SCOPTIQUE
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Designing and Tolerancing for Space Optics

European Space Agency
Agence spatiale européenne

SCOPTIQUE: **Maxime FOLLIN**

Date: **24/10/2014**

Plan

- Introduction
- Practical Optics and Engineering
- Back to basics
- Optical simulation in practice
- Space missions

The Company I am working for

SCOPTIQUE

Scoptique:

Created in 2011 by an optical engineer

Where:

- Headquarters in Bordeaux (France)
- one office in Saint-Etienne
- one office in Jena (Germany)

What do we do ?

- Optical design and tolerancing
- Optical calculation
- Support to optical benches assembly and control

BORDEAUX AERO PARC

Bordeaux Technowest

www.scoptique.com

SCOPTIQUE

SCOPTIQUE is a consulting company specialising in optical engineering. We offer you the services in optical engineering that you look for when running your projects. Our specialisation allows us to **better understand your needs** bringing you **our expertise and reactivity.**

We have experience in working with **a broad range of optical design software** and we **adapt to your needs and software.**

Exploratory studies

R&T

Evaluation of opportunities coming from ne
technological developments

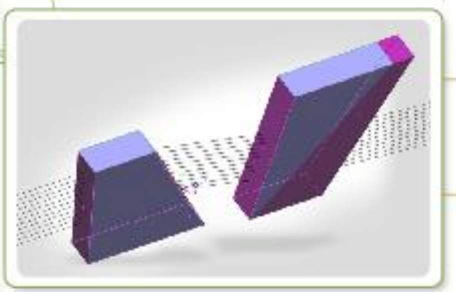
UPSTREAM R&D

Progression of technological readiness leve
Evaluation of architectures

TECHNOLOGY SURVEY

Collection and analysis of information : patents, exhibitions, other

Optical design



SEQUENTIAL OPTICAL DESIGN

Imaging → *CodeV, Zemax, VirtualLab, other*

NON SEQUENTIAL OPTICAL DESIGN

Lighting, Stray light
→ *LightTools, Tracepro, Zemax, other*

SCIENTIFIC COMPUTING

Analytical. Numerical → *Matlab, Metropro, other*

Optical bench

SPECIFICATIONS

Definition of functions and requirements

SIZING CALCULATIONS

Architecture definition, uncertainty calculati

COMPUTING

Motion control, acquisition, image processi
human-machine interface

VirtualLab

UNIFIED OPTICAL MODELING

Simulation techniques ranging from geometrical optics to electromagnetic approaches → *Diffraction, Partial Coherence, Polarization, Interferences*

Systems → *Laser Systems, Lighting, Interferometers, Laser Cavities, other*

DESIGN AND ANALYSIS OF A LARGE VARIETY OF OPTICAL COMPONENTS

Optical components → *Diffractive, Nano- and Micro-optic, GRIN, Hybrid, Fresnel, Phase Plates, Gratings, Free-form, Photonic Crystals, other*

Light sources → *LEDs, Excimer Laser, Ultra-short Pulses, Laser Resonator*

Computing

MACROS WRITING

Development of macros using different opti
design software

DEVELOPMENT OF VBA APPLICATIO

Development of applications using Excel V
to gain in efficiency and interactivity

SOFTWARE DEVELOPMENT

Development of software according to your
specifications

What is designing ?

- **Propose a simulation starting from a set of requirements:**

- Field of view
- Resolution
- Wavelength
- Sensitivity
- Mechanical contraints
- Environment

Other considerations:

- Cost
- Timescale
- Complexity

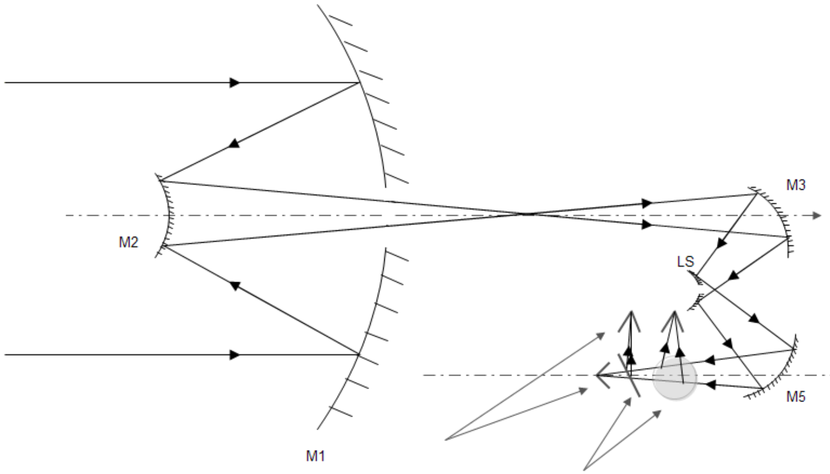
- **Depending on the application**:

- Astronomy
- lithography in the industry
- ground or space based system…

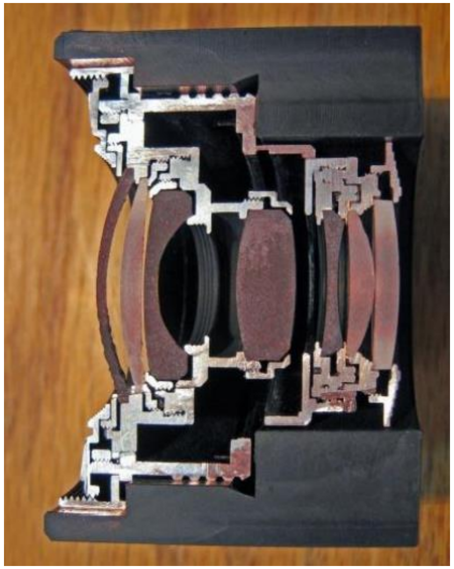
- spectroscopy ?
- imaging ?
- vision ? Integrated optics ? Fiber optics ?

