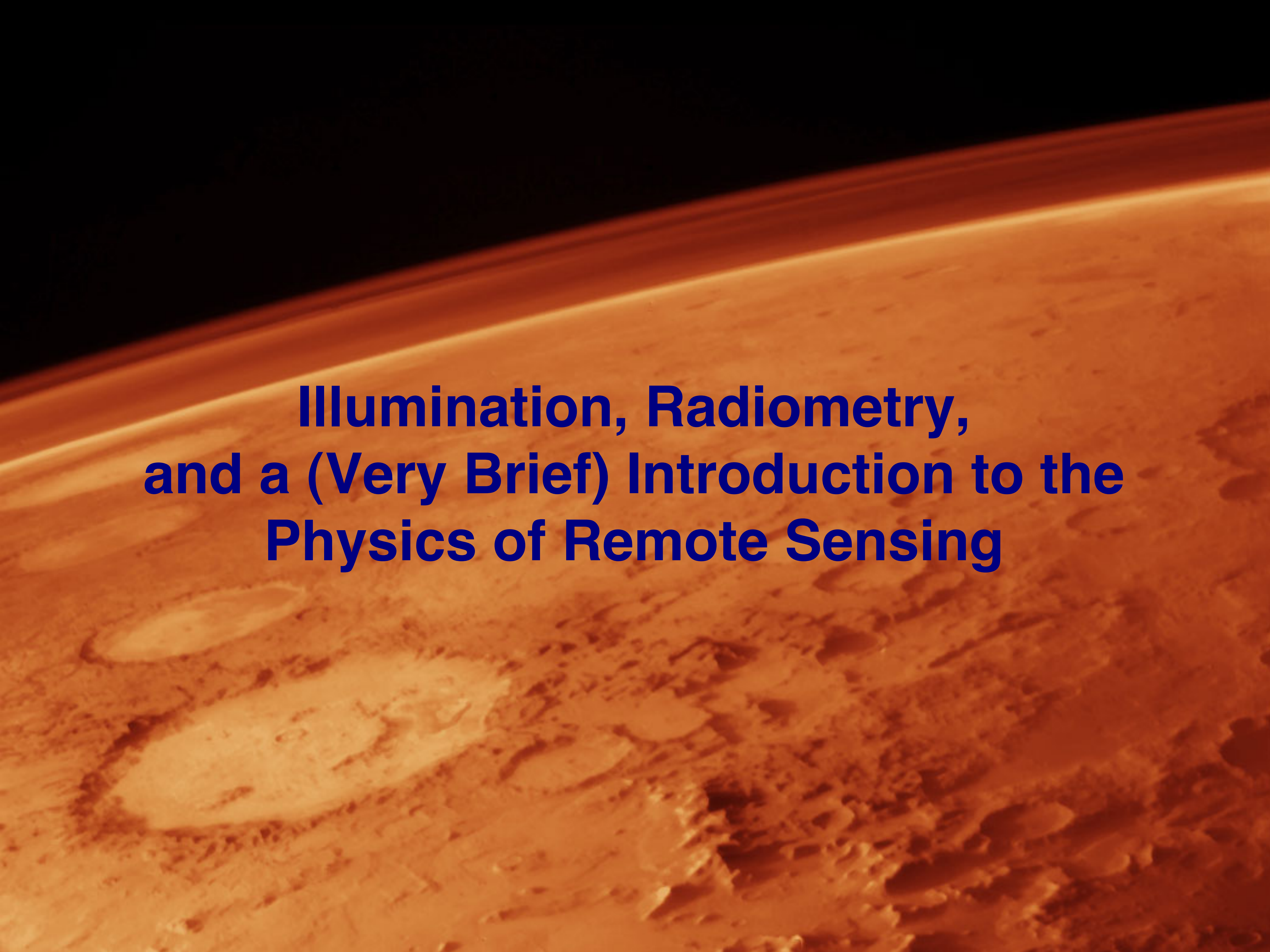
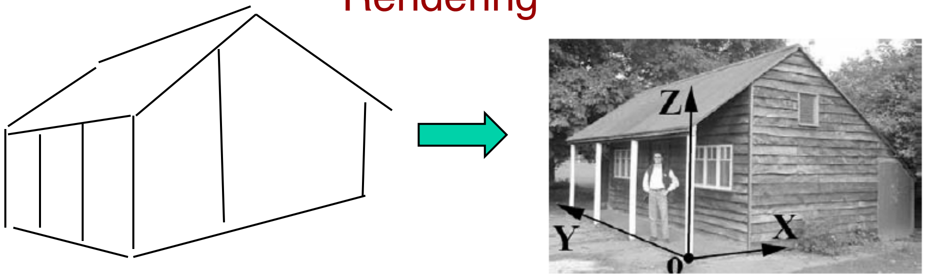
Illumination, Radiometry, and a (Very Brief) Introduction to the Physics of Remote Sensing



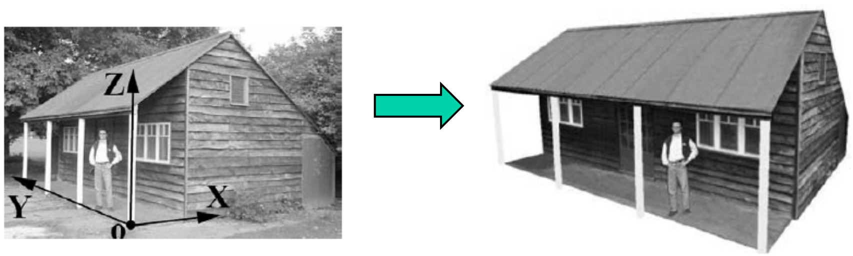
Course Philosophy

Rendering



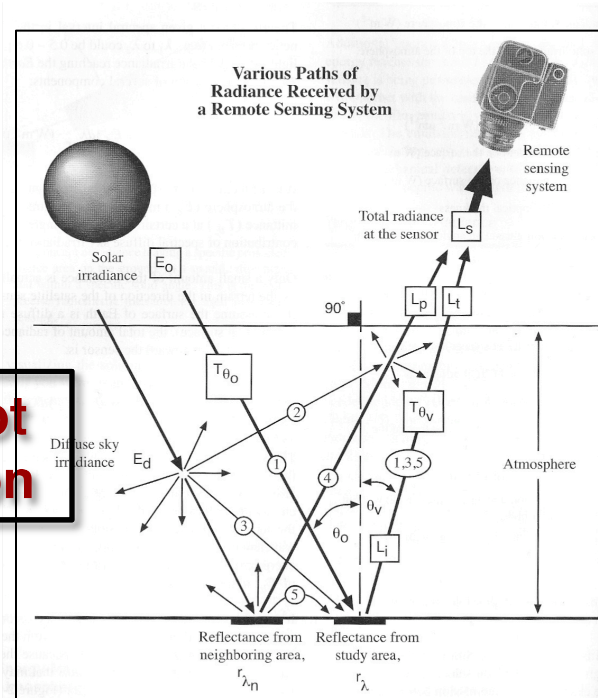
Computer graphics

Estimation



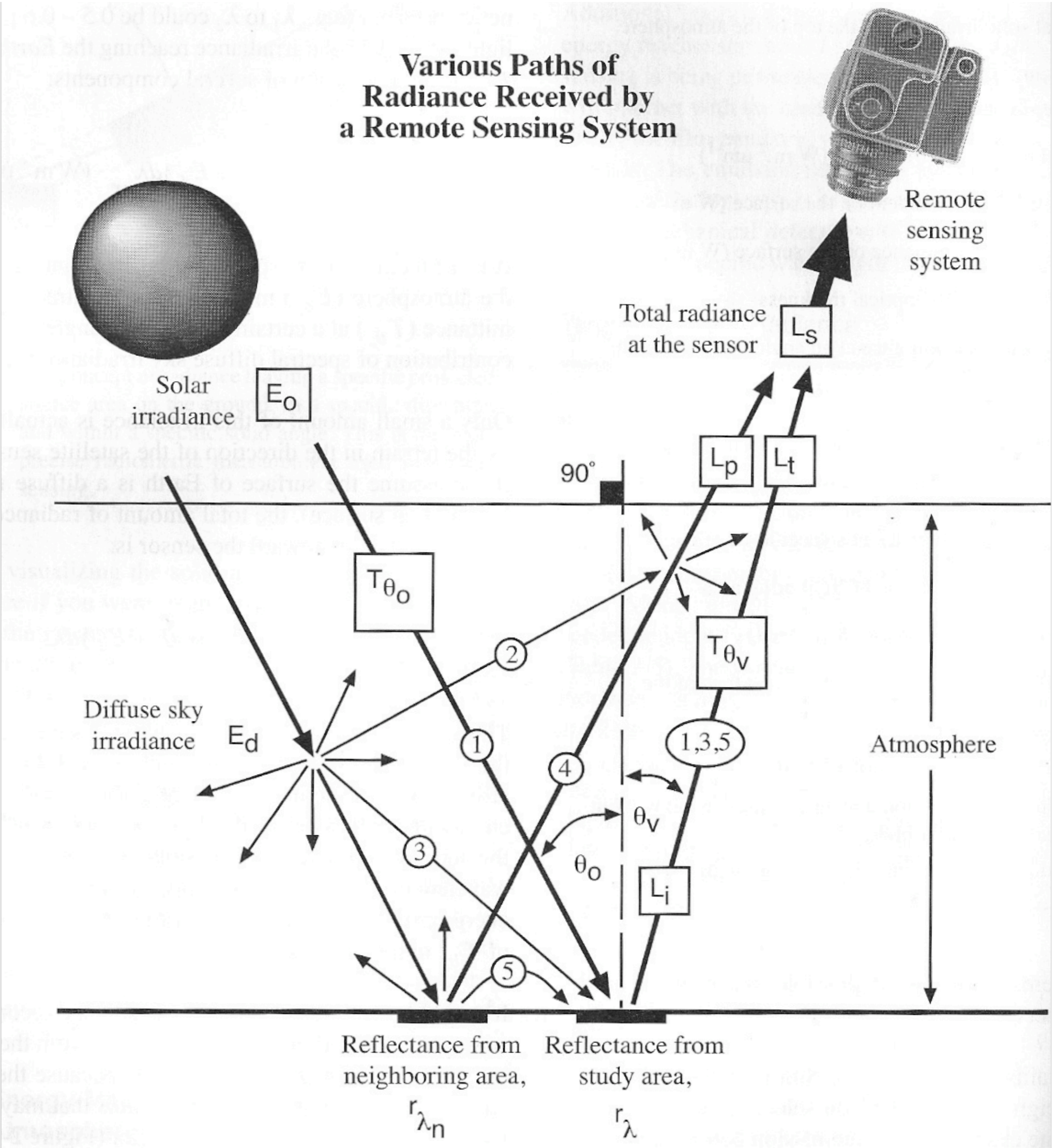
Computer vision

Robot vision



Remote sensing

What This Lecture is About

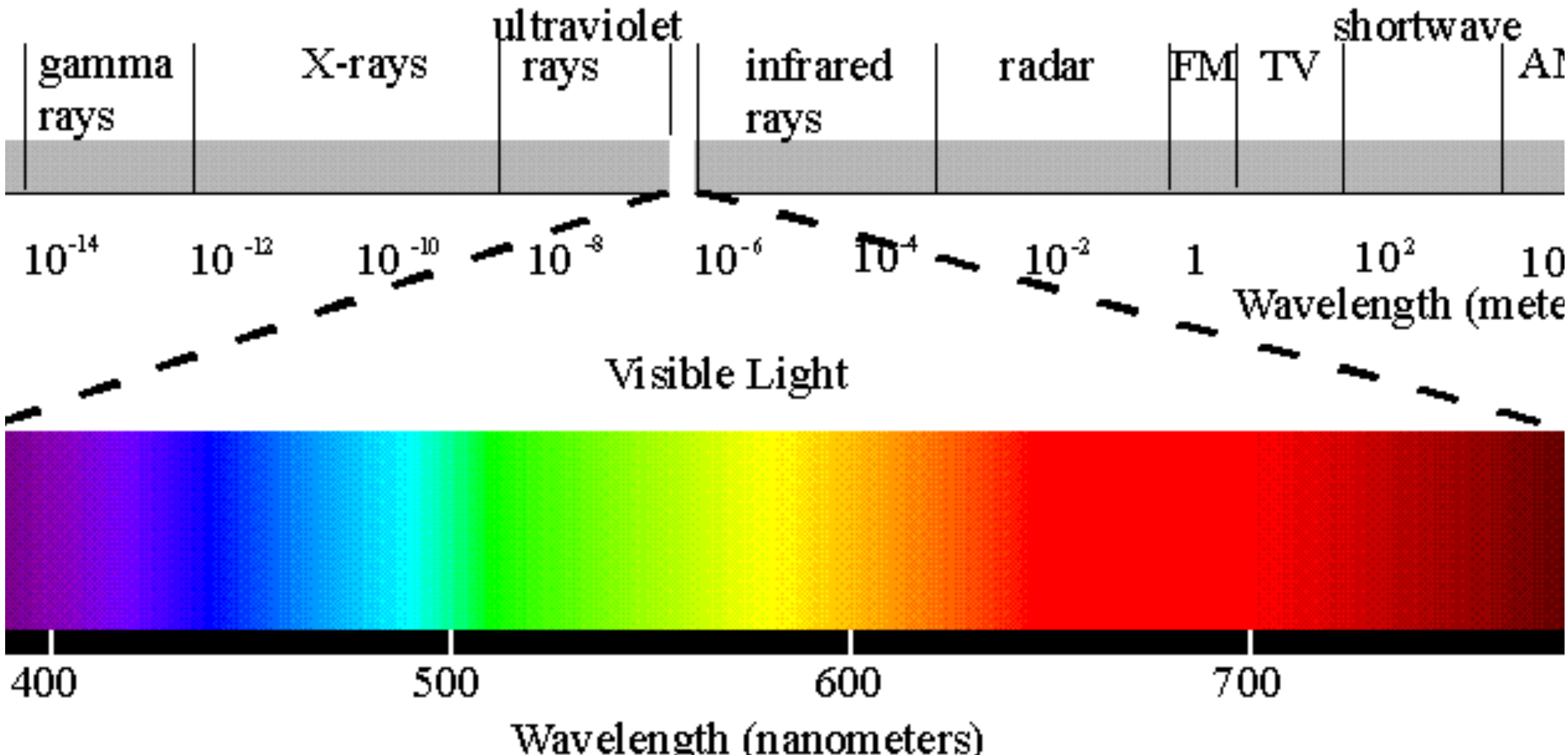


- Characteristics of illumination sources
- Atmospheric attenuation
- Radiometry and reflectance models
- Spectral characteristics of reflectance and thermal emission and their interrelationships

