Infrared Optical Systems

OPTI 696

Practical Optics Seminar

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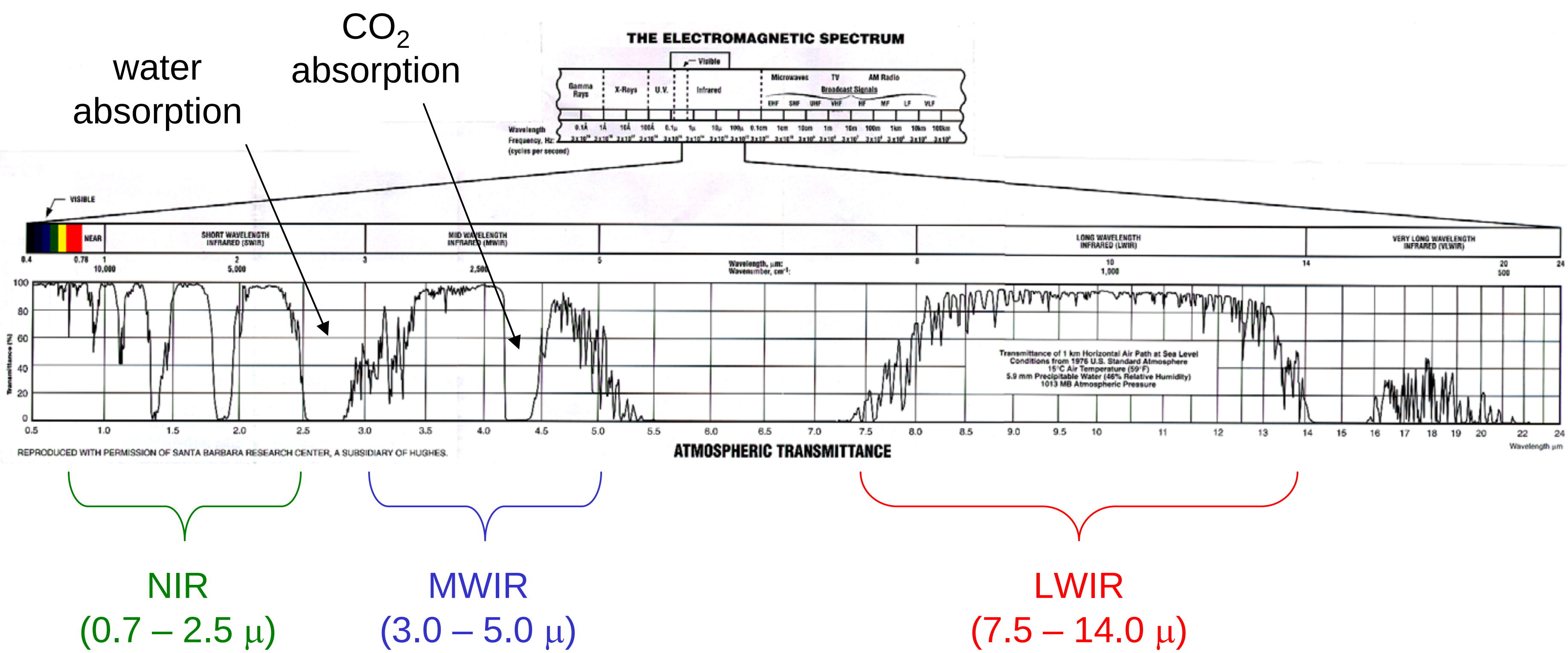
Atmospheric Transmittance



Blackbody Radiation

- Blackbodies emit per the following equation

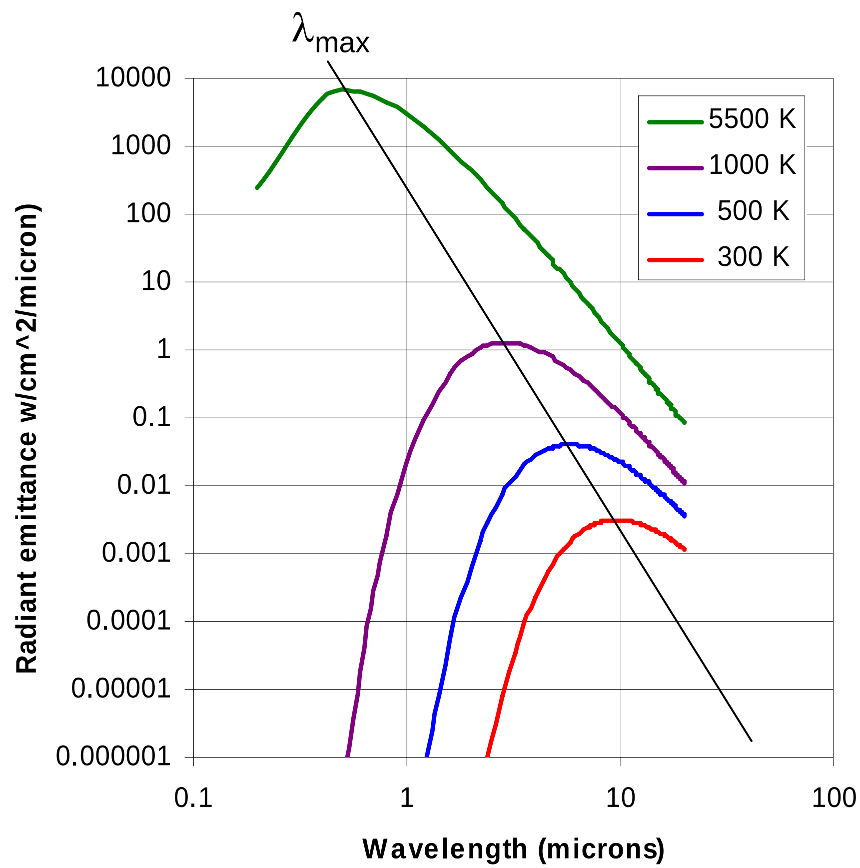
$$W(\lambda) = \frac{c_1}{\lambda^5 (e^{c_2/\lambda T} - 1)}$$

$$c_1 = 2\pi c^2 h = 37418.32 \text{ w}\mu^4\text{cm}^{-2}$$

$$c_2 = hc/k = 14387.86 \ \mu\text{K}$$

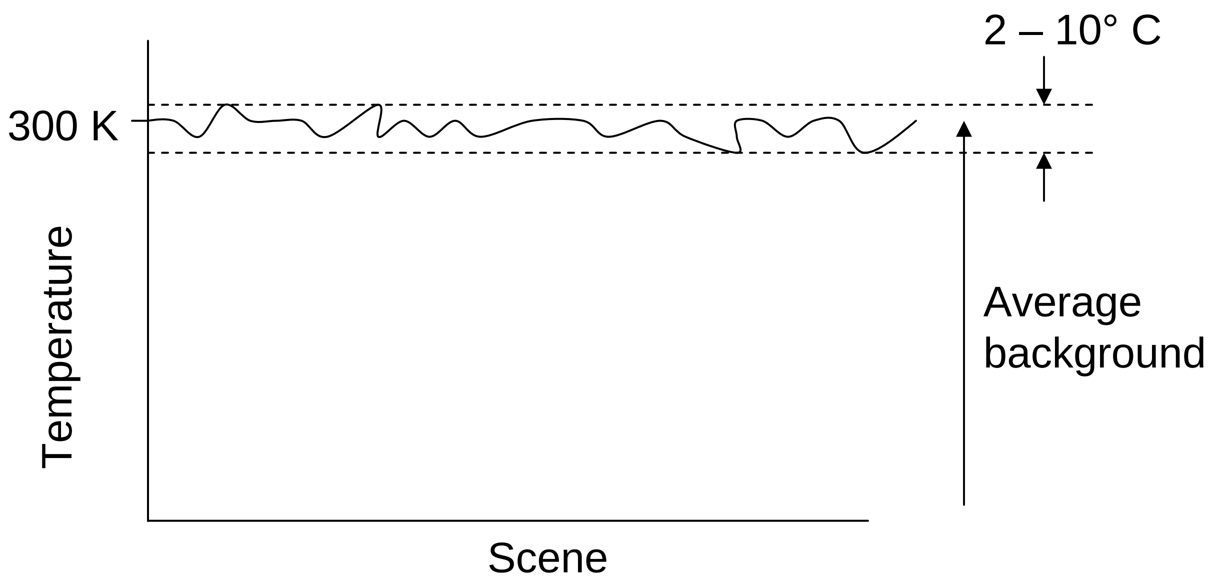
- The peak of the curve occurs at λ_{max} = 2898/T
  - Visible (T = 5500) λ_{max} = 0.53 μ
  - MWIR (T = 500) λ_{max} = 5.8 μ
  - LWIR (T = 300) λ_{max} = 9.7 μ

- The choice of spectral band to use depends on the temperature of the object you want to detect



