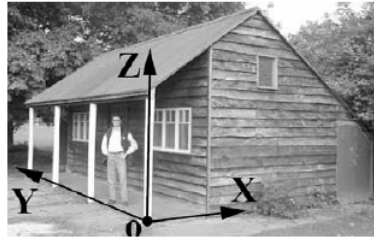
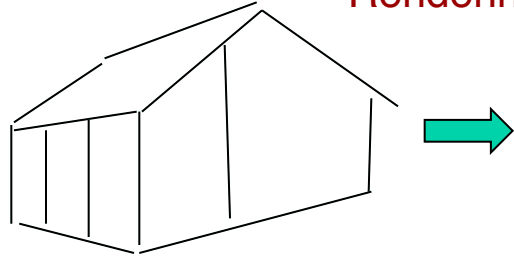


**Illumination, Radiometry,
and a (Very Brief) Introduction to the
Physics of Remote Sensing**



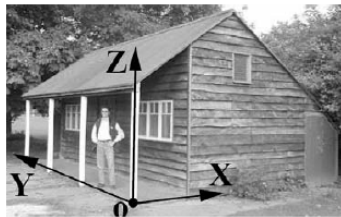
Course Philosophy

Rendering



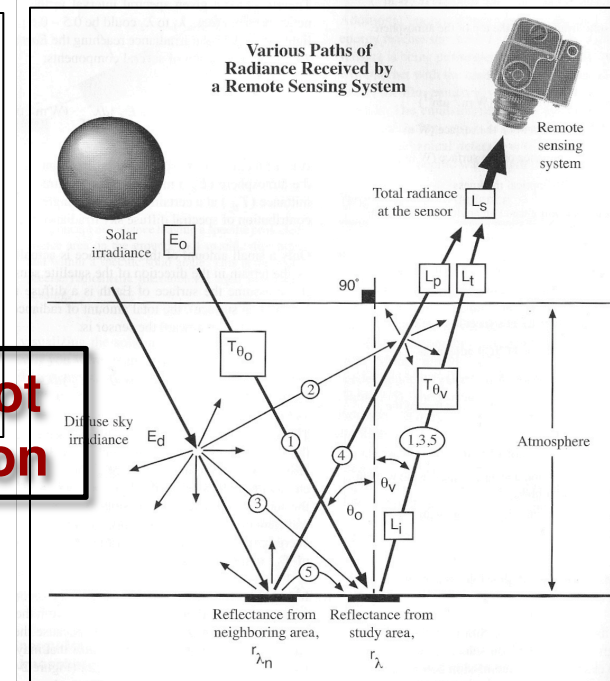
Computer graphics

Estimation



Computer vision

**Robot
vision**

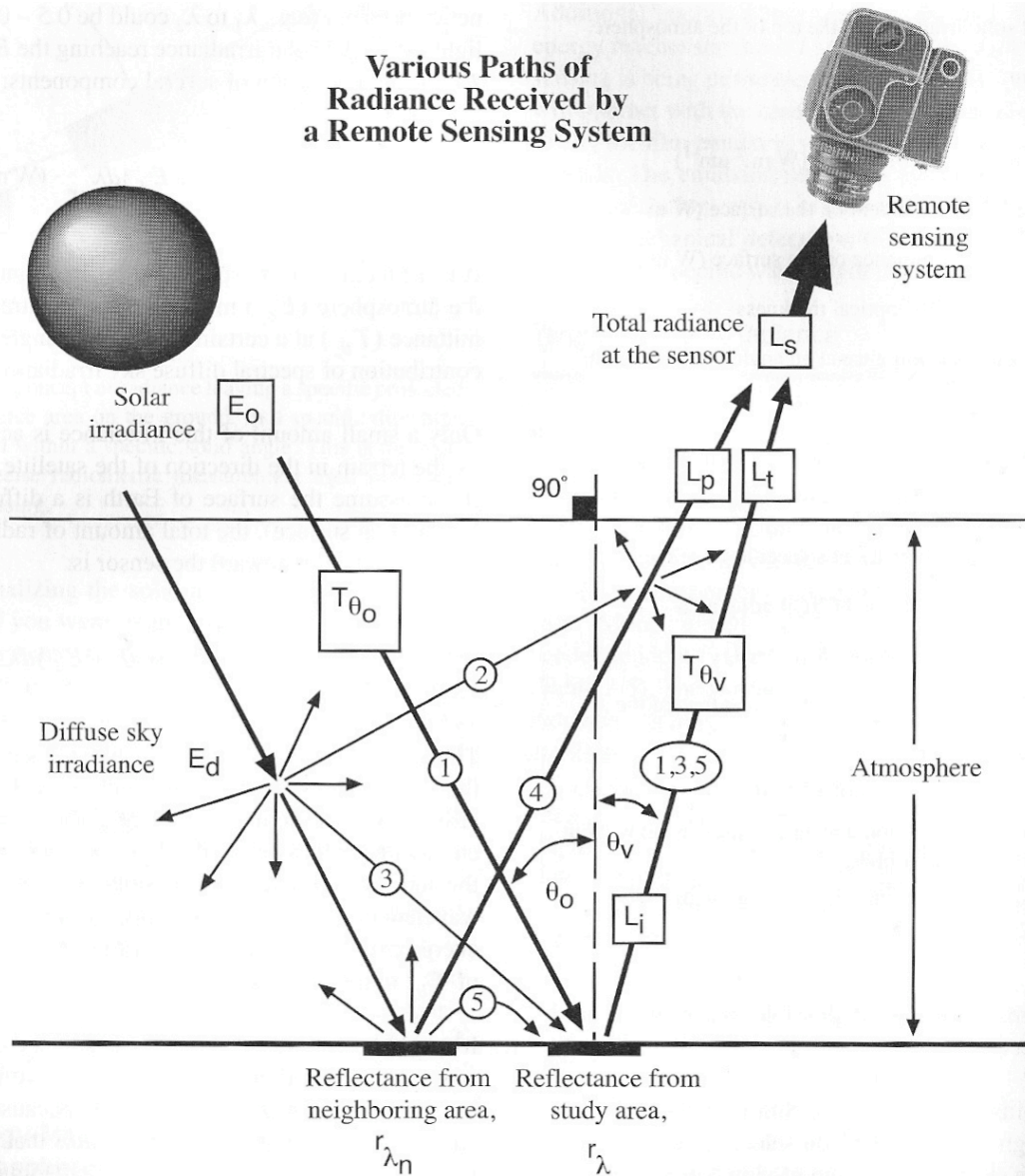


Remote sensing *lhm - 2*



What This Lecture is About

Various Paths of Radiance Received by a Remote Sensing System



- Characteristics of illumination sources
- Atmospheric attenuation
- Radiometry and reflectance models
- Spectral characteristics of reflectance and thermal emission and their interrelationships

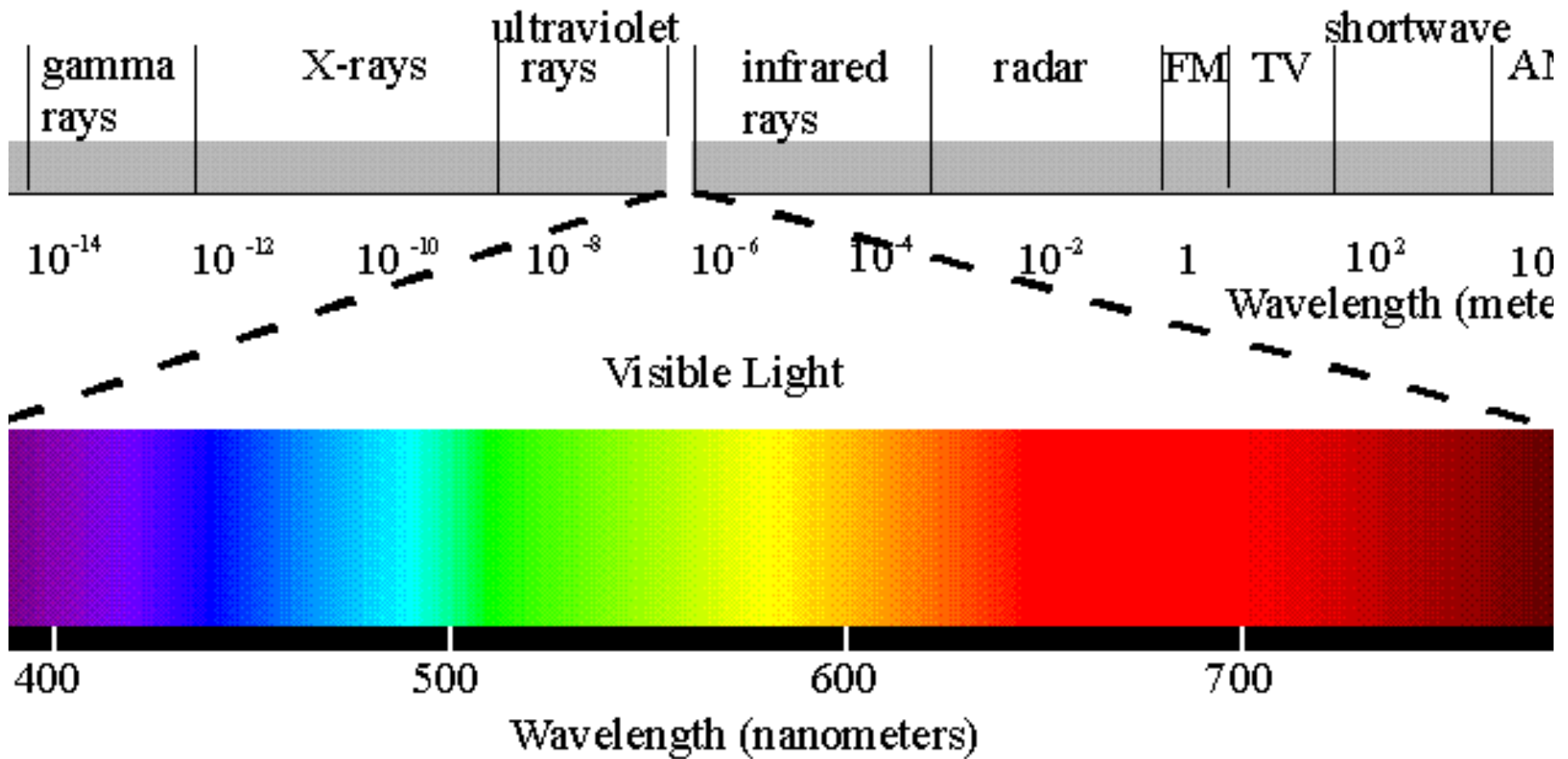


In Context with Coming Lectures

- Today: illumination, radiometry, physics of remote sensing
- Tuesday: cameras: optics, detectors
- Thursday: geometric camera modeling and calibration
- Reading material:
 - Szeliski sec 2.2 (today)
 - Szeliski sec 2.3 (Tuesday)
 - Forsyth ch. 1 (Tuesday)
 - Szeliski sec 2.1 (Thursday)
- Additional reference material:
 - C. Elachi, *Introduction to the Physical and Techniques of Remote Sensing*
 - J. R. Jensen, *Remote Sensing of the Environment*

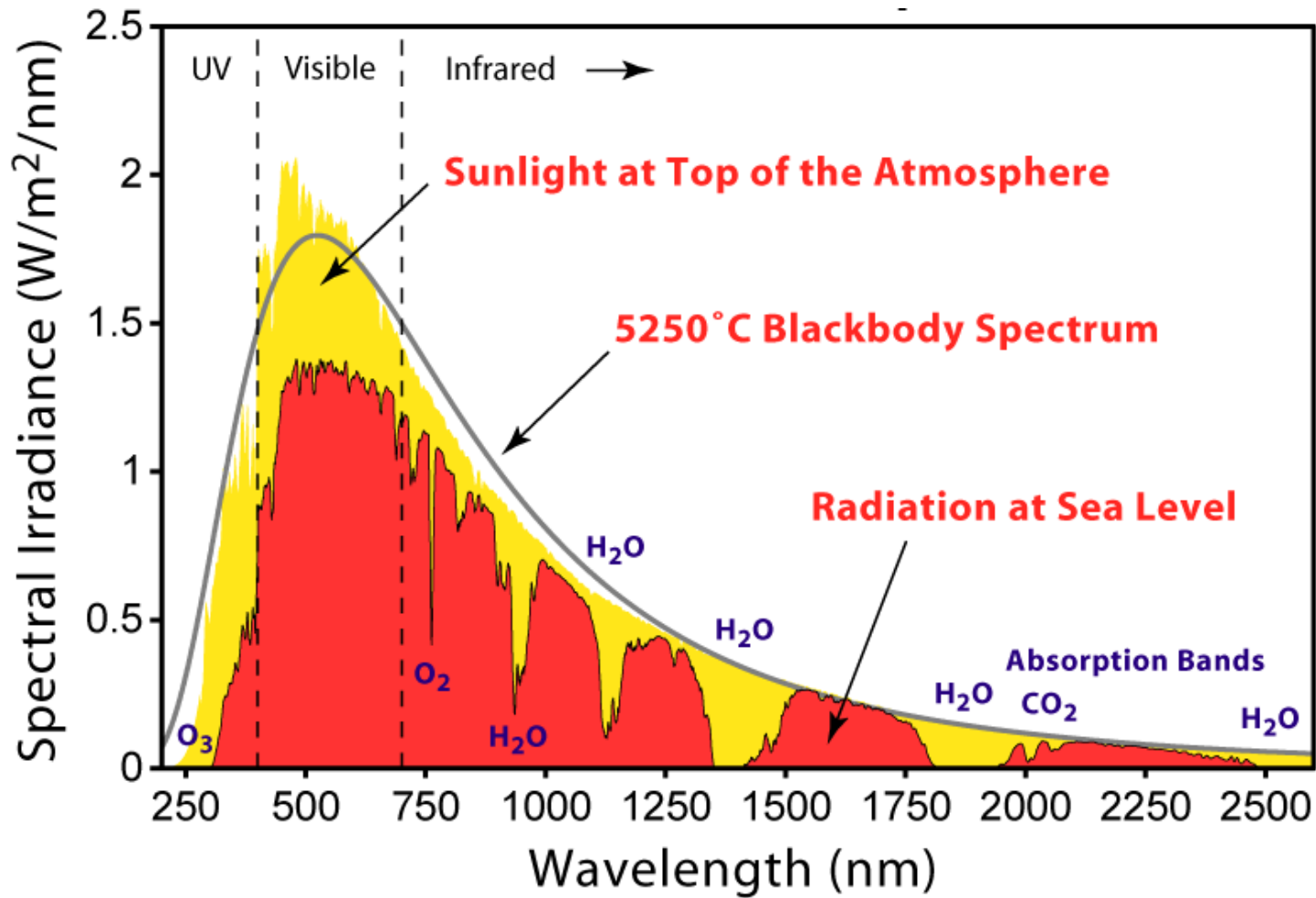


Electromagnetic Spectrum





Solar Spectrum



Total irradiance $\sim 1370 \text{ W/m}^2$ above atmosphere (*solar constant*)



