Infrared Optical Systems

OPTI 696

Practical Optics Seminar

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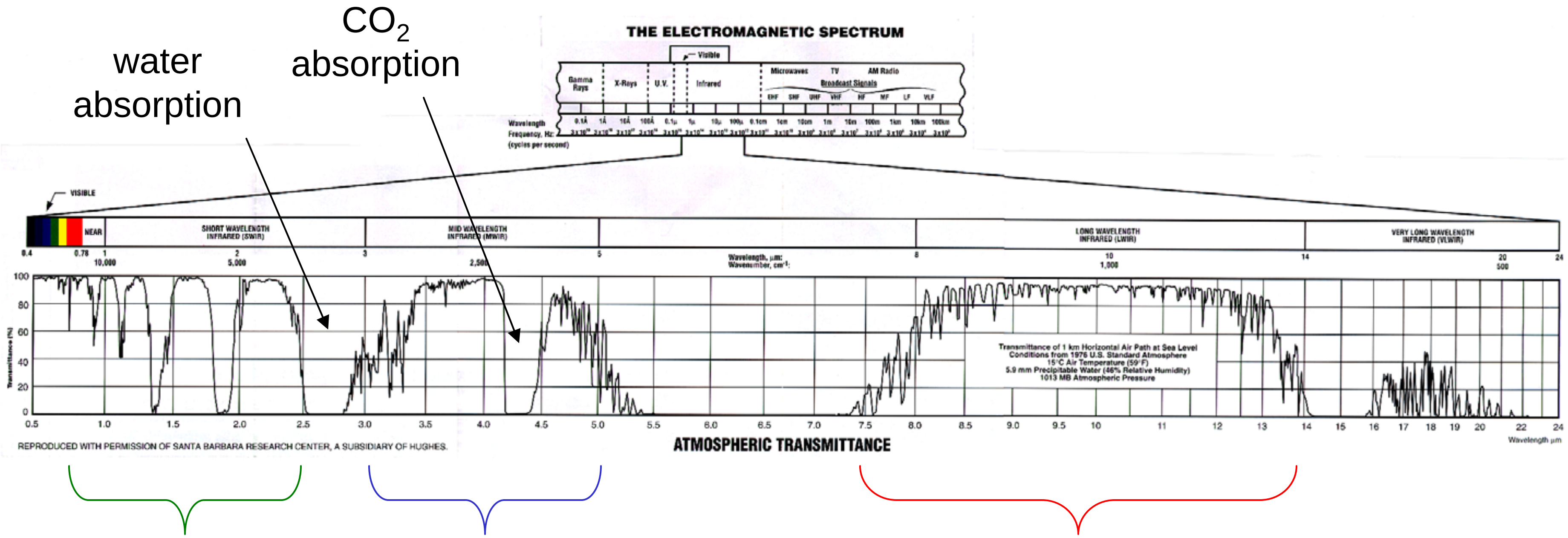
Atmospheric Transmittance



Transmittance of 1 km Horizontal Air Path at Sea Level Conditions from 1976 U.S. Standard Atmosphere
15°C Air Temperature (59°F)
5.9 mm Precipitable Water (46% Relative Humidity)
1013 MB Atmospheric Pressure

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water absorption

CO_2 absorption

NIR
(0.7 – 2.5 μ)

MWIR
(3.0 – 5.0 μ)

LWIR
(7.5 – 14.0 μ)

Blackbody Radiation

- Blackbodies emit per the following equation

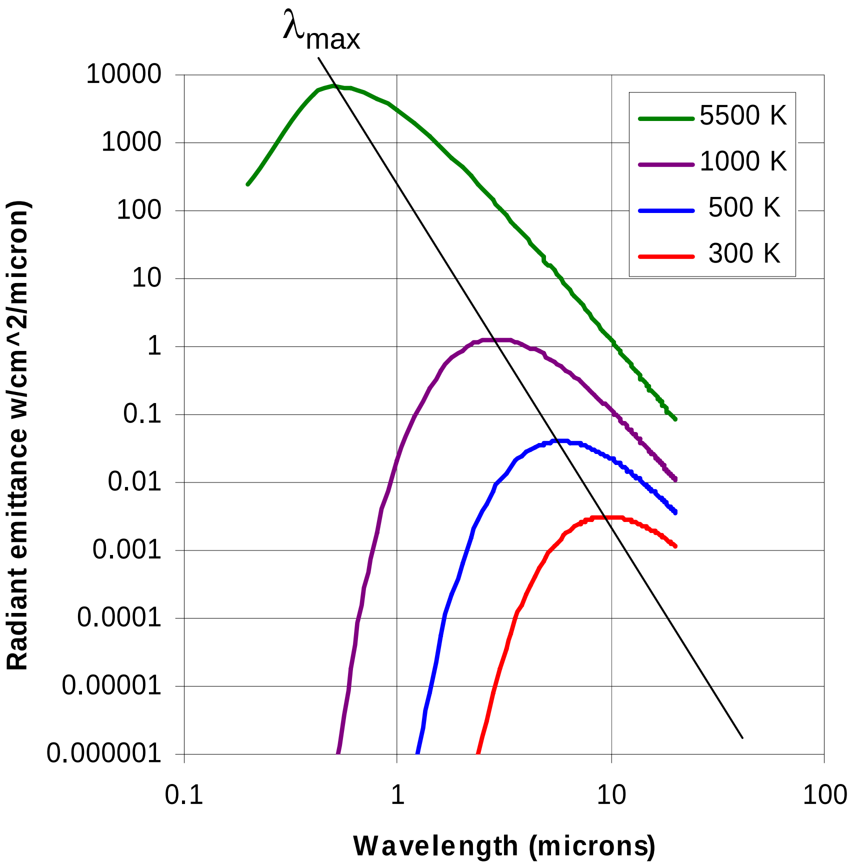
$$W(\lambda) = \frac{c_1}{\lambda^5 (e^{c_2/\lambda T} - 1)}$$

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

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

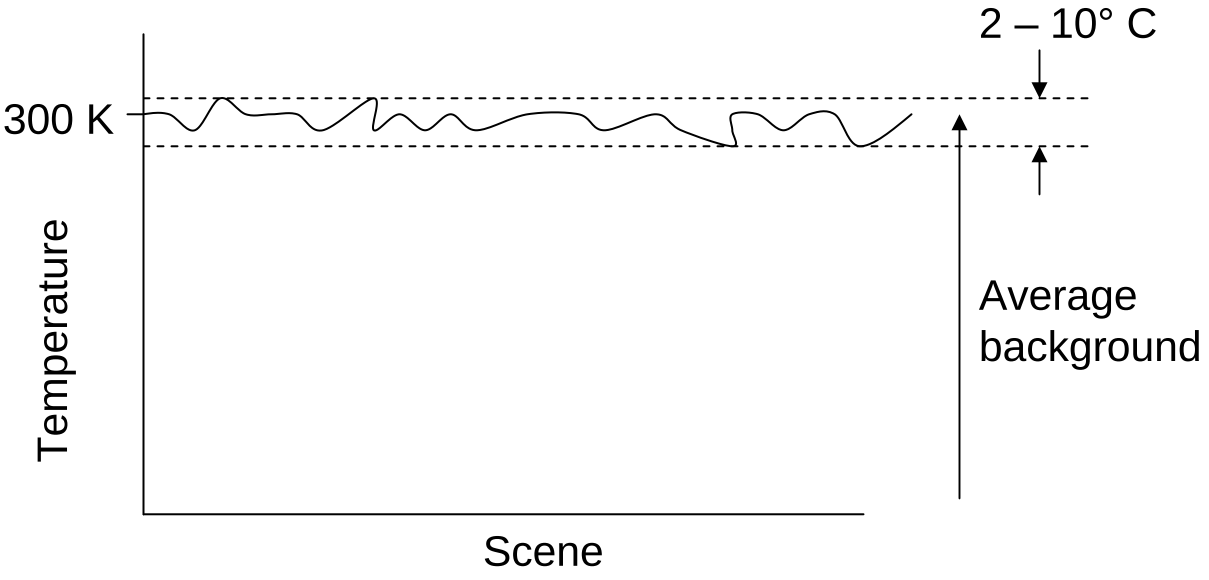
- The peak of the curve occurs at λ_{max} = 2898/T
  - Visible (T = 5500) λ_{max} = 0.53 μ
  - MWIR (T = 500) λ_{max} = 5.8 μ
  - LWIR (T = 300) λ_{max} = 9.7 μ

