. Radial irradiance: spherical aberration.
a = 10.0 mm NA = 0.01
NF = 200

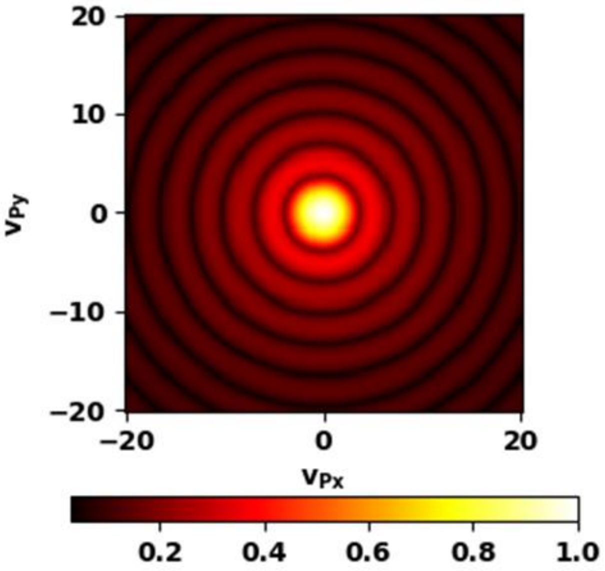
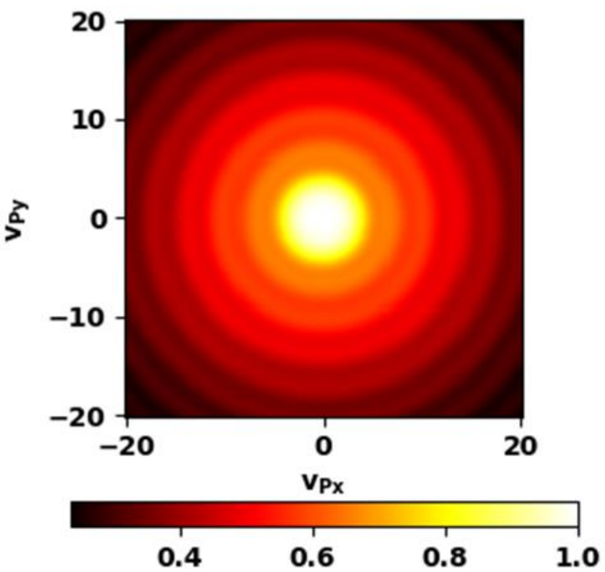


Fig 4C. Radial irradiance: spherical aberration.
a = 20.0 mm NA = 0.02
NF = 800



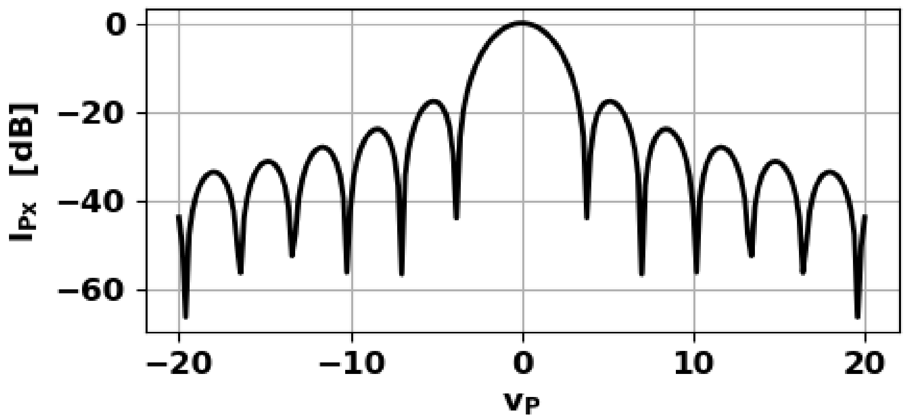


Fig. 4A. Radial irradiance: zero spherical aberration.
a = 10.0 mm NA = 0.01 NF = 200
Dark rings: 3.8 7.0 10.2 13.4 16.4 19.6

