EPFL

MICRO-517

Optical Design with ZEMAX OpticStudio

Lecture 3

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Ye Pu
Sciences et techniques de l’ingénieur
École Polytechnique Fédérale de Lausanne
CH-1015 Lausanne

Outline

Theory

- Process of optical design
- Paraxial model of typical optical instruments
- Paraxial lens design layout and ray tracing

ZEMAX Practice

- Paraxial design layout and ray tracing
- Functional verification

The Optical Design Process

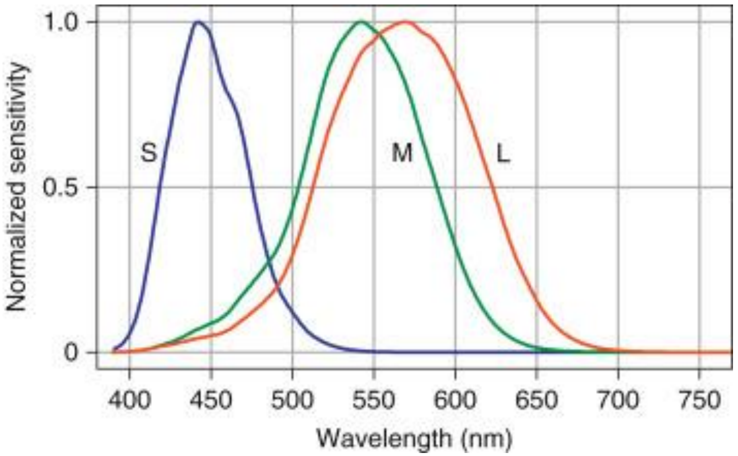
Specification → Layout → Thin-lens Predesign → Surface Model → Optimization → Tolerancing

Specification

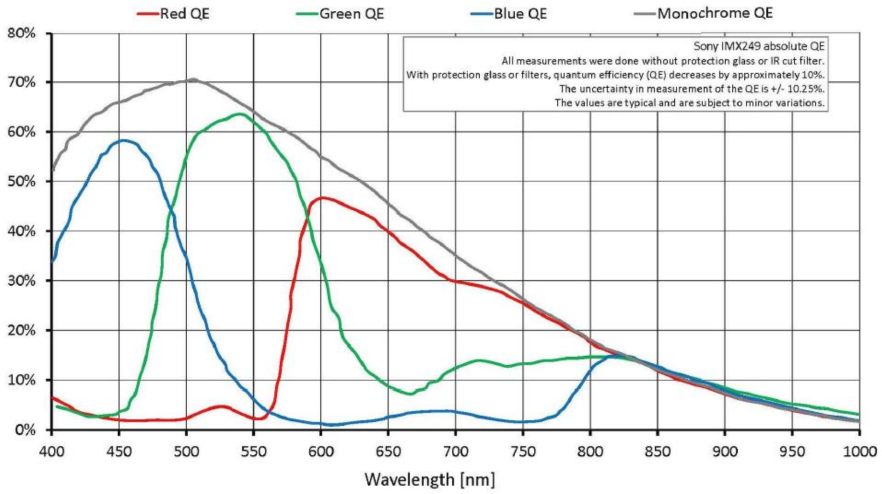
Specification → Layout → Thin-lens Predesign → Surface Model → Optimization → Tolerancing

Spectral Transmission Requirement

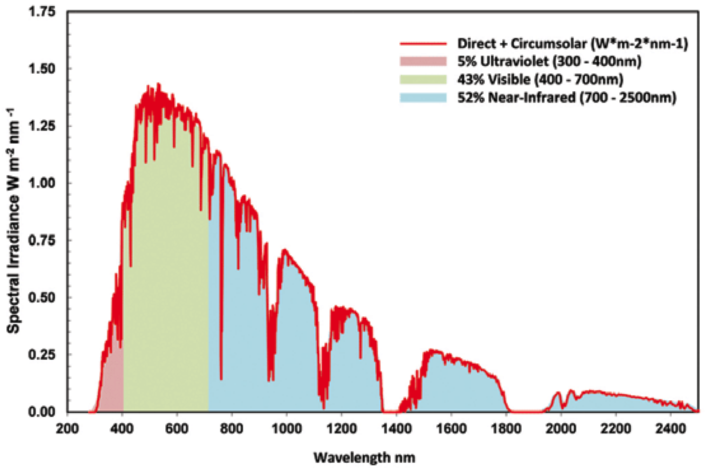
Typical normalized spectral sensitivity of human eye



Typical spectral sensitivity of color image sensor



Solar spectral irradiance



Specification

Specification → Layout → Thin-lens Predesign → Surface Model → Optimization → Tolerancing

Imaging

General

- Focal or afocal design
- Type and size of the object
- Spectrum and illuminance (irradiance) of the light
- Distance of the object
- Size and sensitivity of the detector

Image quality

- Resolution (periods per mm) as a function of field radius and defocus
- Contrast in relation to detector noise
- Depth of field
- Tolerances on field curvature and distortion
- Tolerances on illumination inhomogeneity
- Telecentricity

Specification

Specification → Layout → Thin-lens Predesign → Surface Model → Optimization → Tolerancing

