OPTI 617 Practical Optical System Design
Lecture 1: Introduction

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College of Optical Sciences

Optical System Design

- Understand applications
- Establish requirement/specification
- System solution
- Lens design
  - Select starting points
  - Optimization
  - Tolerancing
- Design for manufacturing
- Opto-mechanical design
- Stray light analysis
- Prototyping and evaluation

Goals

- Learn fundamentals of optical design.
- Gain experience in designing **practical optical systems** through practice.
- Ready to design real systems.

Schedule

- Class: 3:30 pm - 4:45pm M/W, Room 305
- Office hour (online)
  – Zoom: https://arizona.zoom.us/j/82765543193
  – Time
    • 10:30 am – 11:30pm, Wednesday
    • Phone or Zoom discussion by appointment

Notes and Textbook

- Course notes: will be posted before the date of the class in D2L site
  - Please request the access if you cannot access it.
- Recommended textbook:
  - Handbook of Optical Systems, Vol. I-IV
  - Optical System Design, Robert Fisher

Software

- https://wp.optics.arizona.edu/helpdesk/osc-site-licensed-software/
- Optical design software
  - Zemax
  - CodeV
  - LightTools
  - FRED
  - Optilayer
- Opto-mechanical design software
  - Solidworks
- Zemax webinars
  - https://www.youtube.com/user/RadiantZemaxLLC/videos

Tentative Lectures

- Introduction
- Specification and concepts
- Optical fabrication and design for manufacturing
- Optical materials and color correction
- Lens design
- Optomechanical design
- Stray light analysis
- Microscope
- Confocal imaging systems
- Display
- Telescope
- Photographic system
- Endoscope
- Infrared imaging systems
- Toleracing
- Zoom lens
- MicroLithography (recorded video)
- Freeform surfaces
- Optical coating
- Guest lectures

Please contact me if you have any suggestions on the topics.

Design Homework and Course Project

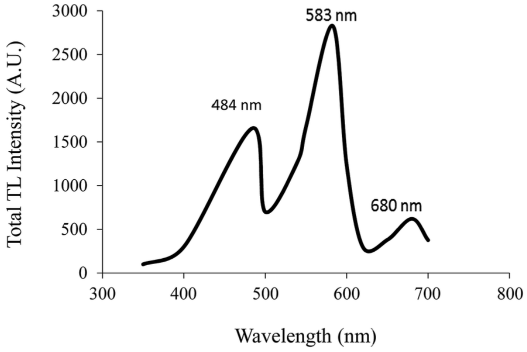
- Homework: one in every 2 weeks
  - ~6 homework (10 points each homework)
  - **Don't wait for the last 1-2 days**
  - What to turn in
    - Report: Word or PPT format
    - Lens files: Zemax or CodeV
  - Submit through D2L site
- One course project (40 points)
- Remote students
  - Allowable delay: one week behind on-campus students
    - The maximum allowable delay is two weeks upon request.
- May discuss some of the students' designs in the class.
  - Will not identify the designers.
  - Students can learn from each other: good designs and lessons to learn

Grading Policy

- Homework
  - Do not just submit Zemax or Codv files (only account for 50% of HW grade).
  - A report is needed to summarize problem, requirement, initial design, final design, performance analysis, and discussion.
- Course project
  - Topic: TBD
  - Need to cover: specification, optical design, tolerancing analysis, simple opto-mechanical design, and stray light analysis.
- Grading scale
  - 85-100%: A
  - 75-85% : B
  - 65-75% : C
  - 50-65% : D
  - < 50% : E

Applications

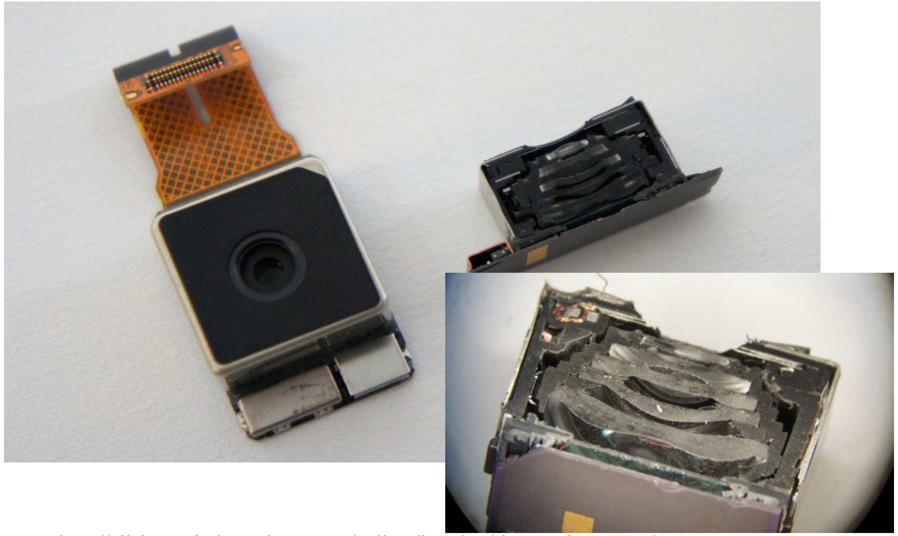
- Working spectrum
  - Spectrum weight
  - Glass selection
  - Light source
  - Detector
- Resolution
  - Numerical aperture (NA)
  - Optical system format
- Field of view and working distance
  - Lens format: single lens, array, scan, etc.
  - Imaging method: area imaging or scanning imaging.
- Environmental requirement
  - Material selection
  - Optomechanical design
- Package
- Evaluation plan
  - Testing requirement



