Designing Optical Systems

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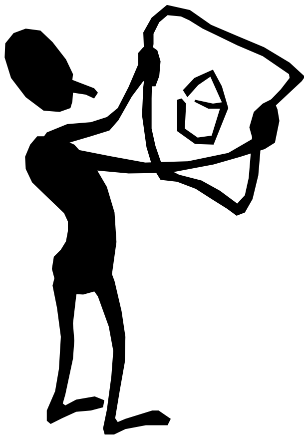
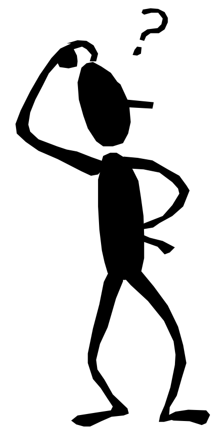
Opti 517



Where Do I Start?



- You've been given an assignment to design an optical system
- How do you pick your starting point?
  - For visible lens designs, several books give good starting points
    - Warren Smith — Modern Lens Design
    - Milton Laikin — Lens Design
    - Rudolf Kingslake — The History of the Photographic Lens
- Patents are also a good source
  - Lens View® is a program with over 10,000 patents
  - Be careful in using designs based on current patents so as to avoid patent infringement issues
- Hopefully, a company has files of its previous designs

- By far, the most important source of starting points is experience and knowledge of design forms and aberration theory

General Approach

Å Start with the requirements for the system

  ï At the start they will probably be incomplete, but will give you enough guidance to start

  ï If you haven't got a complete set of requirements by the time the design is finished, your design may be wrong or useless

Å Analyze the optical system needs and define any subsystem modules that can meet the needs

  ï Trade off subsystem parameters to make them more practicable

Å Use lens starting point resources to survey what forms may be appropriate to your application

  ï Good research on prior art avoids reinventing the wheel or justifies the need for a new concept

  ï Classical solutions are often a good stepping stone to new problems (e.g., double Gauss, Petzval, telephoto, etc.)

Optical System Requirements

- Before you complete the design of an opto-mechanical system, you need a complete set of optical and mechanical requirements
  - These are almost always incomplete at the start of a design job
  - They MUST be complete before the detailed design is completed
- It is IMPERATIVE that the optical and mechanical engineers communicate with each other and with the system engineers all the rules that will shape the final opto-mechanical design
  - At some point the electrical engineers and software engineers may get involved as the optical performance (MTF, ensquared energy, etc.) can affect the signal levels and signal processing
  - Also, manufacturing engineers should be involved to define and optimize the process of building the system in production
- Do not forget to include stray light analyses in the design process also!

Design Requirements (1)

Parameter	Goal/Specification
1. Configuration	Source (target) Optics Detector
2. Field of view	Object space Image space
3. f/number or Magnification	Image space Finite conjugates
4. Effective focal length	Value and tolerance
5. Back focal length	Value and tolerance
6. Spectral range	Band limits Spectral weighting
7. Image quality metric	MTF, RMS WFE, RMS spot size, etc.
8. Distortion %	Relative to chief ray or centroid
9. Vignetting or rel. illum.	% over the FOV
10. Transmittance	Need to specify coating assumptions

Design Requirements (2)

Parameter	Goal/Specification
11. Physical constraints	Overall length Maximum element size Min/max object/image, pupil clearance Weight Glass types allowed Surface types allowed (e.g., aspheres) Number of elements
12. Detector parameters	Array size Pixel size
13. Windows and filters	Location Material Thickness Incidence angle constraints
14. Ghost image/stray light	Signal-to-noise ratio Immunity to off-axis glints AR coatings Use of diffractives

Design Requirements (3)

Parameter	Goal/Specification
15. Fabrication and assembly tolerance limits	Index, V-number, homogeneity, radii, thickness, wedge, air spaces, element tilt and decentration
16. Assembly compensators	e.g., detector focus (and any limits)
17. Environmental	Temperature range, humidity Altitude, pressure Vibration, shock
18. Cost	Prototype cost Unit production cost
19. Project schedule	May limit types of designs or special surfaces or materials
20. Availability of potential suppliers	Are the suppliers you are planning to use available in the time frame? Do they work with the materials selected? Can they hold the tolerances to the required limits?
21. Provide for manufacturing process	Don't assume that because you can design it, it can be built in a cost-effective manner!

Design Phases

Design Phase	Primary Contact	Requirements
Feasibility, conceptual	System engineer Liberal use of goals	Many items are ranges
Preliminary	Mechanical, packaging interface to balance stress before committing	Many items are goals Items added from Phase 1
Final	Fabricator (tolerances) Highlight areas where the design falls short	No goals remain

Often a fourth phase (fabrication support) is added where alignment plans or subassembly tests are developed

Example – Optical System Requirements

- Need a lens for a 35 mm camera (format is 36 mm x 24 mm)
- Goal is an image blur which is not discernible by the eye on an 8 x 10 inch print viewed from 10 inches
- Eye resolves about 1 arc minute (~ 0.3 mrad)
  - Corresponds to 0.003 inch at 10 inches
- A 35 mm film negative is 7.06 times smaller than the print (10 inch/36 mm)
  - Image goal is 0.003/7.06 = 0.00042 inch diameter blur on the film
  - Airy disk diameter for an f/2 lens is about 0.0001 inch, so the lens does not need to be diffraction-limited (i.e., can tolerate some aberrations)
- Since the eye barely distinguishes brightness levels within a factor of 2, the lens can have up to 50% vignetting at the corners of the FOV
- The lens focal length depends on the FOV you want the print to cover
  - For example, for the width of the film to cover 40°, the focal length would be 18 mm/tan(20°) å 50 mm
  - To cover 52° (10 inches wide at 10 inches distance), a 35 mm focal length would be needed
- There would also be requirements for MTF, distortion, mechanical constraints, etc.

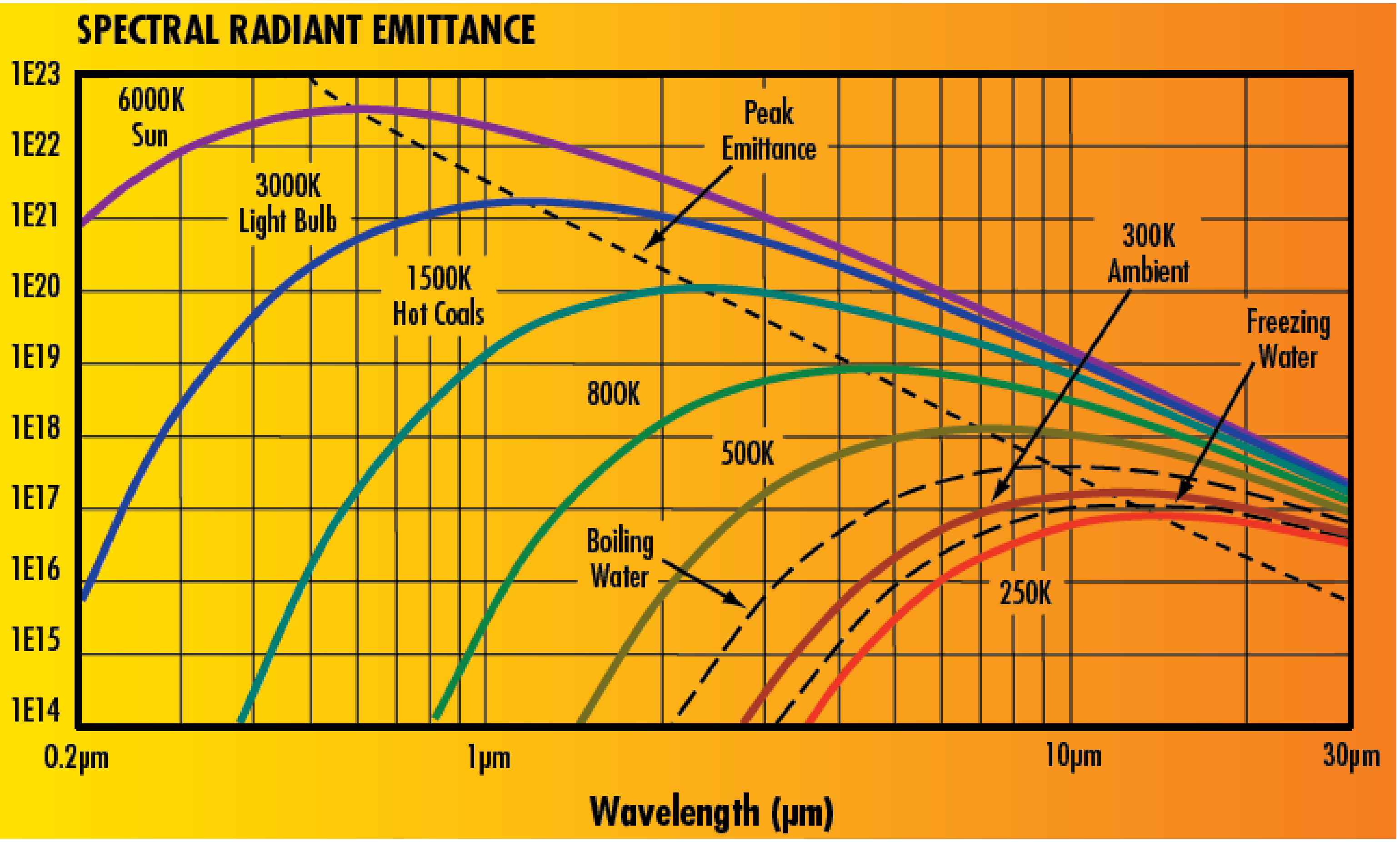
The Complete Optical System

- A complete optical system comprises the following
  - The object being imaged
  - The atmosphere between the object and the optical system
  - The optical elements
  - A detector
- For our purposes, the first two (object and atmosphere) along with the detector mainly affect the spectral weighting of the system
  - Other than that, we will not consider them much in this class
- We will also not dwell too much on the detector except for its role in defining the system resolution
  - Although, surprisingly enough, often you start with the detector