Paraxial Parameters

Microscope objective

- Field diameter
- Aperture angle or numerical aperture
- Magnification
- Working distance (lens-object)
- Tube length (lens-image distance)
- Length and diameter of the objective

Camera and telescope

- Focal length
- Back focal length (working distance)
- F-number
- Field angle

Specification

Specification → Layout → Thin-lens Predesign → Surface Model → Optimization → Tolerancing

Environmental and Economical

- Physical: temperature, pressure, humidity, shocks, vibrations, dust, radiation, …
- Chemical: reactants, corrosion, solvents, …
- Biological: fungi, material toxicity, …
- Economical: cost, market price, batch size, delivery date, packaging, transport, …
- Limits in size and weight (potable and space applications)

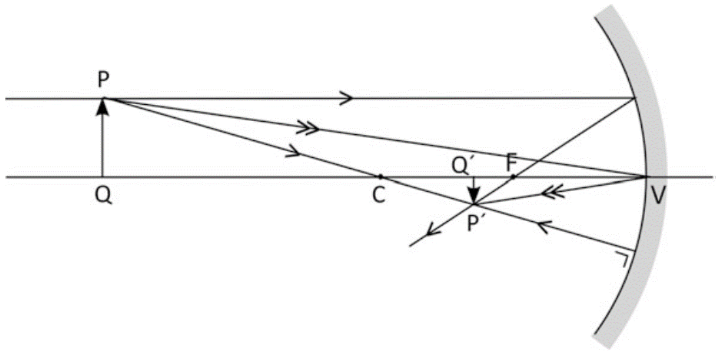
Layout

- Paraxial phase of a design
- Quicker raytracing computation
- Functional verification
- Corrects primary chromatic aberrations
- Third-order aberrations left out except field curvature
- Complex system can involve lots of algebra

Layout

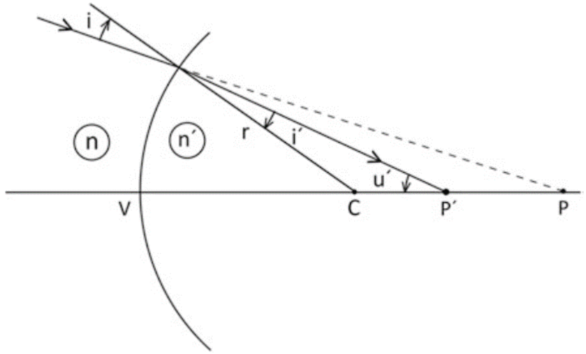
Specification → **Layout** → Thin-lens Predesign → Surface Model → Optimization → Tolerancing

