Course Notes

SPIE Education Services

SC156
Basic Optics for Engineers

Glenn Boreman
The Univ. of North Carolina at Charlotte

SPIE.
SPIE.org

Syllabus for SC 156 – Basic Optics for Engineers

Glenn Boreman, University of North Carolina at Charlotte

This course is for beginners. No fancy mathematics is used. We cover a set of topics that are of practical importance to many optical systems, with an emphasis on back-of-the-envelope calculations. We start with concepts from geometrical optics. What is image formation? What determines the size and location of the image? What determines the spatial resolution of the system? What are F/# and field of view? We then briefly consider Modulation Transfer Function (MTF) – a description of image quality in terms of a spatial frequency response. Next is radiometry, with calculations of power transferred to the image plane for both resolved and unresolved sources. We then consider thermal sources of radiation from the perspective of the Planck equation, which gives the radiated power as a function of wavelength for a particular source temperature. Next, we compare and contrast detectors of optical radiation, both thermal sensors and photon sensors. We consider sensor specifications, with an eye toward calculation of a signal-to-noise ratio. Finally, the course concludes with the calculation of laser-beam quantities such as beam size as a function of distance and wavelength.

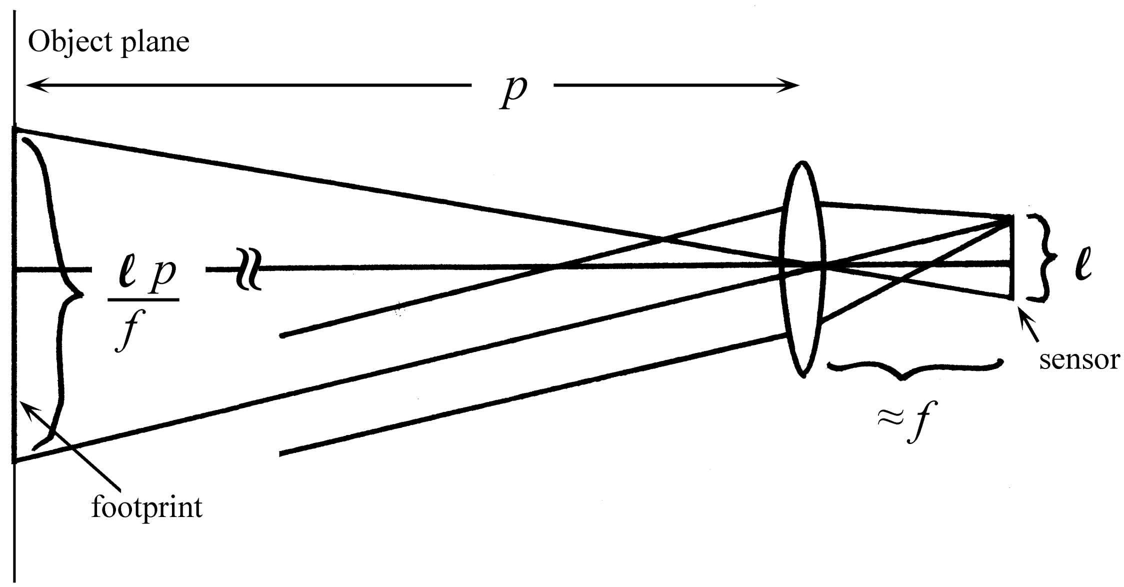
Basic Optics for Engineers

Glenn D. Boreman served as the 2017 President of SPIE, and is Chair of the Department of Physics & Optical Science at the University of North Carolina at Charlotte. From 1984 to 2011 he was on the faculty of University of Central Florida. He received the BS in Optics from University of Rochester and PhD in Optics from University of Arizona. Prof. Boreman is coauthor of the graduate textbooks *Infrared Detectors and Systems* and *Infrared Antennas and Resonant Structures*, and author of *Modulation Transfer Function in Optical & Electro-Optical Systems* and *Basic Electro-Optics for Electrical Engineers*. He has published more than 200 journal articles in the areas of IR sensors, IR materials, and image-quality assessment, and has supervised 27 PhD students to completion. He is a fellow of SPIE, OSA, IEEE, and MSS.

