OPTI 617 Practical Optical System Design
Lecture 1: Introduction

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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](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:
  - Optical System Design, Robert Fisher
Software

- [https://wp.optics.arizona.edu/helpdesk/osc-site-licensed-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](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://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


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

Chief ray
Marginal ray
Exit pupil
Stop
Entrance pupil
D
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
  \[ NA_o = n \cdot \sin(\theta_o) \]
- Image space F/#
  \[ F/# = \frac{1}{2NA_i} \]
- Paraxial working F/#
  \[ F/# = \frac{1}{2ntan(\theta_p)}, \theta_p \text{ is the paraxial marginal ray angle in image space.} \]
  - 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.
Pupil Matching

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.

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.

# Gaussian Parameters

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

### 100mm SWIR Fixed Focal Length Lens, C-Mount

#### 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

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

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
- ...

OPTI617  Ron Liang
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.”
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.
TELESCOPE 7 x 14

1. Focus adjustment.  
2. Eyepiece focus variation ± 5 m⁻¹.  
3. Achromatic lens $f = 63$  
4. Reticle, cemented  
5. Eyepiece $f = 9$

Centring tolerances:

<table>
<thead>
<tr>
<th></th>
<th>Centring tolerances</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4 / 5' (0,1)</td>
</tr>
<tr>
<td>2</td>
<td>4 / 20' (0,05)</td>
</tr>
<tr>
<td>3</td>
<td>4 / 10' (0,05)</td>
</tr>
<tr>
<td>4</td>
<td>4 / 10' (0,05)</td>
</tr>
<tr>
<td>3+4</td>
<td>4 / 30' (0,1)</td>
</tr>
</tbody>
</table>
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.

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.

Material:
Schott N-BK7
$n_e = 1.51872 \pm 0.001$
$v_e = 63.96 \pm 0.5\%$

1. Test volume $1/3 \times 0.1$
2. Test zone $5/3 \times 0.1; L1 \times 0.04$
3. To be cemented

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.

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**
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.
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.
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.

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**
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

<table>
<thead>
<tr>
<th>Number</th>
<th>Document</th>
</tr>
</thead>
</table>

Table 1. Reference Documents List

3.0 Design Specifications
3.1 General design optical parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
<th>Unit</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel Size</td>
<td>1.1</td>
<td>μm</td>
<td>( N_A = 45/4 ) cy/mm</td>
</tr>
<tr>
<td>F-Number</td>
<td>2.8</td>
<td></td>
<td>Cutoff frequency = 700 cy/mm</td>
</tr>
<tr>
<td>Focal length</td>
<td>8.0</td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td>Working Distance</td>
<td>0.6</td>
<td>mm</td>
<td>From last optical lens to the sensor (including IR filter)</td>
</tr>
<tr>
<td>Max Image circle diameter</td>
<td>4</td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td>Max chief ray angle</td>
<td>&lt; 30</td>
<td>degrees</td>
<td></td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Unit</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal mechanical total track length (MITL) for the entire lens</td>
<td>≤ 7.5</td>
<td>mm</td>
<td></td>
</tr>
</tbody>
</table>

Jose Sasian
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.

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Weighting</th>
</tr>
</thead>
<tbody>
<tr>
<td>455</td>
<td>91</td>
</tr>
<tr>
<td>510</td>
<td>503</td>
</tr>
<tr>
<td>555</td>
<td>1000</td>
</tr>
<tr>
<td>610</td>
<td>503</td>
</tr>
<tr>
<td>660</td>
<td>107</td>
</tr>
</tbody>
</table>

Table 5: Wavelength Weighting Table

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.

<table>
<thead>
<tr>
<th>Field Height (%) in terms of Max Image Circle</th>
<th>Min. MTF (225cy/mm) (min. sagittal and tangential)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.50</td>
</tr>
<tr>
<td>100</td>
<td>0.30</td>
</tr>
</tbody>
</table>

Table 6: MTF Design Specifications

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:

- E408R (n = 1.53, Vd = 56.04)
- OKP4HT (n = 1.53, Vd = 23.34)

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

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