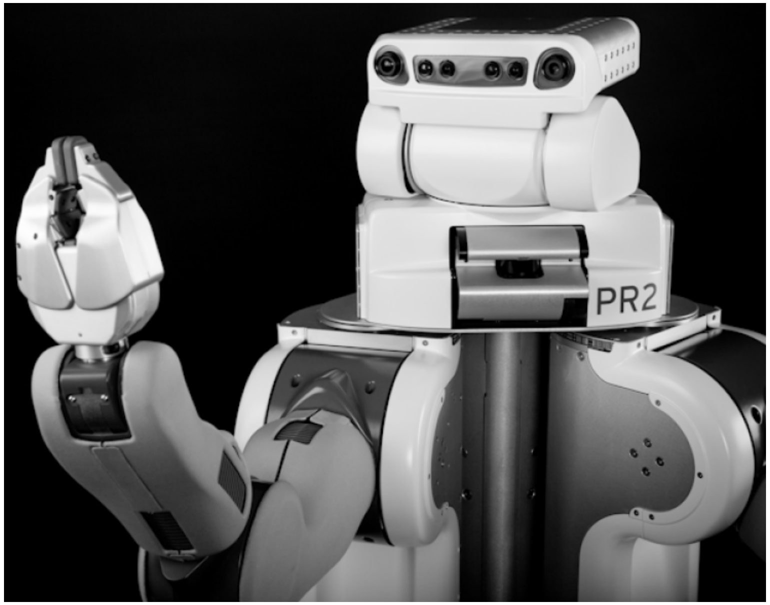

Chapter 8
Perception

Part 2

8.2 Physics and Principles of Radiative Sensors

Outline

- 8.2 Physics and Principles of Radiative Sensors
  - 8.2.1 Radiative Sensors
  - 8.2.2 Techniques for Range Sensing
  - 8.2.3 Radiation
  - 8.2.4 Lenses, Filters, and Mirrors
  - Summary

Outline

- 8.2 Physics and Principles of Radiative Sensors
  - <u>8.2.1 Radiative Sensors</u>
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Radiative Sensors - Introduction

- Most sensors are either:
  - contact
  - noncontact (radiative)
  - inertial
- In this section, concentrate on radiative ones.

Radiative Sensors - Uses

- Path planning
  - where do I go next?
- Navigation
  - where am I?
- Obstacle detection and avoidance
  - is that an obstacle?
- Object recognition
  - is it an animal or a rock?
- Mapping
  - where are all the nasty poisons?
- Teleoperation
  - lets operator drive vehicle remotely
- Manipulation
  - allows intelligent grasping etc.

Radiative Sensors - Tradeoffs

- Major advantages are:
  - wide spatial field of view
  - provides lookahead in time (enables prediction)
  - Perceives while avoiding contact with environment
- Major disadvantages are:
  - sometimes massive computational load
  - physics of radiation can be inconvenient
  - problem of “perception”

8.2.1.1 Classification of Radiative Sensors

- Passive/active
  - passive uses ambient radiation
  - active emits own radiation
- Imaging/nonimaging
  - imaging generates an image
  - nonimaging generates a single “pixel”
- Scanning/nonscanning
  - scanning sensors are moved over a scene
  - nonscanning sensors have sensor array
- Proximity/ranging (range resolution)
  - proximity is binary detector
  - ranging gives range value
  - “shape” means relative range
- Principle of operation
  - triangulation
  - time of flight
  - scene constraint
  - interferometry
- Radiation used
  - electromagnetic
  - sound

8.2.1.2 Classification of Ranging Sensors

Ranging Techniques

Active Triangulation

- Point
- Line
- Grid

Passive Triangulation

- Stereo
- Motion Stereo
- Known Object
- Shape From X

Time of Flight

- Pulsed
- AM-CW
- FM-CW

See next section for details….

Outline

- 8.2 Physics and Principles of Radiative Sensors
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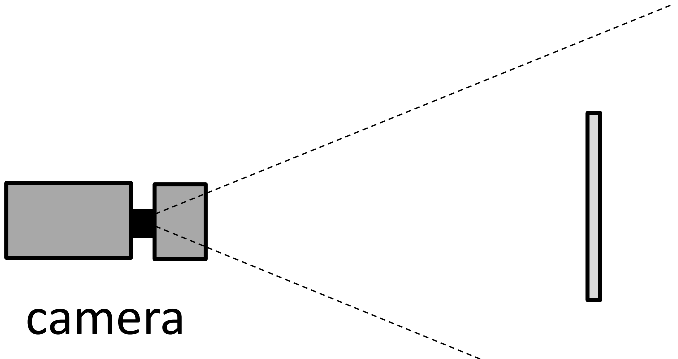
8.2.2.1 Triangulation

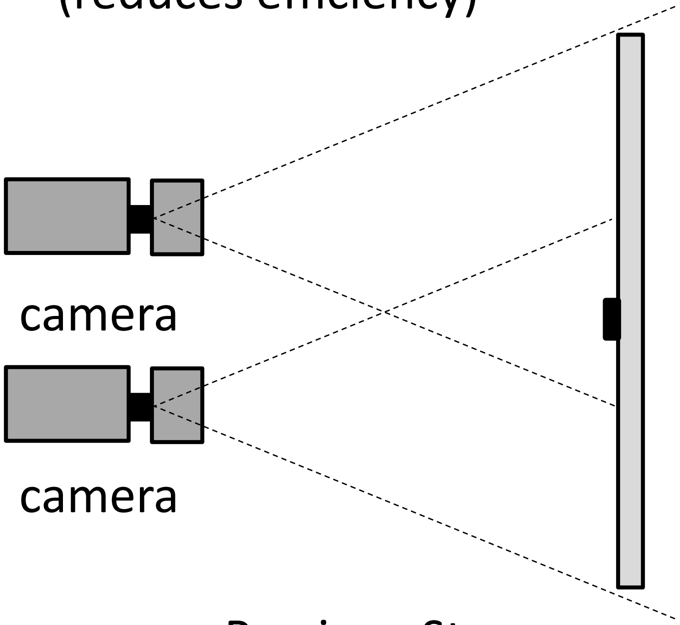
- General:
  - Inverts the parallax effect of two separated views.
  - All techniques suffer "missing parts" problem.
  - Choice of sensor separation causes <u>tradeoff</u>:
    - Better range resolution (+) causes more missing parts (-)
  - All have uncertainty increasing with range

8.2.2.1.1 Passive Triangulation

- Both forms rely on:
  - scene texture
  - ambient illumination (cf night/shadows)
- Case 1: Known Object
- Passivity is both a strength and a weakness.
- Case 2: Passive triangulation ("Stereo")
  - major issue: correspondence (reduces efficiency)



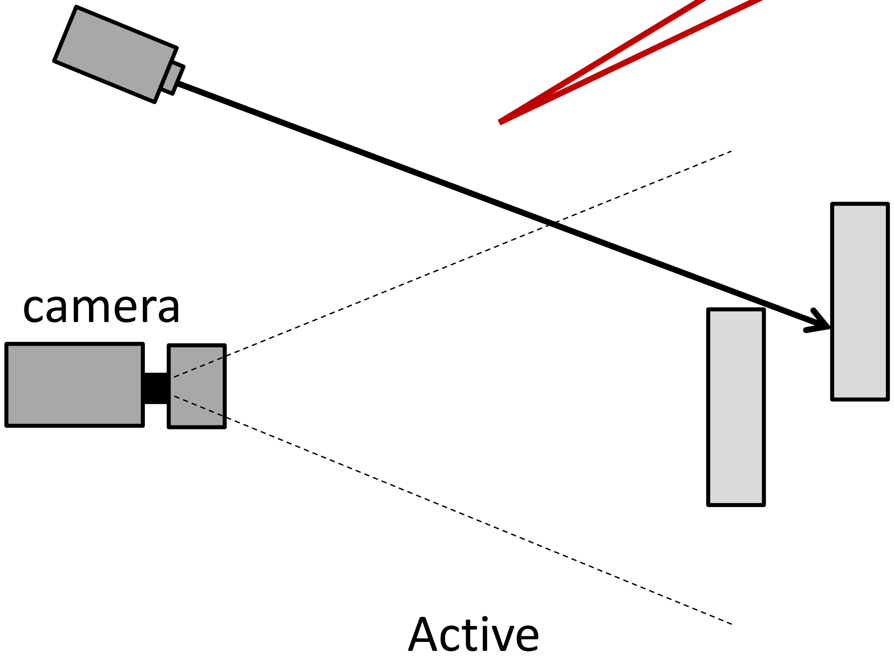
Passive – Known Object



Passive - Stereo

8.2.2.1.2 Active Triangulation

- Emit and sense from two different places.