gboreman@uncc.edu

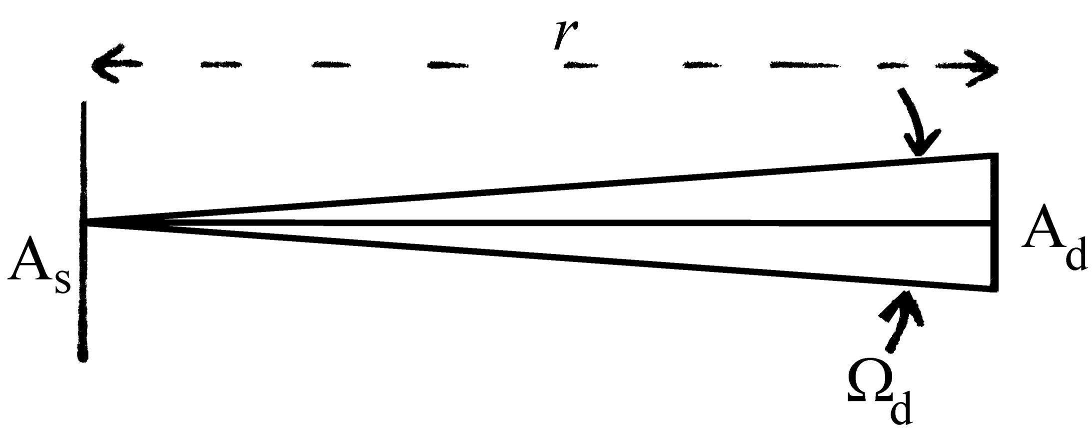
Detector Footprint

- The detector has a "footprint" – the image of the detector onto the object plane – defines the area of the object that contributes flux onto the sensor – detector is the field stop.
- Given lens focal length f and the size of the sensor pixel $\boldsymbol{\ell}$, you get an idea of the resolution element at the object plane.
- Assume that object distance p is large enough the image is formed at f behind the lens.



Radiance Example

- For the simplest calculational example of radiance, let the view angle $\theta_s = 0$.
- Given an extended source of area 1 cm by 1 cm, specified by a radiance of 5 W/(cm^2 ster). At a distance of 10 meters, is a detector of size 1 mm by 1 mm. How much power falls on the detector?



- First calculate the solid angle of the detector.

$$\Omega_d = A_d/r^2 = (1 \times 10^{-3}\ \text{m})^2/(10\ \text{m})^2 = 10^{-8}\ \text{ster}$$

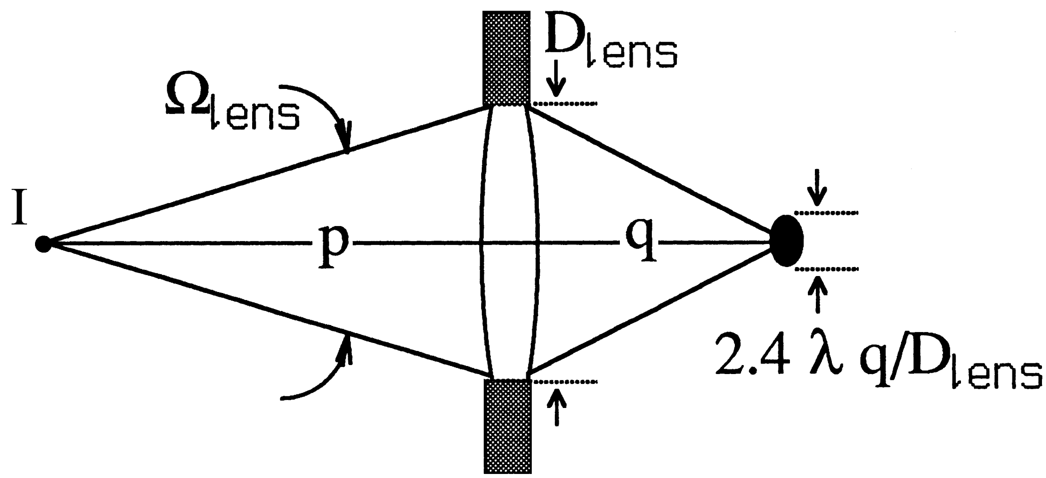
- Multiply this solid angle by the area of the source and the radiance of the source to obtain the power on the detector:

$$\phi_d = L \times A_s \times \Omega_d$$

$$\phi_d = 5\ \text{W/(cm}^2\ \text{ster)} \times (1\ \text{cm})^2 \times 10^{-8}\ \text{ster} = 5 \times 10^{-8}\ \text{W}$$

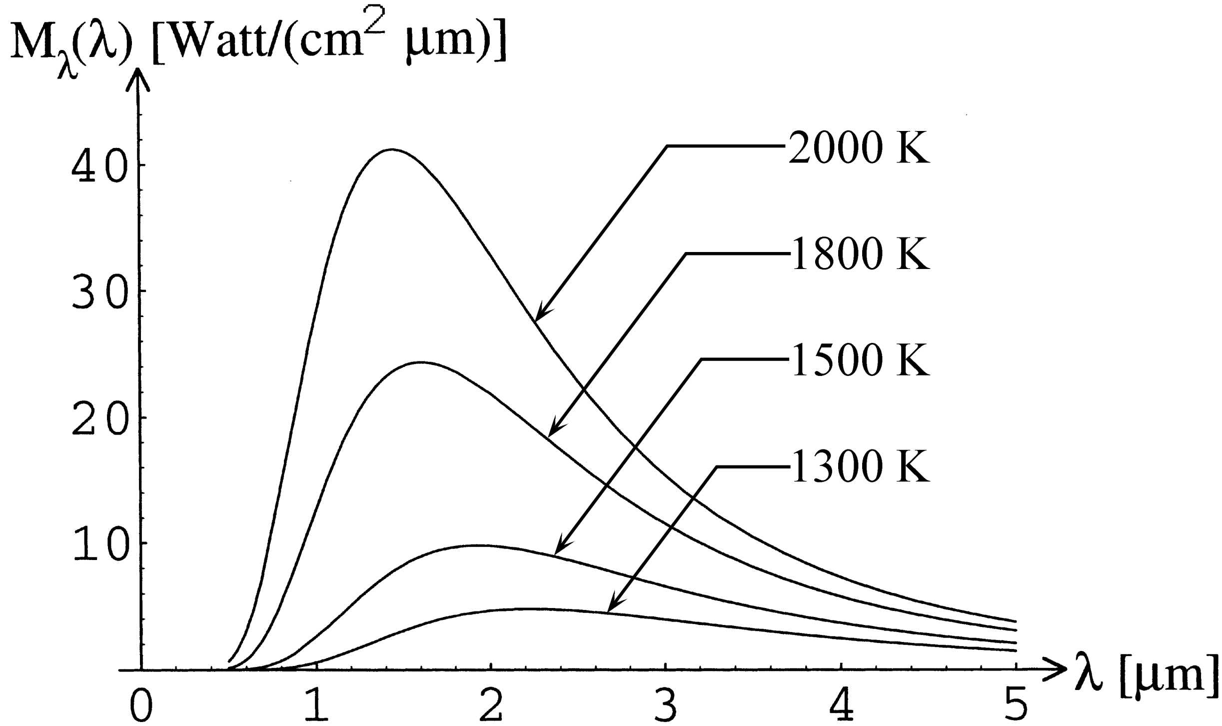
Calculation of Image Irradiance: Point-Source Imaging