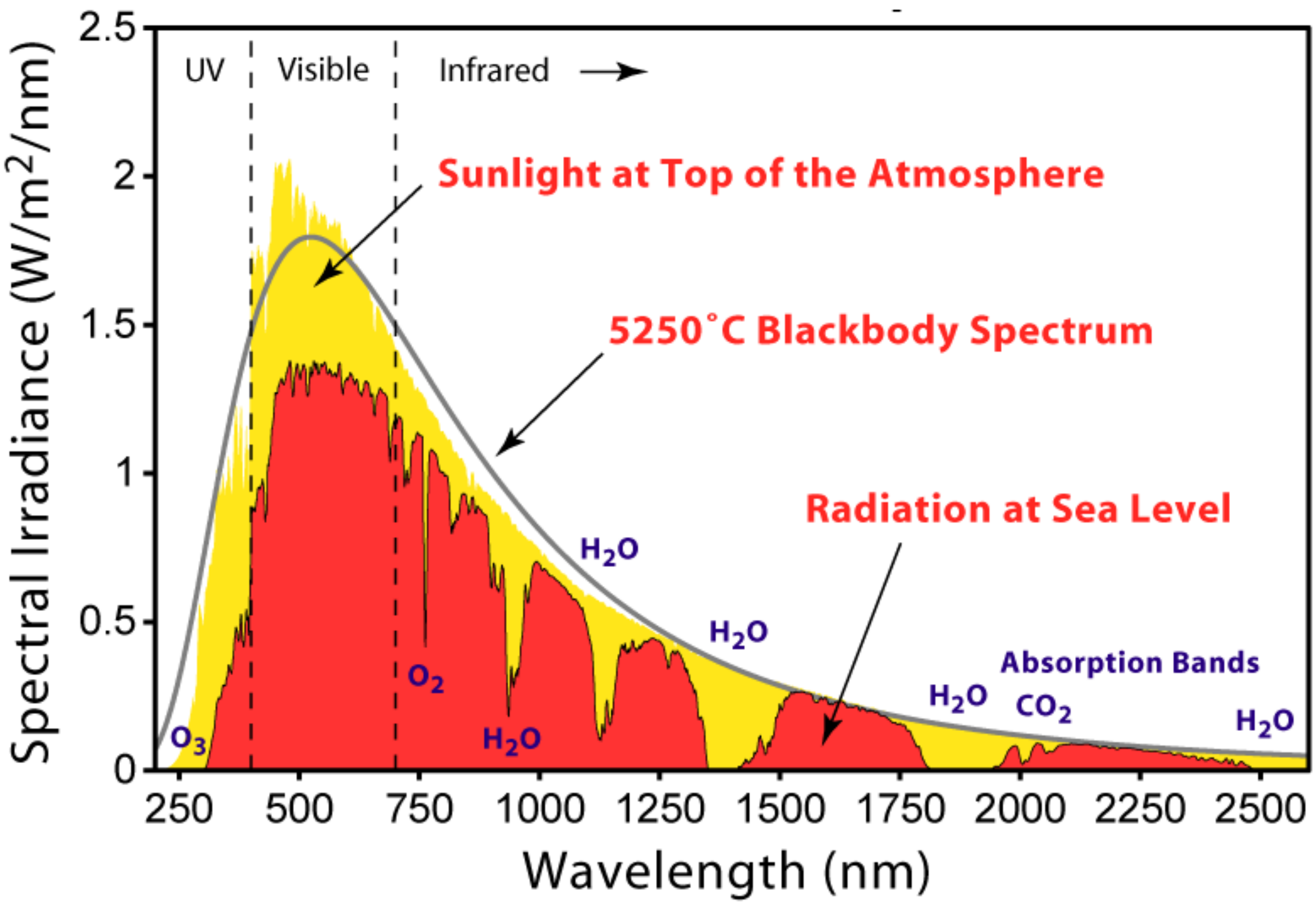
In Context with Coming Lectures

- 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 ~ 1370 W/m^2 above atmosphere (*solar constant*)

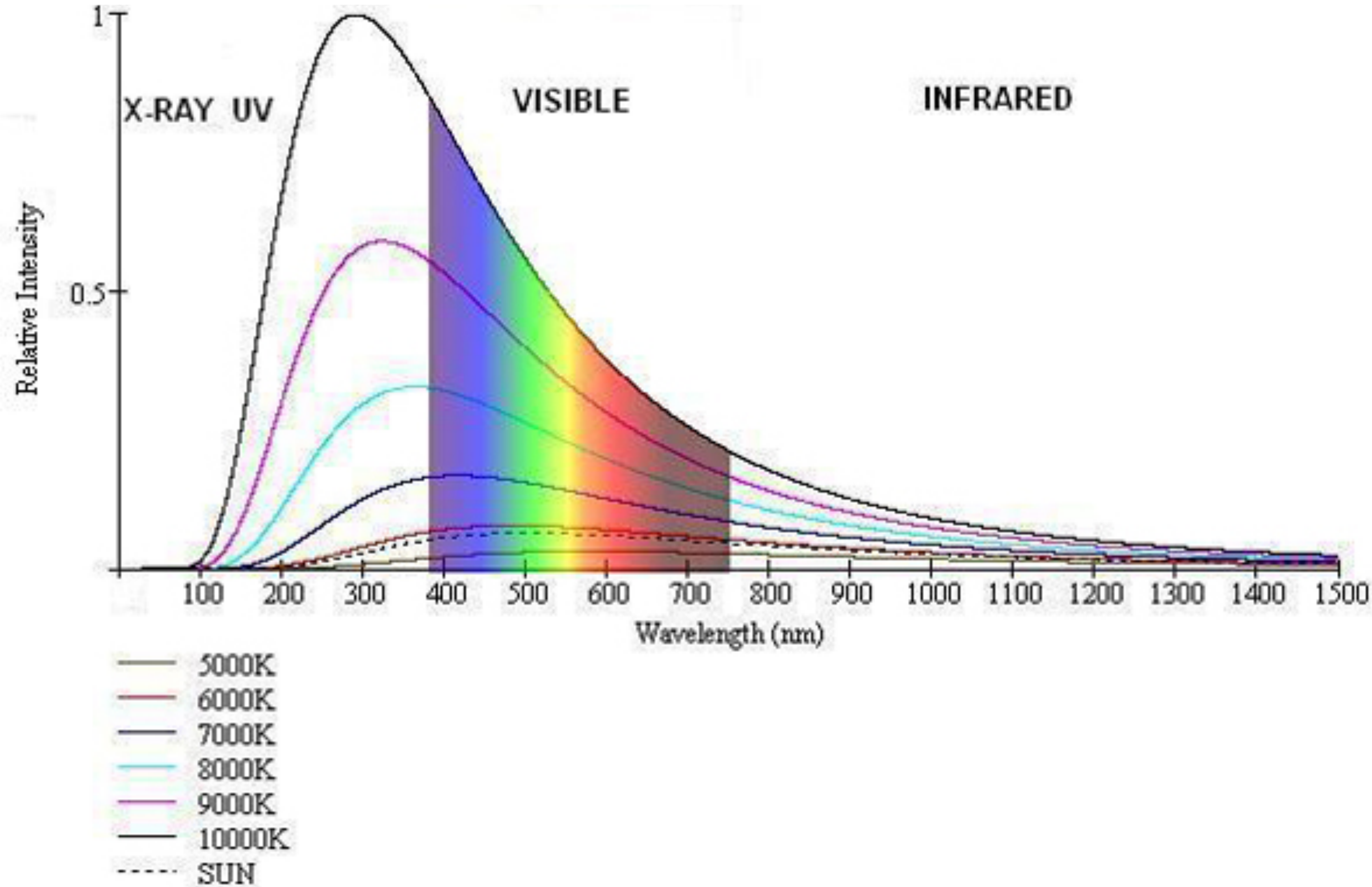
Blackbody Emission: Planck's Law

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

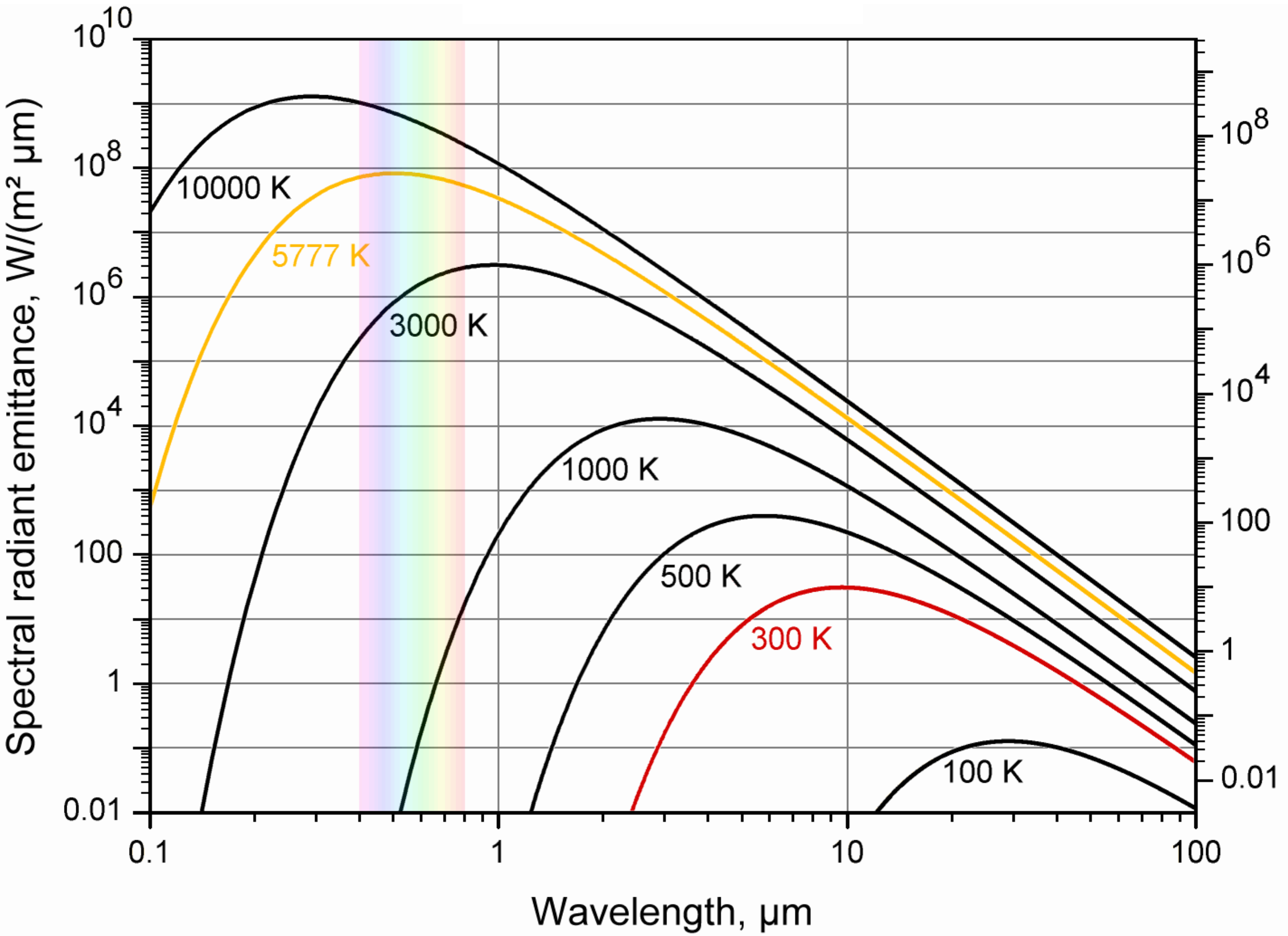
Where

- *S(λ)* = spectral radiant emittance in W/m^3 (watts per unit wavelength per unit area)
- *λ* = radiation wavelength
- *h* = Planck's constant = 6.626 x 10^{-34} W/sec^2
- *T* = absolute temperature in °K
- *C* = velocity of light = 2.9979 x 10^8 m/sec
- *K* = Boltzmann constant = 1.38 x 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 $\sigma = 5.669 \times 10^{-8}$ W/m^{2}K^4