Image Equations Review



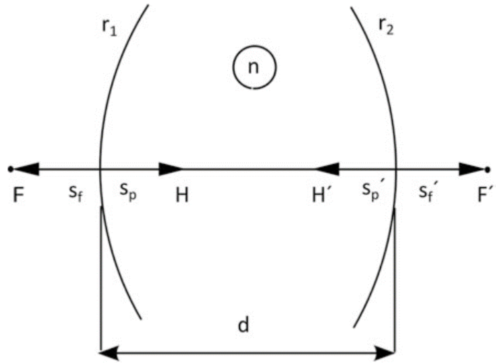
Spherical Mirror

$$\frac{1}{s'}+\frac{1}{s}=-K \qquad K=-\frac{2}{r}$$



Spherical Refractive Surface

$$\frac{n'}{s'}-\frac{n}{s}=K \qquad K=\frac{n'-n}{r}$$

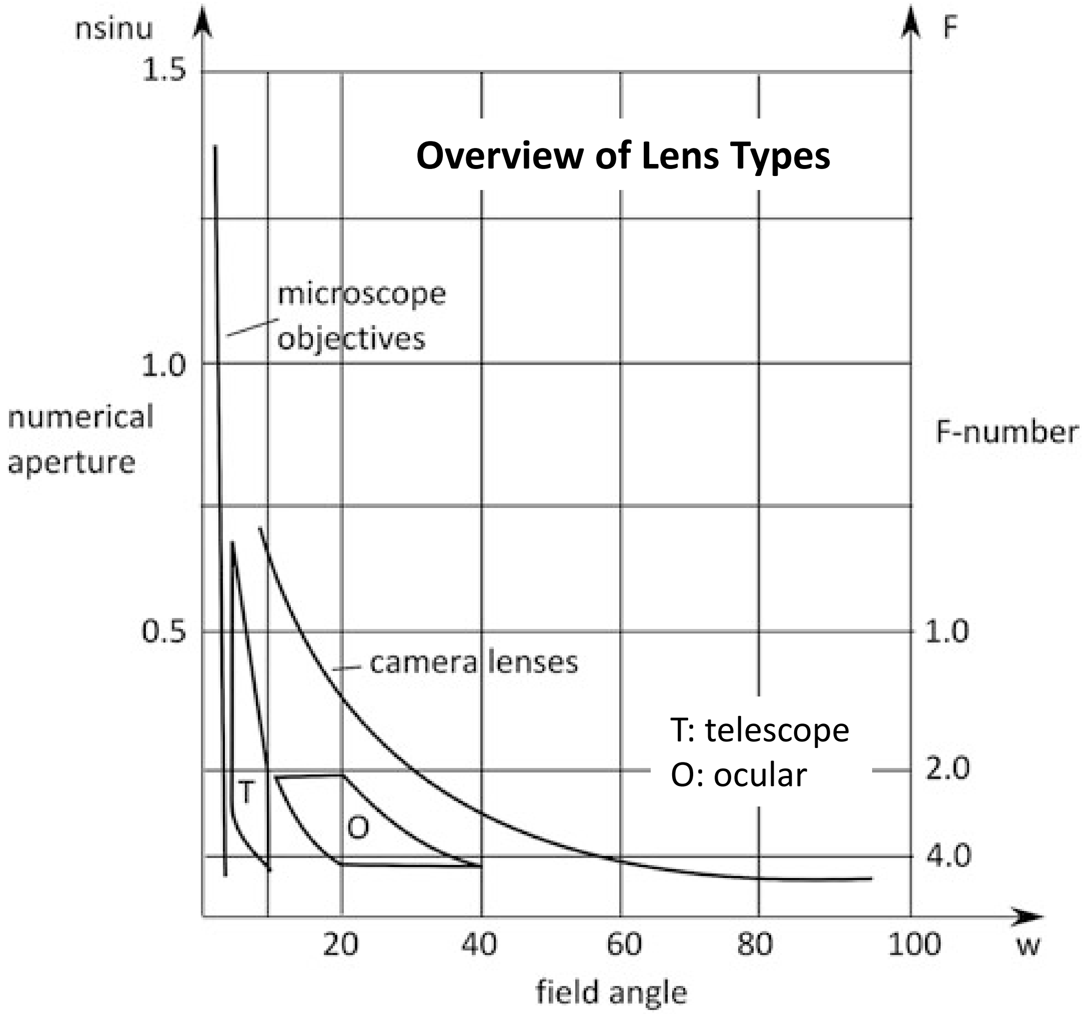


Single Lens

$$\frac{1}{s'}-\frac{1}{s}=K$$

$$K=(n-1)\left[\frac{1}{r_1}-\frac{1}{r_2}+\frac{(n-1)d}{nr_1r_2}\right]$$

Layout



Scale factor

Focal length acts as the scale factor for the system to be designed

$$K = \frac{1}{f} = \frac{1}{h_1} \sum_{i=1}^{k} h_i K_i$$

When a system is scaled by a factor p:

- Focal length: $f \rightarrow pf$
- Radii: $r_i \rightarrow pr_i$
- Distances: $d_i \rightarrow pd_i$
- Aperture angles: $u_i \rightarrow u_i$
- Field angles: $w_i \rightarrow w_i$

Field curvature (Petzval sum)

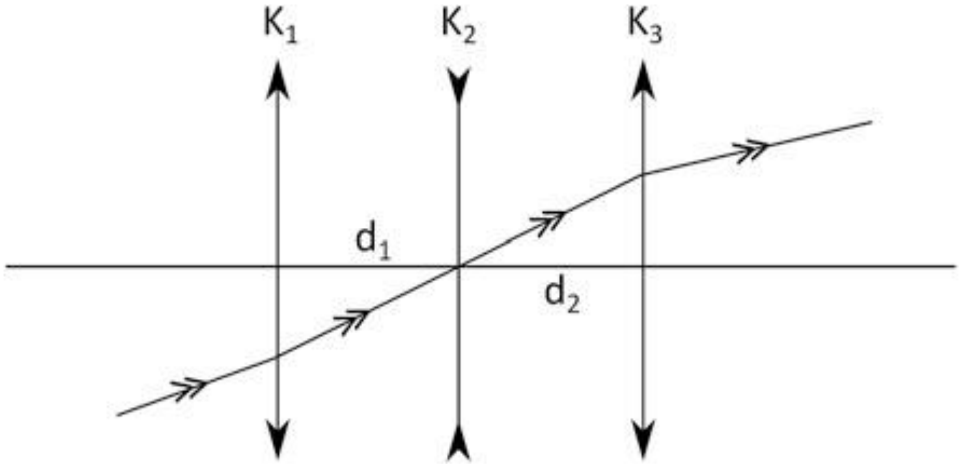
$$P = \sum_{i=1}^{k} \frac{K_i}{n_i}$$

Telescope, microscope: $P < K$

Photographic lens: $P < 0.2K \sim 0.4K$

Lithography objective: no tolerance

Layout



h_i Height of marginal ray at surface *i*

$\bar{h}_i$ Height of chief ray at surface *i*

V_i Abbe number at surface *i*

$$V = \frac{n_d - 1}{(n_F - n_C)}$$

n_d Helium d-line (588 nm)
n_F Hydrogen F-line (486 nm)
n_C Hydrogen C-line (656 nm)

Longitudinal chromatic aberration (LCA)

