Lab work in photonics.

Aberrations.

General presentation

The point source method

Wavefront mesurements

ii

.

TABLE OF CONTENTS

AT THE END OF THE 4 LAB SESSIONS, STUDENTS ARE ABLE TO:

- Implement methods of characterization of optical imaging systems. These methods include the simple star test method, as well as the use of instruments commonly found in the industry such as Zygo interferometer and Schack-Hartmann wavefront analyzer (HASO).
- Analyze quantitatively the performances of an optical system according to the situations of use (conjugation, field, numerical aperture, …), and recognize simple geometrical aberrations as coma, astigmatism, spherical aberration, chromatism.
- Establish the suitability or limitations of an optical system with the imaging application for which it is dedicated

TABLE OF CONTENTS   1

GENERAL PRESENTATION OF THE

ABERRATIONS LAB SESSIONS

The goal of the following lab sessions is to study and analyze the defects of an optical system, i.e. the geometrical and chromatic aberrations. The lab sessions dedicated to this study should be considered as a whole, since you will study the same optical systems by various methods and then summarize and compare the results.

☞ Preparation

Each lab session should be prepared ahead of time: for each lab session, we expect from you that you understand the measurement methods ahead of time, and that you do the preliminary calculations for the set-up specific to this lab session. Preparatory should be answered during this preparation phase.

☞ Lab report

For lab no. 1-2-3, a report per session must be submitted on the e-campus site no later than one week after the session.

The lab report associated with LAB SESSION N° 4 (HASO) should be handed in at the end of the corresponding session.

☞ In practice

– You will analyze by several complementary methods: a simple plano-convex lens, a Clairaut-Mossotti type doublet, and an enlarger objective (see p16).

- *The point source method

    Lab session n°1: spherical aberration and chromatism

    Lab session n°2: off-axis aberrations

During these lab sessions, you will observe the image spot directly with a microscope viewer. Observing the image spot, *i.e.* the **Point Spread Function** of the optical system under test, allows you to evaluate the performance of the optical system rapidly on axis and off axis, in the presence of monochromatic or polychromatic light, even with large aberrations.

- Analysis of the transmitted wavefront

    Lab session n°3: Fizeau interferometer (ZYGO)

    Lab session n°4: Shack-Hartmann analyzer (HASO)

During these lab sessions, you will study the wavefront after transmission through the optical system under test, firstly by an interferometric method (with the ZYGO), and secondly by a geometrical method (with the HASO). Both methods allow you to measure the **Optical Path Delay** between the transmitted wavefront and the ideal spherical wavefront, *i.e.* the "reference sphere". These two methods are well suited for optical systems with small aberrations.

A. THE POINT SOURCE METHOD
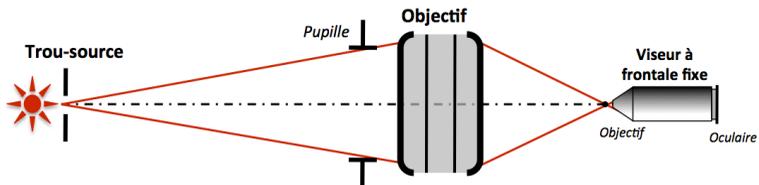
Figure 1: Experimental Set Up

An easy and fairly efficient way to study the quality of an optical system is to observe and measure the image of a point source, also called the Point Spread Function (PSF). The shape and the size of this image depend on the aberrations of the optical system. A perfect system is diffraction limited, i.e. the PSF is an Airy pattern for a circular pupil. The measurements can be made with a microscope viewer and can be performed either with the eye or with a camera. Defocusing the observation plane slightly around the best focus plane gives much more information about the aberrations of the system.

1. HOW TO CHOOSE THE LIGHT SOURCE

⇨*Study of aberrations for a precise wavelength (quasi monochromatic light)*: Spectral lamp, white lamp with a colored filter, colored LED.

⇨*Study of chromatic aberrations:* white source and possibly a monochromator

✋ **Warning: It is crucial to systematically make sure that the pupil of the system under test is fully illuminated** otherwise the aberrations would be grossly under estimated. If required, a condenser can be inserted between the light source and the point source to ensure that the optical system under test is fully illuminated.

2. HOW TO CHOOSE THE PINHOLE:

Ideally, the point source should be infinitely small in order to measure the PSF size of the optical system under test. In practice, however, the pinhole has a finite size. **The observed image is actually the convolution of the PSF that we want to study by the geometrical image of the pinhole.** The geometrical image of the pinhole should thus be kept small with respect to the PSF diameter. For an optical system with a circular pupil, the smallest PSF is the Airy spot. On the other hand, the observation may be difficult by lack of light if the pinhole is too small. The diameter of the pinhole should thus be adapted to the aberrations of the system under test:

→ For small aberrations (lenses that are nearly diffraction limited), the geometrical image of the pinhole diameter should typically be smaller than ¼ of the Airy dark ring diameter in the image plane.
→ For large aberrations, choose a pinhole with a larger diameter to compensate for the spreading of light, whilst keeping the pinhole geometrical image smaller than the dimension of the PSF.

3. HOW TO CHOOSE THE MISCROSCOPE OBJECTIVE?

Numerical aperture of the microscope objective: **the system under test must be the pupil of the whole set-up.** Therefore, the numerical aperture of the microscope objective must be larger than the image numerical aperture of the system under test.

Microscope objective magnification ratio: the PSF must be sufficiently magnified to be observed easily. However, the size of the PSF should not exceed the full field of view of the microscope viewer. **You should thus start with a moderate magnification ratio, and increase it progressively if necessary.**

B. WAVEFRONT MEASUREMENTS

Both the ZYGO and the HASO measure the wavefront error, but they use two different methods. The ZYGO, which is based on the Fizeau interferometer, uses an interferometric approach, while the HASO approach, based on the Shack-Hartmann analysis, is a geometrical measurement. In both cases, the data processing allows a quantitative analysis of the contribution due to the various aberrations, the PSF, the spot diagram, and MTF of the tested optical system.

o <u>ZYGO : interferometric measurement of a wavefront:</u>

The Zygo interferometer analyzes interferences between a reference plane wavefront that has been reflected by a glass reference plane and a plane wavefront that has propagated forth and back through the objective. The back-reflection is provided by a spherical reference mirror. The center of curvature of the spherical mirror is on the objective best focus.

o <u>HASO : geometrical measurement of a wavefront:</u>

Following the Shack-Hartmann method, an array of micro-lenses samples the wavefront and enables the measurement of the **local slopes** of the wavefront. The software reconstructs the wavefront in real time from the slopes measurements. This is very useful for alignment of the optical system under test. By comparison with a ZYGO interferometer, a Shack-Hartmann analyzer has a lower spatial resolution. It is not suited for optical systems with a large image numerical aperture.

1. DECOMPOSITION OF THE WAVEFRONT ON

THE ZERNIKE POLYNOMIALS BASIS

It is possible to evaluate the various geometrical aberrations contribution by decomposing the wavefront defect on the Zernike polynomials orthogonal basis (for circular pupils only). Note that the HASO aslo propose a decomposition over Legendre polynomials which is adapted for rectangular pupils.

The decomposition over the Seidel basis remains widely used for the 3rd order aberrations. The relationships between the Seidel amplitudes and the Zernike coefficients (see Table below) are the following (for systems which have only 3rd order aberrations):

	Seidel (3rd order)	Peak to valley amplitude
Spherical Aberration	$\Delta_{max} = 6 \times C_8$ [1]	$\Delta_{PV} = \Delta_{max}$
Coma	$\Delta_{max} = 3\sqrt{C_6^2 + C_7^2}$	$\Delta_{PV} = 2 \times \Delta_{max}$
Astigmatism	$\Delta_{max} = \sqrt{C_4^2 + C_5^2}$	$\Delta_{PV} = 2 \times \Delta_{max}$

---

[1] Note that if C_{15} is not negligible in the decomposition of the wave front, it is necessary to take it into account to evaluate correctly the spherical aberration of the 3rd order: $\Delta_{max} = 6\,C_8 - 30\,C_{15}$. This can be extrapolated easily to the other terms.

Polynomials used by ZYGO and HASO

C1	$u\cos\varphi$	Basculement	
C2	$u\sin\varphi$		
C3	$2u^2-1$	Défaut de mise au point	
C4	$u^2\cos 2\varphi$	Astigmatisme	$3^{\text{ème}}$ ordre
C5	$u^2\sin 2\varphi$		
C6	$(3u^2-2)u\cos\varphi$	Coma	
C7	$(3u^2-2)u\sin\varphi$		
C8	$6u^4-6u^2+1$	Aberration sphérique	
C9	$u^3\cos 3\varphi$	Trèfle	$5^{\text{ème}}$ ordre
C10	$u^3\sin 3\varphi$		
C11	$(4u^2-3)u^2\cos 2\varphi$	Astigmatisme	
C12	$(4u^2-3)u^2\sin 2\varphi$		
C13	$(10u^4-12u^2+3)u\cos\varphi$	Coma	
C14	$(10u^4-12u^2+3)u\sin\varphi$		
C15	$20u^6-30u^4+12u^2-1$	Aberration sphérique	
C16	$u^4\cos 4\varphi$	Aberration quadrifoliée	$7^{\text{ème}}$ ordre
C17	$u^4\sin 4\varphi$		
C18	$(5u^2-4)u^3\cos 3\varphi$	Trèfle	
C19	$(5u^2-4)u^3\sin 3\varphi$		
C20	$(15u^4-20u^2+6)u^2\cos 2\varphi$	Astigmatisme	
C21	$(15u^4-20u^2+6)u^2\sin 2\varphi$		
C22	$(35u^6-60u^4+30u^2-4)u\cos\varphi$	Coma	
C23	$(35u^6-60u^4+30u^2-4)u\sin\varphi$		
C24	$70u^8-140u^6+90u^4-20u^2+1$	Aberration sphérique	
C25	$u^5\cos 5\varphi$	Aberration pentafoliée	$9^{\text{ème}}$ ordre
C26	$u^5\sin 5\varphi$		
C27	$(6u^2-5)u^4\cos 4\varphi$	Aberration quadrifoliée	
C28	$(6u^2-5)u^4\sin 4\varphi$		
C29	$(21u^4-30u^2+10)u^3\cos 3\varphi$	Trèfle	
C30	$(21u^4-30u^2+10)u^3\sin 3\varphi$		
C31	$(56u^6-105u^4+60u^2-10)u^2\cos 2\varphi$	Astigmatisme	
C32	$(56u^6-105u^4+60u^2-10)u^2\sin 2\varphi$		
C33	$(126u^8-280u^6+210u^4-60u^2+5)u\cos\varphi$	Coma	
C34	$(126u^8-280u^6+210u^4-60u^2+5)u\sin\varphi$		
C35	$252u^{10}-630u^8+560u^6-210u^4+30u^2-1$	Aberration sphérique	
C36	$924u^{12}-2772u^{10}+3150u^8-1680u^6+420u^4-42u^2+1$	Aberration sphérique	$11^{\text{ème}}$ ordre

U is the normalized height in the pupil, and φ is the azimutal angle.