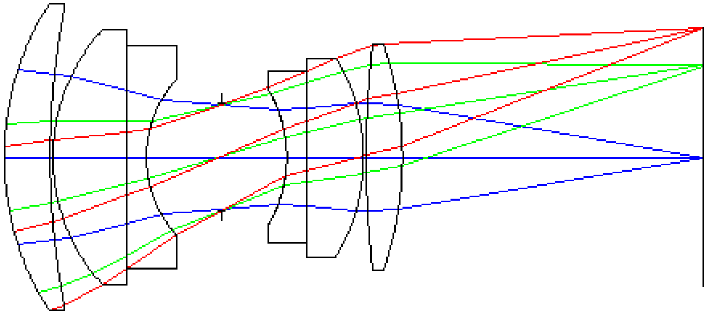
One important step in optical design

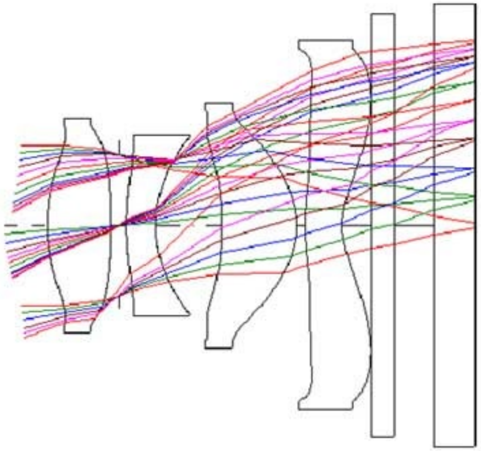
Application: Photography

http://blog.wanken.com/10463/cross-section-view-of-leica-lens/



http://allaboutwindowsphone.com/gallery/item/Nokia_Lumia_1020.php

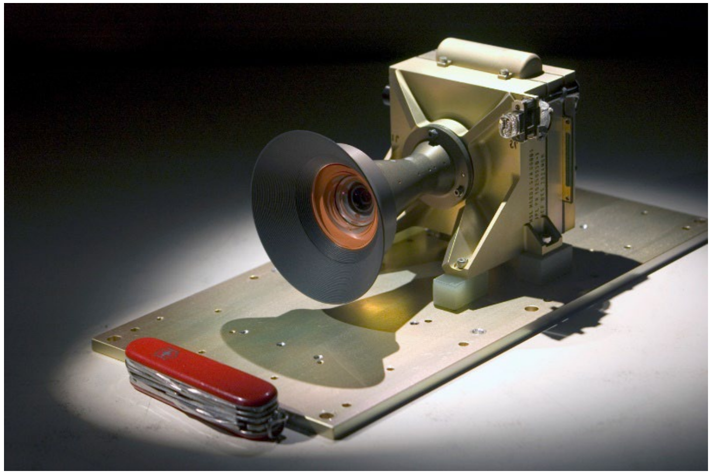




Application: Space Camera

- Spectrum: UV to IR
  - Refractive optical system: Glass selection is challenge
  - Reflective optical system: package and alignment will be difficult
  - Sensor: need to have sufficient quantum efficiency
- Resolution
  - System F/#
  - Sensor
- Field of view
- Environment
  - Radiation
    - Radiation resistant glass
  - Thermal effect
  - Vibration resistant
- Package: as compact as possible
- Evaluation
  - Vacuum environment
  - Vibration testing
  - Thermal testing

MARS DESCENT IMAGER

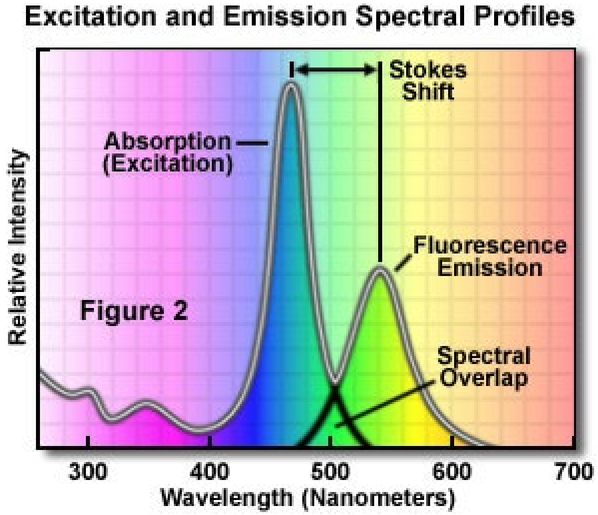


http://www.msss.com/all_projects/msl-mardi.php

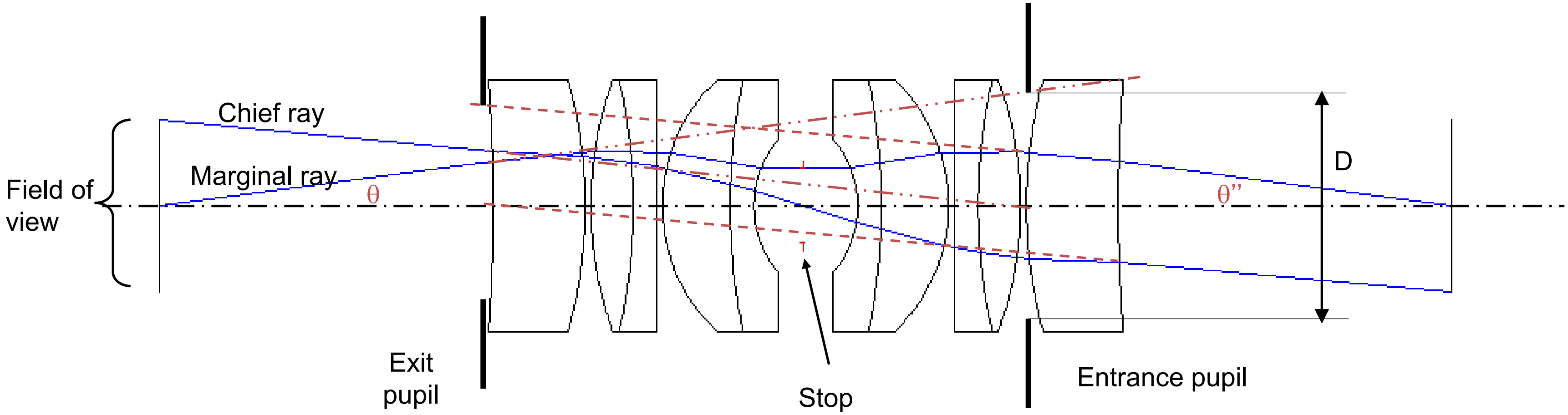
Please read the reading assignment.