Blackbody Emission: Planck's Law

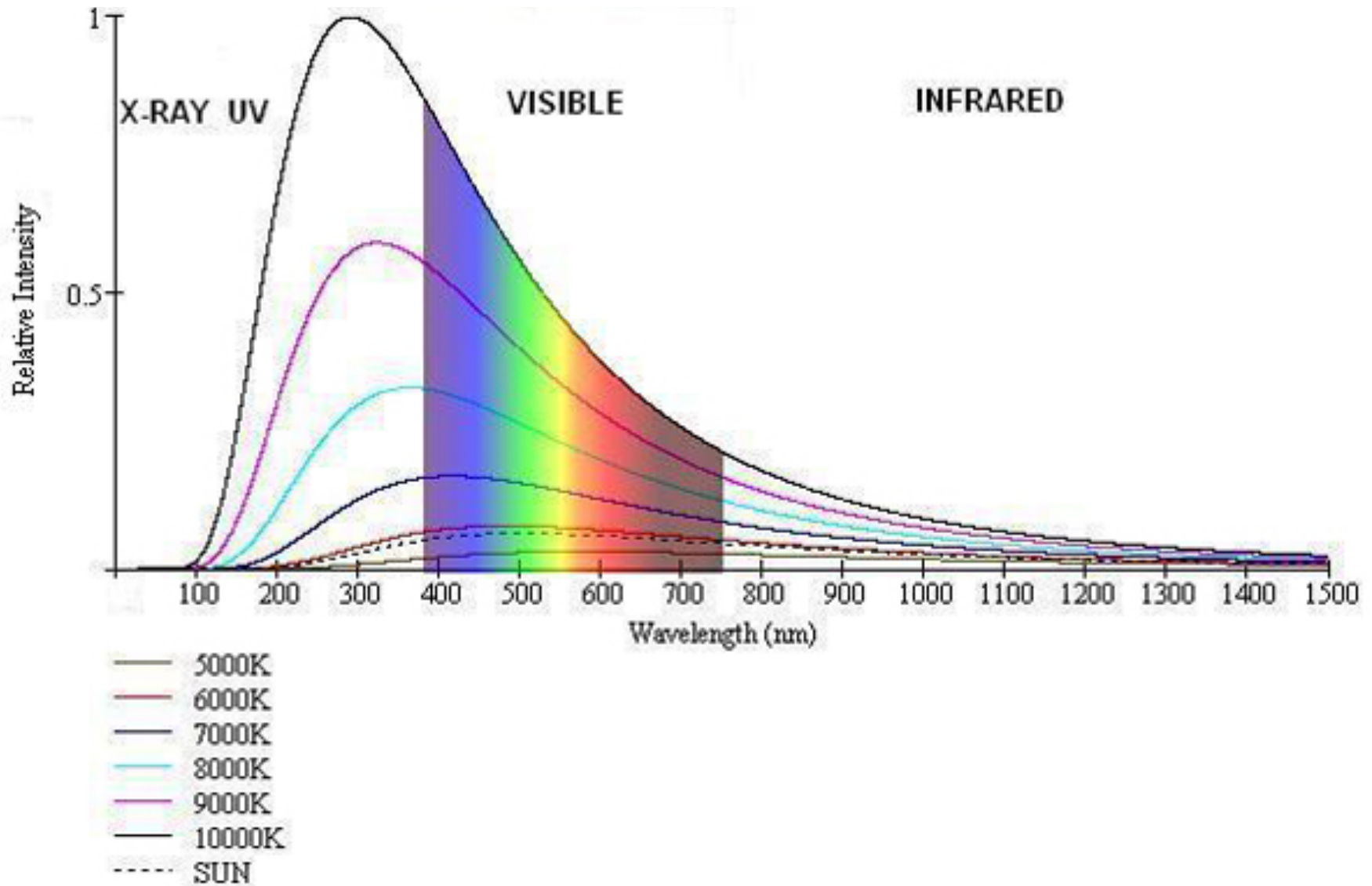
$$S(\lambda) = \frac{2\pi hc^2}{\lambda^5} \frac{1}{e^{ch/\lambda kT} - 1}$$

Where

- $S(\lambda)$ = spectral radiant emittance in W/m³ (watts per unit wavelength per unit area)
- λ = radiation wavelength
- h = Planck's constant = 6.626×10^{-34} Wsec²
- T = absolute temperature in °K
- C = velocity of light = 2.9979×10^8 m/sec
- K = Boltzmann constant = 1.38×10^{-23} Wsec/K

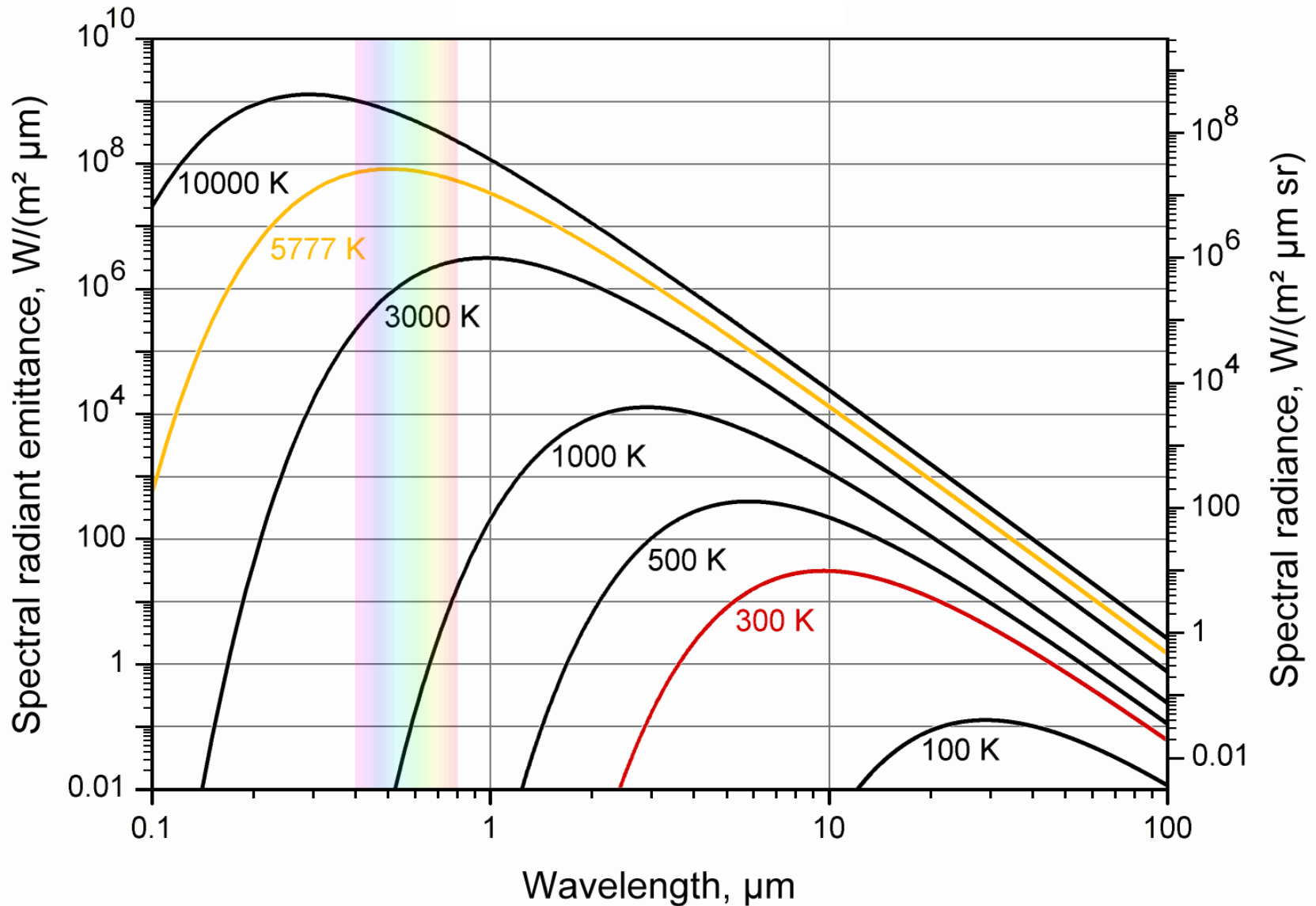


Blackbody Spectrum





Blackbody Spectrum





Stefan-Boltzmann and Wien Laws

- Total flux emitted by a blackbody of unit area (Stefan-Boltzmann law):

$$\int S(\lambda) d\lambda = \sigma T^4$$

– where $\sigma = 5.669 \times 10^{-8} \text{ W/m}^2\text{K}^4$

- Wavelength of maximum emission (Wien's law):

$$\lambda_m = \frac{a}{T}$$

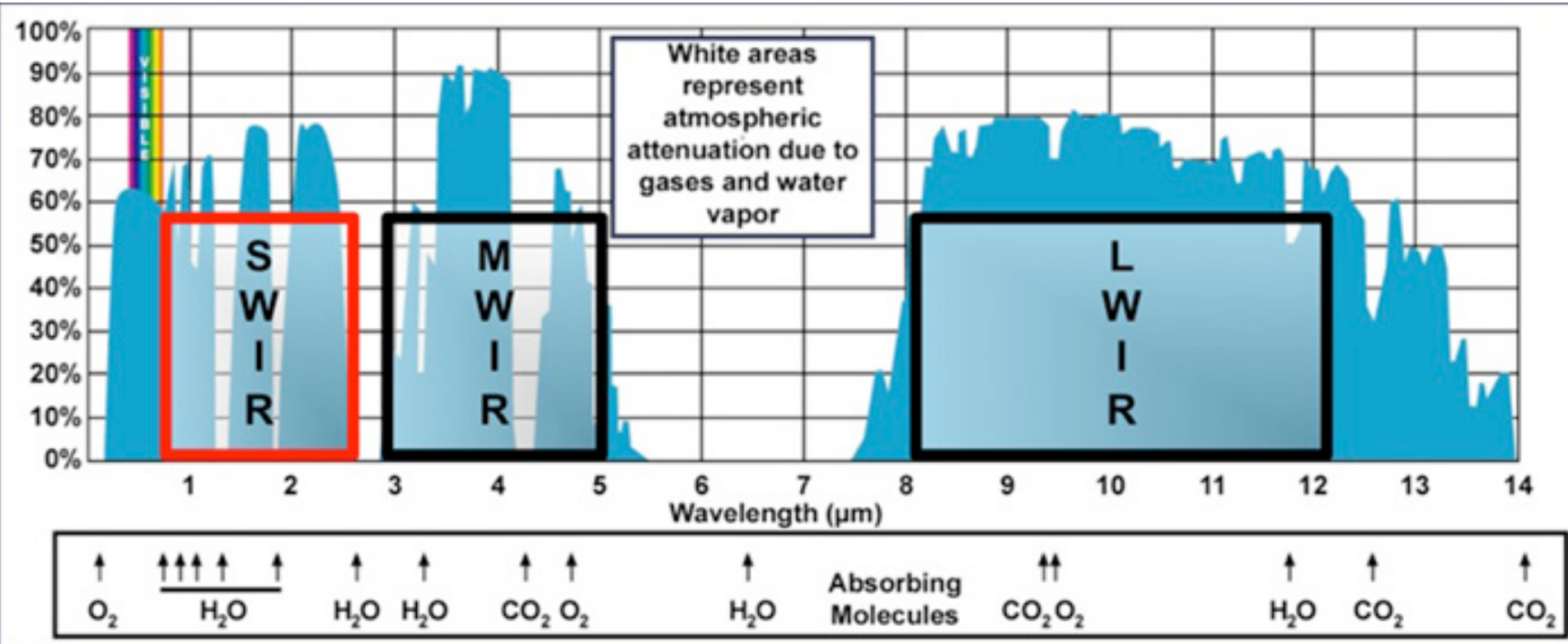
– where $a = 2898 \text{ } \mu\text{mK}$

– for sun ($T \sim 6000 \text{ }^\circ\text{K}$), $\lambda_m = 480 \text{ nm}$; for Earth surface ($T \sim 300 \text{ }^\circ\text{K}$),
 $\lambda_m = 9.66 \text{ } \mu\text{m}$