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



Thermal Contrast

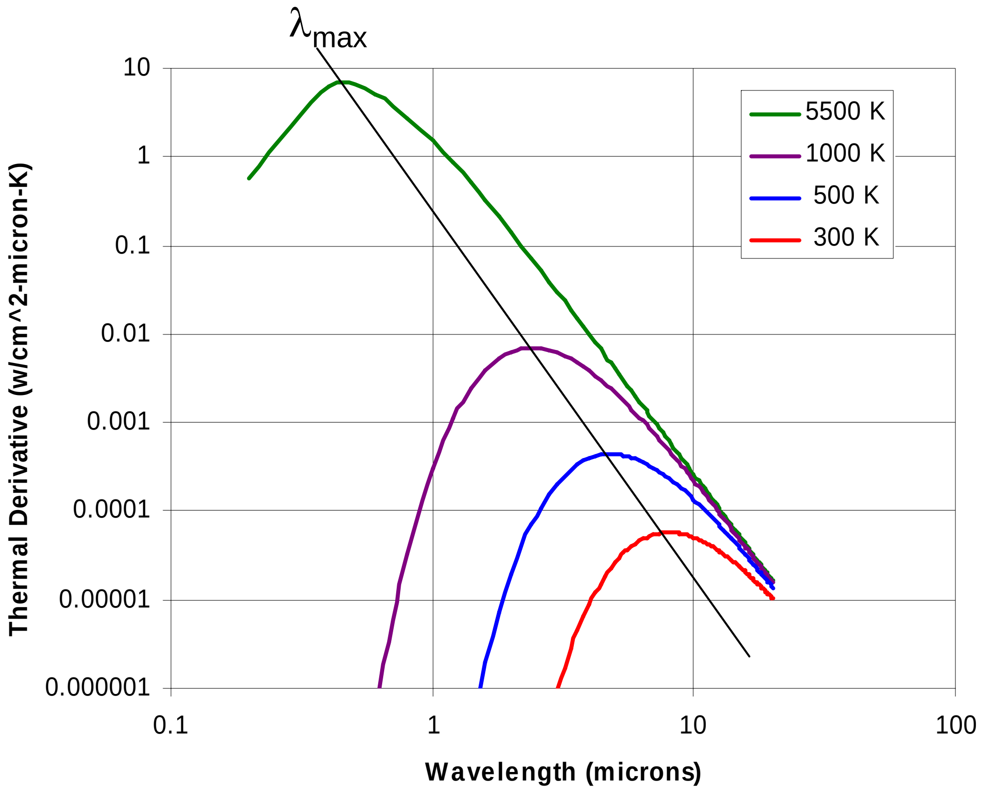
- Terrestrial objects are at about 300 K (~25° C)
  - The human body, for example, has a thermal contrast of about 3 – 8° C
- Thus, a typical IR scene has a contrast of only a few percent (as opposed to visible scenes, which have 100% contrast)
- To maintain the dynamic range in the important part of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

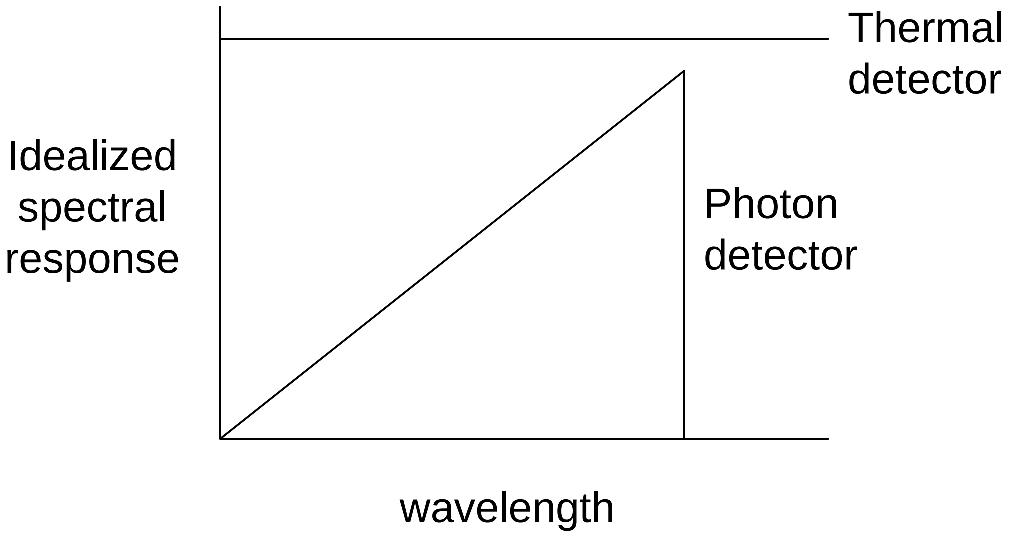
$$\frac{\partial W}{\partial T} = \frac{c_1 c_2 e^{c_2/\lambda T}}{\lambda^6 T^2 (e^{c_2/\lambda T} - 1)^2}$$



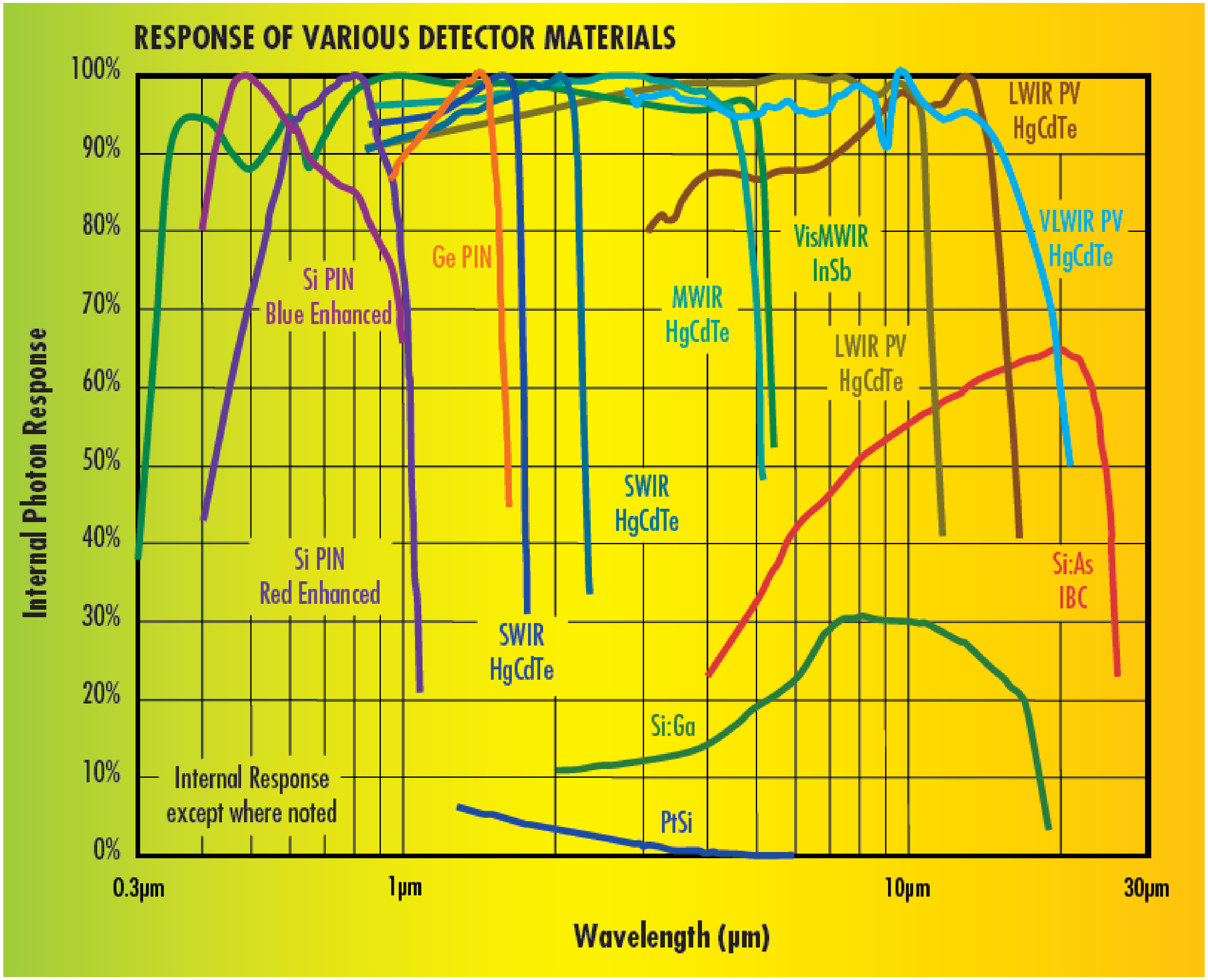
Peak wavelength is at $\lambda_{max} = 2410/T$