Spectral Weighting

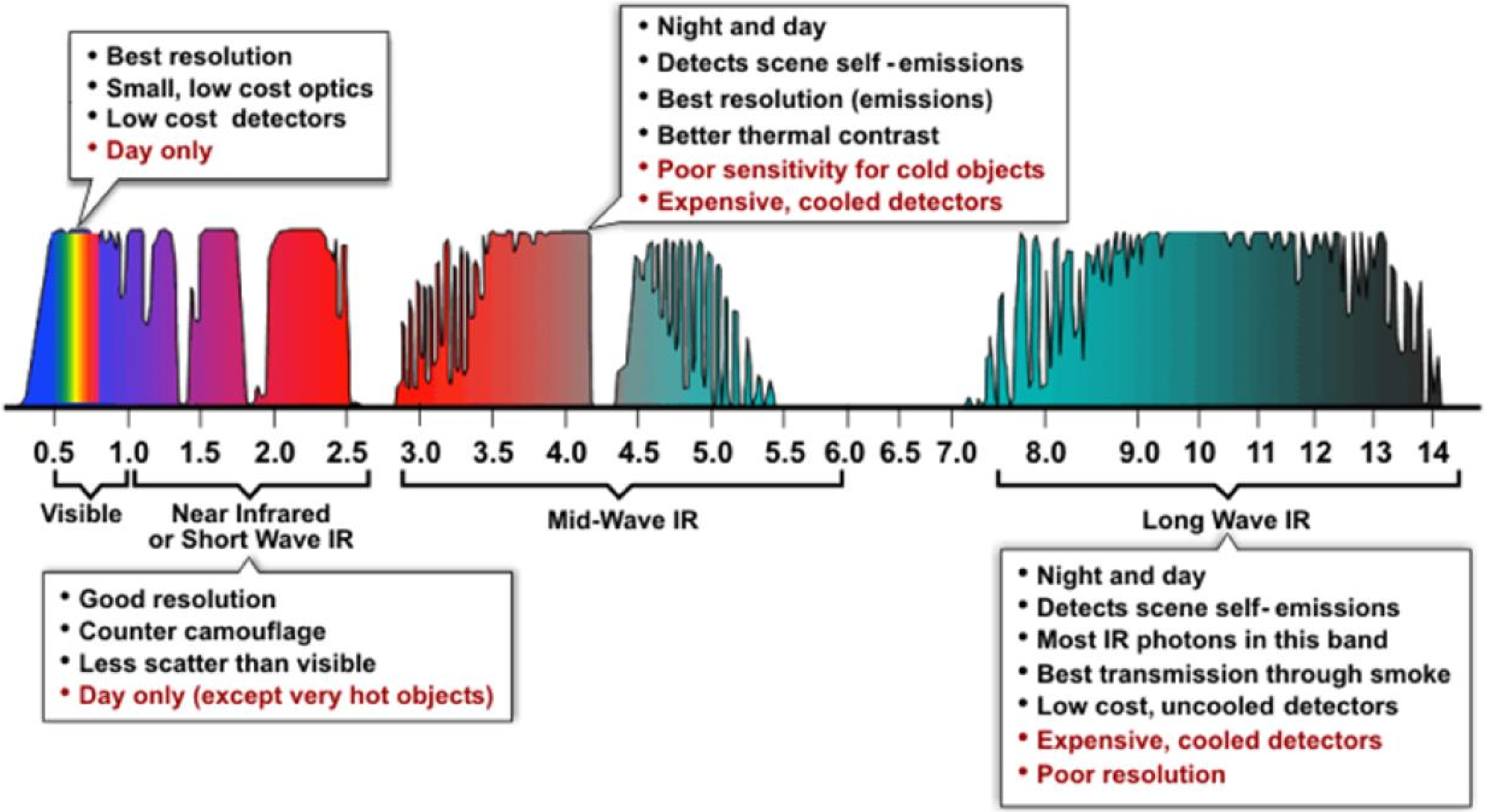
- There are several contributions to the overall spectral weighting of an optical system
  - The target spectral characteristics (blackbody, laser lines, etc.)
  - The atmosphere (function of range, rain, absorbing gases, etc.)
  - Optical element transmittance (coatings, material absorptance)
  - Detector spectral response (including any filters)
- The spectral weighting is important since it can drive many optical considerations
  - Types of optical materials needed (or allowed)
  - Need to color correct
  - Can force special antireflection coatings

Blackbody Radiation (1)



Curve for a given object temperature peaks at λ_p = 2898/T (T in Kelvin)

Atmospheric Transmittance (1)

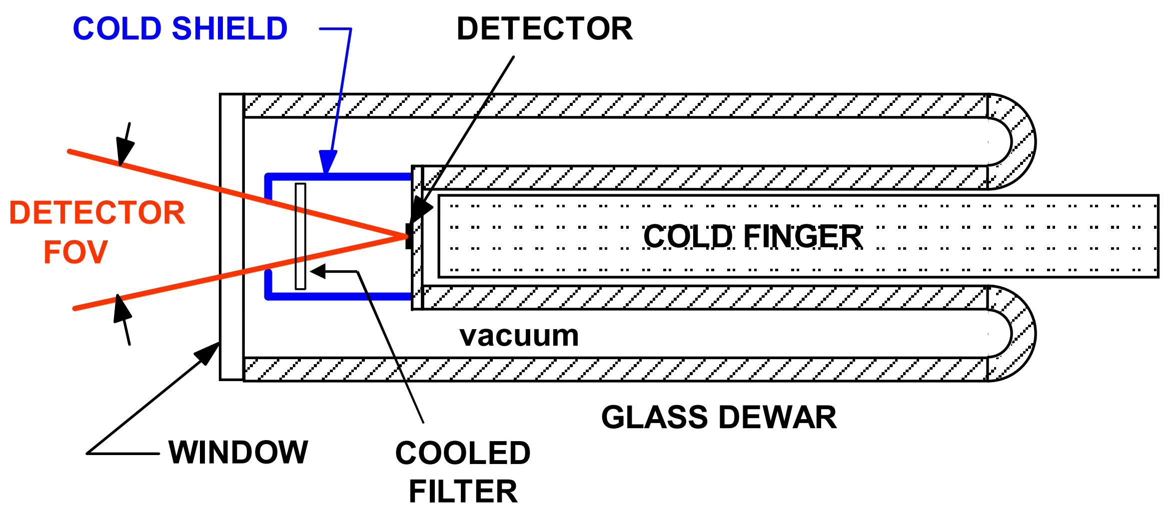


Spectral Filters

- Detectors can usually detect wavelengths outside the spectral band of interest
  - These extraneous wavelengths do not contribute to the signal, but contribute to the background noise, reducing the SNR
- One solution to this is to use a spectral filter
  - The filter is bandpass-limited to only transmit the wavelengths of interest and reflects the wavelengths outside the band
- One limitation is that in IR systems the filter itself emits thermal radiation which adds to the background flux
  - If the filter is cooled, its blackbody self-emission is orders of magnitude less than that of the background and does not contribute significantly to the background noise

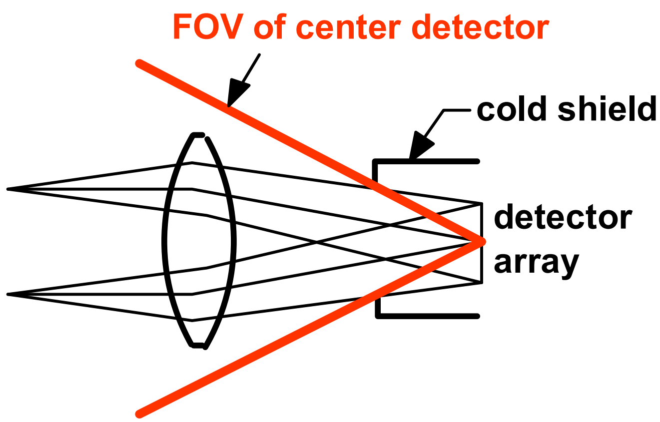
Cooled Detectors

- Many IR detectors are cooled to cryogenic temperatures (e.g., 77 K) to maximize sensitivity
- To avoid frosting up, these detectors are mounted in a thermally insulated vacuum enclosure called a Dewar
- Inside the Dewar, a cold shield limits the solid angle of radiation which can be seen by the detector to reduce the amount of background radiation and increase the detector sensitivity

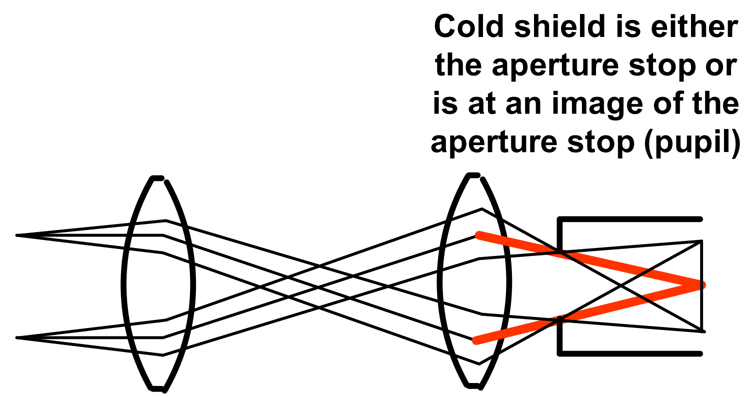


Cold Shield Efficiency

- Most cooled detector systems have a cold shield in the Dewar to minimize the background radiation
  - The size and location of this cold shield determines the amount of background radiation seen by the detector and hence the system sensitivity
  - The maximum sensitivity is when the cold shield is the limiting system aperture (i.e., determines the size of the EPD)



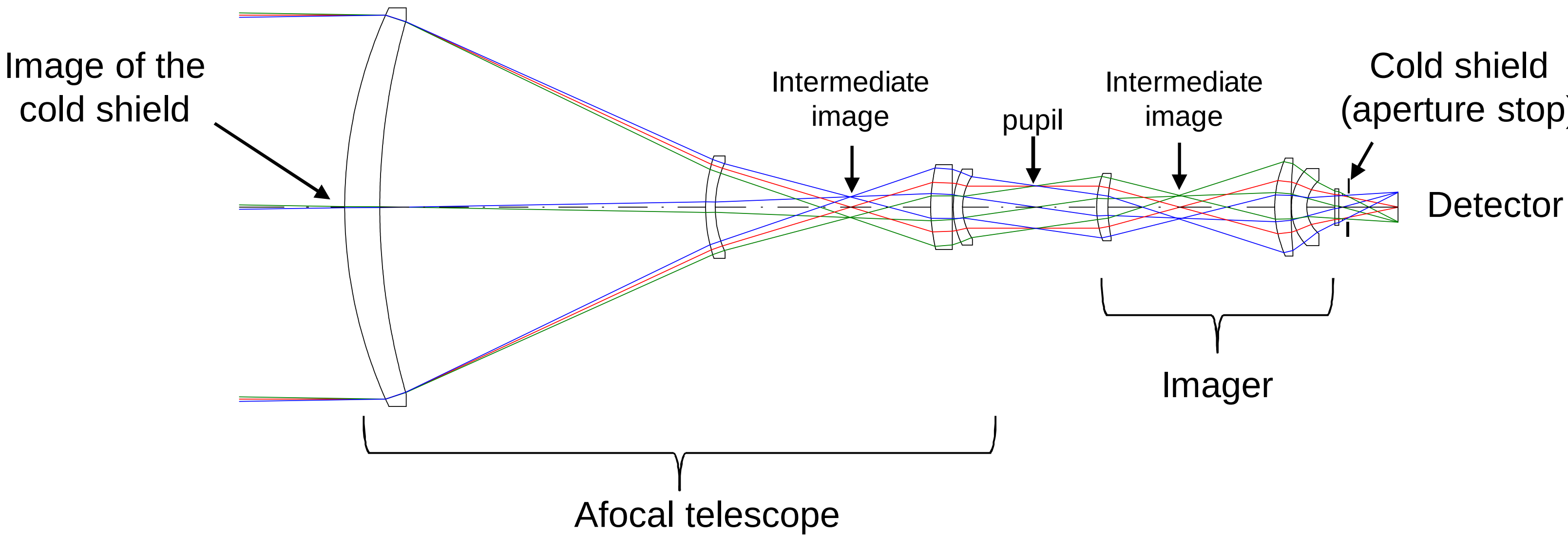
Less than 100% cold shield efficiency
(using simple imager)



100% cold shielding efficiency
(using re-imaging imager)

Cold Shield as the Stop Example

- Afocal telescope and imager
  - The aperture stop is at the cold shield in front of the detector and is imaged onto the front lens to maximize the usage of the front lens aperture



- The magnification from the cold shield to the front lens is $m = EPD/Dia_{CS}$
- A lateral shift of the cold shield by Δx will shift the ray bundle at the front lens laterally by $m\Delta x$
- A longitudinal shift of the cold shield by Δz will cause the location of the front pupil to shift axially by $m^2\Delta z$

Start With the Detector

Å The choice of the detector is maybe the most important initial design choice in optical system design

Å The detector will determine the spectral band you will be using
  ï Visible, NIR, SWIR, MWIR, LWIR, etc.