- Often the object of interest is effectively a point source – one whose size is smaller than the resolution spot projected back to object plane – an "unresolved" object.
- Point source is specified in terms of its intensity I (W/ster).
- Total power collected: $\phi = I \times \Omega_{lens} = I \times A_{lens}/p^2$

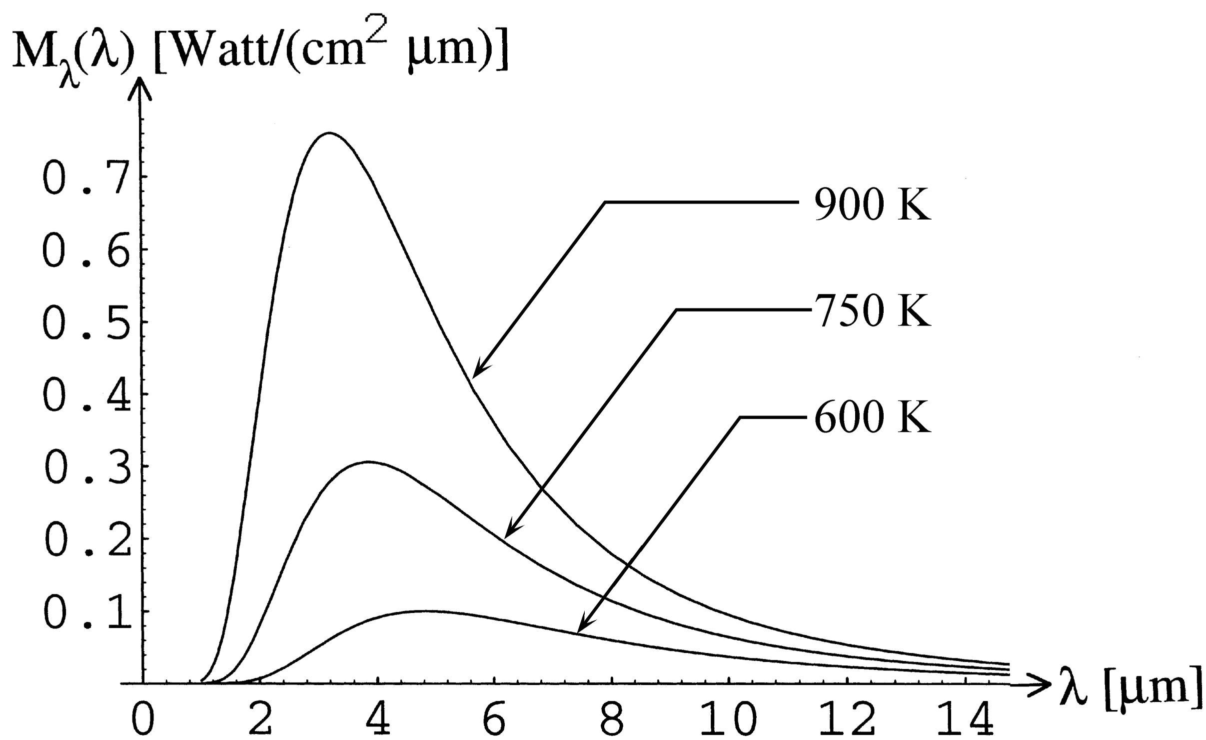


- If the lens is diffraction-limited, 84% of ϕ is concentrated into a spot of diameter $2.4\ \lambda\ (F/\#)_{image\text{-}space}$. In that case, approximate on-axis image-plane irradiance:

$$E_{img} \approx \frac{0.84\, I\, \Omega_{lens}}{\frac{\pi}{4}\left(2.4\, \lambda\, (F/\#)_{image\text{-}space}\right)^2}$$