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

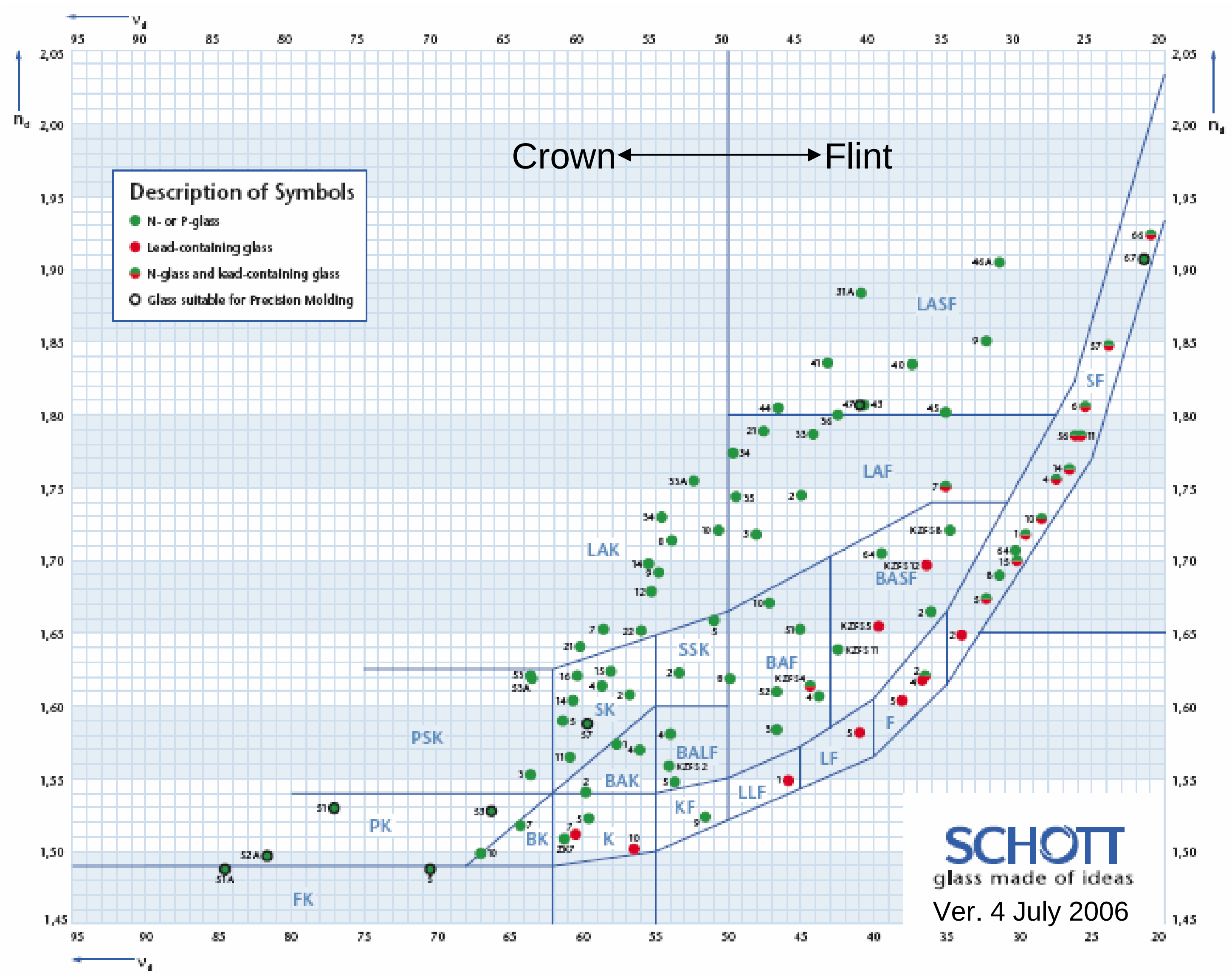
$$\text{Signal} = \int E_{\text{target}}(\lambda)\, \tau_{\text{atmosphere}}(\lambda)\, \tau_{\text{optics}}(\lambda)\, R_{\text{detector}}(\lambda)\, d\lambda$$