Thermal Contrast

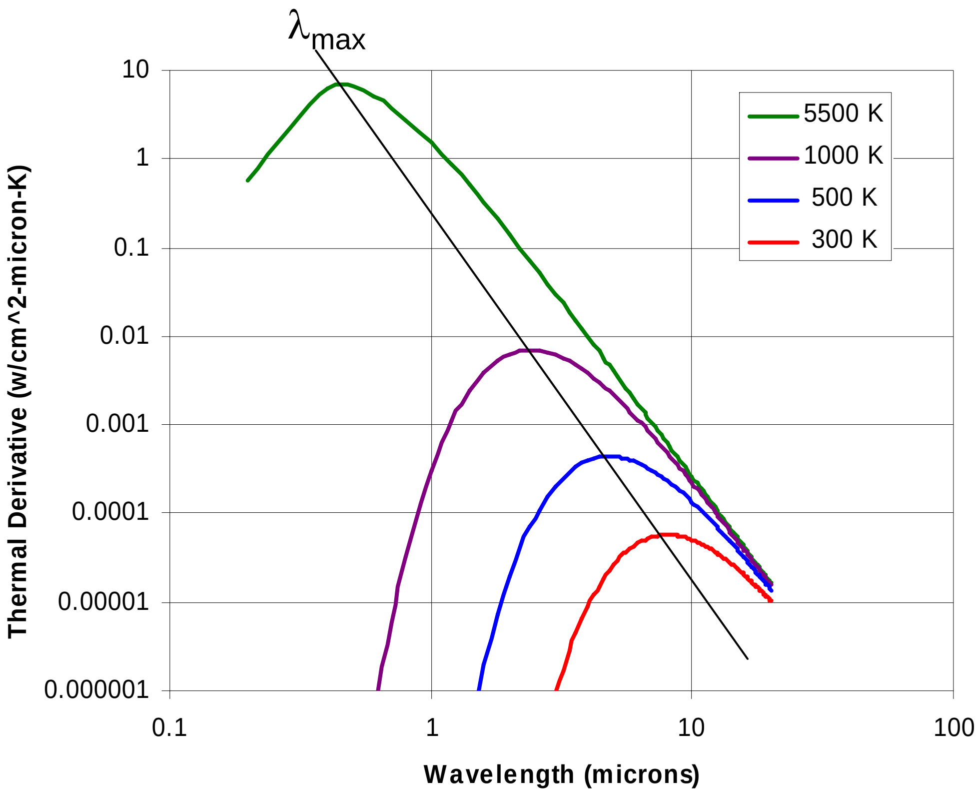
- Terrestrial objects are at about 300 K (~25° C)
  - The human body, for example, has a thermal contrast of about 3 – 8° C
- Thus, a typical IR scene has a contrast of only a few percent (as opposed to visible scenes, which have 100% contrast)
- To maintain the dynamic range in the important part of the image, the background is usually subtracted out



Blackbody Thermal Derivative

- Since the background is subtracted from the IR scene, the sensor really detects the change in temperature, or the thermal derivative $\partial W/\partial T$

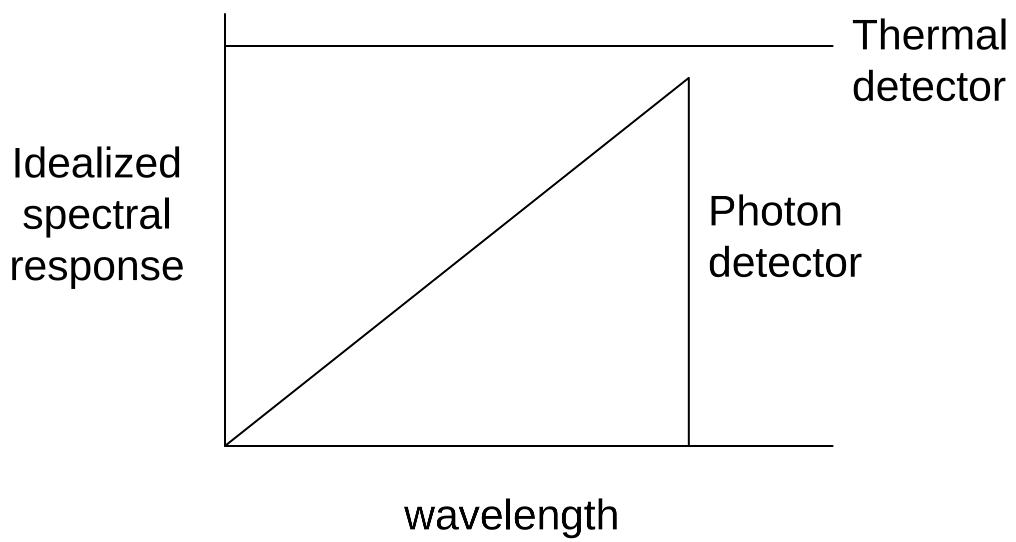
$$\frac{\partial W}{\partial T} = \frac{c_1 c_2 e^{c_2/\lambda T}}{\lambda^6 T^2 (e^{c_2/\lambda T} - 1)^2}$$



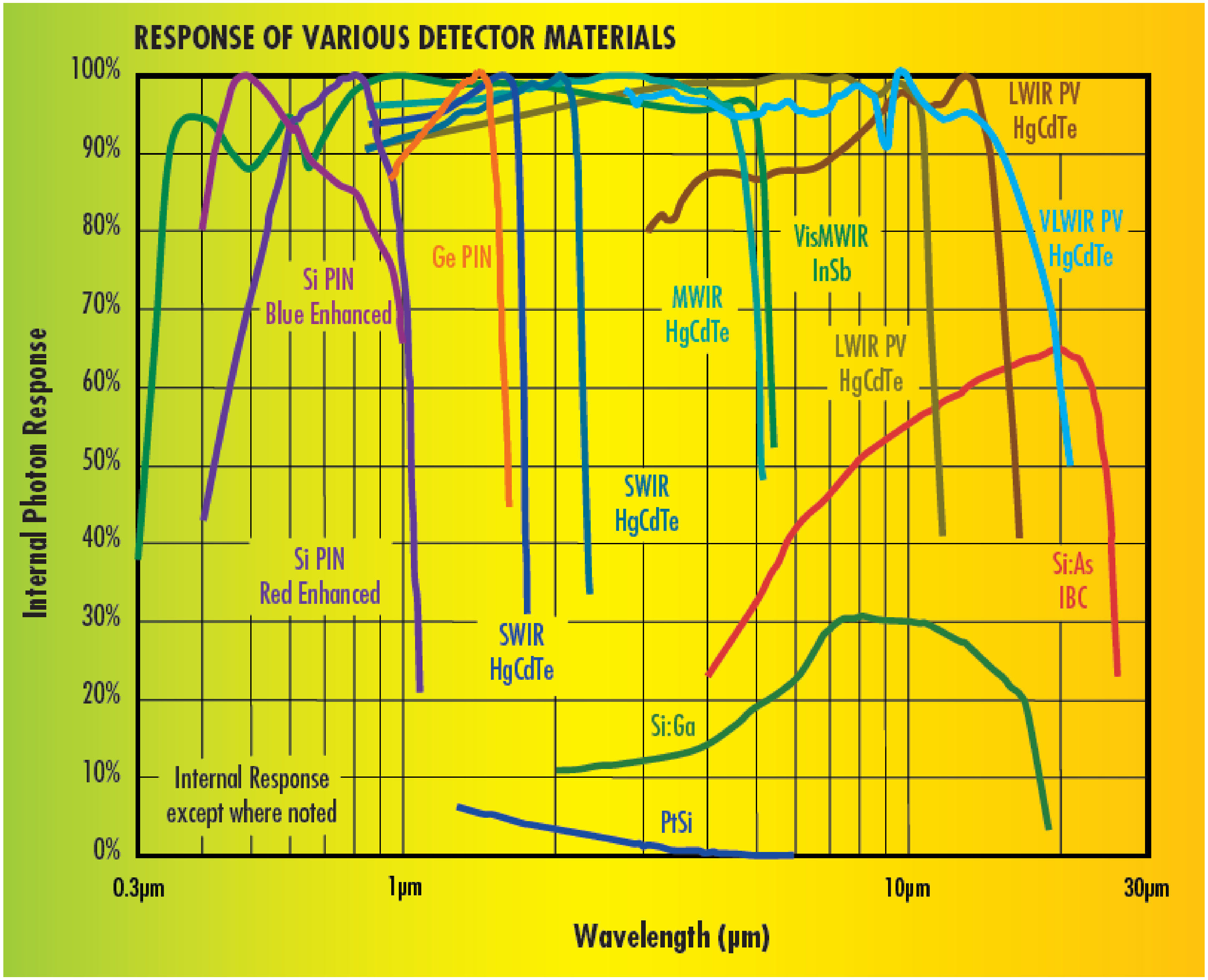
Peak wavelength is at λ_{max} = 2410/T

IR Detectors

- Two kinds of IR detectors
  - Thermal detectors – sense temperature
  - Photon detectors – sense photon energies
- Thermal detectors have a flat spectral response with wavelength
- Photon detectors have a spectral response proportional to wavelength with a peak wavelength (related to material properties such as band gaps) beyond which there is little or no response



Infrared Detectors



IR Signal

- The total signal received by the detectors is the product of the target spectral emission, the atmospheric transmittance, the optical transmittance, and the detector spectral response