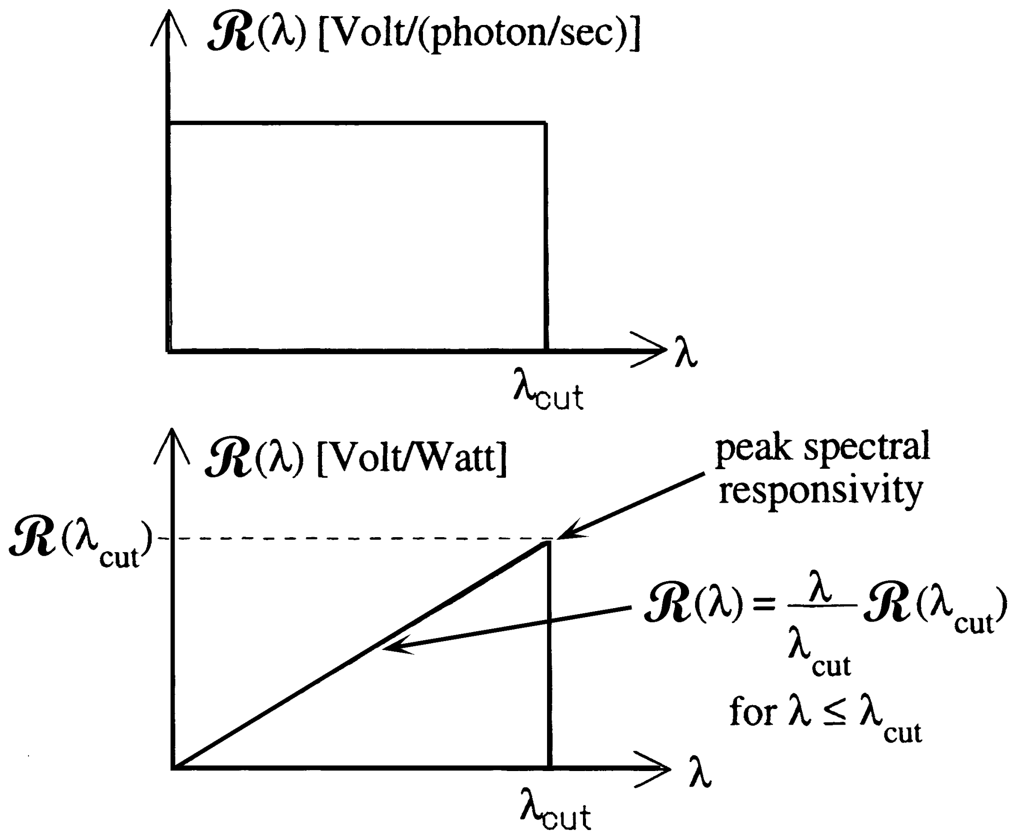


M$_\lambda$(λ) [Watt/(cm^2 μm)]
2000 K
1800 K
1500 K
1300 K
40
30
20
10
0
1
2
3
4
5
λ [μm]



M$_\lambda$(λ) [Watt/(cm^2 μm)]
900 K
750 K
600 K
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
2
4
6
8
10
12
14
λ [μm]

- Example: $\mathcal{R}(\lambda)$ for a photon sensor – plotted in either photon-based or energy-based units.



- In energy units, the ideal photon detector spectral responsivity is linearly proportional to wavelength:

$$\mathcal{R}(\lambda) = \frac{\lambda}{\lambda_{cut}} \mathcal{R}(\lambda_{cut}) \text{ when } \lambda \le \lambda_{cut}; \;\; \mathcal{R}(\lambda) = 0, \text{ when } \lambda > \lambda_{cut}$$

- A linear increase in responsivity is seen up to cutoff, since it takes more photons/sec to make a watt at long wavelength.

- For historical reasons, photon detectors are often plotted with respect to energy-derived units.

Specification of Signal-to-Noise Performance: Normalized Detectivity, D*

- Normalized detectivity, D* – a figure of merit often used in manufacturers' data sheets to specify detector performance.