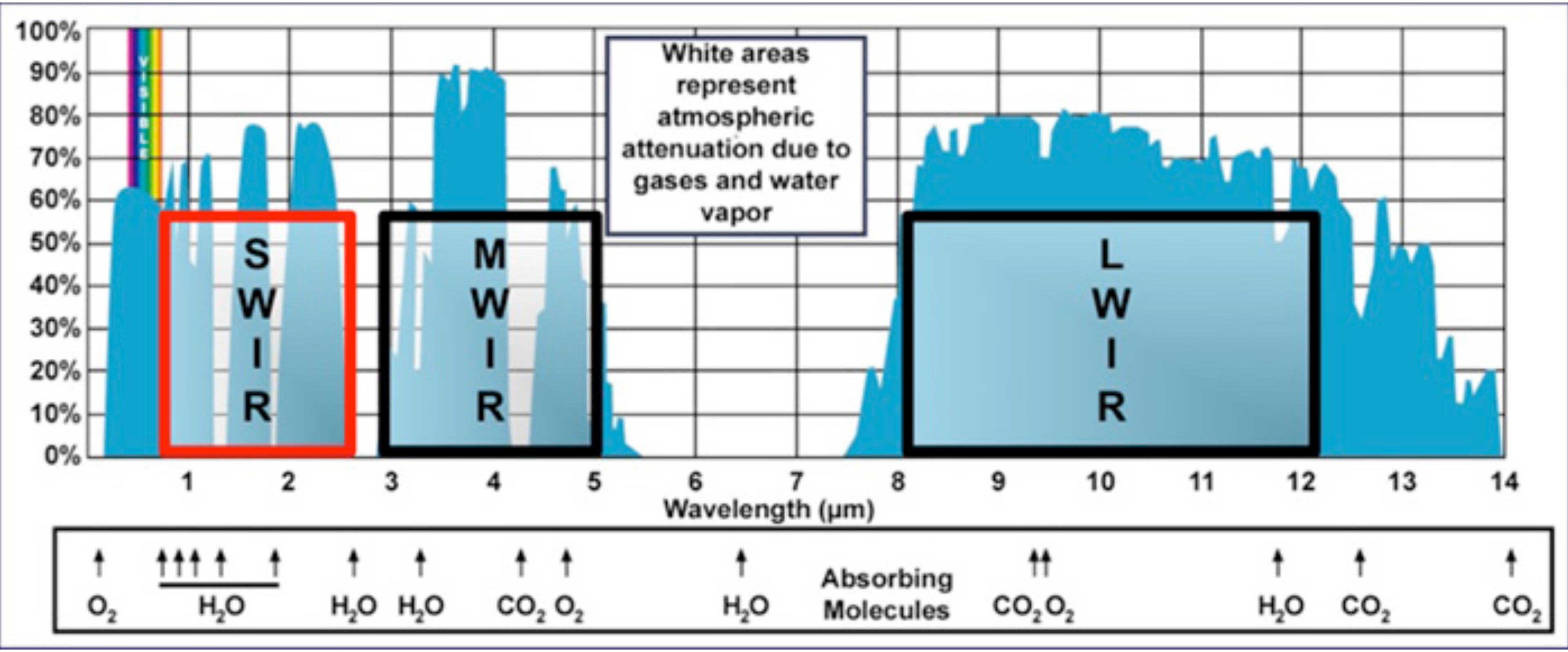
- Wavelength of maximum emission (Wien's law):

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

  - where a = 2898 μmK
  - for sun (T ~ 6000 °K), λ_m = 480 nm; for Earth surface (T ~ 300 °K), λ_m = 9.66 μm

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

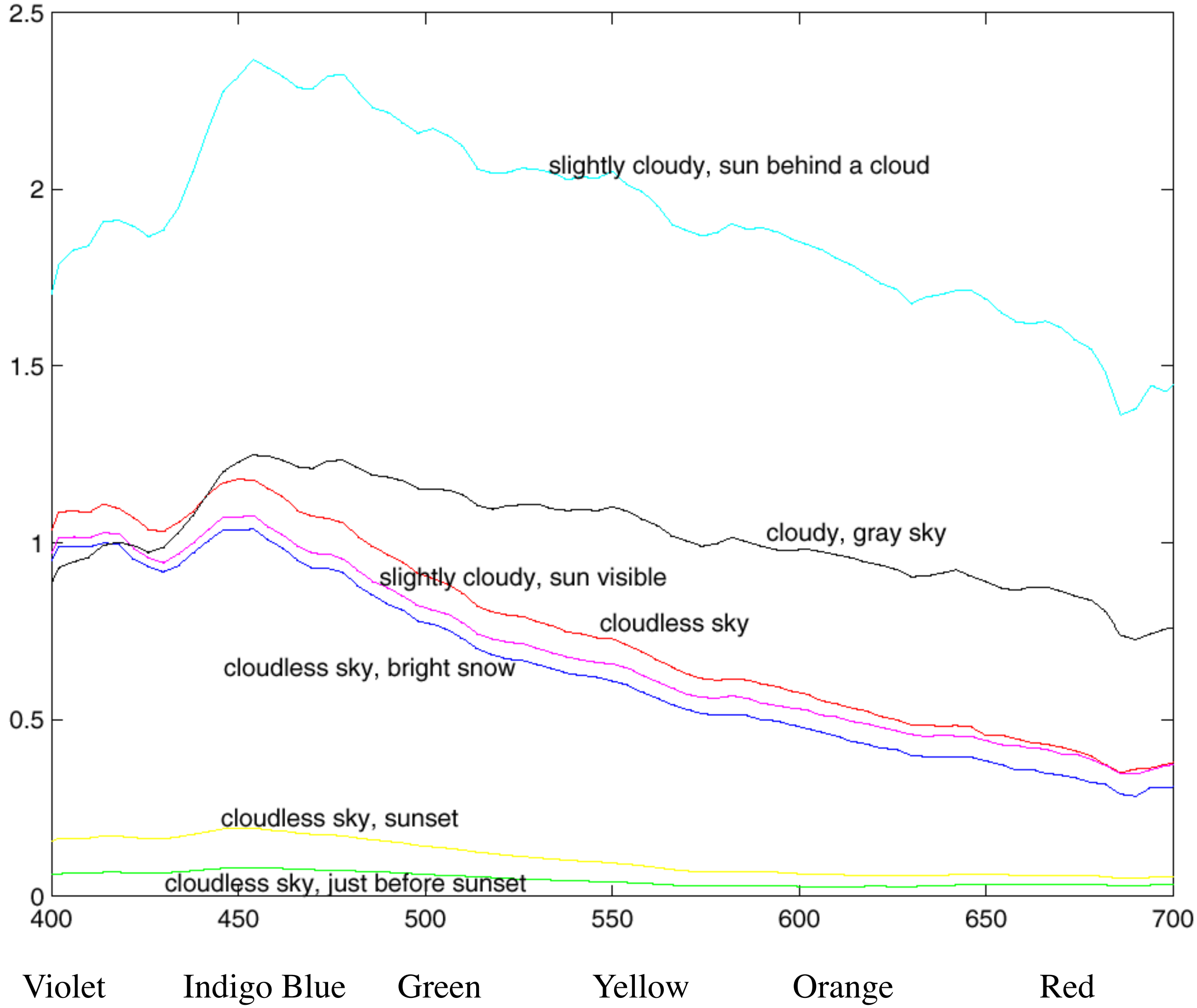
Atmospheric Windows in the Infrared



Some Sources of Illumination

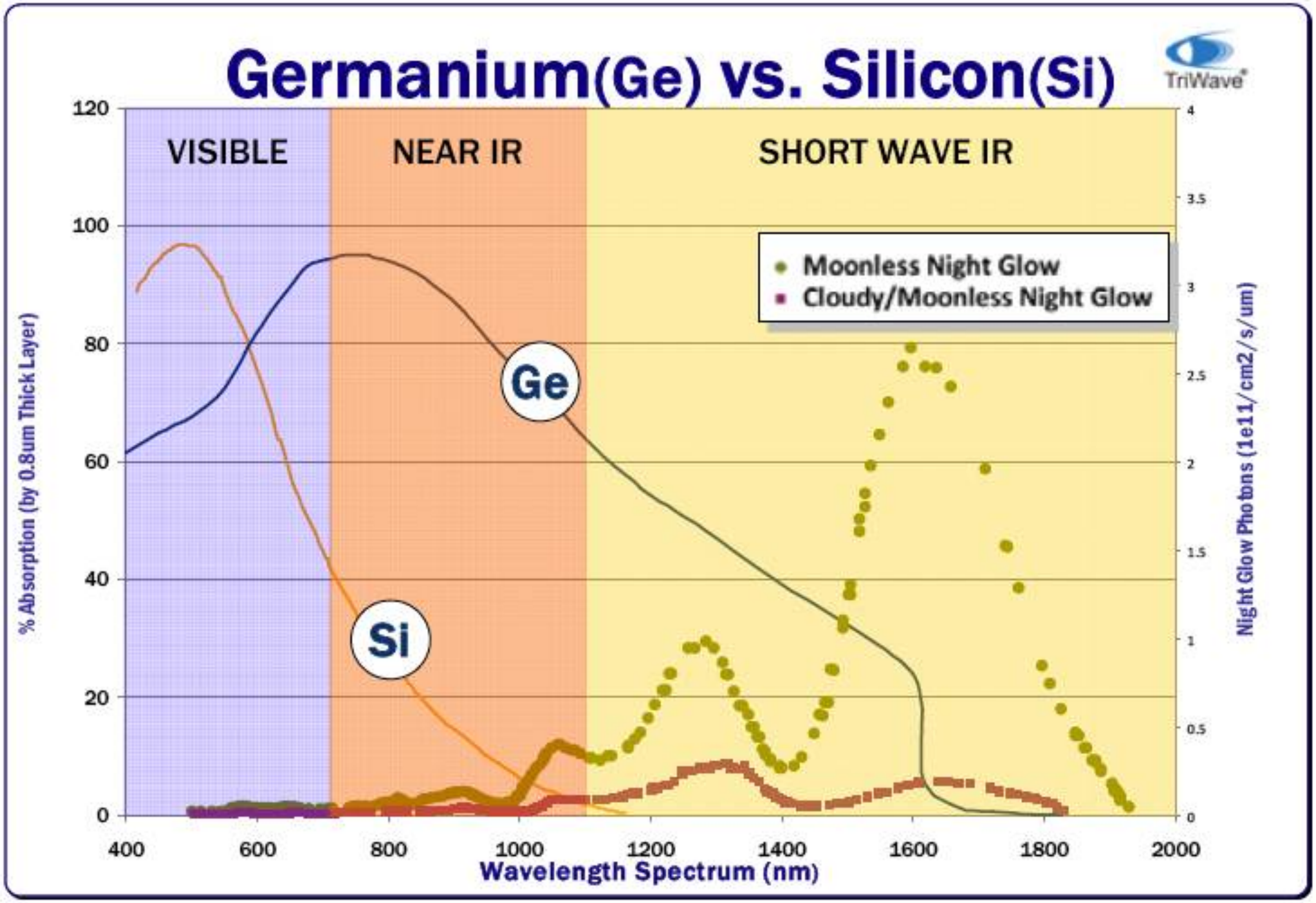
- Sunlight
- Thermal emission
- Skylight
- Night sky glow (*nightglow*)
- Man-made lights: e.g. incandescent bulbs, fluorescent bulbs, arc lamps

Skylight

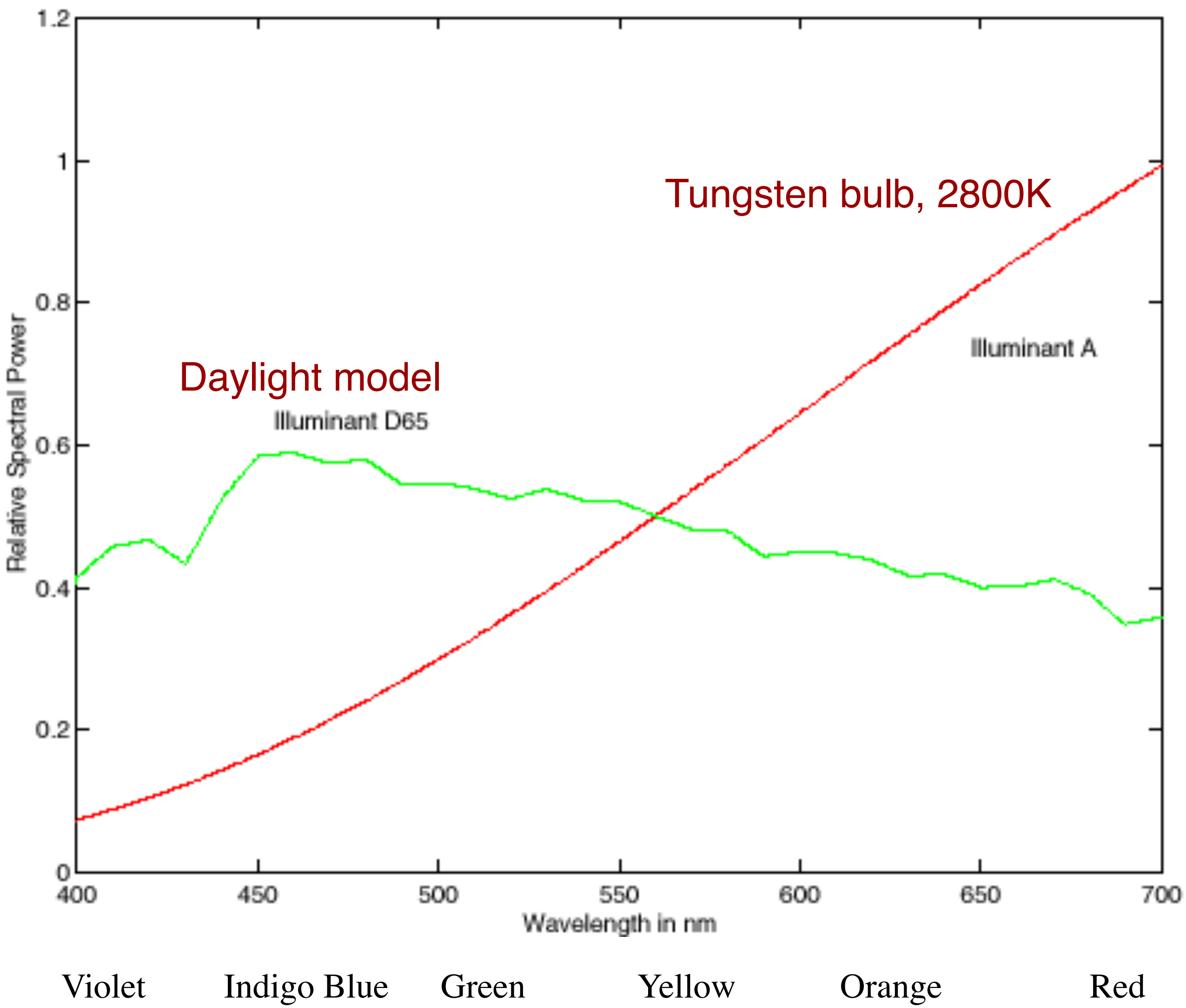


2.5
2
1.5
1
0.5
0
400
450
500
550
600
650
700
slightly cloudy, sun behind a cloud
cloudy, gray sky
slightly cloudy, sun visible
cloudless sky
cloudless sky, bright snow
cloudless sky, sunset
cloudless sky, just before sunset
Violet
Indigo Blue
Green
Yellow
Orange
Red