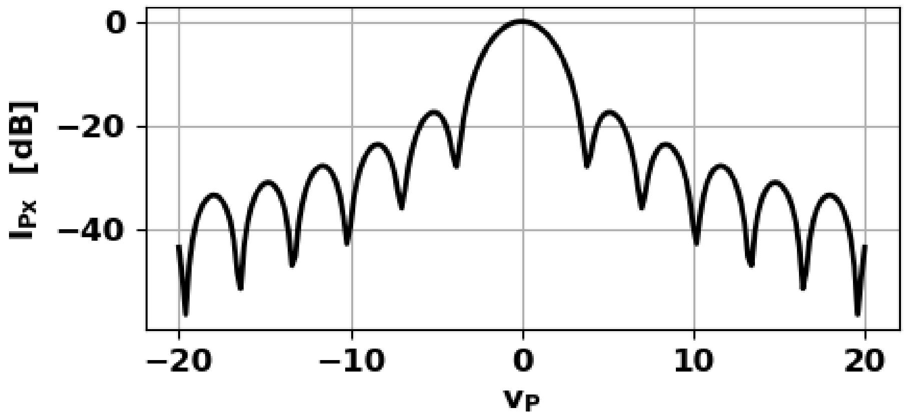


Fig 4B. Radial irradiance: spherical aberration.
a = 10.0 mm NA = 0.01 NF = 200
Dark rings: 3.8 7.0 10.2 13.4 16.4 19.6

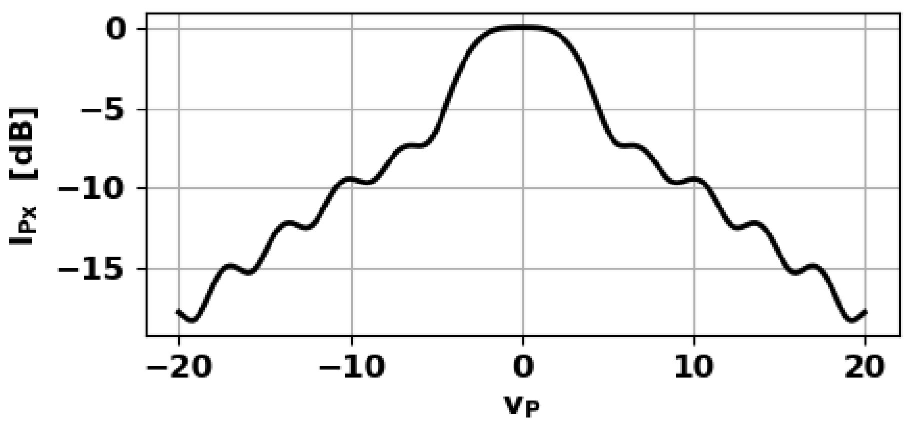


Fig 4C. Radial irradiance: spherical aberration.
a = 20.0 mm NA = 0.01 NF = 200
Dark rings: 6.0 9.0 12.6 16.0 19.2

The maximum radial intensity in figure 4C (**a = 20.0 mm**) is only 10% of the maximum radial intensity in figures 4A and 4B (**a = 10.0 mm**).

Simulation: irradiance in the ZX meridional plane

Figures 5 and 6 show the irradiance in the ZX meridional plane about the geometric focus without and with spherical aberration. The aberration function $\Phi = -\pi\,\rho^4$ is independent of angle position within the aperture. Therefore, the irradiance is rotationally symmetric about the optical axis.

For the aperture radius **a = 10.0 mm** the ZX meridional plane irradiance distributions appear to be very similar. However, for the aperture radius **a = 20.0 mm**, the irradiance pattern is significantly altered by the spherical aberration.