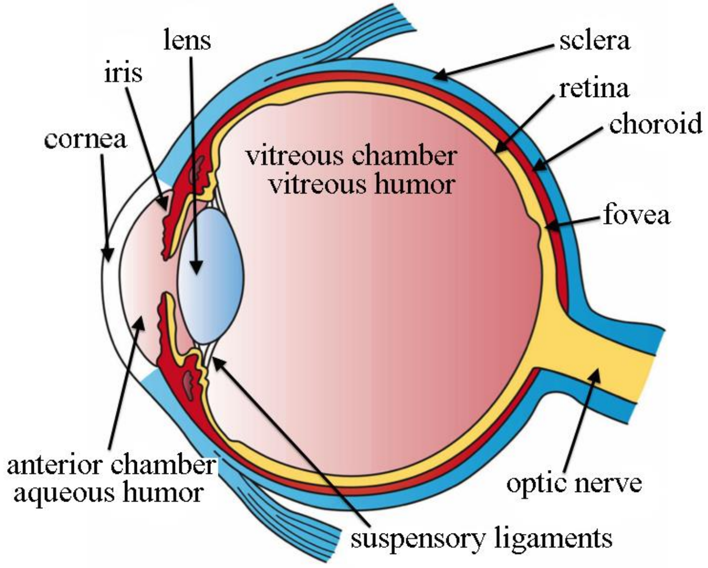
$$C_1 = \sum_{i=1}^{k} h_i^2 K_i / V_i = h_1^2 \, K / V_s$$

Transverse chromatic aberration (TCA)

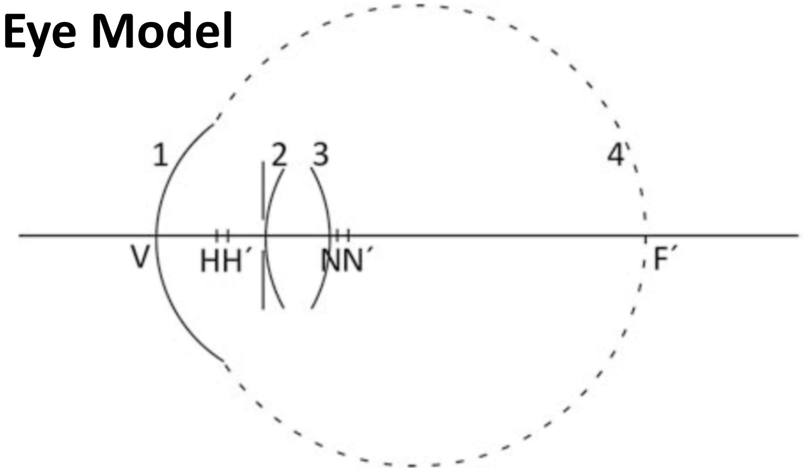
$$C_2 = \sum_{i=1}^{k} h_i \bar{h}_i K_i / V_i$$

Equivalent Abbe number $\dfrac{K_s}{V_s} = \sum_{i=1}^{k} \dfrac{K_i}{V_i} \quad K_s = \sum_{i=1}^{k} K_i$

Typical Optical Instruments | Human Eye



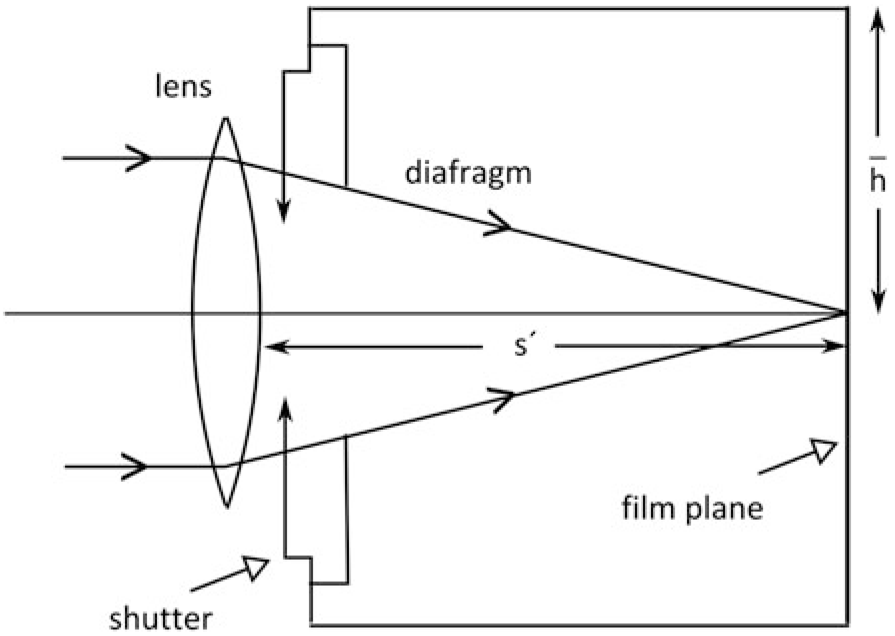
Eye Model



- Cornea: ~50 µm thick, approximately spherical, curvature *r* ~ 7.8 mm (average)
- Aqueous humor: n ~ 1.336
- Crystalline Lens: ~7 mm behind the cornea, n ~ 1.386 (outside) to 1.406 (center), thickness and curvature controlled by ciliary muscle, power ~17 to 25 diopters
- Iris diaphragm: diameter ~2 to 8 mm
- Vitreous humor: n ~ 1.336.
- Retina: ~25 mm behind the cornea, curvature *r* ~ 12 mm
- Resolves ~0.1 mm at a distance of 250 mm