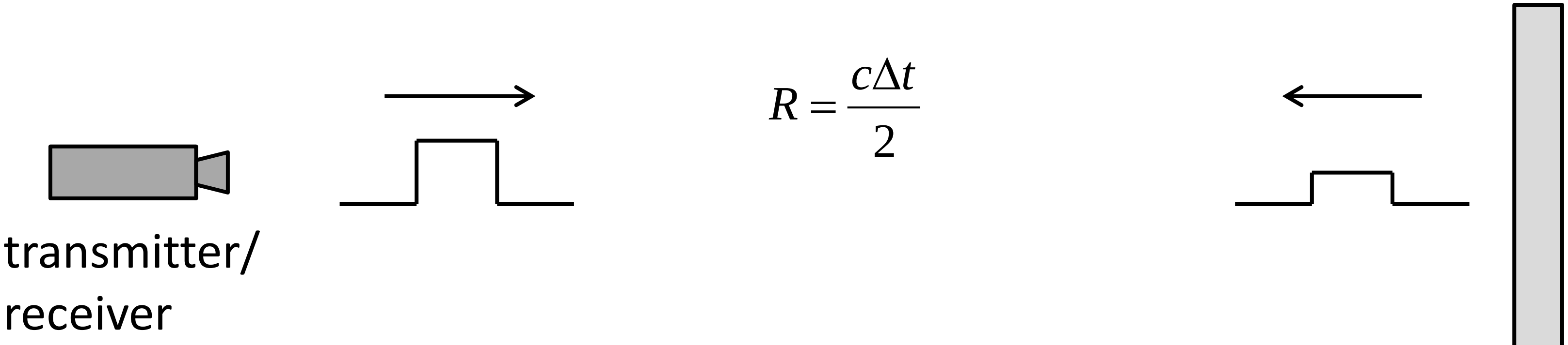
Missing Parts problem is illustrated here.

8.2.2.2 Time Of Flight

- Advantages:
  - (+) No missing parts problem (negligible or no baseline)
  - (0) BUT, scene can still self-occlude
  - (+) No correspondence problem
  - (+) Accuracy basically independent of range (esp. pulsed)
- Disadvantages
  - (-) Complicated, expensive, often non solid state hardware.
  - (-) easy to detect by others.

8.2.2.2.1 Pulsed Time of Flight

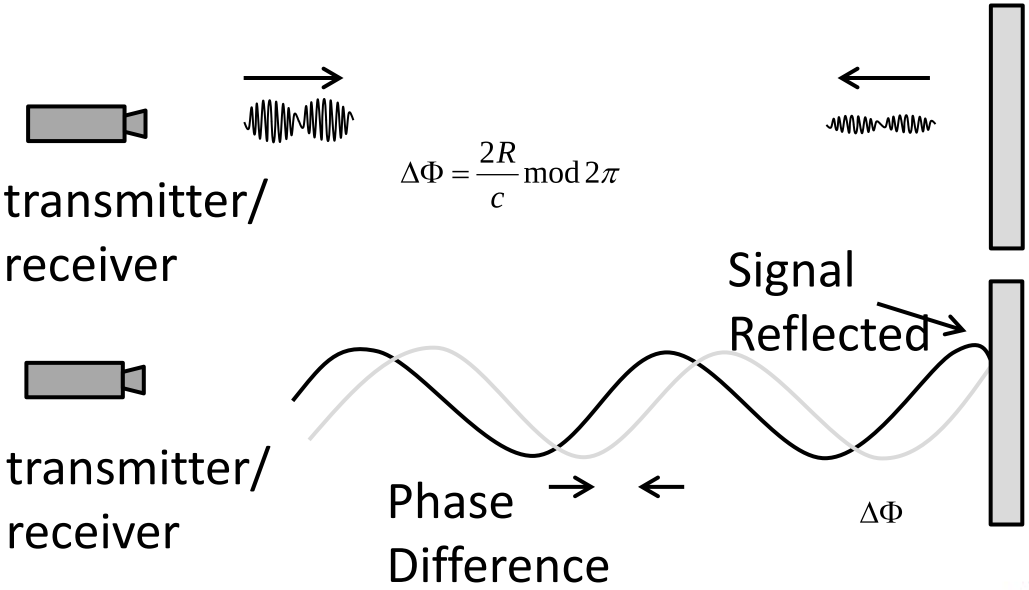
- Resolution comparatively low for high wave speeds (e.g. light)
- Because … measuring subnanosecond TOF requires expensive electronics



$$R = \frac{c\Delta t}{2}$$

8.2.2.2 AM-CW Ranging

- AM modulated carrier. Its the modulator phase that’s measured
- Range is proportional to phase difference of received signal and reference signal.
  - subject to phase ambiguity problem (can only determine range modulo wavelength/2)
  - No ambiguity up to range of wavelength/2
  - Multiple frequencies can resolve ambiguity



transmitter/
receiver

$$\Delta\Phi = \frac{2R}{c} \mod 2\pi$$

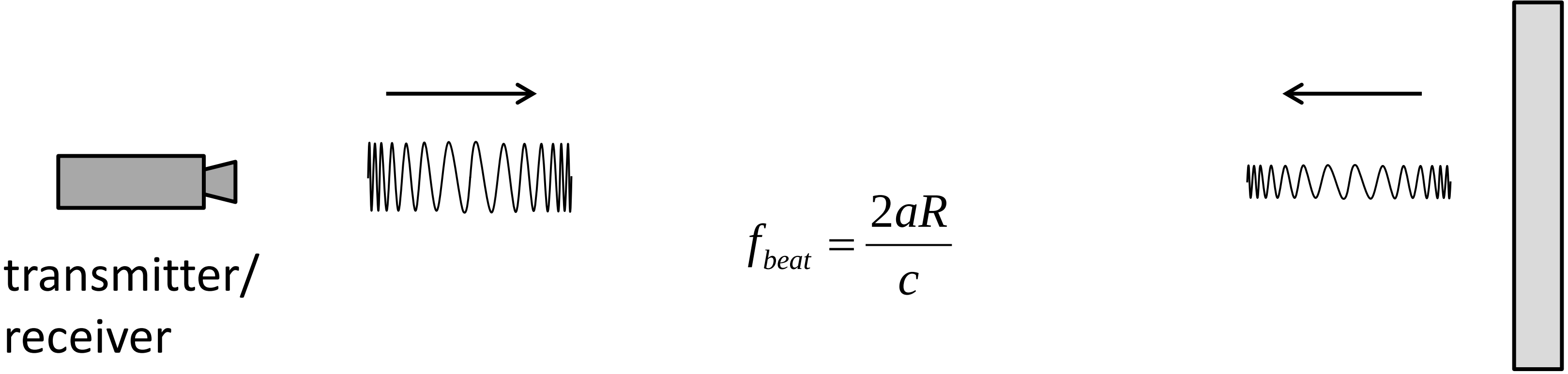
Signal
Reflected

transmitter/
receiver

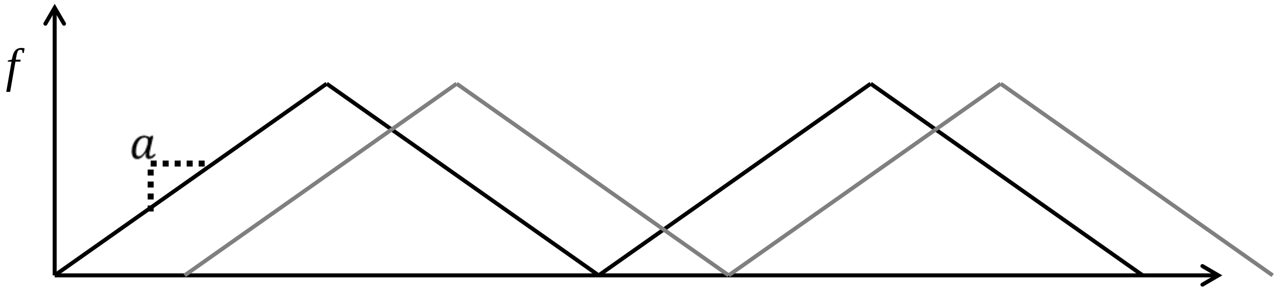
Phase
Difference

8.2.2.2.3 FM-CW Ranging

- Linearly FM modulated carrier
- Range proportional to beat frequency produced when return is mixed with reference.
- Comparatively high noise immunity.