2. PSF SIMULATION

From the measured wavefront error in the pupil, i.e. the Optical Path Difference, both HASO and ZYGO can simulate the image spot of the optical system under test.

o   Geometrical analysis: Spot Diagram :
Rays being perpendicular to the wavefront, it is straightforward to deduce the intersections of the rays with the image plane. This geometrical approach gives the Spot diagram. For a perfect system the spot diagram is a single point (stigmatism).

o   Fourier Analysis : PSF and MTF :
A wavefront analyzer measures the wavefront error at every point of the pupil. Assuming that the pupil is uniformly illuminated, the amplitude of the electromagnetic field in the pupil is related to the wavefront error by:

$$P(X,Y) = a_0 e^{j\varphi(X,Y)} = a_0 e^{-j2\pi\frac{\Delta(X,Y)}{\lambda}}$$

→ The *incoherent* Point Spread Function (the image spot), is calculated by Fourier Transform:

$$PSF(\vec{r}') \propto \left| TF(P(X,Y)) \right|^2_{\left(\frac{\vec{r}'}{\lambda p'}\right)}$$

The PSF of a diffraction limited optical system with a circular pupil is an Airy pattern: it is the smallest image of a point source that an optical system can form. The diameter of the first dark ring of the Airy pattern, including 84% of the total energy of the PSF, is $\emptyset_A = 1,22\lambda/\sin\alpha'_{max}$.

$$E_{Airy}(r') = \left(\frac{A_0}{\lambda z'}\right)^2 (\pi h_{max}^2)^2 \times \left(\frac{2J_1\left(\frac{2\pi}{\lambda}\sin\alpha'_{max} \times r'\right)}{\frac{2\pi}{\lambda}\sin\alpha'_{max} \times r'}\right)^2$$

The encircled energy inside the $\varnothing_A$ diameter drops quickly in presence of aberrations. Comparing the PSF of the system under test with the Airy spot limit is a good way to evaluate how important the defects of the system are. The *Strehl ratio,* R_S , is the ratio between the maximum of the measured PSF and the maximum of the ideal (*i.e.* diffraction limited) PSF. The Maréchal criterion stipulates that, for visual observations, an optical system can be considered as diffraction limited if $R_S \geq 0.8$, which corresponds to $\sigma_\Lambda \leq 0,07$ $\lambda \cong \lambda/14$. In practice, values of R_S below 0.2 are not relevant to describe the quality of an optical system.
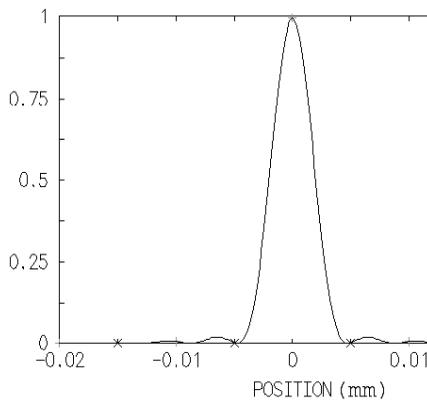
| PSF of a diffraction limited lens with a numerical aperture of 0.08 at $\lambda = 633$ nm | Corresponding encircled energy of the Airy pattern described on the left |
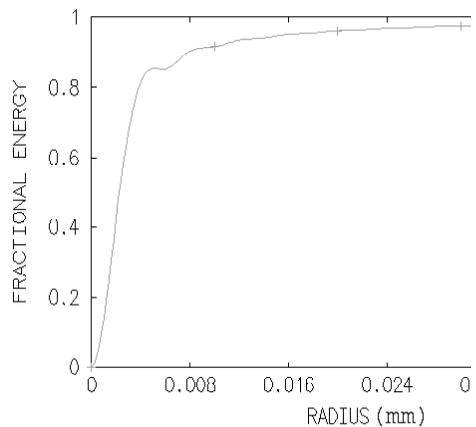
→ The Modulation Transfer Function (MTF) is another way to evaluate the defects of an optical system that is illuminated by incoherent light. It is the Fourier Transform of the PSF. **The MTF, is the autocorrelation of the field amplitude in the pupil**.

$$FTM(\vec{\omega}') = TF\left(PSF(\vec{r}')\right)_{\vec{\omega}'} = \frac{\left(P \otimes P\right)_{\lambda p' \cdot \vec{\omega}'}}{\left(P \otimes P\right)_{\vec{0}}}$$

The Modulation Transfer Function yields the **contrast** in the image formed by the optical system when the object is a sinusoidal test pattern. The MTF is usually plotted versus **the spatial frequency ν, measured in the image plane**.
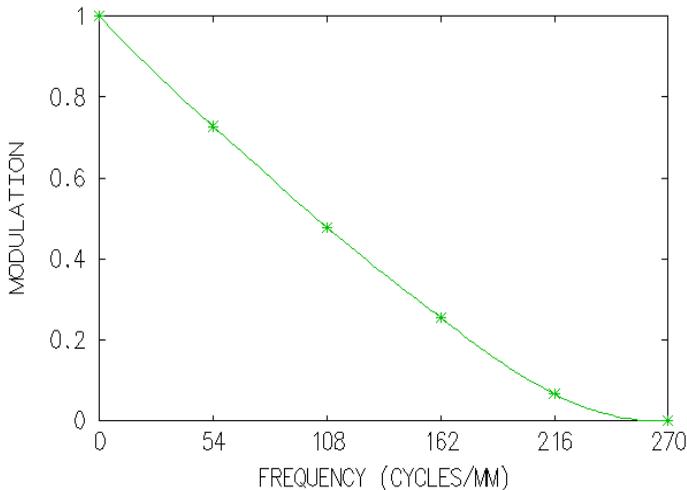
MTF of a diffraction limited lens with a numerical aperture of 0,08 à λ = 633 nm

Comparing the MTF of the system under test with the MTF of a diffraction limited system with the same numerical aperture is also a good way to evaluate how much the aberrations of the system degrade the quality of the image. The cut-off frequency of a diffraction limited system is given by:

$$\nu_c = \left(2\sin\alpha'_{max}\right)/\lambda$$

where $\sin\alpha'_{max}$ is the numerical aperture (NA) of the system under test, in the image space. However it is often useful to define a cut off frequency at 10%, because below this value the image is generally too aberrated to be used. Note that the MTF contains exactly the same information as the PSF: one is merely the Fourier Transform of the other. It is just another way to evaluate the aberrations of an imaging system.

3. IMPORTANT REMARK ON THE WAVEFRONT

MEASUREMENT

The wavefront defect measurement should be performed in a **conjugate plane of the output pupil of the system**. Otherwise, the propagation would lead to a deformation of the wavefront, which is particularly visible on the edge of the pupil when the focus adjustment is not accurate. The ZYGO has a CAM adjustment option (a motorized lens) that allows the output pupil of the optical system under test to be conjugated with the plane where the interference pattern is recorded. In the case of the HASO labwork, this condition is not fulfilled. This may lead to measurement errors.

C. SPECIFICATIONS OF THE LENSES

Lab sessions n°1-2-3 :

● **Plano-convex singlet**

f' = 150 mm (±1%) - ∅ = 25 mm – ON = 0,08.

● **Clairaut-Mossotti doublet (Thorlabs AC254-150-A1)**

f' = 150 mm (±1%) - ∅ = 25 mm – ON = 0,08

There is no air space between the two lenses. The pair of glasses is BK7/SF5. It was designed to be aplanatic (*i.e*. no spherical aberration and no coma) and achromatic in the visible range.

● **magnifying objective**

f' = 150 mm (±1%) – Iris diaphragm

The characteristics of this objective will be measured precisely during the lab sessions. It was designed to magnify pictures taken with a **24mm x 36mm** ISO200 film. The diameter of the grain of an ISO200 film is approximately **20μm**.

Lab sessions n°4 :

● **Clairaut-Mossotti doublet (Thorlabs AC254-150-A1)**

f' = 150 mm (±1%) - ∅ = 25 mm – ON = 0,08

1. PLANO-CONVEX SINGLET (NOMINAL ORIENTATION)

**Glass : BK7   Focal length: 150 mm   Numerical Aperture: 0.08 ($\varnothing_e$ = 25 mm)**

Spot-diagram and PSF at paraxial focus on axis (λ = 633 nm)
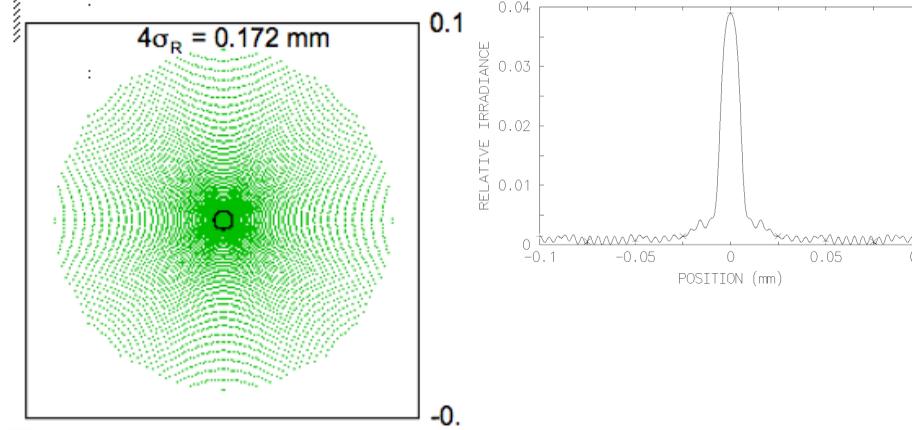
Spot-diagram and PSF at best focus on axis (λ = 633 nm)
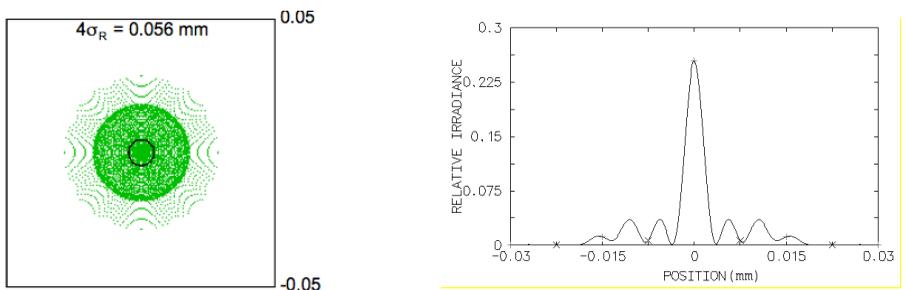
Longitudinal chromatism
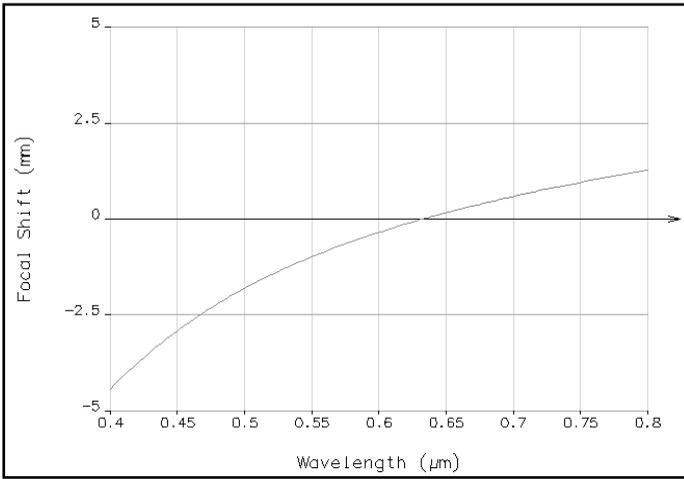
2. THORLABS DOUBLET AC254-150-A1

Focal length : 150 mm , Numerical Aperture: 0.08 (Ø$_e$ = 25 mm)