- Photon energy = hc/λ (J/photon), so # photons = $S(\lambda)\lambda/hc$



Atmospheric Windows in the Infrared



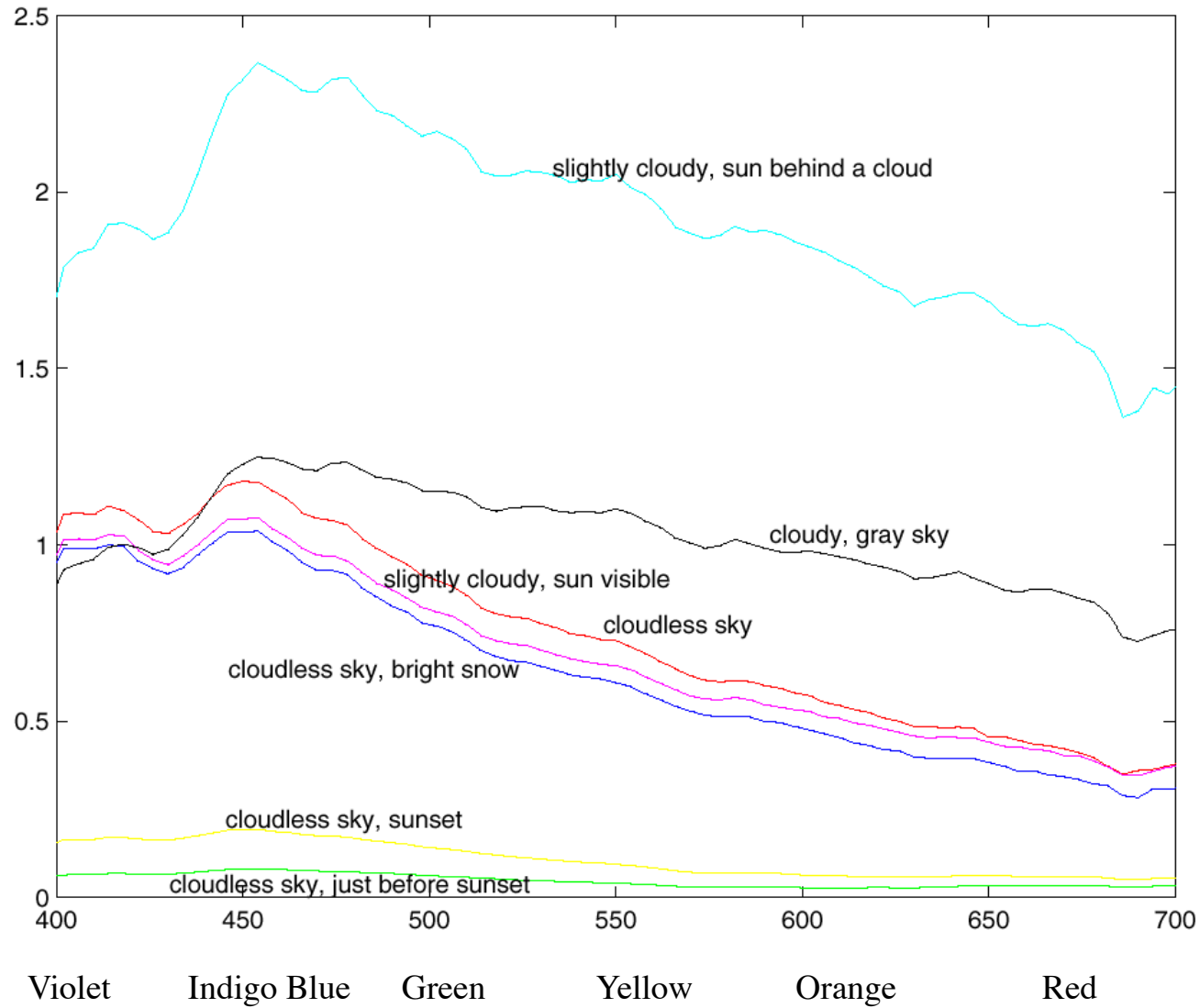


Some Sources of Illumination

- Sunlight
- Thermal emission
- Skylight
- Night sky glow (*nightglow*)
- Man-made lights: e.g. incandescent bulbs, fluorescent bulbs, arc lamps