Application: Fluorescence Microscope

- Spectrum
  - Excitation spectrum: light source
  - Emission spectrum
    - High sensitive detector
    - Emission filter
  - Material: low autofluorescence glass, high transmission
- Resolution
  - NA
  - Microscope, endoscope, or macro imaging system
- Field of view
  - Area imaging or point scanning
  - Detector: 2D or point detector
  - Imaging speed
- Package: depends on application (clinical or lab)



Typical Optical System



System specifications

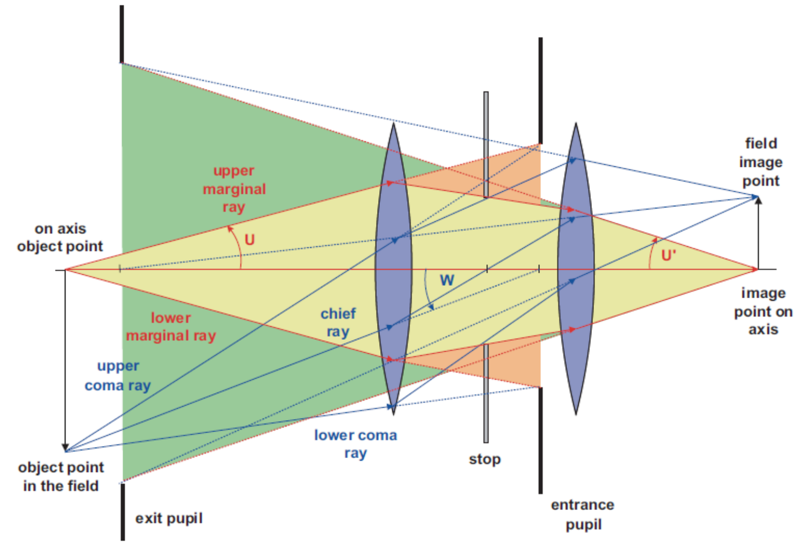
- Relative aperture
- Field of view
- Spectrum range and weights
- Focal length
- Magnification
- Exit pupil (telecentricity)
- Special material
- …

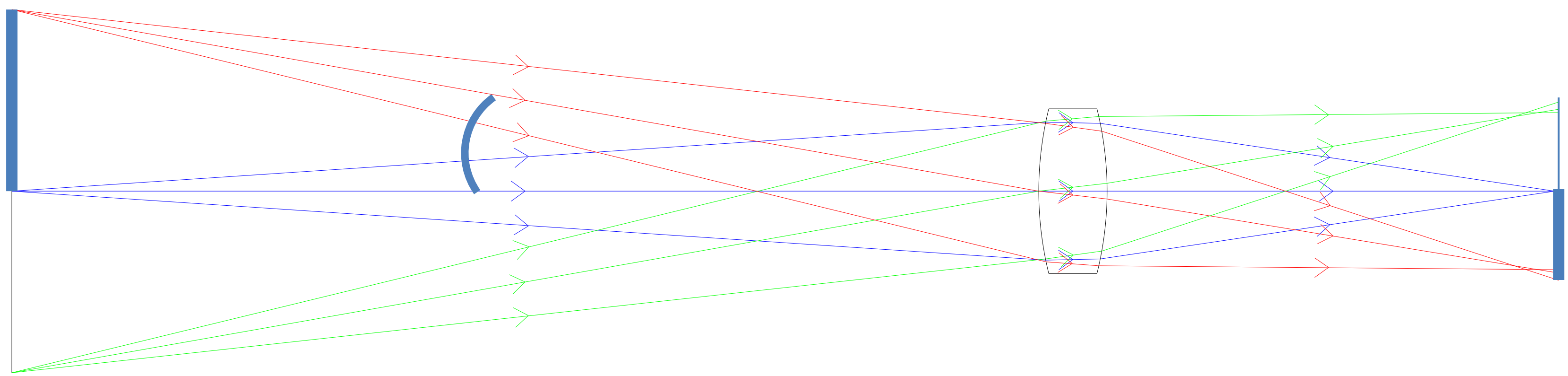
Performance specifications

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

Field of View, Stop, Entrance and Exit Pupils

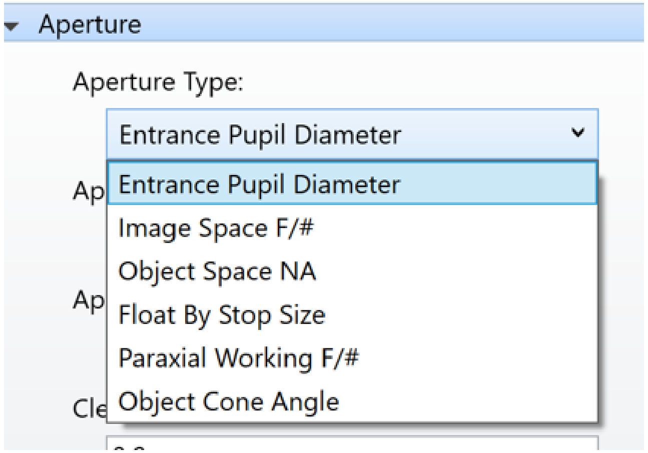
- Field types
  - Angle (object side)
  - Object height
  - Image height
    - Paraxial
    - Real