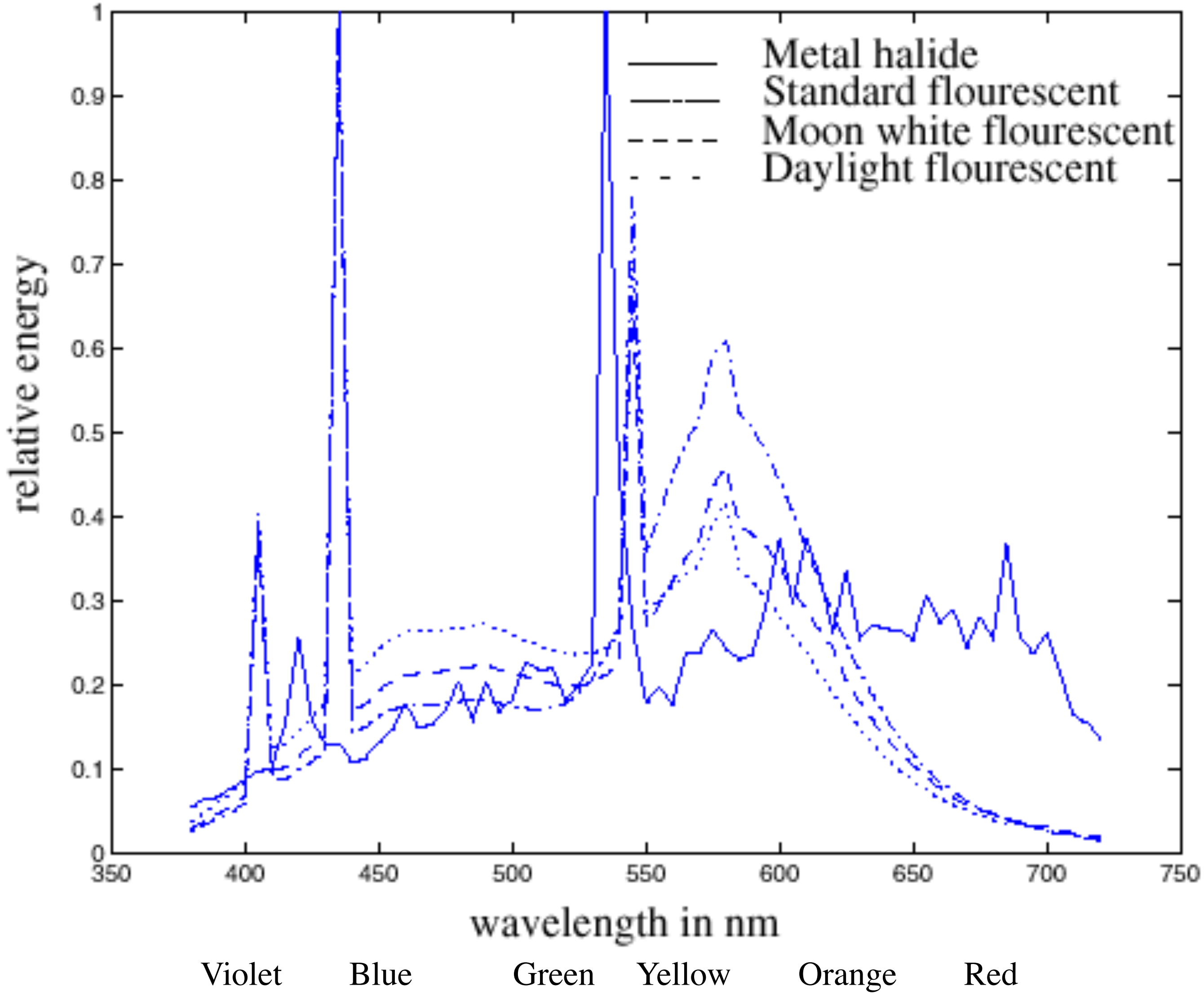
Night Sky Glow



Incandescent Bulb

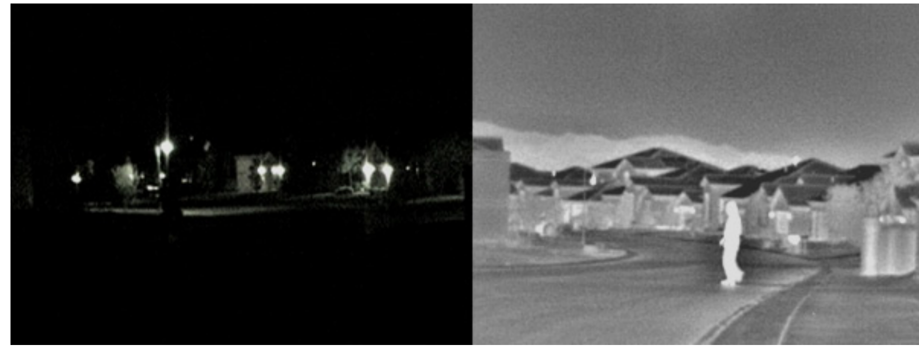


Metal Halide and Fluorescent Lights



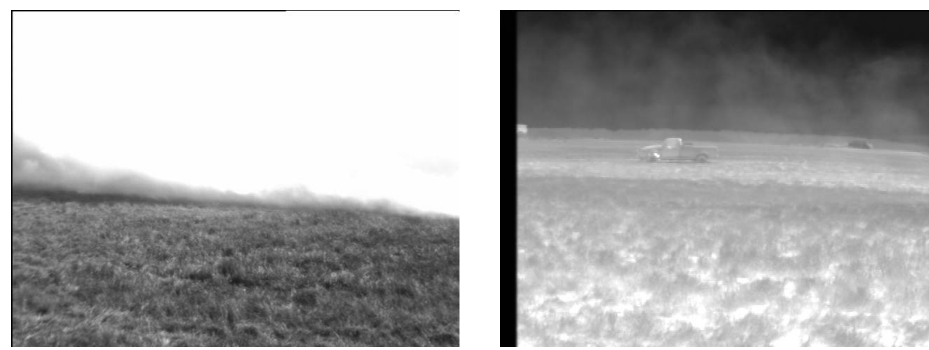
Some Illustrations

SWIR nightglow image (no moon)



Visible vs. thermal image at night

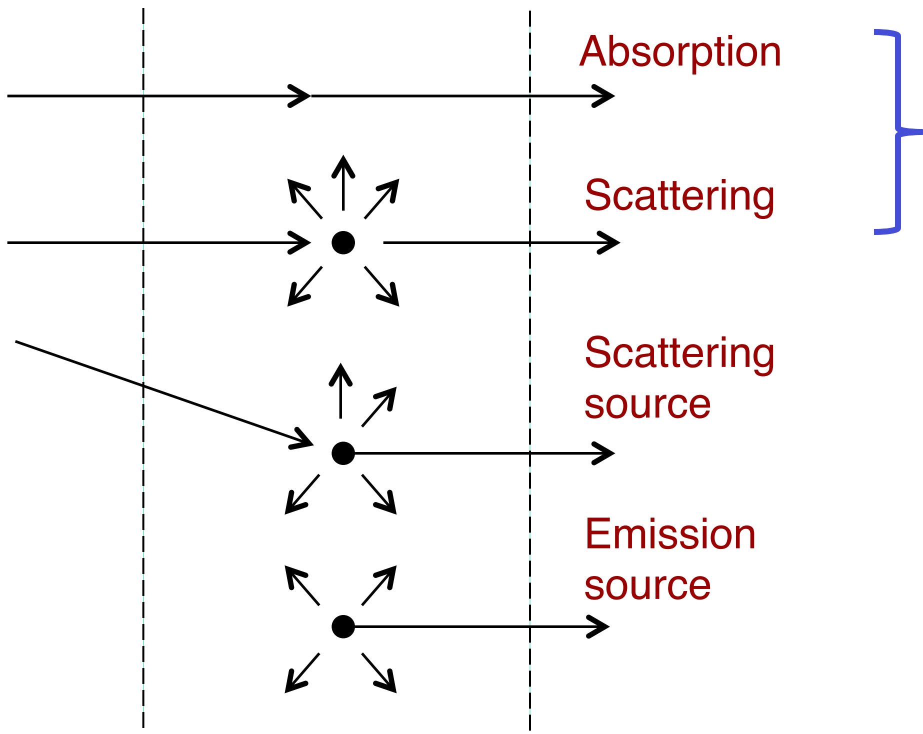
Visible vs. SWIR in haze



Visible vs. thermal in smoke

Atmospheric Propagation

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



Together are “extinction”:

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

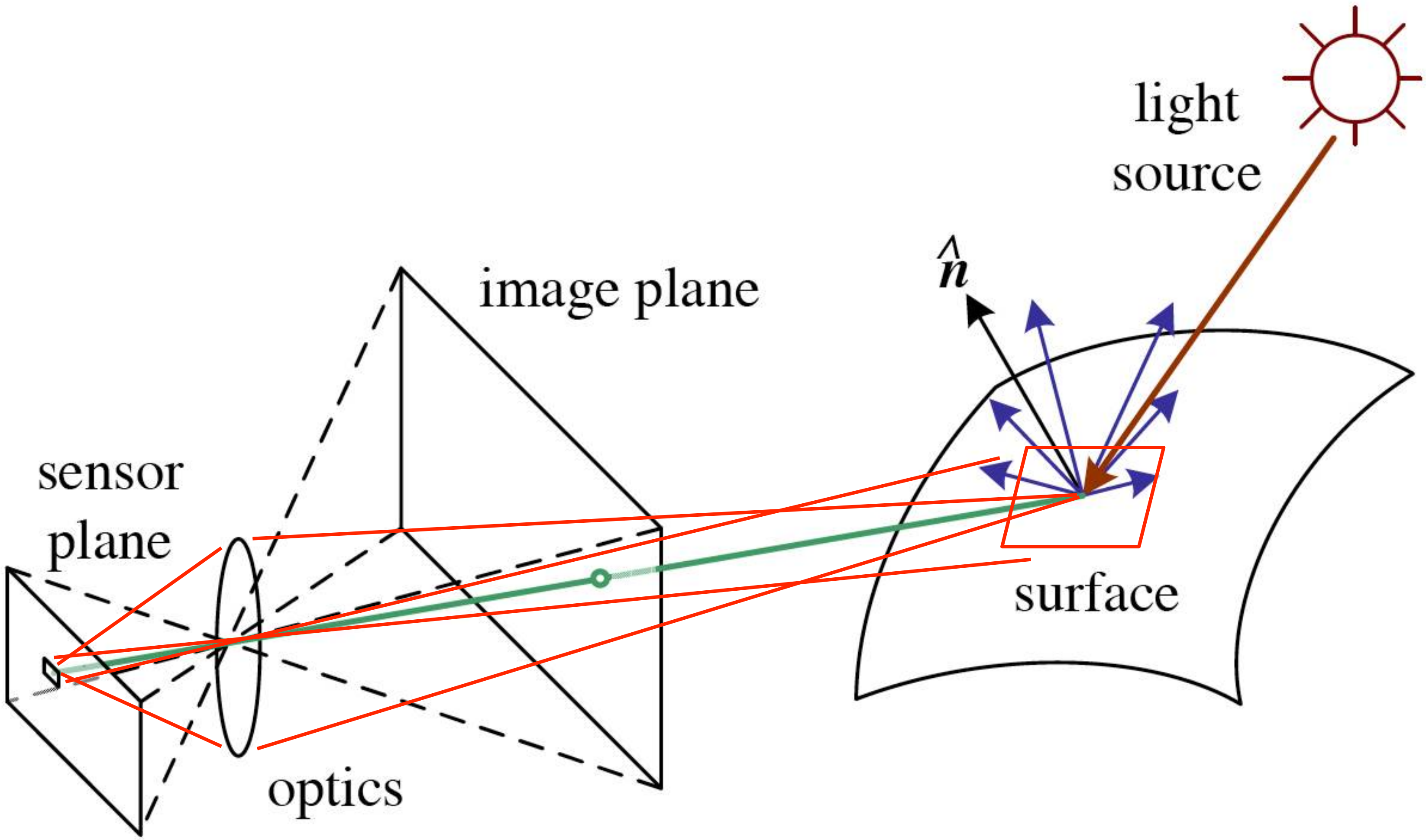
α is the *extinction coefficient* (km^{-1})
T is the *transmission coefficient*

