OPTI503 Optical Design & Instrumentation II
Lecture 1: Introduction

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College of Optical Sciences

Course

- Schedule
  - Lecture: 8:00-9:15am M/W (Room 305)
    - No lecture on Friday
- Office hour:
    - 10:30am - 11:30pm, Wednesday
    - https://arizona.zoom.us/j/82765543193
    - By appointment
    - Zoom discussion by appointment for remote students
- Teaching assistant (TA)
  - TBD
  - Office hour: TBD

What to Cover in OPTI503?

Optical Design and Instrumentation

- First order optics (OPTI502)
- Third order optics
  - Aberrations
    - OPTI518 Introduction to Aberrations
- Lens Design (OPTI517)
- Image quality
- Digital imaging system
- Colorimetry
- Thin film coating
- Stray light analysis

- Examples to discuss optical concepts
- Practical Optical System Design (OPTI617)

Notes and Textbook

- Course notes: Will be posted on D2L site before the class
- Recommended textbook:
  - J. E. Greivenkamp, Field Guide to Geometrical Optics
  - Herbert Gross, Handbook of Optical Systems, Vol. I-V
  - Michael Kidger, Fundamental Optical Design
  - Robert Fisher, Optical System Design
  - Glenn D. Boreman, Modulation Transfer Function in Optical and Electro-Optical Systems
  - Daniel Malacara, Color Vision and Colorimetry: Theory and Applications
  - Angus Macleod, Thin-Film Optical Filters, Angus Macleod

https://www.spiedigitallibrary.org/ebooks?SSO=1

Software

- Optical design software
  - Zemax
  - CodeV
  - Optilayer
- https://wp.optics.arizona.edu/helpdesk/osc-site-licensed-software/
- TA will give a Zemax Tutorial lecture on Zoom
  - Time: TBD

Grading Policy

- Homework (~10): ~40%
- Midterm: ~30%
  - Date: 02/28/2024
- Final: ~30%
  - Date: 05/08/2024
- Grading scale
  - 85-100%: A
  - 75-85% : B
  - 65-75% : C
  - 50-65% : D
  - < 50% : E

Homework and Exam Policy

- Will post on D2L site
- On-campus students
  - Submit through D2L site
- Remote students
  - Allowable delay: one week
    - The maximum allowable delay is two weeks upon request.
  - Submit through D2L site
- Late policy on homework
  - Need to get permission from instructor.
  - 5% deduction for each day after the due date without permission.

Tentative Lectures

	M	T	W	Th	F			Monday		Wednesday
Janurary	8	9	**10**	11	12				1	Introduction
	15	16	**17**	18	19				2	Ray tracing
	22	23	**24**	25	26		3	Aberration - I	4	Aberration - II
Feburary	**29**	30	**31**	1	2		5	Aberration - III	6	Aberration - IV
	5	6	**7**	8	9		7	Aberration - V	8	Seidel Aberrations
	12	13	**14**	15	16		9	Image Quality - I	10	Image Quality - II
	19	20	**21**	22	23		11	Image Quality - III	12	Optical materials & color correction
March	**26**	27	**28**	29	1		13	Optical Design-I	14	Midterm
	4	5	**6**	7	8					
	11	12	**13**	14	15		15	Optical Design-II	16	Optical Design-III
	18	19	**20**	21	22		17	Digital Imaging - I	18	Digital Imaging - II
	25	26	**27**	28	29		19	Digital Imaging - III	20	Colorimetry - I
April	**1**	2	**3**	4	5		21	Colorimetry - II	22	Colorimetry - III
	8	9	**10**	11	12		23	Colorimetry - IV	24	Colorimetry - V
	15	16	**17**	18	19		25	Thin Film Coating - I	26	Thin Film Coating - II
	22	23	**24**	25	26		27	Thin Film Coating - III	28	Thin Film Coating - IV
May	**29**	30	**1**	2	3		29	Thin Film Coating - V	30	Optical Instrumentation

Acknowledgement

- Prof. John Greivenkamp
  - OPTI503 was developed Prof. Greivenkamp

- Some of materials in course notes were developed from
  - Prof. James Wyant, http://wyant.optics.arizona.edu/math.htm
  - Prof. Angus Macleod, Thin-Film Optical Filters, Angus Macleod
  - Prof. Herbert Gross, Handbook of Optical Systems, Vol. I-V
  - Dr. Michael Kidger, Fundamental Optical Design
  - Prof. Glenn D. Boreman, Modulation Transfer Function in Optical and Electro-Optical Systems
  - Daniel Malacara, Color Vision and Colorimetry: Theory and Applications,

Optical Design

- Understand the applications
- Establish requirement
- Lens design
- Image quality criteria
- Tolerance
- Design for manufacturing
- Opto-mechanical design

OPTI617

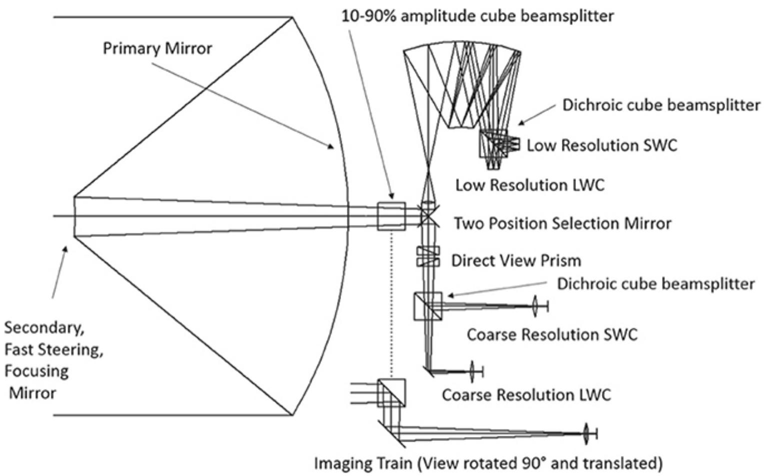
OPTI503, OPTI517 & OPTI696A

OPTI503

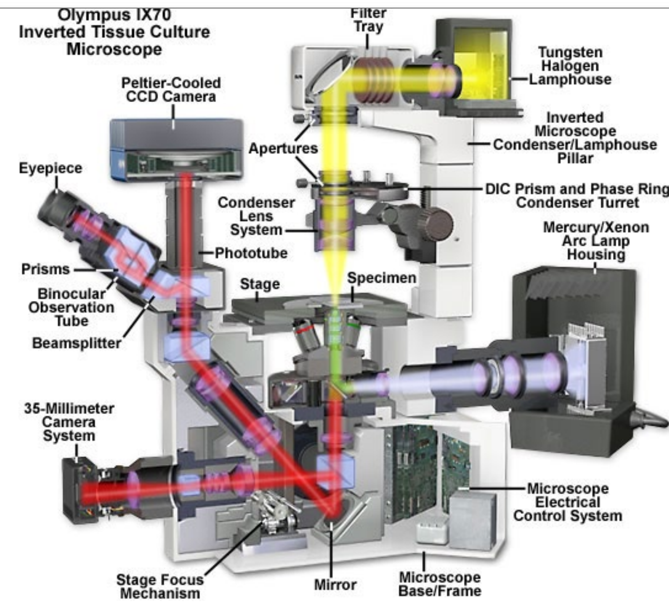
OPTI617

OPTI 421/521 Introductory Optomechanical Engineering

Optical Instrumentation



Near-infrared telescope (NIRT)