Å It also will determine the size and aspect ratio of the image (format) and the resolution (pixel size) in image space
  ï The pixel size will have an impact on the f/# of the system (size of the Airy disk vs. pixel size)

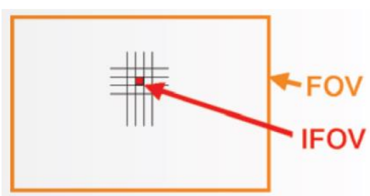
Å For the selected FPA, for a given focal length will determine the FOV, or for a given FOV requirement will determine the focal length

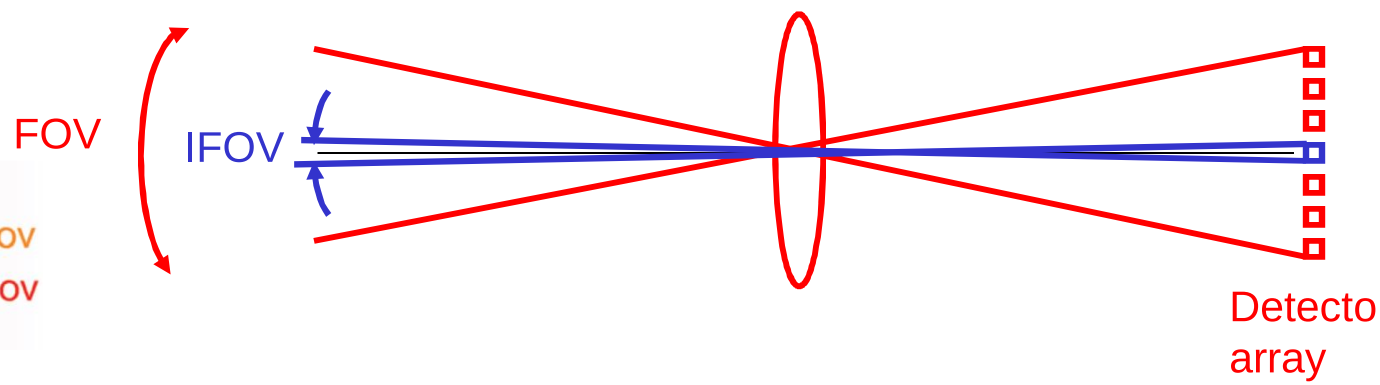
Å The packaging of the selected detector will also have impacts on back image clearance, and in some cases, requirements for telecentricity

Å In the case of infrared detectors with 100% cold-shielding, may dictate the location of the system aperture stop

Detectors and Resolution

- All optical systems have some sort of detector
  - Often this is a 2D focal plane array (FPA)
- No matter what the detector is, there is always some small element of the detector which defines the system resolution
  - This is referred to as a picture element (pixel)
- The size of the pixel divided by the focal length is called the Instantaneous FOV (IFOV ï pronounced eye-fov or eye-eff-oh-vee)
  - The IFOV defines the angular limit of resolution in object space
  - IFOV is <u>always</u> expressed as a full angle





Implications of IFOV

- If the object's angular size is smaller than an IFOV, it is not resolved
  - It is essentially a point object
  - Example is an astronomical telescope imaging a star
- If the object's angular size is larger than an IFOV, it may be resolved to some extent (depending on how many pixels cover the object)
  - This does not mean that you can always tell what the object is

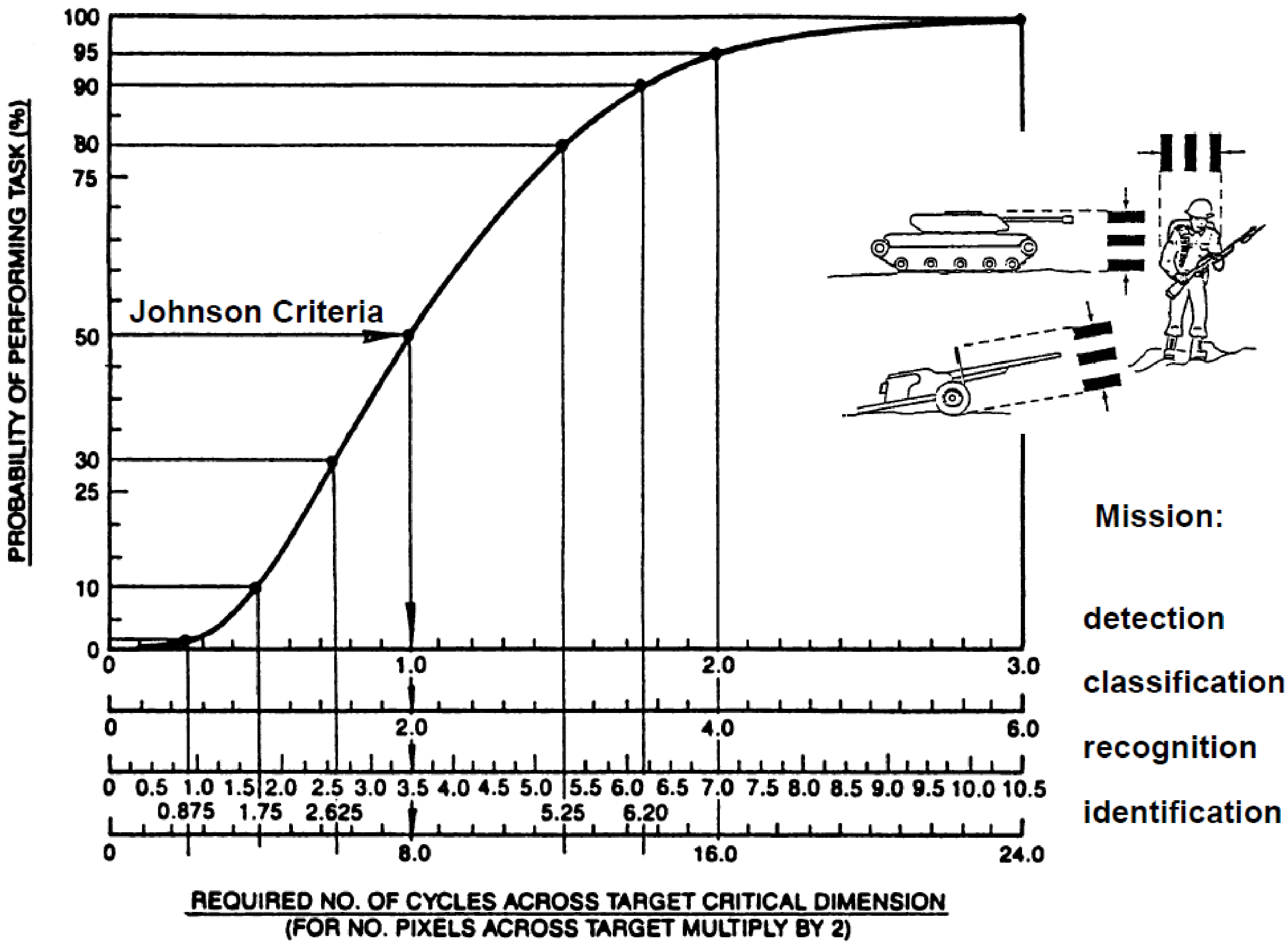
Practical Resolution Considerations

- Resolution required to photograph written or printed copy
  - Excellent reproduction (serifs, etc.) requires 8 line pairs per lower case e
  - Legible reproduction requires 5 line pairs per letter height
  - Decipherable (e, c, o partially closed) requires 3 line pairs per height
- The correlation between resolution in cycles/minimum dimension and certain functions (often referred to as the Johnson Criteria) is

Detect with 50% accuracy	1.0 line pair per minimum dimension
Detect with 90% accuracy	1.75 line pairs per minimum dimension
Recognize with 50% accuracy	3.5 line pairs per minimum dimension
Recognize with 90% accuracy	6.2 line pairs per minimum dimension
Identify with 50% accuracy	8.0 line pairs per minimum dimension
Identify with 90% accuracy	14 line pairs per minimum dimension

- This is for human-in-the-loop
  - Different numbers of pixels are needed for computer target recognition algorithms

Johnson Resolution Criteria



Examples of the Johnson Criteria

Detect
1 bar pair

Maybe something
of military interest

Recognize
4 bar pairs

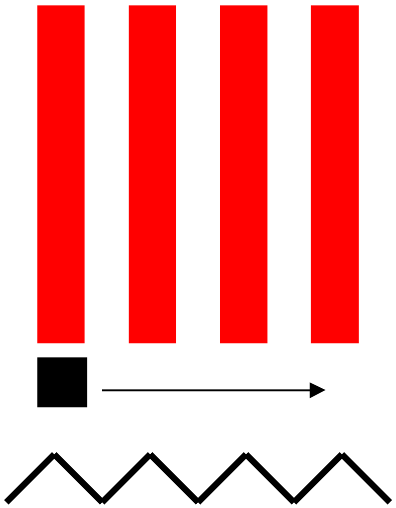
Tank

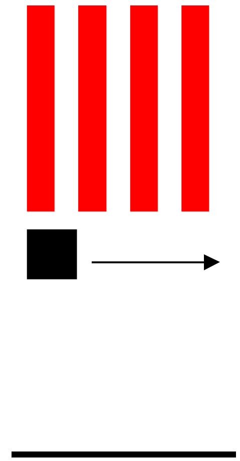
Identify
7 bar pairs

Abrams Tank

MTF of a Pixel (1)

Å Consider a pixel scanning across different sized bar targets





When the pixel size equals the width of a bar pair (light and dark) there is no more modulation

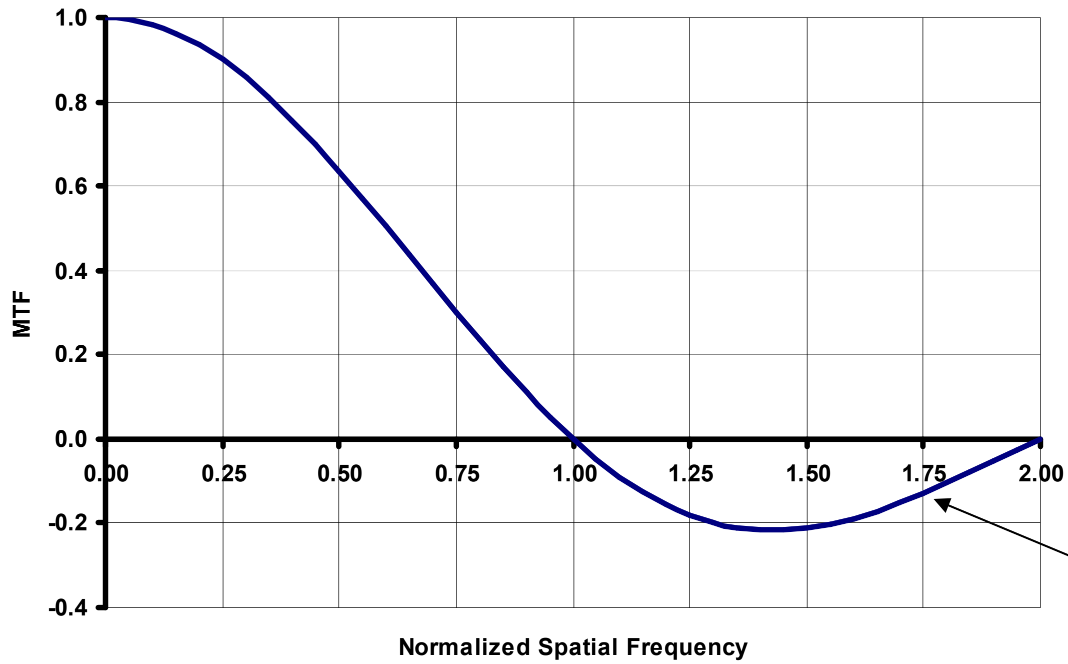
Signal amplitude as pixel moves along bar pattern

MTF of a Pixel (2)

Å If the pixel is of linear width Δ, the MTF of the pixel is given by

$$\mathrm{MTF}(f) = \frac{\sin(\pi f \Delta)}{\pi f \Delta}$$

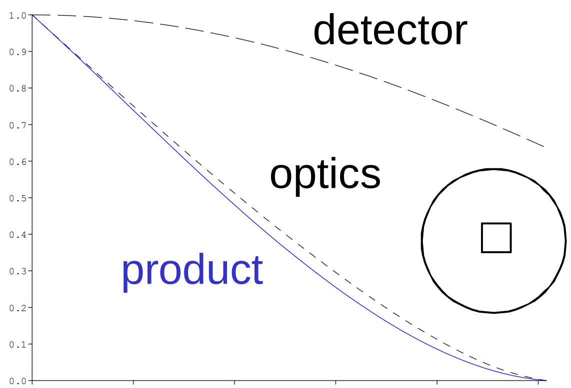
Å The cutoff frequency (where the MTF goes to zero) is at a spatial frequency $1/\Delta$



