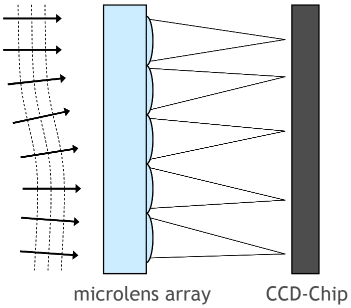
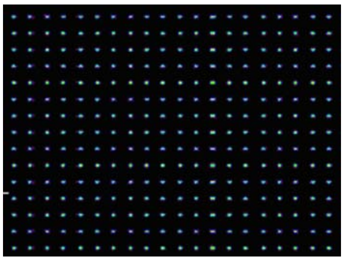
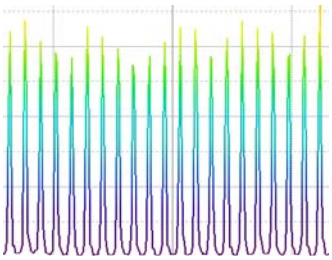
SMO TECHINFO SHEET 11 - SHACK HARTMANN WAVEFRONT SENSORS







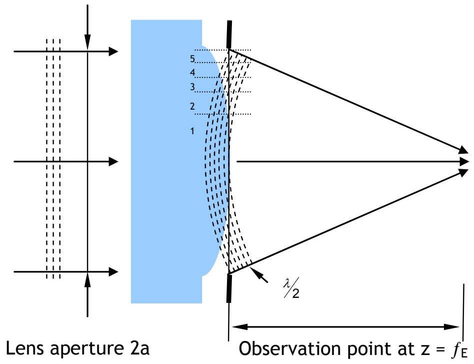
Introduction

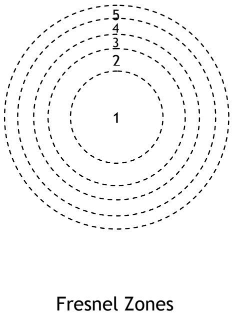
A Shack Hartmann wavefront sensor divides an incident wavefront into a number of beamlets by two-dimensional sub-apertures of a microlens array. Each microlens provides a separate focus on the detector of a CCD camera. The position of each focus spot is displaced by local wavefront aberrations. Thus, the periodical structure of the spots is the initial object for following investigations to be made by computer program. This picture is named the Hartmann pattern.

Shack-Hartmann wavefront sensors measure both intensity distribution and phase distortion in real time and high accuracy. They are widely used in measuring, diagnostic, but also in adaptive optical systems to compensate for phase distortions. This technical information sheet summarizes the optical properties of microlens arrays as required for Shack Hartmann wavefront sensors.

Fresnel Zones

Consider a paraxial lens, lens aperture Ø = 2a, an incident collimated beam, wavelength λ, and an observation point in the focal plane at $z = f_E$. A convergent wavefront is moving from the principal plane, H', towards the observation point. The aperture can be broken into Fresnel zones, each indicating an optical path difference of one-half wavelength. The Fresnel number, FN, is the number of times the phase cycles through π as seen from the observation point.





Fresnel Number*: $FN = \dfrac{a^2}{\lambda f_E}$

When the Fresnel number is low, FN < 1, the observation point is in the "far field"

→ **Fraunhofer Diffraction**

When the Fresnel number is high, FN > 1, the observation point is in the "near field"

→ **Fresnel Diffraction**

Fresnel Number as defined for a paraxial lens: Lens aperture Ø=2a, incident collimated beam, observed at the focal point $z = f_E$

Please note that "near" and "far" are relative to the propagation from lens to the observation point.