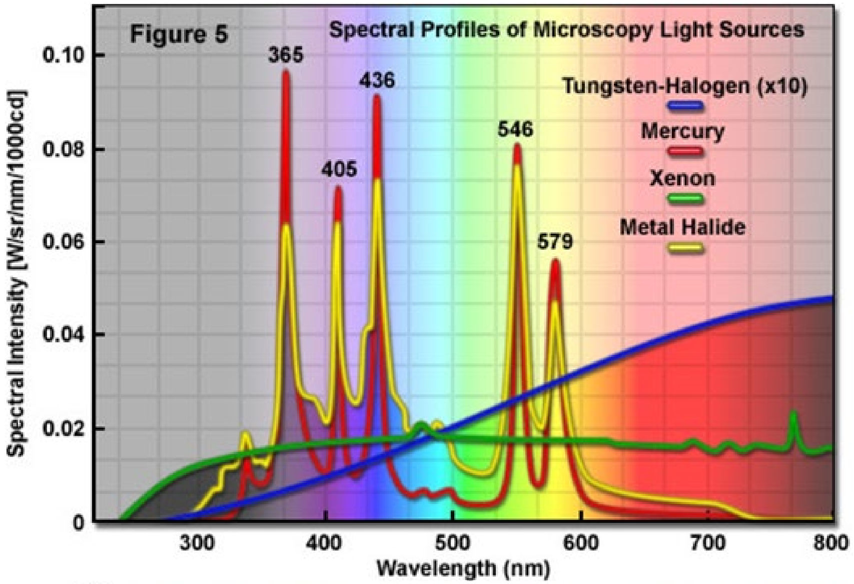
Applications

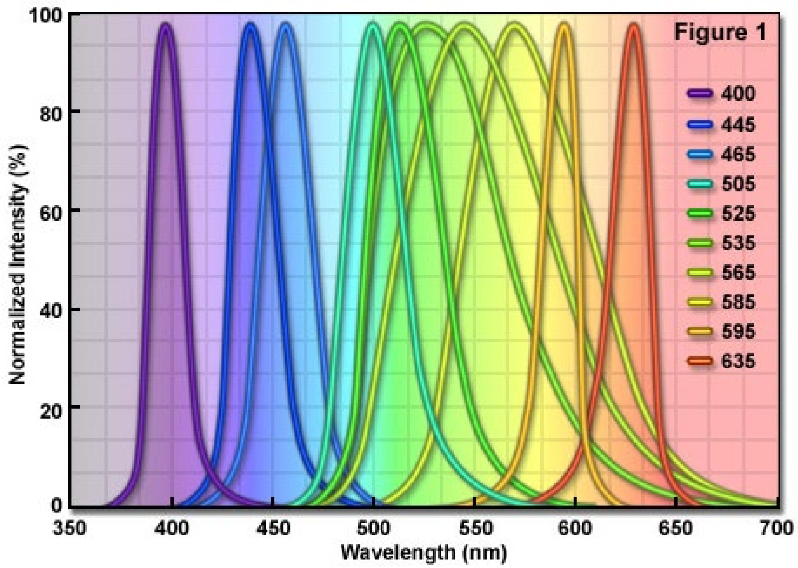
- Imaging?
- Display?
- Illumination?
- Any special requirement?
- Working spectrum?
- …

Light Sources

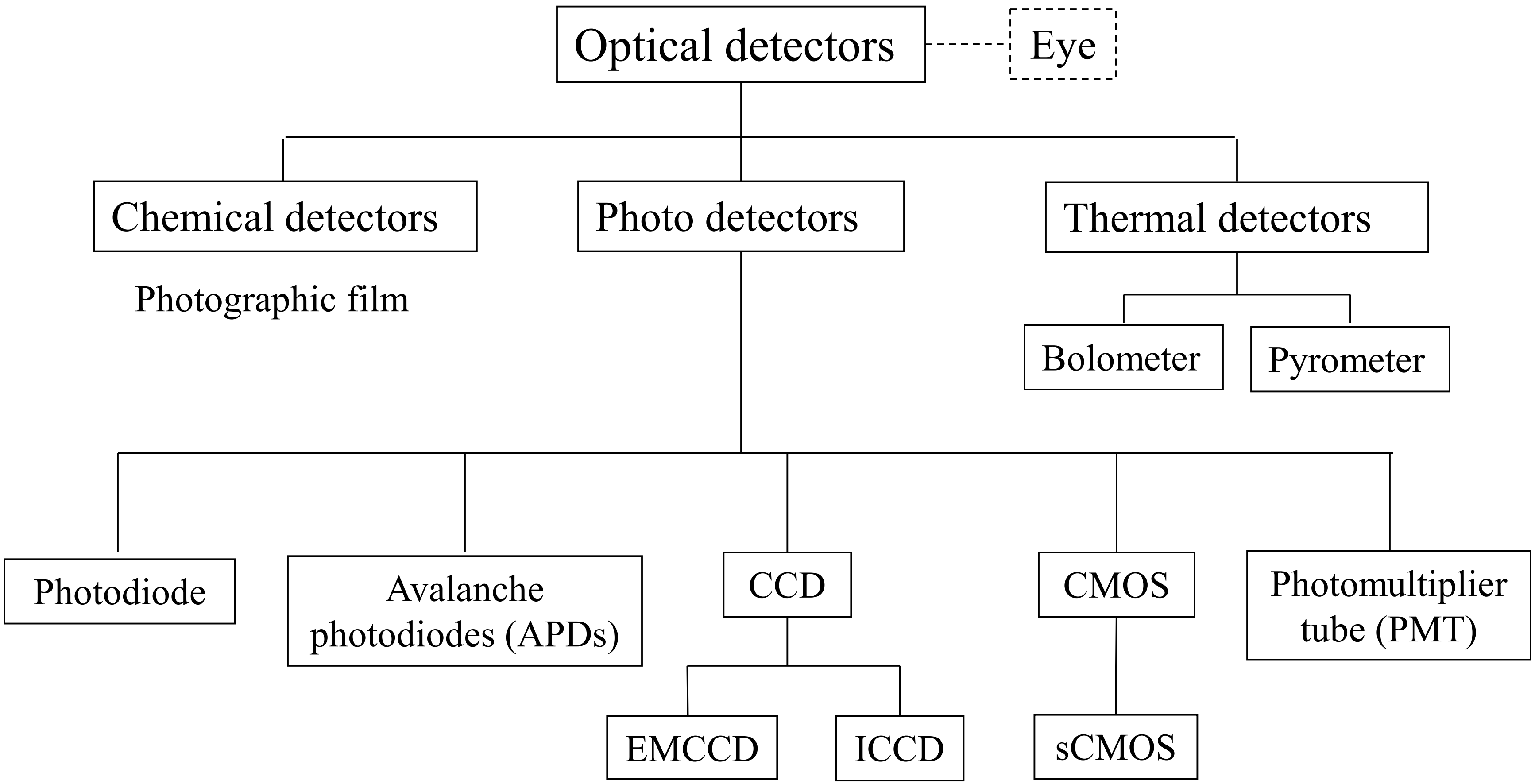
- Sun
- Thermal lamps
  - Incandescent
  - Halogen
- Arc lamp
  - High pressure: Xenon, Mercury, Metal halide
  - Low pressure: Mercury vapor
- Gas discharge lamps
  - Low pressure: Fluorescent, sodium
  - High pressure: Metal halide, sodium, mercury-vapor
- Solid-state light sources
  - Light-emitting diodes (LED)
  - Organic LEDs
- Lasers
  - Semiconductor lasers (LD)
  - Others