- 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

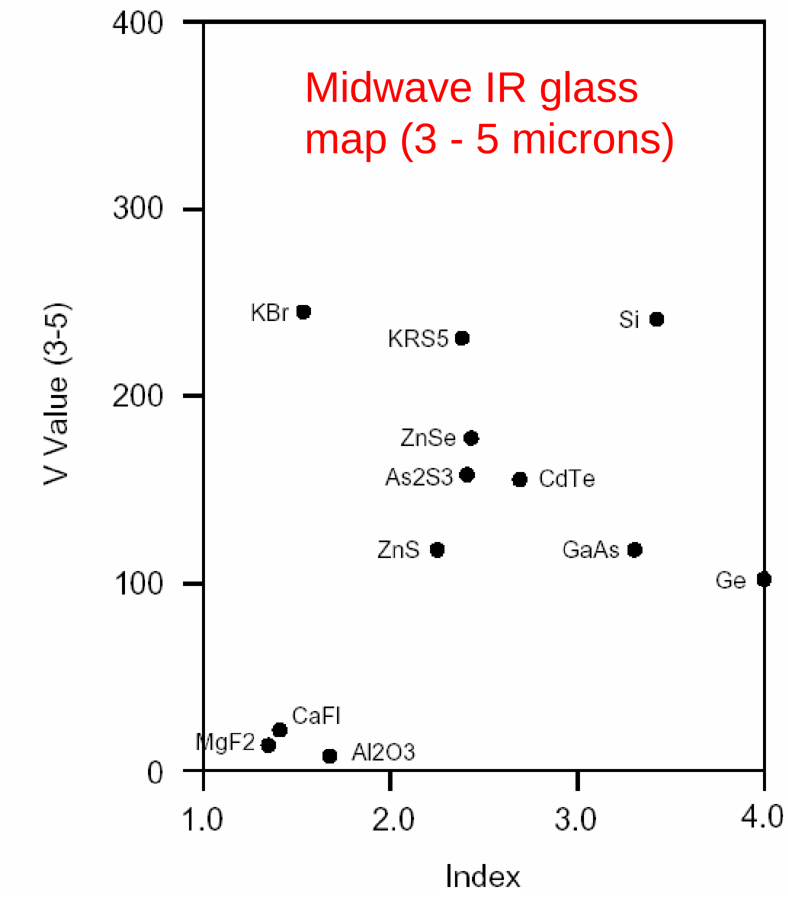
Visible Glass Map

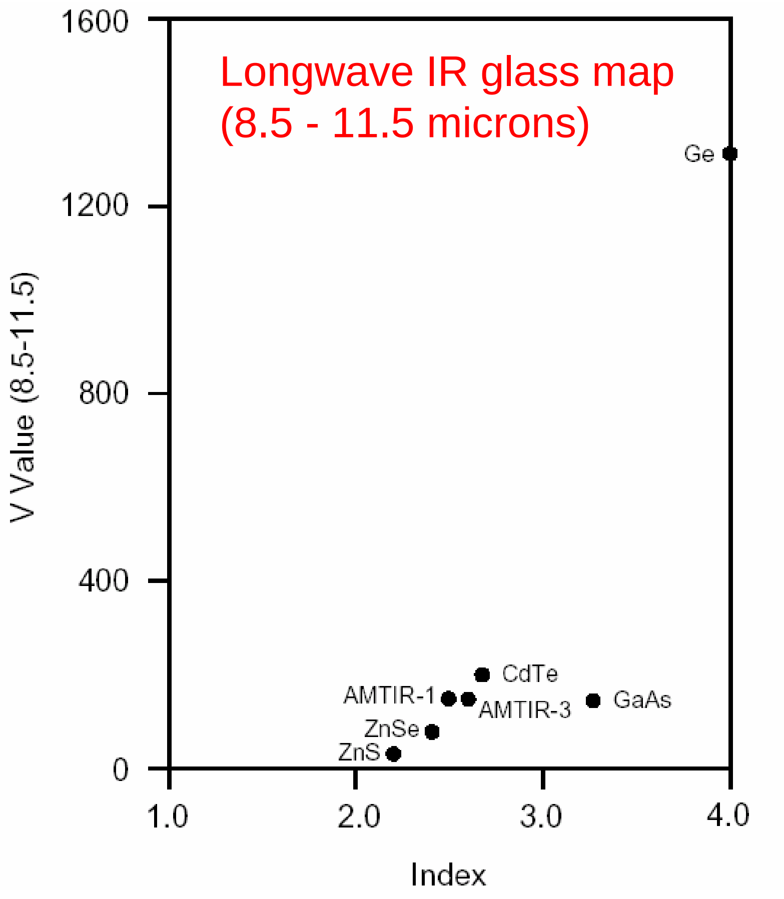


Ver. 4 July 2006

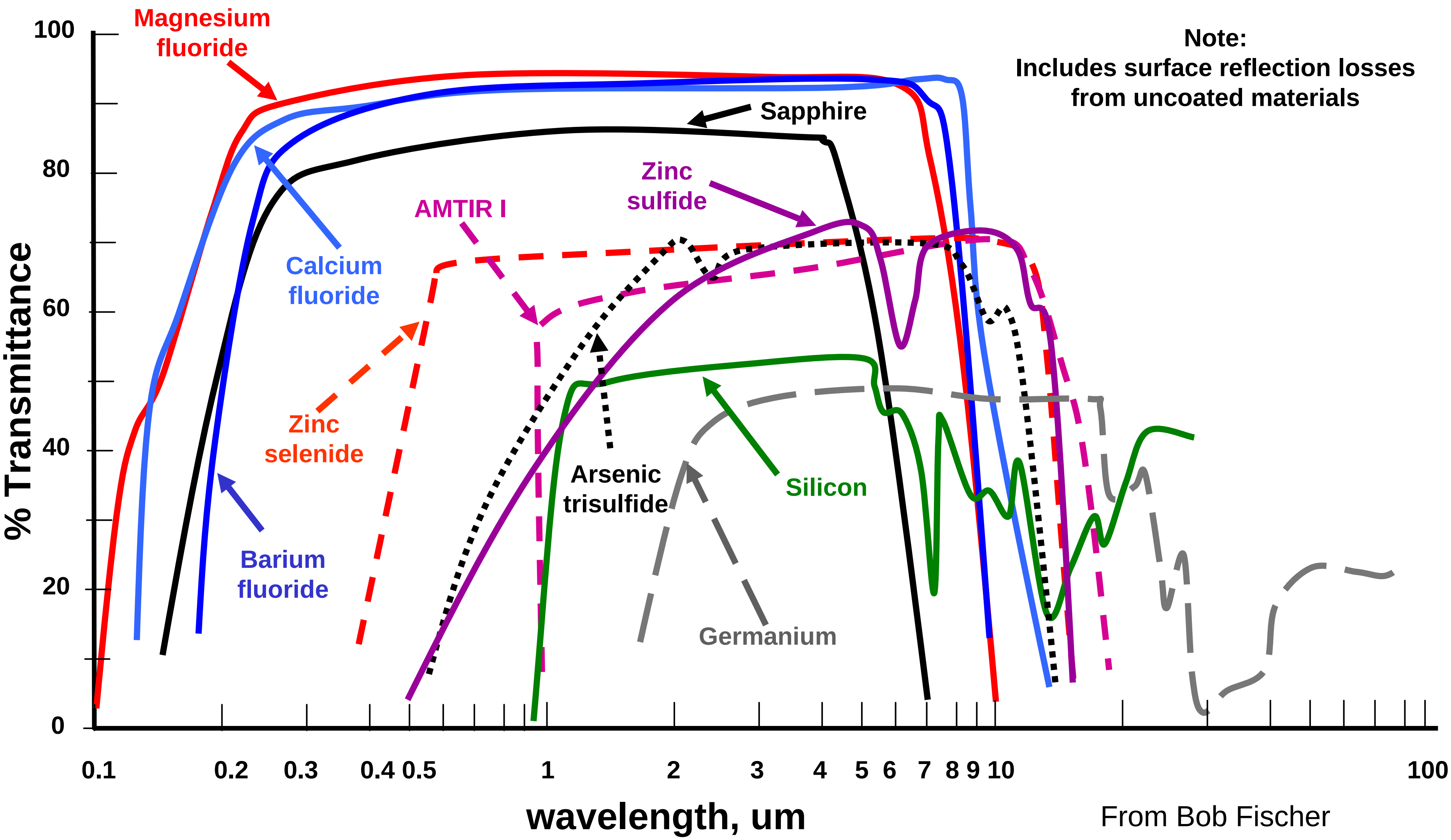
Infrared Glasses

- The list of commonly used IR materials is (unfortunately) pretty short
  - Germanium
  - Silicon
  - Zinc Sulfide
  - AMTIR 1, 3
  - Sapphire
  - Zinc Selenide
  - Magnesium Fluoride
  - Gallium Arsenide
  - Calcium Fluoride





Transmittance of IR glasses



Note:
Includes surface reflection losses from uncoated materials

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)

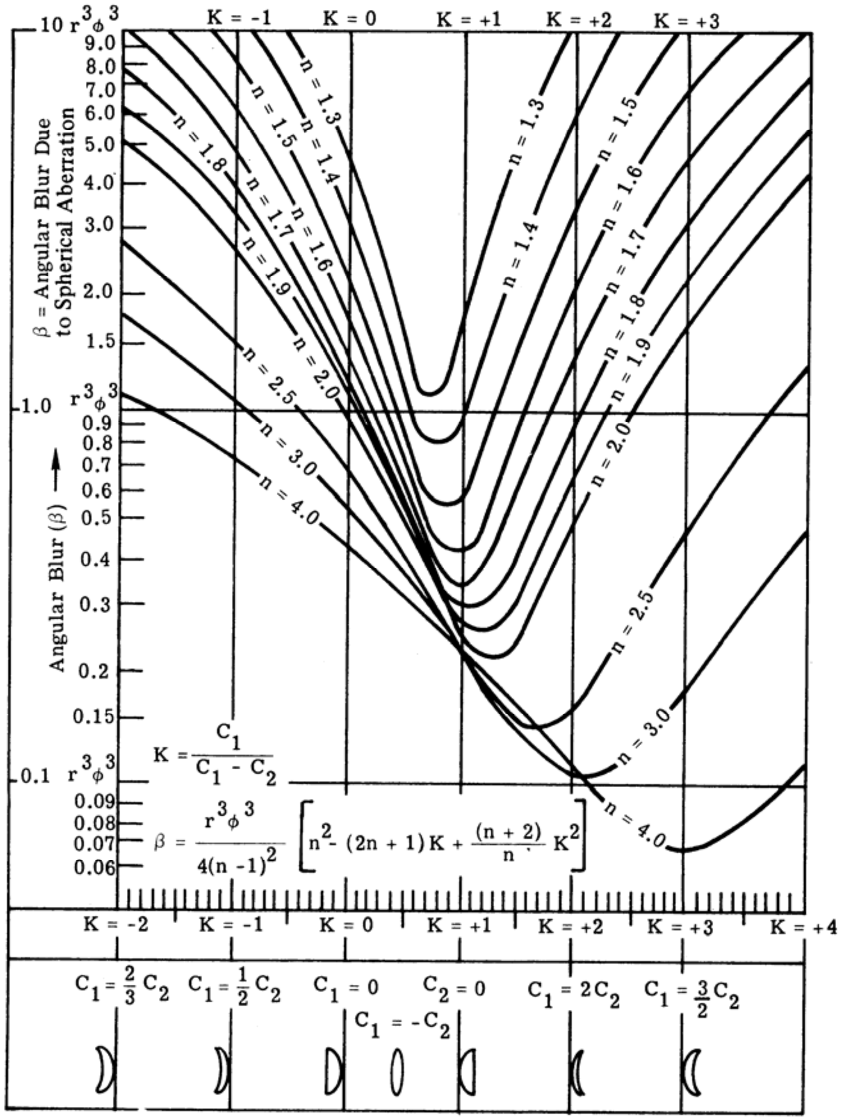
One-inch diameter BK7 lens	$5
One-inch diameter germanium lens	$500
Five-inch diameter sapphire dome	Priceless

  - 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



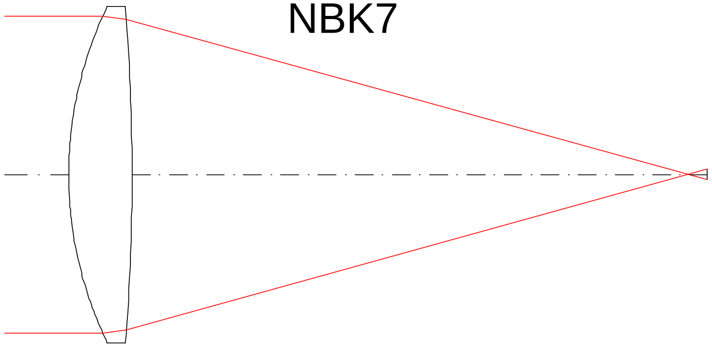
$$K_{min} = \frac{n(2n+1)}{2(n+2)}$$

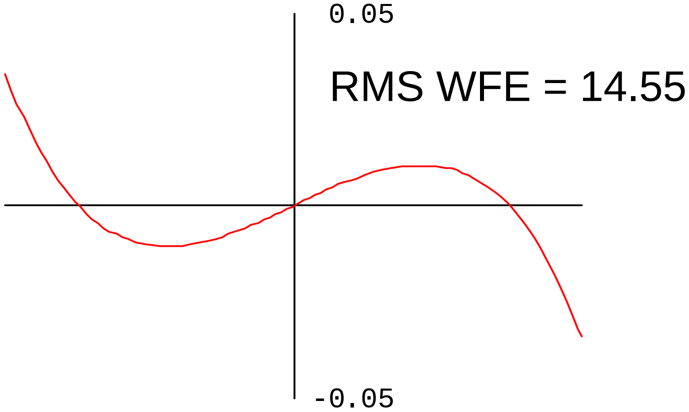
$$\beta \text{ at } K_{min} = r^3\varphi^3 \frac{4n^2 - n}{16(n-1)^2(n+2)}$$