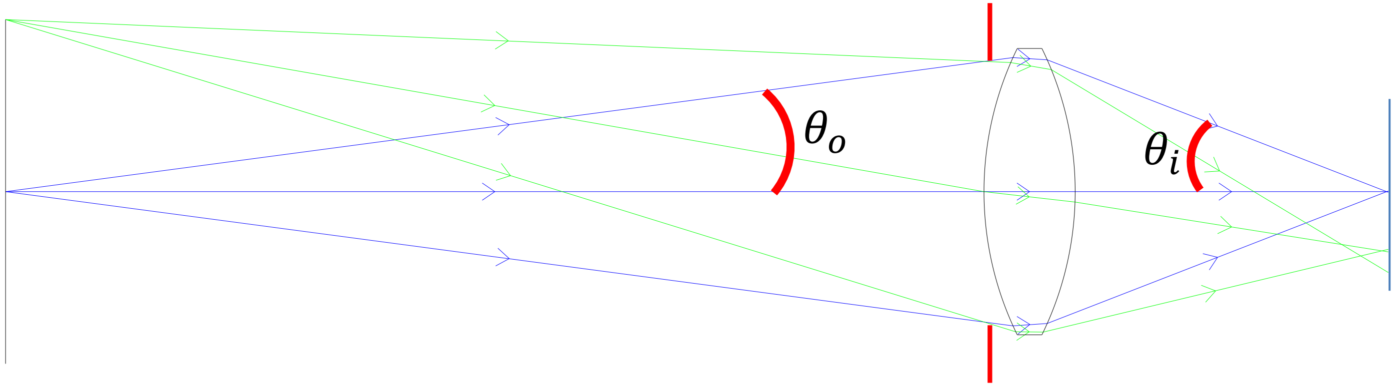




Aperture

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





Telecentricity

- When the aperture stop is at the front/ rear focal plane, the exit/entrance pupil is in infinity.
  – The system is telecentric in the image/object space.
  – The chief ray is parallel to the optical axis.

- The size of the front or back lens must be larger than the object size or the images size.

- Used in optical systems designed for biomedical imaging and inspection systems to increase the coupling efficiency and reduce the measurement error.

Object space telecentric

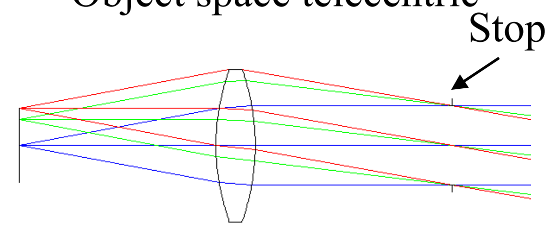
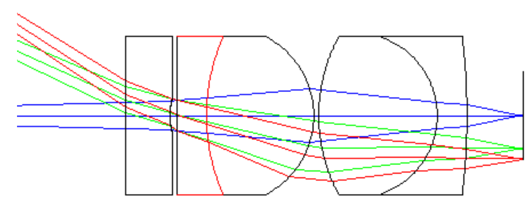
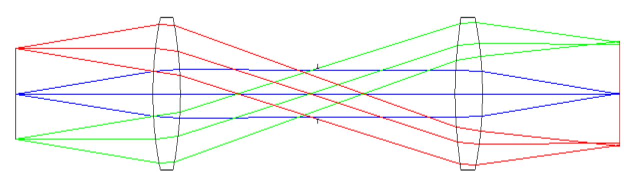