OPTI506 & OPTI617





Optical Detectors

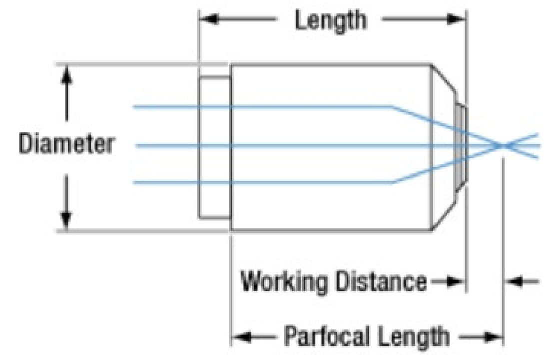


OPTI506 & OPTI617

Optical Design Specifications

- Before beginning the actual lens design, we need to nail down as many specifications as possible.
  - Optical system specifications
  - Performance requirements
  - Environment requirements
- An important part of defining a specification is to determine which specifications are minimums, which are just goals on someone's wish list, and which have some wiggle room, and if so, how much.
- Always pay attention to the specifications
  - Are they theoretically possible and practically feasible in light of the diffraction limit and the conservation of radiance?
  - Can they be met within the constraints of materials, spatial requirements, and the fabrication technology?
  - Which ones are those that define what the customer really wants and needs?

Example of Lens Specification



Olympus Oil-Immersion Objectives

Item #	RMS40X-PFO	RMS60X-PFOD	RMS100X-PFO[a]	RMS100X-PFOD	RMS100X-O
Manufacturer Part #	1-U2B530	1-U2B532	1-U2B5352	1-U2B5362	1-U2B235
Magnification	40X	60X	100X	100X	100X
Numerical Aperture (NA)	1.3	1.25 - 0.65	1.3	1.3 - 0.55	1.25
Field Number	26.5	26.5	26.5	26.5	22
Working Distance (WD)[b]	0.2 mm	0.12 mm	0.2 mm	0.2 mm	0.15 mm
Parfocal Length[b]	45.06 mm				
Compatible Tube Lens Focal Length	180 mm				
Coverslip Correction	0.17 mm				-
Diameter[b]	28 mm	28 mm	26 mm	28 mm	24 mm
Length[b]	49.4 mm	49.5 mm	49.2 mm	49.3 mm	49.2 mm
Design Wavelength	Visible and NIR				Visible
Threading	RMS[c]				

https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=10186

Lens Design

- Aberrations
  - What cause aberrations?
  - How are aberrations defined?
  - How are aberrations calculated?
  - How to minimize the aberrations?
- Materials
- Coating
- Optimization
  - OPTI517
  - OPTI617
  - OPTI696A
- Tolerance: OPTI617
- Manufacturability: OPTI617

Third-order Aberrations

- Spherical aberration
- Coma
- Astigmatism
- Field curvature
- Distortion
- Axial (longitudinal) chromatic aberration
- Lateral chromatic aberration

Monochromatic aberrations

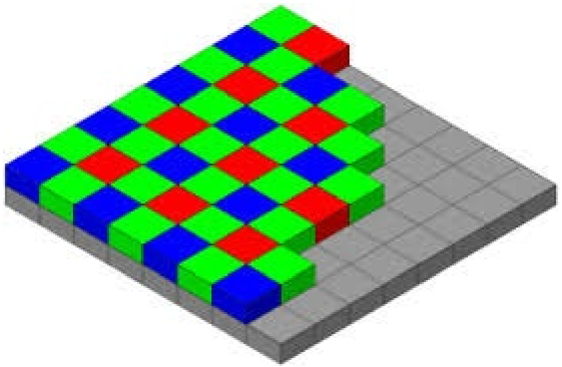
Image Quality Criteria

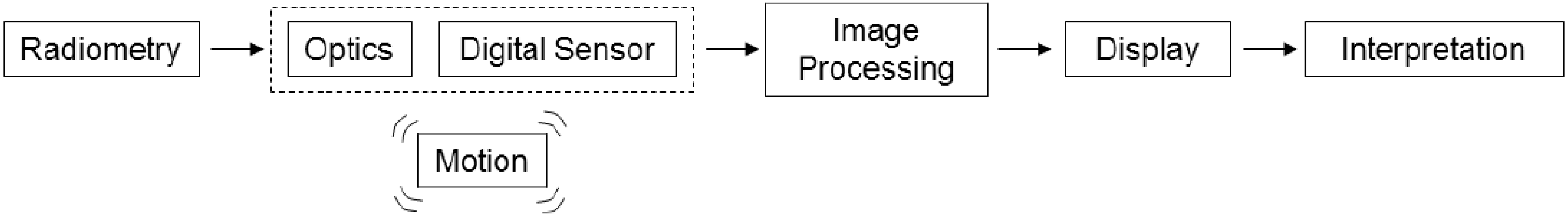
- Resolution
- Modulation transfer function (MTF)
- Encircled/ensquared energy
- RMS wavefront error
- RMS sport size
- Point spread function (PSF)
- Field curvature
- Distortion
- …

- Performance
  - versus diffraction limit
  - versus field
  - versus wavelength
  - versus F/#

Digital Imaging Systems

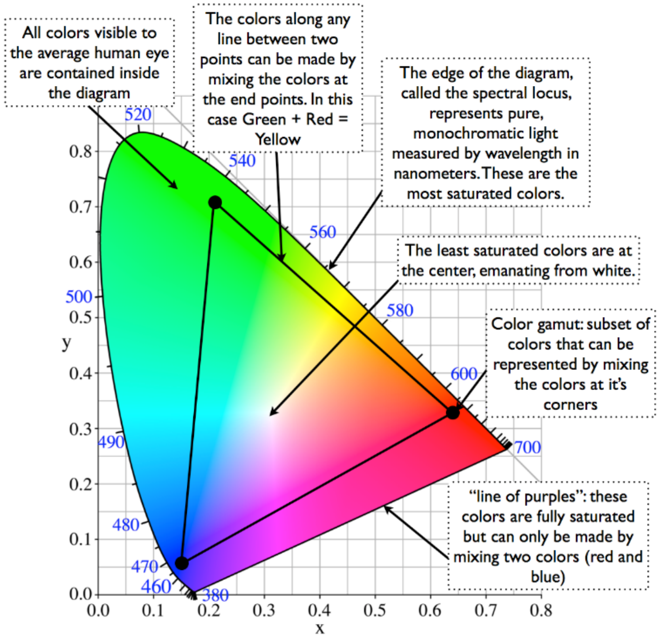
- Two-dimensional sampling and Nyquist frequency
- Optical low-pass filters
- System modeling and analysis
- Image simulation