For germanium n = 4

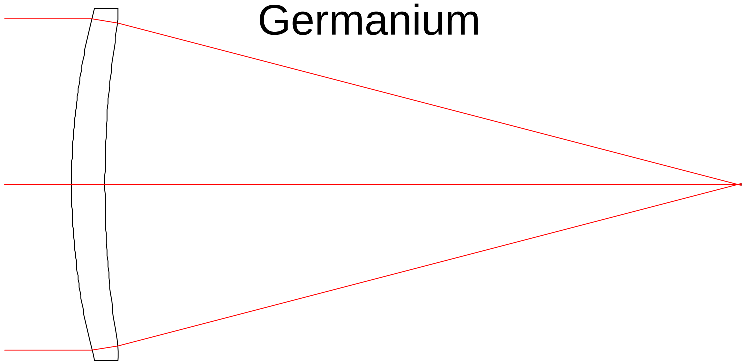
$$\beta = \frac{0.0087}{f^3}$$

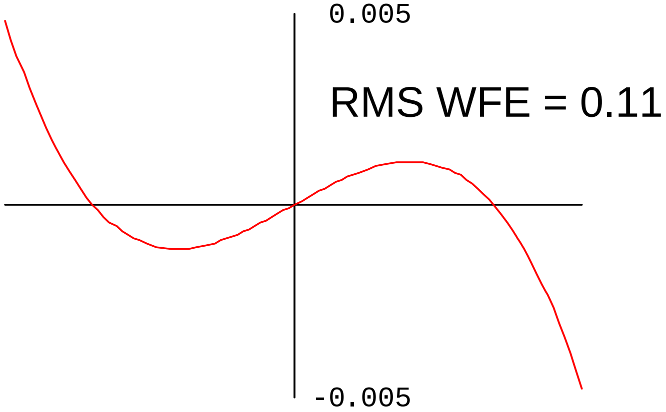
NBK7 vs. Germanium – Spherical Aberration


NBK7



RMS WFE = 14.55


Germanium

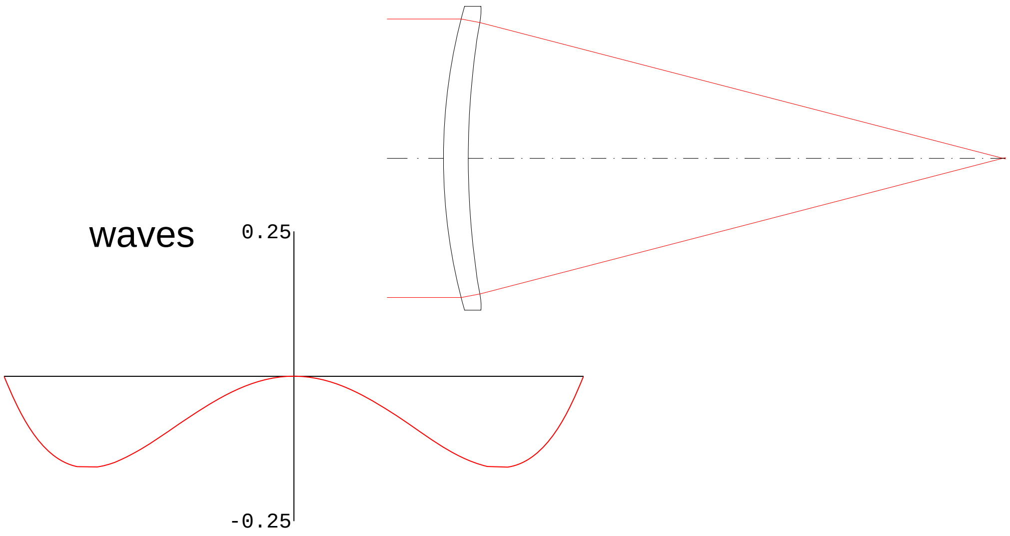


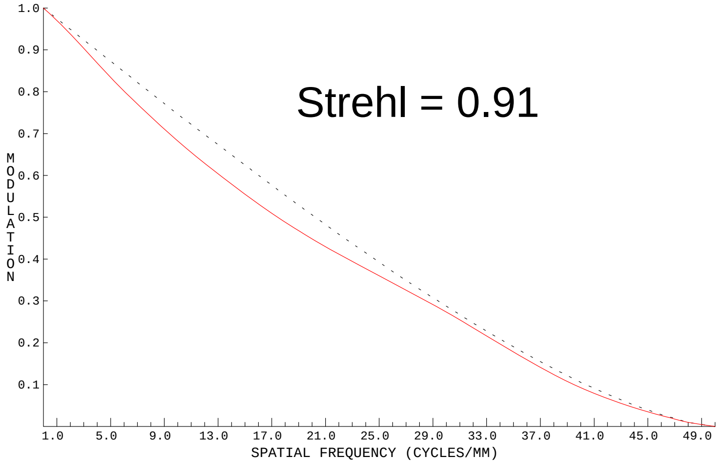
RMS WFE = 0.11

4.0 inch EFL, f/2

Example - Germanium Singlet

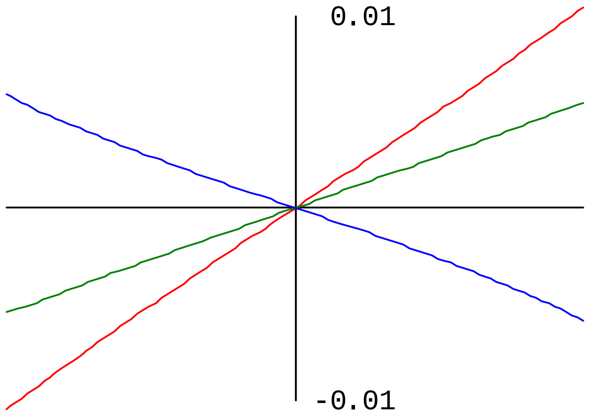
- We want an f/2 germanium singlet to be used at 10 microns (0.01 mm)
- Question - What is the longest focal length we can have and not need aspherics to correct spherical aberration?
- Answer
  - Diffraction Airy disk angular size is $\beta_{diff} = 2.44\ \lambda/D$
  - Spherical aberration angular 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