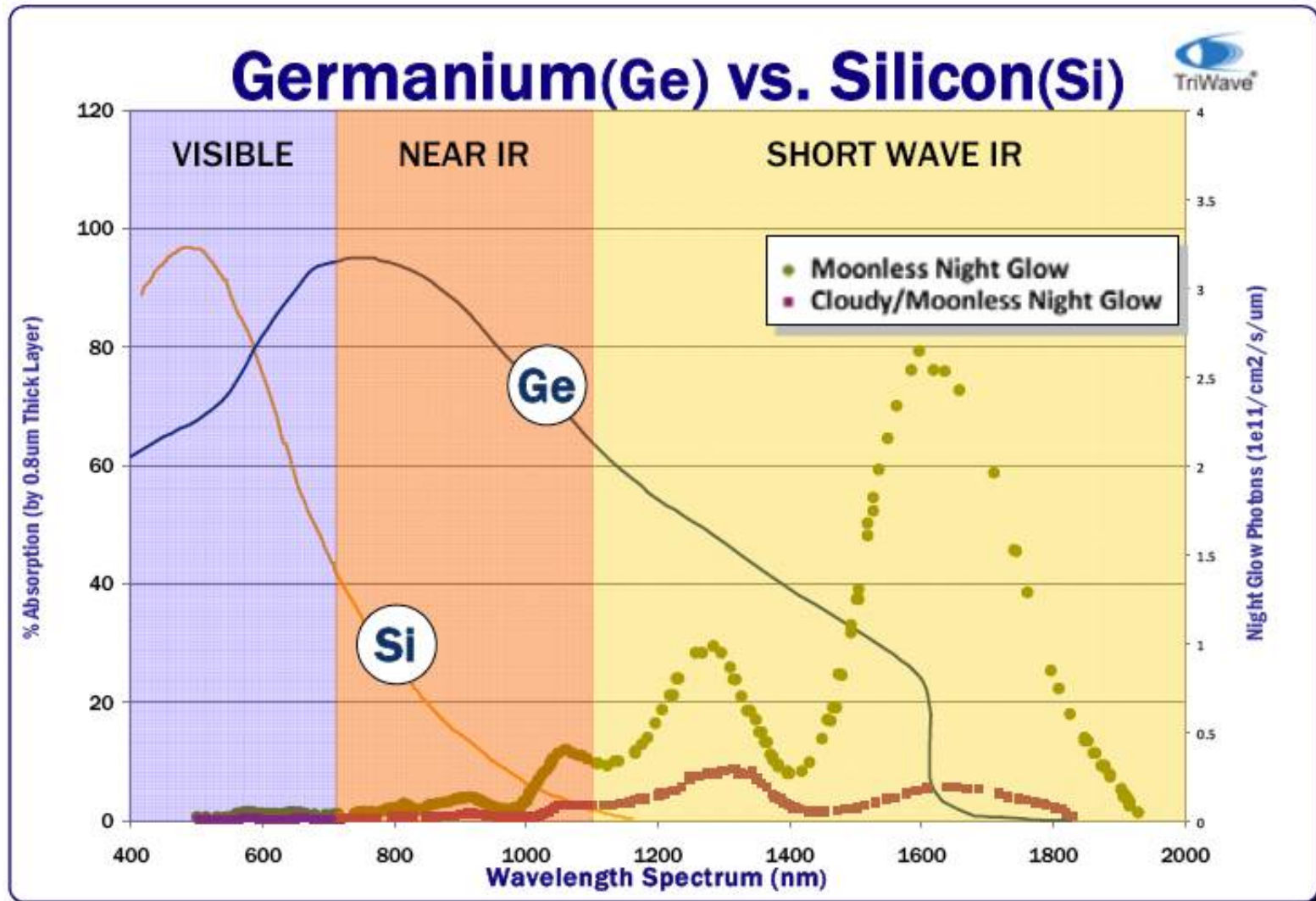


Skylight



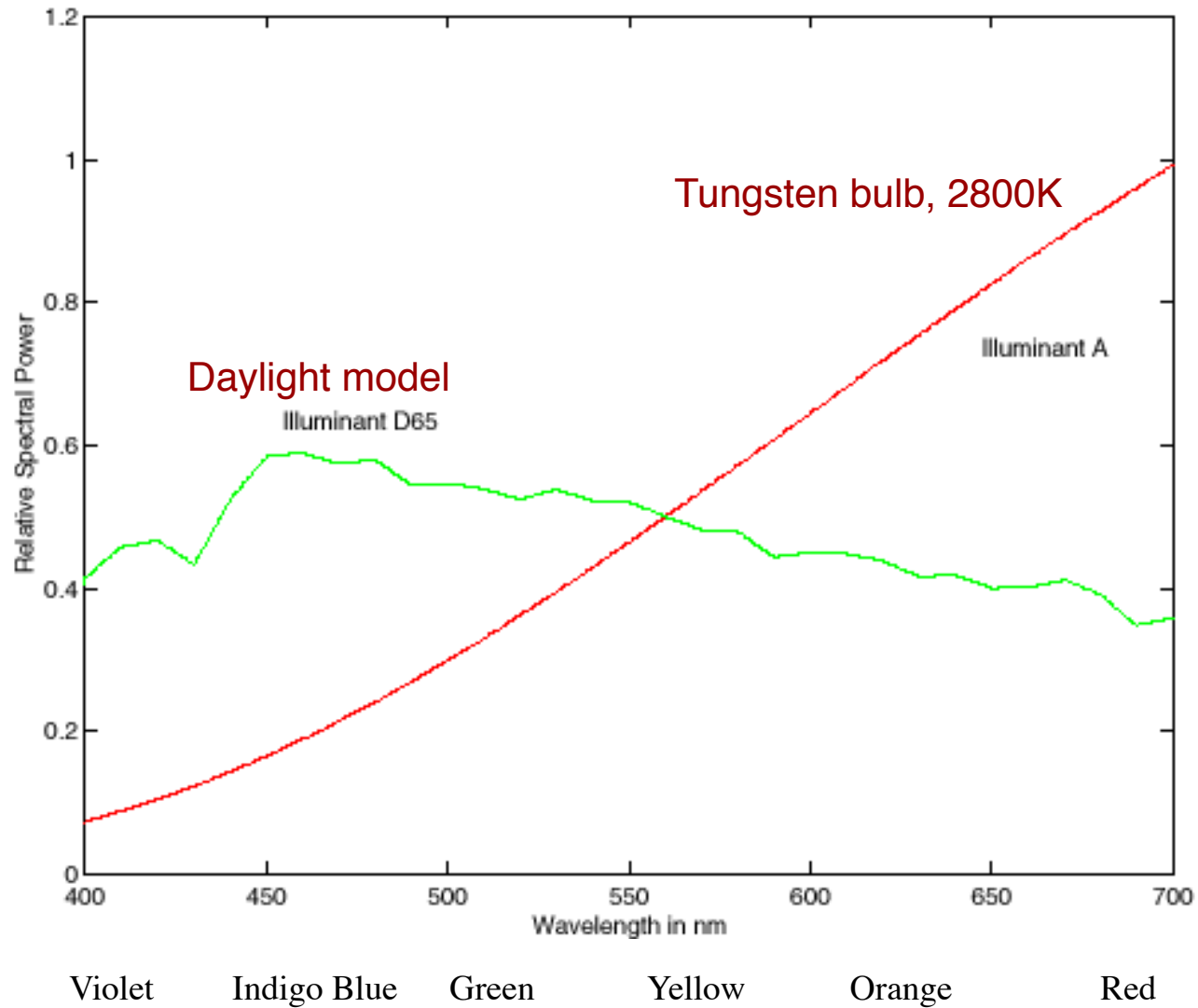


Night Sky Glow



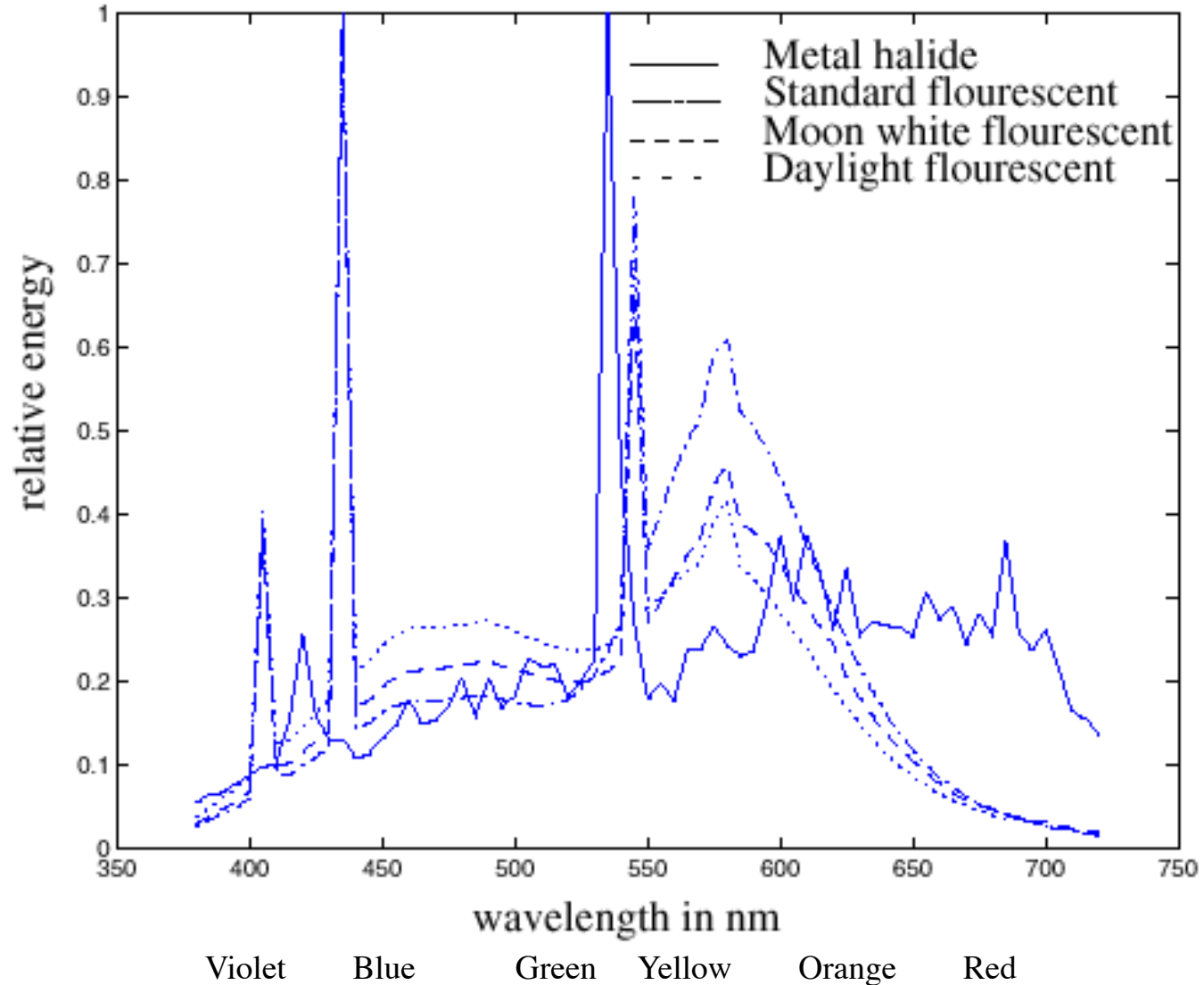


Incandescent Bulb





Metal Halide and Fluorescent Lights





Some Illustrations



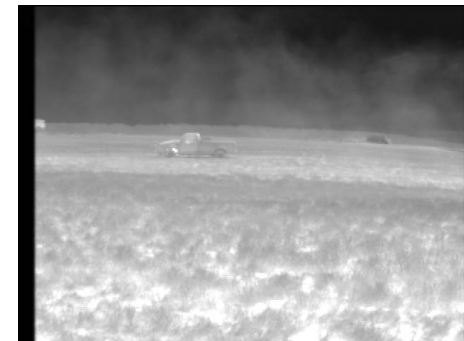
SWIR nightglow image
(no moon)



Visible vs. thermal image at night



Visible vs. SWIR in haze

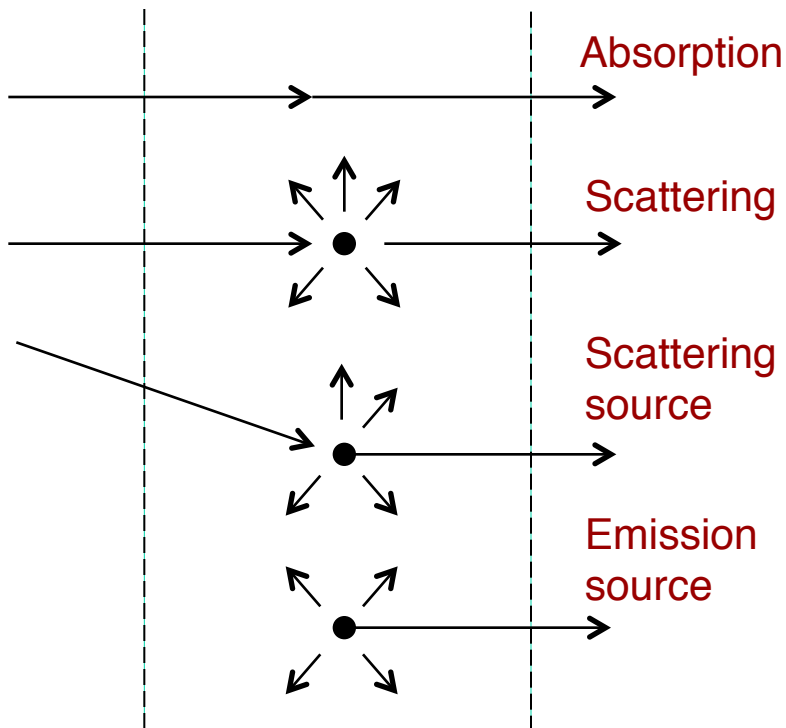


Visible vs. thermal in smoke



Atmospheric Propagation

- In general, radiative transfer in the atmosphere has these elements:



Together are “extinction”:

$$I(D) = I_0 e^{-\alpha D}, \quad T = e^{-\alpha D}$$

α is the *extinction coefficient* (km^{-1})
 T is the *transmission coefficient*

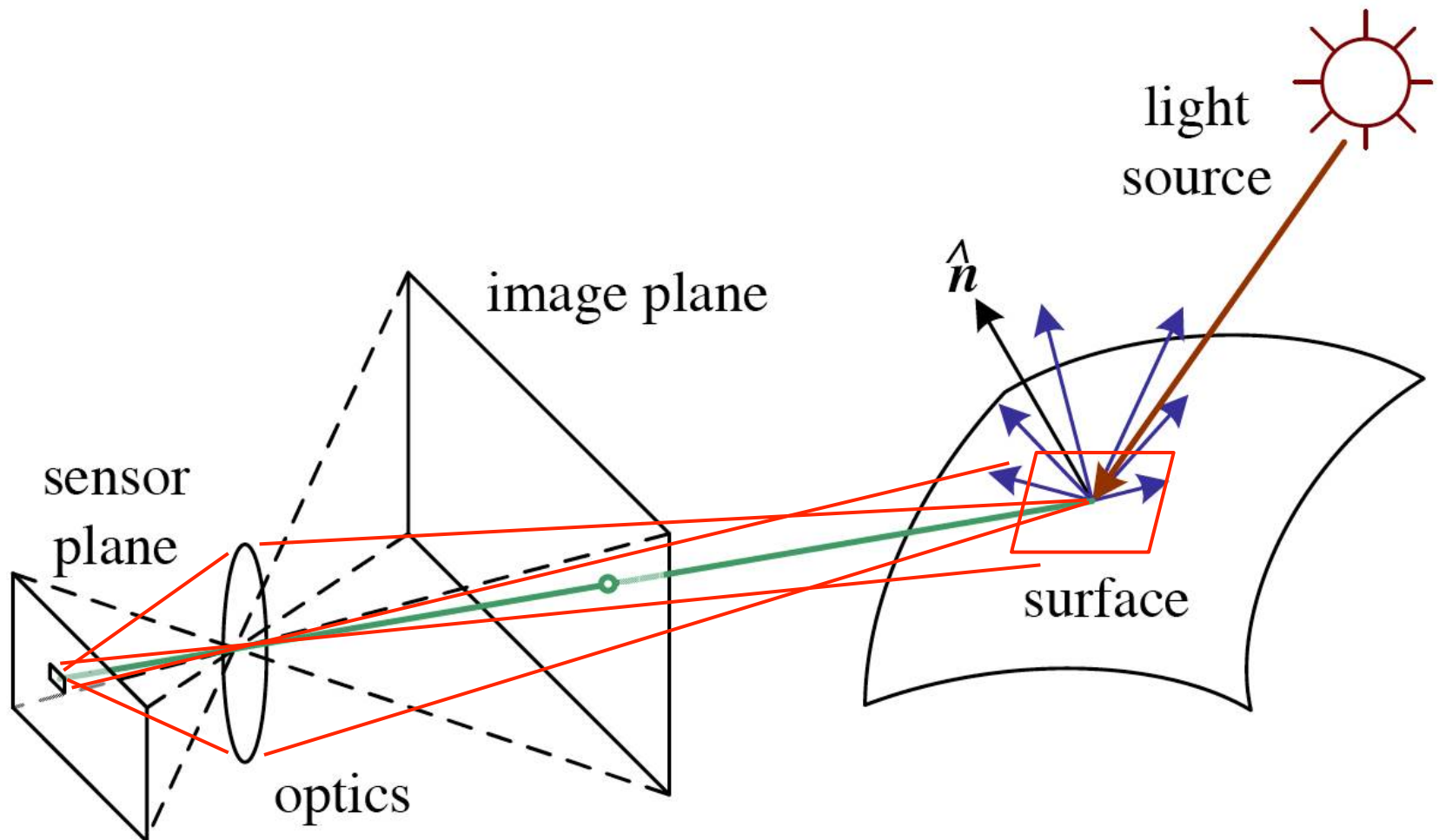
	Visible	LWIR	35 GHz MMW
Haze	0.02-2	0.02-0.4	0.001
Dust	0.2-4	0.2-4	< 0.005
At 0.5 km:			
T_H	0.37	0.82	0.9995
T_D	0.14	0.14	0.998

- We won't study details of each



Basic Radiometry: Motivation

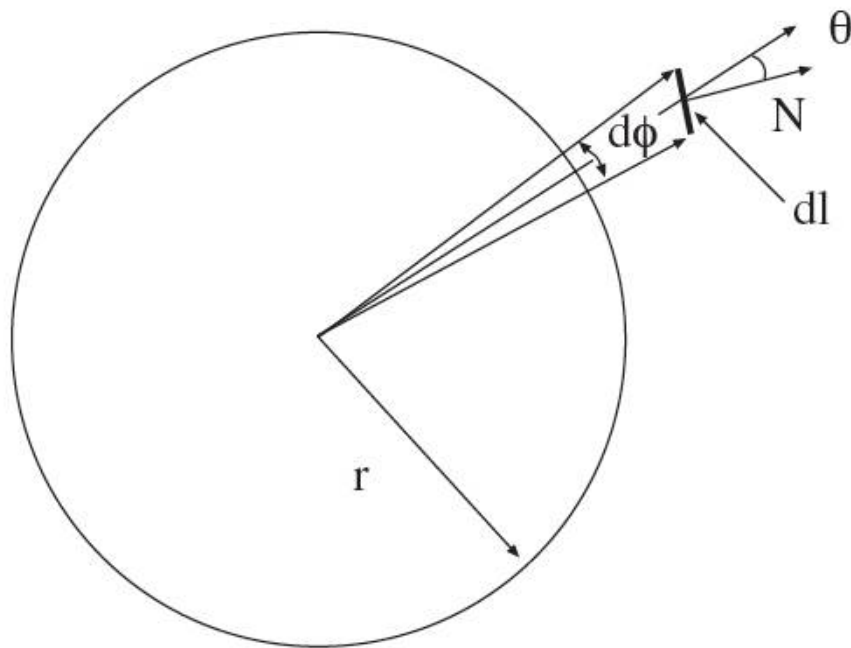
Goal: be able to model the light reaching a pixel in the image or to invert this to estimate scene properties from measured image brightness





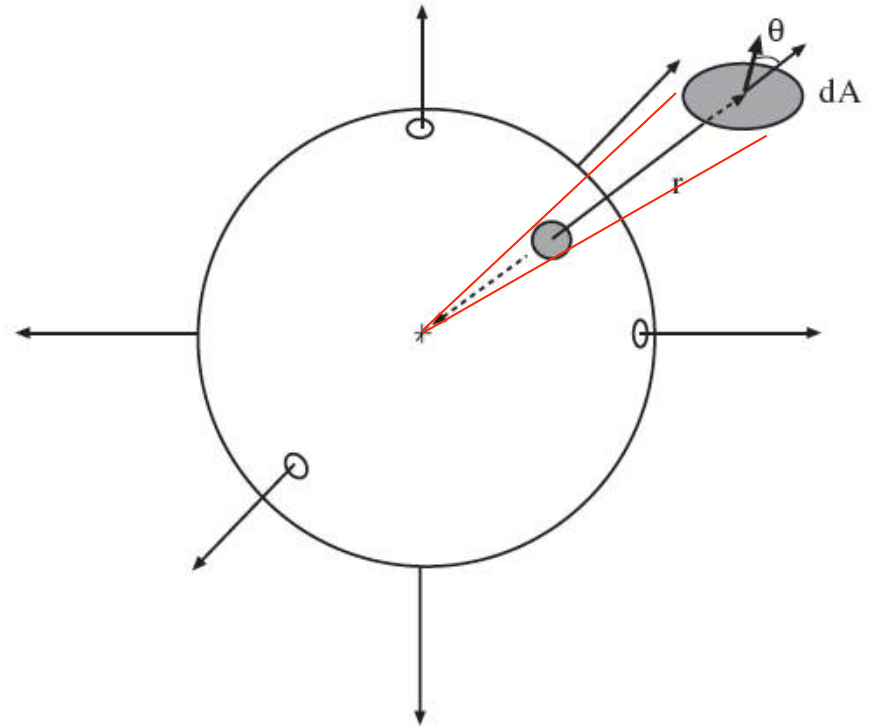
Solid Angles

Angle



$$d\phi = \frac{dl \cos \theta}{r}$$

Solid angle



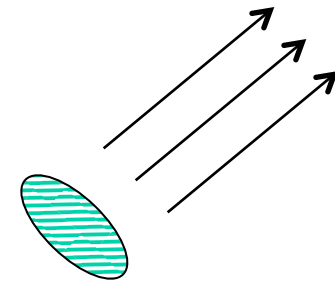
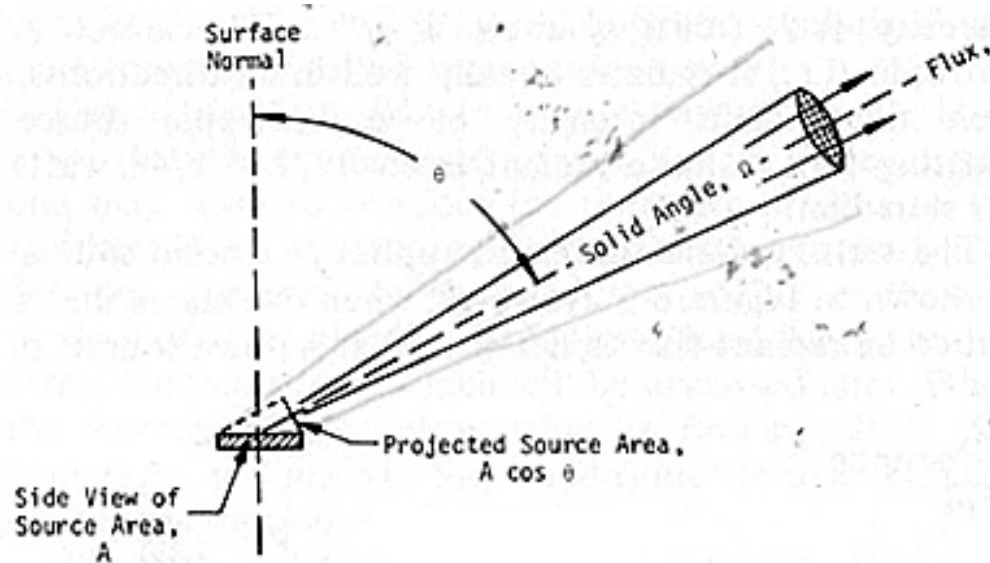
$$d\omega = \frac{dA \cos \theta}{r^2}$$



Radiance and Irradiance

Radiance:

- The amount of energy travelling at some point in a specified direction, per unit time, per unit area perpendicular to the direction of travel, per unit solid angle ($W m^{-2} sr^{-1}$). Usually denoted $L(x, \theta, \phi)$.