	#	Radius	Distance	Index
OBJ	0	–	?	1
	1	7.8	7	1.336
	2	10.0	3.6	1.413
	3	-6.0	13.4	1.336
IMA	4	-12.0	–	–

Typical Optical Instruments | Camera



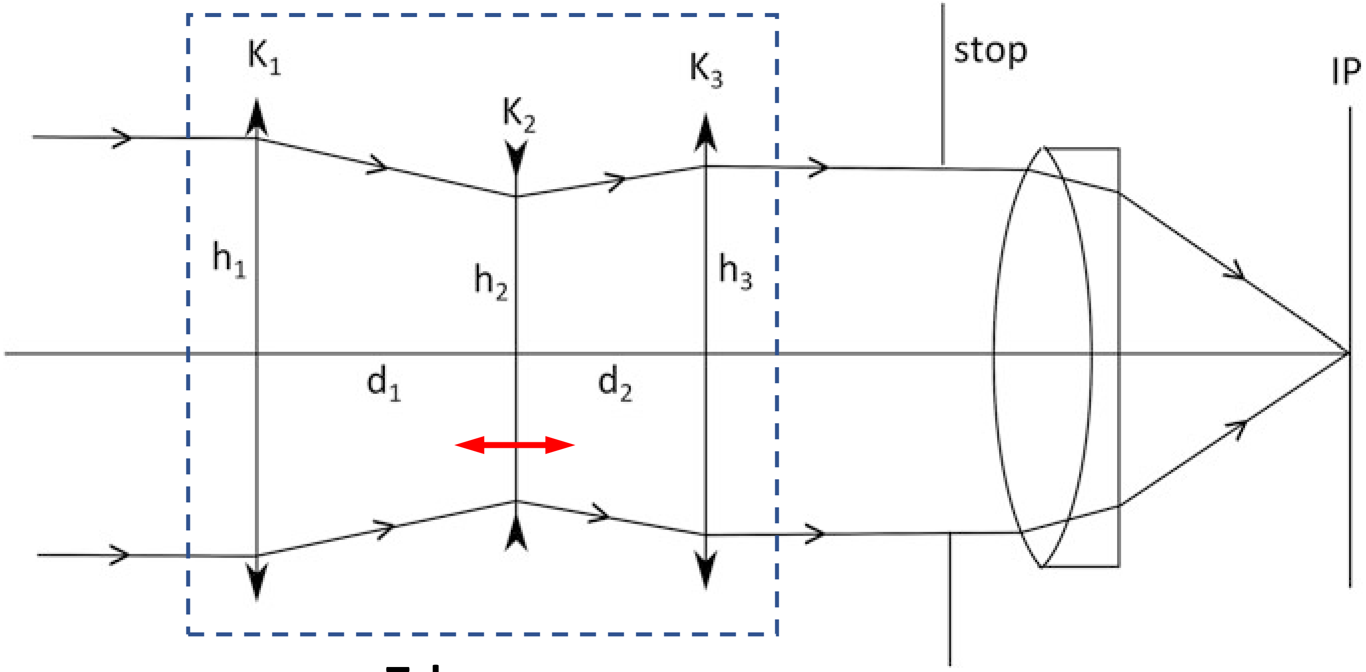
$$\frac{1}{s'} = \frac{1}{s} + \frac{1}{f}$$

F-number $F\# = f'/D$

Depth of field (focus) $\Delta z = \pm \Delta y \cdot F\#$

- Huge variety of lens designs
- 30 period/mm standard resolution for modern camera lens

Typical Optical Instruments | Zoom Lens



For telescope $h_1K_1 + h_2K_2 + h_3K_3 = 0$

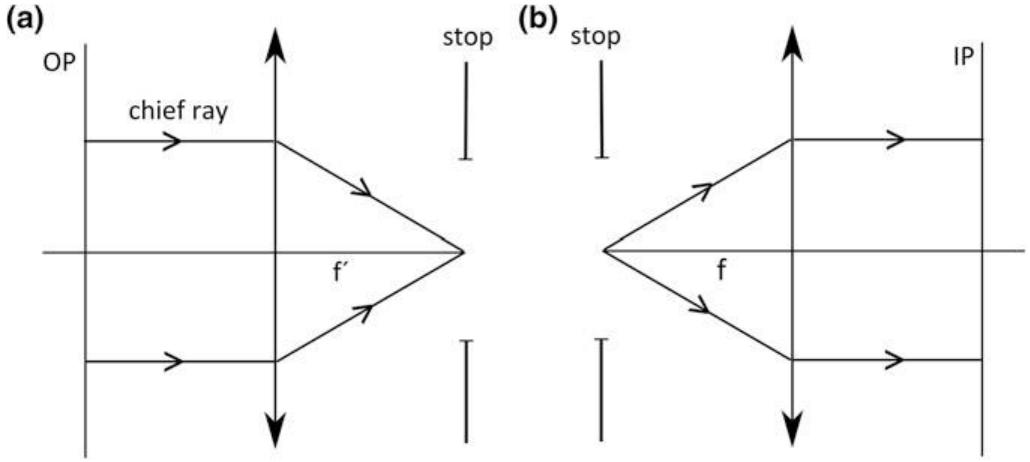
$u_1 = 0 \quad u_2 = -h_1K_1 \quad u_3 = h_3K_3$