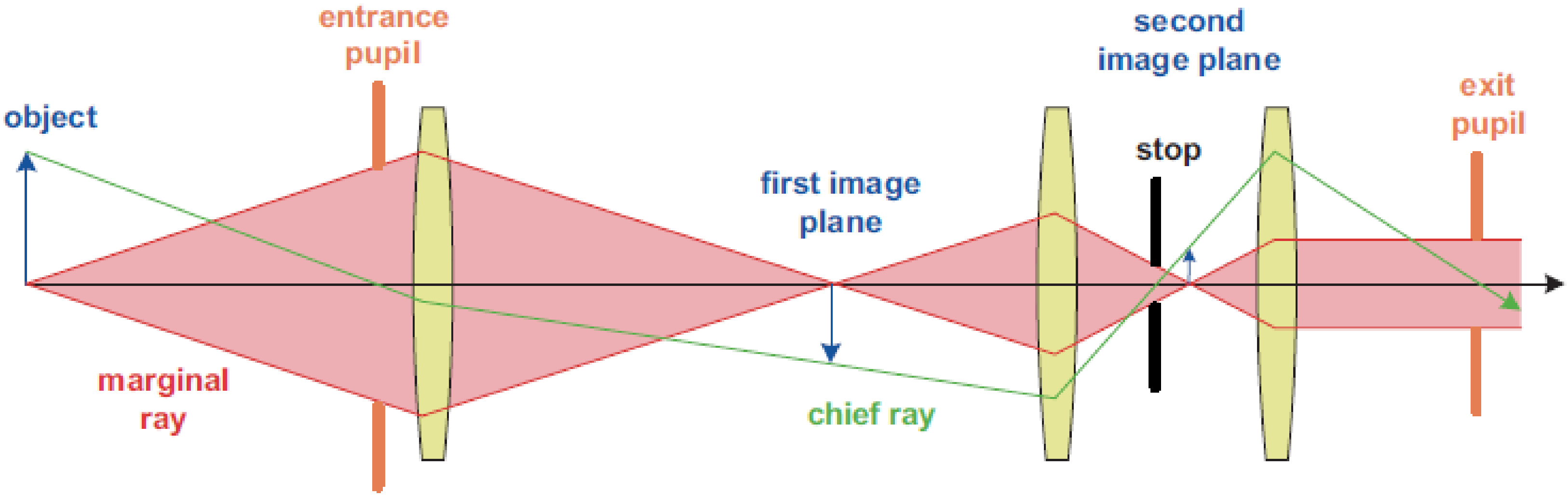
Image space telecentric



Double telecentric



Pupil Matching



Handbook of Optical Systems, Vol. I

Gaussian Parameters

- The Gaussian parameters determine the basic imaging properties of the lens.
  - They are the starting points for setting the specifications for an optical system.
  - In principle these numbers can be specified precisely as desired.
  - In reality, overly tight specifications can greatly increase the cost of the lens.
- There are trade-offs between parameters.
  - The tight specification of magnification and overall conjugate distance will require a very closely held specification upon the focal length. The trade-off between these numbers should be considered to avoid accidentally producing an undue difficulty for the fabricator.
  - It may be appropriate to specify a looser/tighter tolerance on some of these quantities for the prototype lens, and later design a manufacturing process to bring the production values within a tighter/looser tolerance.
  - However, it is appropriate that they are investigated fully at the design stage.

Robert R. Shannon, "Optical Specifications", Handbook of Optics II

System Specifications

- Specifications are usually communicated as a written document following some logical format. Although there are some international standards that may cover the details of drawings of components, there is no established uniform set of standards for stating the specifications on a system or component.
- Each of the specifications must be verifiable during fabrication, and the overall result must be testable after completion.
- The development of system specifications is important both for initiating and for tracking the course of development of an optical instrument.
- In a business or legal sense, specifications are used to establish responsibility for a contractor or subcontractor, as well as to define the basis for bidding on the job. Thus the technical specifications can have business importance as well as engineering significance.

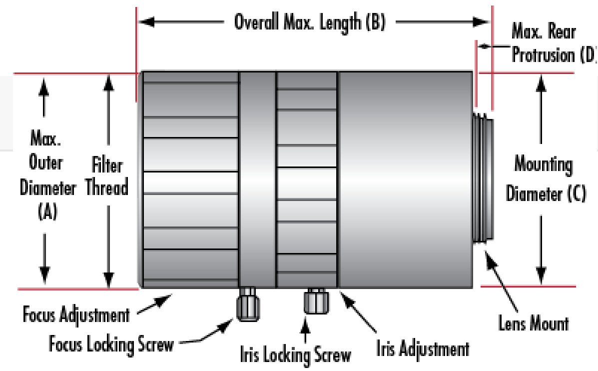
Robert R. Shannon, "Optical Specifications", Handbook of Optics II

Gaussian Parameters

Parameter	Precision target	Importance	How verified
Focal length	1 to 2%	Determines focal position and image size	Lens bench
f-number	$<\pm 5\%$	Determines irradiance at image plane	Geometrical measurement
Field angle	$<\pm 2\%$	Determines extent of image	Lens bench
Magnification	$<\pm 2\%$	Determines overall conjugate distances	Trial setup of lens
Back focus	$\pm 5\%$	Image location	Lens bench
Wavelength range	As needed; set by detector and source	Describes spectral range covered by lens	Image measurement
Transmission	Usually specified as $>0.98^n$ for n surfaces	Total energy through lens	Imaging test, radiometric test of lens
Vignetting	Usually by requiring transmission to drop by less than 20% or so at the edge of the field	Uniformity of irradiance in the image	Imaging test, radiometric test of lens

Robert R. Shannon, "Optical Specifications", Handbook of Optics III

100mm SWIR Fixed Focal Length Lens, C-Mount



Description | Specifications | Accessories | Documents | Resources

Product Family Description

- Designed, Coated, and Tested for SWIR Wavelengths
- Compact, Lightweight, COTS Imaging Lenses
- Low f/# for High Throughput

TECHSPEC® SWIR Series Fixed Focal Length Imaging Lenses are compact, lightweight lenses designed for applications operating in the short-wave infrared (SWIR) spectra, ranging from 0.9 – 1.7μm. These lenses feature SWIR-optimized optical designs, glass types, and AR coatings from 0.8 – 1.8μm. Designed for high throughput and superior performance, the SWIR Series lenses are commercial-off-the shelf (COTS) lenses with low f/#'s, covering large 25mm sensors. TECHSPEC® SWIR Series Fixed Focal Length Lenses are ideal for a range of applications including inspection, sorting, and quality control.

Specifications

Focal Length FL (mm):	100.0	Maximum Camera Sensor Format:	25.6mm (Image Circle)
Field of View @ Max Sensor Format (°):	104.1mm - 14.6°	Aperture (f/#):	f/2.25 - f/22
Working Distance (mm):	400 - ∞	Field of View, 20.5mm Sensor:	83.2mm - 11.7°
Filter Thread:	M72 x 0.75	Flange Distance (mm):	17.526
Length (mm):	180.1	Mount:	C-Mount
Outer Diameter (mm):	84	Weight (g):	1800

https://www.edmundoptics.com/imaging-lenses/fixed-focal-length-lenses/100mm-SWIR-Series-Fixed-Focal-Length-Lens-C-Mount/

Image Quality Criteria

- Performance
  - versus diffraction limit
  - versus field
  - versus wavelength
  - versus F/#
- Resolution
- Modulation transfer function (MTF)
- Encircled/ensquared energy
- RMS wavefront error
- RMS sport size
- Point spread function
- Field curvature
- Distortion
- Coatings
- …

Image Specifications

- The specifications that are applied to the image usually deal with image quality.
  - Examples are modulation transfer function, fraction of scattered light, resolution, or distortion.
- In some cases, these specifications can be quite general, referring to the ability of the lens to deliver an image suitable for a given purpose, such as the identification of serial numbers to be read by an automated scanner.
- In other cases, the requirements will be given in a physically meaningful manner, such as "the MTF will be greater than 40 percent at 50 lines per millimeter throughout the field of view."
- Other criteria may be used for the image specifications.
  - The energy concentration. This approach specifies the concentration of light from a point object on the image surface.
    - For example, the specification might read that "75 percent of the light shall fall within a 25-micrometer-diameter circle on the image."