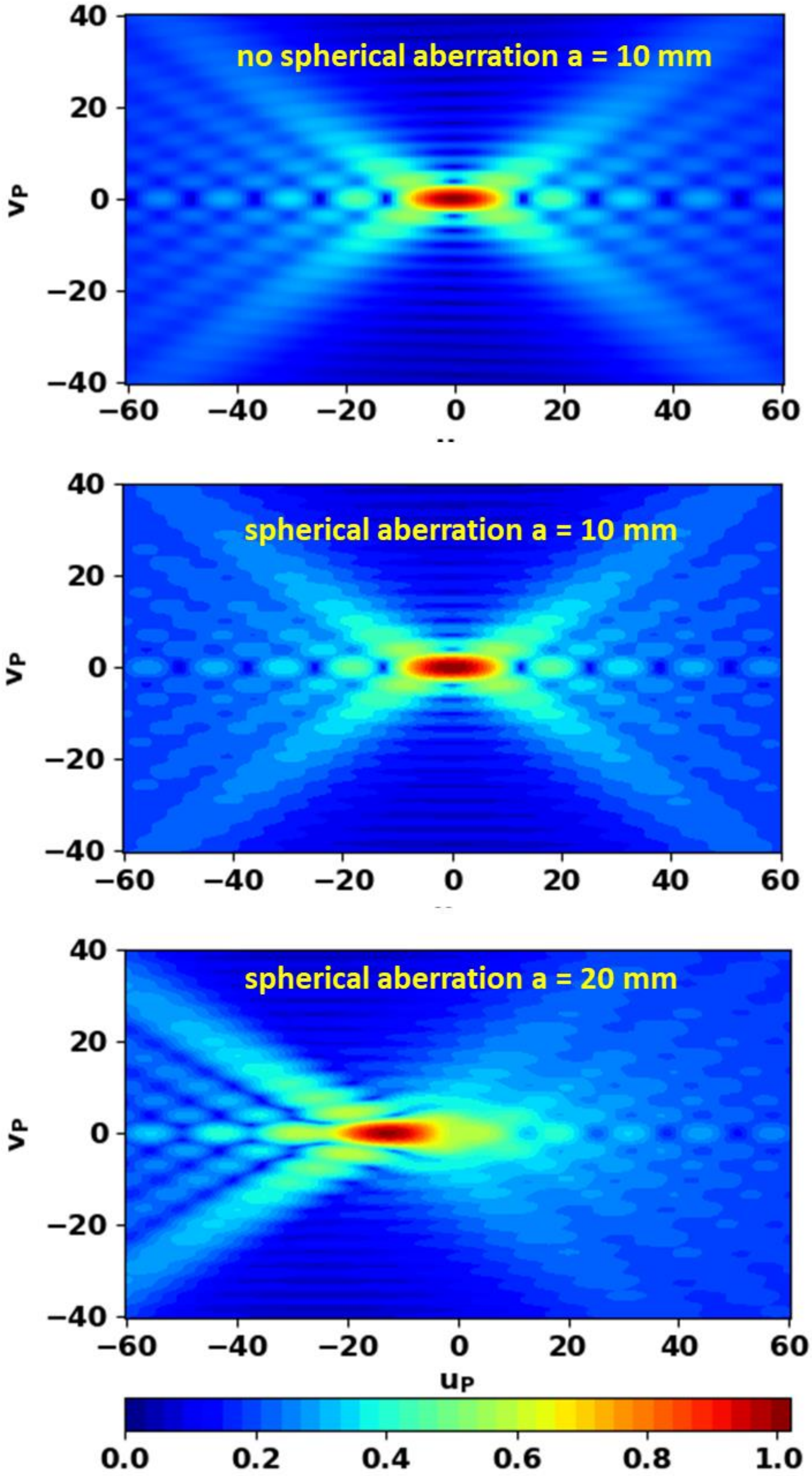


Fig 5. Irradiance in the ZX meridional plane.

```
cf = ax.contourf(UP,VP,IZX**sf, 32,cmap='jet')
cf = ax.pcolormesh(UP,VP,IZX**sf, cmap='jet')
```