$h_2 = h_1\left(1 - K_1d_1\right) = h_3\left(1 - K_3d_2\right)$

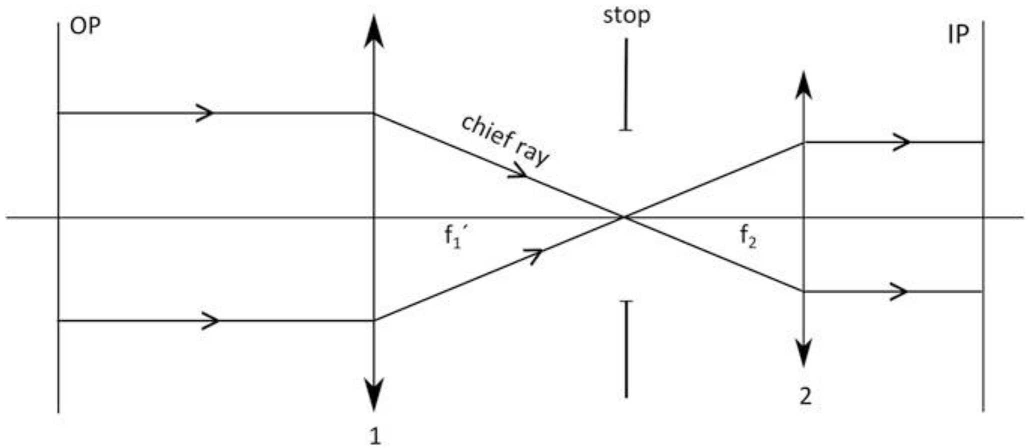
Angular magnification

$$M = \frac{h_1}{h_3} = \frac{-K_3}{K_1 + K_2 - d_1K_1K_2}$$

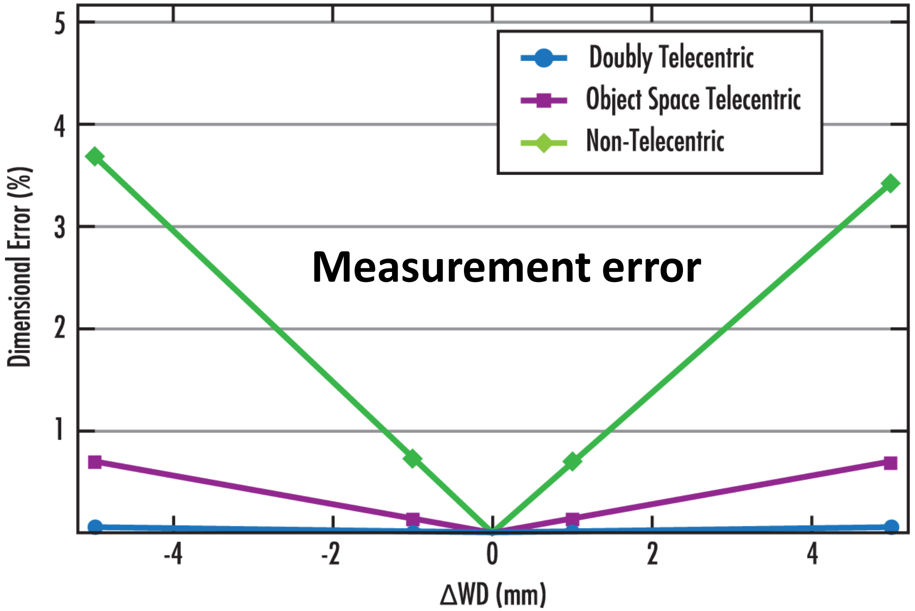
Typical Optical Instruments | Telecentric Lens



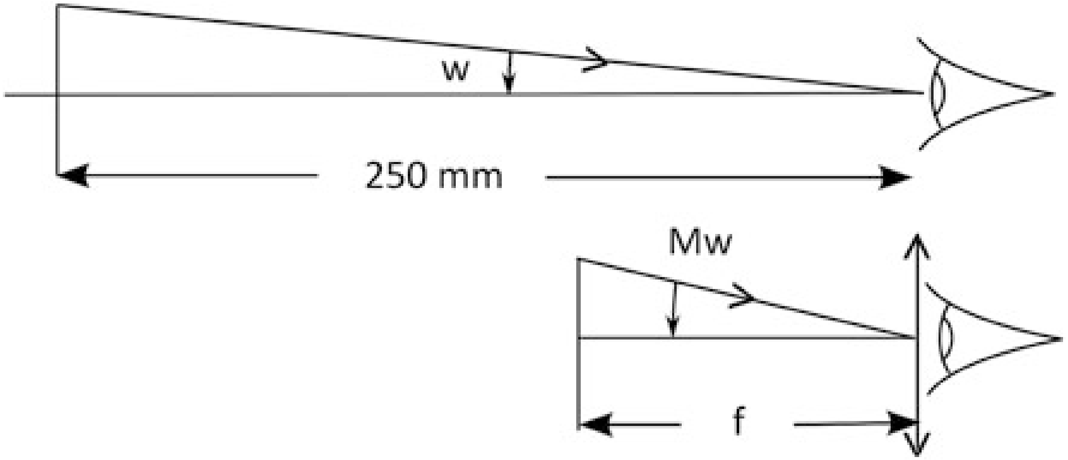
Object space telecentric **Image space telecentric**