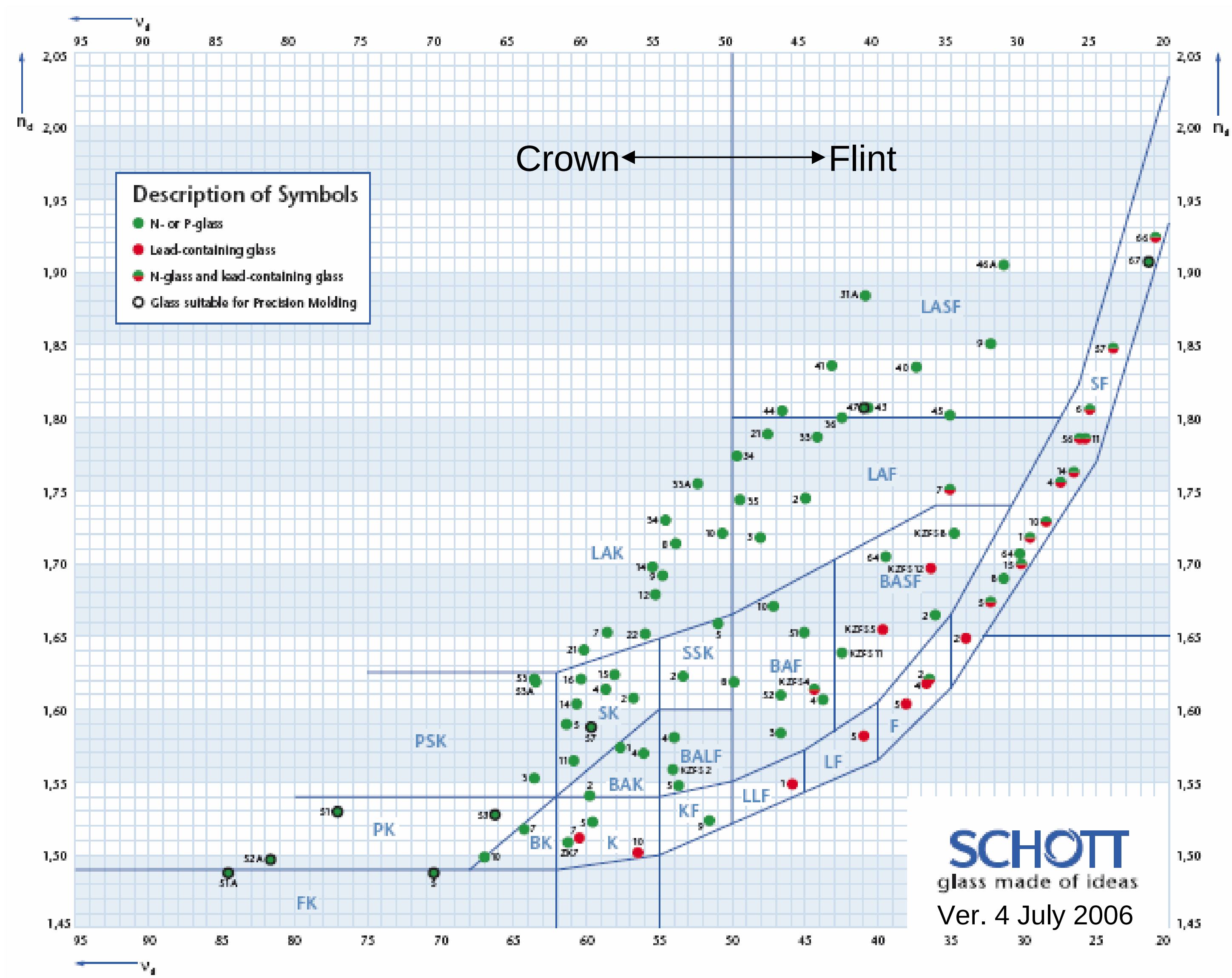
$$\text{Signal} = \int E_{\text{target}}(\lambda)\, \tau_{\text{atmosphere}}(\lambda)\, \tau_{\text{optics}}(\lambda)\, R_{\text{detector}}(\lambda)\, d\lambda$$

- Of course, there's also the radiometric factors such as target size, solid angles, f/numbers, detector size, etc., which we will not go into here
- We are also ignoring for this seminar the noise contributions such as thermal background, detector noise, electronic noise, etc.

Infrared Glasses vs. Visible Glasses

- IR glasses have significantly higher refractive indices
  - Visible glass – n ranges between 1.45 and 2.0
  - IR glasses – n ranges between 1.38 to 4.0
- Dispersion can be significantly lower (depending on spectral band)
  - Visible glasses – V ranges from 20 to 80
  - IR glasses – V ranges from 20 to 1000
- Many IR glasses are opaque in the visible
  - And most visible glasses are opaque in the IR
- IR glasses are often heavier than visible glasses
- IR glasses have significantly higher dn/dT values (factor of 10 or more higher)
- IR glasses cost more than visible glasses (by 2 or more orders of magnitude)
- Significantly fewer number of practical IR glasses than visible glasses