Colorimetry

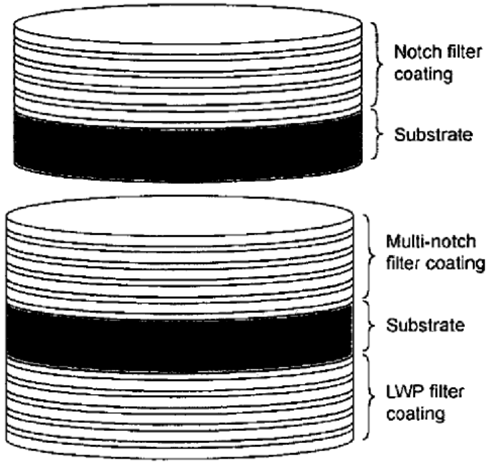
- Visual color perception
- Trichromatic theory
- CIE color specification system
- Uniform color systems
- Color mixtures
- Color measurements

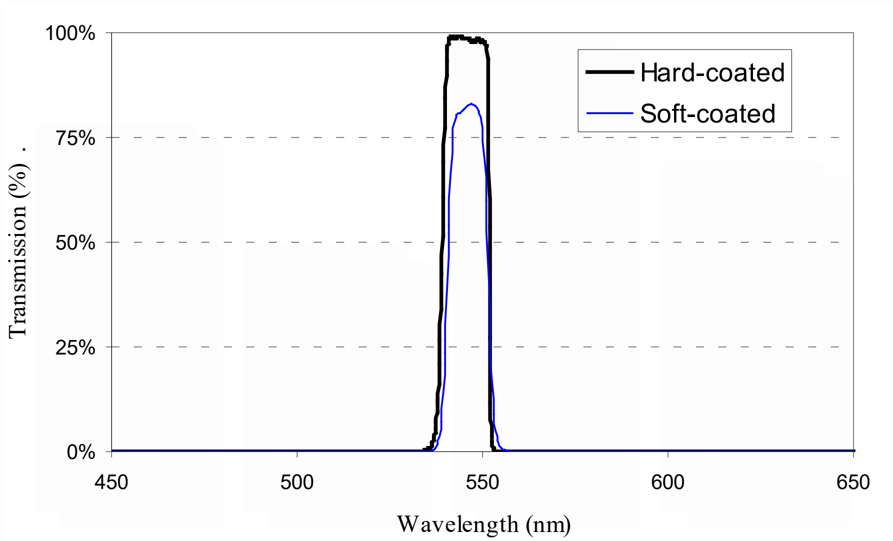


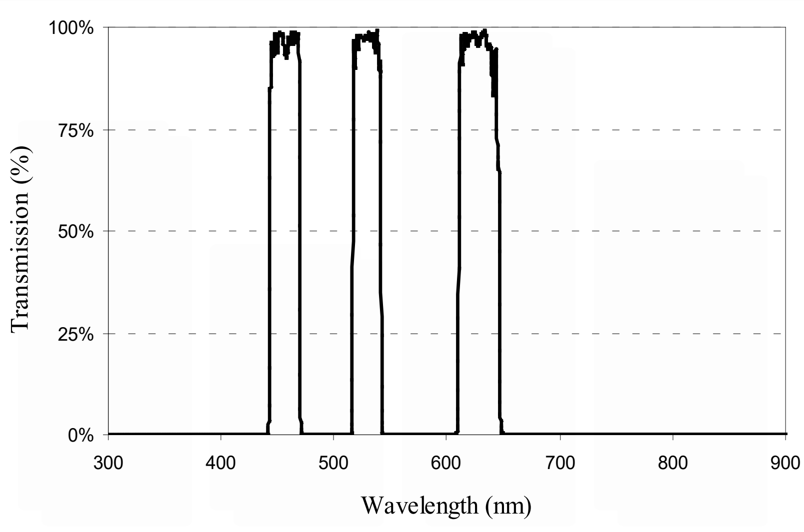
Anatomy of a CIE Chromaticity Diagram

Thin Film Coating

- Fundamentals of thin film coating
- Coating with dielectric layers
- Multiple cavity filters
- Coating with metallic layers
- Special filters

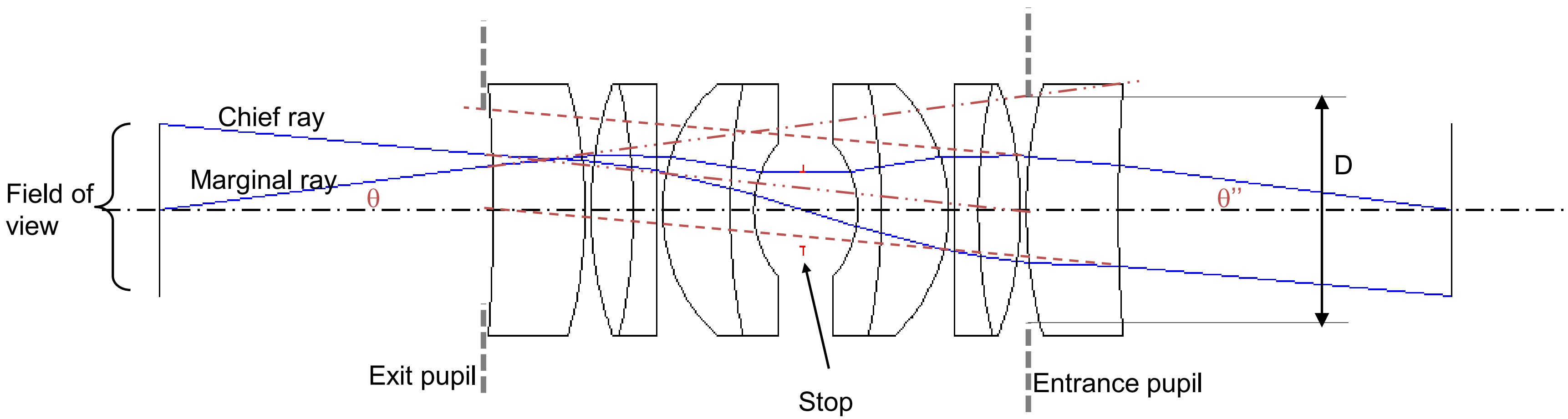






Properties of Optical Systems

Typical Optical System



System specifications

- Object/image distance
- Relative aperture
- Field of view
- Spectrum range and weights
- Focal length
- Magnification
- Exit pupil (telecentricity)
- Special material
- …

Performance specifications

- MTF
- RMS wavefront error
- Encircled energy
- Transmittance and relative illumination
- Size, space or location limitations
- Temperature range and thermal gradients
- Environmental parameters
- …