LENS DATA

SRF	RADIUS	THICKNESS	AP. RADIUS	GLASS
OBJ	--	1.00e+20		AIR
1	91.62	5.70	12.50	BK7
2	-66.68	2.20	12.50	SF5
3	-197.70	146.29	12.50	AIR

Foyer paraxial à λ= 633 nm
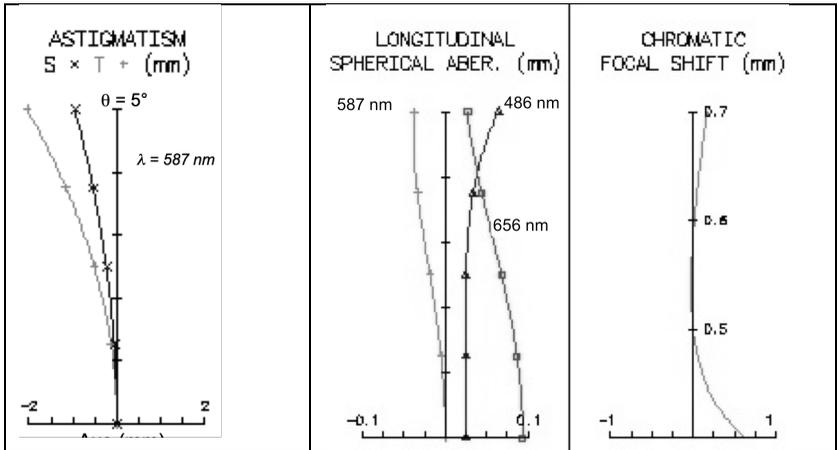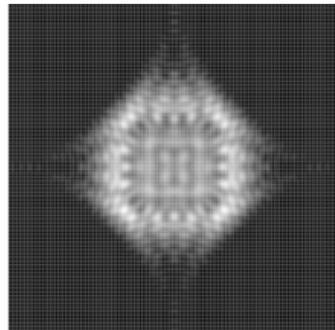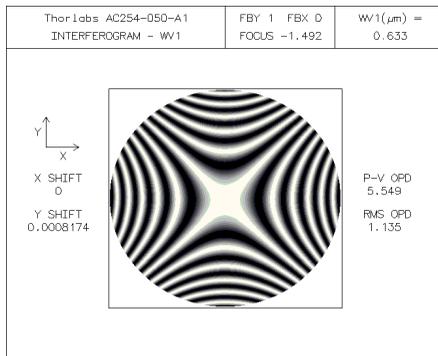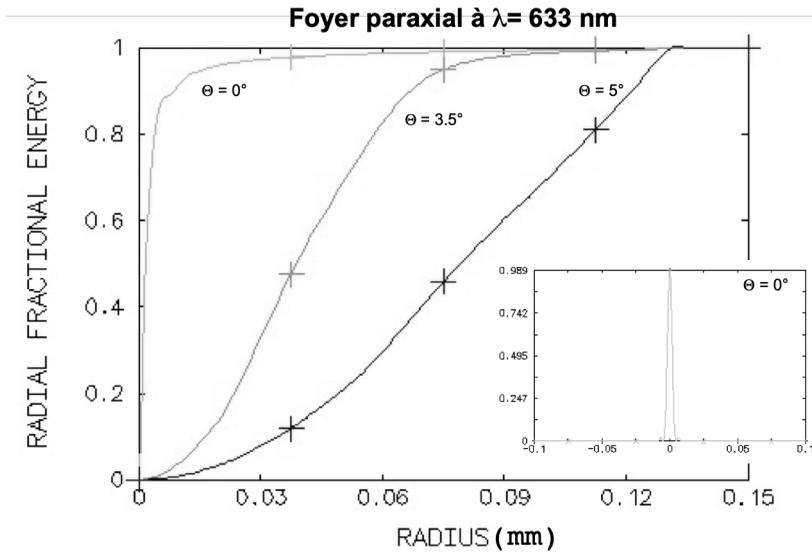
Theoretical interferogram at best focus, θ = 5°, λ = 633 nm

PSF simulation at best focus, θ = 5°, λ = 633 nm (image size = 160 μm)

LAB SESSION N°1

ON-AXIS ABERRATIONS USING

THE "POINT SOURCE METHOD"

In this lab session, you will study and compare the **on-axis aberrations** of three optical systems using the "point source method", *i.e.* **spherical aberration** and **axial chromatism**.

The optical systems are the following: a **plano-convex singlet**, a **Clairaut – Mossotti doublet**, and a **magnifying objective**. The characteristics of these systems are given in the global presentation. In particular, you will compare the performance of the singlet and the doublet, which have the same focal length and the same numerical aperture.

☞Preparatory work: read carefully the principle of the point source method presented in the introductory part of this book and in the text below. Do the prelimilary calculations labelled with the ☞ symbol.

A. REMINDERS

1. CHROMATISM AND GLASS DISPERSION

The dispersion of a transparent optical medium is defined as the variation of its refractive index **n** as a function of the wavelength λ. This function is usually regularly decreasing in the visible domain.

So, it is possible to characterize a glass by the mean value of the index $\bar{n}$ and by the variation Δn of the index over the visible domain. In fact, instead of Δn, we use the **constringency** (also called Abbe number), defined as, $\nu = (\bar{n} - 1)/\Delta n$ which is a useful quantity to calculate the chromatic aberrations:

$$\nu_d = \frac{n_d - 1}{n_F - n_C}$$

where d, F et C denote the following spectral rays:

ray	element	color	wavelength (nm)
d	Helium	Yellow	587,6
F	Hydrogen	Blue	486,1
C	Hydrogen	Red	656,3

The available glasses may be represented in a graph (ν, **n**) as shown on Figure 1.

Reminder : For a **singlet**, the variation of the focal length is given by: $\delta f' = f'_B - f'_R = - f'/\nu_d$.

☞ *Evaluate the longitudinal chromatism $\delta f'$ of the studied singlet.*
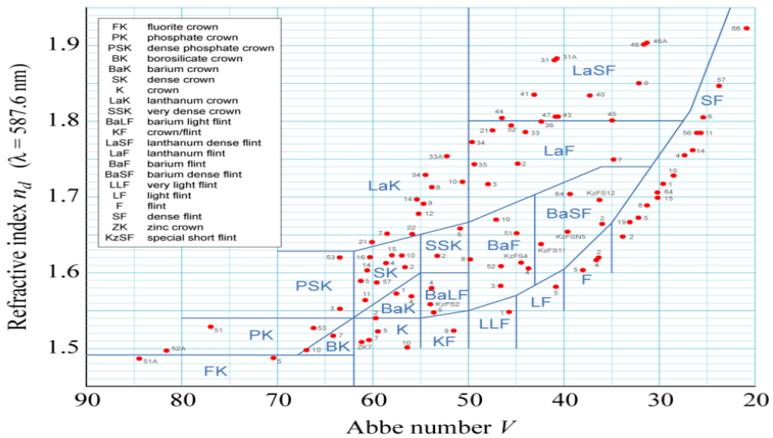
Figure 2: different glasses in the (ν, n) plane (SCHOTT)

2. THIRD-ORDER SPHERICAL ABERRATION

Spherical aberration appears on axis and remains constant all over the field. It appears when the aperture of the system becomes too wide to predict the ray trajectory using paraxial calculation. Spherical aberration creates a variation of the focal plane depending on the height of impact of rays in the pupil. Within the 3rd order approximation, using a purely geometrical approach (no diffraction), it can be shown that spherical aberration has the following properties:

- Axial caustic length : $l(\alpha') = \overline{F'_P F'_{\alpha'}} = a\alpha'^2$, where α' is the image aperture angle
- PSF radius at paraxial focus: $dy' = -l(\alpha') \times \alpha' = -a\alpha'^3$
- Optical path delay (OPD) at paraxial focus $: \Delta(\alpha') = -\dfrac{a}{4}\alpha'^4$

For a plano-convex singlet in the infinite-focus conjugation:

For a plano-convex singlet in the infinite-focus conjugation, the coefficient denoted as '**a**' which characterizes the amplitude of spherical aberration, is given by :

In the nominal orientation:

$$a = \frac{n^3 - 2n^2 + 2}{2n(n-1)^2} f'$$

In the wrong orientation (convex surfaces towards the focus) :

$$a = \frac{n^2}{2(n-1)^2} f'$$

☞ *What is the theoretical diameter of the PSF of the studied singlet, in both orientations, at paraxial focus ? Compare these calculations with the Airy diameter and the OSLO simulations. And at the focus of least confusing circle ?*

☞ *What is the theoretical caustic length of the spherical aberration ?*

B. EXPERIMENTAL SET-UP

During this session, you will implement two different set-ups:

- One using a white light source followed by a monochromator and a fixed front focus visor. It will allow you to directly observe the point spread function and to measure the longitudinal chromatism of the systems. The point source is placed far away from the lens under test.
- One using a fibered laser diode at $\lambda = 635$ nm and a CMOS camera to capture the point spread function and compare it to the diffraction limit. The source is placed at the object focal point of a collimator.

## 1. FIRST SET-UP: MONOCHROMATOR AND FIXED FRONT FOCUS VISOR
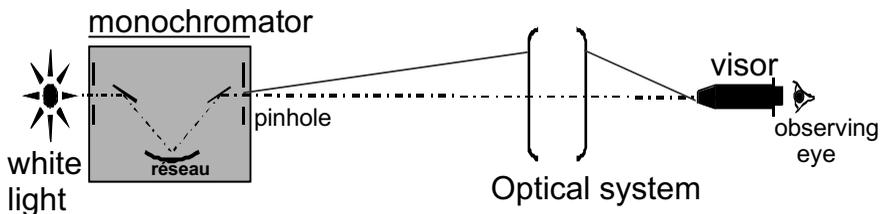
Figure 3 : Schematic of the set-up n°1

Pinhole choice

During this experiment we will visually study with a microscope the on axis aberrations of optical systems on an infinite-focus conjugation. To measure the aberrations of such systems the object must be a point source located at infinity (i.e. at least at a distance ten times superior to the focal length of the lens under test, or in the focal plane of a collimator). In practice, the pinhole should be sufficiently small so that its geometrical image does not limit the resolution of the observation. On the other hand, it should give an acceptable amount of light (see general presentation).

The monochromator

The light source used for this set-up is a white iodine lamp filtered by a monochromator (Jobin-Yvon H10) located at approximately **6 meters** from the lens under test.

The spectral resolution is 8nm/mm. It means that an 1mm input slit (or output) correspond to a 8nm spectral width

☞ *Evaluate the spectra width for a 3mm input slit and a correctly calculated output pinhole to measure the PSF.*

2. 2ND SET-UP : FIBERED LASER DIODE AND CMOS CAMERA

Figure 4 : Schematic of the monochromator
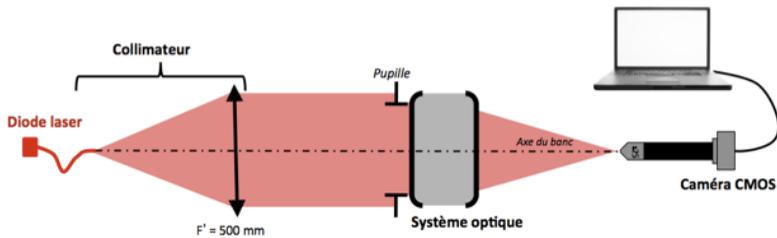
Figure 4 : Schematic of the Set up n°2

THE LIGHT SOURCE

The source used on this set-up is a laser diode emitting at a wavelength of λ = 635 nm. The SM600 monomode fiber has a mode diameter of 4,3μm and a numerical aperture of approximatively 0,1 at the source wavelength. The diode is powered by a stabilized ILX Lightwave power supply which can adjust the intensity and thus the emitted flux up to 40mA.