Microlenses for Shack Hartmann

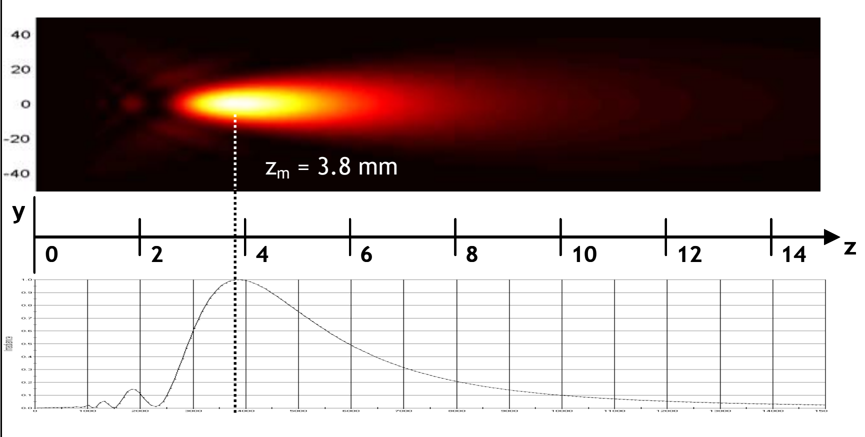
Microlens arrays for Shack Hartmann wavefront sensors usually have **small lens apertures** to provide high spatial resolution for wavefront sensing. Each microlens provides a separate focus on the detector of a CCD camera. The position of each spot is displaced by local wavefront aberrations. For highly aberrated wavefronts, microlenses with a **short focal length** are preferred. For small wavefront aberrations, microlenses with a **long focal length** are required.

Microlenses with small lens apertures and long focal lengths usually have low Fresnel Numbers near 1 and below. It is not surprising that low-FN microlenses are more dominated by diffraction effects at the lens aperture than by refraction of the incident light at the lens profile.

We will illustrate this at the example of a refractive plano-convex microlens in Fused Silica with lens aperture 2a = 150 µm, radius of curvature R_C = 2.3 mm and a Fresnel Number FN = 1.8. The microlens is illuminated with a plane wave of 633nm wavelength. From ray tracing the focal length is $f_E = \frac{R_C}{(n-1)} \approx 5mm$; the diameter of the diffraction limited focus spot is $Ø_{\mathrm{dl}} = 1.22\frac{\lambda f_E}{a} \approx 51\mu m$.

An analysis of the irradiance distribution behind the microlens by using diffraction theory shows that the focal length f_E and the diffraction limited spot diameter $Ø_{\mathrm{dl}}$ do not describe the optical properties of this low-FN microlens correctly.

Example (1). Lens aperture 2a = 150 µm, R_C = 2.3 mm

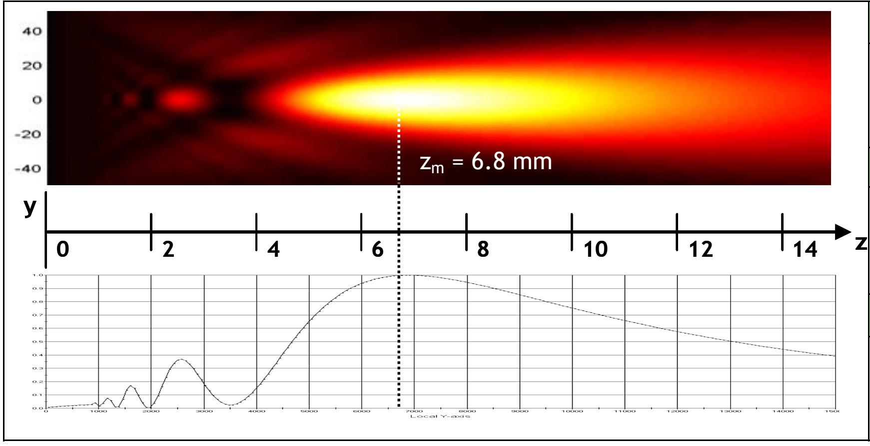


Lens parameters	
Lens type:	refractive, plano-convex
Lens aperture 2a:	150 µm
Radius of curvature R_C:	2.3 mm
Paraxial "classical" optics	
Focal length f_E:	5.0 mm
Spot $Ø_{\mathrm{dl}}/2$ at z $=f_E$:	25.5 µm
Fresnel Number FN:	1.8
Simulation using diffraction theory	
Peak irradiance z_m-position:	3.8 mm
FWHM at z_m:	17.6 µm
Peak irradiance*:	38