Basic System Parameters

- Object distance
- Image distance
- Object to image total track
- Effective focal length
- Full field of view
  - Field angle
  - Object size
  - Image size
- Aperture
  - F/# (infinity versus working)
  - Numerical aperture (NA)
  - Stop size
  - Entrance pupil diameter
- Wavelength and bandwidth
- Spectral distribution and weight
- Magnification (if finite conjugate)
- Zoom ratio (if zoom system)
- Pupil location, size, and eye relief
- Stops: aperture, field, and cold
- Telecentric
- Anamorphic ratio
- Depth of focus/field
- Focus range
- …

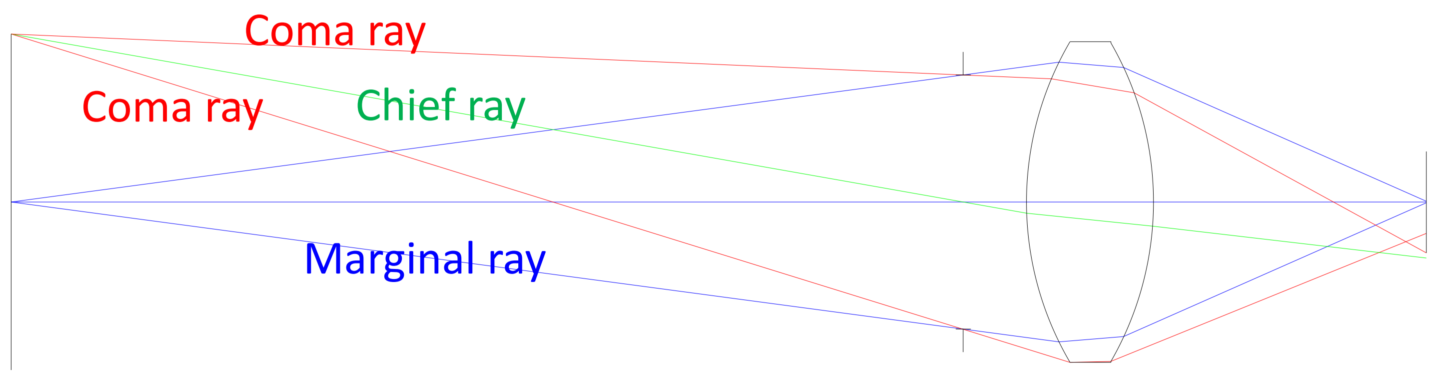
Example

3X, 40mm WD CompactTL™ Telecentric Lens

Primary Magnification PMAG:	3X	Maximum Sensor Format:	2/3"
FOV @ Max Sensor Format, H x V (mm):	2.9 x 2.2	Working Distance (mm):	40.00
Aperture (f/#):	f/16	Coating:	MgF_2 (400-700nm)
Mount:	C-Mount	Type:	Telecentric Lens
Coating Specification:	$\lambda/4$ MgF_2 @ 550nm	Depth of Field (mm):	±0.08mm (20% @ 20 lp/mm)
Field of View, 1/2" Sensor:	2.1mm	Field of View, 1/3" Sensor:	1.6mm
Field of View, 2/3" Sensor:	2.9mm	Filter Thread:	Adapter #88-212 Required
Length excluding Threads (mm):	48.00	Maximum Diameter (mm):	18.00
Number of Elements (Groups):	5 (3)	Numerical Aperture NA, Object Side:	0.093
Typical Distortion @ 588nm (%):	<0.075	Typical Telecentricity @ 588nm (°):	<0.200
Weight (g):	32	Working Distance Tolerance (mm):	±1

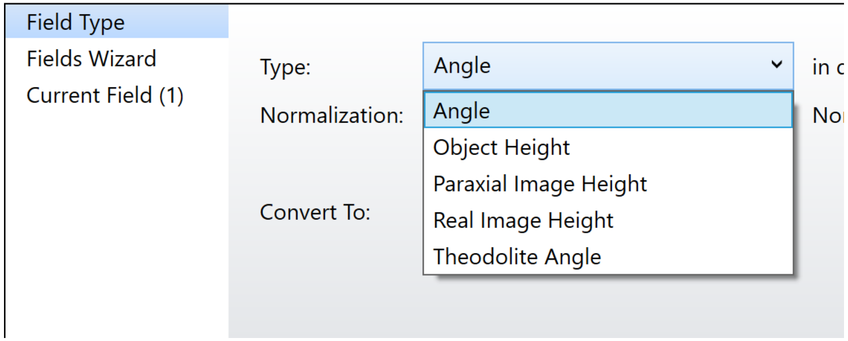
Special Rays

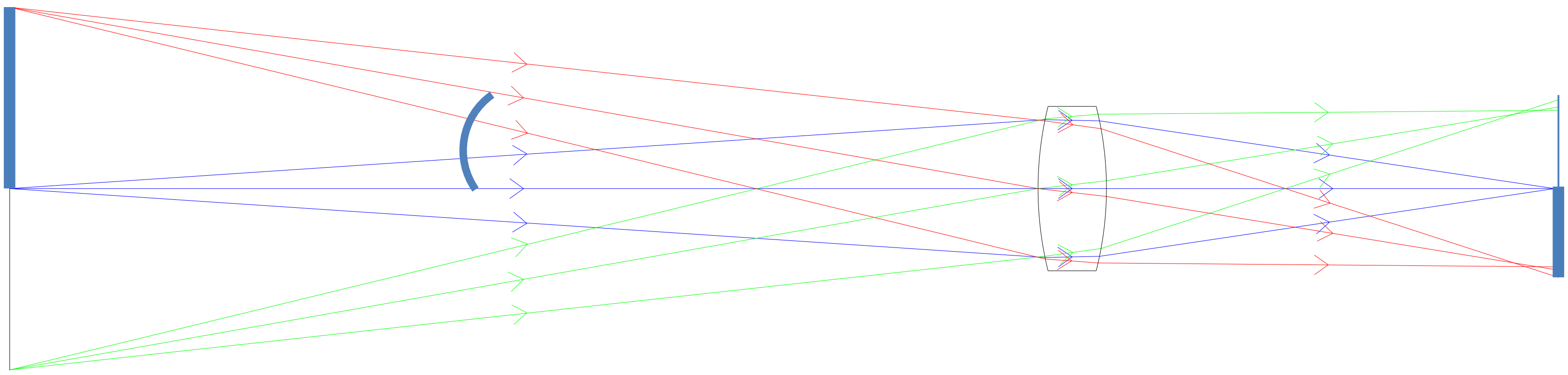
- Marginal ray: connects the center of the object field and the rim of the pupil
- Chief ray: connects the off-axis field point and the center of the pupil
- Coma ray: connects the off-axis field point and the rim of the pupil



Field of View

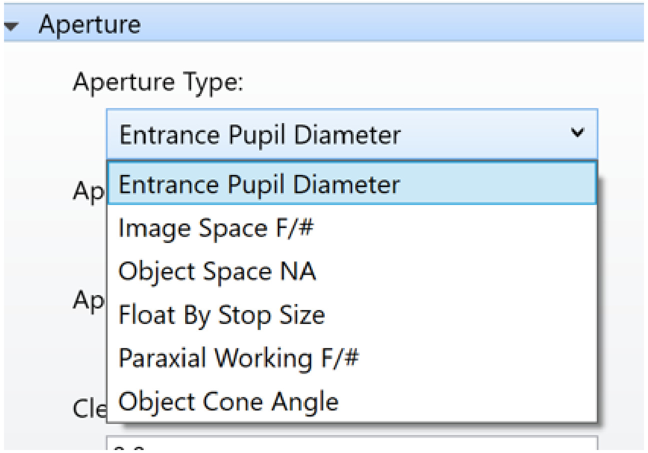
- Field types
  - Angle (object side)
  - Object height
  - Image height