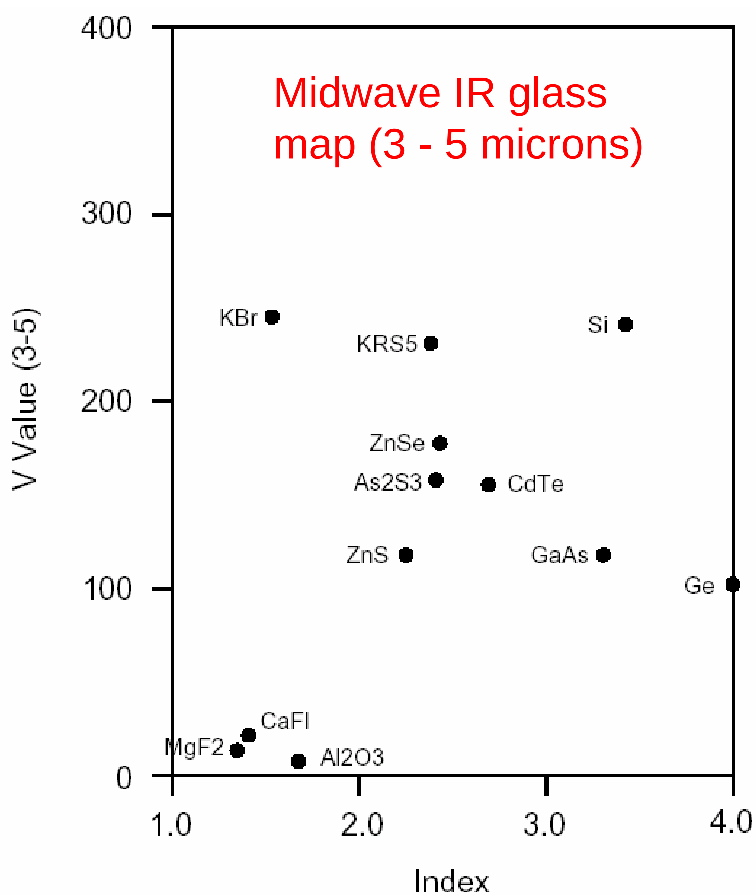
Visible Glass Map

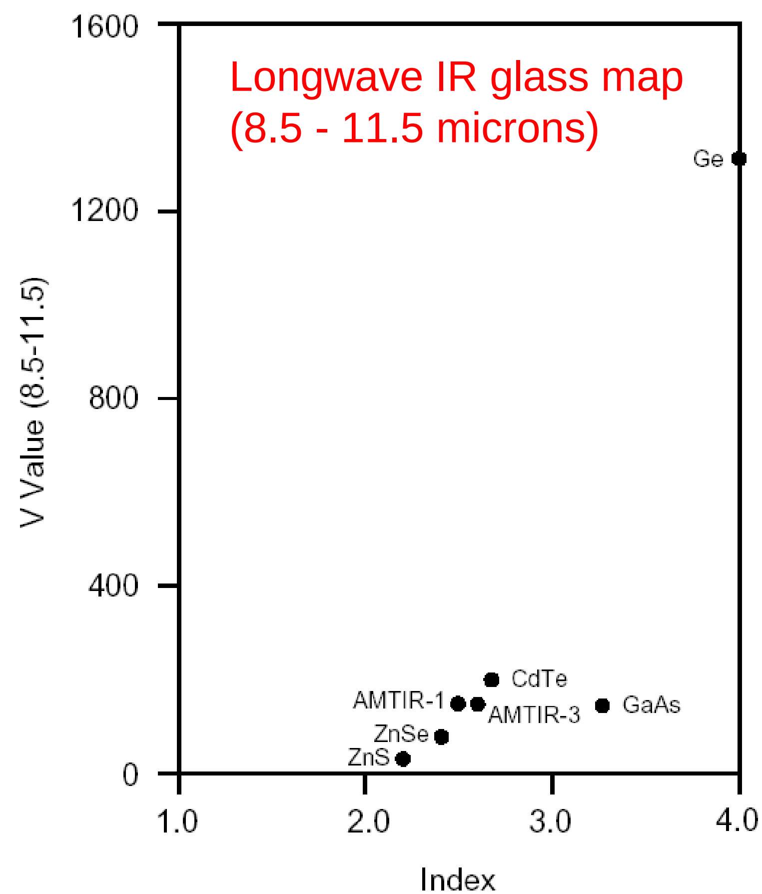


Infrared Glasses

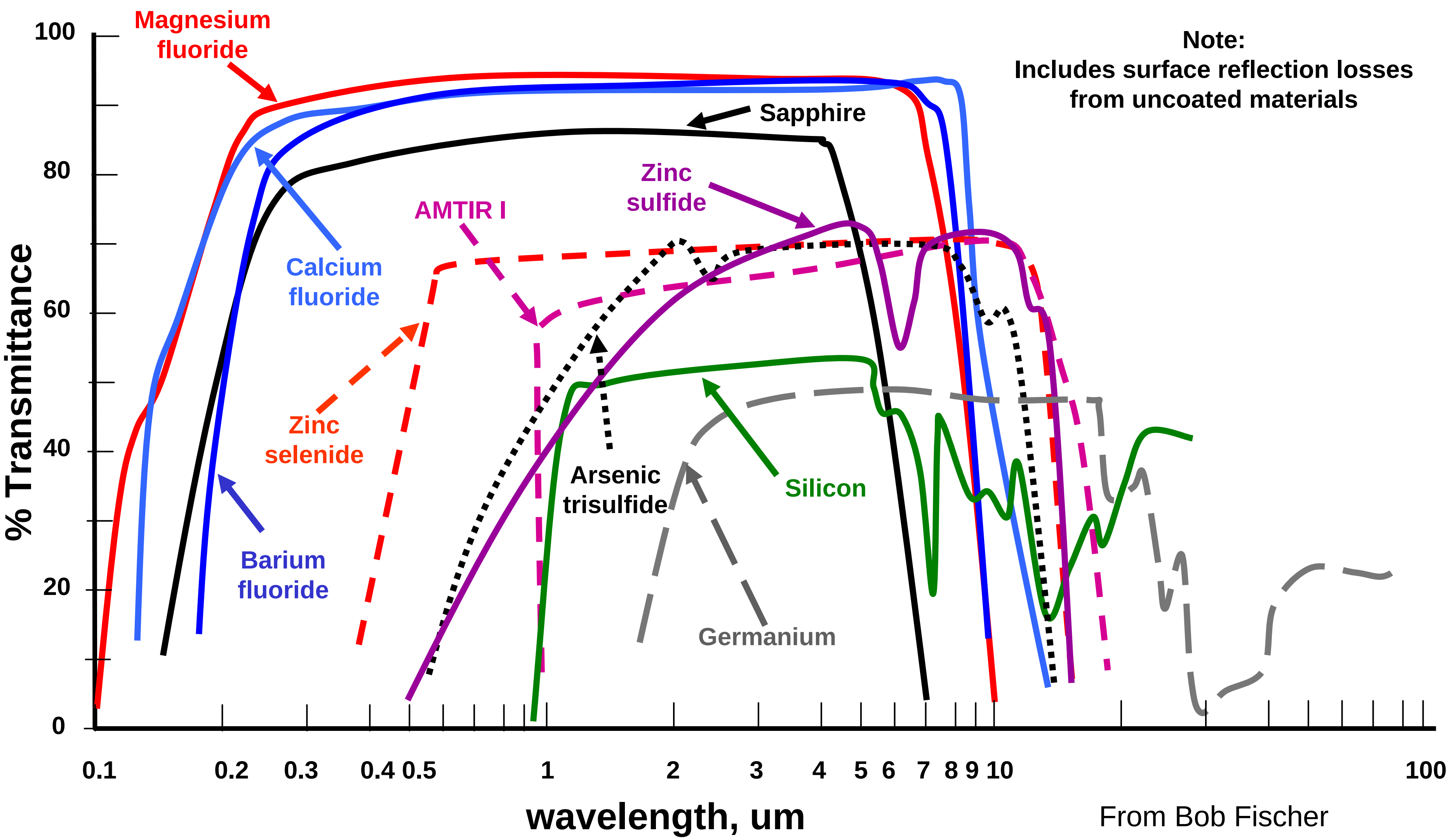
- The list of commonly used IR materials is (unfortunately) pretty short

Germanium	AMTIR 1, 3	Magnesium Fluoride
Silicon	Sapphire	Gallium Arsenide
Zinc Sulfide	Zinc Selenide	Calcium Fluoride





Transmittance of IR glasses



From Bob Fischer

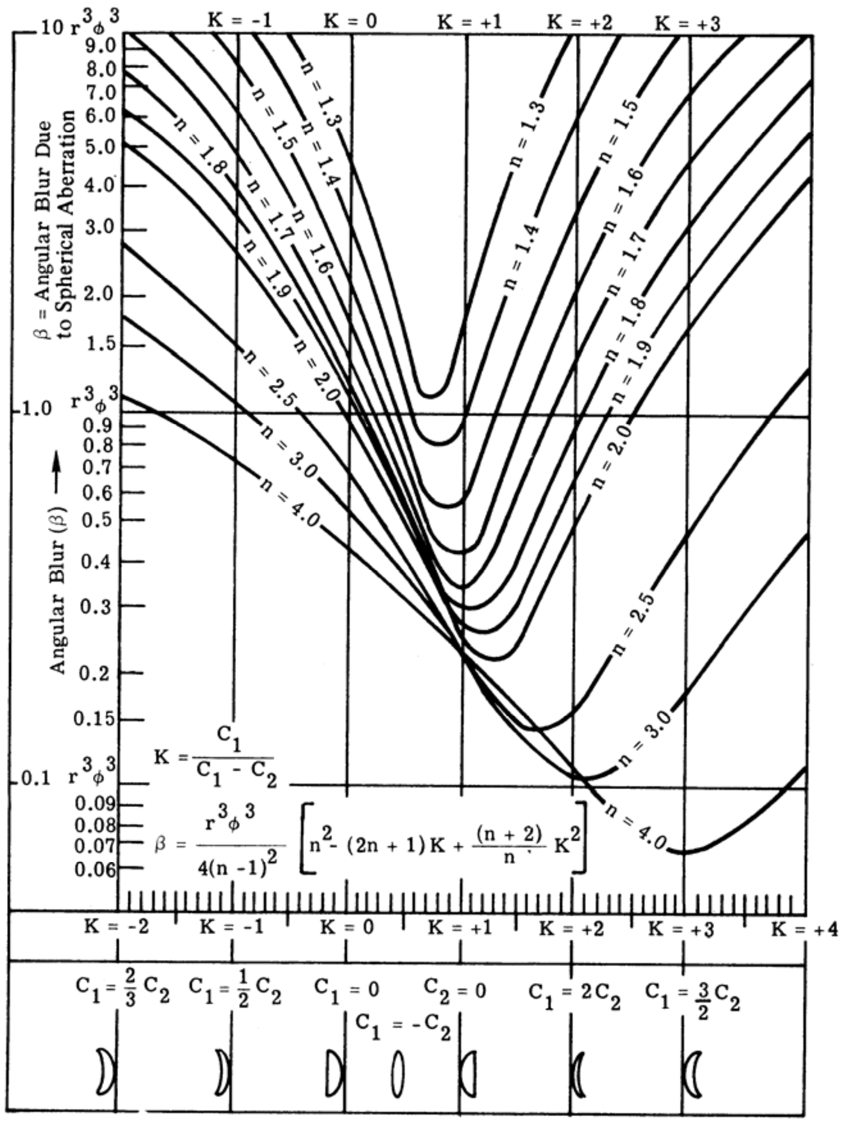
Designing With IR Glasses

- Advantages ☺
  - Refractive index is usually higher, so fewer lenses are needed to achieve diffraction-limited performance
  - Dispersion is often low enough such that color correction may not be necessary
  - Most IR materials can be diamond point machined, so aspherics are commonly used in designs
  - The Airy disk size and diffraction-limited depth of focus are larger for the IR than for the visible, so achieving diffraction-limited performance is easier
- Disadvantages ☹
  - Small choice of glasses
  - Materials are expensive (~1$/gram)
    - One-inch diameter BK7 lens $5
    - One-inch diameter germanium lens $500
    - Five-inch diameter sapphire dome Priceless
  - Some IR materials are difficult to fabricate and/or antireflection coat
    - Fragile, soft, chip easily, low thermal conductivity, etc.
  - Most IR materials have large dn/dT values, so athermalizing can be difficult

Cautions on IR Glasses and Optics Software

- There is only one source of data on Schott glasses – Schott Optical Glass
- However, there is no "source" of data on IR glasses
- Most optical software programs depend on some literature source of data for IR materials, then fit the data to Sellmeier equations
  - Some programs do a better job of this than others
- Some IR glasses, such as AMTIR, are made by a specific supplier who publishes index data on the material
  - Sometimes these data are not consistent, come from different measurement sources, and may not have sufficient significant digits
  - In these cases, if your design is sensitive to the glass dispersion, you may need to double-check the index data
- Thermal data, such as thermal expansion coefficient and dn/dT data may vary widely for some materials, depending on who measured it
  - Usually, optical software do not include these data, as there is no official "source" for these data

Spherical Aberration vs. Refractive Index



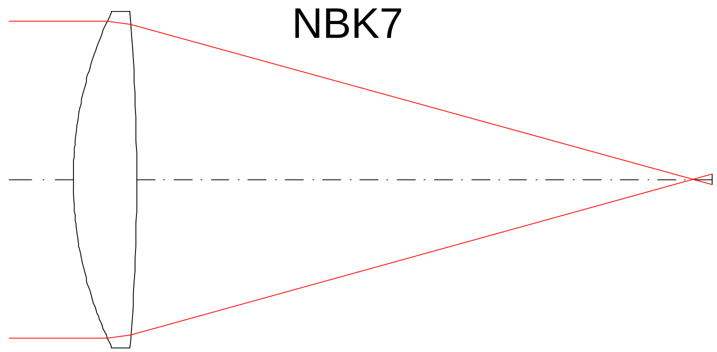
$$K_{min} = \frac{n(2n+1)}{2(n+2)}$$

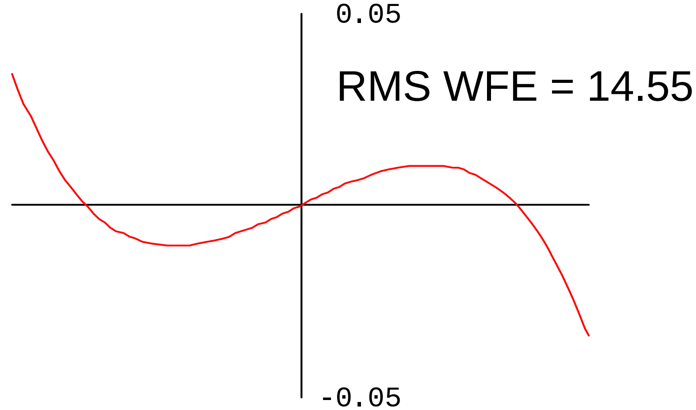
$$\beta \text{ at } K_{min} = r^3 \varphi^3 \frac{4n^2 - n}{16(n-1)^2(n+2)}$$