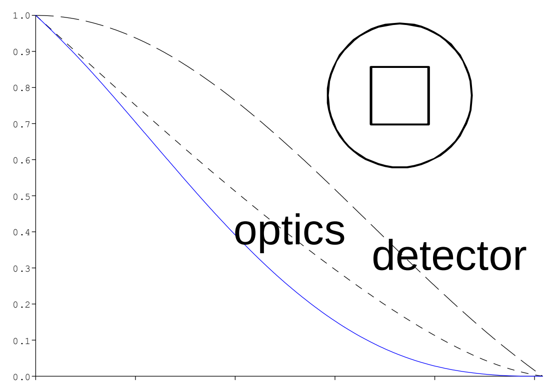
When detector MTF goes negative, aliasing and contrast reversal can occur

Optical MTF and Pixel MTF

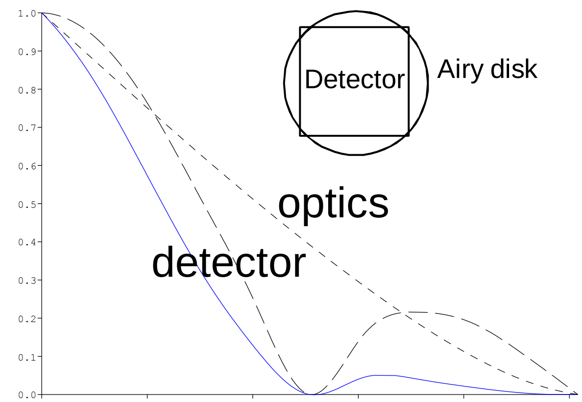
Å The total MTF is the product of the optical MTF and the detector MTF



Case 1 - Optics limited



Case 2 - Optics and detector are matched

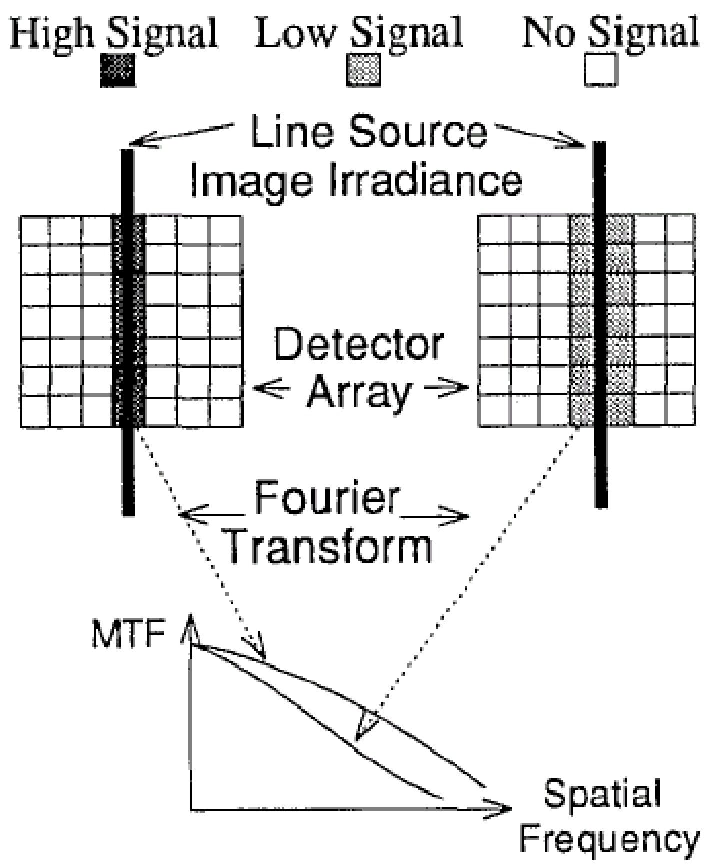


Case 3 - Detector limited

Å Of course, there are other MTF contributors to total system MTF also

ï Electronics, display, line-of-sight jitter, target smear, eye, atmospheric turbulence, etc.

Effects of CCD/Signal Alignment on the MTF



A sampled imaging system is not shift-invariant

MTF of Alignment

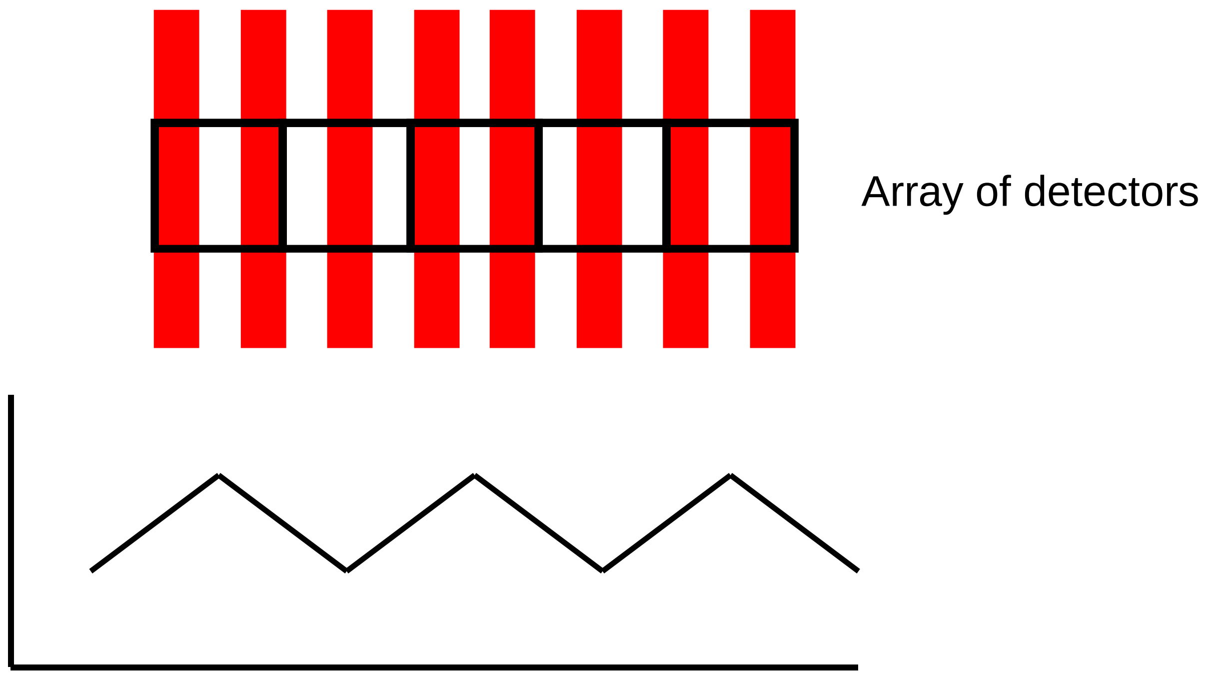
- When performing MTF testing, the user can align the line image with respect to the system to produce the best image
  - In this case, a sampling MTF would not apply
- A natural scene, however, has no optimum alignment with respect to the sampling sites
- To account for the average alignment of unaligned objects a sampling MTF must be added
  - $MTF_{sampling} = \sin(\pi f \Delta x)/(\pi f \Delta x)$ where Δx is the sampling interval
  - This MTF is an ensemble average of individual alignments and hence is statistical in nature

Aliasing

Å Aliasing is a very common effect but is not well understood

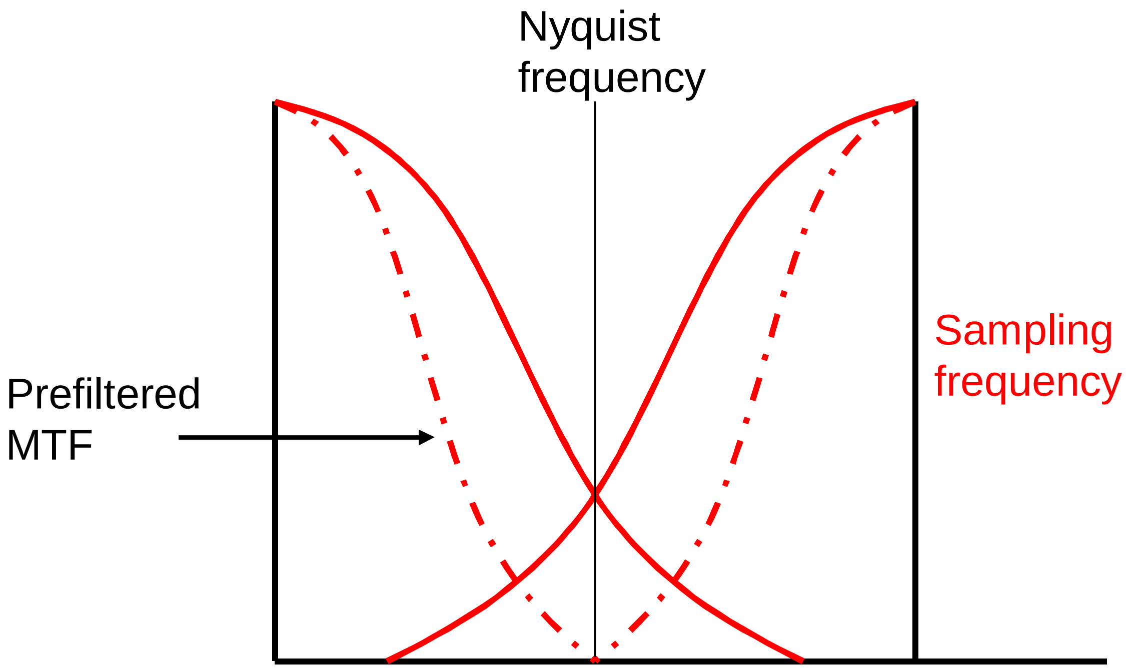
Å Aliasing is an image artifact that occurs when a waveform is insufficiently sampled

- ï It is evidenced as the imaging of high frequency objects as low frequency objects



Sampled MTF Fold-over

- The effect of sampling is to replicate the MTF back from the sampling frequency
  - This will cause higher frequencies to appear as lower frequencies



- The solution to this is to prefilter the MTF so it goes to zero (or close to zero) at the Nyquist frequency (half the sampling frequency)
  - This is sometimes done by deliberate blurring of the image

Types of Optical Systems

Å Dioptric
  ï Uses all refractive elements
  ï For example, cameras, binoculars

Å Catoptric
  ï Uses all mirrors
  ï For example, astronomical telescopes

Å Catadioptric
  ï Uses both refractive and reflective elements
  ï For example, telescopes with eyepieces

Dioptric (All Refractive) Systems

- Advantages ☺
  - No obscurations
    - More signal
    - Higher MTF
  - Can get faster f/numbers and larger fields of view than usually possible with all-reflective systems
  - Often can be made with all spherical surfaces
- Disadvantages ☹
  - Usually longer than mirror systems
  - Heavier than mirror systems
  - Chromatic aberration
    - Requires extra elements to correct
  - Optical materials can be expensive (especially in the IR)
  - Athermalization can be a problem (especially in the IR)

Catoptric (All Reflective) Systems

Å Advantages ☺

- ï No chromatic aberration
- ï Can be inherently athermal (if mounts and mirrors are made of same material)
- ï Are often shorter than corresponding refractive systems
- ï Can be cheaper than corresponding refractive systems
- ï Often lighter weight than corresponding refractive systems
- ï Potentially lower cost than refractive systems (especially in the IR)

Å Disadvantages ☹

- ï Have central obscurations (which costs signal and MTF) or are off-axis (which takes up more room)
- ï Usually require aspheric surfaces
- ï Have small FOVs and high f/numbers

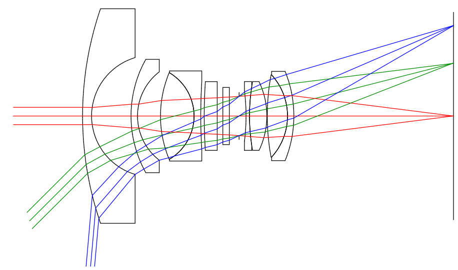
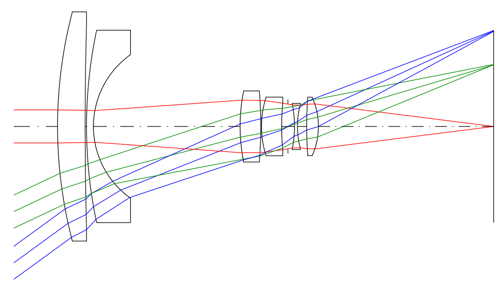
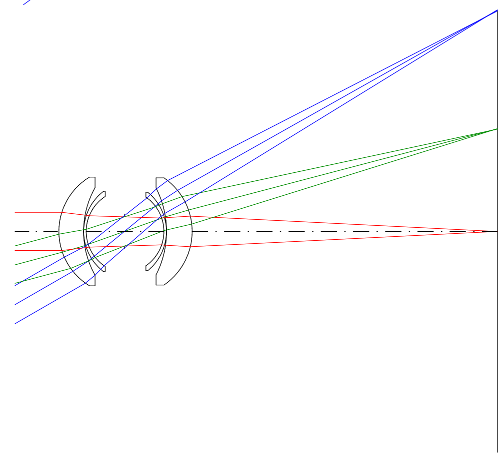
Catadioptric Systems