Doubly telecentric

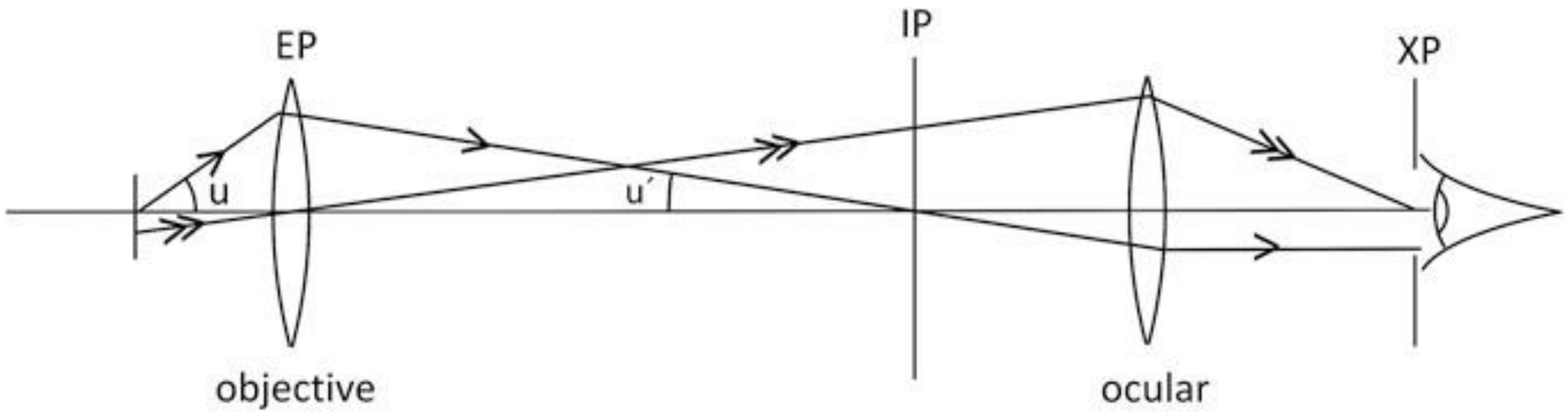


Typical Optical Instruments | Magnifier



Angular magnification $M = \dfrac{250}{f}$

Typical Optical Instruments | Microscope

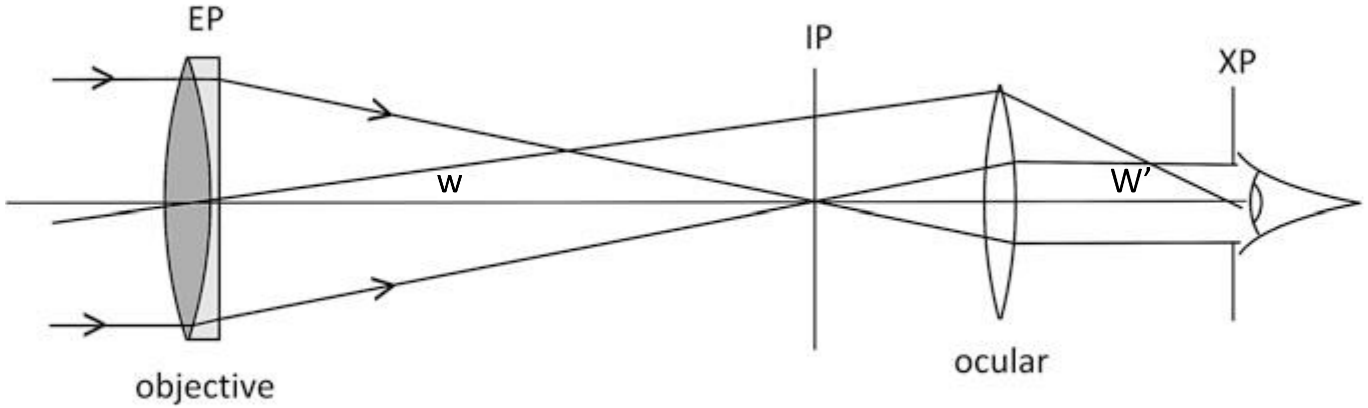


Angular magnification $M = M_{ob}\dfrac{250}{f_{oc}}$ where M_{ob} is linear magnification of objective

- Objective design is the key
- "Infinity-conjugated" objective
  - Objective plane at front focal plane
  - Require a tube lens for image formation