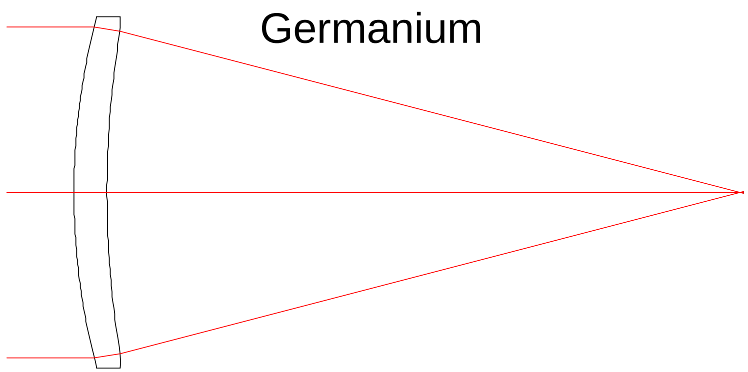
For germanium n = 4

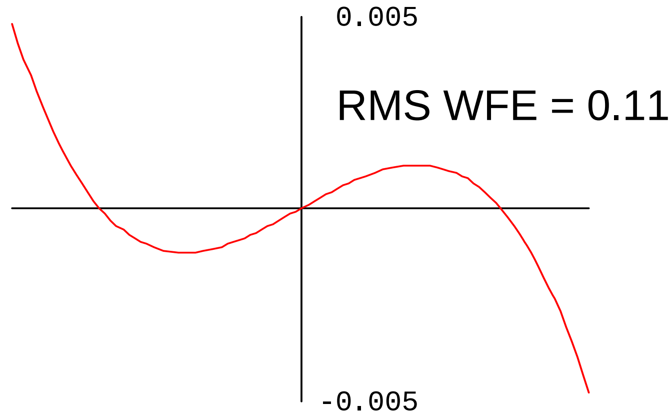
$$\beta = \frac{0.0087}{f^3}$$

NBK7 vs. Germanium – Spherical Aberration





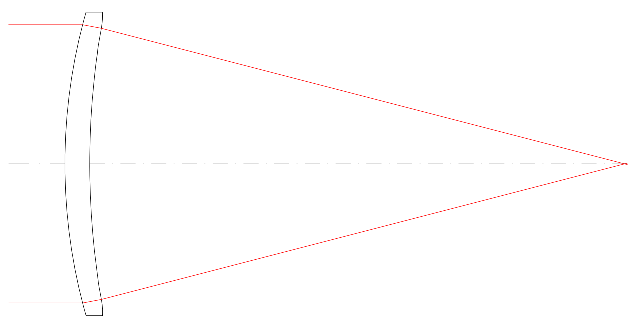


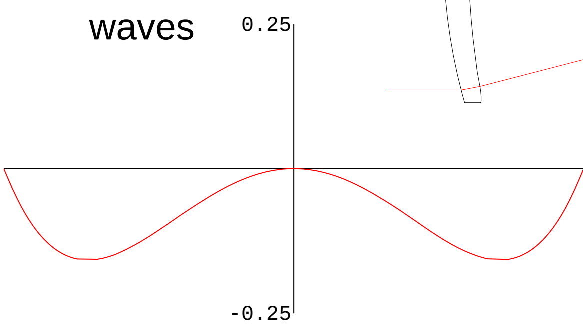


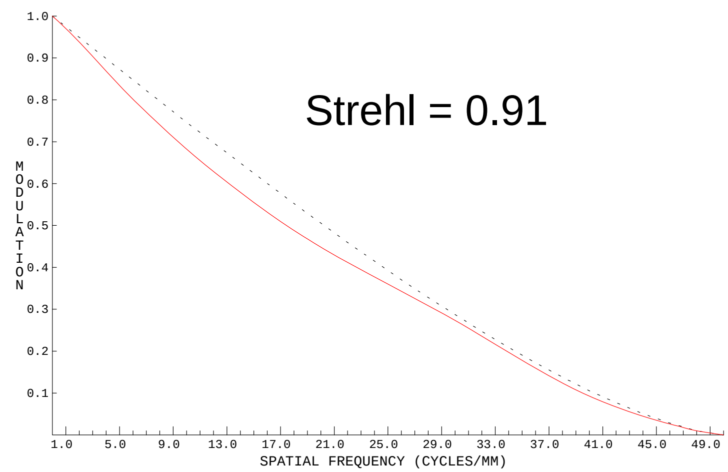
4.0 inch EFL, f/2

Example - Germanium Singlet

- We want an f/2 germanium singlet to be used at 10 microns (0.01 mm)
- Question - What is the longest focal length we can have and not need aspherics to correct spherical aberration?
- Answer
  - Diffraction Airy disk angular size is $\beta_{diff} = 2.44\ \lambda/D$
  - Spherical aberration angular blur is $\beta_{sa} = 0.0087 / f^3$
  - Equating these gives $D = 2.44\ \lambda\ f^3 / 0.0087 = 22.4$ mm
  - For f/2, this gives $F = 45$ mm