- **And then the first studies**:

- design
- tolerancing



Cosmology: OLIMPO, Far-Infra-red and submillimeter telescope

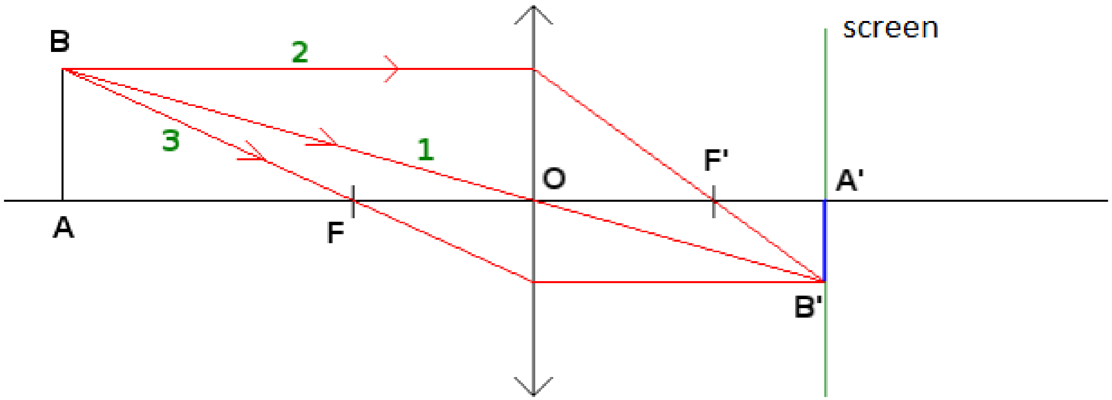


Photography: Fischer objective

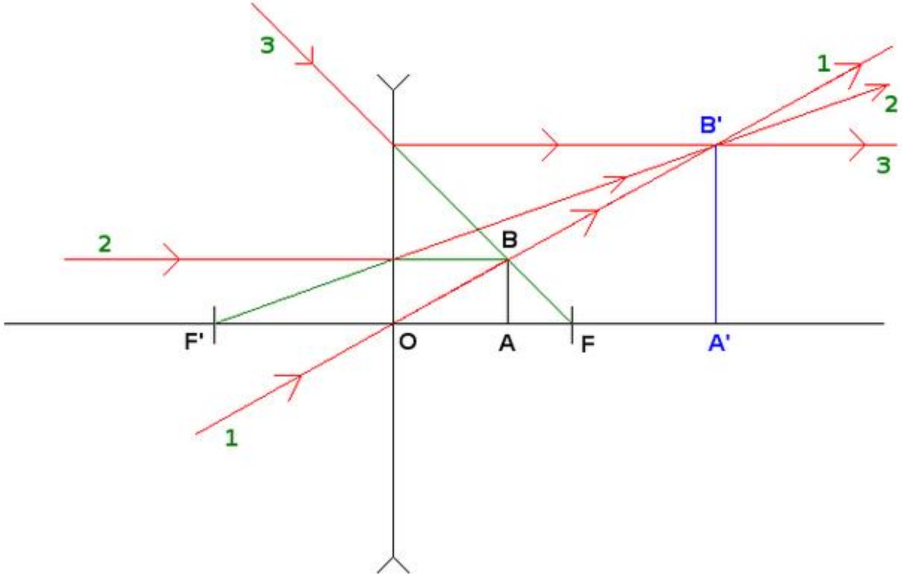
Back to basics…

- Law of Descartes-Snell: $n_1 \sin(i_1) = n_2 \sin(i_2)$
- Thin Lens Equation: $\frac{1}{\overline{OA'}} - \frac{1}{\overline{OA}} = \frac{1}{\overline{OF'}} = \frac{1}{f'}$

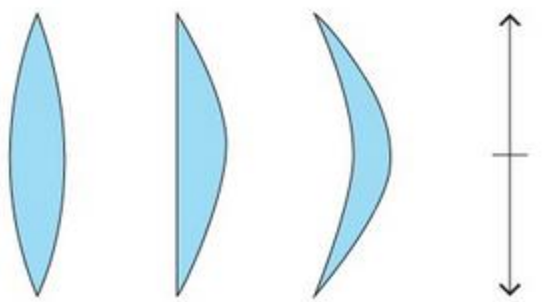
1. Convergent lens:

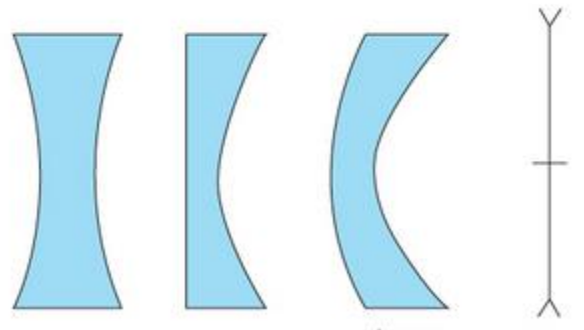


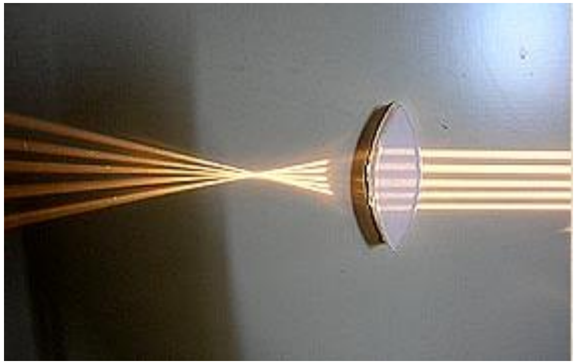
2. Dispersive lens:

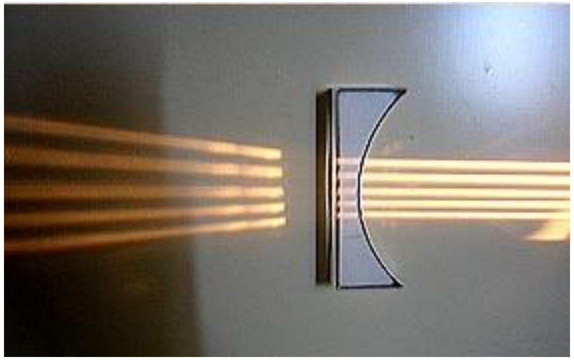


Lenses:

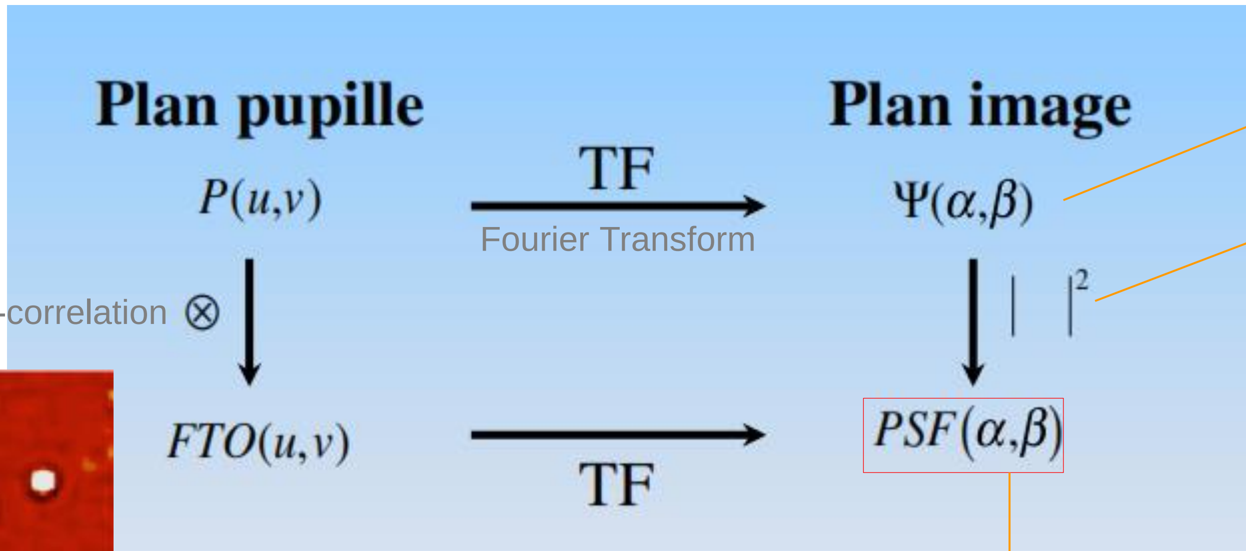

biconvex
Plane-biconvex
Convergent meniscus
symbol

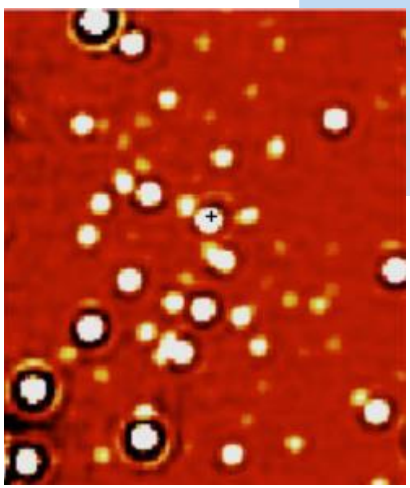

biconcave
Plane-concave
Dispersive meniscus
symbol

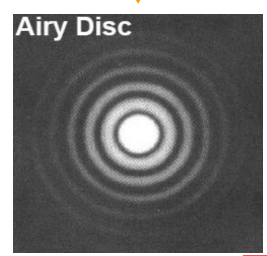




From the **object space** to the **image space**: the '**Point Spread Function**' (PSF)







Center of the Milky Way
(VLT –NACO, ESO)

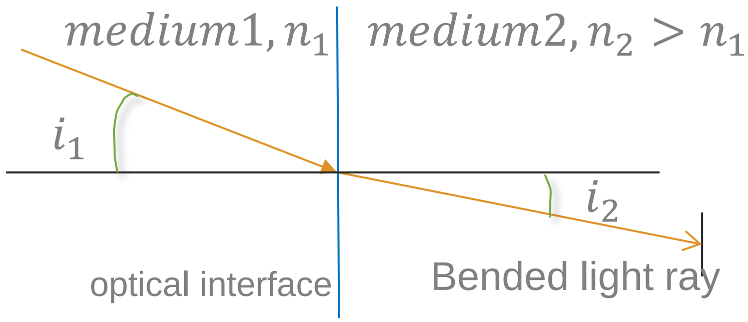
→a main fundamental limitation (Resolution): $\alpha = 1.22\,\frac{\lambda}{D}$

wavelength

Diameter (aperture size) of your system

Aberrations

Approximations and aberrations…



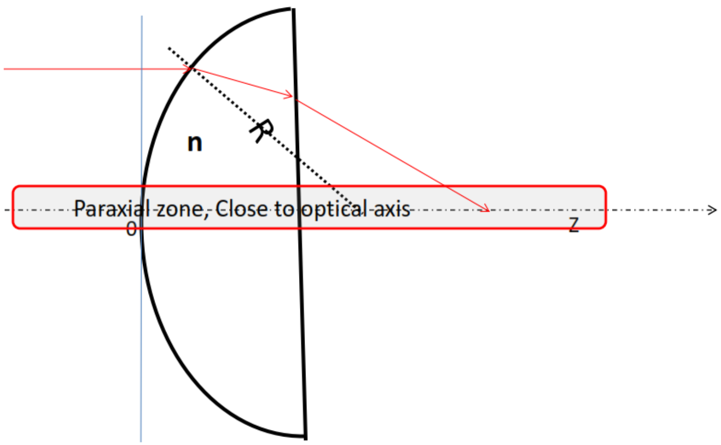
Law of Descartes-Snell: $n_1 \sin(i_1) = n_2 \sin(i_2)$

Approximation of the sinus:

$$\sin(\boldsymbol{\theta}) = \boldsymbol{\theta} + \frac{\boldsymbol{\theta}^3}{3!} + \frac{\boldsymbol{\theta}^5}{5!} \ldots$$

Paraxial Optics (1st order) **Geometric aberrations (3rd order)**

Gauss conditions:



Geometric aberrations:

- at large incident angles with respect to the normal of the optical surface

- at larger distances from the optical axis

→ That's why, to avoid them: in the paraxial conditions (the so-called **Gauss conditions**) (not large angles with respect to the normal of the optical surface ; not far from the optical axis)

→ Geometrical limitations : minimized during manufacturing of the optical elements but we have first to study **the tolerances**…

Aberrations

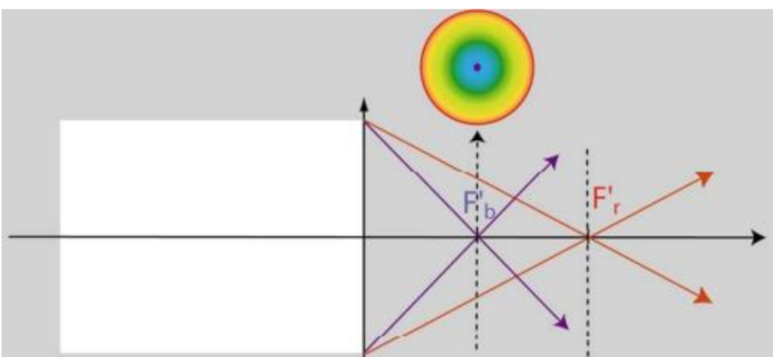
Main aberrations:

- Spherical aberration
- Coma
- Field curvature
- Astigmatism
- distortion

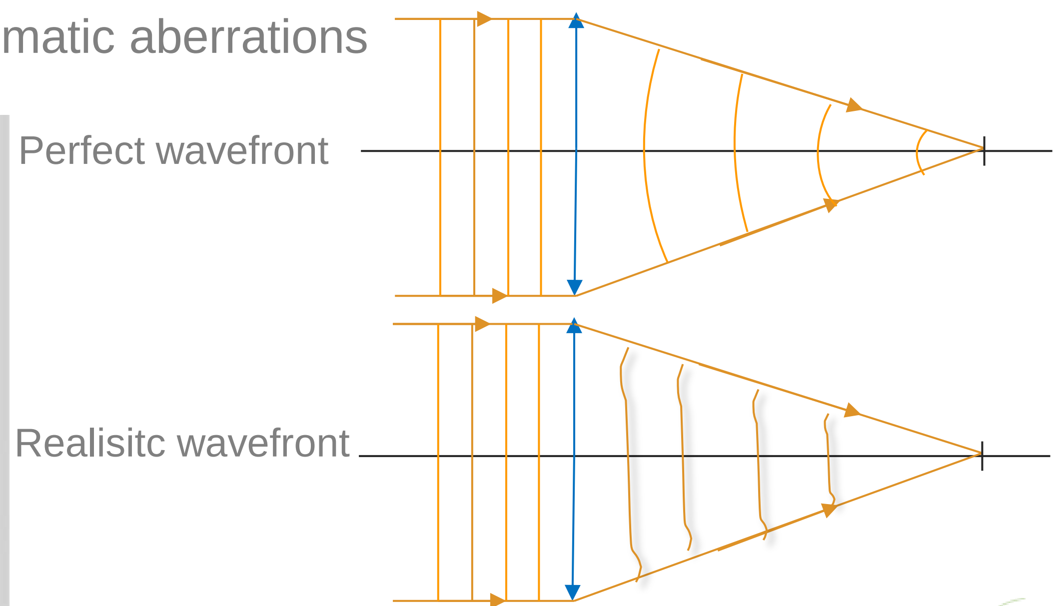
Monochromatic aberrations (3rd order aberrations)

- Axial colour
- Lateral colour

Chromatic aberrations



The **axial colour** aberration (focus depends on the wavelength)



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Mathematical formalism to model the wavefront error:

- Orthogonal polynomials on the unity disc;

- Describing quite well the different types of aberrations

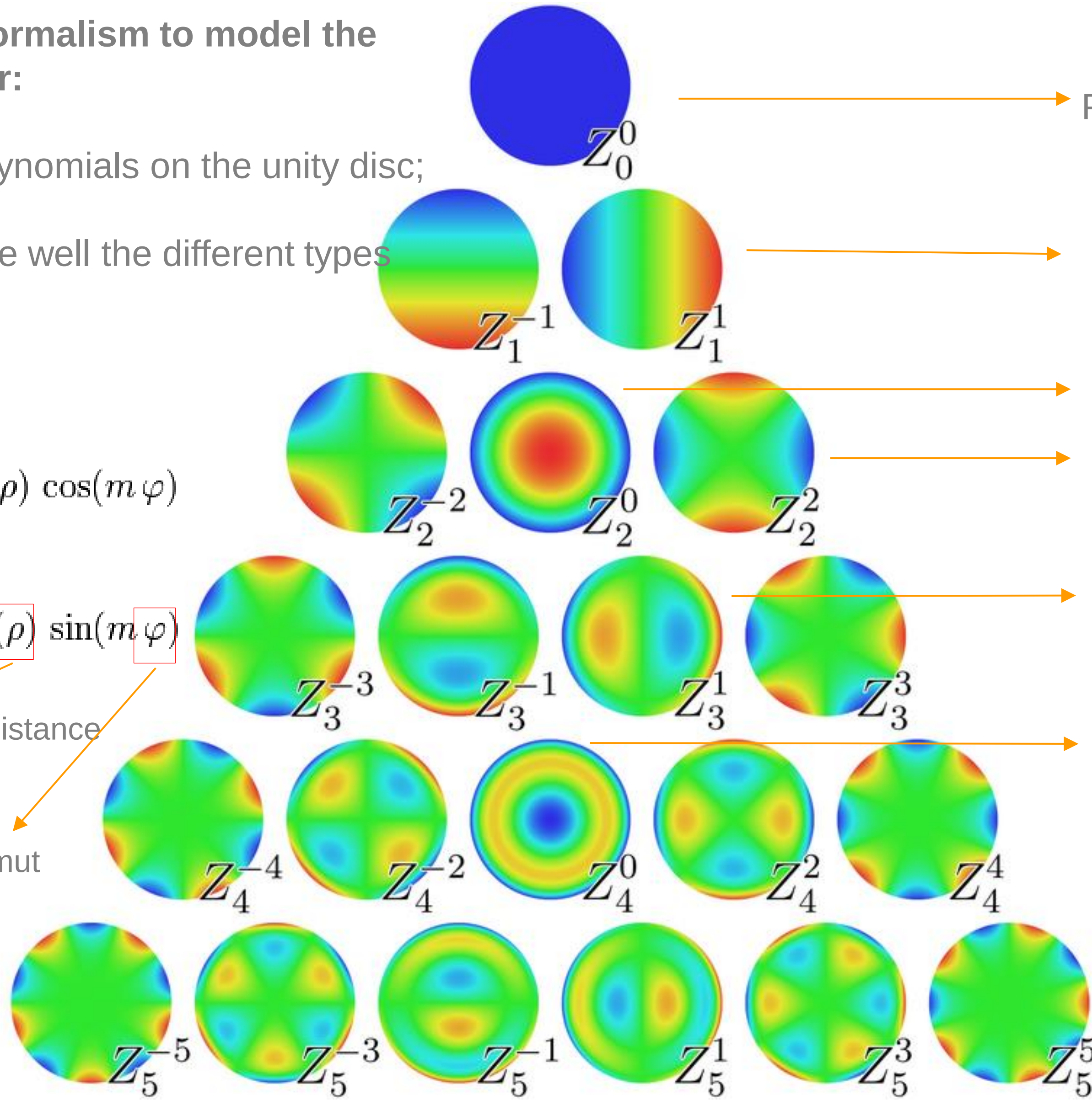
Described by:

$$Z_n^m(\rho,\varphi) = R_n^m(\rho)\,\cos(m\,\varphi)$$

$$Z_n^{-m}(\rho,\varphi) = R_n^m(\rho)\,\sin(m\,\varphi)$$

Normalized radial distance

Azimut



Piston (perfect image)

Tilt along the X and/or Y-axis

Focus

Astigmatism

Coma

Sphericity

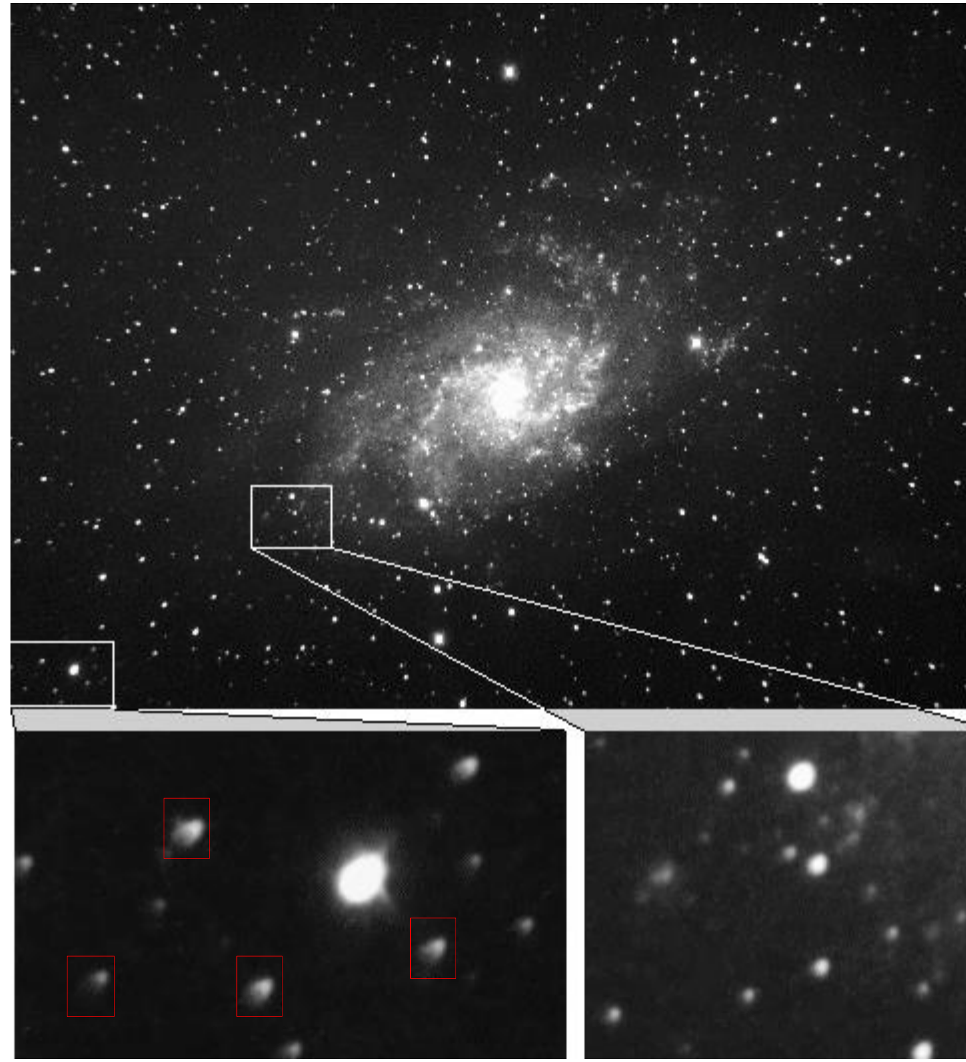
ESAC

Aberrations: A few examples

1. Chromatic aberration on the image of the Moon

2. Distortion and vignetting on the image of a cathedral

3. Astigmatism and Distortion on the image of the Eiffel Tower



4. Coma on the image of a galaxy (stars look like comets… The farther we are from the center of the image, the stronger the effect is)