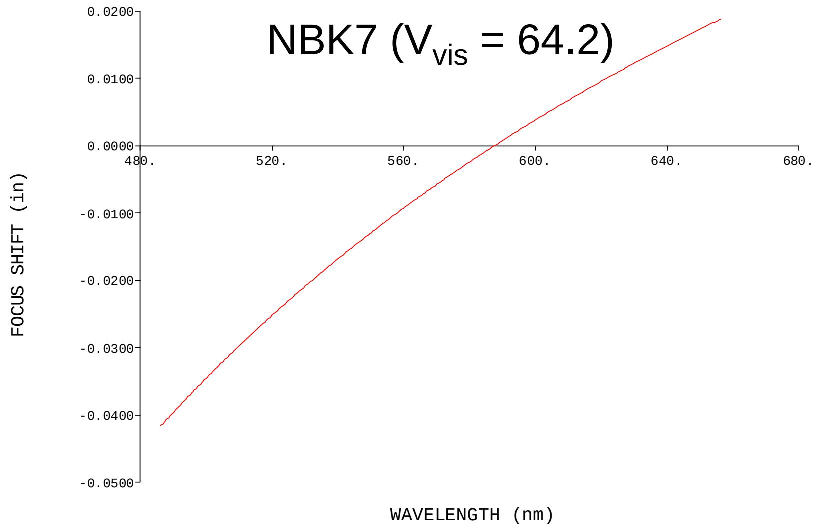


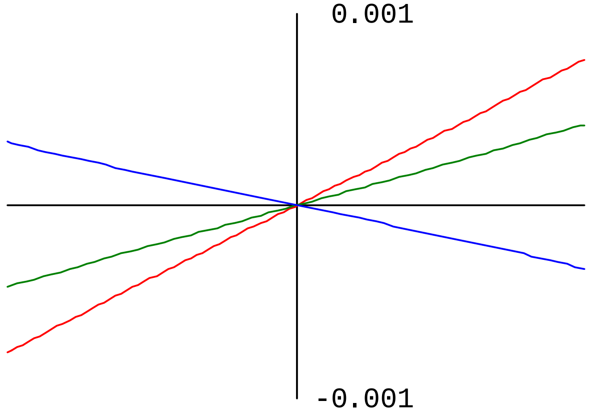


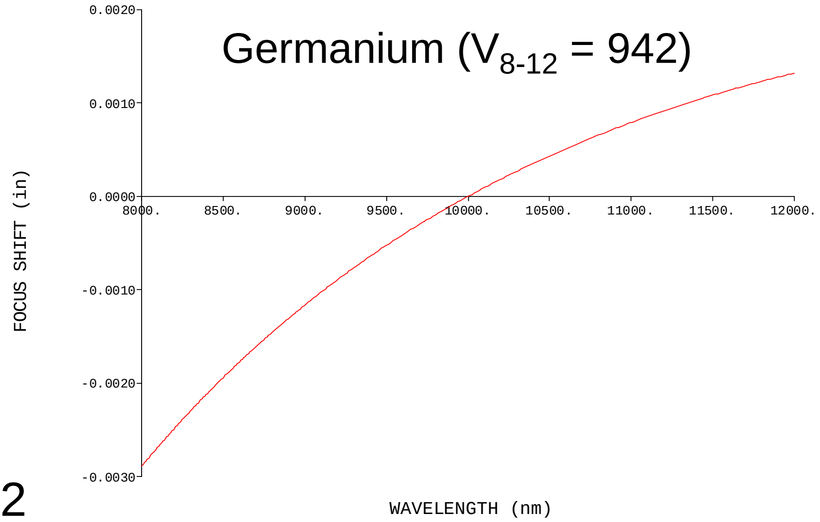
Strehl = 0.91

NBK7 vs. Germanium – Chromatic Aberration




NBK7 (V_{vis} = 64.2)

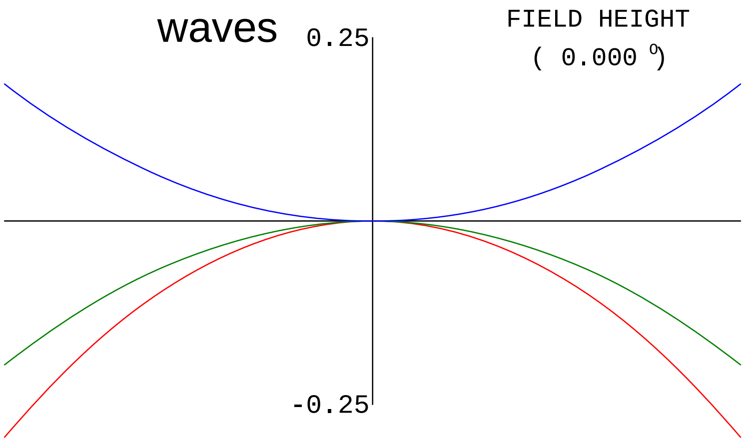


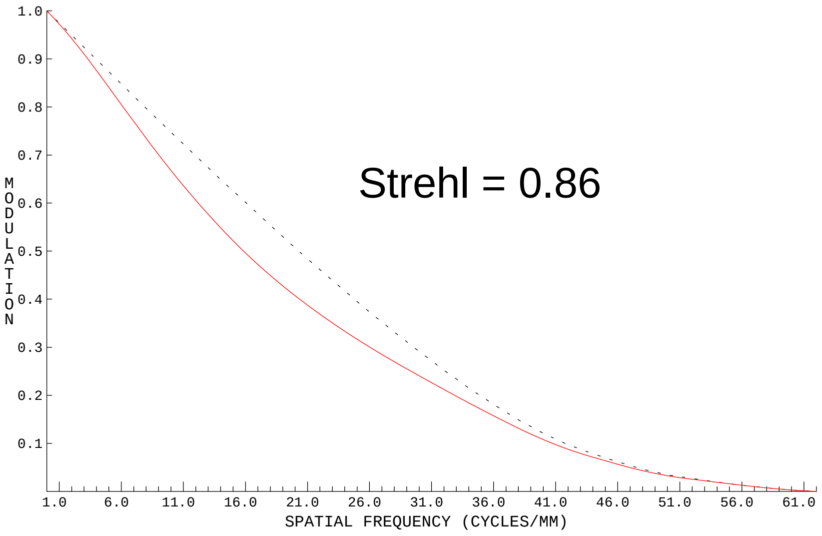

Germanium ($V_{8\text{-}12}$ = 942)

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

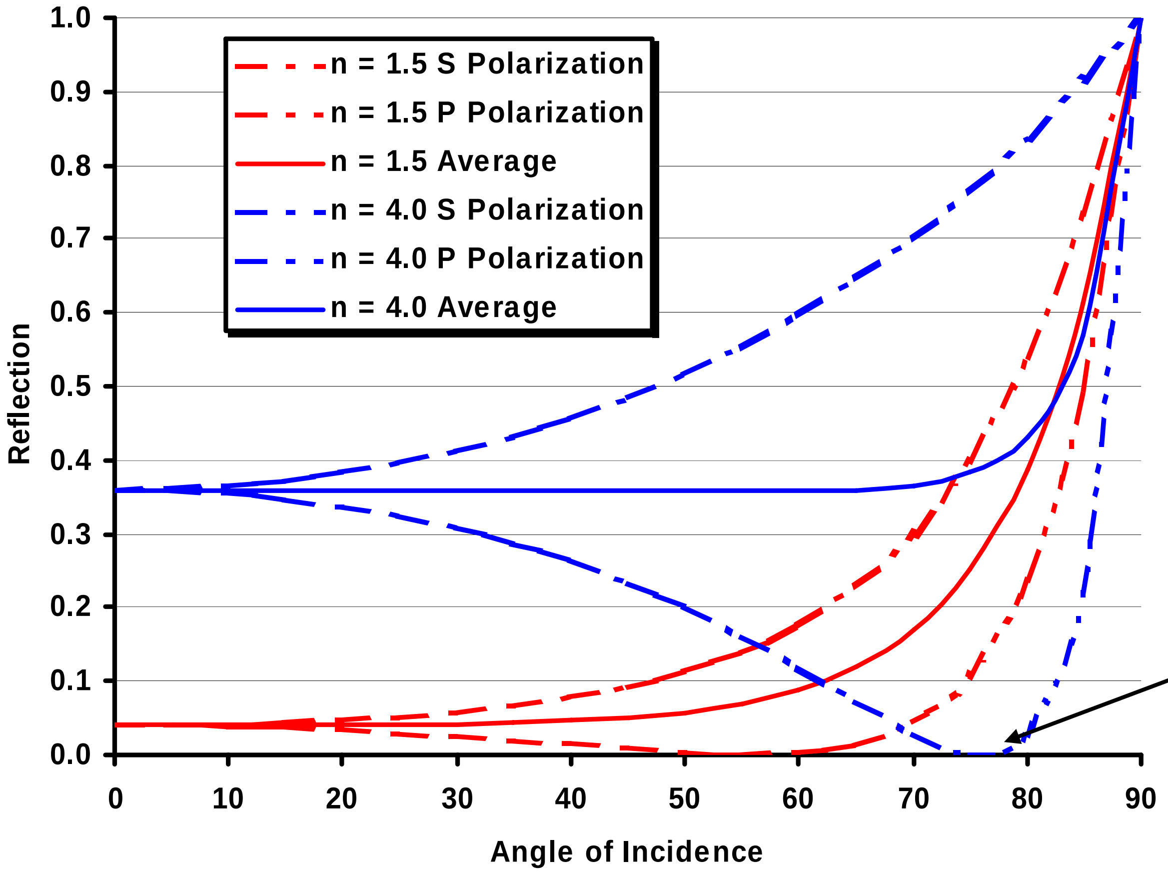




Strehl = 0.86

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

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

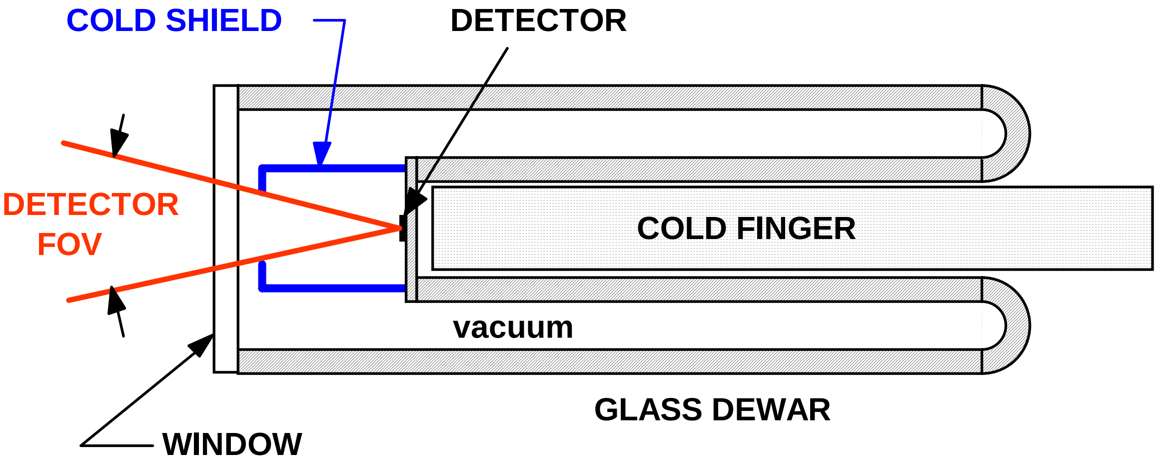
  - R is minimized when cosX = -1, or when $n_1 t = \lambda/4$