	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

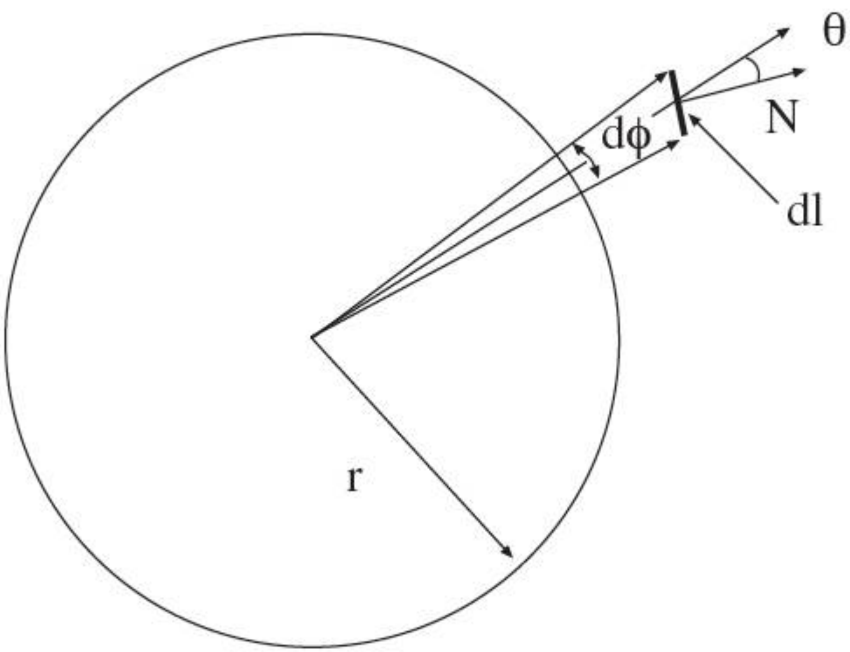
Basic Radiometry: Motivation

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



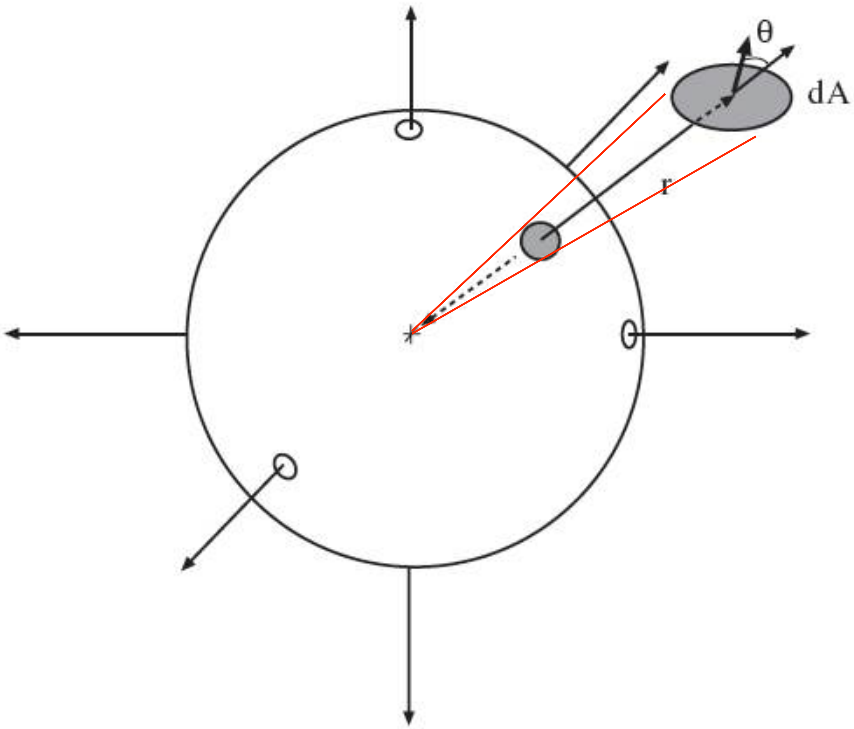
Solid Angles

Angle



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

Solid angle

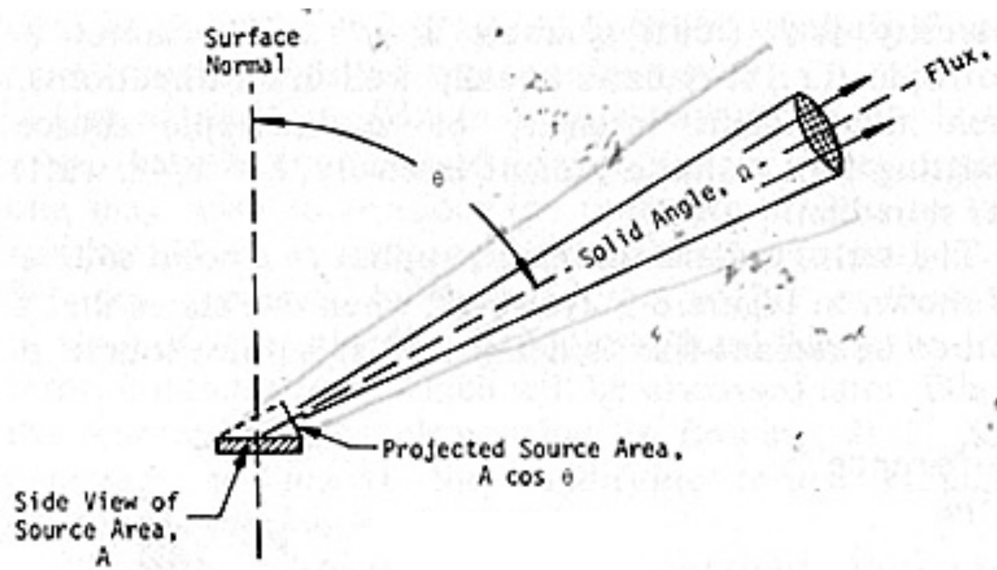


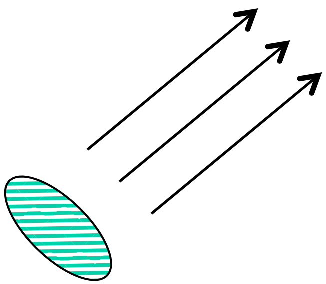
$$d\omega = \frac{dA \cos\theta}{r^2}$$

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:

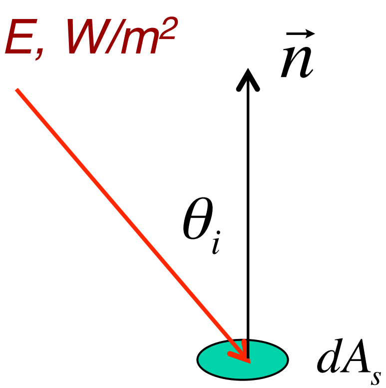
- Power per unit area of a collimated beam ($W\ m^{-2}$). Usually denoted E.
- Power per unit area impinging on a surface.

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

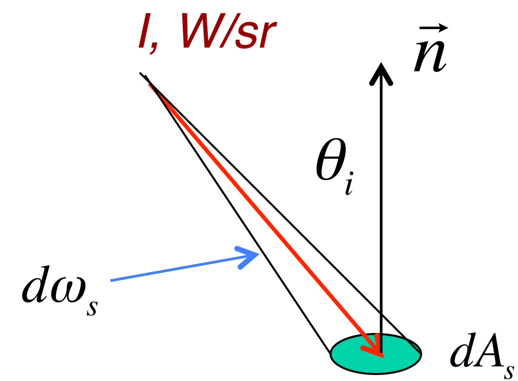
Point source at infinity (e.g. sun)



$$E_i = E\cos\theta_i$$

$$d\Phi_i = E_i\, dA_s$$

Point source at range r

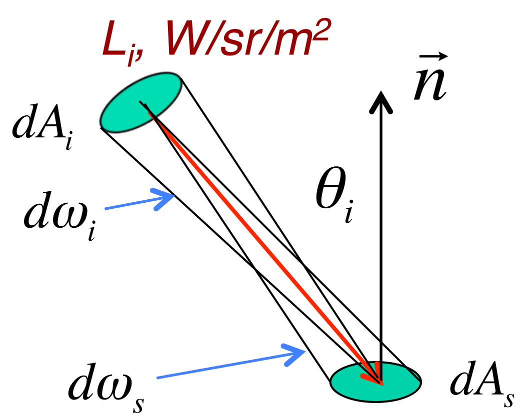


$$d\omega_s = \frac{dA_s \cos\theta_i}{r^2}$$

$$d\Phi_i = I\, d\omega_s$$

$$E_i = \frac{I\cos\theta_i}{r^2}$$

Extended source at range r



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

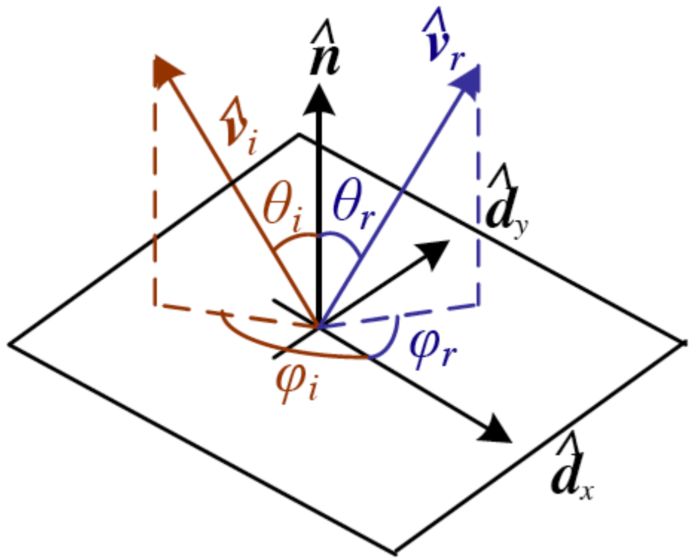
$$d\Phi_i = L_i\, d\omega_s\, dA_i = L_i\, d\omega_i\, dA_s \cos\theta_i$$

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

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:

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

Units: sr^{-1}

Isotropic case:

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

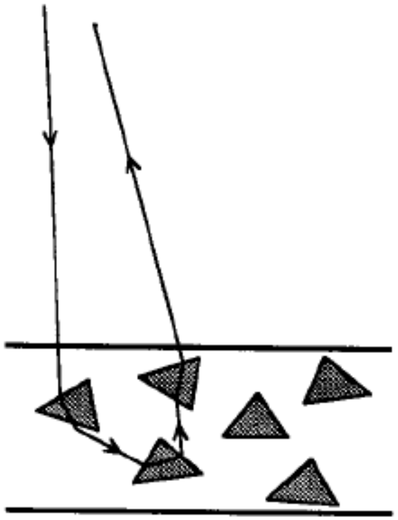
BRDF as the Ratio of L and E

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

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

Diffuse Reflection

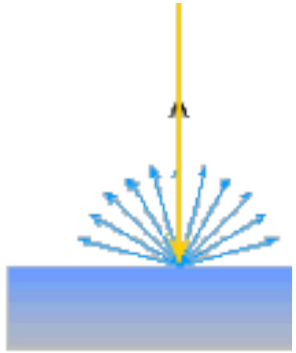
- Diffuse reflection
  - Dull, matte surfaces like matte paper
  - Often has a strong body color due to absorption by the material



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



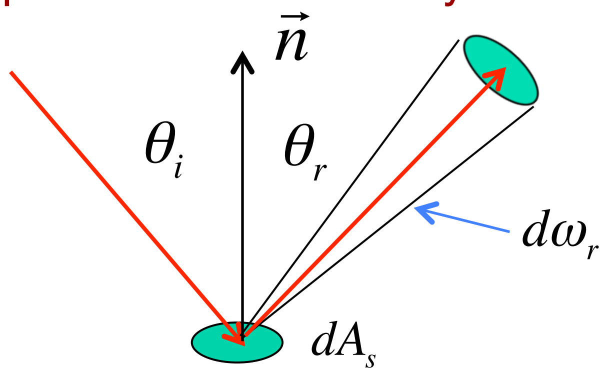
$$f(\theta_i, \phi_i, \theta_r, \phi_r) = k$$

$$E_i = E \cos \theta_i$$

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

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:

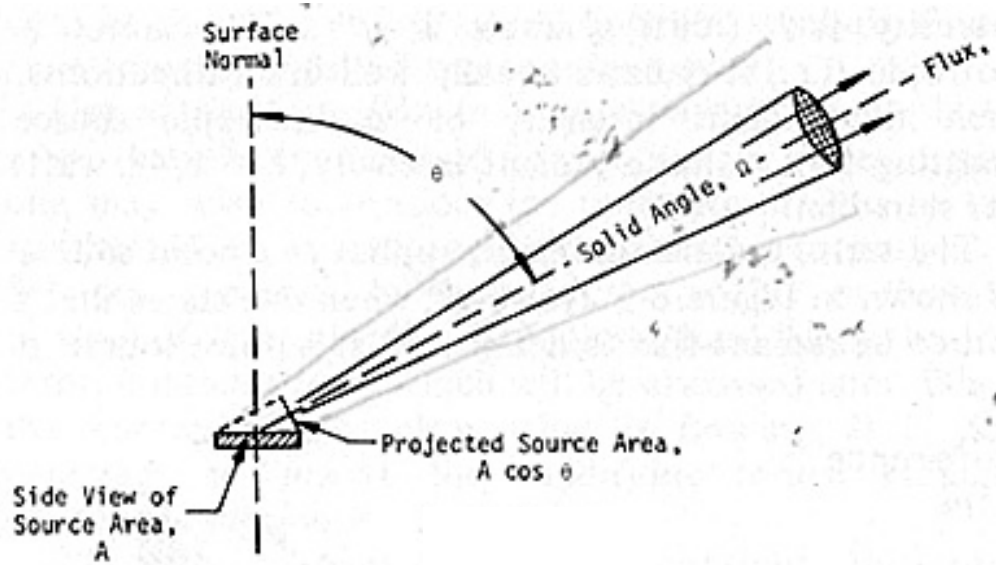
$$d\Phi_r = L_r \, dA_s \cos\theta_r \, d\omega_r$$
$$= k \, E \cos\theta_i \, dA_s \cos\theta_r \, d\omega_r$$

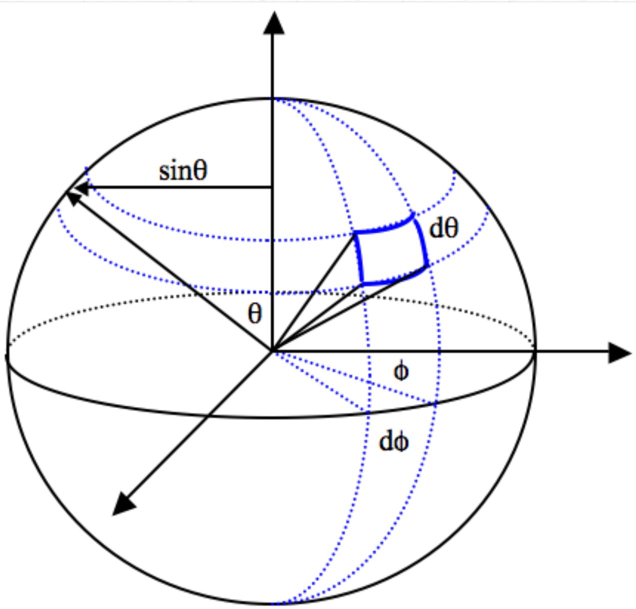
Assume a fixed fraction ρ is absorbed by the surface.
Equate total incoming with total outgoing:

$$\rho \, d\Phi_i = \int_\Omega d\Phi_r$$

$$\rho = \int_\Omega k \cos\theta_r \, d\omega_r$$

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

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

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

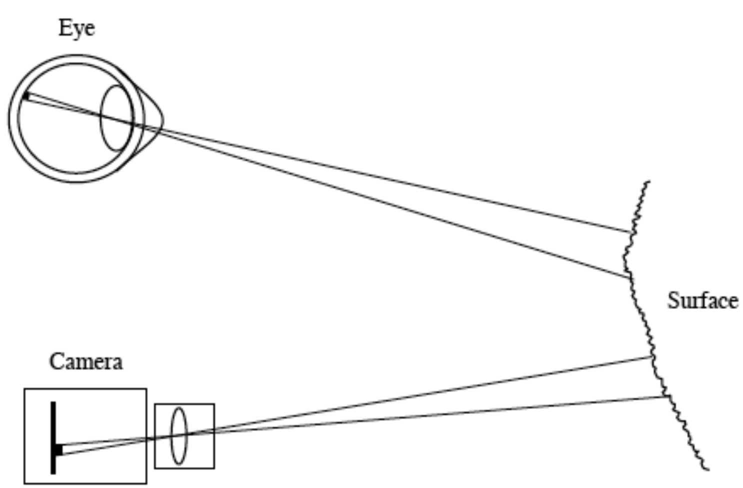
(patterned after Horn, *Robot Vision*, ch. 10)