Irradiance:

- Power per unit area of a collimated beam ($W m^{-2}$). Usually denoted E .
- Power per unit area impinging on a surface.



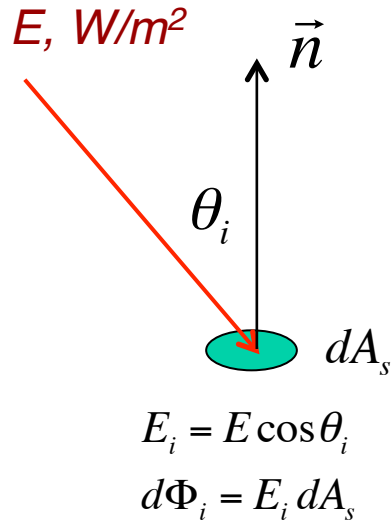
Definitions of Radiometric Terms

- Radiance: L . Units: $W m^{-2} sr^{-1}$
- Irradiance: E . Units: $W m^{-2}$
- Spectral quantities are per unit of wavelength, e.g.
 - Spectral radiance, $W m^{-2} sr^{-1} nm^{-1}$
 - Spectral irradiance, $W m^{-2} nm^{-1}$
- Radiant energy: Q . Units: J
- Radiant flux: Φ . Units: W
- Radiant intensity: I . Units: W/sr

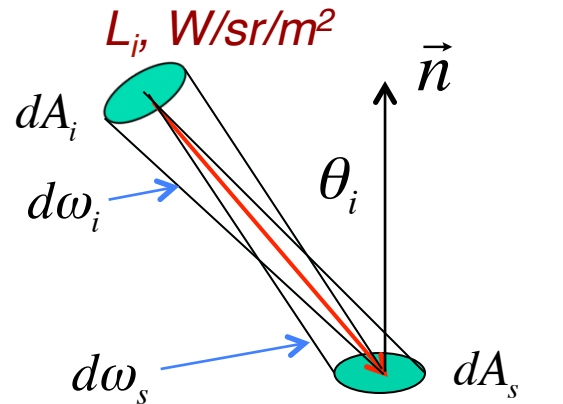


Surface Irradiance for Various Lighting Conditions

Point source at infinity (e.g. sun)



Extended source at range r

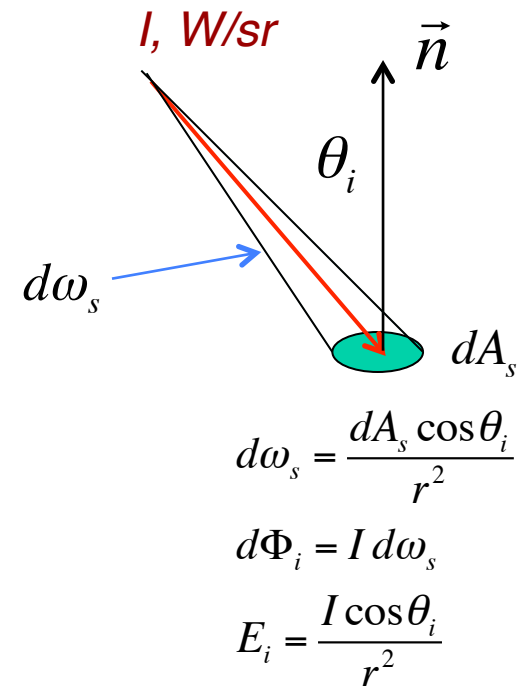


$$d\omega_s = \frac{dA_s \cos \theta_i}{r^2}, \quad d\omega_i = \frac{dA_i}{r^2}$$

$$d\Phi_i = L_i d\omega_s dA_i = L_i d\omega_i dA_s \cos \theta_i$$

$$E_i = \frac{d\Phi_i}{dA_s} = L_i \cos \theta_i d\omega_i$$

Point source at range r

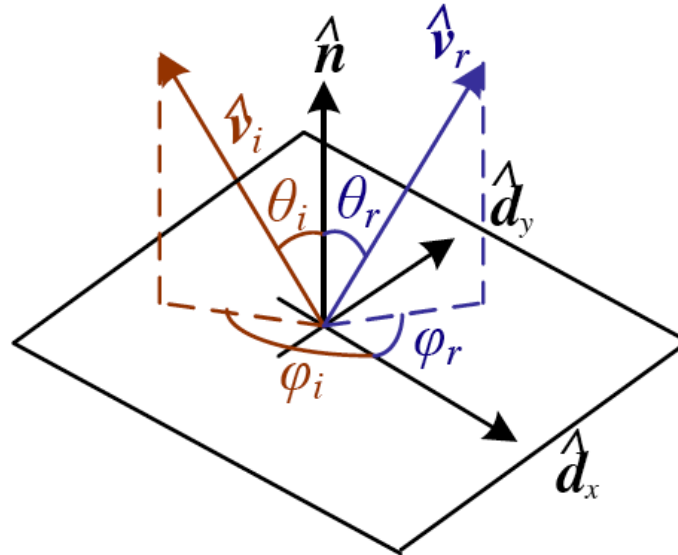


Same for extended source at infinity (e.g. sky)



Bidirectional Reflectance Distribution Function

Given an incoming ray (θ_i, ϕ_i) and outgoing ray (θ_r, ϕ_r)
what proportion of the incoming light is reflected along outgoing ray?



Answer given by the BRDF:

$$f(\theta_i, \phi_i, \theta_r, \phi_r) \quad \text{Units: } sr^{-1}$$

Isotropic case:

$$f(\theta_i, \theta_r, |\phi_i - \phi_r|)$$



BRDF as the Ratio of L and E

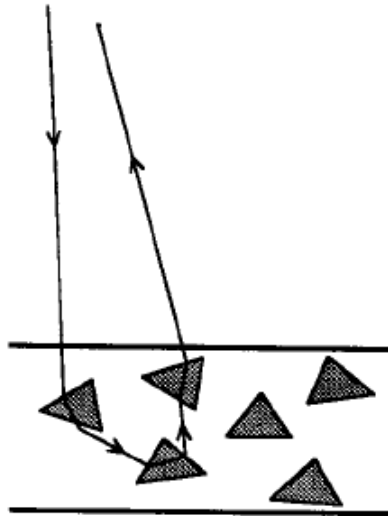
$$f(\theta_i, \phi_i, \theta_r, \phi_r) = \frac{dL_r(\theta_r, \phi_r)}{dE_i(\theta_i, \phi_i)} = \frac{dL_r(\theta_r, \phi_r)}{L_i(\theta_i, \phi_i) \cos \theta_i d\omega_i}$$

$$\therefore dL_r = f dE_i = f L_i \cos \theta_i d\omega_i$$



Diffuse Reflection

- Diffuse reflection
 - Dull, matte surfaces like matte paper
 - Often has a strong body color due to absorption by the material

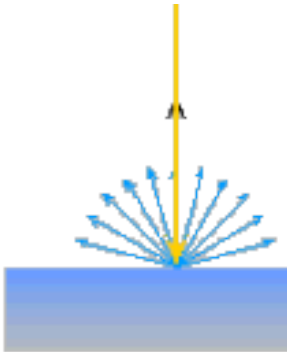


Internal scattering



Diffuse Reflection

- Diffuse reflection is governed by **Lambert's law**
 - Viewed brightness does not depend on viewing direction
 - Brightness *does* depend on direction of illumination
 - This is the model most often used in computer vision



$$f(\theta_i, \phi_i, \theta_r, \phi_r) = k$$

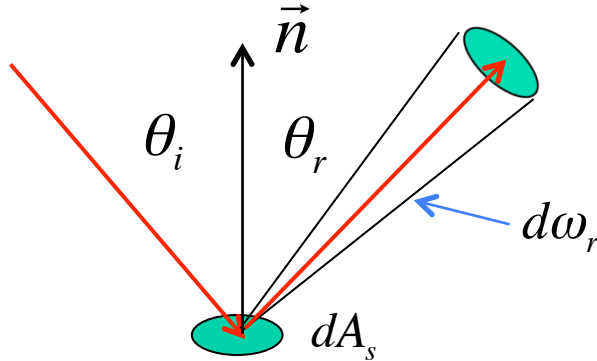
$$E_i = E \cos \theta_i$$

$$L_r = k E \cos \theta_i$$



What is k?

Consider a point source at infinity. Total flux on the surface patch is:



$$d\Phi_i = E_i dA_s = E \cos \theta_i dA_s$$

Flux leaving the surface patch through a given solid angle is:

$$\begin{aligned} d\Phi_r &= L_r dA_s \cos \theta_r d\omega_r \\ &= k E \cos \theta_i dA_s \cos \theta_r d\omega_r \end{aligned}$$

Assume a fixed fraction ρ is absorbed by the surface.

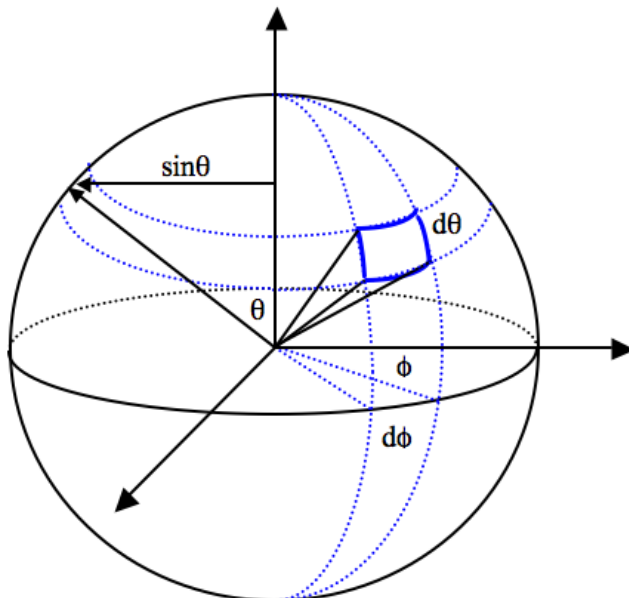
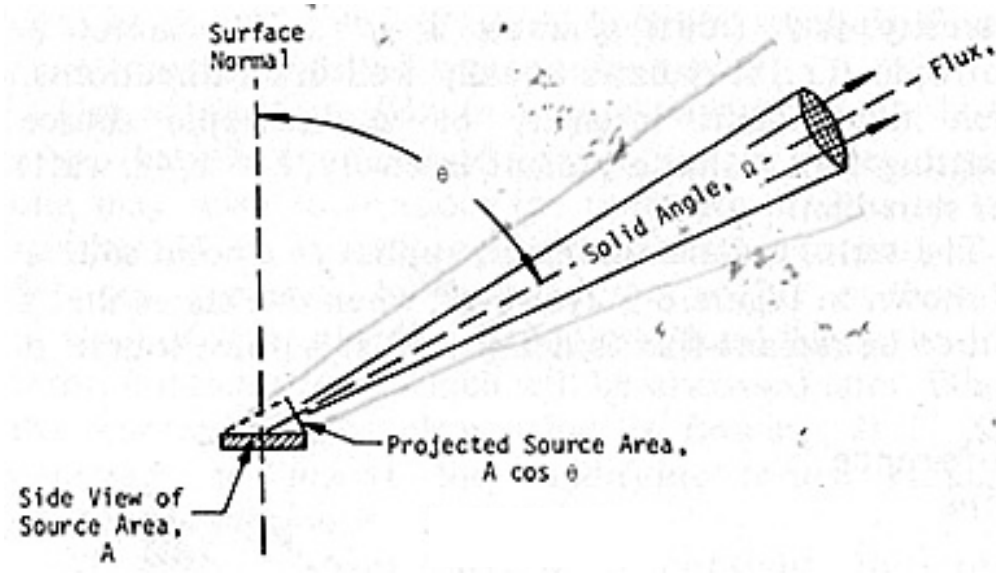
Equate total incoming with total outgoing:

$$\rho d\Phi_i = \int_{\Omega} d\Phi_r$$

$$\rho = \int_{\Omega} k \cos \theta_r d\omega_r$$



What is k?