Simulation: a commonly used software as an example for ray-tracing

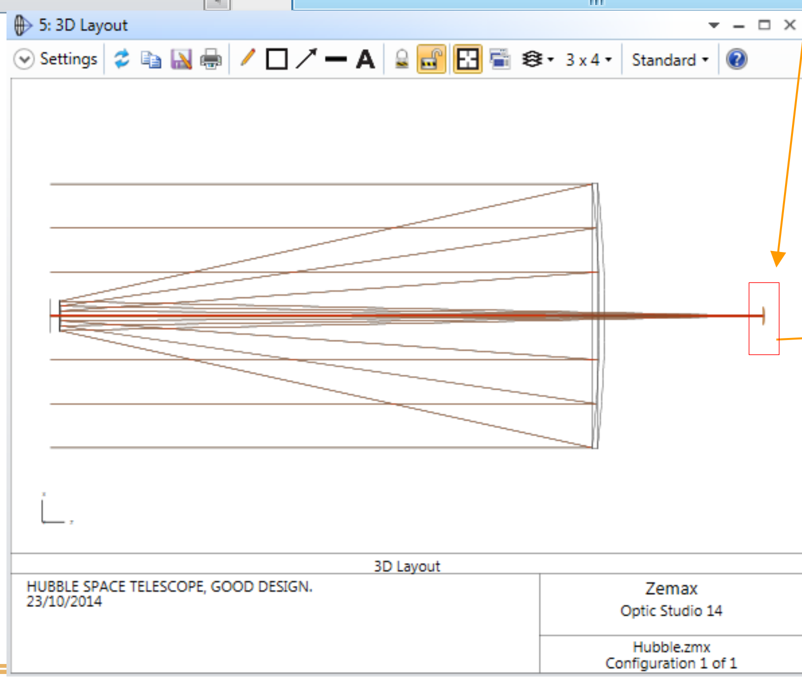
Sequential and Non-Sequential ray-tracing:

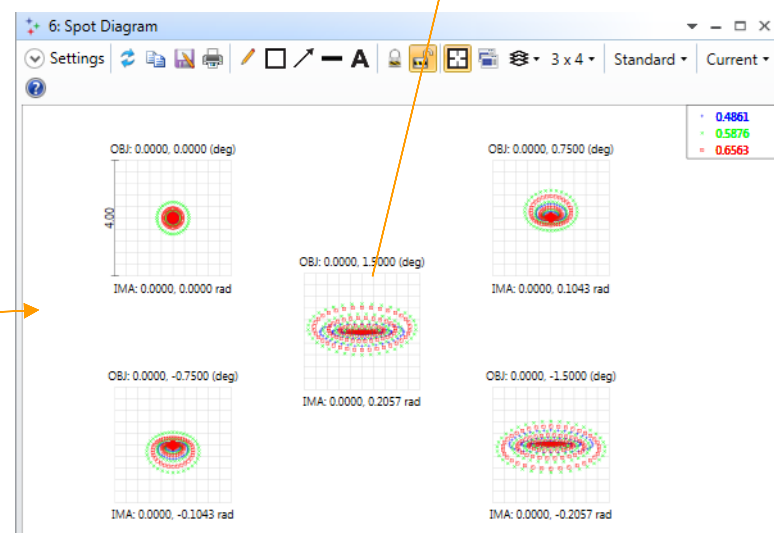
Lens Data

Surface 4 Properties — Configuration 1/1

	Surf:Type		nt	Radius	Thickness	Material	Coating	Semi-Diameter
0	OBJECT	Standard		Infinity	Infinity			Infinity
1	(aper)	Standard		Infinity	5.000			0.155 U
2	STOP (aper)	Standard		-11.040	-4.906	MIRROR		1.200
3		Standard		-1.358	6.406 M	MIRROR		0.141
4	IMAGE	Standard		-0.631 V	-			0.080

Sequential listing of the elements and surfaces



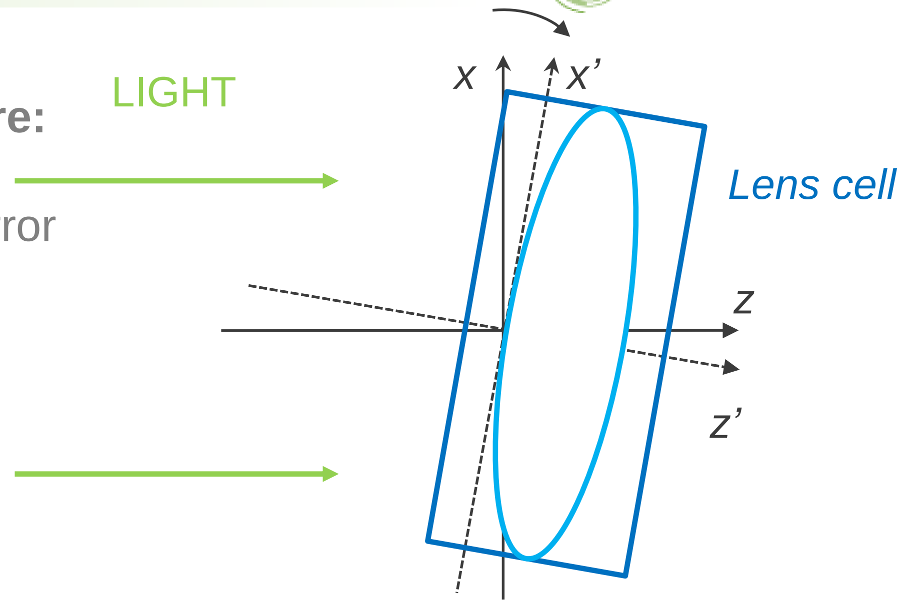


Spot of the light rays on the image plane

Steps to simulation and tolerancing

What you can study with such a software:

- The optical path delay, the wavefront error
- The distortion
- The spot size on the image plane
- …



Tilt around
y- axis

First step: You design the system

Second step: You simulate it

Third step: You tolerance it

Tolerancing is to get close enough to reality before manufacturing

Listing of tolerances:

- decenter/tilt of surfaces/elements/groups of elements
- Radius inaccuray
- Spacing between the different elements
- …

- Tolerances on elements
- Tolerances on spacing between the elements

Tolerancing

Tolerancing is basicaly like building a house:

We want to avoid that (but for the image quality):

How to do so:

- Chose a criterion or several for the image quality
- Simulate the deformation of the light wavefront
- All the different aberrations we know
- List the tolerances
- See how sensible is the system wrt the tolerances