- Catadioptric systems have both refractive and reflective components

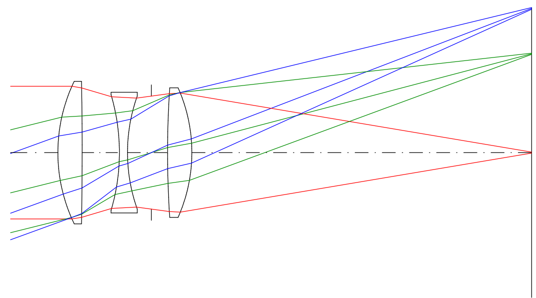
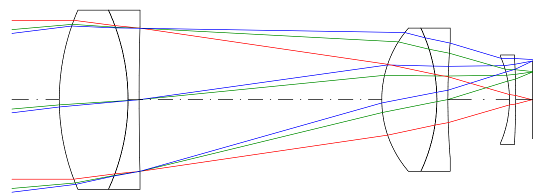
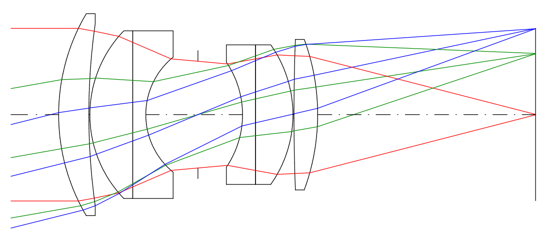
- They have some of the advantages of all-refractive and all-reflective systems
  - They can be shorter than all-refractive systems
  - They can cost less than all-refractive systems
  - They can have faster f/numbers than traditional all-reflective systems

- They also have some of the disadvantages of all-refractive and all-reflective systems
  - They have chromatic aberration, but it may be much less than an all-refractive system
  - They have athermalization issues, but are often easier to athermalize than all-refractive systems

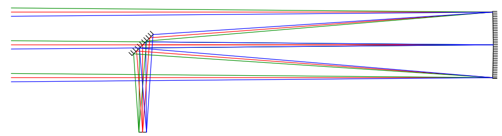
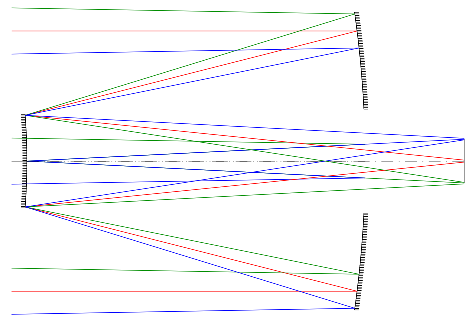
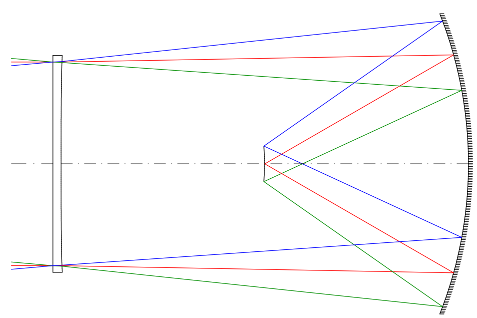
Common Refractive Design Types (1)

Application	Typical Type	Typical Cross-section	Attribute
FOV > 160° f/# > 3	Fisheye		length >> EFL
FOV > 60° f/# > 4	Inverted Telephoto		BFL > EFL
FOV > 60° f/# > 8	Symmetrical Wide-angle		Low distortion

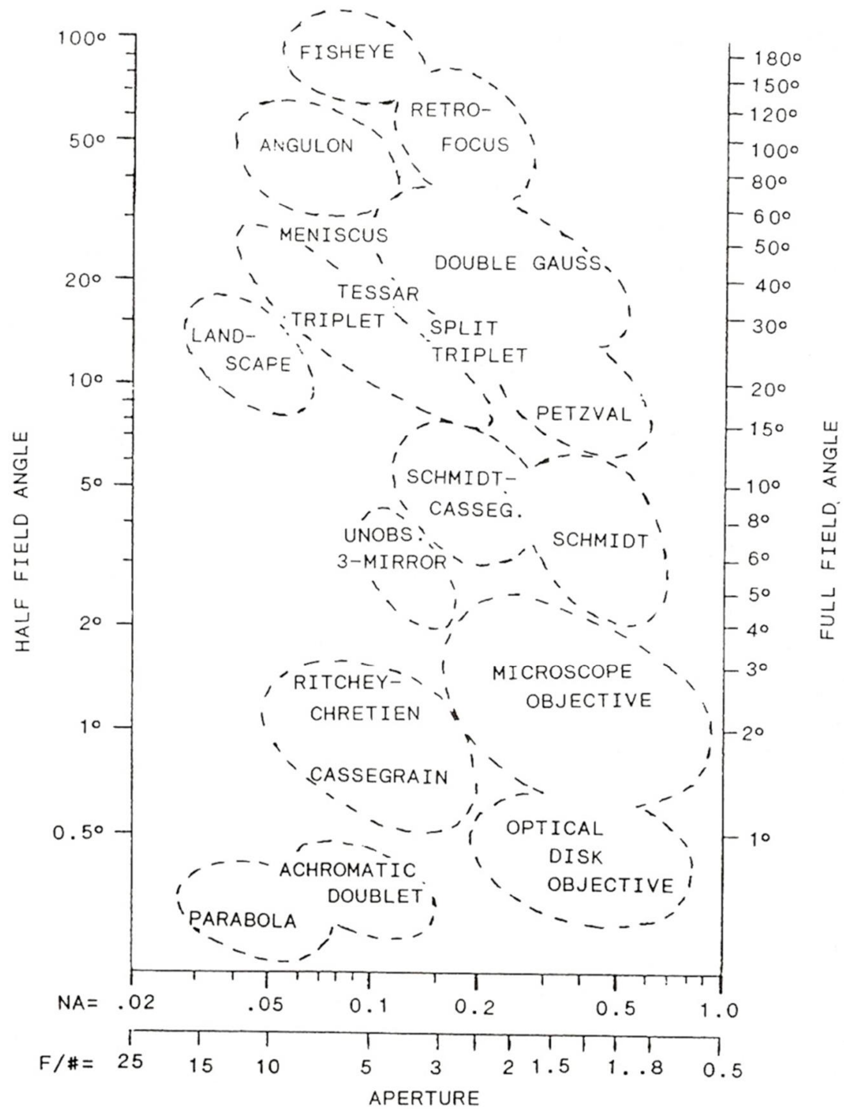
Common Refractive Design Types (2)

Application	Typical Type	Typical Cross-section	Attribute
FOV < 45° f/# > 3	Cooke Triplet		BFL > 0.7 EFL
FOV < 20° f/# > 1.5	Petzval Lens		Low f/#
FOV > 45° f/# > 2	Double Gauss		Length ~ 1.2 EFL

Common Reflective Design Types

Application	Typical Type	Typical Cross-section	Attribute
FOV < 1° f/# > 4	Newtonian		Common for amateur astronomers
FOV < 3° f/# > 4	Cassegrain		Parabola Hyperbola
FOV < 8° f/# > 2	Schmidt		Spherical primary aspheric corrector curved image

Optical Systems Arranged by FOV and f/number



How to Select a Design Form

- Select which requirement (or requirements) is most stressing (e.g., f/number, FOV, wavelength band, etc.)
- Choose a basic design form suitable for the stressing requirement(s)
- If the requirement is beyond known state-of-the-art limits, determine the type of modifications to existing design forms that could improve the performance with respect to this stressing requirement, such as splitting elements, using a higher index, special materials, etc.
- Sometimes several stressing requirements may cause a need for a combination of existing forms

Modifications of Existing Designs

- The entire design may be scaled uniformly
- A subgroup of the design may be scaled, such as the objective of an afocal telescope to change magnification
- The glass choices for the elements may be changed to provide correction of a different spectral range
- A new group may be added to accomplish a specific requirement, such as telecentricity
- Elements may be split, cemented, or decemented to meet new requirements for f/number, FOV, performance, or mechanical requirements
- Aspherics or diffractives may be added

Optical System Scaling Laws

Å If we scale an optical system by a factor K, what happens to the various optical parameters?

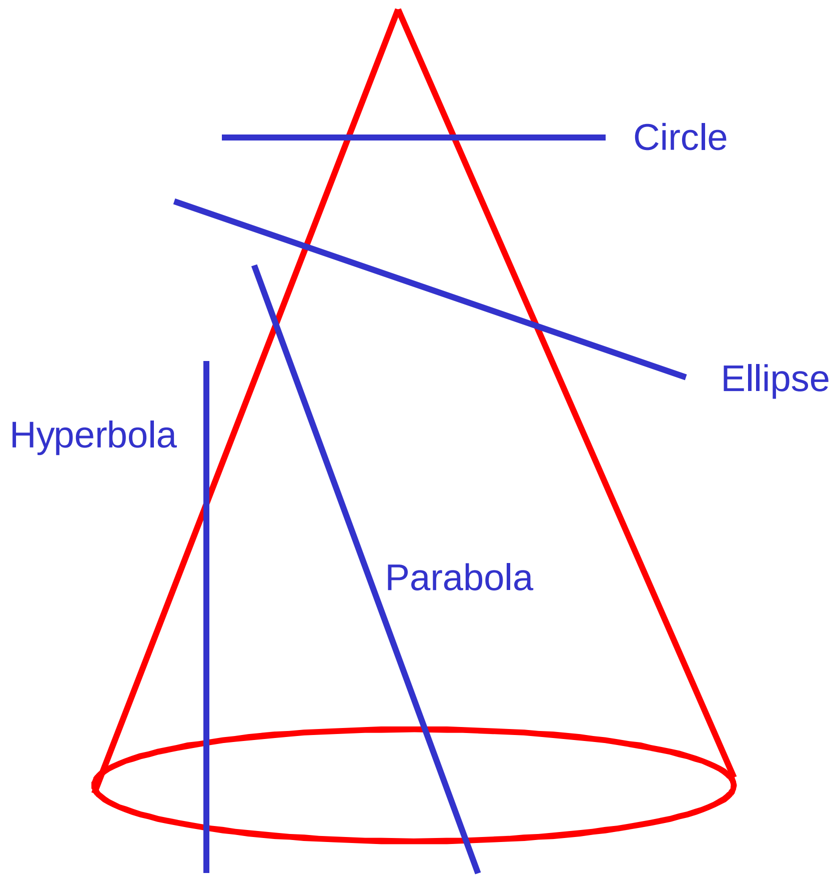
Parameter	Scale factor	
Overall Length	K	
Focal Length	K	
Lens sizes (and EPD)	K	
f/number	1	
Lens parameters	K	(radii, thickness, diameter, etc.)
Conic constant	1	
Nth-order aspheric coefficient	$1/K^{N-1}$	
Decentrations	K	
Tilt angles	1	
Weight	K^3	
FOV	$1/K$	(assuming constant FPA size)
IFOV	$1/K$	(assuming constant FPA size)
Aberrations (transverse)	K	
Diffraction Airy disk size	1	