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

Rough cylinder

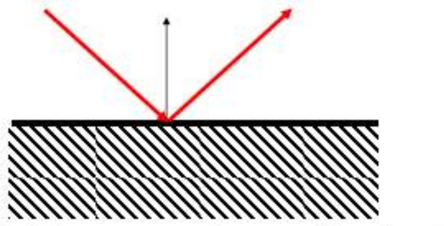
Smooth cylinder

(a)

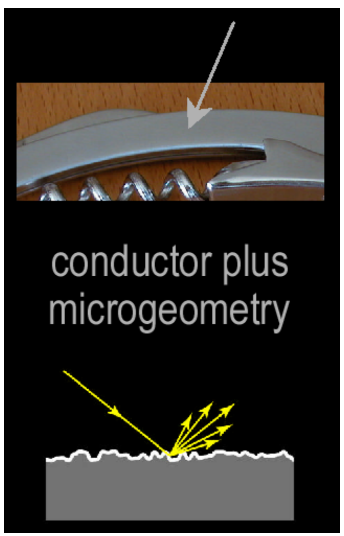


S. Nayar and M. Oren, "Visual Appearance of Matte Surfaces", *Science*, Vol. 267, pp. 1153-1156, 1995

Other Reflectance Models



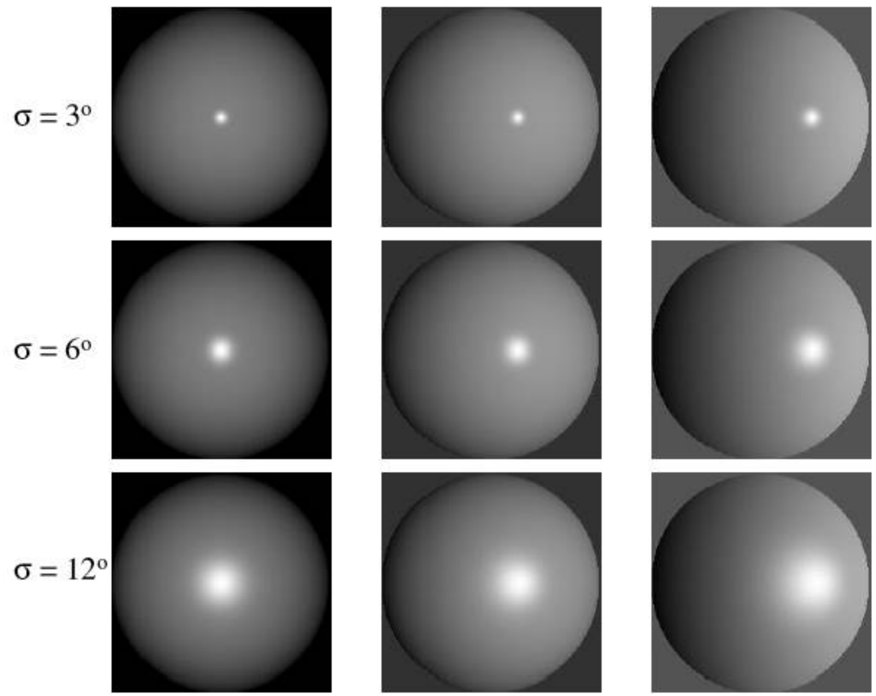
Pure specular



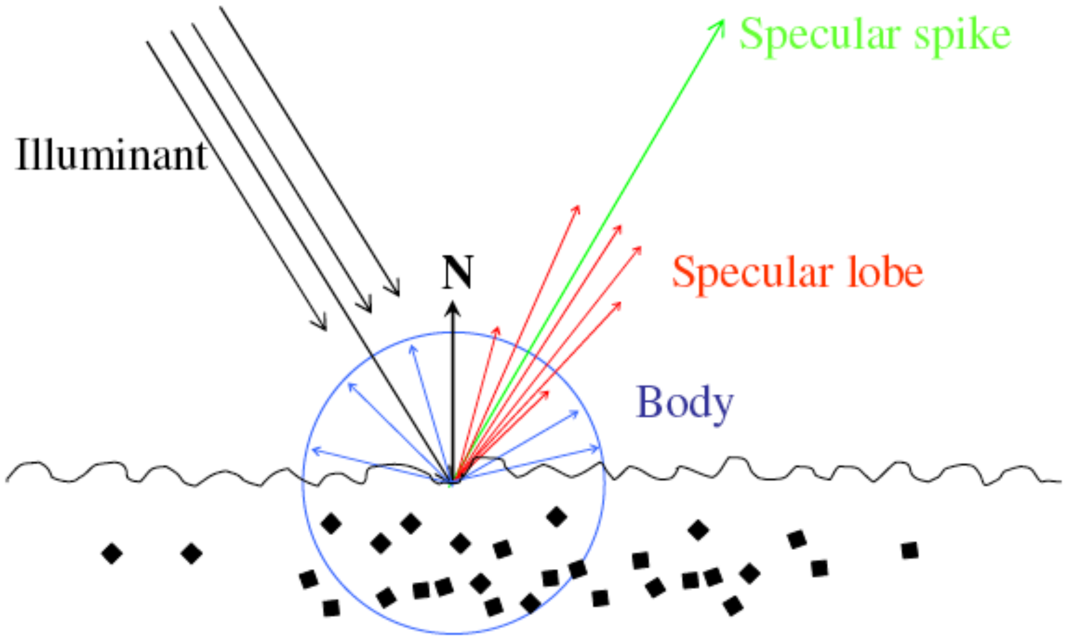
Specular lobe

Varying incidence angle

Varying roughness



Other Reflectance Models



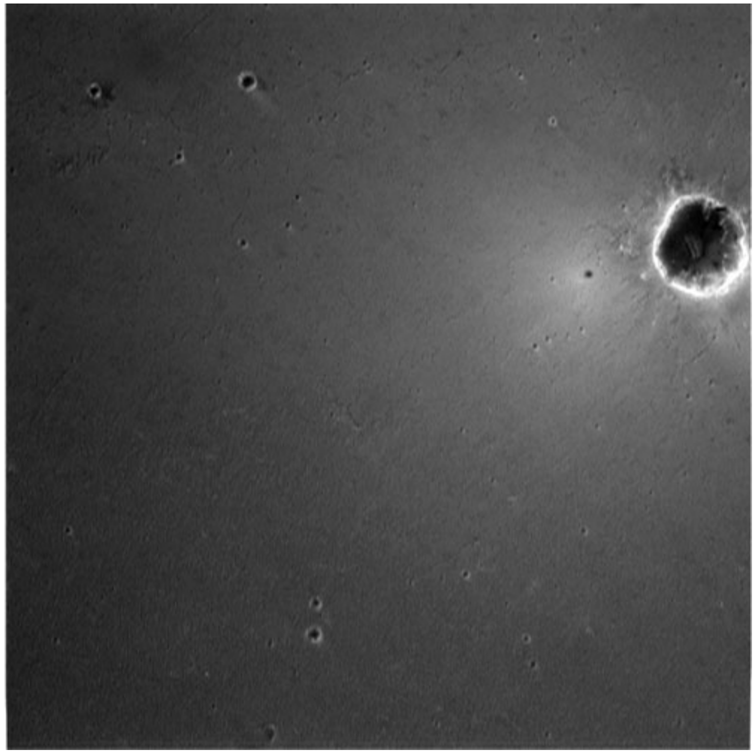
Also: surface vs. body reflection (dichromatic reflectance model)

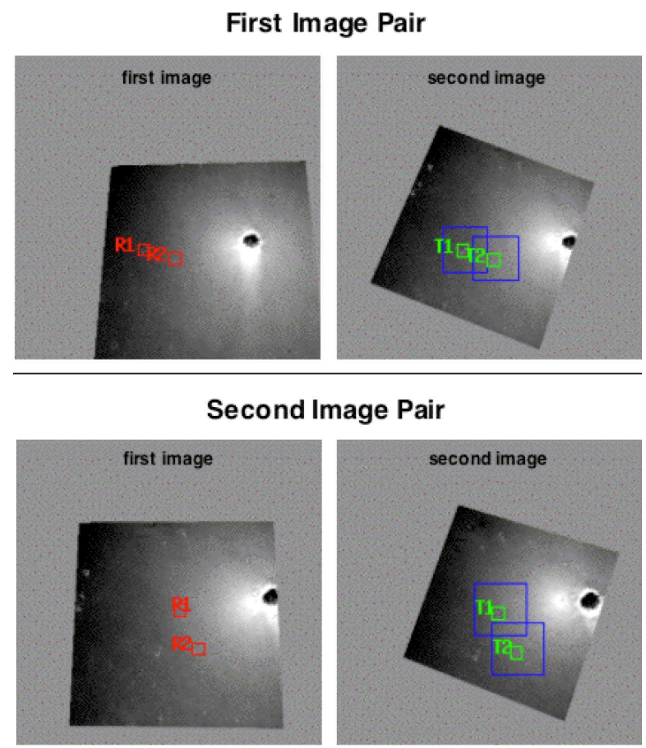
$$a\cos\theta_i + \frac{b}{\cos\theta_e} e^{-\frac{\beta^2}{2\sigma_\alpha^2}} + c\,\delta(\theta_i-\theta_e)\,\delta(\varphi_i-\varphi_e-\pi)$$

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

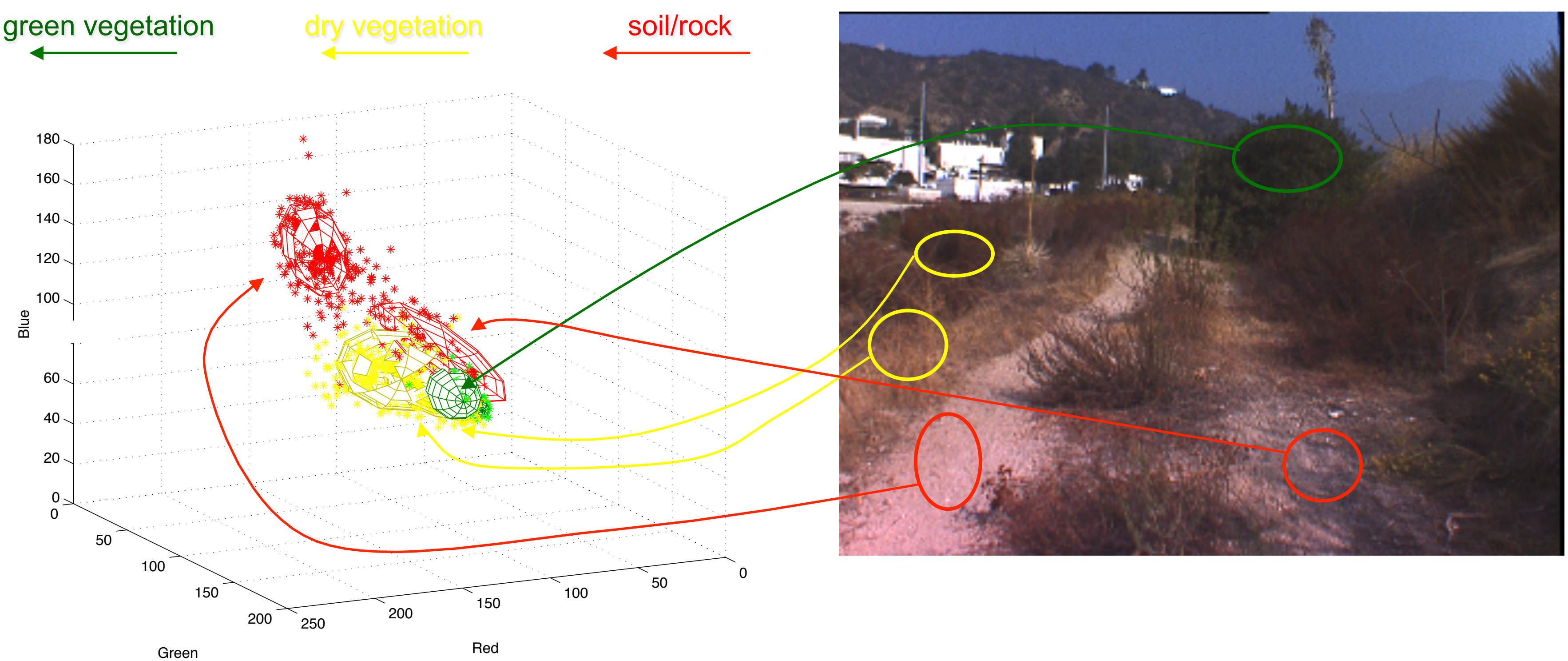
Other Reflectance Models: Opposition Effect