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

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

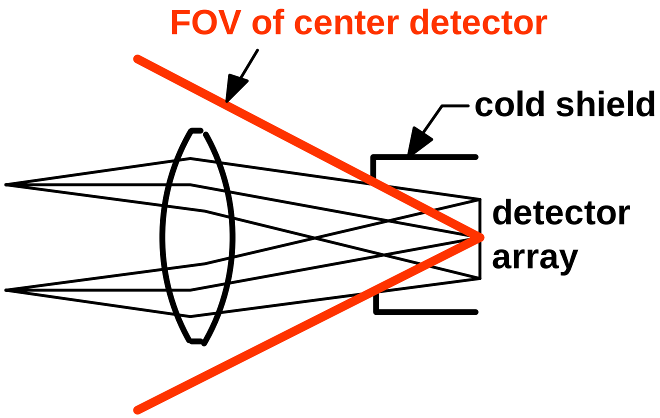
Cooled Detectors

- 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*)

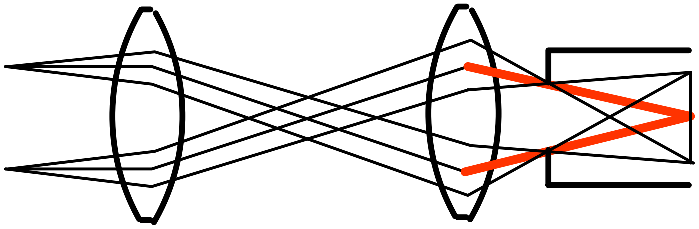


Cold Shield Efficiency

- 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)

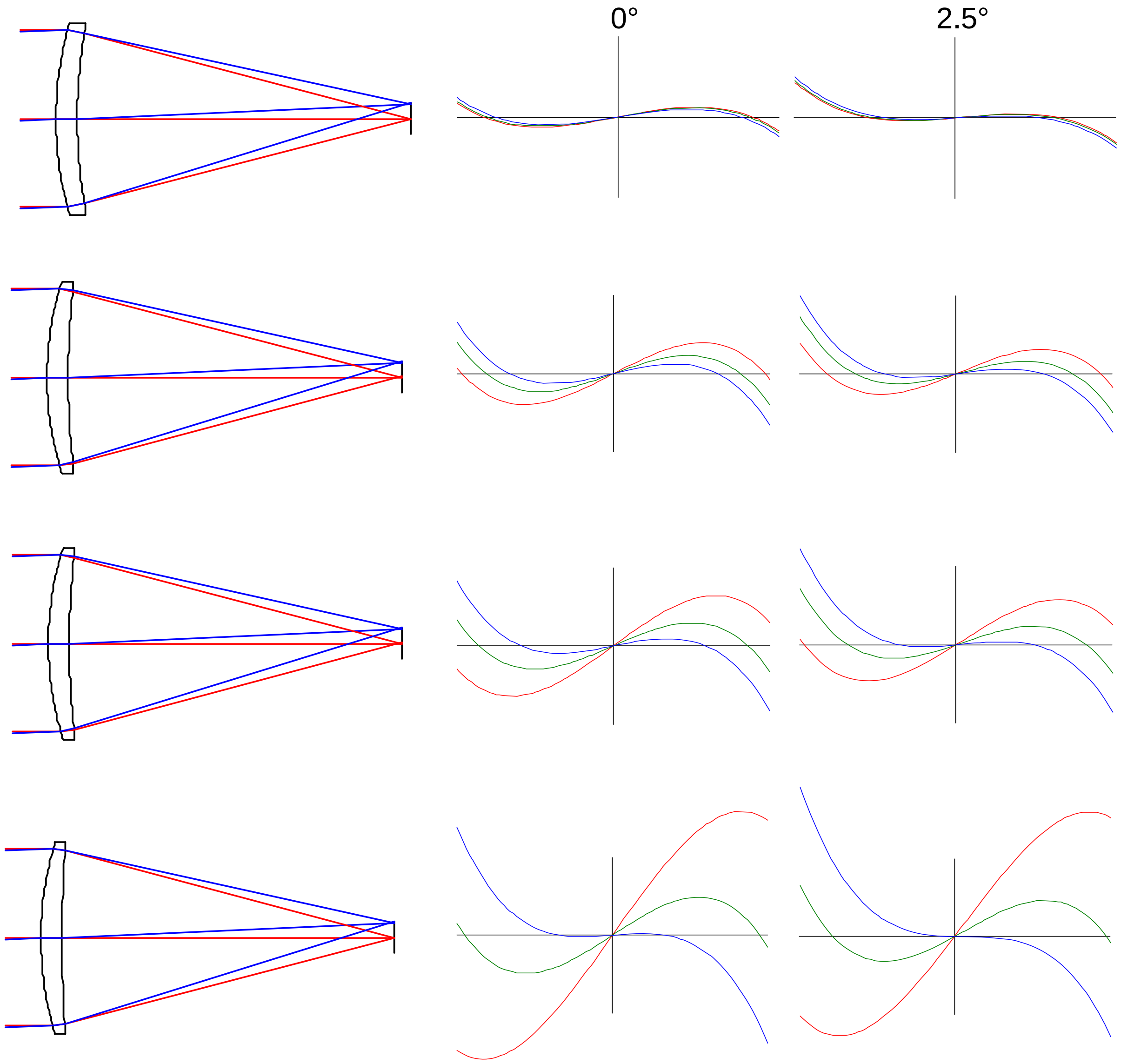


100% cold shielding efficiency (using re-imaging imager)

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

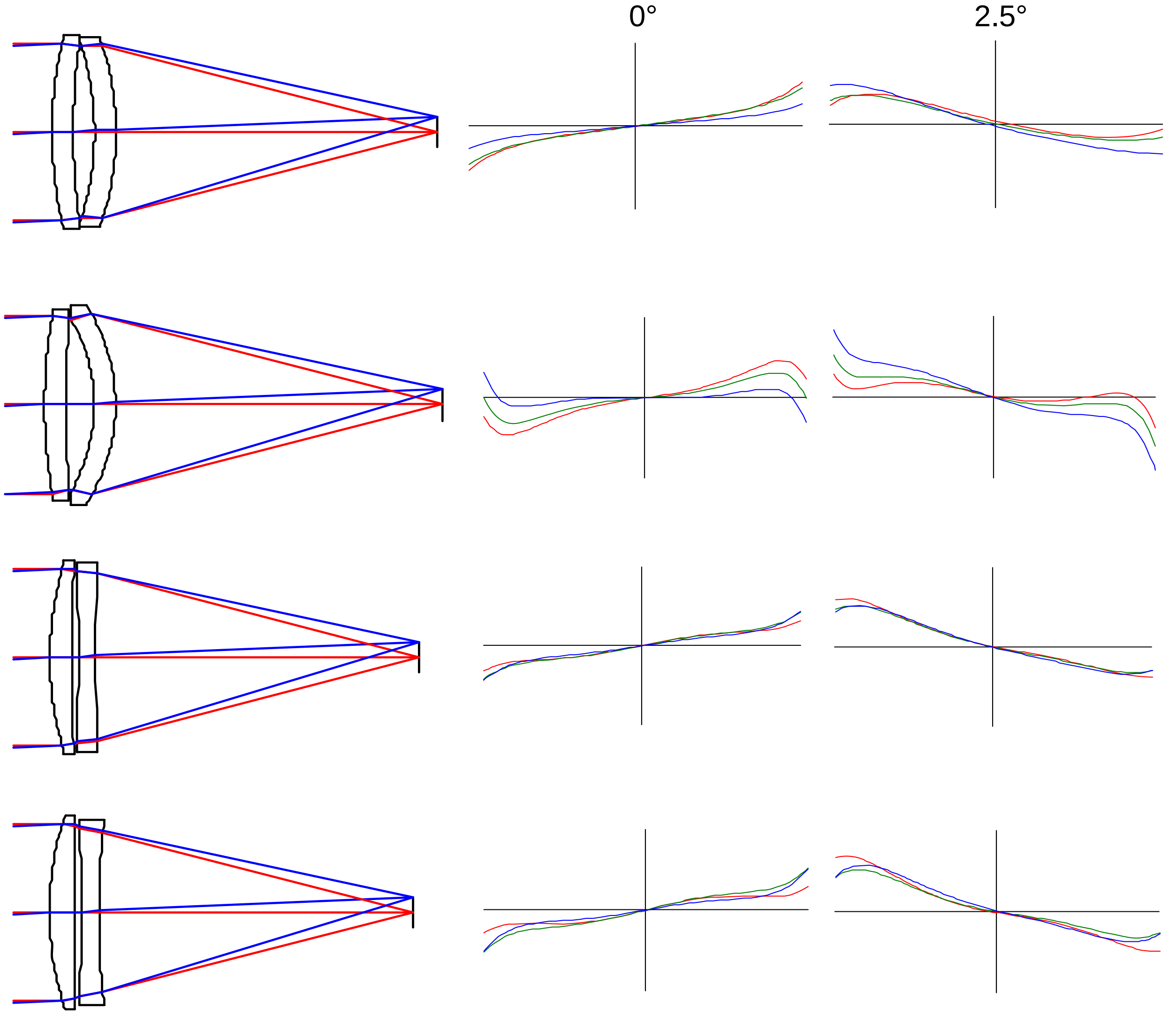
ZnSe singlet (V = 58)