$$f_{beat} = \frac{2aR}{c}$$



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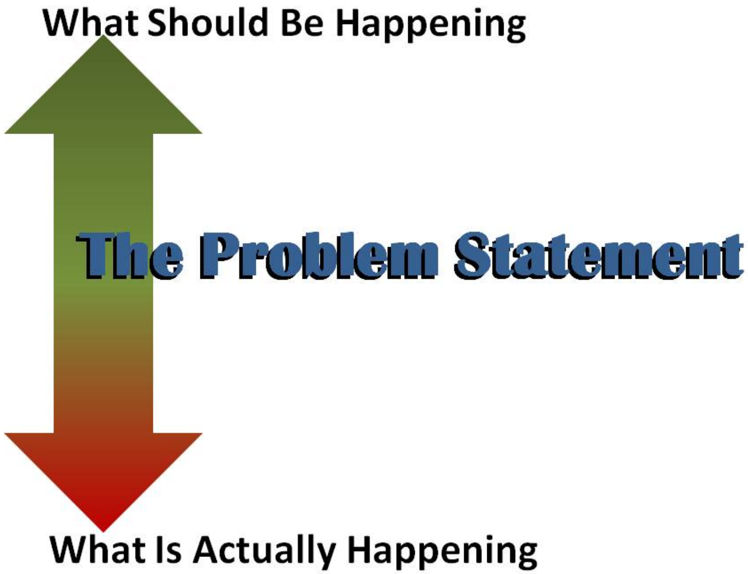
8.2.3 Radiation

(Impact of the Physics)

- Problems:
  - derive from physics of radiation.
  - apply to both active and passive sensors.
  - Whether good or bad depends on what you are doing.



What Should Be Happening

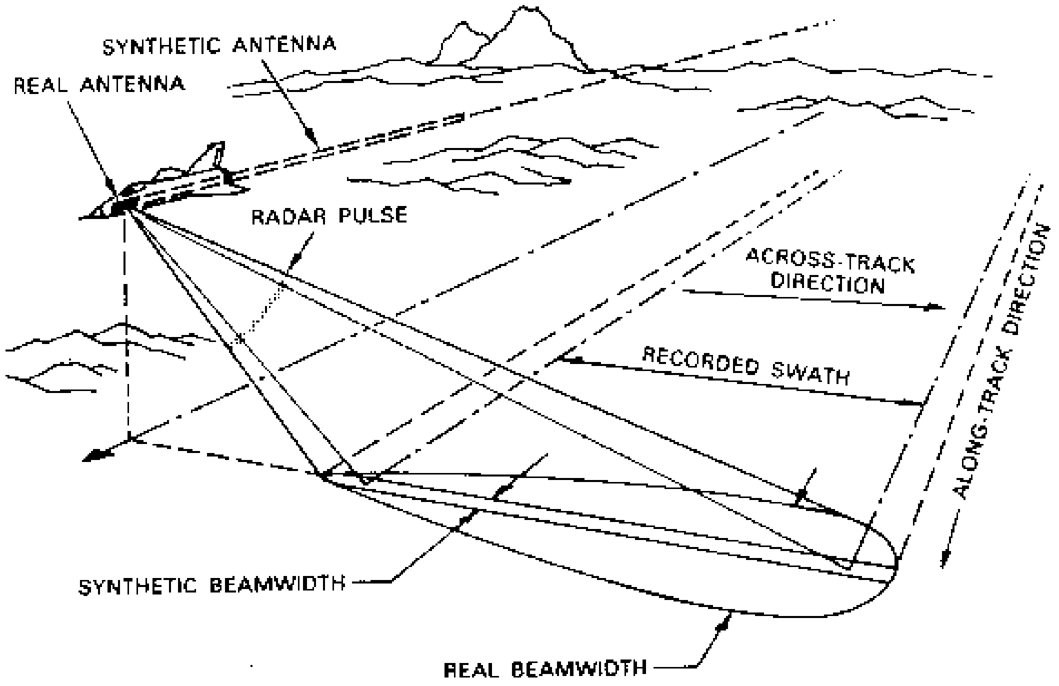
The Problem Statement

What Is Actually Happening

8.2.3 Radiation

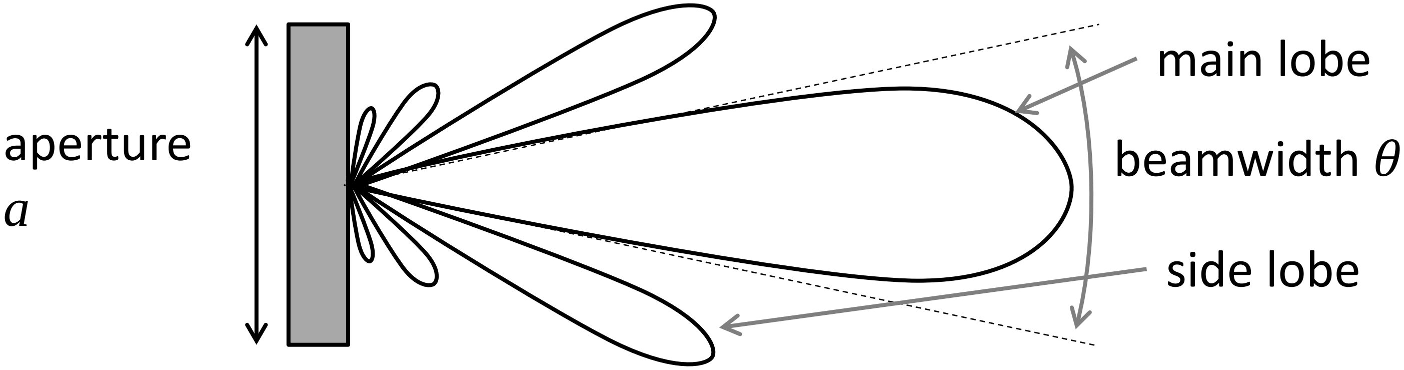
(Important Factors)

- Characteristics of returned energy depend on:
  1. Beam properties
  2. Medium physical properties
  3. Object material properties
  4. Geometry
  5. Ambient radiation
  6. Sensor motion



8.2.3.1 Beam and Antenna Properties

- Angular resolution is a function of beamwidth.
- Beamforming is accomplished by exploiting interference.
- Beamwidth is angle where intensity drops to some percentage of maximum.
- Beam shape (and receiver sensitivity) is typically shown with a directivity diagram like so:

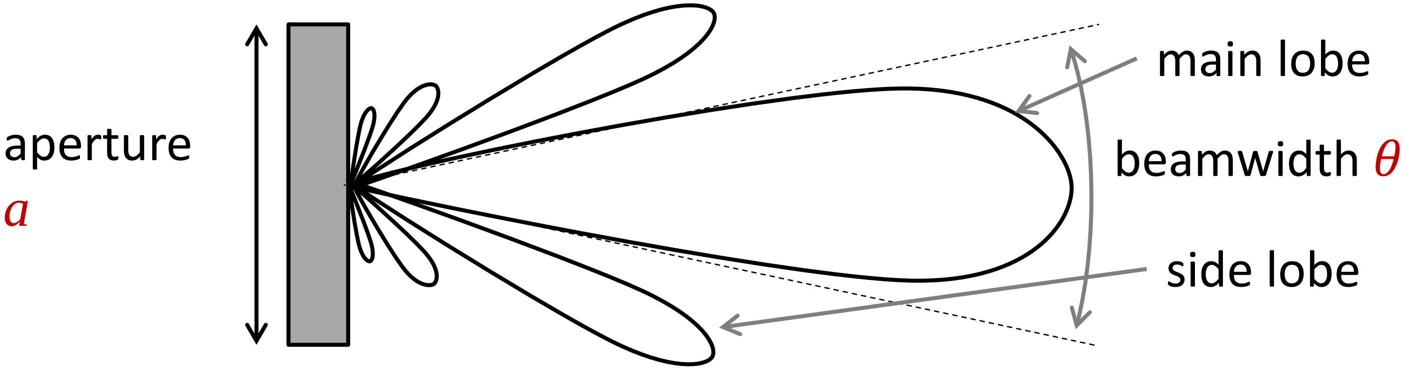


8.2.3.1 Beam and Antenna Properties

- Diffraction limit on resolution is:

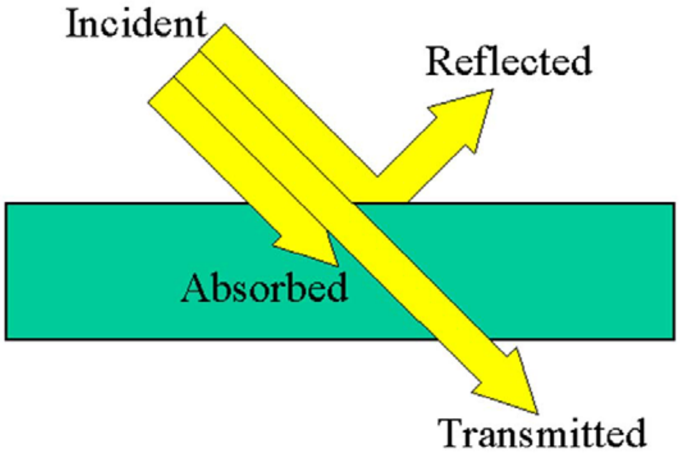
$$\boxed{\sin\theta = \frac{\lambda}{2a}}$$

- Therefore, narrowing the beam requires:
  - larger antennae
  - antenna motion, or
  - smaller wavelength
- BUT small wavelength increases attenuation.