**Peak Irradiance: The initial beam peak irradiance in power per area.*

As shown in (1) the best focus spot is found at z_m = 3.8 mm behind the microlens and not at the paraxial focal position f_E = 5 mm. This "focal shift" for low-FN lenses is described extensively in optics literature. The essential point for our application is that diffraction at the aperture of the microlens contributes to the optical power of the lens and leads to a shorter focal length z_m. As Shack Hartmann sensors require a long focal length we will now reduce the optical power of the lens by increasing the radius of curvature to R_C = 10mm.

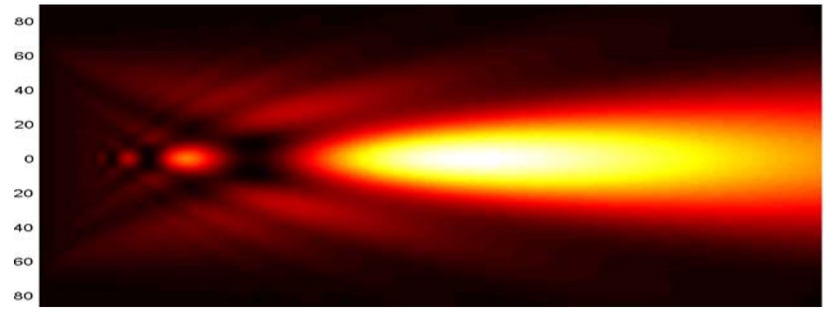
Example (2). Lens aperture 2a = 150 µm, R_C = 10 mm



Lens parameters	
Lens type:	plano-convex
Lens aperture 2a:	150 µm
Radius of curvature R_C:	10 mm
Paraxial “classical” optics	
Focal length f_E:	21.9 mm
Spot $Ø_{dl}/2$ at z = f_E:	112 µm
Fresnel Number FN:	0.4
Simulation using diffraction theory	
Peak irradiance z_m-position:	6.8 mm
FWHM at z_m:	30.0 µm
Peak irradiance:	9

As shown in (2) the best focus is at z_m = 6.8 mm. The 4x larger R_C has only a minor influence on the spot position; however, it has a major influence on the amount of the light in the spot. The peak irradiance drops from 38 to 9. The diffraction pattern for a further increase of R_C to 100mm is shown in (3). It seems that for very large R_C the value z_m converges to a maximum value.

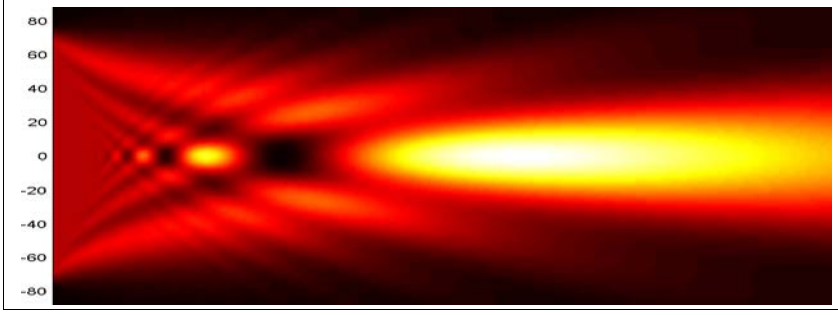
Example (3). Lens aperture 2a = 150 µm, RC = 100mm



Lens parameters	
Lens type:	refractive, plano-convex
Lens aperture 2a:	150 µm
Radius of curvature R_C:	100 mm
Paraxial “classical” optics	
Focal length f_E:	220 mm
Spot $Ø_{dl}/2$ at z = f_E:	1.13 mm
Fresnel Number FN:	0.04
Simulation using diffraction theory	
Peak irradiance zm-position:	7.9 mm
FWHM at zm:	41.0 µm
Peak irradiance:	5.6

For $R_C = \infty$ the microlens is identical to an aperture or pinhole with no optical power. As shown in (4) the best focus for a circular aperture is z_m = 8.9 mm. This is the maximum value for z_m.