☞ *What is the image size of the fiber in the focal plane of the doublet (f' = 150mm) ? Compare it to the Airy disc size of the doublet.*

THE COLLIMATOR

The collimator is made with a doublet (f' = 500mm) and allows to study the lenses with an infinite-focus conjugation. During the experiment, the collimator will be used to study the systems on axis.

MICROSCOPE AND CAMERA

The image spot is observed with a microscope objective of x10 or x25 and a CMOS camera with 640x480 10µm square pixels. The image is digitized over 8bits (0 to 255 gray level). It is controlled with the uEye Demo software and the pictures are analyzed using the Matlab Script **Mesure_PSF**.

Be careful during your measurements that the detector is not saturated. If so, adjust the Exposure Time and/or the power supply of the source. The software manuals are at your disposal in the lab room.

C. LAB WORK ON SET-UP 1

1. SINGLET STUDY

Glass: BK7   Focal length: 150 mm
Numerical aperture: 0.08 ($\varnothing_P = 25$ mm)

<u>Spherical aberration of the singlet lens:</u>
> The monochromator is located at 6 meters of the studied optical system. At start, adjust the wavelength at $\lambda = 546$ **nm**, and remove both entrance slit and exit pinhole.

Point source and microscope objective selection:
► Calculate the image plane position in relation to the image focal plane and the magnification of this set-up.
► Calculate the Airy disk diameter in this plane for an ideal optical system with the same numerical aperture than the singlet.
► Deduce the pinhole diameter to use for a diffraction limited optical system.
► Explain why the numerical aperture of the microscope objective should be greater than 0.08, the numerical aperture of the studied doublet.

First observations:
► Place the plano-convex singlet in the chuck in the nominal direction.
► To quickly find the image using the microscope objective, do not use any pinhole at the monocromator output and use an objective with a small magnification.
► Place the pinhole only when the image is correctly focus and centered.
► Adjust the chuck orientation to get a circular image.

► To observe and analyze the point spread function, do not stay in the best focus plane but on the contrary observe the evolution of the out of focus image around this position.
► What other aberration(s) appear when the source is not on-axis?
► Determine the position of the paraxial focus and the best focus and measure the distance between those 2 positions. Draw a clear sketch to explain thoses positions.

Call the professor to cross-check your alignment, observations and measurements.

PSF measurements:
► Measure the PSF diameter at the paraxial focus and at the best focus.
Remark: Try to evaluate your measurement accuracy. Even if you are very cautious, it can't be less than 20-25%.
► Add the 12mm diaphragm and redo those measurements.
► Compare your measurements with your theoretical calculations based on the third order theory and with the spot diagrams calculated with an optical design software (page 12).
► Measure the caustic length using the annulus diaphragm. Compare it with the theoretical calculation. Make the same measurements with the lens in the wrong orientation.

Chromatism

Now place the 3mm slit at the monochromator entrance. The spectral width is now about 24 nm. If the image spot is not bright enough for some wavelength, adjust the pinhole size at the output of the monochromator.

► Vary the wavelength and measure the paraxial focus position for the singlet

► Now measure the paraxial focus position for the singlet and for wavelengths ranging in the visible spectrum (450 to 700 nm) with 50 nm steps. Don't forget to measure the F ray (486nm), the d ray (587,6) and C ray (656nm) that are used for constringency calculations.

- Trace the variation of the foci $\overline{F'_C F'_\lambda}$ as a function of wavelength λ. Compare your results with the simulations made with datasheets. What is the principal axial chromatism (between F and C rays of hydrogen) for the singlet?

- Evaluate experimentally your accuracy on your measurements of $\overline{F'_C F'_\lambda}$ and add the uncertainty bars on your figure. Also take into account the uncertainty on the wavelength and add the corresponding bars.

- In practice, the point source is located at a finite distance so you measured the evolution of the position of A', the image of the point source which is located near F', the focus. In the approximation of thin lenses, calculate the position of A' and the correction factor to apply on your measurements of $\overline{A'_C A'_\lambda}$ to have $\overline{F'_C F'_\lambda}$ and correct your graph.

- Is your accuracy the same on the edges of the spectrum and for the central wavelengths? Why?

- Deduce from your results the constringency v_d of the glass the lens is made of. What type of glass could it be? What is your uncertainty on the constringency?

2. DOUBLET STUDY

Doublet Thorlabs AC254-150-A1 Focal length : 150 mm ,
Numerical aperture : 0.08 (Ø$_e$ = 25 mm)

PSF measurements :
Adjust the monochromator at $\lambda = 546$ nm.
- Place the doublet in the wrong orientation and quickly evaluate the spherical aberration (PSF and caustic length). Compare those values to those from the singlet characterization in the best orientation.

► Place the doublet in the nominal orientation and carefully analyze the image spot. Comment the apparition or not of a black center when you slightly defocus around the best focus (in both directions). Explain why this test shows that the doublet is almost ideal for this conjugation.

► Measure the diameter of the image spot and compare it the the Airy pattern size.

Secondary chromatism of the doublet:

Now place the 3mm slit at the monochromator entrance. The spectral width is now about 24nm. If the image spot is not bright enough for some wavelength, adjust the pinhole size at the output of the monochromator.

► For a doublet, the primary chromatism should be corrected. Measure the position of the pinhole image for the 3 reference wavelengths below:

d	Helium	Yellow	587,6
F	Hydrogen	Blue	486,1
C	Hydrogen	Red	656,3

► Check that the primary axial chromatism, $\overline{F'_C F'_F}$, is close to zero, and evaluate the secondary chromatism, $\overline{F'_d F'_F}$,. Compare your results from the simulations.

D. LAB WORK ON SET UP N°2

1. SINGLET STUDY

- ► Place the singlet in the nominal orientation in the chuck. Launch the Ueye Cockpit software to display the PSF and find the best focus.
- ► Save the image and launch the Mesure_PSF script in Matlab.
- ► Measure the encircled energy radius at 80% and compare it to your results in the first setup.

doublet study

► Ajust the doublet orientation (in the nominal orientation) so that it works on axis. To do that, rotate the chuck until the PSF is rotationnaly symmetric. Check if the doublet is diffraction limited. Observe the evolution of the PSF around the best focus.

► Using the script mesure_PSF, measure the Airy pattern diameter and compare it to your visual observations from setup 1.

► The experimental plot might be above the experimental one for a stigmatic system. Explain this error.

2. MAGNIFYING OBJECTIVE STUDY

► For N =4, 5.6, 8 et 11, using the same method, measure the encircled energy radius at 80% and trace this radius as a function of F number.

► Which aperture gives the best resolution ? What is the highest aperture giving a diffraction limited PSF ?

In this lab session, you will study the off-axis aberrations of two lenses in infinite-focus conjugation. Firstly, you will study the astigmatism and field curvature of **a Clairaut – Mossotti doublet**, which is virtually corrected of spherical aberration and coma. Then, you will characterize a standard **magnifying objective** over its full field.

☞ Preparation: read carefully the global introduction to the point source method as well as the text below and do every calculation marked with the ☞ symbol.

A. REMINDERS

1. THIRD ORDER COMA

Coma is an off-axis aberration that leads to a PSF that resembles a comet. Coma is related to the fact that, when the field dimension and the aperture angle become large, Abbe's formula (aplanatic system) $ny \sin \alpha = n'y' \sin \alpha'$ is not valid anymore.

Within the 3rd order approximation, the characteristic dimension $\boldsymbol{\rho}$ of a coma PSF is given by:

$$\rho = by' \sin^2(\alpha')$$

        with α' the image numerical aperture angle
                    b the coma parameter
                    y' the image position in the field

The length of the coma PSF is then 3ρ and its width is 2ρ. The coma varies linearly with the field and quadratically with the aperture.
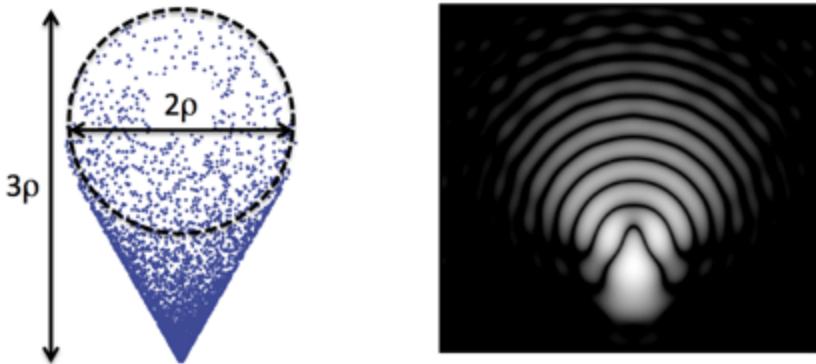

Coma spot-diagram (left) and PSF (right)

The associated wavefront error is given by : $\Delta_{\text{coma}}(\varphi) = by'\alpha'^3 \cos\varphi$.

# 2. ASTIGMATISM AND FIELD CURVATURE

The field curvature describes how the image of a plane is curved.
The astigmatism describes how the PSF takes the shape of a small segment (either tangential or sagittal depending on the focus) or a small diamond shape at the best focus. (see below)
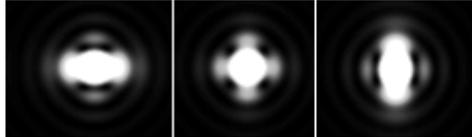
PSF shape for a small astigmatism (0.37 λ) at sagittal focus, best focus and tangential focus.
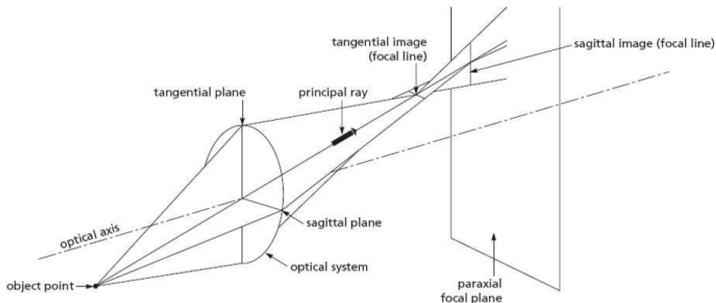
s and *t* are the projected distances on the optical axis between S and T foci and the paraxial focal plane. (see figure below).

In the 3rd order approxiamtion, those distances vary quadratically in the field, and the best focus is in the middle of sagittal and tangential foci.

$$s = C_S \frac{y'^2}{2} \qquad \text{et} \qquad t = C_T \frac{y'^2}{2}$$

$$A = (C_S - C_T)/2, \; C = (C_S + C_T)/2$$

The sagittal foci PSF sizes are : $2Ay'^2\alpha'_{max}$

The width of the PSF at the best focus is : $Ay'^2\alpha'_{max}$.