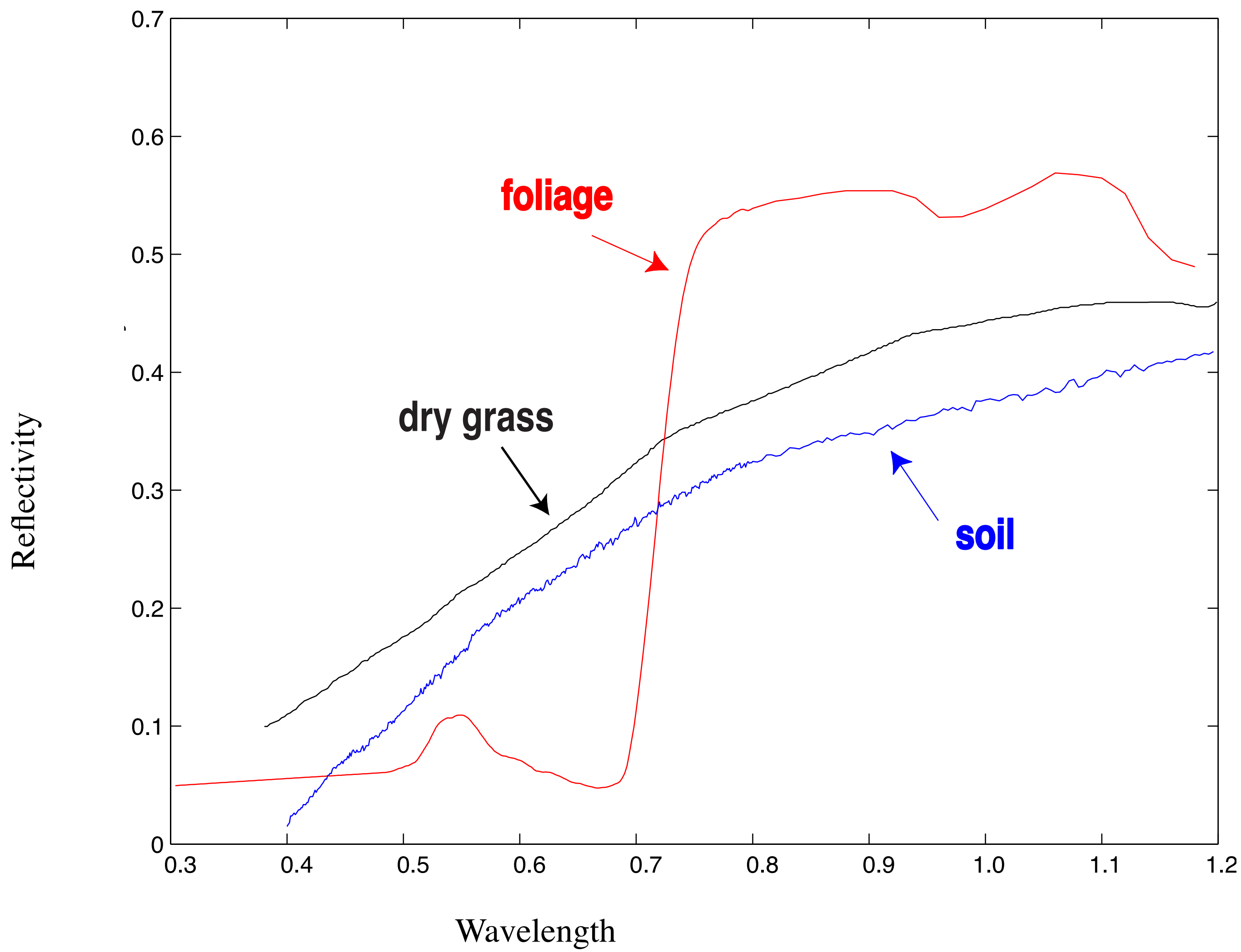


B. Hapke, *Theory of Reflectance and Emittance Spectroscopy*, 1993

Color


green vegetation
dry vegetation
soil/rock
Blue
180
160
140
120
100
60
40
20
0
0
50
100
150
200
Green
250
200
150
100
50
0
Red

Spectral Reflectance: Visible and Near Infrared (VNIR)



Spectral Reflectance: Visible and Near Infrared (VNIR)

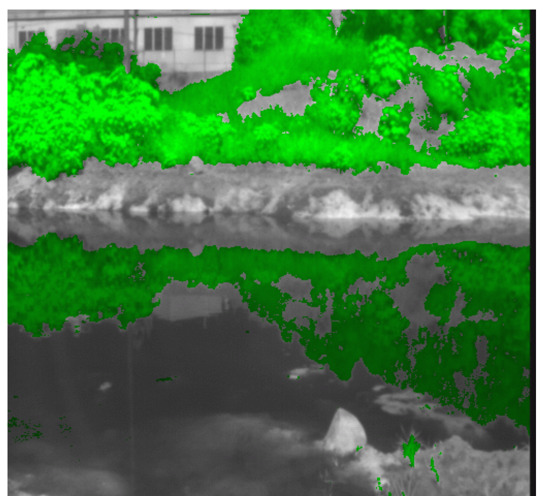
650nm image

:

800nm image

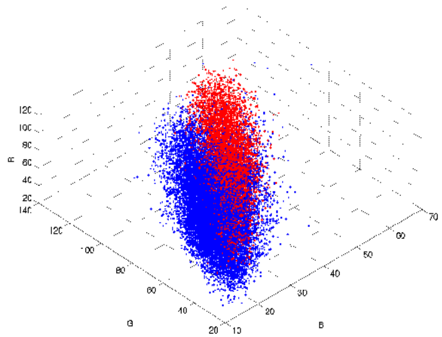
=

650:800 ratio image

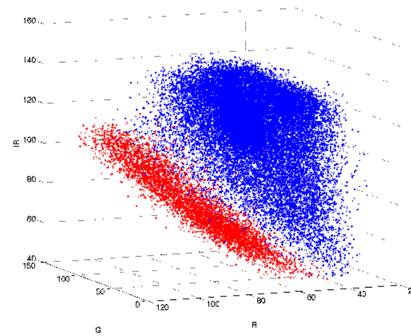


Classified image

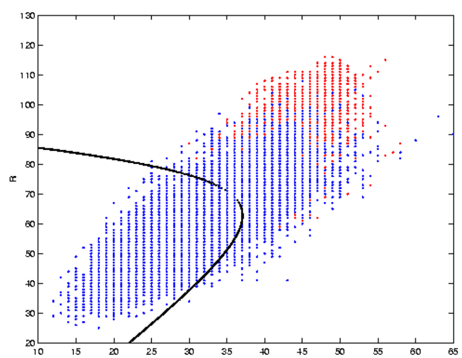
Spectral Reflectance:
Visible and Near Infrared (VNIR)



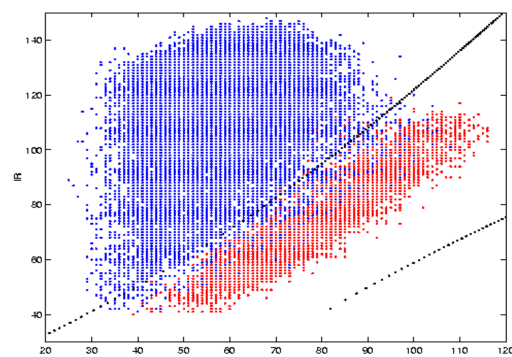
B-G-R



G-R-IR

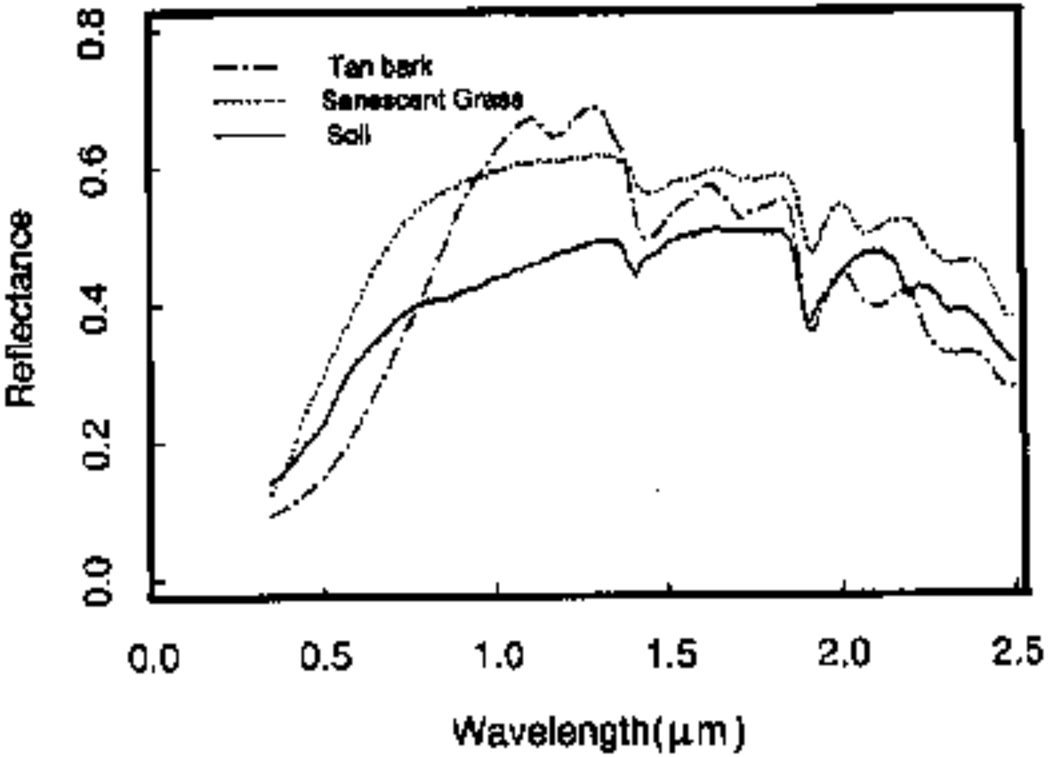


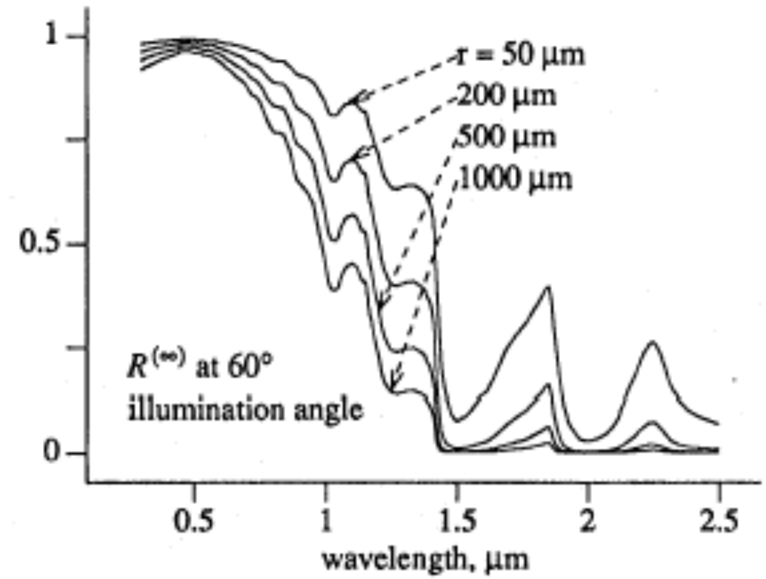
B-R



R-IR

Spectral Reflectance:
Short Wave Infrared (SWIR)





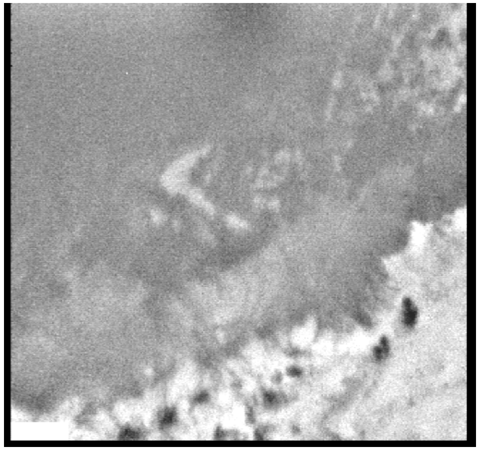
Snow reflectance

Thermal Infrared

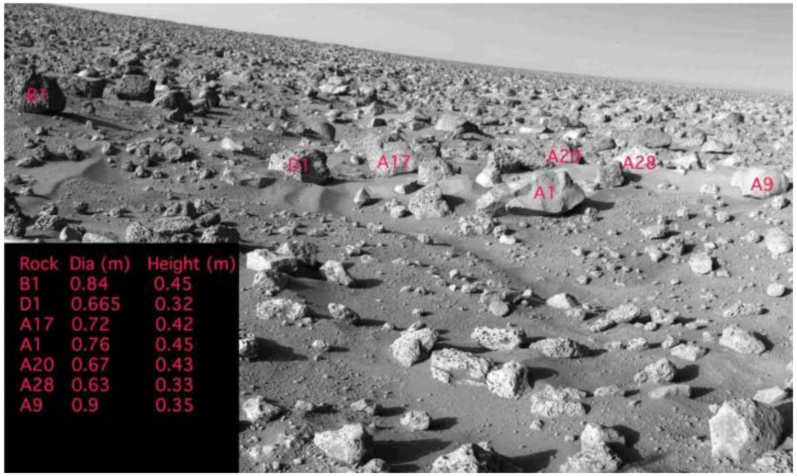
- Seeing in the dark
- Seeing through atmospheric obscurants
- Recognizing things due to:
  - Intrinsic heat
  - Heat transfer characteristics
  - Thermal “color”