- D* is normalized with respect to detector area and bandwidth – but ***in order to predict SNR you must choose the sensor area and bandwidth for your application***.

$$D^* \equiv \frac{\sqrt{A_{\text{det}}}\sqrt{\Delta f}}{NEP} = \frac{\sqrt{A_{\text{det}}}\sqrt{\Delta f}}{\phi_{\text{det}}} SNR = \frac{\sqrt{A_{\text{det}}}\sqrt{\Delta f}}{\phi_{\text{det}}} \frac{v_{\text{signal}}}{v_{\text{noise}}}$$

  - D* has units $\left[\frac{\text{cm}\sqrt{\text{Hz}}}{\text{Watt}}\right]$, typically large numbers 10^9 to 10^{12}
  - Definition is in terms of "per Watt," but sensor typically receives much less power than 1 Watt!
  - Inversely proportional to NEP – bigger D* better sensitivity
  - Proportional to square root of detector area
  - Proportional to square root of measurement bandwidth.

- We have seen that rms noise voltage v_{noise} (and hence NEP) is generally proportional to $\sqrt{A_{\text{det}}}$ and $\sqrt{\Delta f}$.

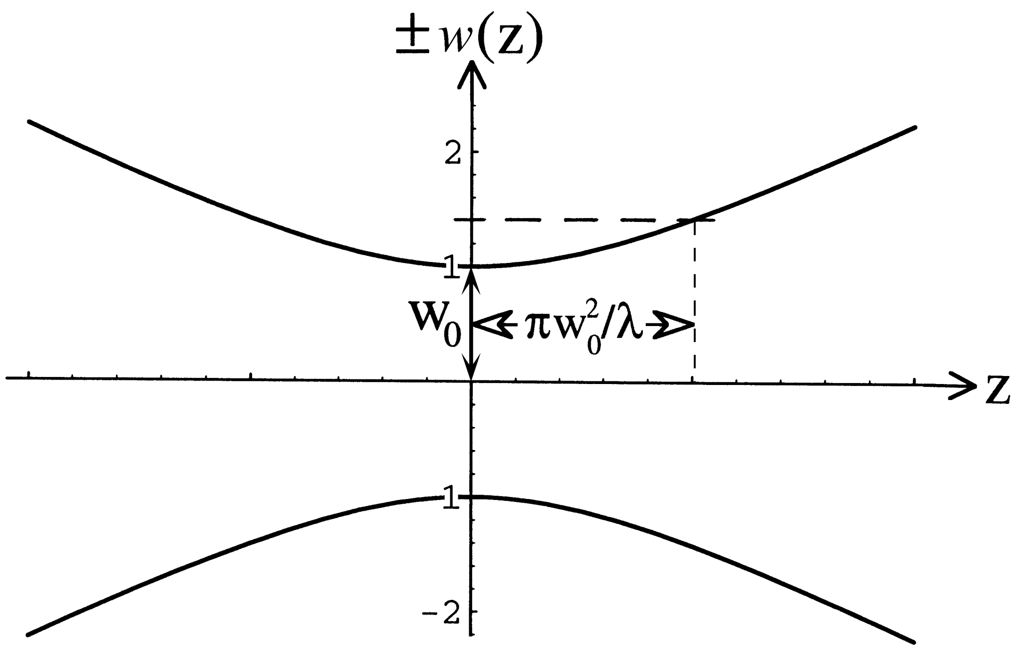
- ***The way that D* is defined, these dependences cancel out***.

Beam Propagation Equation

- Find w as a function of z – given wavelength λ and the beam waist size w_0 set at $z = 0$.

$$w(z) = w_0 \sqrt{1 + \left[\frac{\lambda z}{\pi w_0^2} \right]^2}$$

- Identify $\frac{\pi w_0^2}{\lambda}$ as the Rayleigh range – the distance at which w has increased by a factor of $\sqrt{2}$ over its initial value w_0.



- Rayleigh range is a measure of the distance over which the beam remains approximately collimated.