8.2.3.2 Object and Medium Physical Properties

- Objects are simply solid media, so you can understand the physics based on what materials they are made of.
- Whenever radiation passes through an interface between two media, portions of the energy may be …
  - reflected at the interface …
  - transmitted through the second medium …
  - or absorbed by it.



8.2.3.2.1 Wave Speed

- Electromagnetic

$$\boxed{c = \frac{1}{\sqrt{\mu\varepsilon}}}$$

ε = dielectric_constant

μ = magnetic_permeability

- Sound

$$\boxed{\begin{aligned} c_{liquid} &= \sqrt{\frac{B}{\rho}} \\ c_{solid} &= \sqrt{\frac{Y}{\rho}} \\ c_{gas} &= \sqrt{\frac{B}{\rho}} = \sqrt{\frac{\gamma R T}{M}} \end{aligned}}$$

M = molecular_weight

Y = Young's_modulus

γ = specific_heat

T = absolute_temperature

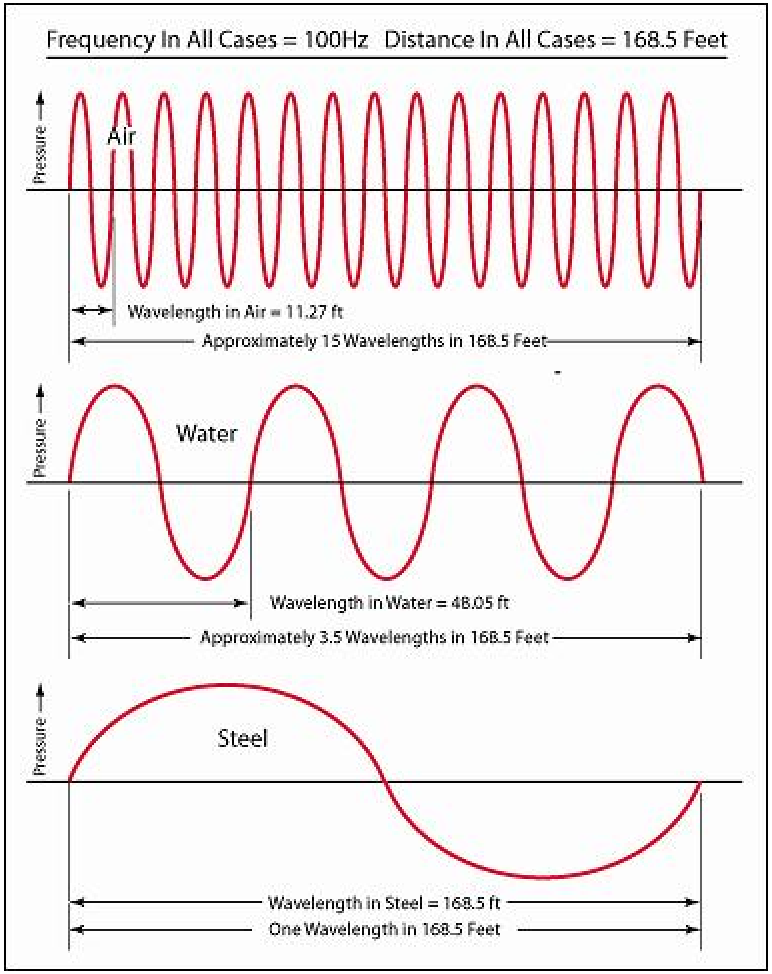
B = bulk_modulus

R = gas_constant

8.2.3.2.1 Wave Speed

(Sound Speed)

- 5 X times faster in water than in air

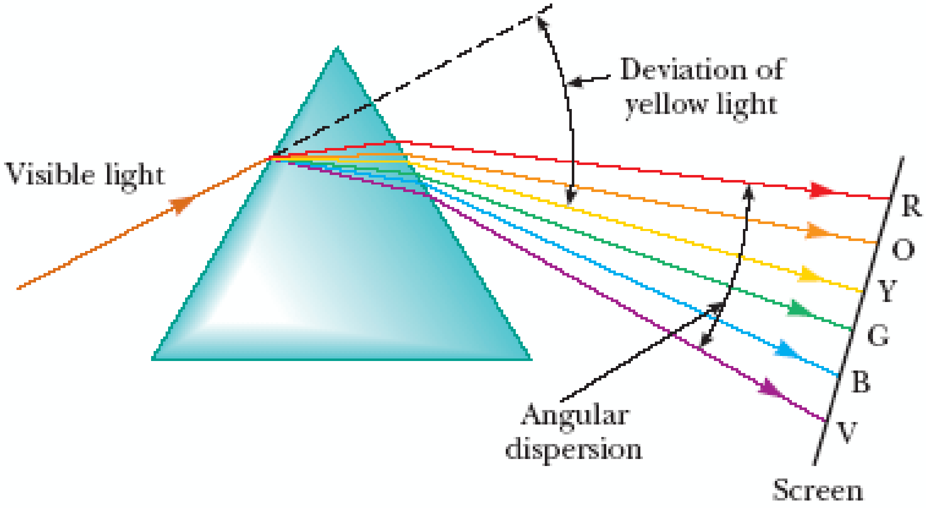


- Very temperature dependent in air

8.2.3.2.1 Wave Speed

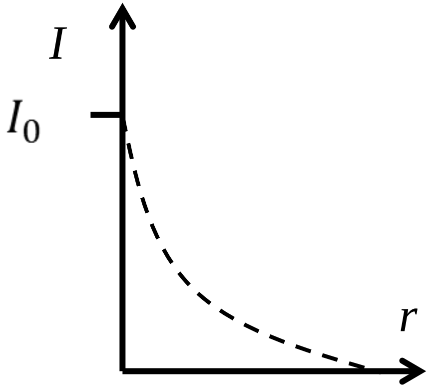
(Dispersion)

- Variation of above material properties with wavelength can cause "dispersion" (variation of speed with wavelength).
  - Hence the prism.
- Speed variation affects calibration of time of flight sensors



8.2.3.2.2 Attenuation

- Attenuation = absorption + scattering
- Inherently its neither good nor bad:
  - Sensor signal attenuated - bad
  - Ambient noise attenuated - good



8.2.3.2.2 Attenuation

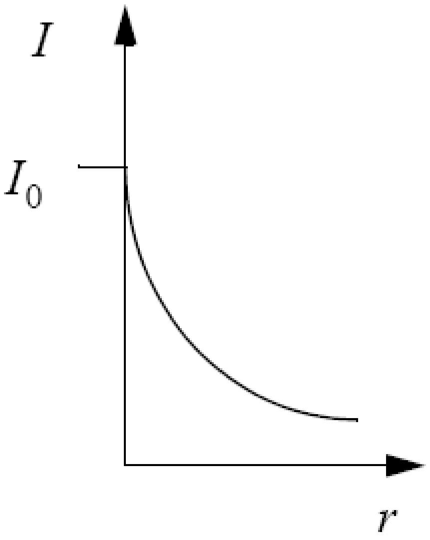
(Absorption)