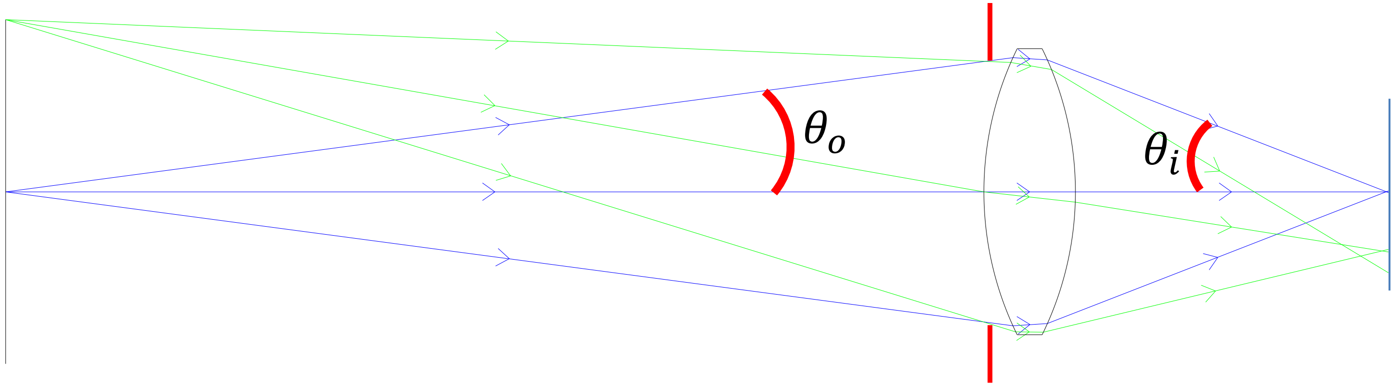




Aperture

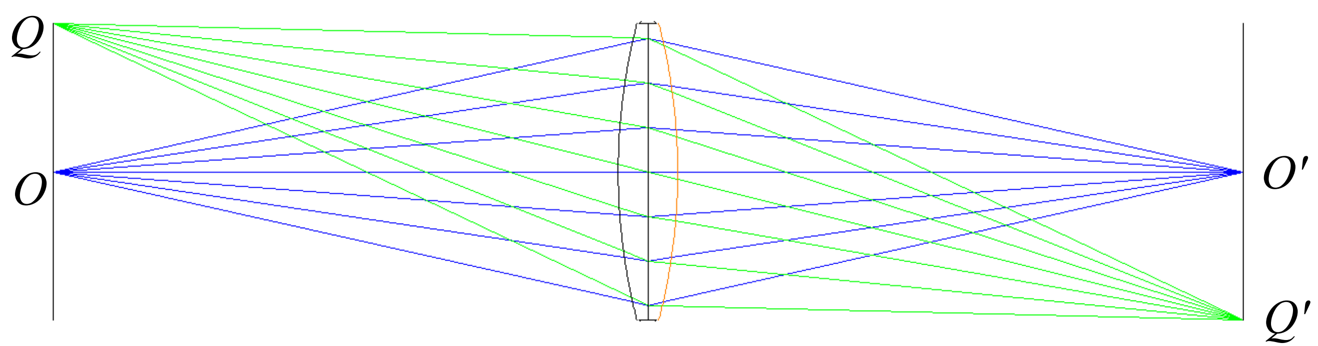
- Entrance pupil diameter
- Objective space NA
  - $NA_o = \mathrm{n} \cdot \sin(\theta_o)$
- Image space F/#
  - $F/\# = \dfrac{1}{2NA_i}$
- Paraxial working F/#
  - $F/\# = \dfrac{1}{2n\tan(\theta_p)}$, θ_p is the paraxial marginal ray angle in image space.
  - The paraxial working F/# is the effective F/# ignoring aberrations.





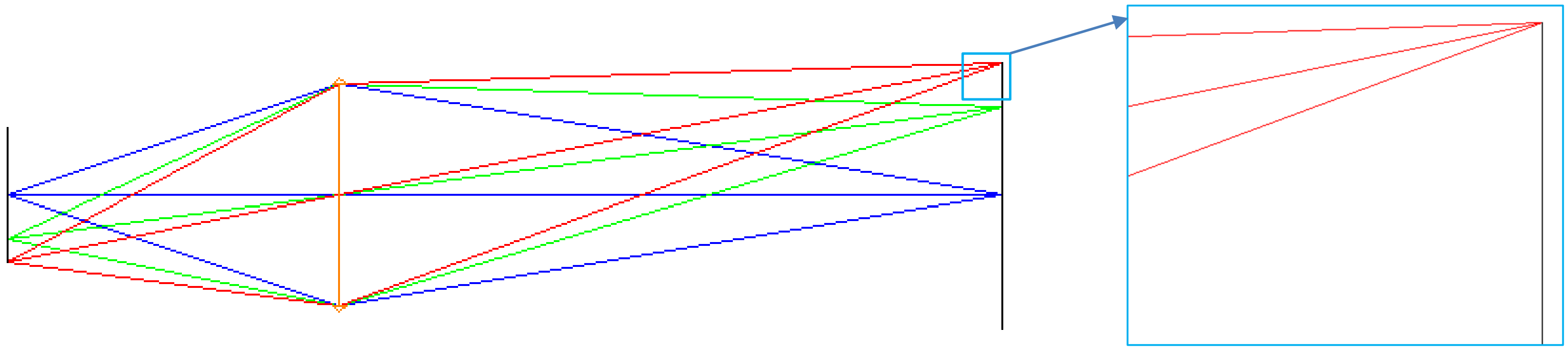
Perfect Geometrical Image

- Three conditions for the lens to form a perfect geometrical image:
  - All the rays from object point after passing through the lens, must go through the image point.
  - Every segment of the object plane normal to the optical axis that contains the point Q must be imaged as a segment of a plane normal to the optical axis, which contains its image Q'.
  - The image height must be a constant multiple of the object height no matter where the object point is located in the object plane
- Violation of the first condition results in the image degradation.
- Violation of the second condition results in the presence of image curvature.
- Violation of the third condition results in image distortion.