The Tolerance Data Editor:

Tolerance Data Editor

Operand 1 Properties

	Type			Nominal			Comment
1	TOFF						COMPENSATOR
2	TOFF						WAVELENGTH
3	TWAV				0.546		test wavelength in microns (ISO xxx given by
4	TOFF						RADIUS TOLERANCE (IN FRINGES)
5	TFRN	2		0.000	-1.000	1.000	surface TES1a
6	TFRN	3		0.000	-1.000	1.000	surface TES1b
7	TFRN	4		0.000	-1.000	1.000	surface TES2a
8	TFRN	5		0.000	-1.000	1.000	surface TES2b
9	TFRN	6		0.000	-1.000	1.000	surface TES3a
10	TFRN	7		0.000	-1.000	1.000	surface TES3b
11	TFRN	8		0.000	-1.000	1.000	surface TES4a

Test wavelength for manufacturers (ISO standard)

Tolerances chosen with respect to what can be done,
It has to be **realistic**

We choose a **Maximum and a Minimum**

We apply them to the elements or surfaces we want (here surface of lenses)

Criterion for tolerancing

The quality criterion:

To compute the values of the different aberrations:

- Distortion
- Magnification factor
- Intra-band or Inter-band spectral co-registration
- …

We can have:

- Values just for **readout** (**performance parameters**)
- Values for **optimization**

We set a ‘Merit Function’ to follow the behavior of our system:

Merit Function Editor

Wizards and Operands

Merit Function: 0,0030921867989623

	Type	Cfg#											
1	CONF	1											
2	BLNK	UVVIS conf. average EPFL											
3	ZPLM	1	0	0.000	0.000	0.000	0.000			0.000	0.000	215.016	0.000
4	CONF	2											
5	BLNK	NIR conf. average EPFL											
6	ZPLM	1	1							0.000	0.000	214.703	0.000
7	BLNK	Ratio of the 2 average EPFL											
8	ZPLM	1	2							0.000	0.000	1.001	0.000
9	BLNK	Max of all distortion values on all the FoV and all the wavelengths for the NIR channel											
10	ZPLM	3	0	0.000	0.000	0.000	0.000			0.000	0.000	-4.312E-014	0.000
11	BLNK	Max of all distortion values on all the FoV and all the wavelengths for the UVVIS channel											
12	ZPLM	5	0	0.000	0.000	0.000	0.000			0.000	0.000	2.609E-014	0.000
13	BLNK	IB-distortion											
14	ZPLM	6	1							0.000	0.000	8.259E-005	0.000
15	BLNK	Spectral co-registration for the NIR channel											
16	ZPLM	7	0	0.000	0.000	0.000	0.000			0.000	0.000	1.806E-004	0.000
17	ZPLM	7	1							0.000	0.000	1.806E-004	0.000
18	ZPLM	7	2							0.000	0.000	1.806E-004	0.000

The value of the Merit function is a an evaluation of the quality of the system

Values of average focal lengths

Value of distortion (in microns)

Value of spectral co-registration (in microns)

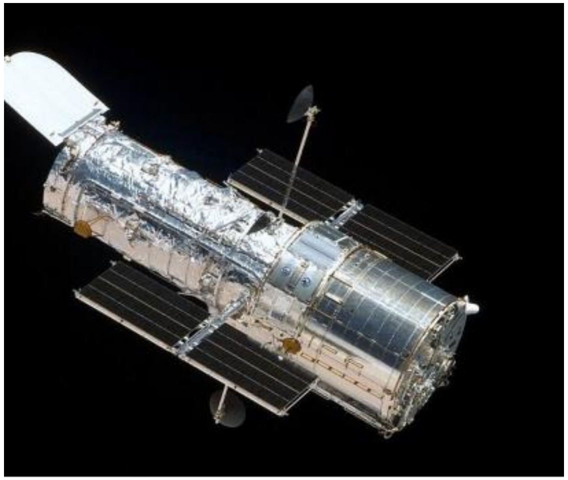
Criterion for optimizing

It is important to chose well **the criterion for the image quality** with respect to what you are asked:

- relevant (and realistic) to comply with the requirements
- used to modify somehow the preliminary designed system

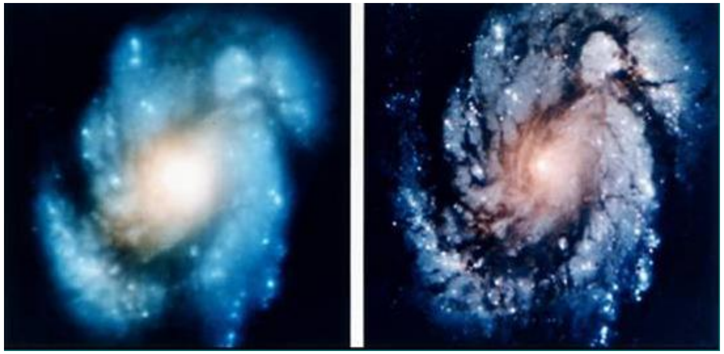
<u>**2 main sets of tolerances:**</u>

- For the **as-built system (Manufacturing)**
- **Stability**: For the behavior of the system under different conditions (pressure, temperature) and through time



Hubble Space Telescope

M100 as seen by Hubble before and after the set-up of the optical corrector



Before After

<u>**For a space mission:**</u>

- Several years of exploitation
- No way to go and fix a trouble once it is launched→ **so tolerancing is useful** (remember Hubble…)

Analysing and optimizing the system

We have 2 main analysis to go through during the studies:

- The **Sensitivity analysis**: we want to see how sensible your system is with respect to your defined quality criteria:

$$S = \frac{criterion}{Max\_tol - Min\_tol}$$

criterion → Defined in the Merit Function

Max_tol − Min_tol → Amplitude of the different tolerance

→ These tolerances are **deterministic**

→ To be evaluated **for each surface/element** or set of element of the optical system

The **Monte-Carlo analysis**: see how behave the system putting tolerances (uncertainties) in the range we define.