- Media tend to absorb fixed percentage per unit length (hence exponential behavior).
- For electromagnetic:

$$\boxed{\alpha = c\sigma\mu = \sigma\sqrt{\frac{\mu}{\varepsilon}}}$$

α = absorption_coefficient

c = wave_speed



EM & Sound

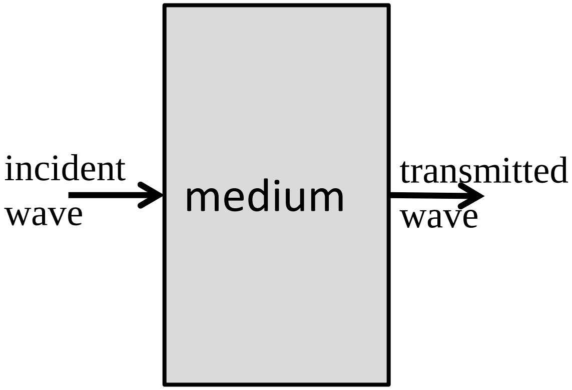
$I(r) = I_0 e^{-\alpha r}$

I_0 = initial_intensity

$I(r)$ = intensity

r = distance

α = absorption coeff



incident wave

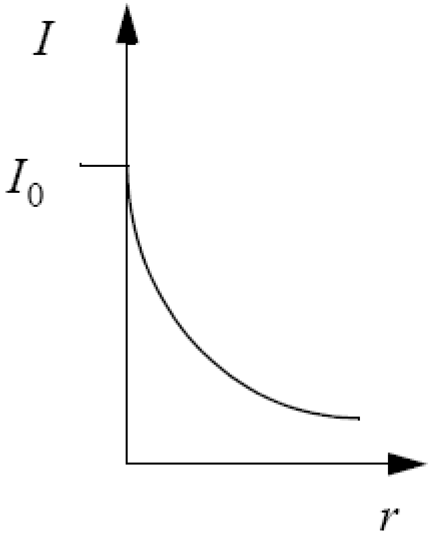
medium

transmitted wave

8.2.3.2.2 Attenuation

(Sound Absorption)

- For sound, absorption:
  - increases with frequency in both H_20, air
  - increases with relative humidity in air
    - hence the fog horn



EM & Sound

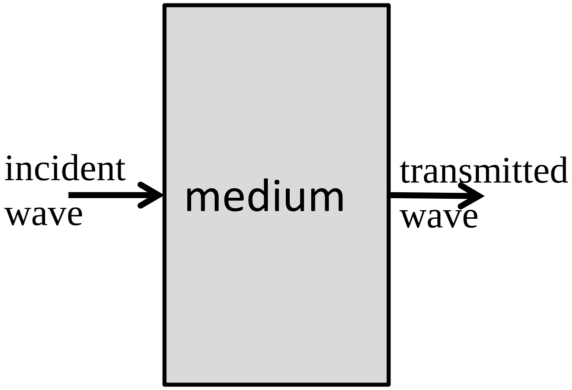
$I(r) = I_0 e^{-\alpha r}$

$I_0 =$ initial_intensity

$I(r) =$ intensity

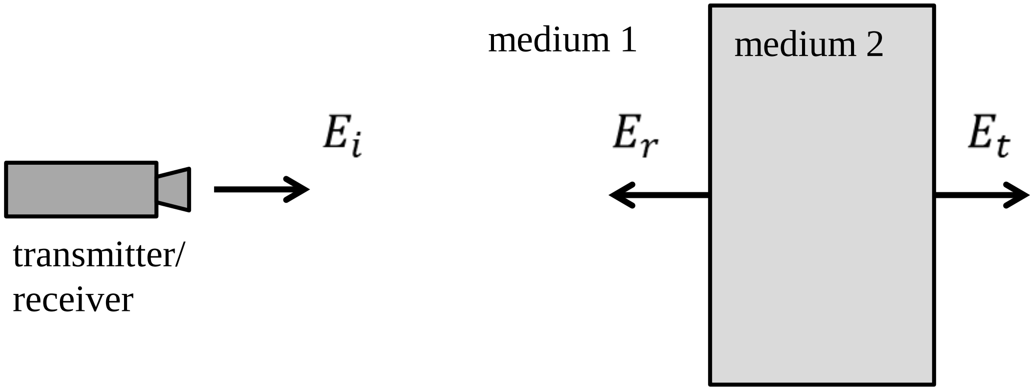
$r =$ distance

$\alpha =$ absorption coeff



8.2.3.2.3 Transmission and Transparency

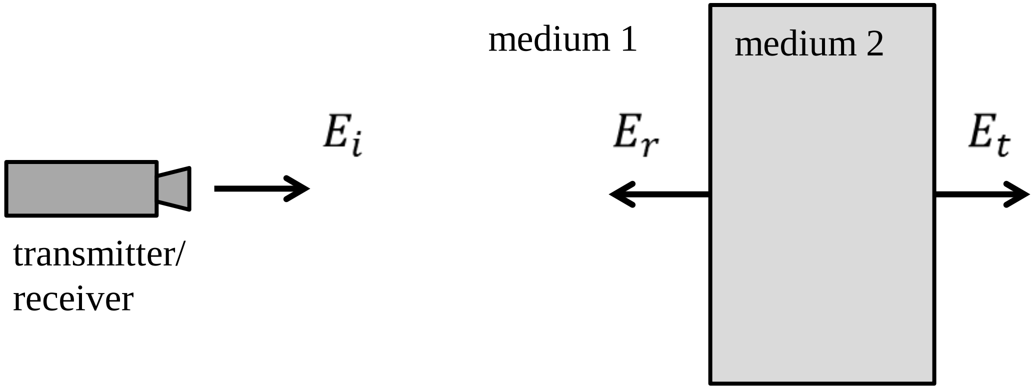
- Absorptive properties indirectly affect how much energy is transmitted after reflection.
  - Sometimes get no return if most of the incident energy is absorbed or transmitted.
- Transparency
  - Some materials are transparent to radar, lidar - bad
  - Millimeter wave radar goes through underbrush - good
  - Some materials are strong sonar absorbers - bad



8.2.3.2.3 Transmission and Transparency

(Transmission)

- Magnitude of the transmitted and reflected components of electromagnetic or sound energy is given by:



EM (normal incidence)

$$(K_r)_\perp = \left[\frac{E_r}{E_i}\right]_\perp = \left[\frac{\mu_2 c_2 - \mu_1 c_1}{\mu_2 c_2 + \mu_1 c_1}\right]$$

$$(K_t)_\perp = \left[\frac{E_t}{E_i}\right]_\perp = \left[\frac{2\mu_2 c_2}{\mu_2 c_2 + \mu_1 c_1}\right]$$

E = electric_field_amplitude

Sound (normal incidence)

$$K_r = \left[\frac{p_r}{p_i}\right] = \left[\frac{\rho_2 c_2 - \rho_1 c_1}{\rho_2 c_2 + \rho_1 c_1}\right]$$

$$K_t = \left[\frac{p_t}{p_i}\right] = \left[\frac{2\rho_2 c_2}{\rho_2 c_2 + \rho_1 c_1}\right]$$

p = pressure_amplitude

8.2.3.2.4 Reflection & Refraction

- Non-normal incidence can cause bending.
- Depends on the relative wave speed in the media involved.
- Laws apply to both EM and sound.

Snell's Laws

law for reflection:

$$\theta_i = \theta_{rfle}$$

index of refraction:

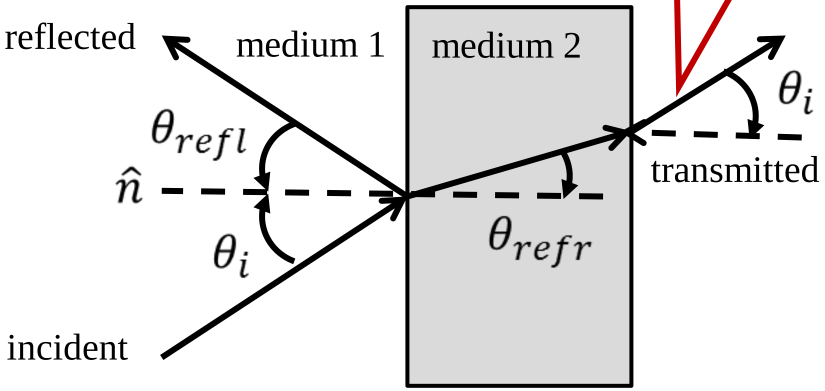
$$n = \frac{c_{reference}}{c_{medium}}$$

law for refraction:

$$n_i \sin\theta_i = n_{rfra} \sin\theta_{rfra}$$

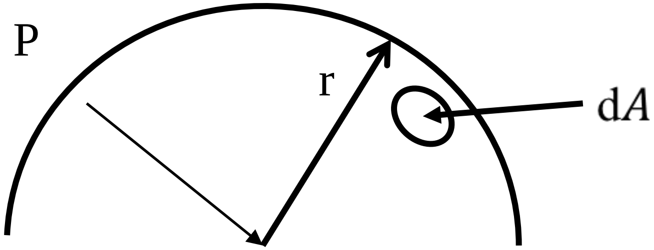
$$\frac{\sin\theta_i}{c_i} = \frac{\sin\theta_{rfra}}{c_{rfra}}$$