$$\rho = \int_{\Omega} k \cos \theta_r d\omega_r$$

$$\rho = \int_0^{2\pi} \int_0^{\pi/2} k \cos \theta_r \sin \theta_r d\theta_r d\phi_r$$

$$\rho = 2\pi k \int_0^{\pi/2} \cos \theta_r \sin \theta_r d\theta_r$$

Substituting $2 \sin \theta \cos \theta = \sin 2\theta$

$$\rho = k\pi, \quad k = \frac{\rho}{\pi}$$

$$L_r = \frac{\rho}{\pi} E \cos \theta_i$$

(patterned after Horn, *Robot Vision*, ch. 10)



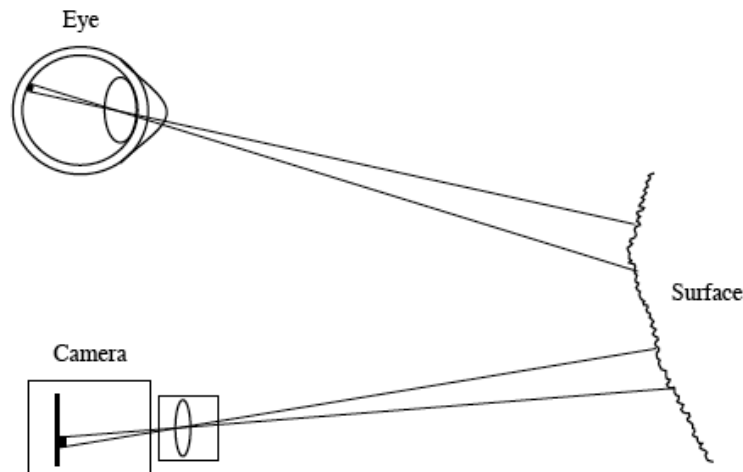
Lambert's Law is an Idealization; the Real World is More Complex

Rough cylinder



Smooth cylinder

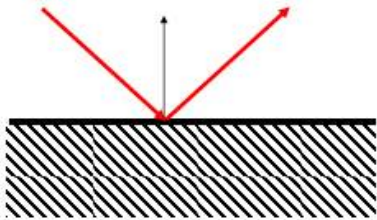
(a)



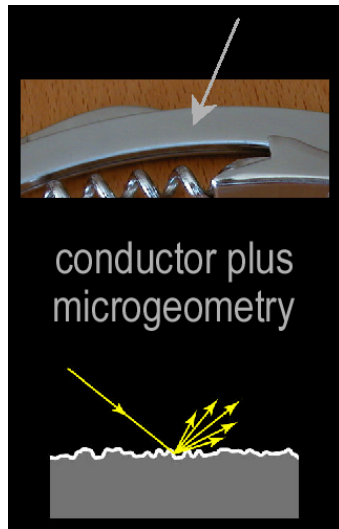
S. Nayar and M. Oren, "Visual Appearance of Matte Surfaces", *Science*, Vol. 267, pp. 1153-1156, 1995



Other Reflectance Models



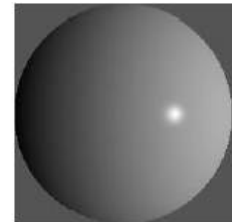
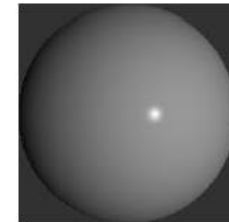
Pure specular



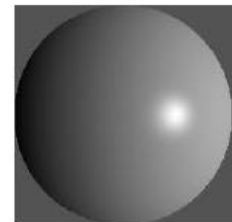
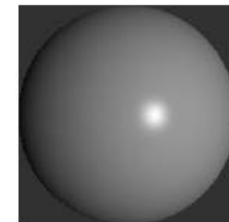
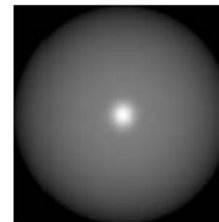
Specular lobe

Varying roughness

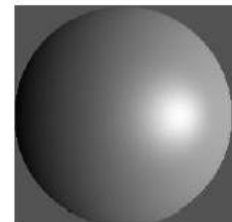
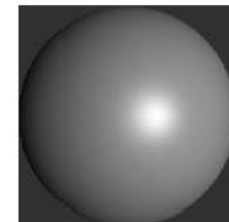
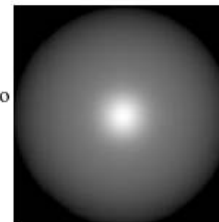
$\sigma = 3^\circ$



$\sigma = 6^\circ$



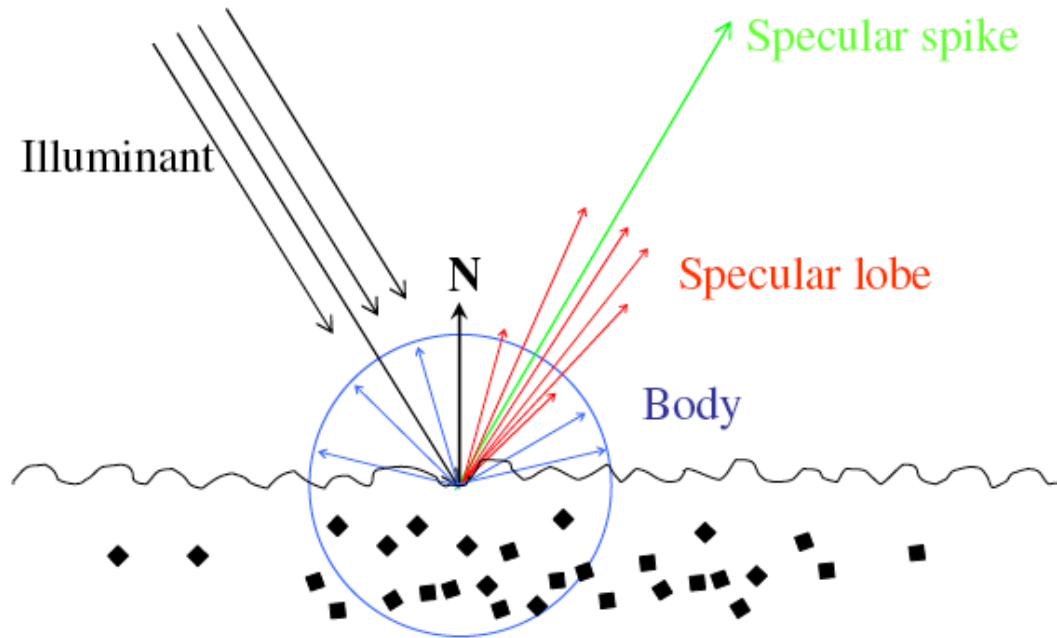
$\sigma = 12^\circ$



Varying incidence angle



Other Reflectance Models



Also: surface vs. body reflection (dichromatic reflectance model)

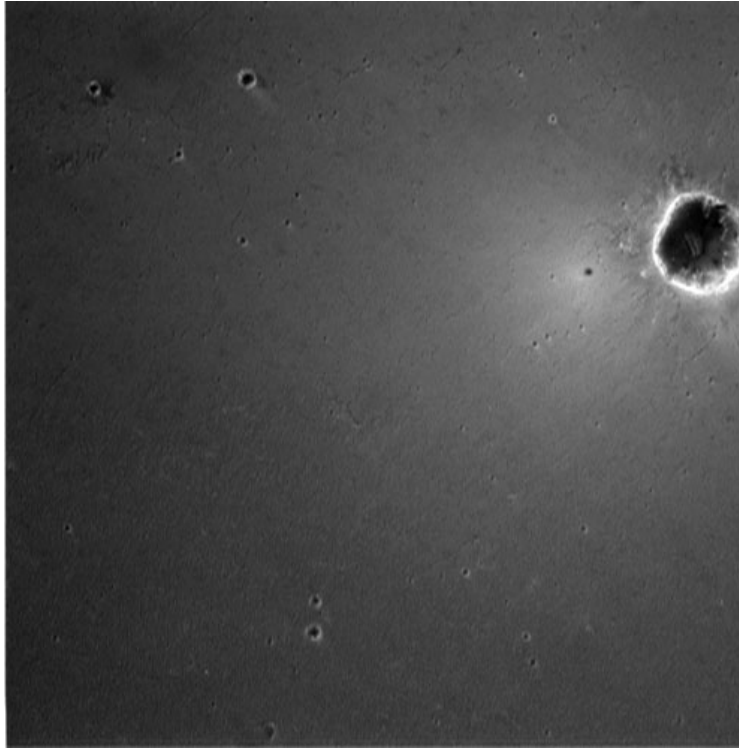
$$a \cos \theta_i + \frac{b}{\cos \theta_e} e^{-\frac{\beta^2}{2\sigma_\alpha^2}} + c \delta(\theta_i - \theta_e) \delta(\varphi_i - \varphi_e - \pi)$$

Diffuse lobe
Specular lobe
Specular spike

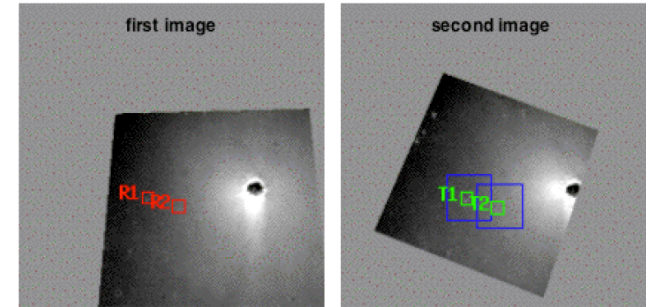
S. Nayar, K. Ikeuchi, T. Kanade, "Surface Reflection: Physical and Geometrical Perspectives", *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol. 13, No. 7, 1991



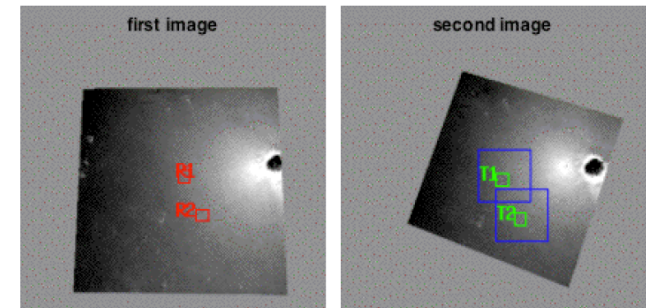
Other Reflectance Models: Opposition Effect