Limitations of an Optical Design Form

- Understanding the physical and optical limitations of various optical forms will save many false starts
  - This typically comes with experience and exposure to different designs
- Limitations may be minimum f/#, maximum field, minimum obscuration ratio, or performance limitations such as minimum distortion
  - There are often packaging limitations (size, BFL, scanner clearance, etc.)
- Sometimes limits are cost related, such as tight tolerances, expensive materials, aspherics, etc.
- Map out ALL your requirements with a candidate design as soon as is feasible

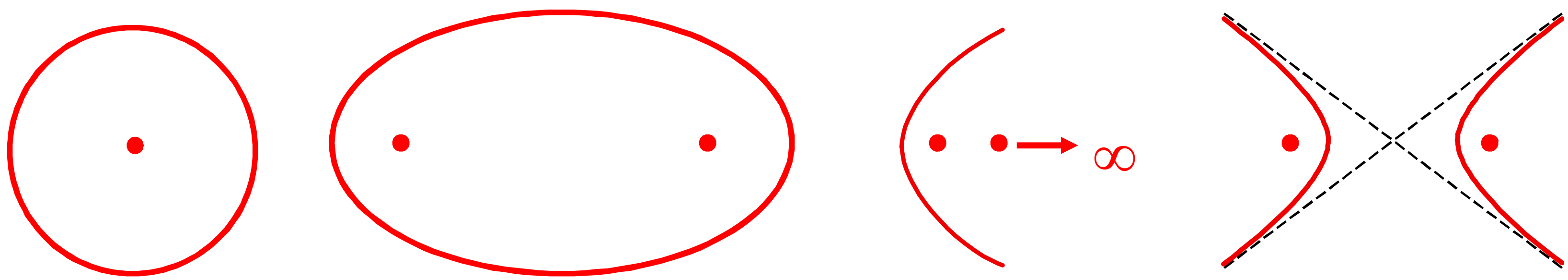
Conic Surfaces

Å Conic surface profiles are the cross-sections made when a plane surface intersects a right circular cone



More on Conic Surfaces

- Conic surfaces of revolution are often used on mirror surfaces
- Their advantage is that they are easy to test and provide significant aberration control beyond that available with just spherical surfaces
- All conic surfaces have two foci
    - Both of the sphere's foci are at the same point
    - One of the parabola's foci is at infinity
- Conics are described by a parameter called the conic constant k



sphere
k = 0

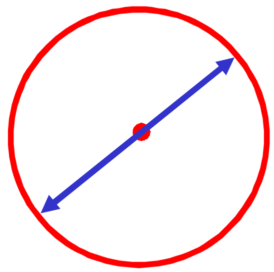
ellipse
-1 < k < 0

Parabola
k = -1

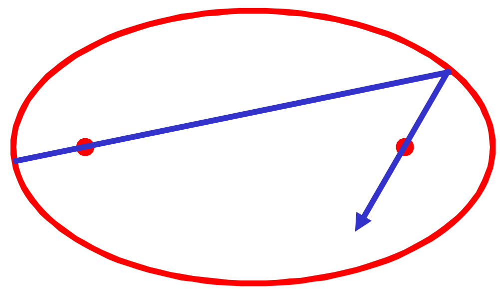
Hyperbola
k < -1

The Conic Property

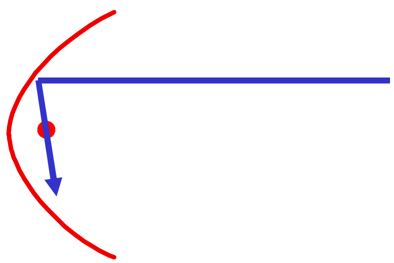
Å Any ray that passes through one focus of a conic will, after reflection off the conic, pass through the other focus <u>with no aberrations of any order</u>



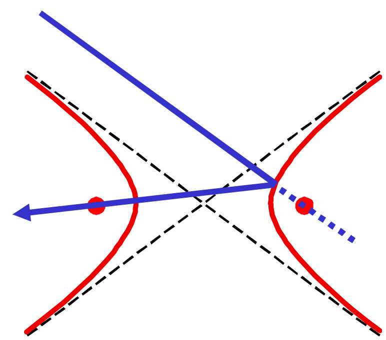
Sphere



Ellipse



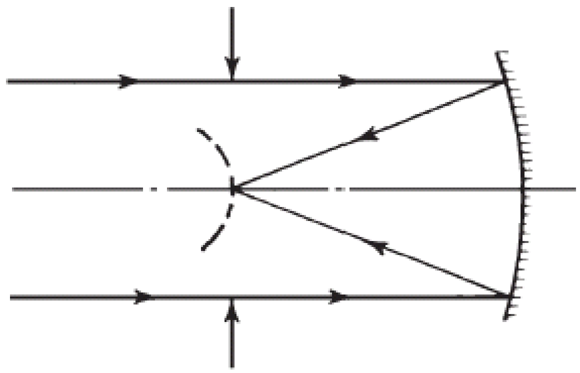
Parabola



Hyperbola

The Parabola

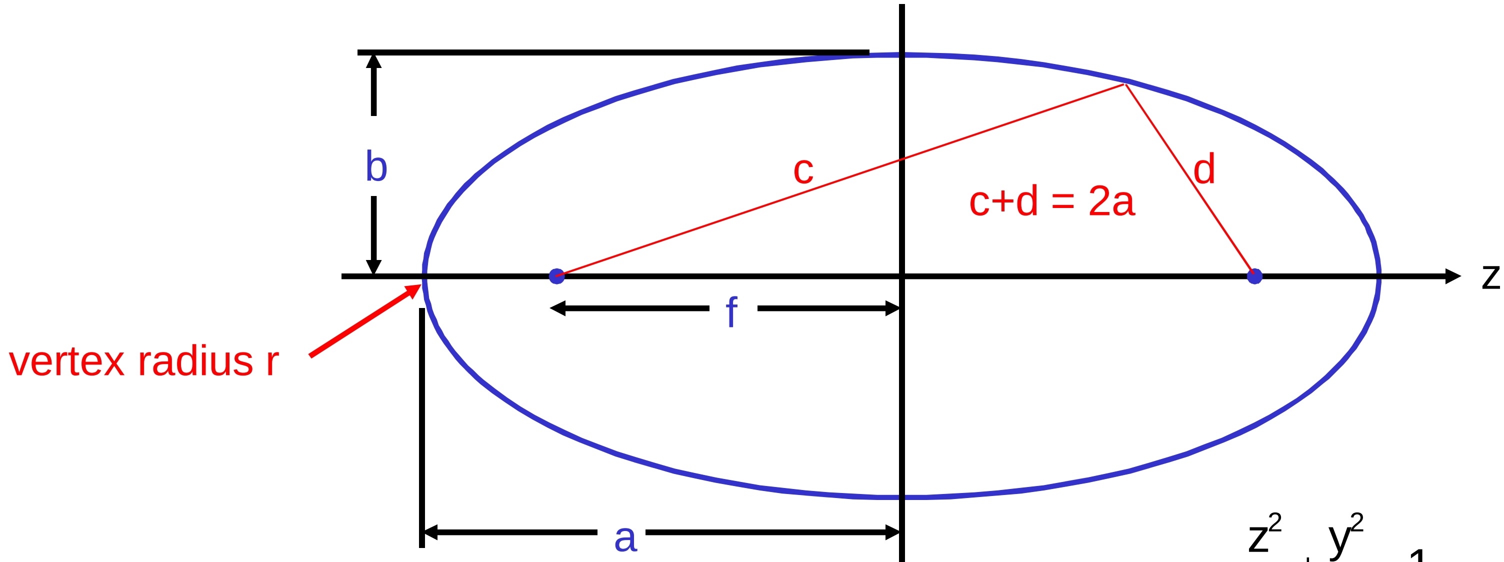
- A parabola is a pure second-order equation: $z(h) = h^2/(2R) = h^2/(4F)$
  - Note that $F = R/2$, as in a spherical reflector
- The parabola images collimated light parallel to its axis perfectly
  - Thus, it has no spherical aberration of any order
  - It has off-axis aberrations such as coma, astigmatism, and curvature of field the same as spherical reflectors with the same EFL and F/#
    - The coma and astigmatism are a function of the stop position
- Example - amateur telescope mirrors are often a parabola



If the stop is at the focus, a parabolic reflector is free of astigmatism (note the curved focal surface)

The Ellipse

Å Defined by a semi-major axis a and semi-minor axis b and two foci

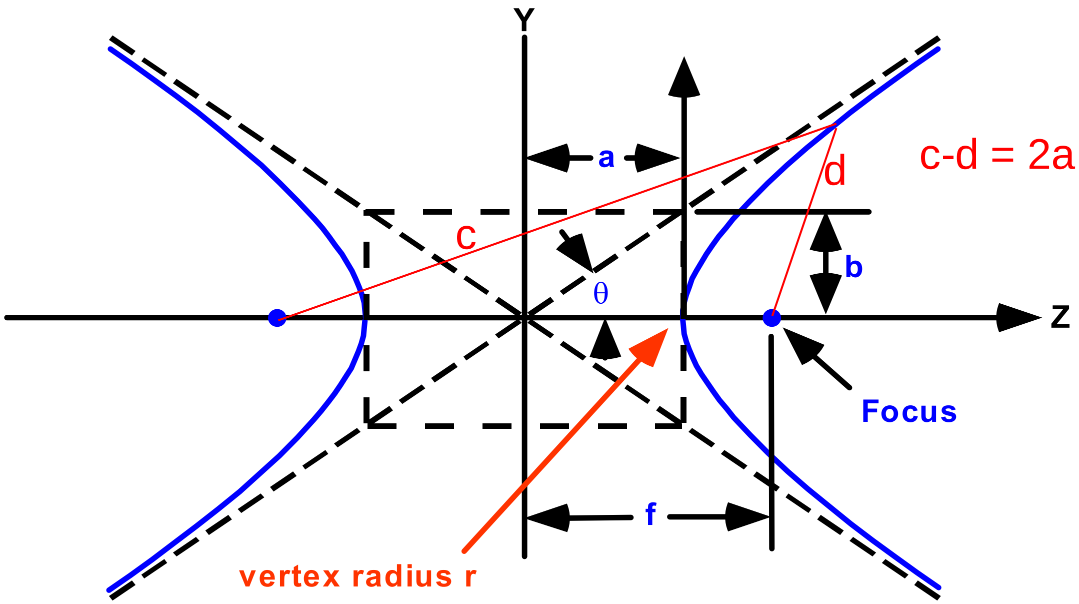


$$\frac{z^2}{a^2}+\frac{y^2}{b^2}=1$$

vertex radius	$r = b^2/a$
conic constant	$k = (b^2-a^2)/a^2$
center distance to foci	$f = (a^2-b^2)^{1/2}$
vertex distance to foci	$a \pm f$
semi-major axis	$a = r/(k+1)$
semi-minor axis	$b = r/\sqrt{k+1}$

The Hyperbola

Å Defined by axes a and b, asymptote angle θ, and two foci



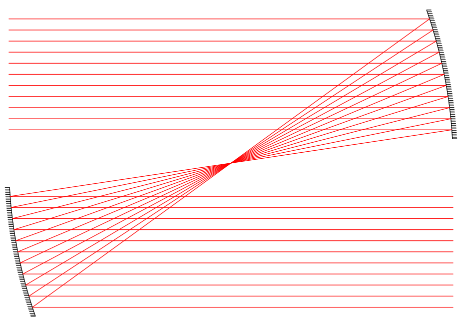
$$\frac{z^2}{a^2} - \frac{y^2}{b^2} = 1$$

vertex radius	$r = b^2/a$
conic constant	$k = -(a^2+b^2)/a^2 = -(1+\tan^2\theta)$
asymptote angle	$d = \tan^{-1}(\sqrt{-k-1})$
distance to foci	$f = \sqrt{a^2+b^2} = -r\sqrt{-k}/(k+1)$
vertex distance to foci	f ± a $\quad f - a = -r(\sqrt{-k}-1)/(k+1)$
semi-major axis	$a = -r/(k+1)$
semi-minor axis	$b = r/\sqrt{-(k+1)}$