Typical Optical Instruments | Telescope

Keplerian telescope



Linear magnification $M_L = -f_2 / f_1$

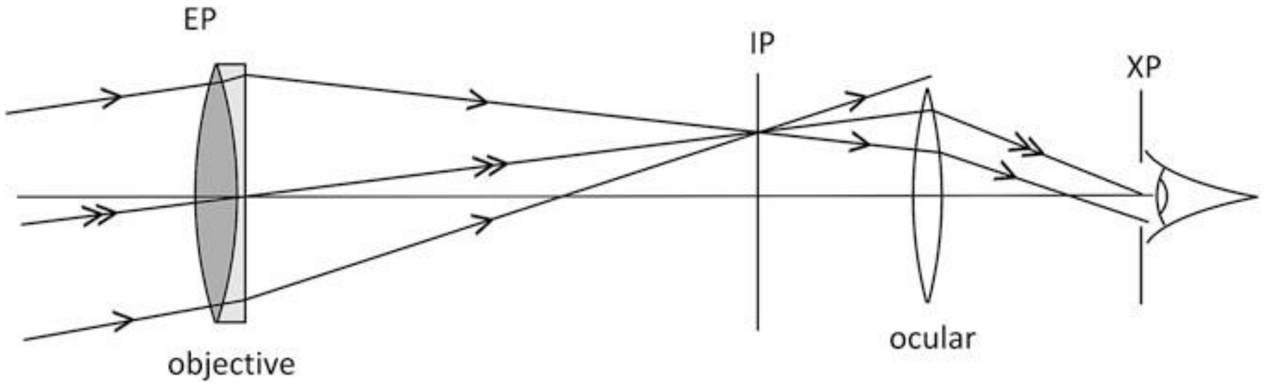
Angular magnification $M_A = -f_1 / f_2$

Lagrangian invariant

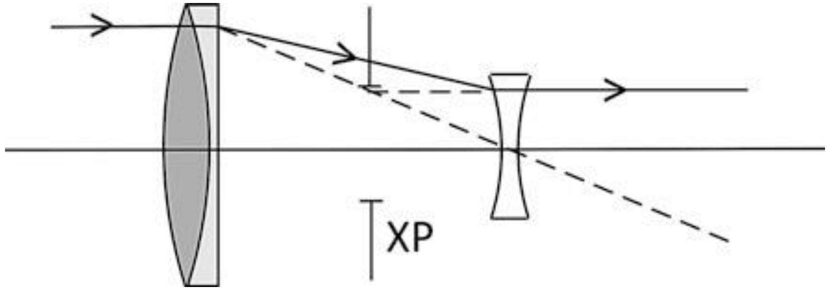
$M_A = 1/M_L$

Typical Optical Instruments | Telescope

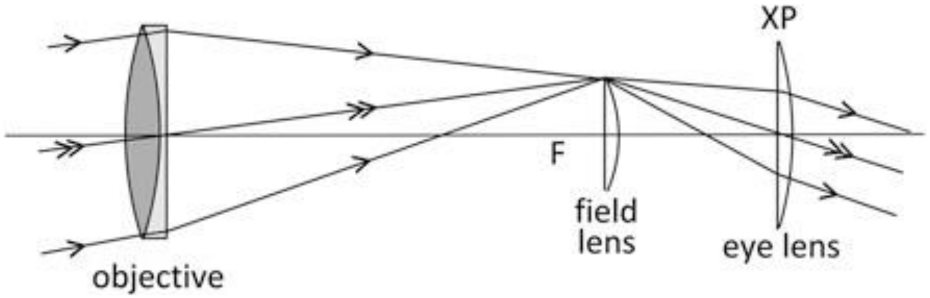
Vignetting



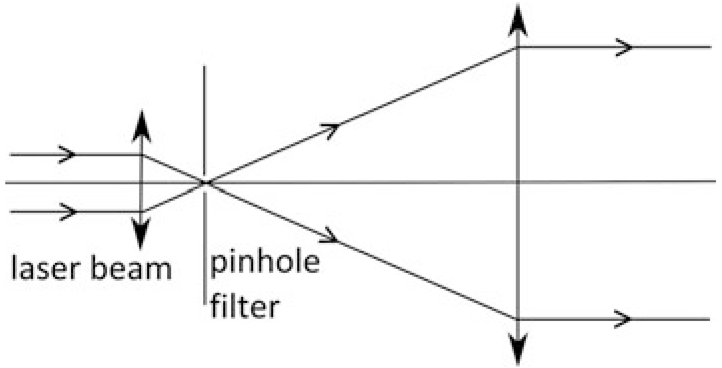
Galilei’s telescope



Vignette correction with field lens



Laser beam expander



MICRO-517

ZEMAX OpticStudio

Hands-on Time

Homework

Objective

- Practice ZEMAX ray tracing with paraxial models
- Familiarize yourself with principles of various optical instruments
- Understand functional verification of your design

1. Design a paraxial telescope of magnification M = 100 and objective lens aperture diameter of 300 mm. Note that Zemax OpticStudio always works with semi-diameter. Use an appropriate field lens to improve vignetting.
2. Design a paraxial microscope of magnification M = 100. The microscope objective works at "infinite-conjugate" (object at the front focal plane). Use a tube lens of 200 mm.
3. Design a paraxial doubly telecentric lens with magnification M = 0.1. Use field heights of 0, 30, 100 mm at an object distance of 200 mm.
4. Design a paraxial zoom lens with the range of angular magnification M = 2 – 5. Assume object at infinity. Use field angle of 0, 3, and 5 degrees. Use another paraxial lens as the last focusing lens.

You should submit the ZEMAX design files (.zos). No need to generate spot diagram since we are in a paraxial regime. However, it may help you diagnose design problems at various stages.