The wavefront error is : $\Delta_{ast} = \dfrac{A}{4} y'^2 \alpha'^2 \cos 2\varphi$

For a thin lens, the field curvature :

$$C = \frac{-2}{f'} - \frac{1}{nf'}$$

And the astigmatism is :

$$A = \frac{C_S - C_T}{2} = \frac{1}{f'}.$$

☞ *Theoretically evaluate the astigmatism A and the field curvature C of the studied doublet from its characteristics. Also evaluate the C_S and C_T curvatures. Compare with simulations.*

☞ *What is the expected size of the PSF at the best focus for a 5° field angle?*

B. EXPERIMENTAL SET-UP

The experimental set-up is there based on the use of a collimator (focal length 500mm) which allows to have a source at infinity. The angular size of the object is given by the pinhole diameter placed at the collimator focus. You can choose between several values ($\varnothing$ = 12,5 µm, 50 µm, 100 µm, 400 µm, 5 mm). The objectif under test is placed in a chuck, with adjustable orientations. The rotation of the collimator allows to explore the field. The experiment is summarized in the scheme below :
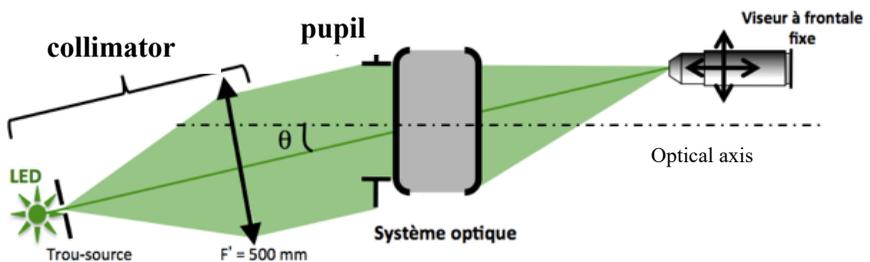
1. THE LIGHT SOURCE

Four light sources are available for this set-up. Three colored LED (red λ = 630 nm, green λ = 530 nm, blue λ = 470 nm) and a white LED.

☞ *Evaluate the Airy pattern diameter for the optical systems on test and for the three wavelengths?*

2. THE PINHOLE

The collimator (f' = 500mm) allows to study the objective for an infinite-focus conjugation. You have to choose the pinhole you put in its object focal plane (diameters available : 12,5 µm, 50 µm, 100 µm, 400 µm et 5 mm).

☞Evaluate the maximal diameter of the pinhole acceptable to observe the point spread function if the system is diffraction limited.

☞What is the geometric diameter of the image of the hole in the focal plane of the objective system under test?

If the image is too shallow, we might need to use a bigger hole to ensure observation quality but we must check that the geometrical image of the pinhole stays smaller than the PSF.

3. TRANSLATION THE MICROSCOPE VIEWER

AND THE COLLIMATOR

Both the collimator and the microscope viewer are mounted on motorized stages (translation and rotation stages, respectively), which allow you to study the off-aberrations of the lens under test on a wide range of field angles and with a high accuracy. Each stage can be displaced manually. The front panel of the stages controller is shown on Figure 6. The digital displays indicate the horizontal displacement of the translation stage with a resolution of 10µm (bottom display) and the angular displacement of the rotation stage with a resolution of 0.01°.

The motorized stages are very accurate but extremely fragile. **Use them with care!**

4. **MICROSCOPE OBJECTIVE CHOICE**

5. ☞ <u>THE OPTICAL SYSTEM TO STUDY MUST BE THE PUPIL OF THE SETUP</u>

For each of the studied optical systems:

☞Calculate the minimal numerical aperture needed for the microscope objective.

☞What is the other constraint on the microscope objective aperture for the off axis analysis?

6. **FINE ORIENTATION ADJUSTMENTS OF THE STUDIED OBJECTIVE**

By observing the image spot, adjust the orientation of the obective so that the image of the source hole is rotationnaly symmetric. This adjustement is more precise than one using a laser.

C. LAB WORK

1. DOUBLET IN THE NOMINAL ORIENTATION

Doublet Thorlabs AC254-150-A1

Focal length:150 mm , Numerical Aperture :   0.08 (Øe = 25 mm)

On axis analysis of the spot :

Pinhole choice and the microscope objective :
- ► Evaluate the Airy pattern diameter (for the wavelengths of the LED sources of the collimator) for an ideal optical system with the same numerical aperture than the doublet.
- ► Deduce from this the hole diameter to use for a diffraction limited system.
- ► Explain why the object the numerical aperture of the microscope objective must be higher than 0.08, the image numerical aperture of the doublet.

PSF measurements on axis :
- ► Place the doublet in the nominal orientation in the chuck.
- ► To quickly find the image using the microscope, start by the biggest hole, find the image, center it and reduce the pinhole diameter.
- ► Carefully adjust the chuck orientation to have a rotationnaly symmetric image spot.
- ► To observe and analyze the PSF, look the evolution of the image before and after the best focus.
 *Is the doublet diffraction limited?*
- ► Measure the PSF diameter at the best focus for all 3 wavelengths and under white illumination and compare it to the Airy pattern diameter.

► Add the 12mm diaphragm and redo those measurements. Conclude.

Call the professor to cross-check your alignment, observations and measurements.

Off axis analysis of the spot : astigmatism and field curvature
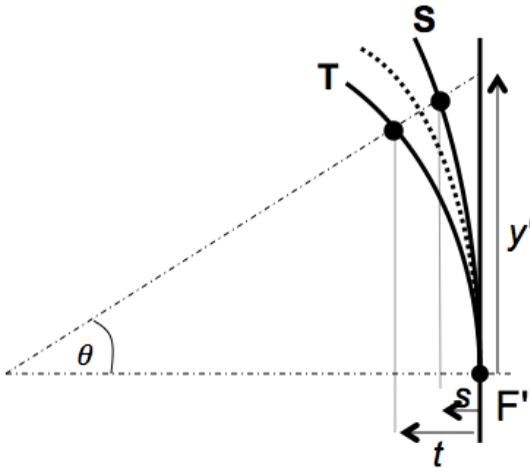
- ▶ Use the white LED and a x10 microscope objective.
- ▶ For field angles ranging from -10 to +10 degrees (with increments of 2.5°), observe the sagittal and tangential foci and the best focus. Also measure the distances s, t, c of those foci regarding the paraxial focal plane and y' the position of the image in the focal plane.
- ▶ Write down those measurements in a sheets software to draw the figures.

- ▶ With the $y' = f'\times\tan\theta$ method (for small θ ie $<5°$) measure the doublet focal length.

- ▶ Trace the position of the sagittal focus S, the tangential focus T and the best focus C regarding to the paraxial focal plane as a function of y'.

- ▶ Deduce from your measurements the field curvature C, the sagittal curvature C_S and the tangential curvature C_T. Deduce from those values the astigmatism coefficient A. Compare A and C to the 3rd order predictions and to the simulations.

- ▶ Rotate the collimator of exactly 5°. Measure the dimension of the focal segments at sagittal and parraxial foci and the diameter of the spot at best focus. Evaluate the accuracy on your measurements.

- ▶ Compare this PSF measurement of the doublet with your previous theoretical prevision and with the ZYGO calculation (Lab session 3) from a wavefront measurement.

- ▶ Place the 12.5mm diaphragm and measure again the size of the focal segments and the spot diameter at best focus. Evaluate the accuracy of those new measurements.

- ▶ Is the result predicted by 3rd order aberration theory?

2. CHARACTERIZATION OG THE MAGNIFYINBG

OBJECTIVE

The 150mm objective is made to project on paper the image of a 24x36mm photography film.

► Calculate the maximum field corresponding to the film size for an object at infinity.

The resolution of argentic films decreases with their sensitivity. The average size of the film grains for argentic films is about 20µm. We also find similar MTF for colored films.

Courbes FTM
(Transfert de modulation)

Fréquence sp Spatial frequency (cycles/mm)

► Calculate the diameter of the Airy patterns for all the apertures of the magnifying objective and the cut-off frequencies of the associated MTFs.

Place and adjust the magnifying objective on axis and study the optical quality on axis at maximum aperture.

- ► If the objective have a visible field aberration (coma as an example) on axis, how can we know if it is a misalignment or a defect of the objective ?

- ► Measure the dimension of the image spot on axis as a function of the f number N. Trace the associated figure. Add on the graph the diameter of the Airy pattern. Deduce the f number from which the the objective is diffraction limited on aixs.

- ► Do the same analysis on the edge of the field.

- ► Conclude. Is this objective quality enough for its application (magnification) ?

LAB SESSION N°3

ZYGO WAVEFRONT ANALYSER

ZYGO is a **Fizeau laser interferometer** (using an amplitude division) equipped with a phase shift system. It allows to measure wavefront errors down to approximately *λ/10 (PV)*.

☞ <u>Preparatory work :</u> carefully read the general presentation, the introduction to wavefront measurements and the lab session text below. Do all calculations marked with the ☞ symbol.

A. PRINCIPLES

Schematic of the ZYGO

☠ WARNING ☠

The reference flat of the ZYGO if of <u>excellent quality</u> (a few λ/100 RMS), but is also extremely fragile and expensive. Be very careful and NEVER touch it ! Put the optical system under test far from it and always **put the plastic protection back on the reference flat after use.**

---

1. INTERFEROGRAM

A perfect lens transforms a plane wavefront into a spherical one: this is known as rigorous stigmatism. If this wave converges at the center of curvature of the reference spherical mirror, the reflected wavefront is again transformed into a plane wavefront. If the adjustment is perfect and if the objective under test is perfectly stigmatic, the Optical Path Delay (OPD) is a constant over the surface of the pupil and the interferogram is uniform, *i.e.* there is no fringe visible in the interferogram.

For a real lens with aberrations, we observe fringes corresponding to the **optical path difference** between the ***real* wavefront and the *ideal* spherical wavefront**. This fringe pattern contains information about the geometrical aberrations of the optical system (excluding the chromatic aberrations).

Because the incoming wavefront travels twice through the optical system under test, it experiences the defects of the system twice. Thus, from one white fringe of the interferogram to the next one, the OPD, which is defined as the defect of the wavefront accumulated after *one way* propagation only, varies by $\lambda/2$.

The 3rd order aberrations amplitudes are then calculated by decomposition over Zernike polynomials. The coefficients are calculated as a least square best fit of the wavefront.

The software can also simulate the PSF (and the Strehl ratio) and the MTF.

2. FRINGES VISIBILITY

This interferometer uses a monomode stabilized HeNe laser with a long coherence length. Thus, the visibility of the fringes is not limited by spatial nor temporal coherence. The constraints on the reference mirror are then :

→ A bigger aperture than the aperture of the optical system.

→ For convex mirrors, a smaller radius of curvature than the back focus of the studied objective.

→ An optical quality close to the quality of the reference flat.

The light reflection ratio of the reference flat is 4 % (glass-air interface). By using non aluminated spherical mirrors the fringes contras twill be excellent. Those fringes are materialized on a rotating frosted glass. The only case when the measurement in impossible with a ZYGO is when the optical quality of the system is too low and thus the wavefront error is wide and the fringes periods are really high, to the point that it becomes higher than the sampling period of the camera.

3. REMARKS

▪ We effectively measure the objective defects if the spherical mirror and the reference flat have a far better optical quality than the studied ebjective. *For the ZYGO, the reference plane have less than λ/100 RMS wavefront error (WFE) and the spherical mirrors have a WFE of about λ/20 RMS, (λ=632.8 nm).* Moreover, it is necessary that the spherical mirror is stigmatic. The only conjugation possible is the image of its center of curvature.

▪ The aberration are often studied for an infinite-focus conjugation. However, it is possible to study the aberration for finite conjugations using a reference sphere.

▪ PSF and MTF calculations by the software are normalized in regard to the numerical aperture. It is **mandatory to indicate the aperture number of the studied objective to the software** (f-number).

B. ZYGO-GPI USE

1. ADJUSTMENTS OF THE OPTICAL SYSTEM

The alignment procedure is entirely done with autocollimations.