All rays lie in same plane



8.2.3.3.1 Range from Source

- By conservation, energy has to “thin out” as it goes.
- Opposite is for a point source. Power at any radius is the same:
  - Ignoring attenuation
- Amplitude therefore falls off as 1/R.



$$P_0 = \int_A I\,dA$$

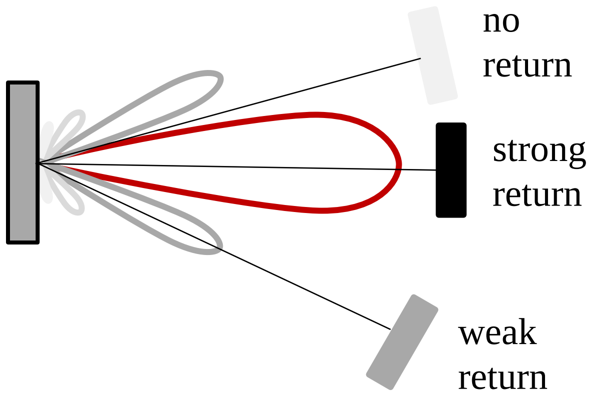
$$P(r) = 4\pi r^2 I$$

$$I(r) = \frac{P_0}{4\pi r^2}$$

“Intensity” is power passing through a surface <u>per unit area</u>

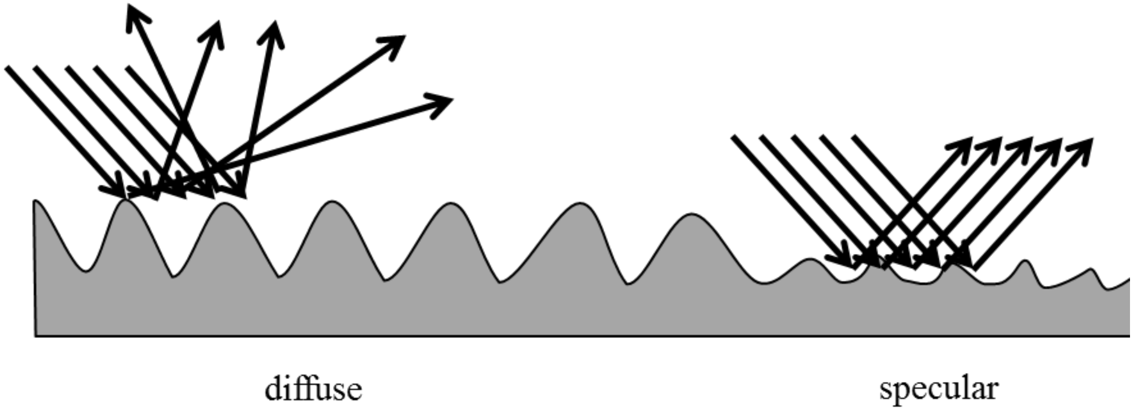
8.2.3.3.2 Angle Off Symmetry Axis

- For highly directive (focused) beams, returned energy depends on where the sensor points
- Blind spot is good or bad depending on whether you want to detect objects off the beam axis



8.2.3.3.3 Microscopic Surface Geometry

- Geometry on the nanometer scale matters.
- Waves may be reflected
  - “specularly” = like a mirror
  - “diffusely” = spread out
- Real surfaces display both types of reflection to some degree.

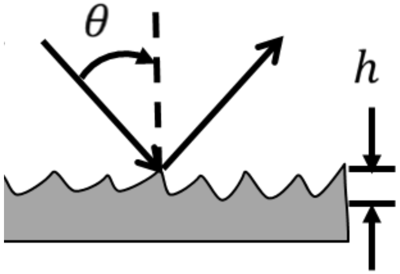


8.2.3.3.3 Microscopic Surface Geometry

- Specular reflection requires surface roughness "roughly" less than the wavelength.
- The transition from diffuse reflection to specular takes place when this criterion is satisfied:

Rayleigh Criterion

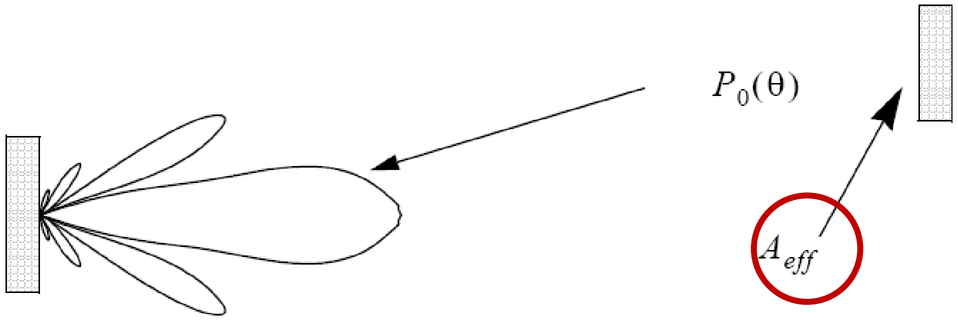
$$h < \frac{\lambda}{8 \sin \theta}$$



8.2.3.3.3 Microscopic Surface Geometry

(Three Effects Combined)

- Specular received power falls of as range squared,
- Diffuse received power falls off as range to the fourth power!
- Specular reflectors generate high power, but may not point it at the receiver.



Emitted Intensity: →

$$I_e(r,\theta) = \frac{P_0(\theta)}{4\pi r_e^2}$$

Surface Incident Pwr:

$$P_r = \frac{P_0(\theta)A_{eff}}{4\pi R^2}$$

Reflected Intensity (Specular):

$$I_r(r,\theta) = \frac{P_0(\theta)A_{eff}}{4\pi(R+r_r)^2}$$

Reflected Intensity (Diffuse):

$$I_r(r,\theta) = \frac{P_0(\theta)A_{eff}}{(4\pi R^2)4\pi r_r^2}$$

Sensor Incident Pwr (Specular):

$$P_e(r,\theta) = \frac{P_0(\theta)A_{eff}A_e\cos\theta}{16\pi R^2}$$

Sensor Incident Pwr (Diffuse):

$$P_e(r,\theta) = \frac{P_0(\theta)A_{eff}A_e\cos\theta}{16\pi^2 R^4}$$

Result (Specular):

$$P_{spec} = K\left(\frac{P_0(\theta)\cos\theta A_{eff}}{\boxed{R^2}}\right)$$

Diffuse

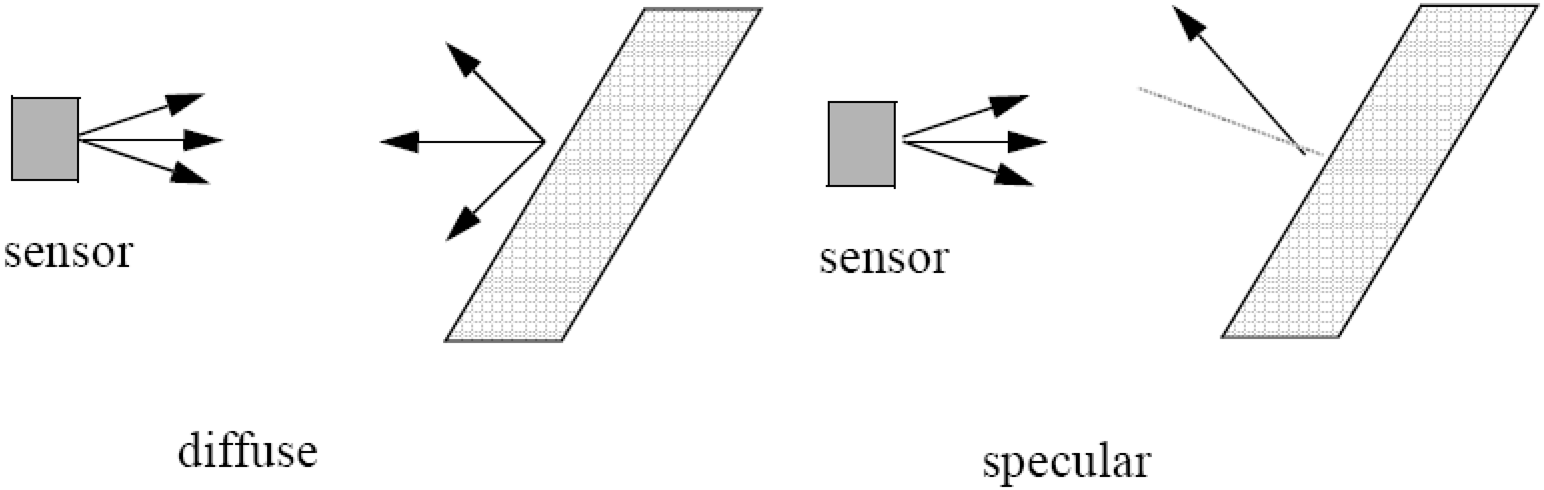
Result (~~Specular~~):

$$P_{diff} = \frac{K}{\pi}\left(\frac{P_0(\theta)\cos\theta A_{eff}}{\boxed{R^4}}\right)$$