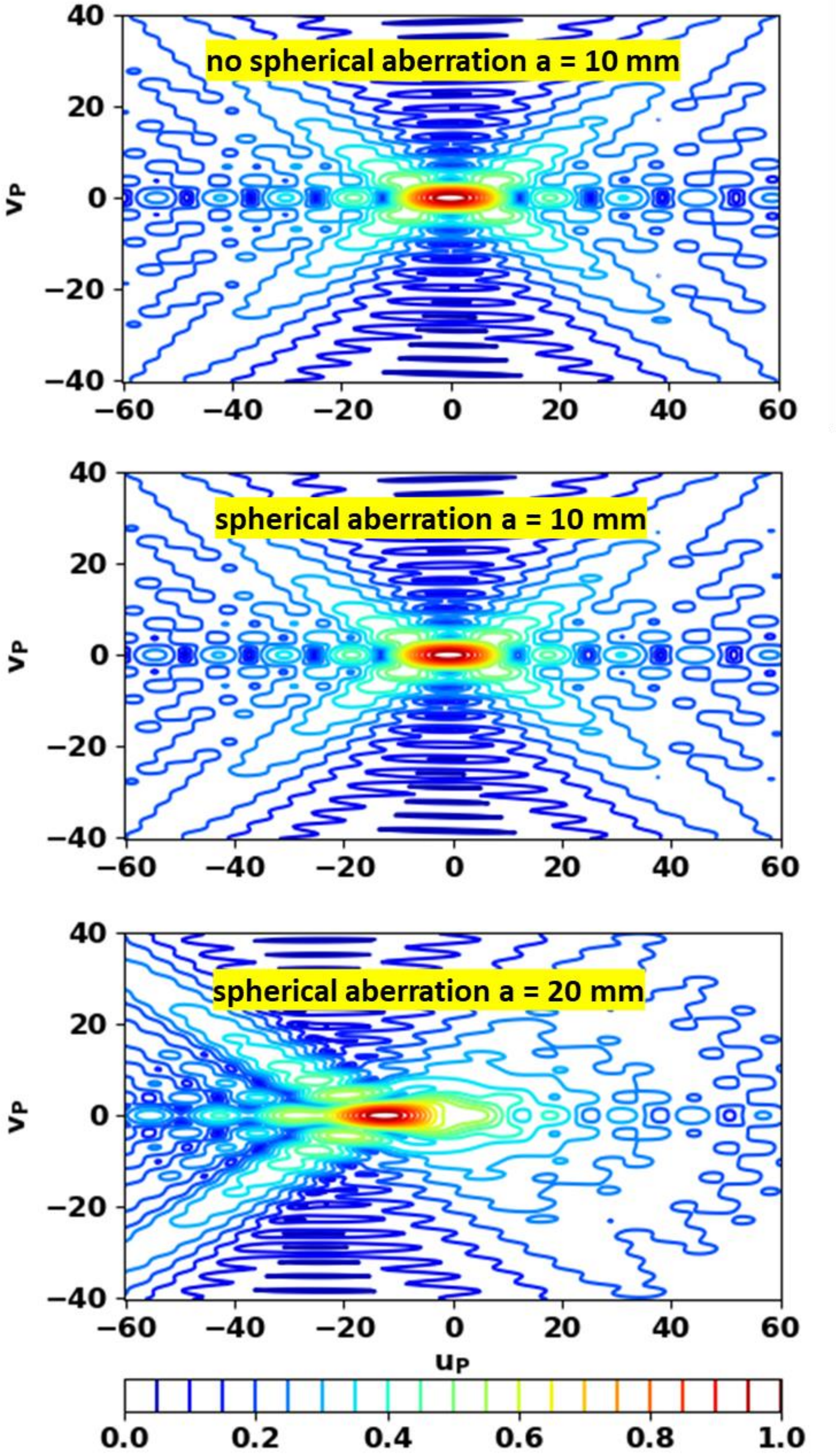


Fig 6. Irradiance in the ZX meridional plane.

cf = ax.contour(UP,VP,IZX**sf, 20,cmap='jet')