Robert R. Shannon, "Optical Specifications", Handbook of Optics II

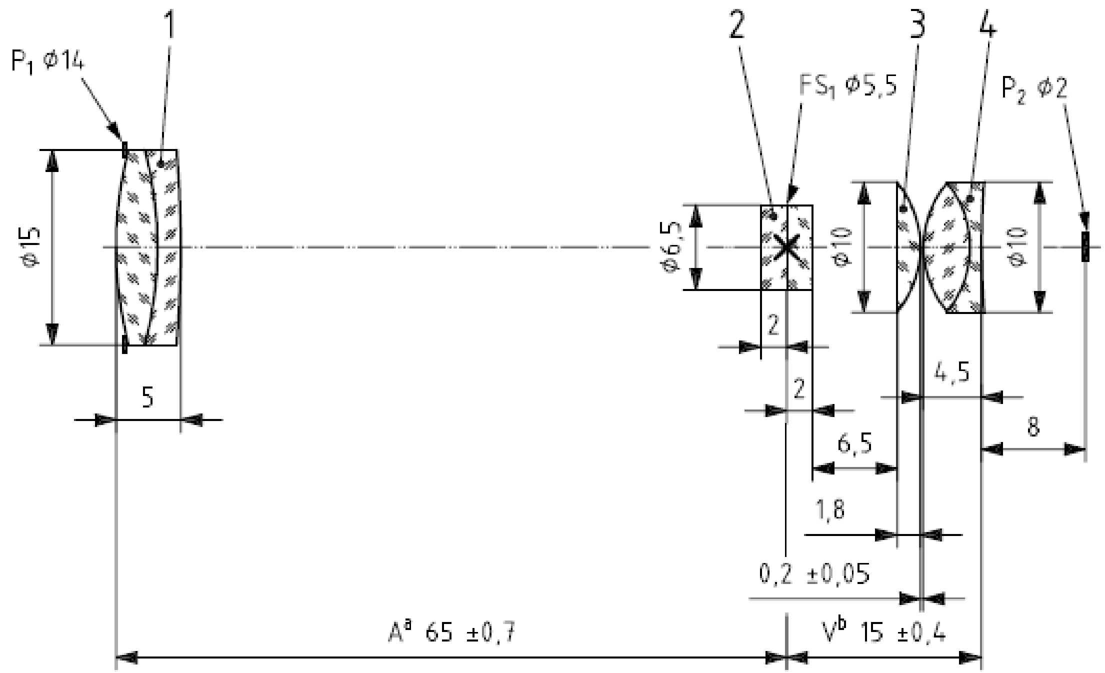
System and Element Specifications

- Some specifications have meaning only with respect to the behavior of the entire optical system.
  - An example is a set of numbers limiting the range of acceptable values of the modulation transfer function (MTF) that are required for the system.
  - Another system specification is the total light transmission of the system.
- Others apply to the individual components, but may affect the ability of the entire system to function.
  - An example is tolerances on surface irregularity, sphericity, and scattering.
  - The related component specification based on the system light transmission specification might provide detailed statements about the nature and properties of the antireflective coatings to be applied to the surface of each element.

Robert R. Shannon, "Optical Specifications", Handbook of Optics II

Ind. acc. ISO 10110

TELESCOPE 7 × 14



[a] Focus adjustment.

[b] Eyepiece focus variation ± 5 m^{-1}.

1 achromatic lens f = 63

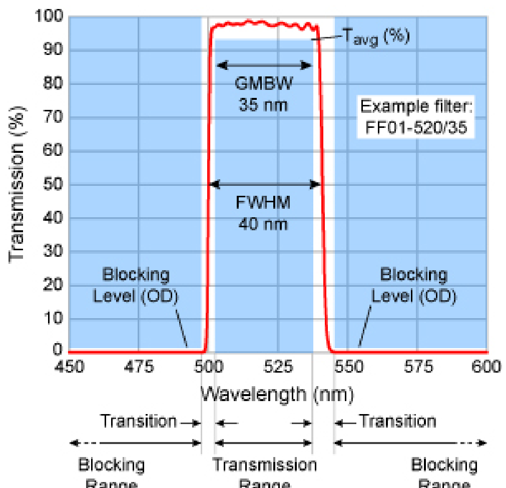
2 reticle, cemented

3 + 4 eyepiece f = 9

	Centring tolerances
1	4 / 5' (0,1)
2	4 / 20' (0,05)
3	4 / 10' (0,05)
4	4 / 10' (0,05)
3 + 4	4 / 30' (0,1)

Element Specification

- Optical parameters
- Material specifications
- Coating specifications
  - The thin film coatings that are applied to the optical surfaces require some careful specification writing.
  - The spectral characteristics need to be spelled out, such as passband and maximum reflectivity for an antireflection coating.
  - Requirements for the environmental stability also need to be described, with reference to tests for film adhesion and durability.