First Image Pair



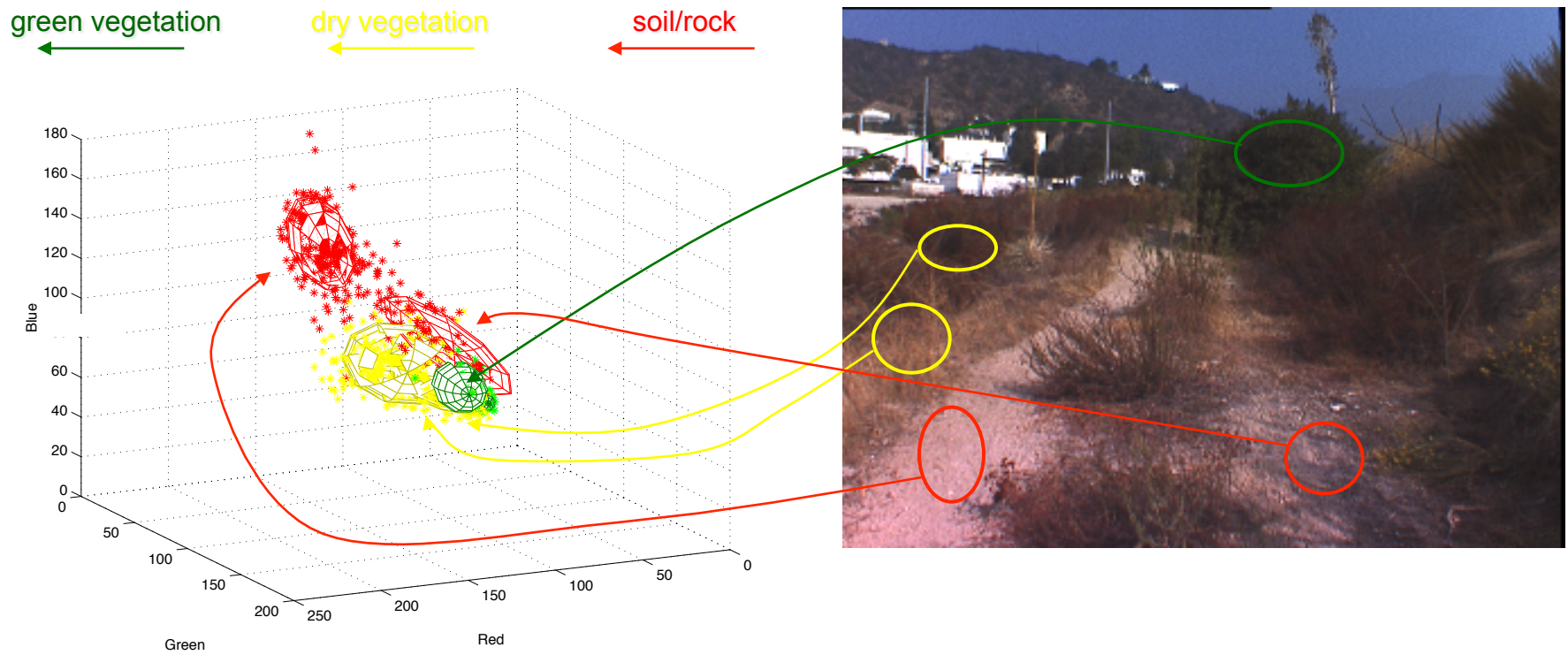
Second Image Pair



B. Hapke, *Theory of Reflectance and Emittance Spectroscopy*, 1993

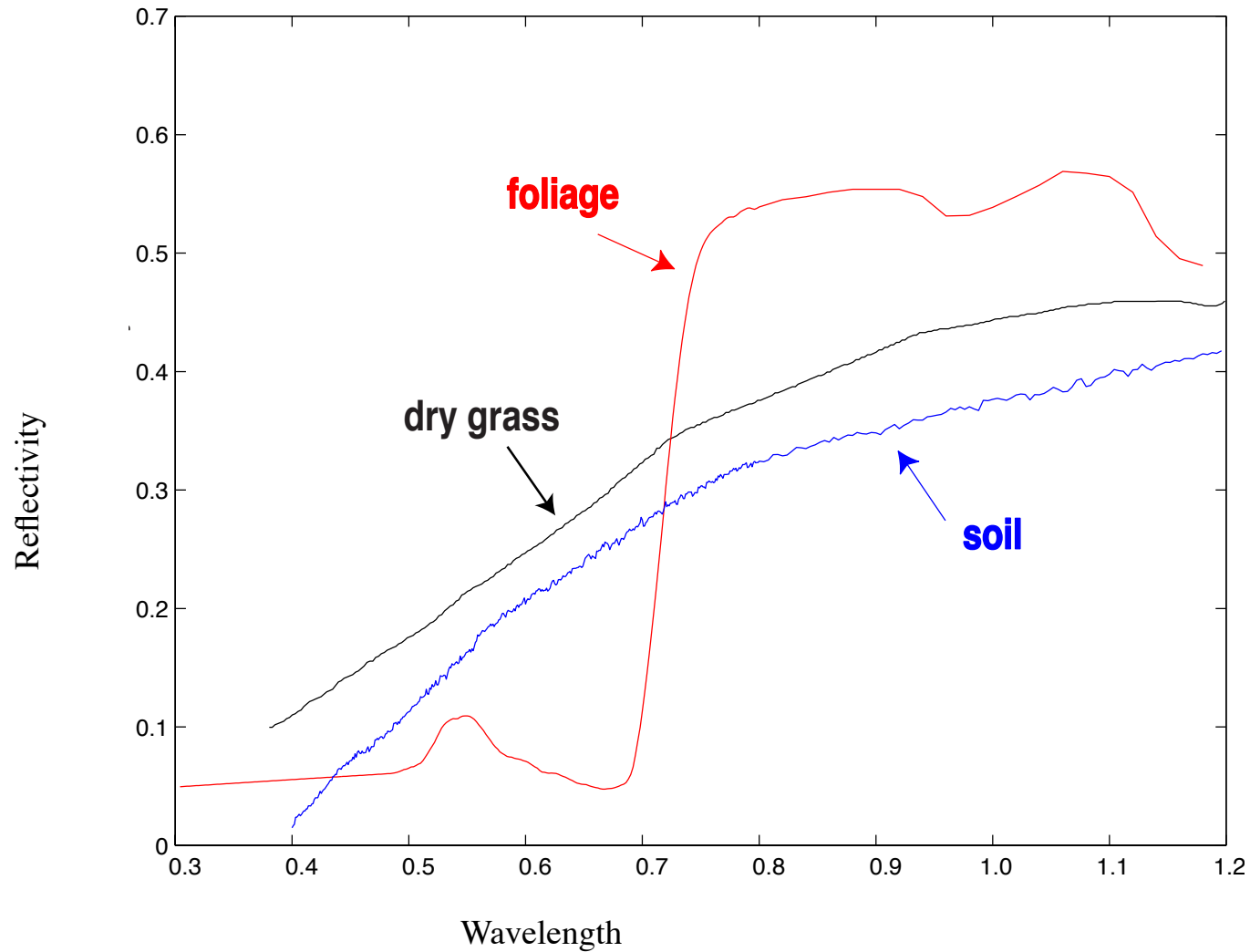


Color





Spectral Reflectance: Visible and Near Infrared (VNIR)





Spectral Reflectance: Visible and Near Infrared (VNIR)



650nm image

:

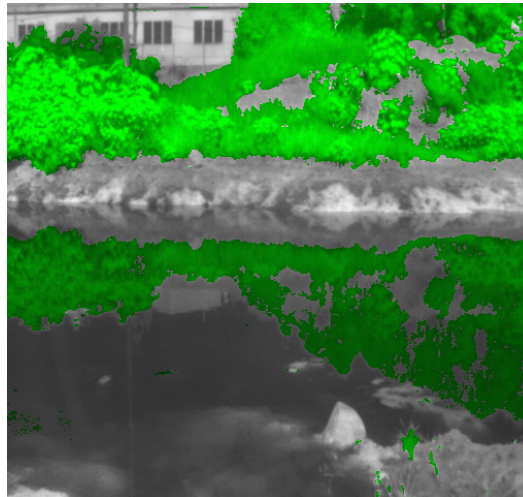


800nm image

=



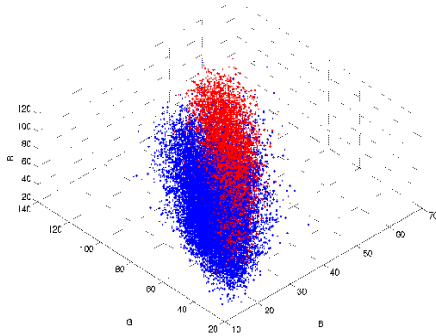
650:800 ratio image



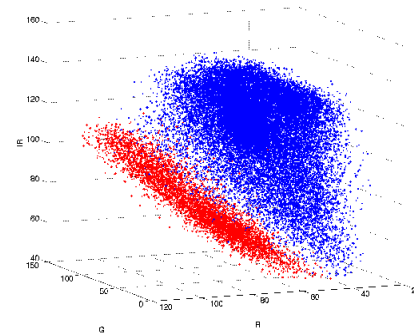
Classified image



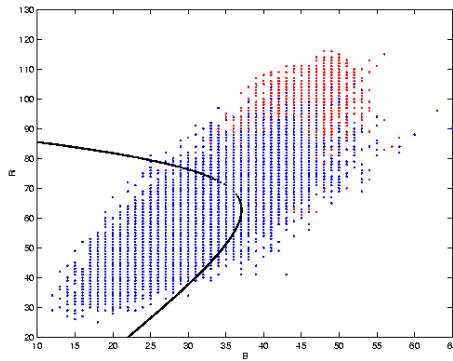
Spectral Reflectance: Visible and Near Infrared (VNIR)



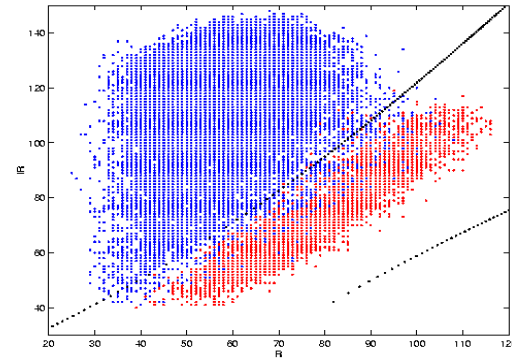
B-G-R



G-R-IR



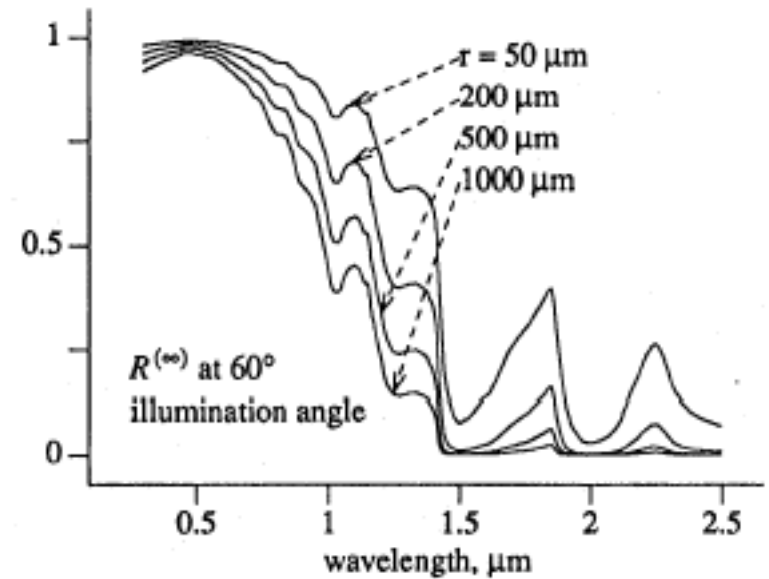
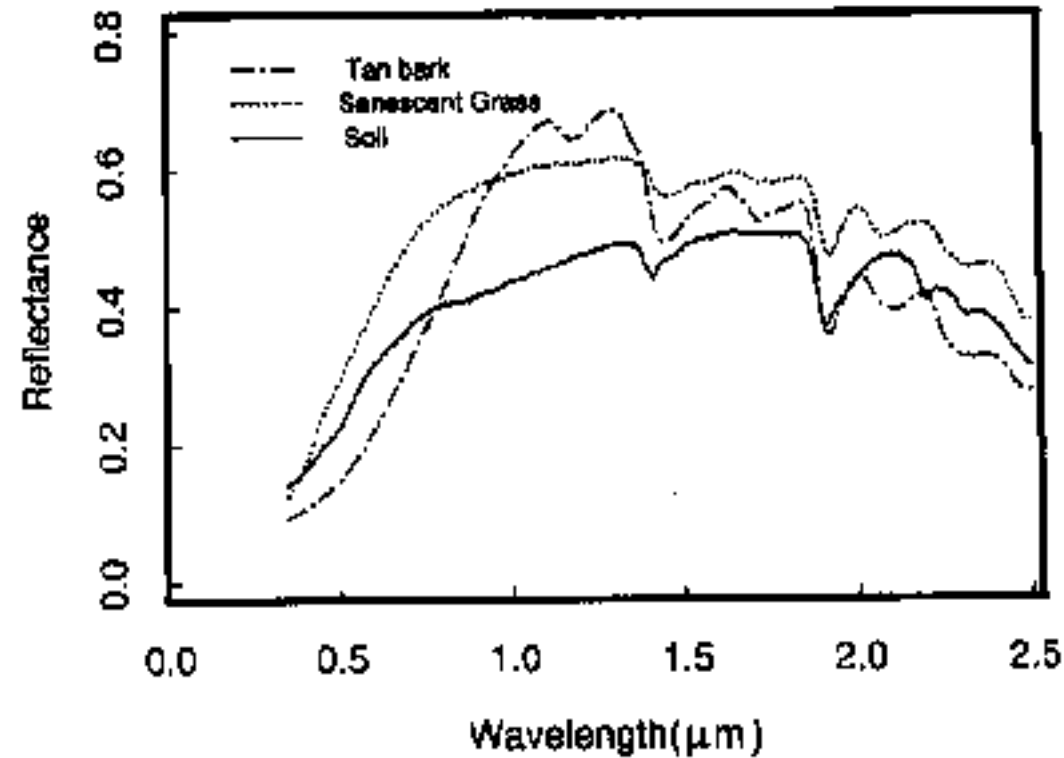
B-R



R-IR



Spectral Reflectance: Short Wave Infrared (SWIR)



Snow reflectance





Thermal Infrared

- Seeing in the dark
- Seeing through atmospheric obscurants
- Recognizing things due to:
 - Intrinsic heat
 - Heat transfer characteristics
 - Thermal “color”

Visible

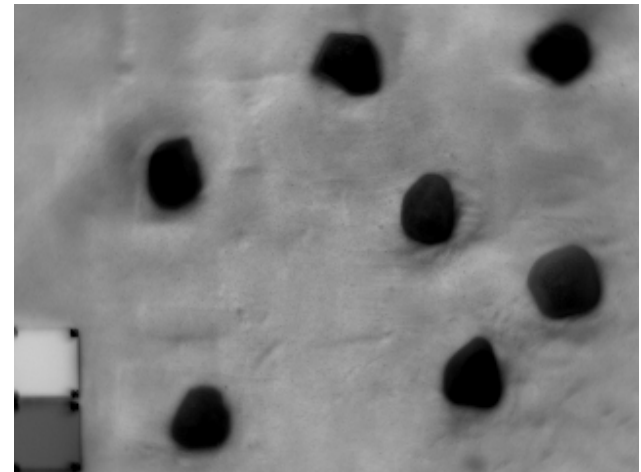
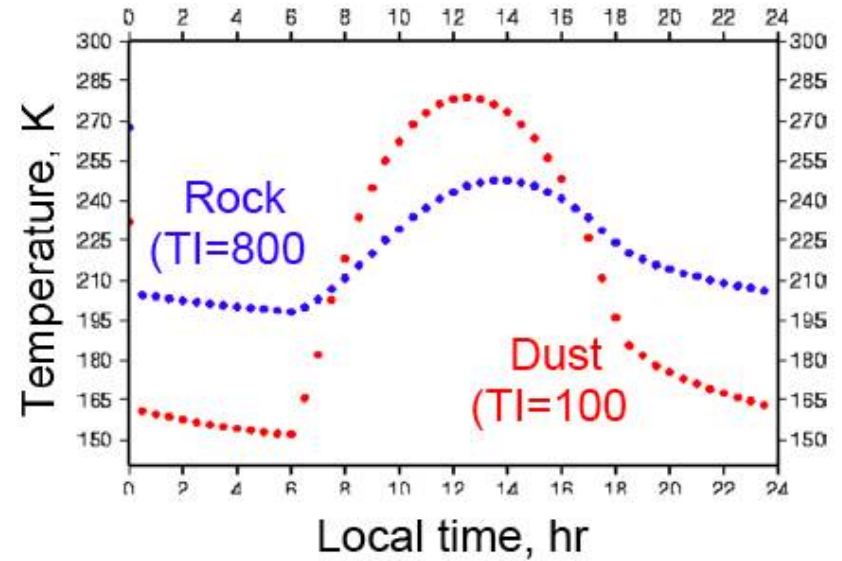
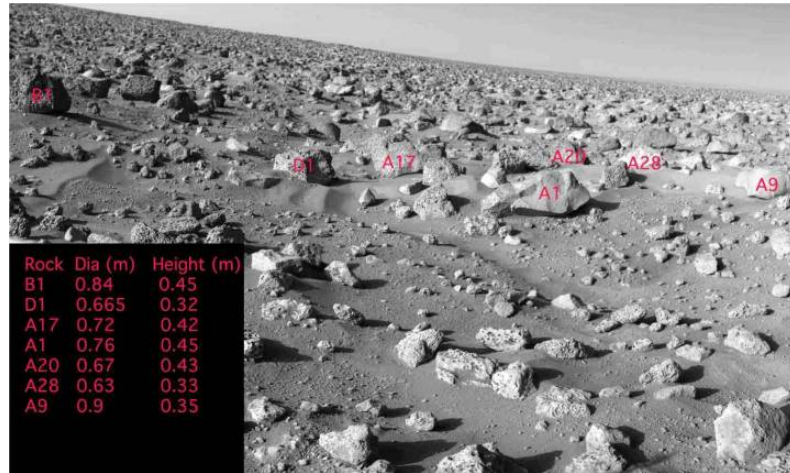