→ In 'Align Mode' (ALIGN), make sure that the reference flat is well aligned: the retro-reflection should hit the target, on the video monitor.

→ Place the optical system to test in the chuck, carefully centered on the pupil of the ZYGO and align it by autocollimation using a small flat mirror placed over the mount of the system.

→ Choose the spherical mirror adapted to the back focus of the optical system.

→ Ensure that the beam from the optical system is focalized at the **center of curvature** of the spherical mirror **and not at its vertex ! (**common mistake). Align the returning beam in ALIGN mode in the cented of the sight using the lateral adjustments of the mirror. The spot should disappear behind the cross of the sight.

→ Pass in VIEW mode to see the fringes.

→ Adjust, using the CAM button of the remote the conjugation between the pupil plane and the rotation frost glass. To do so, try to have the edge of the pupil as sharp as possible. Adjust the ZOOM to have the biggest image but without vignetting of the pupil.

→ With a fine tuning of transverse and longitunal position of the mirror, try to have a flat interferogram or the leat number of fringes, which is equivalent to the smallest wavefront error.

2. MEASURE AND CHARACTERIZATION OF THE

WAVEFRONT
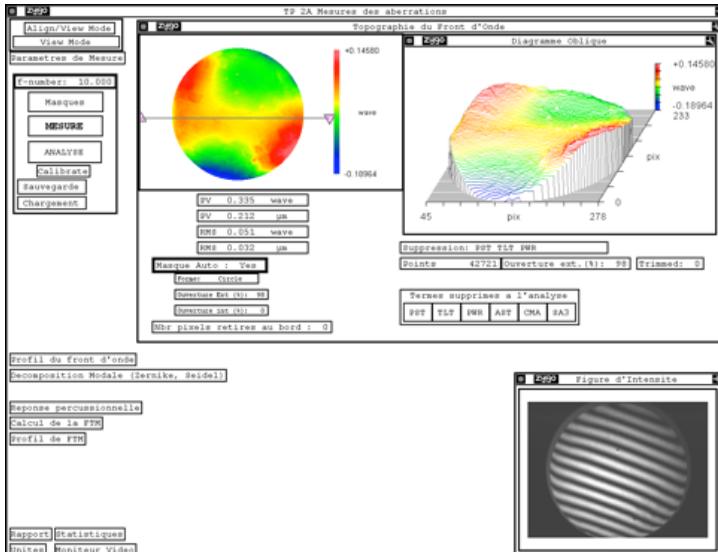
→ **Insert the f-number of the objective under test:** it is mandatory to calculate the PSF with a FFT of the wavefront and the MTF by FFT of the PSF.

→ Launch the wavefront measurement by clicking on MESURE. The software uses a phase-shifting method: it reconstructs the wavefront from the acquisition of 5,7 or 11 interferograms, from different positions of the flat reference.

→ By default, the software defines a circular mask that covers 98% of the pupil (Masque Auto: Yes). You can visualize the mask in the 'Masque" window (clicking on MASQUES) or on the video screen[3].

→ The Topographie du front d'onde window displays the wavefront and the statistics of the wavefront (PV and RMS values). Some defects may be subtracted from the measured wavefront before display, such as the Piston (PST), the Tilt (TLT), the sphere that best fits the wavefront (PWR), and 3rd order aberrations such as spherical aberration (SA3), coma (CMA) and astigmatism (AST). The substraction of one of these terms may be observed without launching another wavefront measurement by clicking ANALYSE.

→ The Décomposition Modale window displays the first 36 Zernike polynomial coefficients and the Seidel coefficients for 3rd order aberrations, in units of λ. The quality of the fit is also displayed (rms): it corresponds to the RMS value of the residuals. See Table 1 in the "General presentation of the aberrations lab sessions".
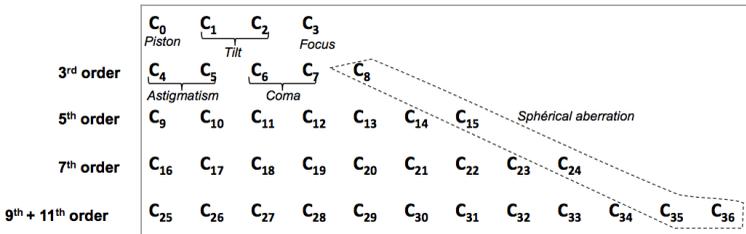

Coefficients of the Zernike decomposition

Zernike coefficients are show in a table, in the order above, and are exprimed as wavefront fractions. The calculation is made up to the 9th order (11 for the spherical aberration). The software also gives the root mean square difference (RMS) between the projection and the effective wavefront which gives the accuracy of the Zernike decomposition of the real wavefront.

The Seidel coefficients are evaluated from Zernike coefficients as shown below. Thoses terms are the WFE at the edge of the pupil in wavefront units.

Amplitude

TILT $\quad\sqrt{C_1{}^2 + C_2{}^2}$

FOCUS $\quad 2C_3 - 6C_8$

ASTIGMATISM $\quad 2\sqrt{C_4{}^2 + C_5{}^2}$

COMA $\quad 3\sqrt{C_6{}^2 + C_7{}^2}$

$\quad 6C_8$

SPHERICAL

3. RESULTS ANALYSIS

→ The window 'Réponse Percussionnelle' calculates the PSF with a FFT from the wavefront and show the PSF (in log scaling) the strehl ratio and the circled energy.

Reponse Percussionnelle (analyse par diffraction)

Encircled Energy Plot

Rapport de Strehl   0.909

Taille du Point: 256
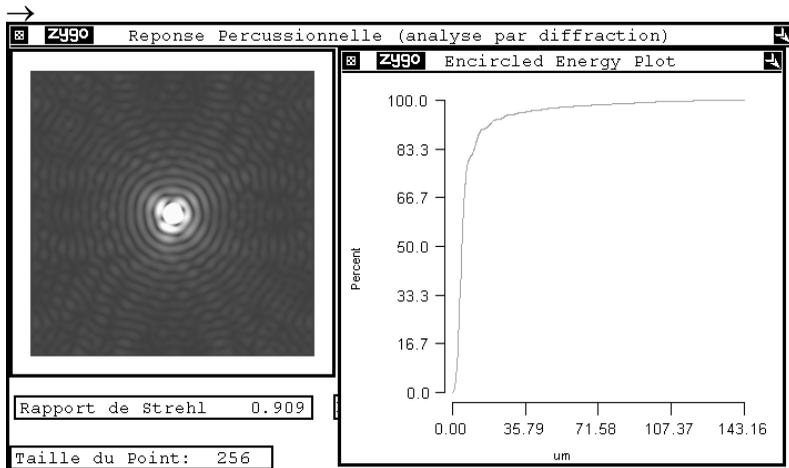
→ The window 'Calcul de la FTM' shows the MTF calculated with a FFT
of the PSF. The theoretical cut-off frequency is 1/λN, *calculated from
the f number N given by the user.*

C. LAB WORK

1. SINGLET CHARACTERIZATION

Focal length: 150 mm   Numerical Aperture: 0.08 (Ø$_P$ = 25 mm)

Spherical aberration of the singlet:

► Place the singlet in the nominal orientation on axis. Adjust its orientation and the convex mirror position to have an interferogram with the smallest number of fringes.
► Write the f-number of the singlet in the software.
► Measure the wavefont error at paraxial focus, best focus and marginal focus.
► For each case, explain where precisely the center of curvature of the spherical mirror is and explain the wavefront error shape (paraxial, marginal and best focus).
► Analyze for each case the PSF and MTF. Explain there signification. Explain how PSF and FTM are calculated by the sofware?
► Measure the caustic length.
► Measure the PSF diameter at best focus.
► Measure and comment the MTF of the singlet.
► Place the 12,5mm diaphragm and redo the previous measurements. Compare with the third order approximation predictions.

2. CHARACTERIZATION OF THE DOUBLET IN

THE NOMINAL ORIENTATION

Thorlabs Doublet AC254-150-A1

Focal length : 150 mm ,   Numerical Aperture :   0.08 (Øe = 25 mm)

On axis study of the doublet :

► Place the singlet on axis in the nominal orientation. Adjust its orientation and the convex mirror position to have an interferogram with the smallest number of fringes.

► Perform a visual study of the interferogram at the best focus, then with a small defocus before and after the best focus. Is the doublet diffraction limited on axis?

► Complete your study with a PSF and MTF analysis of the doublet on axis.

Off axis study of the doublet:

► Rotate the objective around the vertical axis of exactly 2.5°. Observe the different interferograms when the center of the mirror is at the sagittal focus, best focus or tangential focus. Study the associated PSF, the encircled energy diagram and the FTM.

► For each position note the astigmatism coefficient and the PSF diameter.

► Complete ypur measurements with measures between -5 and 5° with or without the 12.5 diaphragm. Compare with the third order approximation predictions.

Magnifying objective

The 150mm objective is made to project on paper the image of a 24x36mm photography film.

► Calculate the maximum field corresponding to the film size for an object at infinity.

The resolution of argentic films decreases with their sensitivity. The average size of the film grains for argentic films is about 20µm. We also find similar MTF for colored films.

Courbes FTM
(Transfert de modulation)

Spatial frequency (cycles/mm)
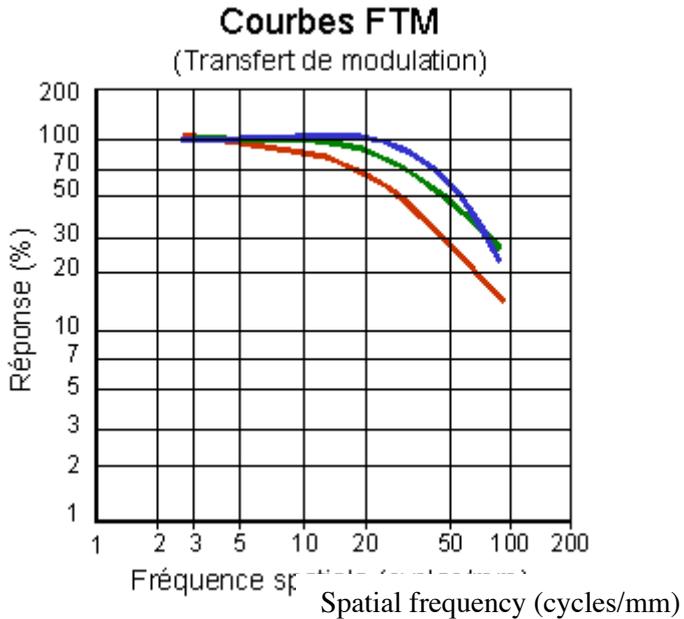
- ► Calculate the diameter of the Airy patterns for all the apertures of the magnifying objective and the cut-off frequencies of the associated MTFs.

- ► Study with the ZYGO the aberrations of this objective at full aperture both on and off axis (in particular at the edge of the field of 24mm x 36mm).

- ► Give an evaluation of the PSF dimension on axis and at the edge of the field.

- ► Evaluate the MTF of this objective on axis and at the edge of the field. What is the 10% cut-off frequency.

- ► What are the parameters that seem adequate to you to evaluate this objective quality ?

- ► Comment your results taking into account the purpose of this magnifying objective. Conclude.

► What are other mandatory measurements to ensure the optical quality of this objective (still taking into account its purpose) ?