Goal: To get the closest possible to the real system (simulating as many situations as we can, e.g; for a Monte-Carlo run: $(\#\ tolerances)^2 = \#$ files generated)

→ this time tolerances are applied **randomly**

Analyzing and optimizing the system

Step of the analyze process:

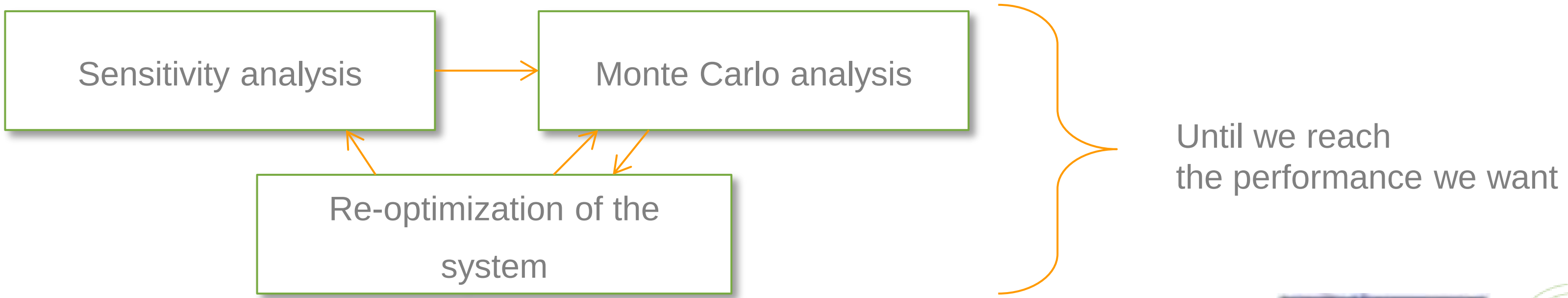
- see **how sensible** the system is with respect to the tolerances and criteria

- **re-optimize** the Monte-Carlo files generated by the software putting the uncertainties in the system

For a space mission:

- tolerances are chosen **to the tenth of the values for manufacturing** (e.g.: we take a few microns for decentering of elements and of few arcmin for their tilting)

- simulate the (severe) changes in temperature and to know if the system will behave the same during all the time of the mission.



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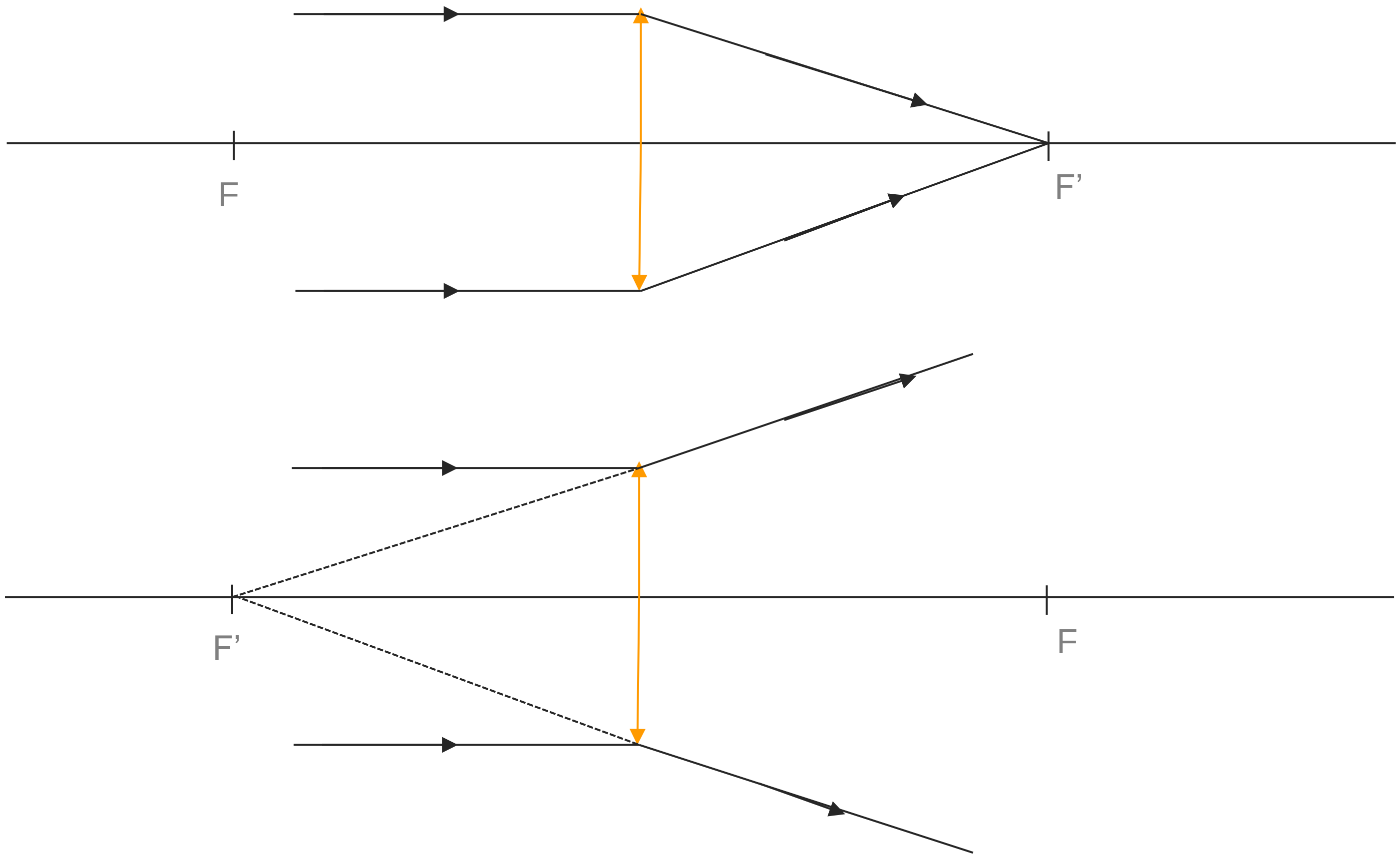
Thank you for your attention

Questions ?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