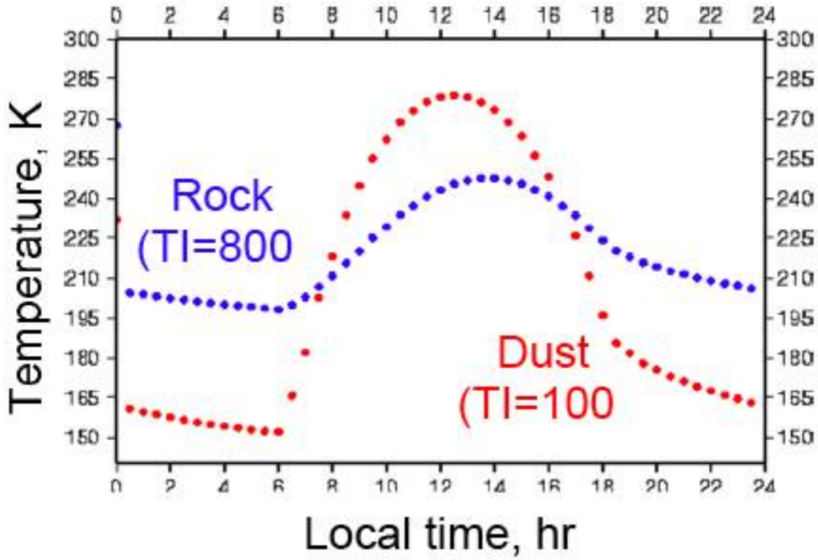
Visible

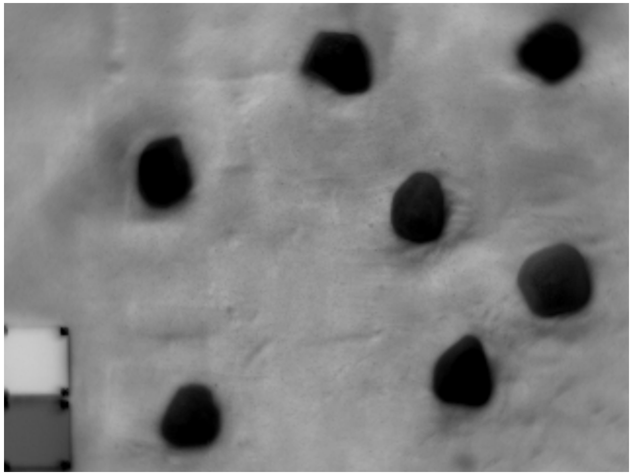
LWIR



Heat Transfer Characteristics: Thermal Inertia

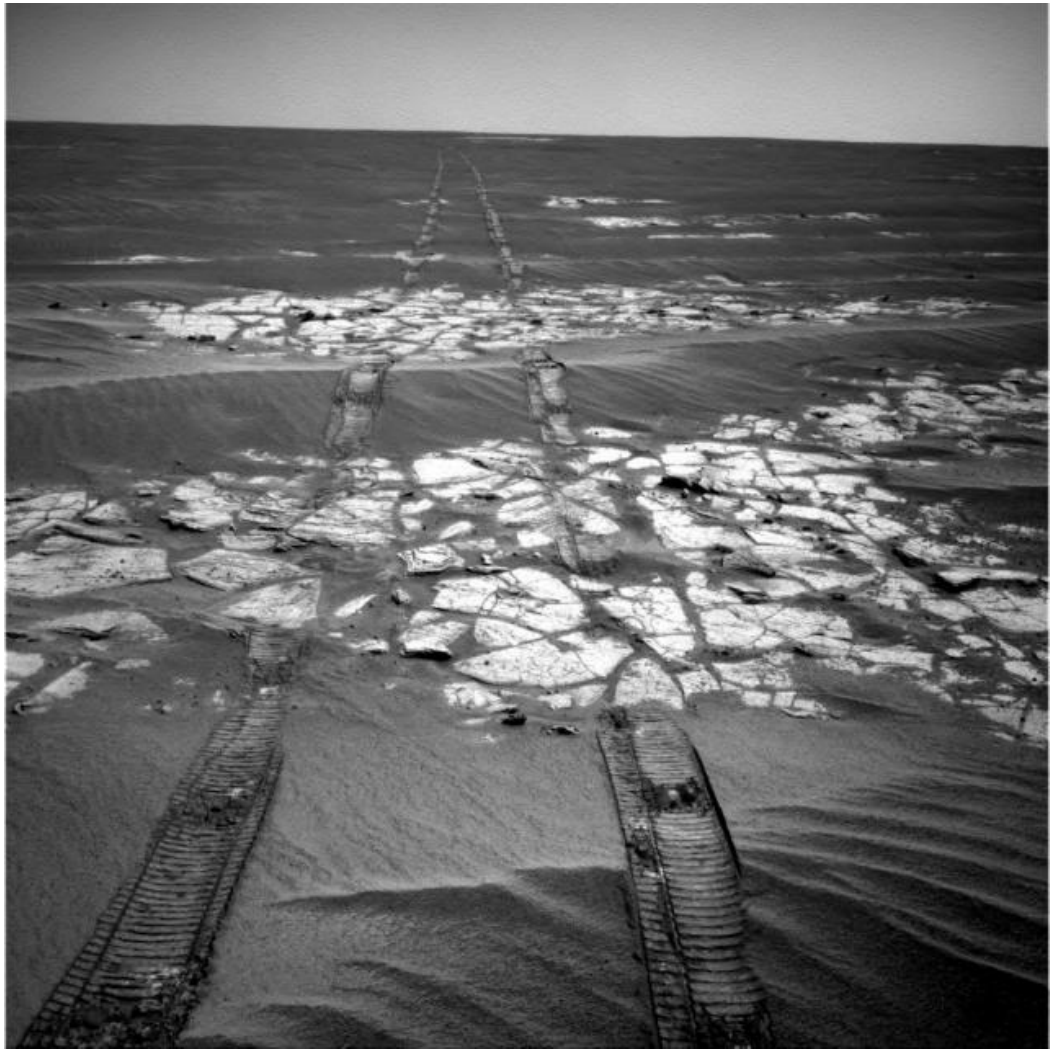






(U. Arizona)

Open Problem:
Terrain Classification for Mars Rovers



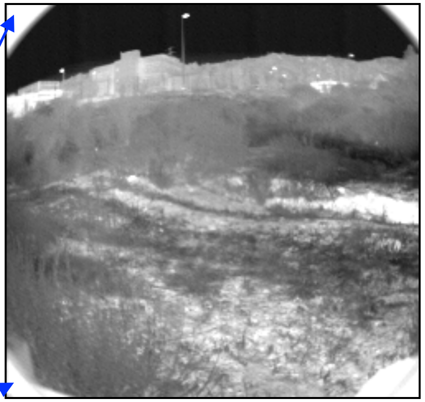
Rovers sometimes get stuck in the ripples; easily cross the bedrock

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

Heat Transfer Characteristics

Color crosswise view

Color lengthwise view

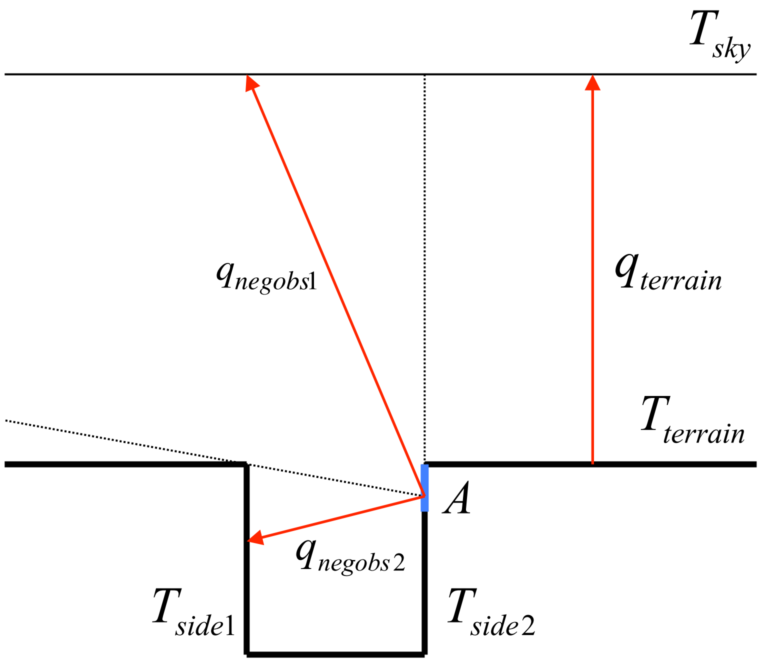


MWIR image 1 hr after sundown

Weatherproof sensor enclosure

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

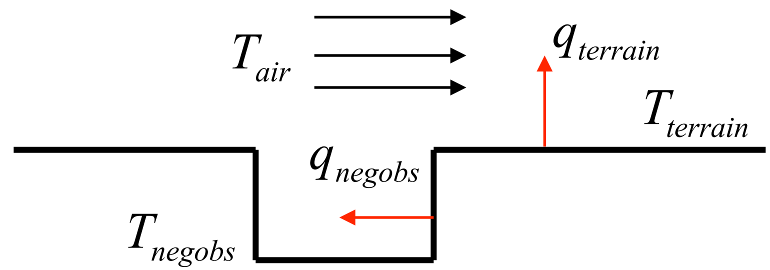
- **Radiation**



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

- **Evapotranspiration** (ignored here)

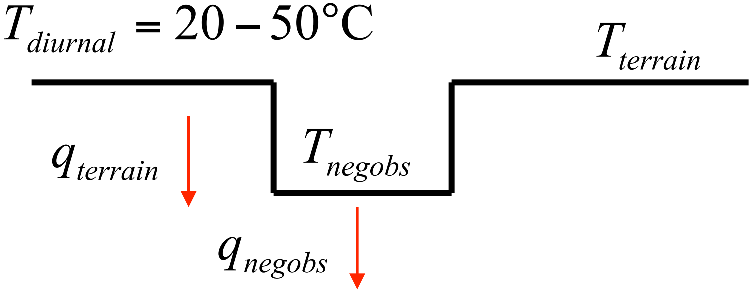
- **Convection**



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

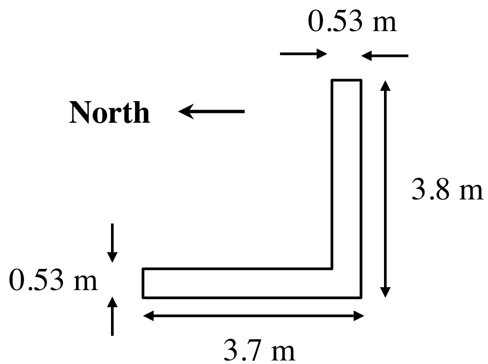
- **Conduction**

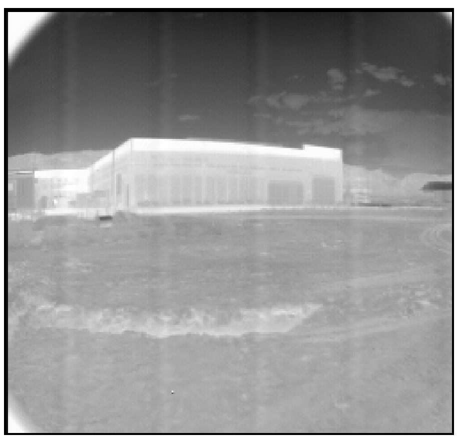
$T_{diurnal} = 20 - 50°\text{C}$



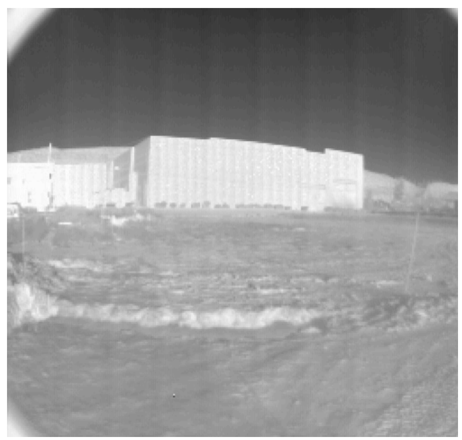
$$q_{terrain} = -k\frac{dT}{dx}$$

Heat Transfer Characteristics



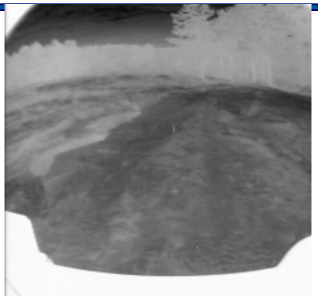


9 pm



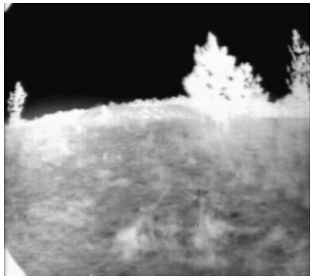
7 am

9 am



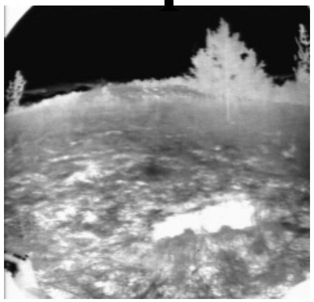
9 pm

5 pm



5 pm

10 pm



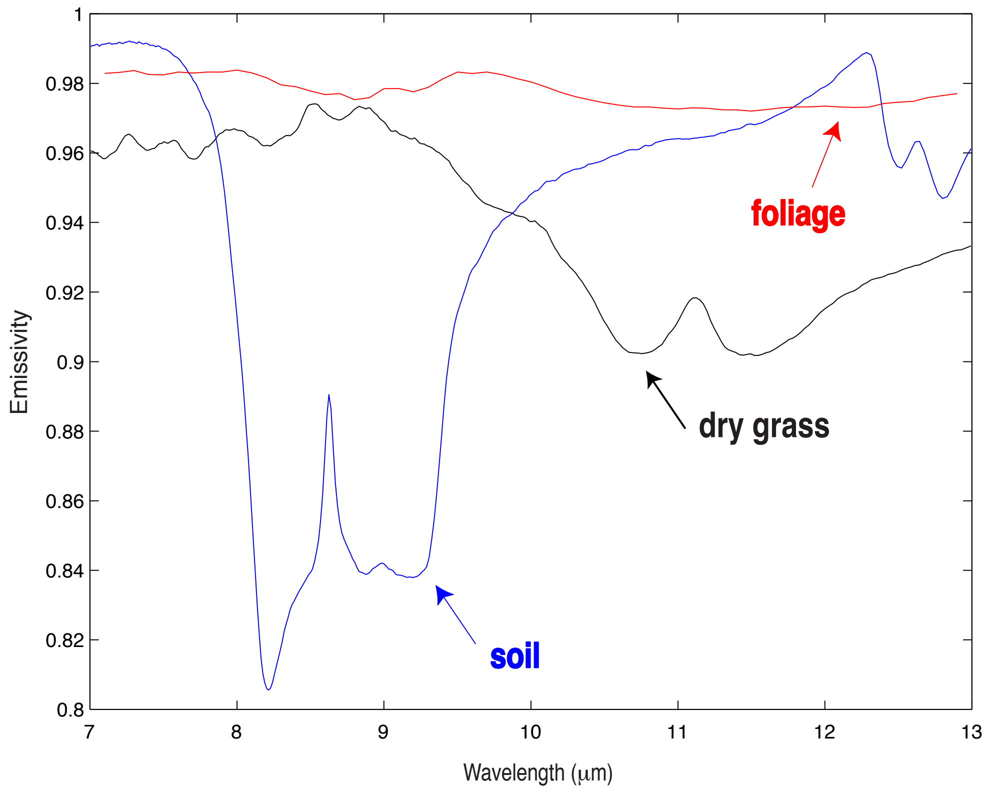
7 am

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