Example (4). Circular aperture 2a = 150 µm, no lens



Lens parameters	
Aperture type:	circ., Ø = 150m
Radius of curvature R_C:	∞
Paraxial “classical” optics	
Focal length f_E:	∞
Simulation using diffraction theory	
Peak irradiance z_m-position:	8.8 mm
Peak irradiance:	4.9

Wavefront sensors using aperture or pinhole arrays as shown in (4) are the so-called Hartmann sensors, The best spot of a Hartmann sensor is usually found for a Fresnel number of FN = 1. Then wavefronts at rim of the aperture and in the center have an optical path difference of $\lambda/2$. For the previous example with Ø = 150µm diameter and 633nm wavelength the corresponding focal length for FN = 1 is f_E = 8.8mm which fits well to the results from simulation.

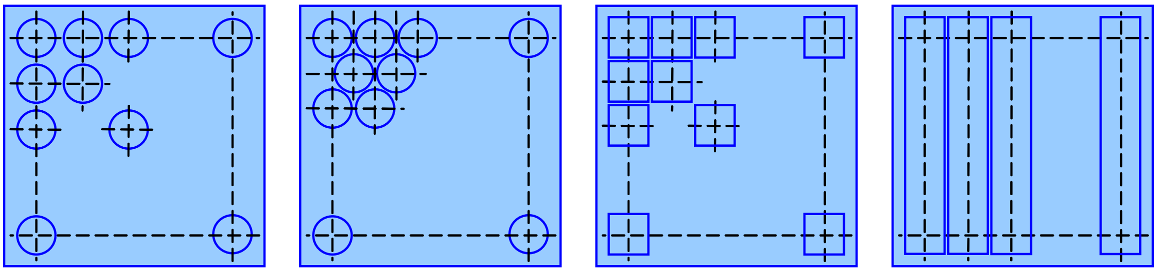
In 1971 Shack and Platt modified the Hartmann test by replacing the apertures with microlenses. The now called Shack-Hartmann wavefront sensor offers better photon efficiency due to the light gathering function of the lens. In addition, the diffraction pattern at the focus of a lens corresponds to the Fourier transform of the electric field pattern of the incident light. Thus, the position of the focal spot is only proportional to the average wavefront slope over the aperture and independent of higher-order aberrations and intensity profile variations. The Shack-Hartman wavefront sensor examines the entire wavefront, not just small samples like the Hartmann sensor does.

Conclusion

For a given microlens aperture Ø = 2a the maximum distance from the microlens array to the focal plane z_m is limited by diffraction at the lens aperture.

- For a smaller R_C (FN > 1) the best focus position z_m is shifted closer to the lens.
- For larger R_C the focus z_m gets closer to its maximum – but the irradiance decreases.

The optimum choice seems to be a focus position of 0.8x the maximum value of z_m and an adapted microlens that provides a high contrast in the spot pattern. Please note that this is only a general rule to obtain the best spot with the maximum peak irradiance. Modern image sensors and today's sophisticated software can handle very poor image contrasts. The spot pattern could also be detected far behind the best focus positions.



SUSS MicroOptics provides circular, cylindrical, and square-type microlens arrays for high precision wavefront sensing. Apertures (Chromium) on front- and backside of the microlenses, pin holes, alignment crosses, etc. are available on request.

SUSS MicroOptics provides optical designs for wavefront sensing systems and assists in finding suitable solutions for all type of measurement and diagnostics applications.

Please contact our micro-optics experts: info@suss.ch or phone +41-32-7205104.