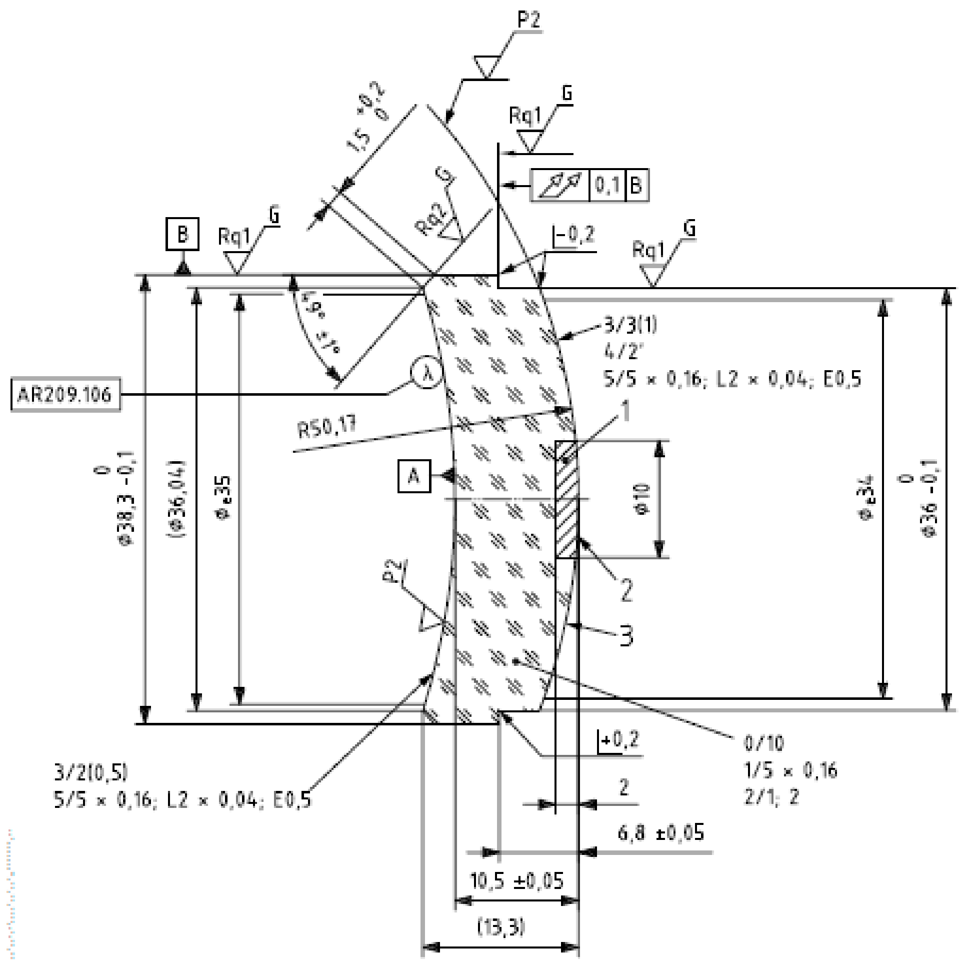


Robert R. Shannon, "Optical Specifications", Handbook of Optics II

Element Specification

- Each element to be fabricated must be described in detail, usually through a drawing.
- All dimensions will require tolerances, or plus and minus values that, if met, lead to a high probability that the specified image quality goals will be met.
- Mechanical specifications
  - The mechanical dimensions are specified to ensure that the element will fit into the cell sufficiently closely that the lens elements are held in alignment. This will be a result of tolerance evaluation, and must include allowances for assembly, thermal changes, and so on.
  - An important item for any lens is the interface specification, which describes the method of mounting the lens to the optical device used with it.
    - For some items, such as cameras and microscopes, there are standard sizes and screw threads that should be used.

Robert R. Shannon, "Optical Specifications", Handbook of Optics II



1 Test volume 1/3 × 0,1

2 Test zone 5/3 × 0,1; L1 × 0,04

3 To be cemented

Material:

Schott N-BK7

n_e = 1,51872 ± 0,001

ν_e = 63,96 ± 0,5 %

Protective chamfers: 0 - 0,2

Environmental Specifications

- Temperature and humidity
  - Specification setting should also include a description of the temperature range that will be experienced in use or storage.
  - This greatly affects the choice of materials that can be used.
- Shock and vibration
  - The ruggedness of an instrument is determined by the extent to which it survives bad handling.
  - The lens shall survive some specified drop test. In other cases, stating the audio frequency power spectrum that is likely to be encountered by the lens is a method of specifying ruggedness in environments such as spacecraft and aircraft.
  - In some cases, the delivery and storage environment is far more stressing than the usage environment.
  - Any specification should be careful to state the limits under which the instrument is actually supposed to operate, and the range over which it is merely meant to survive storage.

Robert R. Shannon, “Optical Specifications”, Handbook of Optics II

Packaging and Environment

- Packaging
  - Object to image total track
  - Entrance and exit pupil location and size
  - Back focal distance
  - Maximum diameter
  - Maximum length
  - Ergonomics
  - Weight
  - Size and packaging constraints
- Environment
  - Thermal soak range to perform over
  - Thermal soak range to survive over
  - Athermalization
  - Vibration
  - Shock
  - Other (condensation, humidity, sealing, etc.)

Others

- Illumination
  - Source type
  - Power
- Radiometry issues
  - Relative illumination
  - Illumination method
  - Illumination profile
  - Transmission
  - Veiling glare and ghost images
  - Stray light attenuation
- Schedule and cost
  - Number of systems required
  - Initial delivery date
  - Target cost goal
- Intellectual property

Presentation of Specifications

- The format used in conveying specifications for an optical system is sometimes constrained by the governmental or industrial policy. There is no specific format for expressing the specifications.
- What the specifications should include
  - The goals for the use of the instrument being specified.
  - The most important optical parameters, such as focal length, F-number and field size (object and image) should be stated. In some cases, magnification and overall object-to-image distance along with object dimension will be the defining quantities.
  - The wavelength range, detector specifications, and a statement regarding the required image quality should be given.

Robert R. Shannon, "Optical Specifications", Handbook of Optics II

Presentation of Specifications

- What the specifications should include (Cont.)
  - The transmission of the lens is also important.
  - The mechanical and environmental requirements should be stated.
  - The temperature and humidity relations under which the optical system needs to operate as well as a statement of storage environment are needed.
  - Descriptions of the mechanical environment, such as shock and vibration, are also important, even if expressed generally.
  - Any special conditions, such as the need to be exposed to rapid temperature changes or a radiation environment, should be clearly stated.
  - Some statement of the finish quality for the optical system should be given.