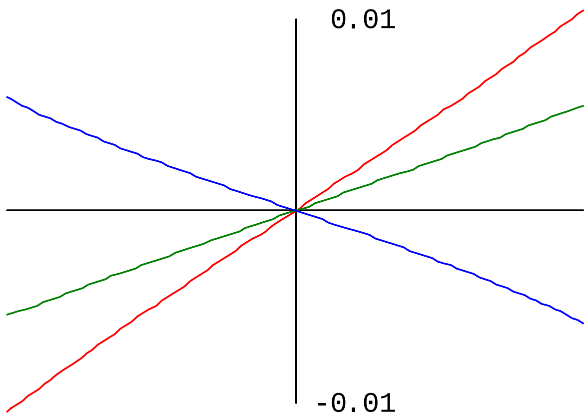


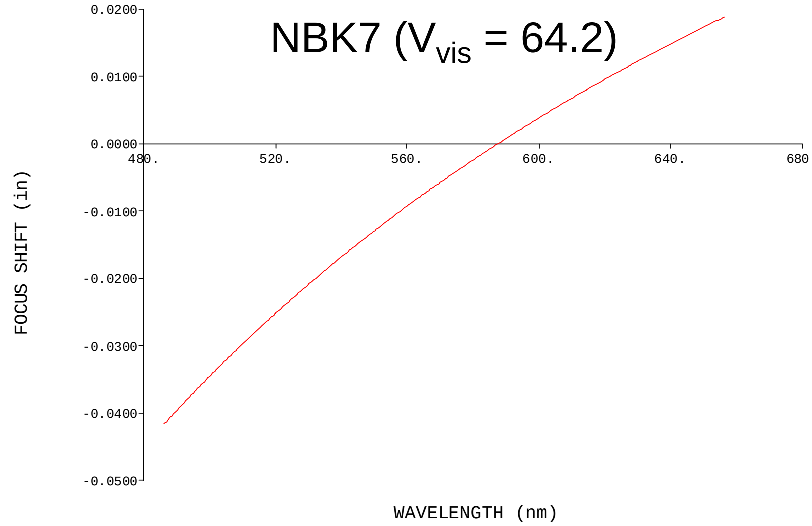


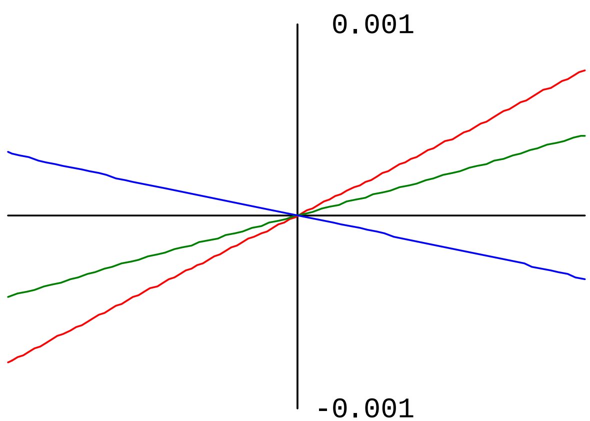


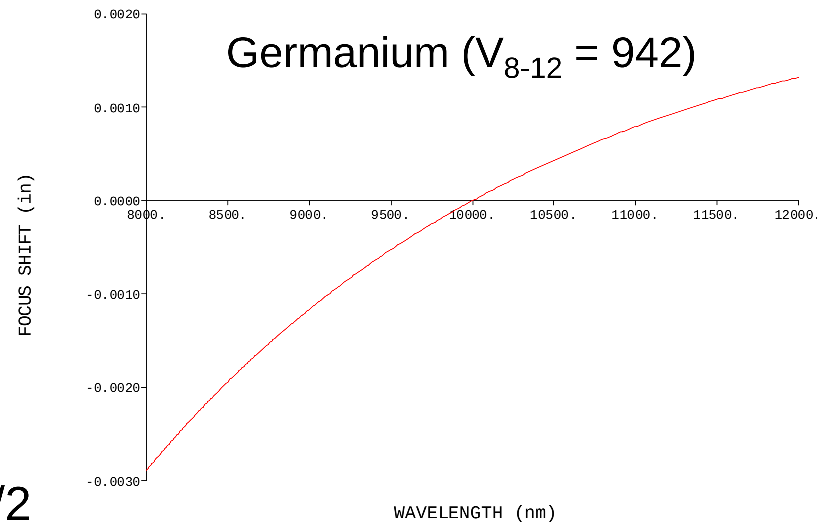
Strehl = 0.91

NBK7 vs. Germanium – Chromatic Aberration





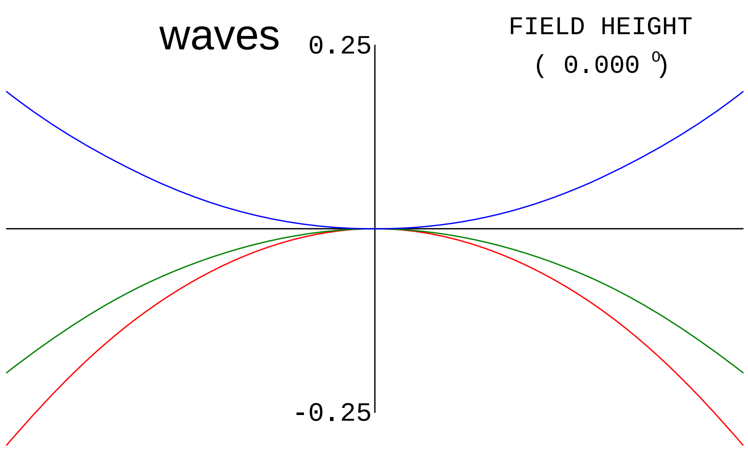


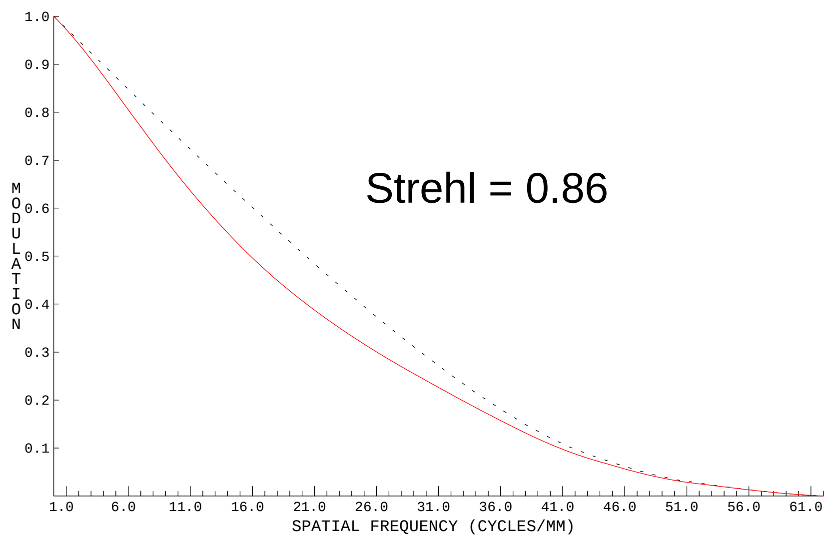


4.0 inch EFL, f/2

Chromatic Aberration Example - Germanium Singlet

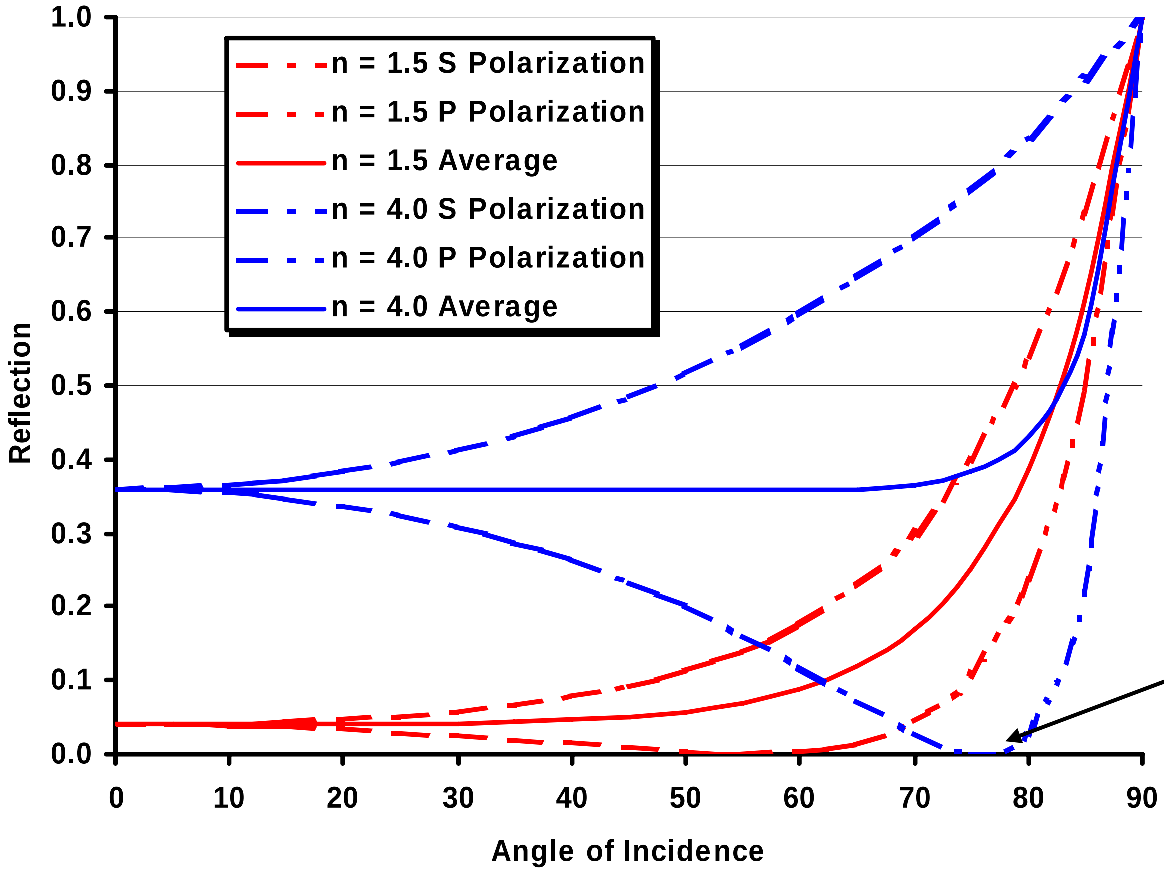
- We want to use an f/2 germanium singlet over the 8 to 12 micron band
- Question - What is the longest focal length we can have and not need to color correct? (assume an aspheric to correct any spherical aberration)
- Answer
  - Over the 8-12 micron band, for germanium V = 942
  - The longitudinal defocus = F / V = F / 942
  - The 1/4 wave depth of focus is $\pm 2\lambda f^2$
  - Equating these and solving gives $F = 4*942*\lambda*f^2 = 150$ mm





Surface Reflection

- Bare glass reflects a portion of the light hitting it
  - The amount reflected depends on the index of the glass, the angle of incidence of the light, and the polarization of the light



$$R_S = \frac{\sin^2(\theta - \theta')}{\sin^2(\theta + \theta')}$$

$$R_P = \frac{\tan^2(\theta - \theta')}{\tan^2(\theta + \theta')}$$

Brewster's angle = $\tan^{-1} n$

Single Layer Anti-reflection Coating

- The single layer is the simplest anti-reflection (AR) coating
- Let the incident medium be n_0 (usually air, so n_0 = 1), the index of the coating be n_1, and the index of the substrate be n_2
- The reflectivity of the surface for an incident angle θ is

$$R = \frac{r_1^2 + r_2^2 + 2r_1r_2\cos X}{1 + r_1^2r_2^2 + 2r_1r_2\cos X} \qquad \text{where} \qquad X = \frac{4\pi n_1 t\cos\theta}{\lambda}$$

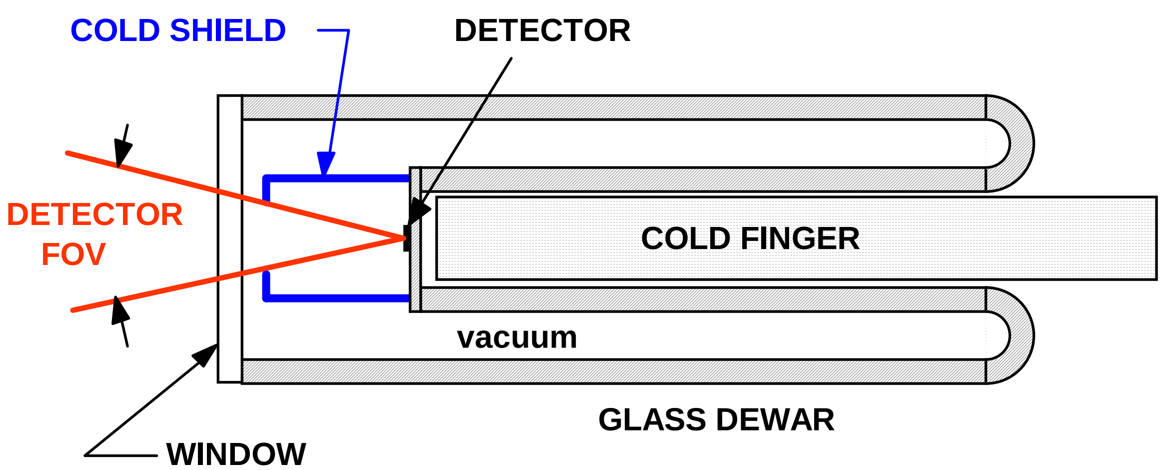
  - R is minimized when cosX = -1, or when $n_1 t = \lambda/4$

- For normal incidence, $r_1 = \frac{n_0 - n_1}{n_0 + n_1}$ $\quad r_2 = \frac{n_1 - n_2}{n_1 + n_2}$

Then $R = \left[\frac{n_0n_2 - n_1^2}{n_0n_2 + n_1^2}\right]^2$ minimized when $n_1 = \sqrt{n_0n_2}$

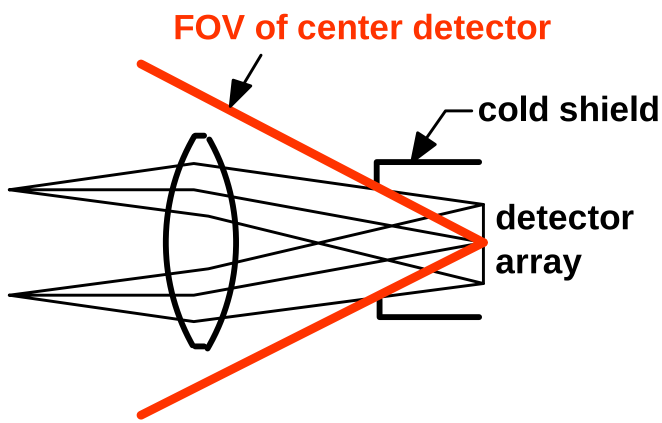
Cooled Detectors

- Many IR systems require a cooled detector
  - Typically cooled to 77 K or lower (liquid nitrogen temperatures)
- To avoid frosting up, the detectors are mounted in a thermally insulated vacuum enclosure called a dewar
- Inside the dewar, a cold shield limits the angle of radiation which can be seen by the detector
  - This increases the detector sensitivity (D*)