8.2.3.3.3 Microscopic Surface Geometry

(Effect on Exponent)

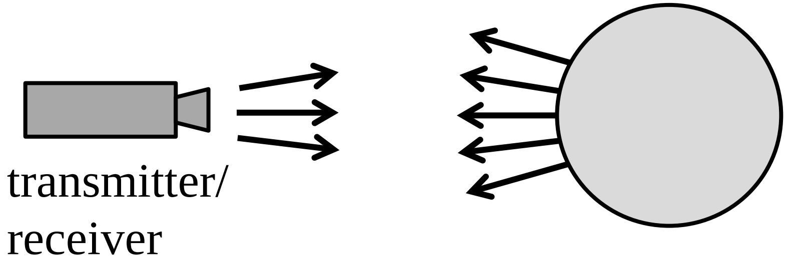
- Whether it is R^4 or R^2 depends only on the surface roughness.
- Next lets look at what affects the “Effective Area” of a surface patch.



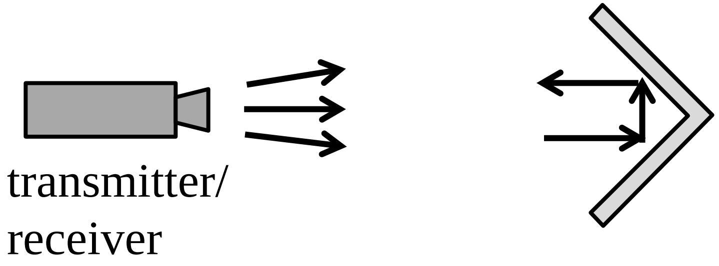
8.2.3.3.4 Macroscopic (Object) Surface Geometry

(Macroscopic Determines Cross Section)

- Integrated effect of both orientation and projected area gives cross section.
- Both objects below have same projected area and material properties.
- Each can be good or bad.



Low Cross Section

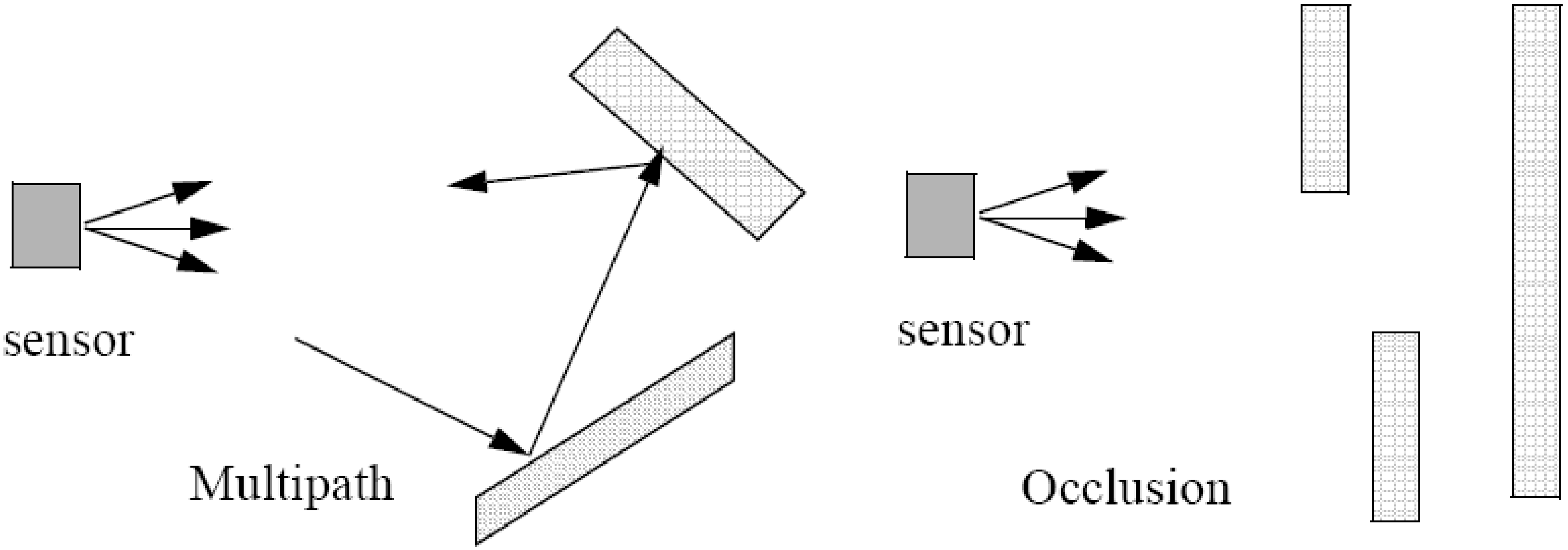


High Cross Section

8.2.3.3.5 Macroscopic (Scene) Surface Geometry

(Scene Geometry Transcends Cross Section)

- Object spatial relationships can dramatically enhance or suppress returns.



8.2.3.4 Sensor Motion

- This is an issue for sonar mostly.
  - Must wait for narrow beam to return (cannot rotate too fast)
  - Must remember where you were when you sent the pulse (ladar too).

- Doppler shift is useful for velocity measurement.

8.2.3.5 Ambient Radiation

- For active sensors, ambient effects can cause problems:
  - – random spurious readings
  - – gradual degradations of model fidelity.
- BUT: Passive sensors (e.g. cameras) rely on it:
  - – It must exist or be created (lights)
- Every modality cares about ambient radiation:
  - – Sonar is sensitive to ambient noise.
  - – IR lasers are sensitive to ambient illumination.
  - – Radars sensitive to radio sources.

Here

- This is test test

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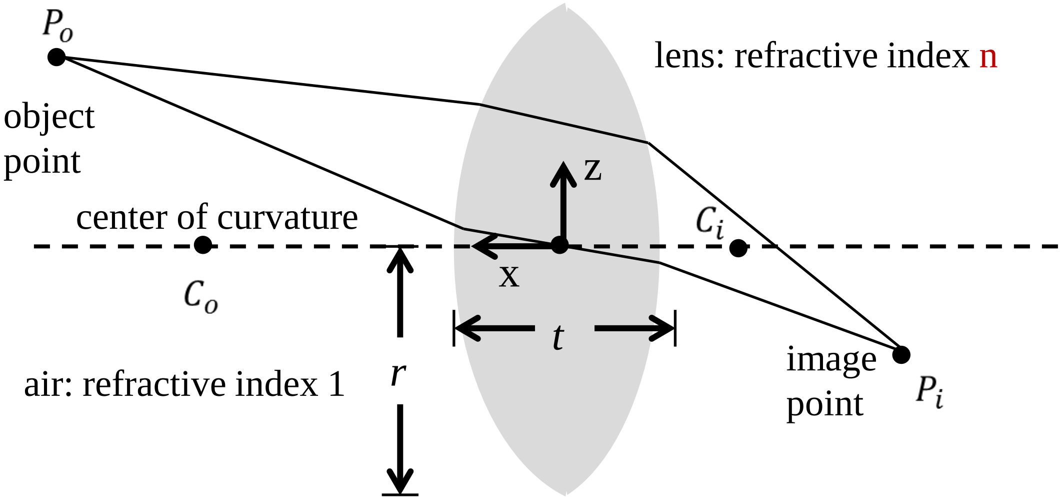
8.2.4.1 Thin Lenses

(Descartes Lensmaker's Formula)

- Based on Snell's law of Refraction.
- Lenses both transmit, and refract light.
- Descartes: All rays emanating from P_0 meet again at image point P_i.
- When object is at infinity, we get the distance to the image focal point Fi.