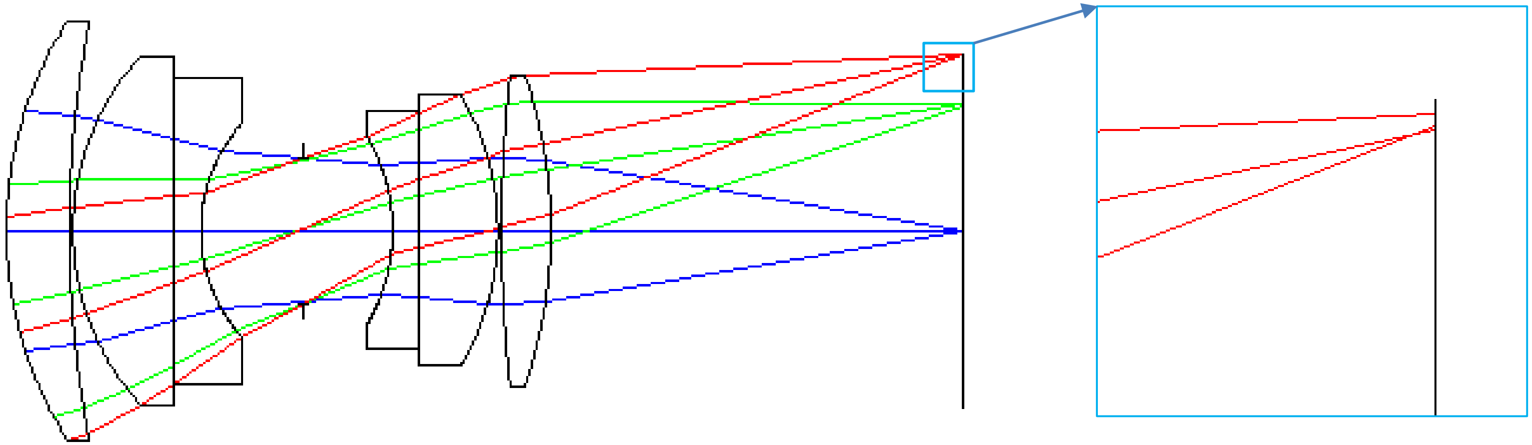


Ideal and Real Systems

Ideal system

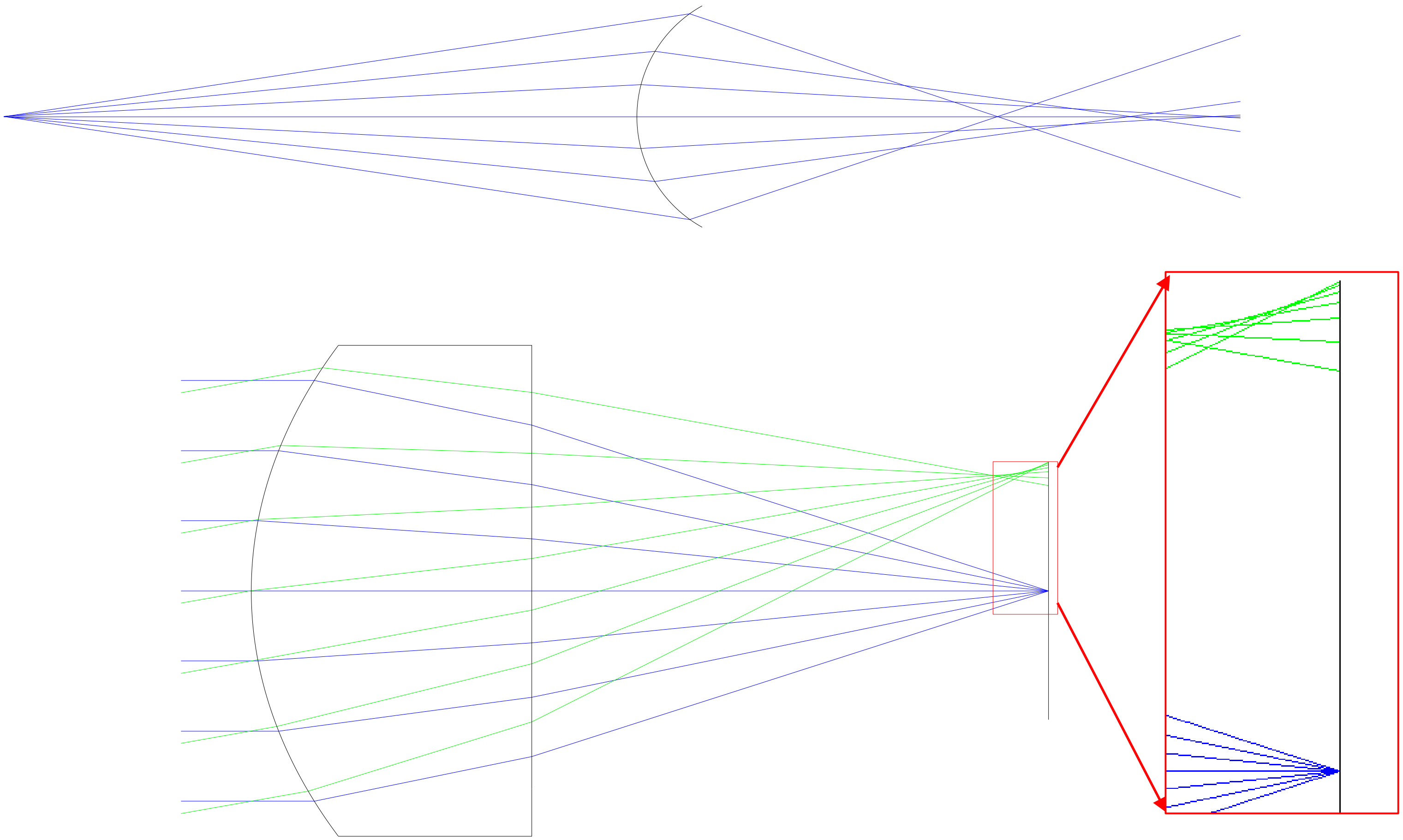


Real system

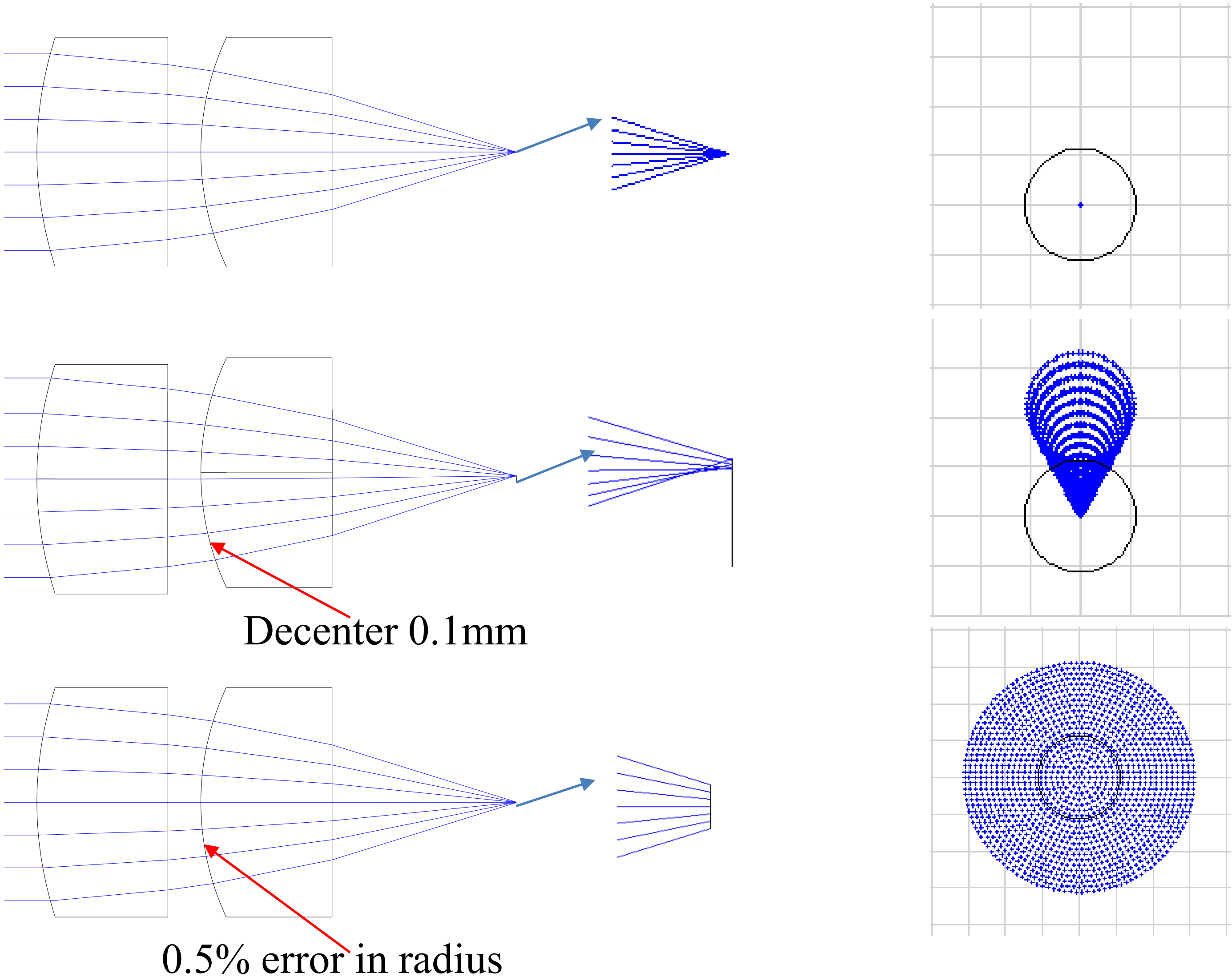


Surface Contribution

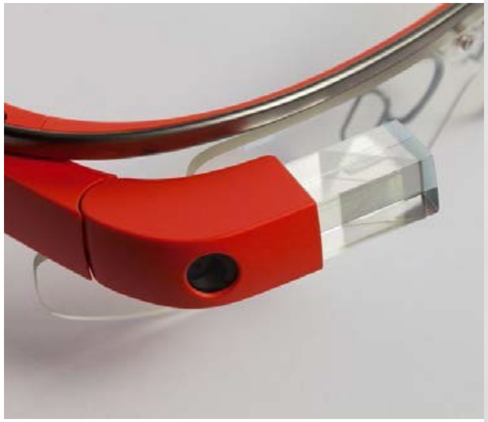
Real Surface

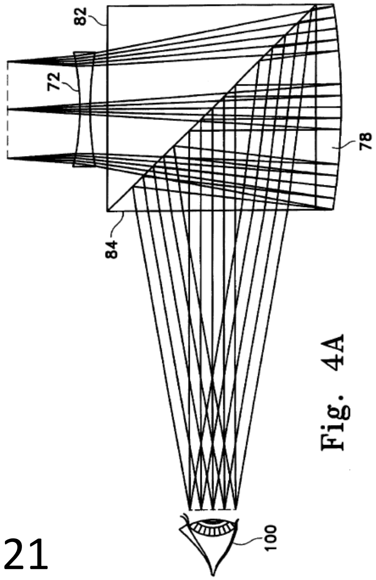


Manufacturing and Assembly Errors



Google Glass