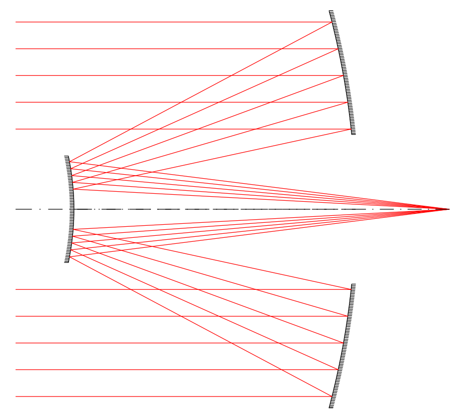
Combinations of Conics

Å Confocal conics are a series of conics wherein one of the foci of one conic is placed at one of the foci of another conic

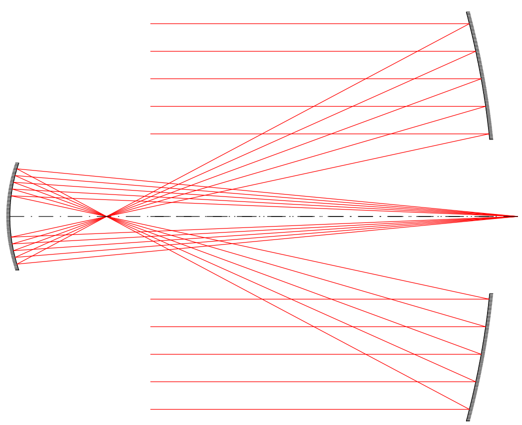
  ï In this way, there is no spherical aberration in the system (it still can have off-axis aberrations, such as coma, astigmatism, and curvature of field)



Mersenne telescope
parabola-parabola
(afocal)

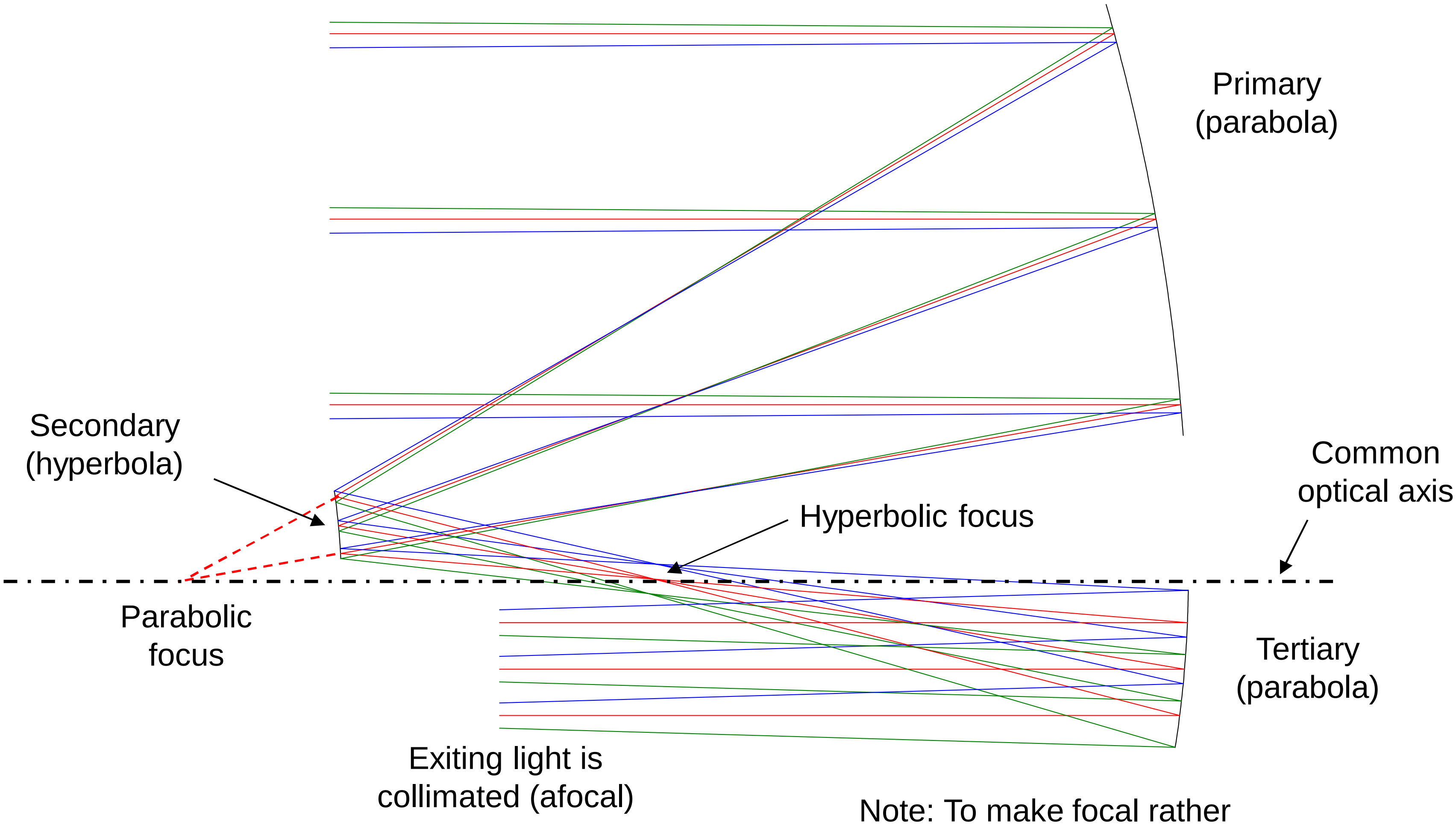


Cassegrain telescope
parabola-hyperbola



Gregorian telescope
parabola-ellipse

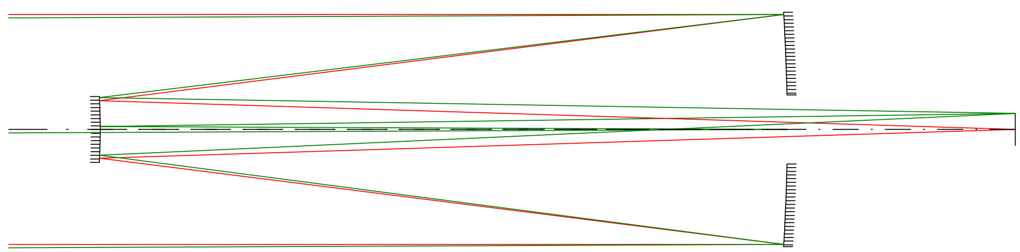
The Three Mirror Anastigmat (TMA)

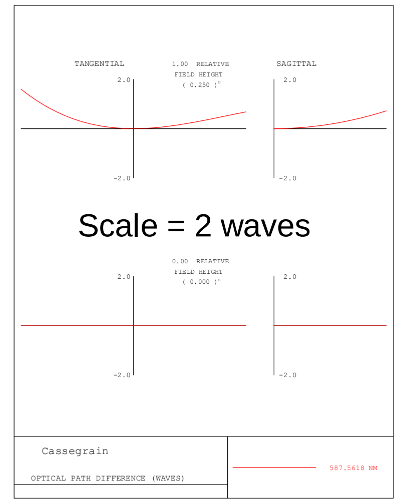


Note: To make focal rather than afocal, make the tertiary an ellipse

The Ritchey-Chrétien Telescope

Å A Cassegrain is perfect on-axis, but has off-axis aberrations (coma, astigmatism, curvature of field) for even modest fields of view (e.g., ±0.25°)



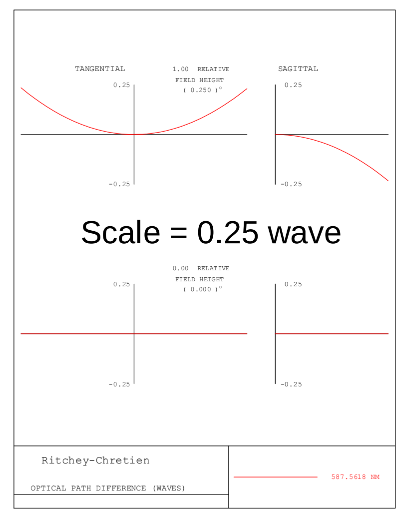


Å A Ritchey-Chrétien telescope (RCT) slightly changes the conics

- ï The primary becomes slightly hyperbolic
- ï The secondary becomes more hyperbolic

Å The result is free of third-order spherical and coma, but still has fifth-order coma, astigmatism, and field curvature

- ï Performance is significantly improved



Aspheric Surfaces

- Aspheric surfaces are usually polynomial deformations from a conic surface
  - They are used to correct various aberrations (usually spherical aberration and astigmatism) beyond the correction obtainable with just a conic

- An important concern is the surface figure and the alignment
  - For aspheric surfaces near pupils, the figure tolerance must be very tight (typically a few microinches)
  - For aspheric surfaces closer to image surfaces, the surface figure can be looser (by maybe a factor of 2 or 3)
  - Aspheric surfaces often must have tighter tilt and/or decentration tolerances than spherical surfaces

- For aspheric mirrors (especially primary mirrors), the method of mounting can be critical
  - The bolt-up distortion can severely impact the mirror's surface figure

Aspheric Surfaces

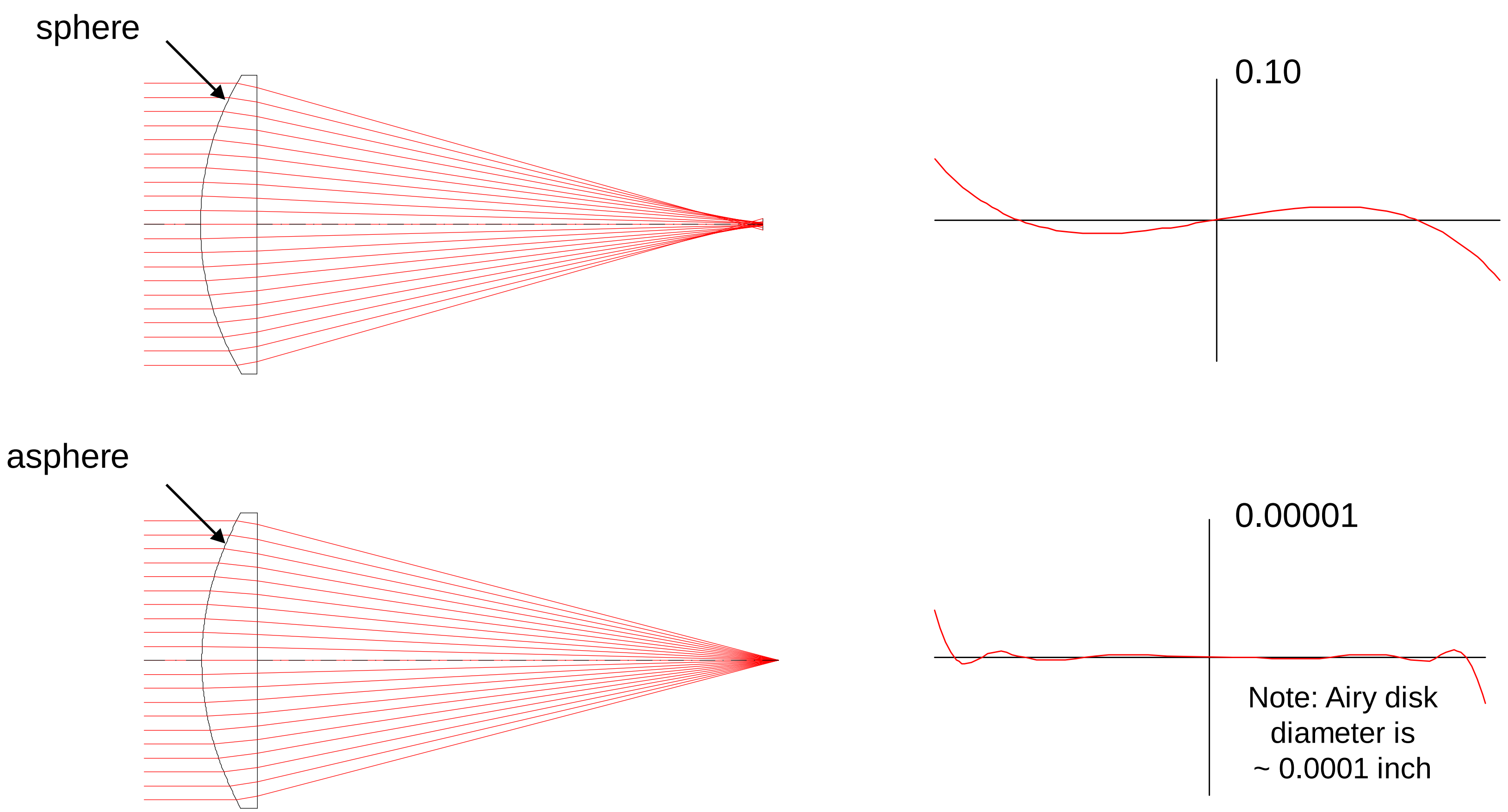
- Aspheric surfaces technically are any surfaces which are not spherical, but usually refer to a polynomial deformation to a conic
  - The most commonly used equation for aspherics is

$$z(r) = \frac{r^2/R}{1+\sqrt{1-(k+1)(r/R)^2}} + A\,r^4 + B\,r^6 + C\,r^8 + D\,r^{10} + \ldots$$