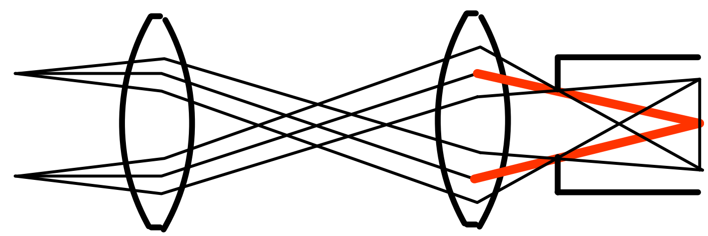


Cold Shield Efficiency

- All IR systems with cooled detectors have a cold shield in the dewar to minimize the background radiation
  - The size of this cold shield determines the amount of background radiation seen by the detector and hence the system sensitivity



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

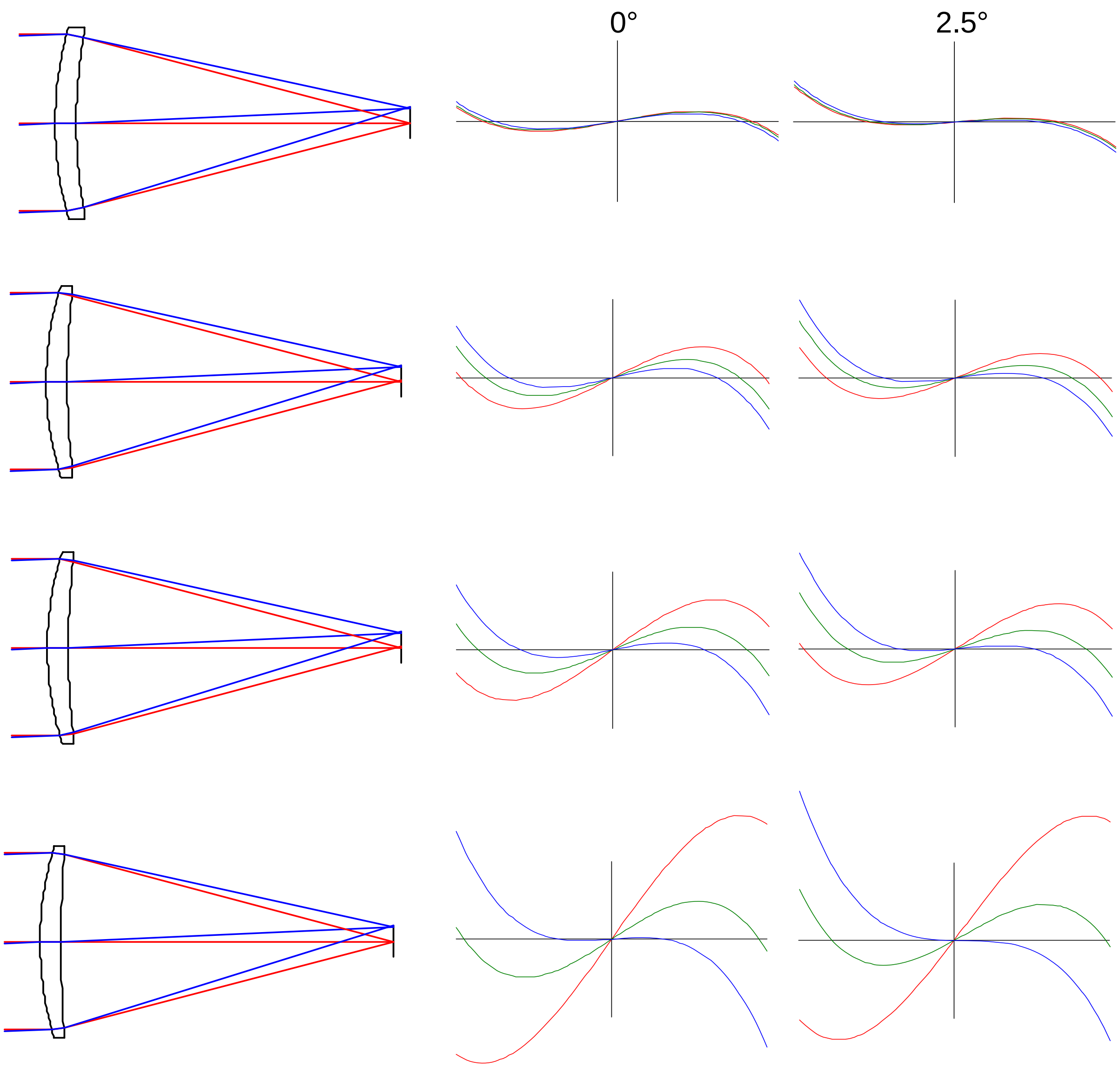


100% cold shielding efficiency (using re-imaging imager)

Aperture Stop and Pupil Aberration

- The aperture stop is usually at one of two locations
  - On the front lens
  - At the cold shield
- Whichever one it is located at, it is often imaged onto the other to minimize its size
- Pupil aberration (spherical or coma of the pupil) usually causes the image of the stop to be oversized by about 10-15%
  - If the stop is at the front objective, this requires an enlarged cold shield
    - Result is lower detector sensitivity and lower system performance
  - If the stop is at the cold shield, this requires an oversized objective
    - This increases cost and weight

Singlet Design Examples – f/2, 50 mm EFL (8 – 12 μ)



Germanium singlet (V=942)

RMS WFE = .096

AMTIR-1 singlet (V = 110)

RMS WFE = .209

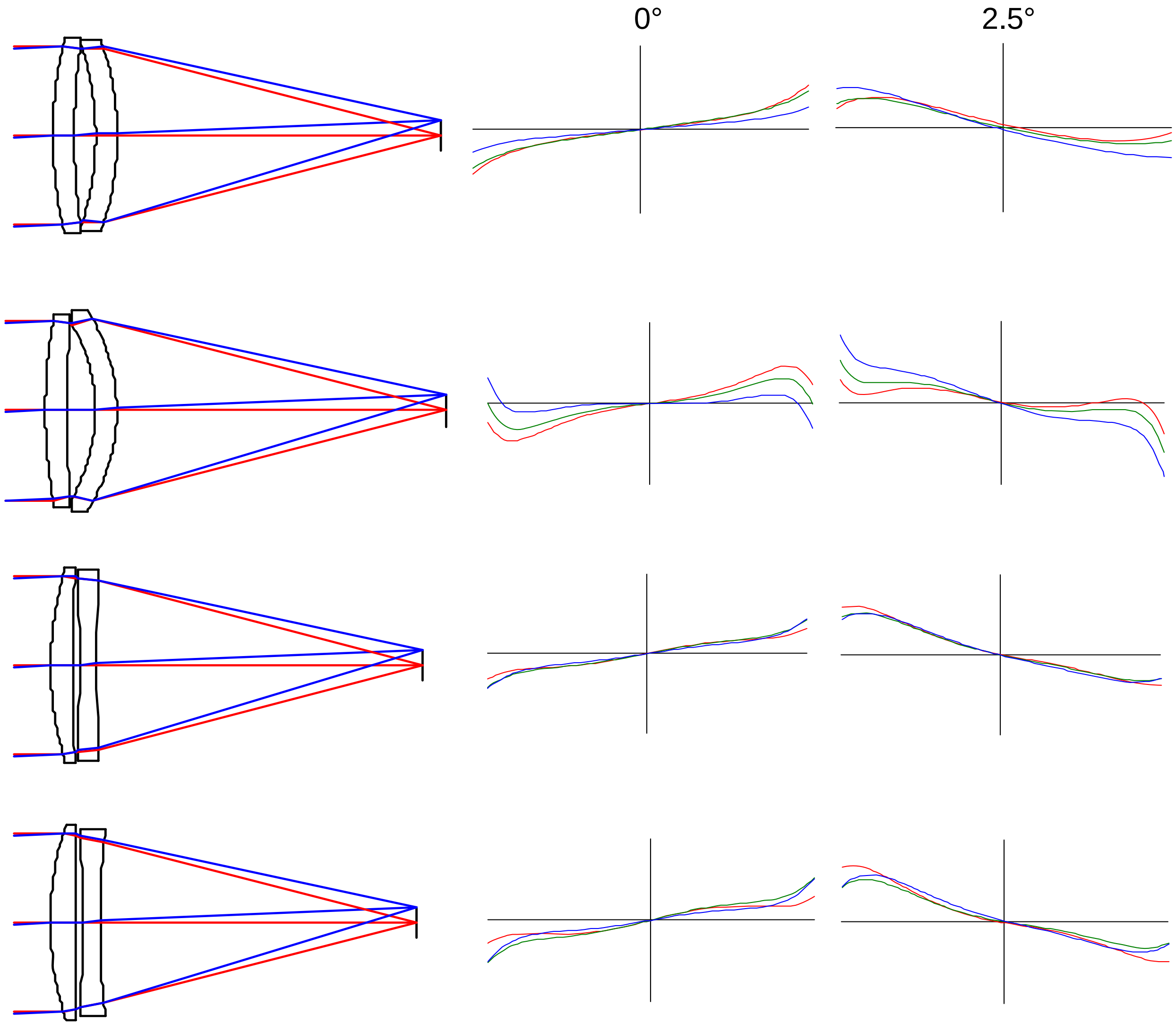
ZnSe singlet (V = 58)

RMS WFE = .331

ZnS singlet (V = 23)

RMS WFE = .769

Doublet Design Examples – f/2, 50 mm EFL (8 – 12 μ)