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

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

- Infrared glasses

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

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

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

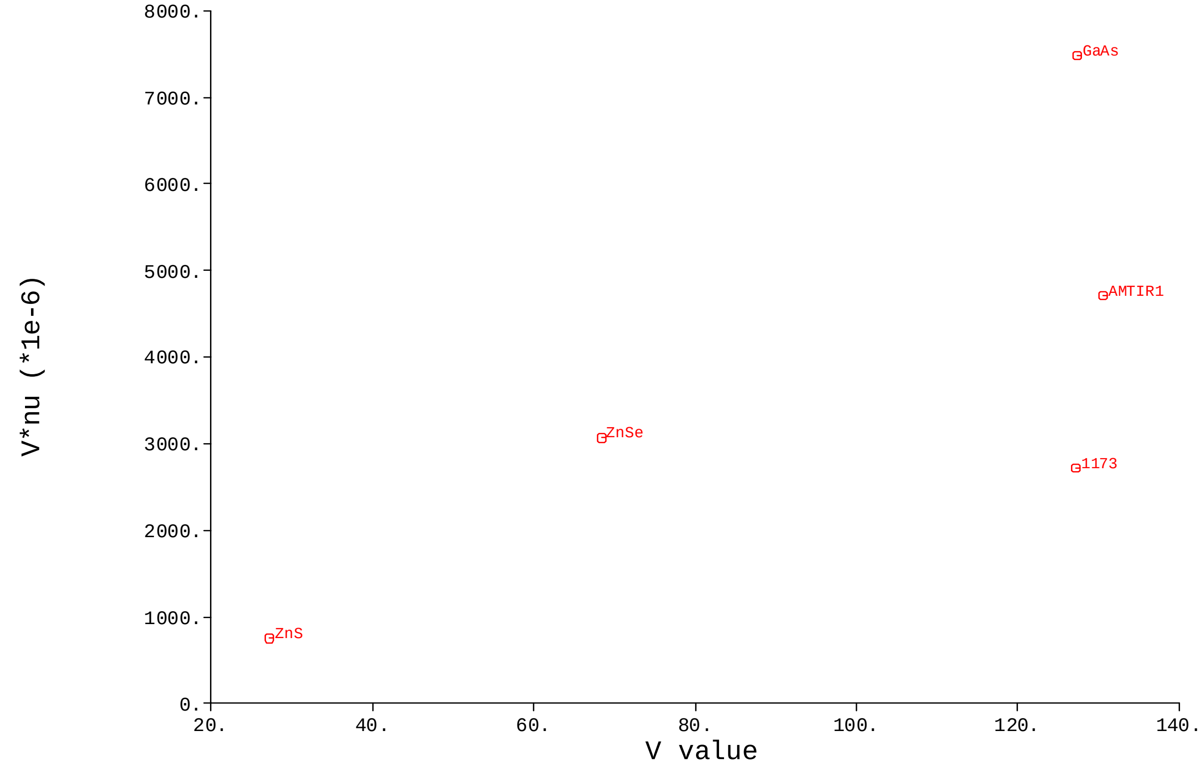
Aluminum 6061	23.4
416 stainless	9.9
Invar35	0.6
Titanium	8.7
Beryllium	11.6

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 $\Delta_{focus} = 4(-127-23)\text{x}10^{-6}/°\text{C} = -0.0006$ 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

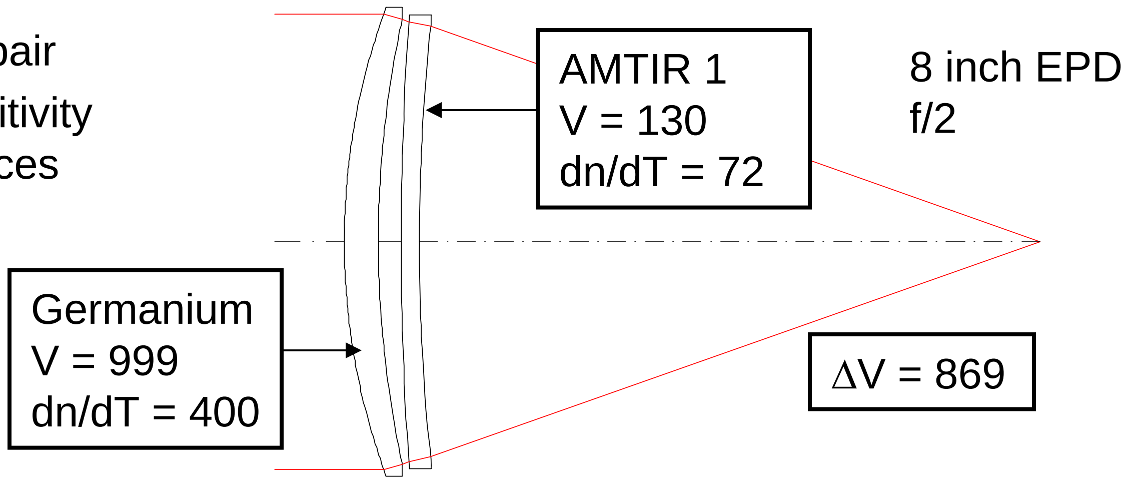
Making an Athermal Doublet

- 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



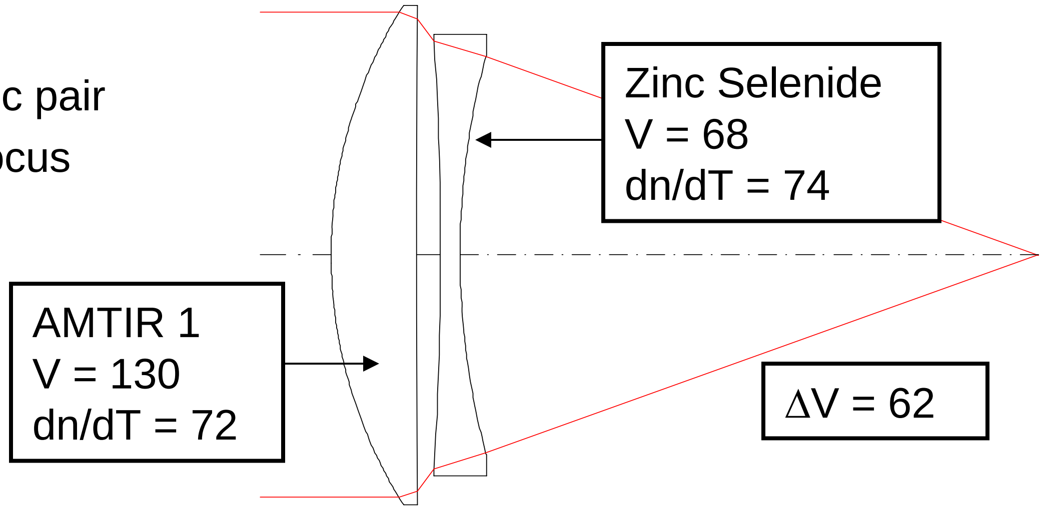
AMTIR 1
V = 130
dn/dT = 72

8 inch EPD
f/2

Germanium
V = 999
dn/dT = 400

ΔV = 869

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



Zinc Selenide
V = 68
dn/dT = 74

AMTIR 1
V = 130
dn/dT = 72

ΔV = 62

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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