D. APPENDICES

1. PHASE-SHIFT INTERFEROMETER

(more details il the 1A lab textbook)

The ZYGO is a Fizeau interferometer which have a movable reference flat. These moves are controlled displacements by fractions of the wavelength. In a 2 waves interferometer (which is not a multiple waves interferometer ! see below) the illuminance during the translation of the reference plane varies as a sinusoid function of the optical path difference. All phase shift algorithms use this property.

The image is numerized (gray levels) for some positions of the reference flat. (As an example, in the below figures, there is an astigmatism error and the reference plane is moved by $\lambda_0/10$ increments from one image to another).
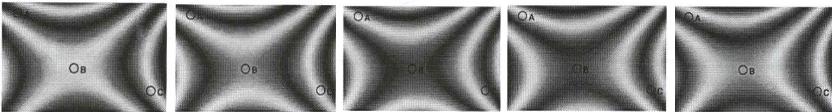
Important remark : In the Fizeau interferometer, there is always a Fabry-Perot effect between the studied surface and the reference plane, thus a multiple waves interference. In the ZYGO case, the reference plane and the studied objective are not treated. The main interference is then a 2 waves interference as the third one is attenuated by a factor $R^2 = 0.04^2 = 1.6 \ 10^{-3}$ regarding the first 2 waves.

The next figure shows the sinusoidal evolution (period $\lambda/2$) of the gray level for 3 pixels A,B,C corresponding to 3 different points on the interferogram during the displacement of the reference flat.
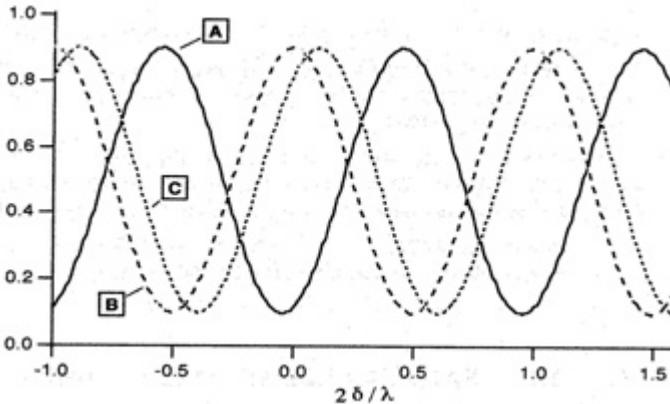
The phase difference between those illuminance sinusoids is directly linked to the phase difference on the waves that interfer and thus to the defects of the studied surface. The multiple phase-shift (there are dozens) algorithms aim to determine as precisely as possible this phase difference. The ZYGO use 5 to 11 images of about 220 by 180 points. *The huge benefit of the phase-shift method in regard to a classical interferometer is that the error will be measured on each of those 220 x 180 = 39600 points !*) Using a preliminary calibration the reference plane is translated by precise $\lambda_0/8$ steps (thus a optical path delay variation of λ_0 /4 and a phase difference of $\pi/2$ between each numerization of the interferogram. The phase determination is given modulo 2π radians. So the phase has to be unwrapped (removing 2π ambiguities). This algorithm is based on the hypothesis that the surface has no 2π, or more, steps (the surface is supposed to be smooth enough). This is a drawback of any interferometric methods (except in white light interferometers).

2. EXAMPLES OF INTERFEROGRAMS AND WAVEFRONT ERRORS DUE TO 3RD ORDER ABERRATIONS

Complete the missing labels and values below

1- <u>Défaut de mise au point par rapport au foyer paraxial</u> (FOCUS^2 = 2 λ)

2- <u>Spherical aberration</u> (SPHERICAL = ? λ)

Paraxial Focus   ?   Marginal Focus

3- <u>Coma</u> (COMA = ? λ)

---

^{2} Avec les notations du ZYGO.

4- <u>Astigmatism</u>

Spherical mirror at the best focus
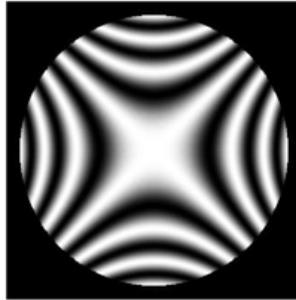
(ASTIGMATISM = 3λ)
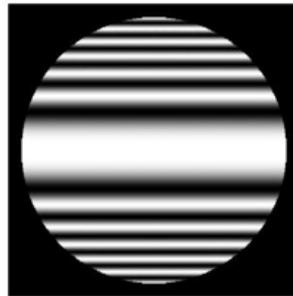
? focus   ? focus

LAB SESSION N°4

HASO WAVEFRONT ANALYZER

The lab report for this session must be handed at the end of the session. It is necessary to carefully prepare this lab session ahead of time by reading the introduction of this textbook and answer to the questions marked with the ☞ symbol.

A. DESCRIPTION OF THE HASO

1. PRINCIPLE

The HASO 32 is an array of 32×32 micro-lenses associated with a 5 mm $\times$ 5 mm CMOS camera. The CMOS matrix is placed in the focal plane of the micro-lenses. These lenses are 160 µm-square lenses with a 6 mm focal length (*i.e.* the aperture number is N = 37.5). The matrix has 512×512 square pixels. The pixel size is 10 µm $\times$ 10 µm, so that the micro-lenses array has exactly the same surface as the CMOS chip: each micro-lens is associated to an area of 16×16 adjacent pixels.

16 × 16 pixels

PSF of the

Optical axis of the micro-
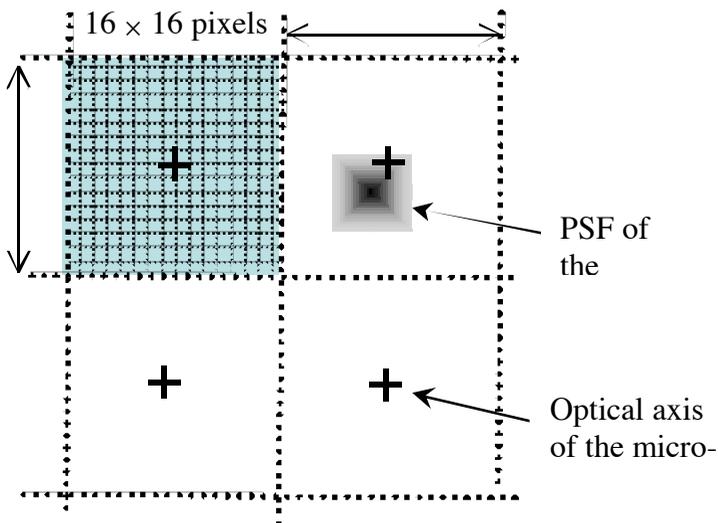
The HASO is illuminated by the wavefront to be analyzed, which is sampled by the micro-lenses array. Each micro-lens forms an image spot in the CCD plane. If the wavefront is plane and perpendicular to the lenses axis, each spot will be on the optical axis of the associated micro-lens. On the contrary, if the wavefront is tilted with respect to the micro-lenses array or is not a plane, the positions of the spots will depend on the local slope values of the wavefront sampled by each micro-lens.
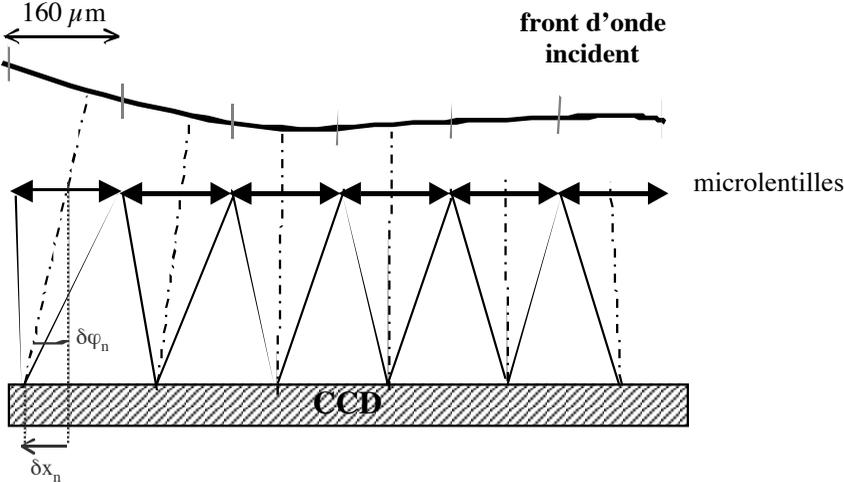
The HASO software measures accurately the mean displacement of each spot $(\delta x_n, \delta y_n)$ with respect to the nth micro-lens axis. The mean displacements are related to the local slope of the wavefront in each direction by $\delta\varphi_x = \delta x_n / f'$ and $\delta\varphi_y = \delta y_n / f'$. The software is able to associate each spot with the corresponding lens for displacements larger than the micro-lens size. This feature is based on the shape comparison of each spot to recorded reference spots for each of the 1024 micro-lenses. It increases the dynamics range of the HASO noticeably, and is launched by the TRIMMER button. The accuracy guaranteed by the manufacturer on the wavefront measurement is l/100 RMS.

☞ *What is the shape and size of the image spot at the focus of a microlens? (it is square pupil !) Compare it to the pixel size of the camera. How much pixels are needed to image the central lobe of the spot?*

Remark : The number of pixels in the spot width must be large enough to have a precise measurement of the spot center, but not too large to keep a sufficient flux on each illuminated pixel.

☞   *The maximal tilt the HASO can measure is 3°. What is the associated translation of the image spot regarding the center of each microlens ? Compare it to the microlens size and comment.*

Remark : Thanks to a clever algorithm, the HASO is capable to associate each spot to the corresponding microlens on a much bigger surface than the surface of the microlens, which augments the measurement range of the HASO.

Wavefront measurements

The HASO software displays the values of the local slopes measured right after each micro-lens. The wavefront is deduced from the local slopes either by direct integration (*zonal method*) or by decomposition of the whole set of measured slopes over the derivatives of the Zernicke polynomials (*modal method*): we will use the latter in the following.

The software fits the measured wavefront to a sphere (often called the *reference sphere*). Hence, it calculates the radius of curvature of the wavefront in the plane of the micro-lenses array. Knowing the pupil diameter and the radius of this sphere, the HASO software deduces the numerical aperture of the optical system under test as well as the *best focus* position. Hence, the *reference sphere* used by the HASO software is automatically centered on the best focus.

R

α'

sphère Sphere

**front d'onde
mesuré** Measured
wavefront
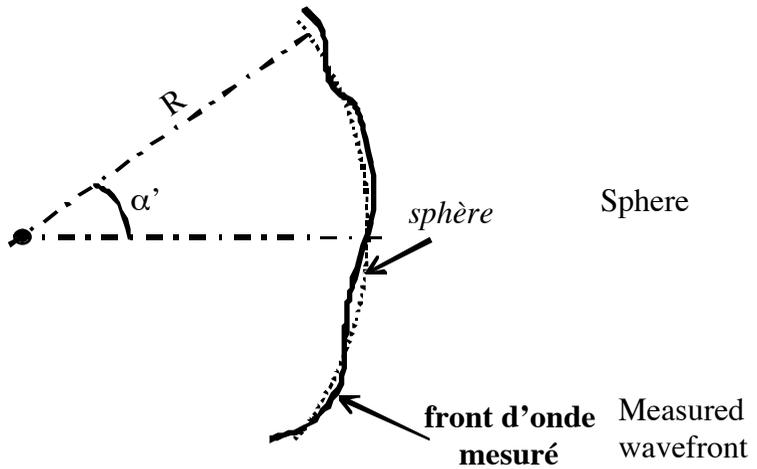
☞ *The HASO is only able to measure wavefronts that have a curvature
radius greater than 25mm. What is the maximal numerical aperture
that can analyze the instrument?*

2. EVALUATION OF THE IMAGE SPOT: PSF AND

SPOT DIAGRAM

The PSF at the best focus and the Strehl ratio are deduces with a 2D FFT
of the measured wavefront. And the software can calculate the MTF by a
2D FFT of the PSF. The spot diagram is easily evaluated thanks to the
measured slopes of the wavefront.