Germanium/ZnS

RMS WFE = .065

Germanium/AMTIR-1

RMS WFE = .064

AMTIR-1/ZnS

RMS WFE = .074

ZnSe/ZnS

RMS WFE = .079

Temperature Effects

- An optical element has two properties which cause changes in optical performance with temperature
  - The coefficient of thermal expansion, CTE, usually denoted by α with units of length/length/°C
  - The change in refractive index with temperature dn/dT
- The change in focal length of a lens with temperature is given by

$$\Delta F = F\left(\alpha - \frac{1}{n-1}\frac{dn}{dT}\right)\Delta T$$

- Since in most cases the focal length decreases with temperature, the equation is usually stated as $\Delta F = -\nu F \Delta T$ where

$$\upsilon = \frac{1}{n-1}\frac{dn}{dT} - \alpha$$

  - ν is often referred to as the thermo-optic coefficient
- The shift in focus relative to the image plane also includes the CTE of the lens mount, so the shift in focus is given by $\Delta_{focus} = -(\nu + \alpha_{mount})\ F\ \Delta T$

ν Values of Optical Materials ($x10^6$/°C)

- Visible glasses

BK7	1.5
BaK4	0.3
BaK50	-11.4
SK16	3.4
SF4	-3.8

- Infrared glasses

Germanium	127
TI-1173	34
ZnS	28
ZnSe	35
Silicon	63

- CTE of common mount materials ($x10^6$/°C)

Aluminum 6061	23.4
416 stainless	9.9
Invar35	0.6
Titanium	8.7
Beryllium	11.6

It is possible to find combinations of visible glasses to make an athermal design with common mounting materials

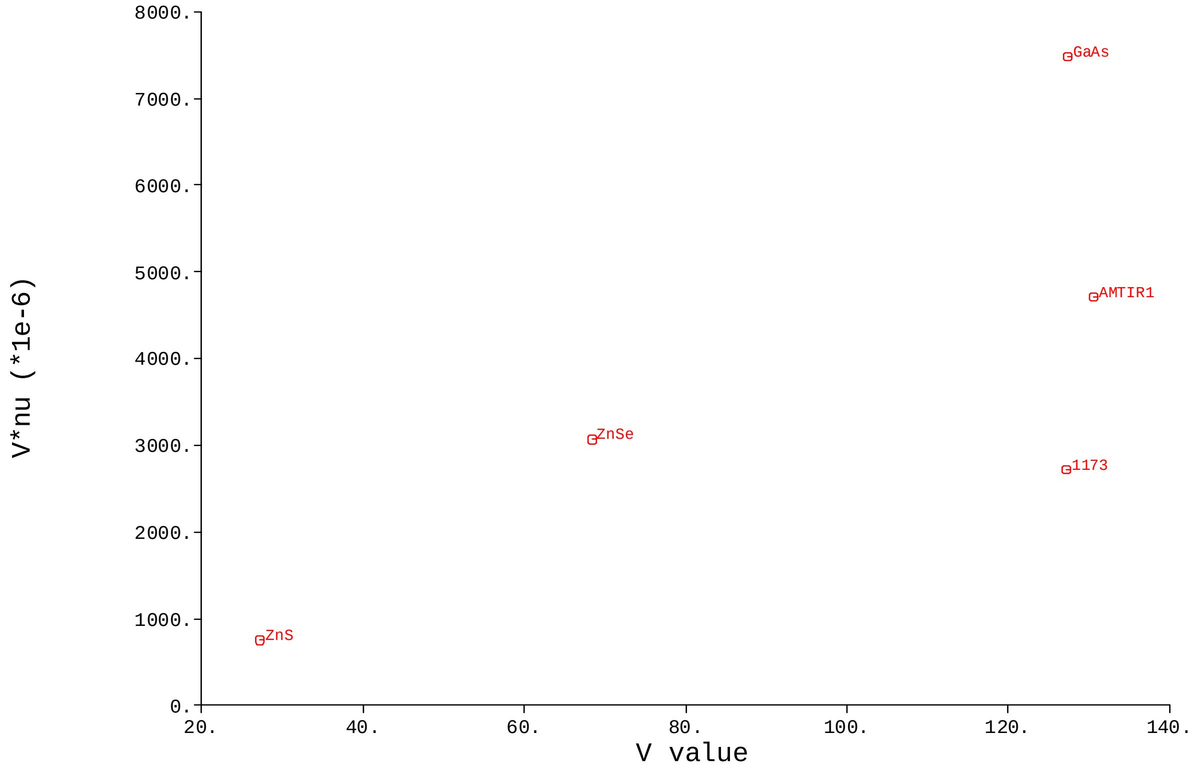
Most common IR materials have positive ν, so it is more difficult to make a passive athermal design

Example of Temperature Change

- An IR lens is made of germanium for use at 10 microns
- It has a focal length of 4 inches and an aperture of 2 inches (f/2)
- The diffraction-limited depth of focus is $\pm 2\lambda f^2 = \pm 0.0032$ inches
- If we mount the lens in an aluminum mount, the change in focus is $\Delta_{focus} = 4(-127-23) \times 10^{-6}/°C = -0.0006$ in/°C
- The lens defocus will exceed the diffraction depth of focus over a change in temperature of ±5° C
  - Note that for military applications, the operating temperature range is typically ±50° C

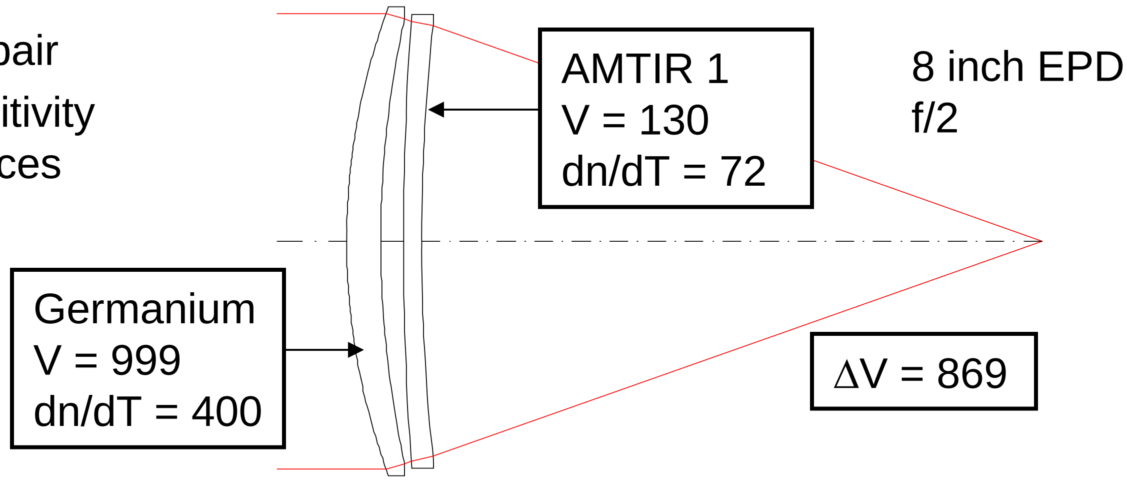
Making an Athermal Doublet

- To satisfy achromatism, the two lenses of a doublet must satisfy the usual achromatic equations
  $f_a = f\,(V_a - V_b)\,/\,V_a$
  $f_b = f\,(V_b - V_a)\,/\,V_b$
- To be athermalized, the lenses must also satisfy
  $V_a \nu_a = V_b \nu_b$

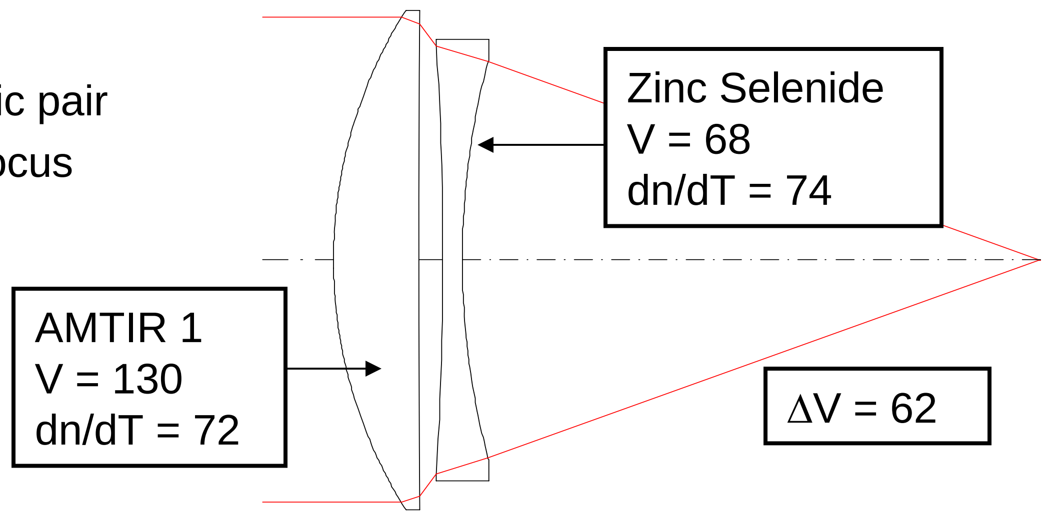


IR Achromatic Doublet Examples (8 - 11.5 microns)

- Common IR achromatic pair
  - Up to 25% less sensitivity to dispersion tolerances



- Reduced dn/dT achromatic pair
  - 3X lower change in focus due to temperature



Infrared Optics Suppliers

- Elcan Optical Systems, Richardson, TX
- Corning NetOptix, Keene, NH
- Exotic Electro-Optics, Marietta, CA
- Optimum Optical Systems, Camarillo, CA
- II-VI Incorporated, Saxonburg, PA
- Janos Technology, Keene, NH
- DRS Optronics, Palm Bay, FL
- Coherent, Auburn, CA
- Diversified Optical Products, Salem, NH
- Telic OSTI, North Billerica, MA

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- Optical System Design, Fischer and Tadic-Galeb, McGraw-Hill (2000)
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