Robert R. Shannon, "Optical Specifications", Handbook of Optics II

Problems with Specifications

- Under-specification
  - Failure to specify all of the conditions leaves the user vulnerable to having an instrument that will not operate properly in the real world.
  - In many cases, the designer may not be aware of situations that may arise in operation that may affect the proper choice of solutions. Therefore, the design may not meet the actual needs.
- Over-specification
  - Over-specification would seem to ensure that the needs will be met, but difficulties in meeting these requirements can lead to designs that are difficult and expensive to build.
  - Too-tight specifications upon such items as weight, space, and materials can force the design engineer into a corner where a less desirable solution is achieved.
- Boundary-limit specification
  - In most cases, the statement of goals or boundaries within which a lens must operate is better than stating specific values. This leaves the designer with some room to maneuver to find an economic solution to the design.
  - Obviously, some fixed values are needed, such as focal length, *F*-number, and field angle.

Robert R. Shannon, "Optical Specifications", Handbook of Optics III

Establish Design Specifications

- Before beginning the actual lens design work on a project, we need to nail down as many specifications as possible.
  - The specifications are often prepared by someone who is not knowledgeable in optics or optical design.
  - The designer must convert the system specifications into terms meaningful in optics, and should also be sure that the reality of fabrication tolerances is taken into account.
- An important part of defining a specification is to determine which specifications are minimums, which are really just goals on someone's wish list, and which have some wiggle room, and if so, how much.
  - Which ones are those that define what the customer really wants and needs?
  - Identifying areas where the specifications could be altered with benefit to all parties is an important business and engineering responsibility.
- It always pays to question 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 expected state of the fabrication technology?

Phases of the Design Process

- Conceptual Phase
  - Determine the basic system requirements based upon customer needs
  - Identify design/system tradeoffs
- Feasibility Phase
  - Identify the preferred configuration (# elements, etc.)
  - Rough estimate of the tolerance sensitivity
  - System layout
  - Mechanical/system interfaces
- Design Phase
- Final Phase
  - Match design to manufacturing tolerances
  - Final prescription
  - Mechanical/mounting design
  - Test plan
- Fabrication Support

Example

1.1 Application

This lens is to work as a rear mobile depth camera. As a depth camera, it is used to calculate the distance to the world of the different objects that appear in the conventional 2D image. The depth measurement capabilities of this lens are considerably affected by some key optical parameters like the focal length or the f number. Big focal lengths and fast lenses lead to better depth estimations. At the same time, the performance of this lens is affected by the pupil aberrations, which we are interested in correcting as much as possible.

2.0 Reference Information

2.1 Applicable Documents

Number	Document

Table 1. Reference Documents List

3.0 Design Specifications

3.1 General design optical parameters

Parameters	Values	Unit	Comments
Pixel Size	1.1	µm	Ny = 454 cy/mm
F-Number	2.8		Cutoff frequency = 700 cy/mm
Focal length	8.0	mm	
Working Distance	0.6	Mm	From last optical lens to the sensor (including IR filter)
Max Image circle diameter	4	mm	
Max chief ray angle	< 33	degrees	
Relative illumination at 100% IH	> 40	%	Including some vignetting if needed.
Optical distortion	< 1.5	%	
Axial chromatic focal shift	-	µm	Diffraction limited or near
Lateral chromatic shift	-	µm	Diffraction limited or near
Pupil spherical aberration	TBD		
Pupil coma aberration	TBD		
Pupil astigmatism and FC	TBD		
Field curvature separations from on-axis through-focus MTF peak	< 15	µm	
Object distance range	Inf-150	mm	*Need to confirm hyperfocal
Hyperfocal distance	300	mm	*How do we define the CCM?
IR filter thickness	110	µm	

Table 2. Design Optical Parameters

- The aperture stop shall be located as a first optical element or between the first and second lens elements.

3.2 Mechanical Design Requirements

The main mechanical design parameters relevant to optical design are listed in the Table below.

Parameters	Value	Unit	Comments
Nominal mechanical total track length (MTTL) for the entire lens	≤7.5	mm	

Jose Sasian

barrel and lens elements to image plane			
Lens barrel diameter	8	mm	For object side
Lens weight (whole module)	TBD	g	

Table 3. Design Mechanical Parameters

3.4 Design Modulation Transfer Function (MTF) requirements

3.4.1 Wavelength Weighting

The following table defines the wavelength weighting for MTF specifications and testing of the lens.

Wavelength (nm)	Weighting
465	91
510	503
555	1000
610	503
650	107

Table 5. Wavelength Weighting Table

The above weights are to be used for lens design optimization, design performance evaluation and manufacture testing.

3.4.2 Design MTF requirements for the lens

MTF for a perfectly built lens, minimum of sagittal and tangential, performance corner to corner. For Zemax calculation, one should use real ray aiming.

Field Height (%) in terms of Max Image Circle	Min MTF @ 227cys/mm (Ny/2) (minimum of sagittal and tangential)
0	0.50
100	0.30

Table 6. MTF Design Specification

3.5 Materials

This lens is intended to be designed fully in plastic, but we may consider the inclusion of a first glass element if performance cannot be achieved with plastic. We firstly consider the use of two materials but may be three if required.

Recommended materials are:

- E48R (n = 1.53, Vd = 56.04)
- OKP4HT (n = 1.63, Vd = 23.34)

- D263 (for the IR filter)
- Other plastics used in the industry of mobile phone telephony
- Other materials from Zeonex
- A first glass lens to be consider if the optical design requires it

Reading Material

- Ghaemi, F. T. (2009). Design and fabrication of lenses for the color science cameras aboard the Mars Science Laboratory rover. *Optical Engineering*, *48*(10), 103002.