LWIR





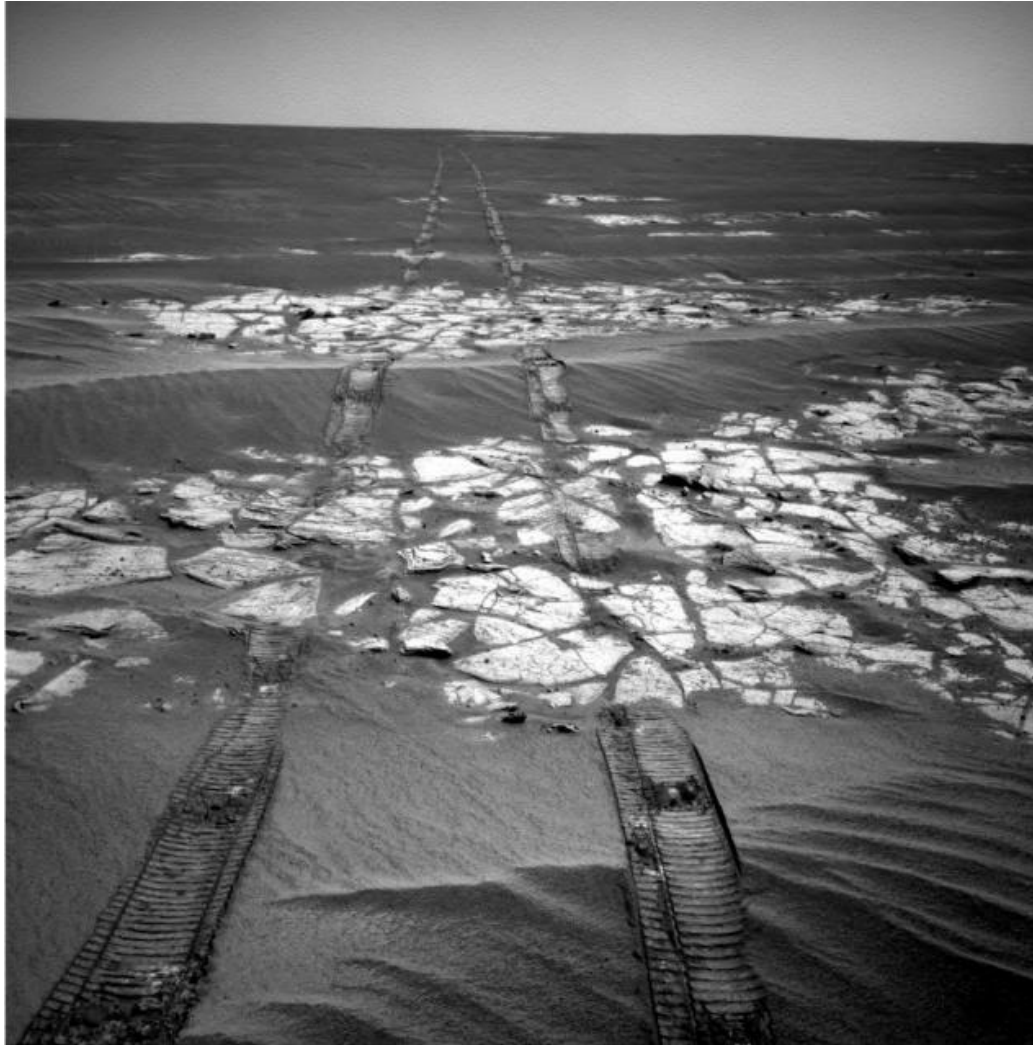
Heat Transfer Characteristics: Thermal Inertia



(U. Arizona)



Open Problem: Terrain Classification for Mars Rovers



Rovers sometimes get stuck in the ripples; easily cross the bedrock

How to discriminate the two reliably at low cost for sensors and processing?



Heat Transfer Characteristics

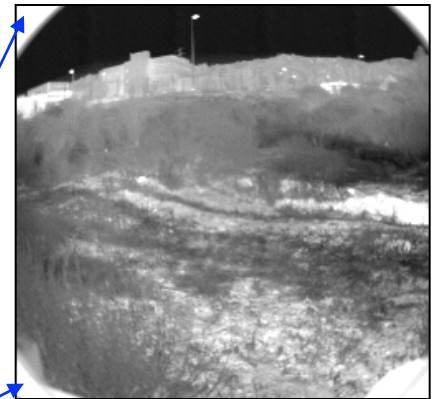


Color crosswise view



Color lengthwise view

Weatherproof sensor enclosure

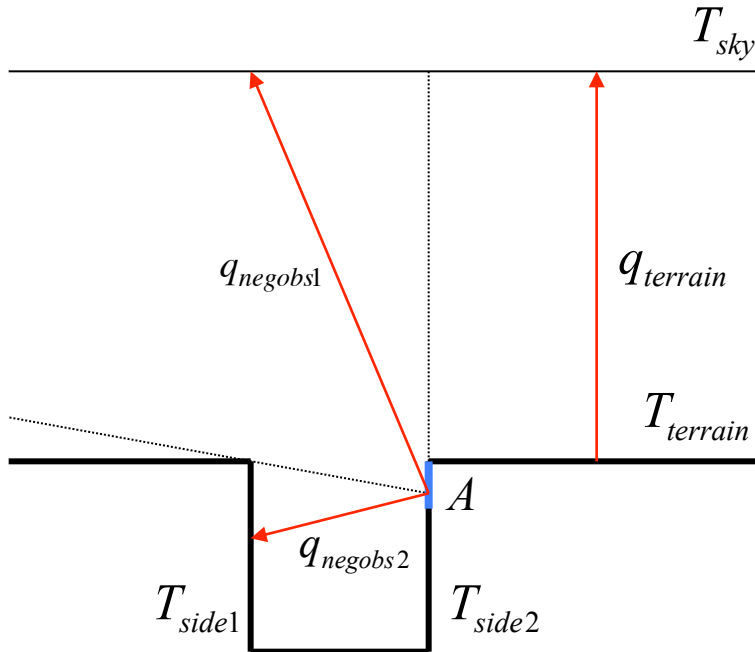


*MWIR image 1 hr
after sundown*



Heat Transfer Characteristics: After Sundown, Holes Cool More Slowly than Surface

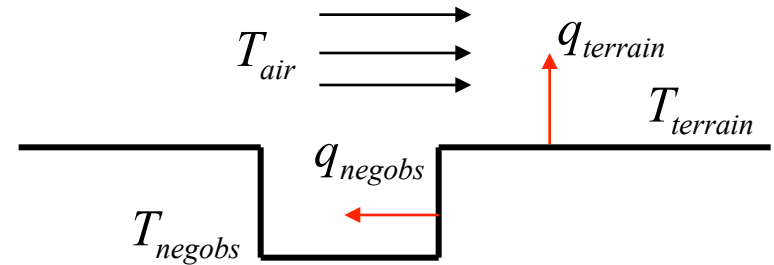
- Radiation**



$$q_{terrain} = \varepsilon \sigma (T_{terrain}^4 - T_{sky}^4)$$

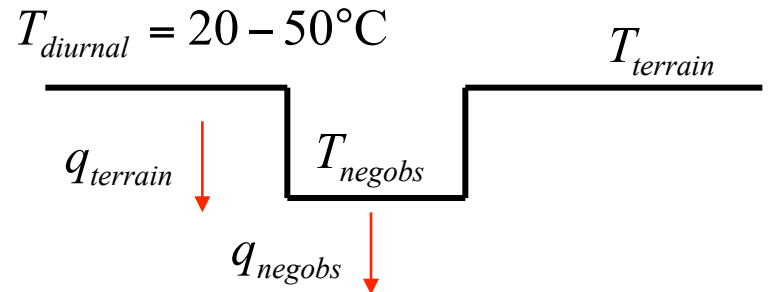
- Evapotranspiration (ignored here)**

- Convection**



$$q_{terrain} = h(T_{terrain} - T_{air})$$

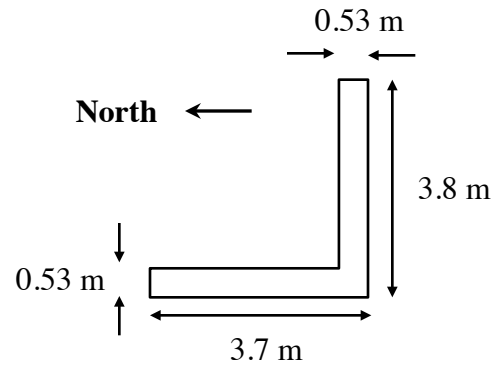
- Conduction**



$$q_{terrain} = -k \frac{dT}{dx}$$



Heat Transfer Characteristics



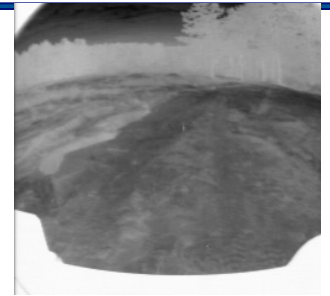
9 pm



7 am



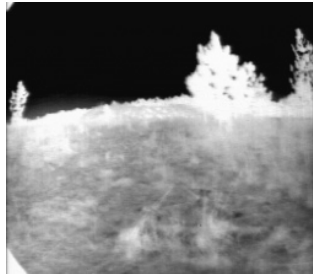
9 am



9 pm



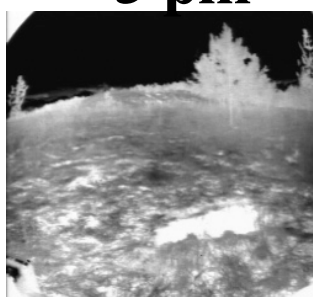
5 pm



5 pm



10 pm



7 am

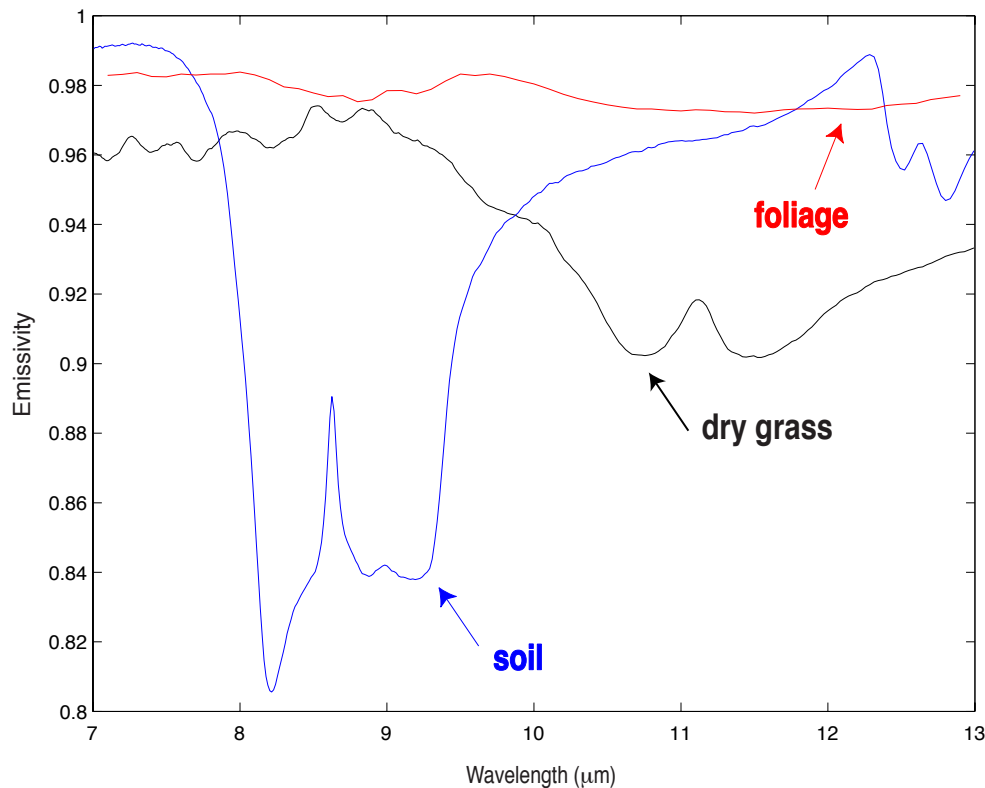


Thermal “Color”

Spectral emittance: $S(\lambda) = \varepsilon(\lambda) \frac{C_1}{\lambda^5 \left(e^{\frac{C_2}{\lambda T}} - 1 \right)}$

↓ Emissivity

↓ Blackbody emittance



Issues:

- Separate temperature and emissivity
- Exploit thermal inertia information
- Determine robust spectral features