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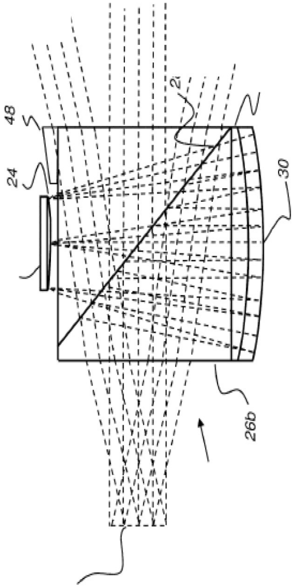
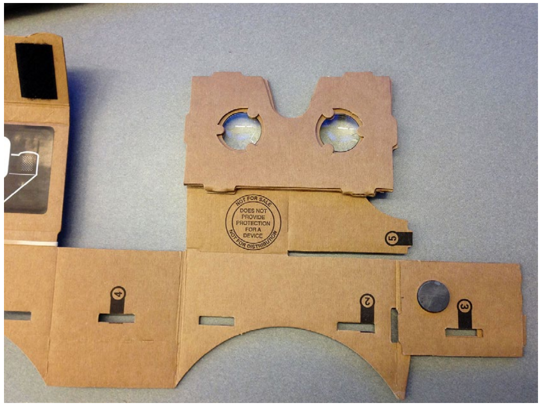
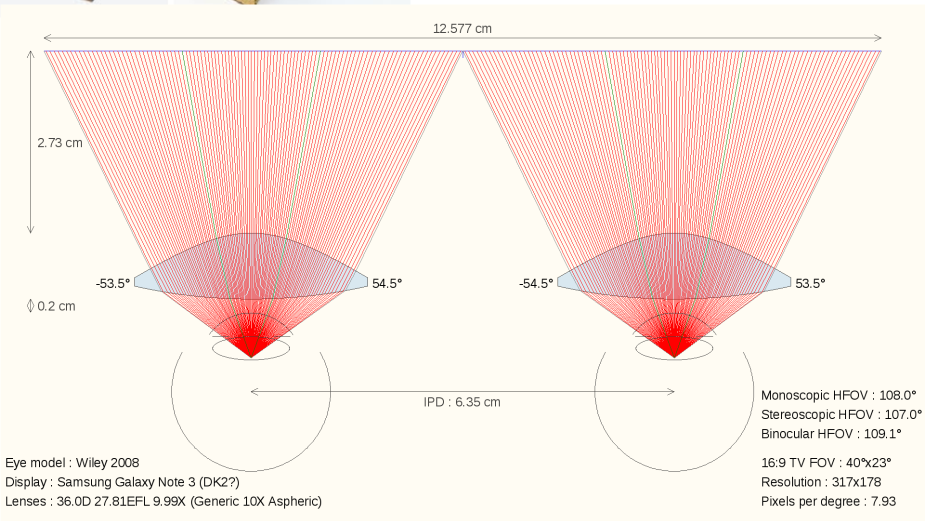


Google Cardboard

WORKS WITH Google Cardboard

Google Cardboard
G.CO/CARDBOARD





http://www.mtbs3d.com/phpBB/viewtopic.php?f=138&t=19923

Zemax

- https://www.youtube.com/user/RadiantZemaxLLC/videos
- https://www.zemax.com/blogs/webinars