3. WAVEFRONT MEASUREMENTS

Lighting and exposure time

Ideally, the camera working point is near the saturation (>90%). The '*exposure duration*' is adjustable in the '*configuration*' window. It can also be automatically chosen by the software ('*Auto Exposure*'). In this case, check that the illumination of the microlenses is bright enough to ensure an exposure time shorter than 300ms.

Start of a new acquisition

Starting the acquisition

Illumination level of the camera

Image spots display

Local slopes display

Referencing the image spots with respect to the micro-lenses (Standard mode / Trimmer mode)

Measurement pupil

Acquisition

Measuring the local slopes

Results

Configuration
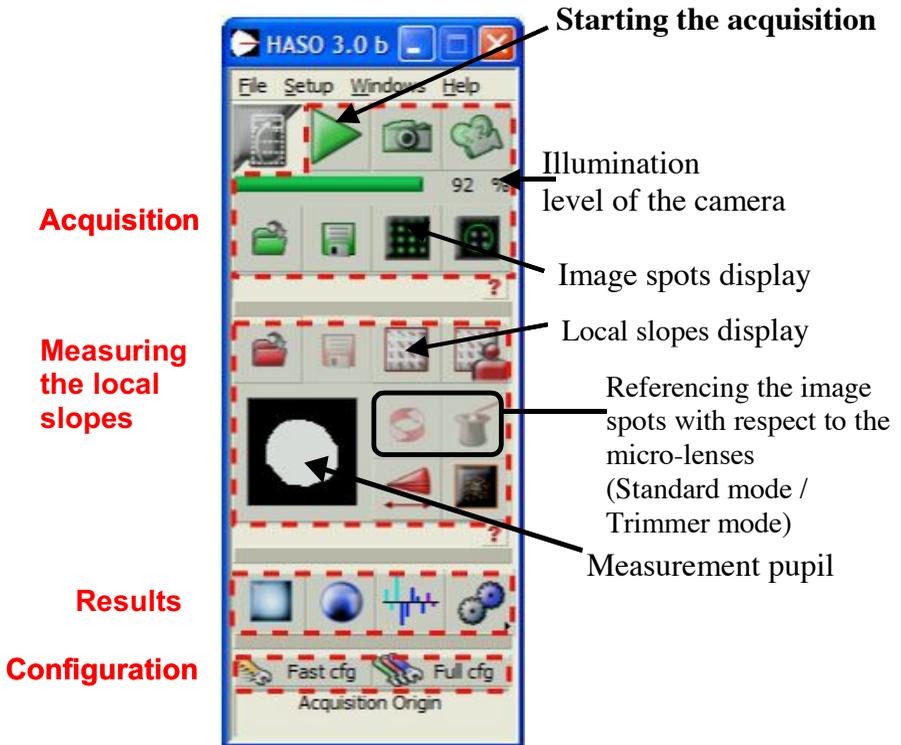
► **Start the acquisition**( ).

► **Open the camera window** ( ). **:** This window is the first to open and must always be visible to adjust the camera position (with transverse and longitudinal translations) so the beam is <u>centered on the detector and fully included in the microlens matrix</u>.

Slopes
measurements

Beam

Spot diagram
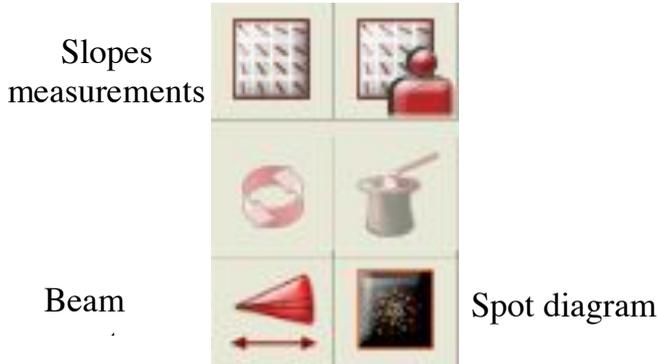
► Click on the 'NEW LENS' or the 'TRIMMER' buttons to reinitialize the association spot-microlenses if needed.

► **Local slopes window** : Open this window at the beginning of each measurement to visualize the displacements vectors of the spots centers. It gives us the measure of the mean slope of the wavefront on each microlens. To observe the effect of aberrations, we need to remove the tilts and focus. This window also gives the number of illuminated subpupils (=microlenses) that defines the analysis pupil.

The menus for the analyzes are :

Measured   Polynomials
intensity   coefficients

Wavefront   MTF and PSF
calculations
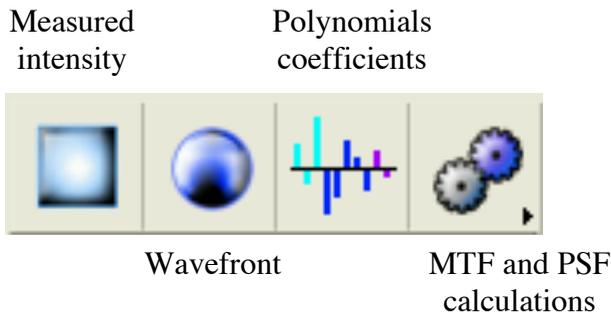
- o <u>Measured intensity :</u> visualization of the illuminance in the microlenses plane. The flux on each microlens is obtained by summation of the pixel response in the corresponding spot.

- o <u>Wavefront</u> : wavefront visualizations, PV and RMS measurements. This window allows to filter the unwanted parameters, like those linked to the measurement conditions as tit and focus.

- o <u>Polynomial coefficients</u> : With modal reconstruction of the wavefront, this window shows in real time the values of the Zernike coefficients in µm of the reconstructed wavefront.

- o <u>MTF and PSF calculations:</u> This menu allows to access the visualization of the PSF, calculated from the 2D FFT of the wavefront, the Strehl ratio and the MTF obtained with 2D FFT of the PSF.

B. EXPÉRIMENTAL SETUP
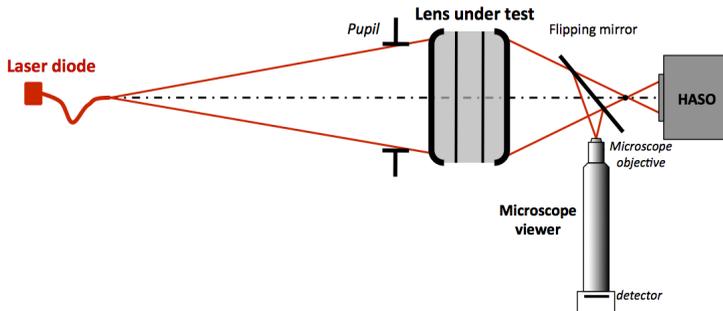
Experimental Setup

The light source is a laser diod at à λ = 635 nm; the source point is the end of the transverse monomode fiber ? The mode diameter is 4,3μm at 635 nm and the numerical aperture is 0,10. The laser is has a stabilized power source (in intensity, Imax = 40mA). The intensity must be adjusted to reach the needed illuminance value.

A microscope equipped with a camera will allow to compare the HASO measurement and the real spot shape. You can switch from one or the other using the movable mirror.

The objective you have to test is a doublet with a 150mm focal length and 25mm diameter. It is equipped with an iris diaphragm.

Doublet Thorlabs AC254-150-A1
Focale : 150 mm , Ouverture numérique image : 0.08 (Øe = 25 mm)

The conjugation for the characterization of the doublet is so that the magnification is $g_y = -1/3$.

☞ *What is the distance between the objective and the fiber end to ensure that magnification factor (you will approximate the   of a thin objective)?*

☞ *Suppose that the objective is a thin lens. Evaluate for each aperture number (25, 20, 15, 10 and 5mm) the associated numerical aperture. What is the corresponding Airy pattern diameter?*

You can use the support of the optics to adjust the orientation of the doublet to align it with the source.

Remark : In principle, you should (as in the ZYGO interferometer) add a lens at the image to conjugate the microlens array with the pupil of the objective.

C. LABWORK

During this lab session, you will analyze the shape and size of the PSF in the focus plane with the point source method and the wavefront with the HASO wavefront sensor. You will compare the calculate PSF from the wavefront made by the HASO to your direct measurements.

1. VISUAL STUDY OF THE PSF ON AXIS

► Power the laser source : POWER, then ENBL, ON and adjust the intensity.

► Adjust the objective position so that the magnification is -1/3. Check that the beam totally covers the objective pupil.

► Using the CMOS camera (uEye Cockpit) observe and analyze the PSF. How does the spot chages when you add a slight defocus around the best focus ?

► Change the aperture using the iris diaphragm. What is the maximal aperture for which the doublet is diffraction limited?

► Using the Matlab Mesure PSF, measure the PSF diameter at best focus for entrance pupils of 5, 10, 15, 20 and 25mm and compare those values to the corresponding Airy pattern diameters.

2. STUDY OF THE OBJECTIVE ON AXIS BY

WAVEFRONT MEASUREMENT:

► Remove the moving mirror start the acquisition ( ) and open the camera window ( ). Adjust the camera position so that the beam is centered and fully included in the detector.

► Visualize and measure the size of the spots in the microlenses focal plaine and compare this measure to your calculations.

► Open the local slopes window . Put a gain equal to 1. At camera level, does the beam converge or diverge?

► What are the FOCUS and TILT terms? Why do we need to ignore them to analyze the optical system aberrations?

► After having suppressed the TILT and FOCUS terms, augment the gain, observe the slopes of the wavefront and deduce the dominant aberration.

► Affichez les fenêtres du défaut de front d'onde, des polynômes de la décomposition de Zernike et de la PSF.

Comment le logiciel calcule-t-il PSF ? Comparez cette PSF avec l'observation de la tache au point lumineux. Comparez les diamètres.

► Adjust the objective orientation to minimize the field aberrations. Use the real time Zernike polynomial decomposition to do so.

► What is the measured numerical aperture and given by the HASO in the polynomials window ? Compare it to your preliminary calculation.

How the HASO is able to measure it (while the ZYGO needs it as an input)?

► For a 25, 20, 15, 10 and 5 mm pupil diameter, note the spherical aberration coefficient, the PSF diameter and the Strehl ratio of the image spot.

Trace the curve of the PSF diameter as a function of N : $N_{image} = \frac{1}{2\sin(\alpha')}$

Add the Airy pattern diameter on the graph.

For which aperture number the objective is diffraction limited on axis?

For which aperture number the best resolution is obtained?

3. STUDY OF THE OBJECTIVE OFF AXIS USING

THE HASO:

► At full aperture, study the doublet (wavefront and PSF) for several field points (-4° to +4°). Study carefully :

• The evolution of the Zernike coefficients associated to the 3rd order aberrations.

• The variations of the shape and size of the PSF.

Add your PSF measurements off axis to the on axis PSF graph.

Why is the PSF calculation impossible when the field angle is too large?

4. STUDY OFF AXIS WITH THE POINT SOURCE

METHOD :

► Replace the moving mirror and study the image spot using the visor and the camera for all field points (de -4 ° à +4°).

► Compare your results obtained with the HASO and the direct observation.