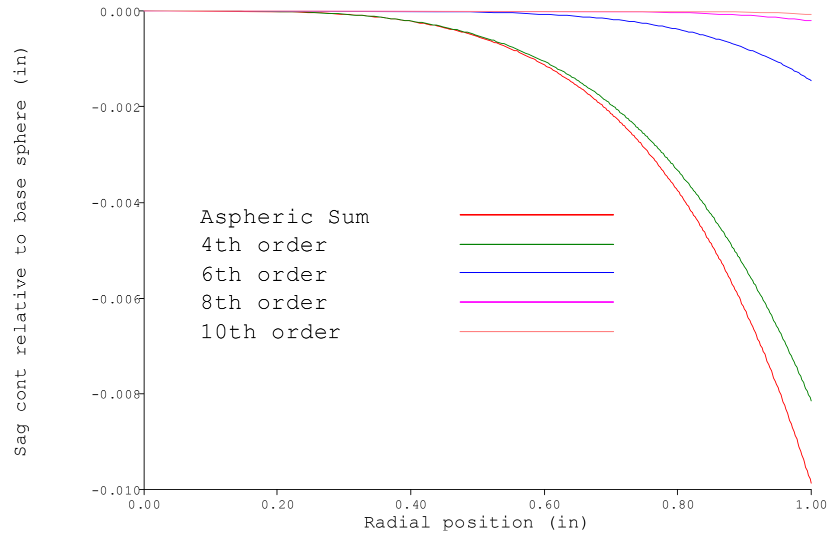
- The aspheric coefficients (A, B, C, D, é) can correct 3rd, 5th, 7th, 9th, é order spherical aberration
- When used near a pupil, aspherics are used primarily to correct spherical aberration
- When used far away (optically) from a pupil, they are used primarily to correct astigmatism by flattening the field
- Before using aspherics, be sure that they are necessary and the increased performance justifies the increased cost
  - Never use a higher-order asphere than justified by the ray aberration curves
  - Single point diamond turning can be a cost-effective way to generate aspherics (if the material is turnable)

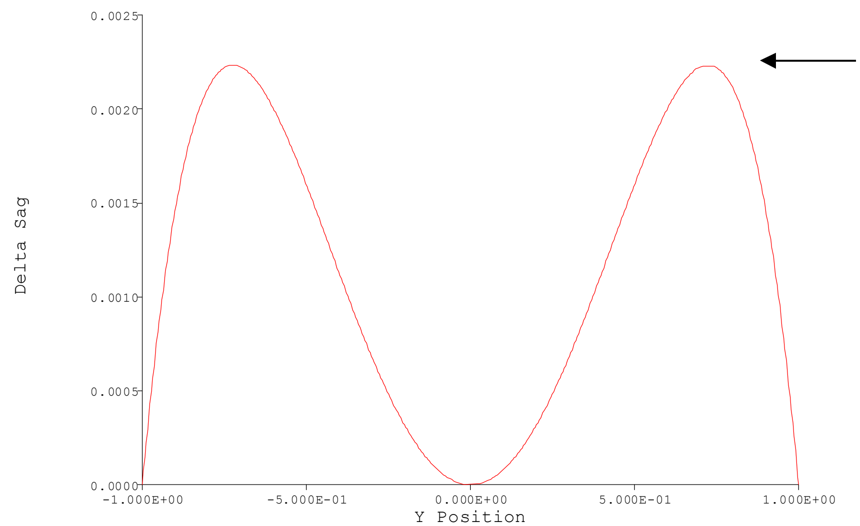
Aspheric Example (1)

Å 2 inch diameter, f/2 plano-convex lens



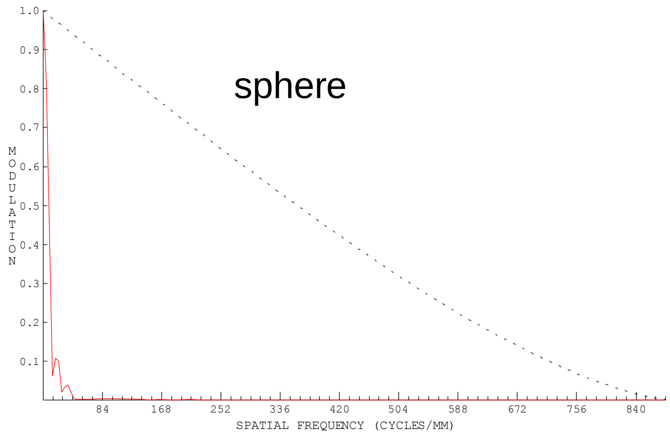
Aspheric Example (2)

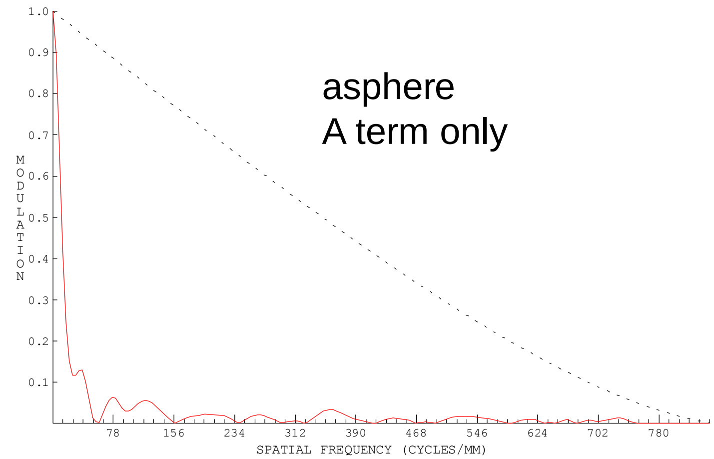


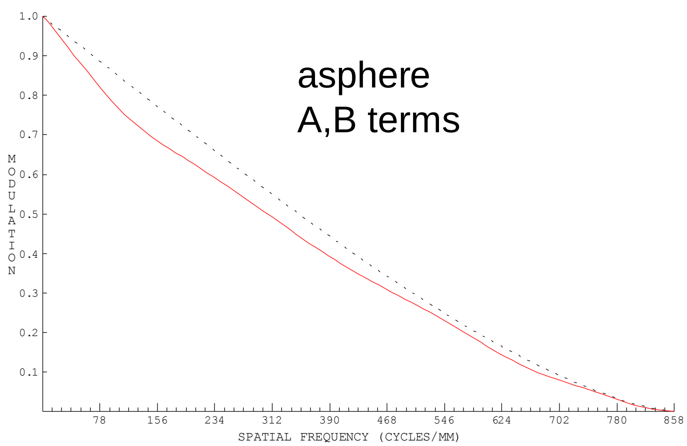


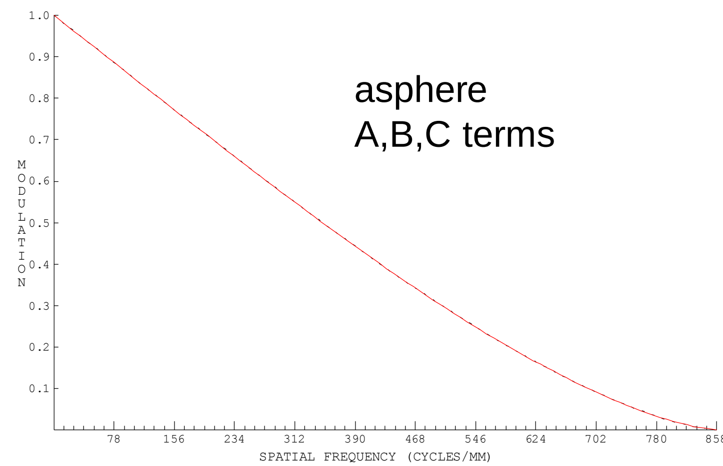
Corresponds to ~114 waves of asphericity from the best-fit sphere

Aspheric Example (3)









Aspheric Manufacture

- Aspherics on glass elements have historically been difficult to make
  - Easier now with deterministic microgrinding and magnetorheological finishing (MRF)
    - The magnitude of the asphericity may be an issue (especially for MRF)
  - A 2-inch glass spherical lens may cost about $50-$100 in small quantities, but a 2-inch glass asphere can easily cost $1,000 or more
- Aspherics on metal mirrors or on many infrared materials are relatively easy to make if they can be single point diamond turned
  - Often, a lens manufacturer may DPT an IR spherical lens, and thus, adding an asphere adds little additional fabrication cost (cost increase is mainly in testing)
  - Another advantage to DPT is that the positioning and runout of mounting features (sag flats, shoulders, etc.) can be held very tightly
- Flats, spheres, and conics can be easily tested with interferometers
  - Aspheres may need special optics to aid in the testing of the parts
  - This will add cost and time to the procurement of aspheres

Cautions on the Use of Aspheres

- It may seem that aspheres are magical surfaces which can correct all your aberrations
  - Also, if your system is an IR system and the materials can be diamond point turned, adding the aspheres may seem to be almost free
- First of all, they cannot correct all your on-axis and off-axis aberrations, and they have no effect on chromatic aberration
- Secondly, they introduce additional testing costs (e.g., need for null optics)
- Thirdly, they may bring with them additional manufacturing errors which can impact the transmittance and the image quality
  - The surface roughness of a diamond point turned surface is often 5 to 20 times worse than a conventionally polished surface (higher scatter)
  - The DPT process may introduce additional surface errors, such as mid-spatial frequency ripple and cusping (reduces MTF and EE)
- Before you commit to using a given asphere, you should discuss the asphere shape with the supplier to determine manufacturability
- The bottom line is that aspheric surfaces are useful, and often necessary, but you should try to minimize the number of them in your system

Commercial Off-the-Shelf (COTS) Optics

- There are basically two forms of COTS optics
- Single optical elements and cemented doublets
  - Available from Edmund Optics, Thor Labs, etc.
- Precision lenses, such as camera lenses and special purpose lenses, available from many sources
  - These are typically multi-element assemblies mounted in a suitable housing
  - Cost can be significantly lower than custom optics
    - True for small quantities, but when production reaches 50-100 or more, then the prices of custom optics comes closer to that of COTS optics
  - Optical performance, mechanics, and basic specifications of a COTS optic may not be appropriate or good enough for your application

Cost of COTS Optics vs. Custom Optics

- The cost of COTS single elements and achromatic doublets is around $60-$150 each (higher for COTS IR elements)
- COTS optics are usually anti-reflection coated and of reasonable quality
  - However, optical and mechanical quality cannot be assured
  - Tolerances of COTS optics are often relatively loose
  - The AR coating may not be for the spectral range of interest
  - It is important to test any COTS optic you use
- A problem is that you may not be able to get a specific COTS optic later or in the quantities you may need
- Custom lenses require significant time for design, tolerancing, mechanical design, fabrication, and assembly
  - Custom glass lenses may be around $700 or more per element (more for IR elements), not including assembly time
  - A six-element custom glass lens may cost upwards of $10,000 for the first unit (more for IR systems)
- The primary advantage of custom lenses is that you get a lens or lens system which meets <u>all</u> your requirements