$$\frac{1}{x_{Po}} - \frac{1}{x_{Pi}} = (n-1)\left(\frac{1}{x_{Co}} - \frac{1}{x_{Ci}}\right)$$

$$\frac{1}{x_{Fi}} = -(n-1)\left(\frac{1}{x_{Co}} - \frac{1}{x_{Ci}}\right)$$

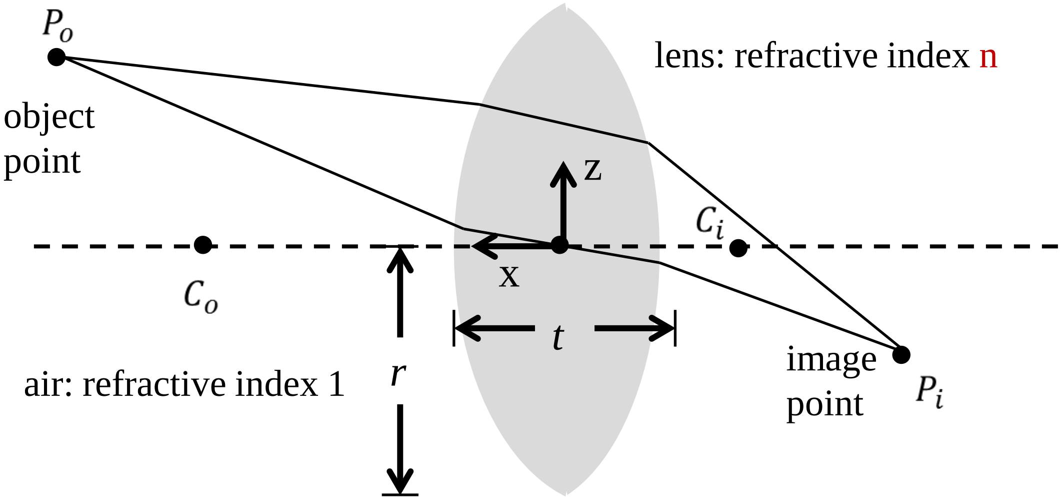


8.2.4.1 Thin Lenses

(focal length)

- Substitute second formula into first to get the thin lens formula (where $f = x_{Fi}$ is called the focal length of the lens):

$$\frac{1}{x_{Po}} - \frac{1}{x_{Pi}} = \frac{1}{f}$$



8.2.4.1 Thin Lenses

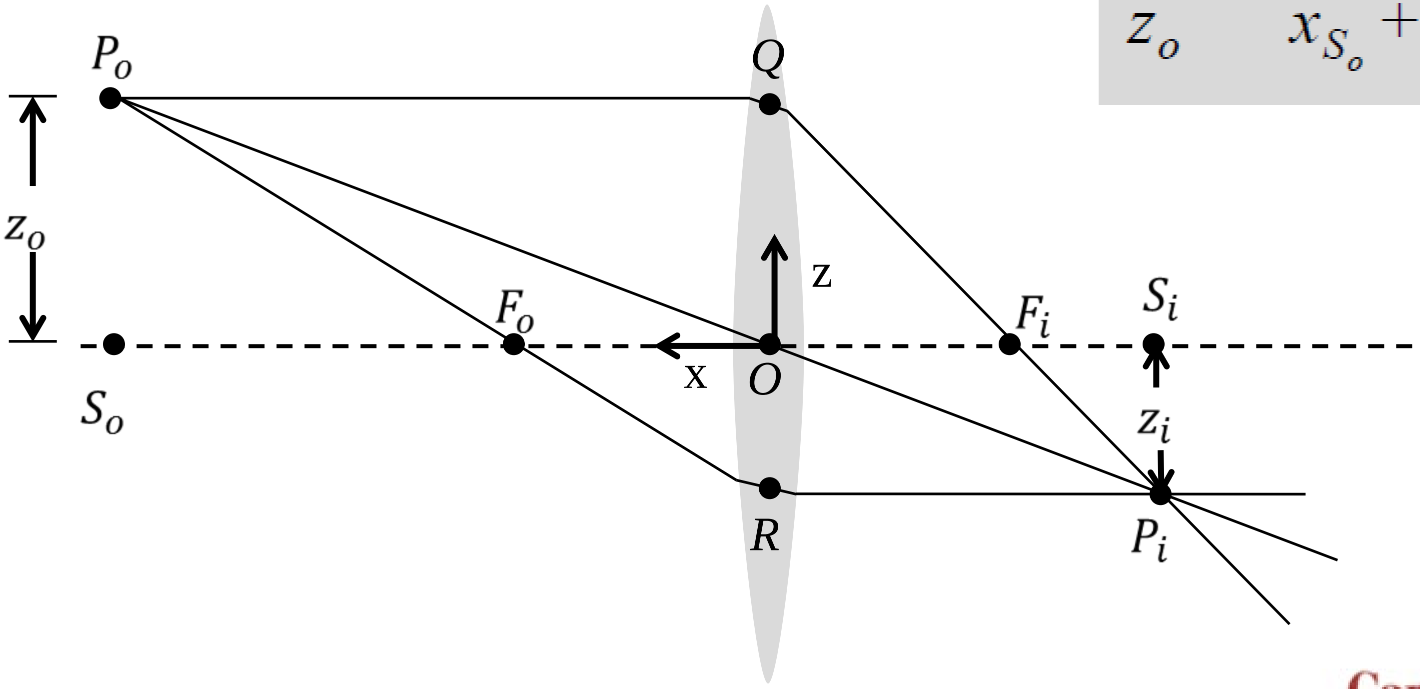
(Magnification)

- Define the magnification as ratio of image size to reality.

$$M = z_i / z_o = x_{S_i} / x_{S_o}$$

- Manipulating, we can derive the basic camera model.

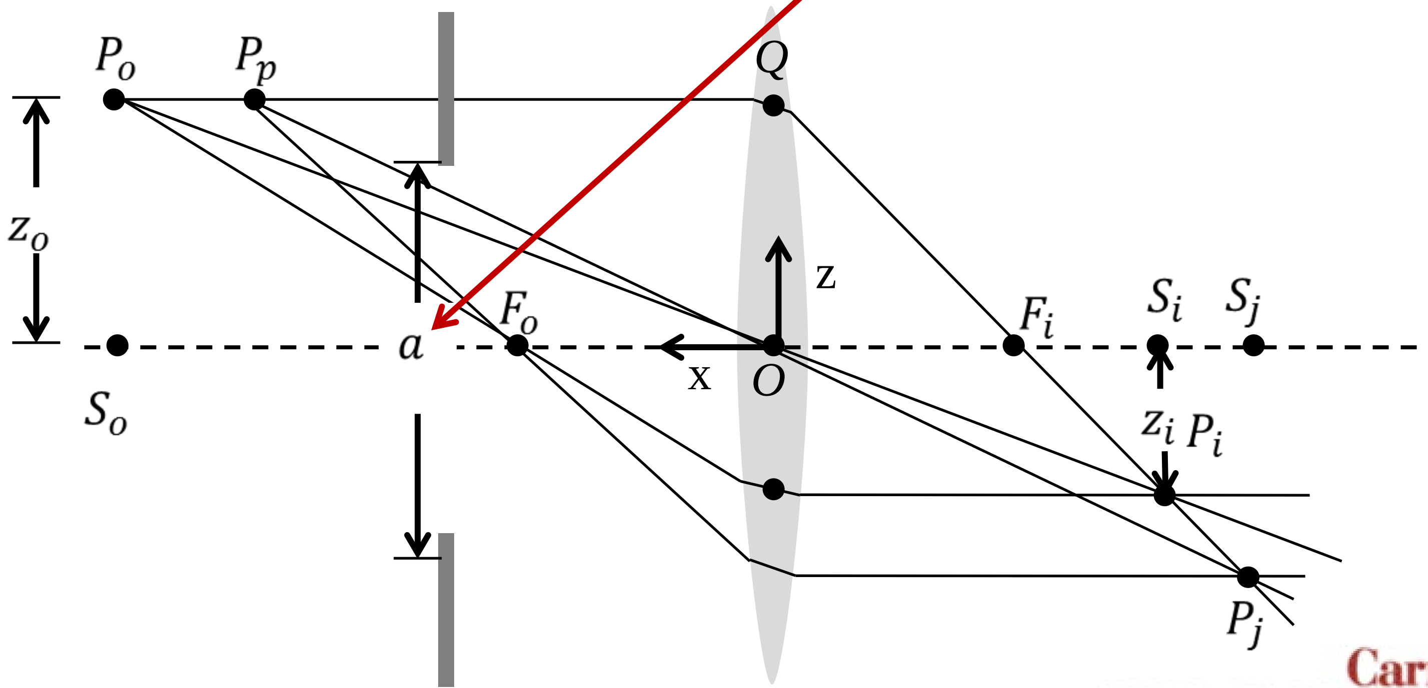
$$\frac{z_i}{z_o} = \frac{f}{x_{S_o} + f}$$



8.2.4.1 Thin Lenses

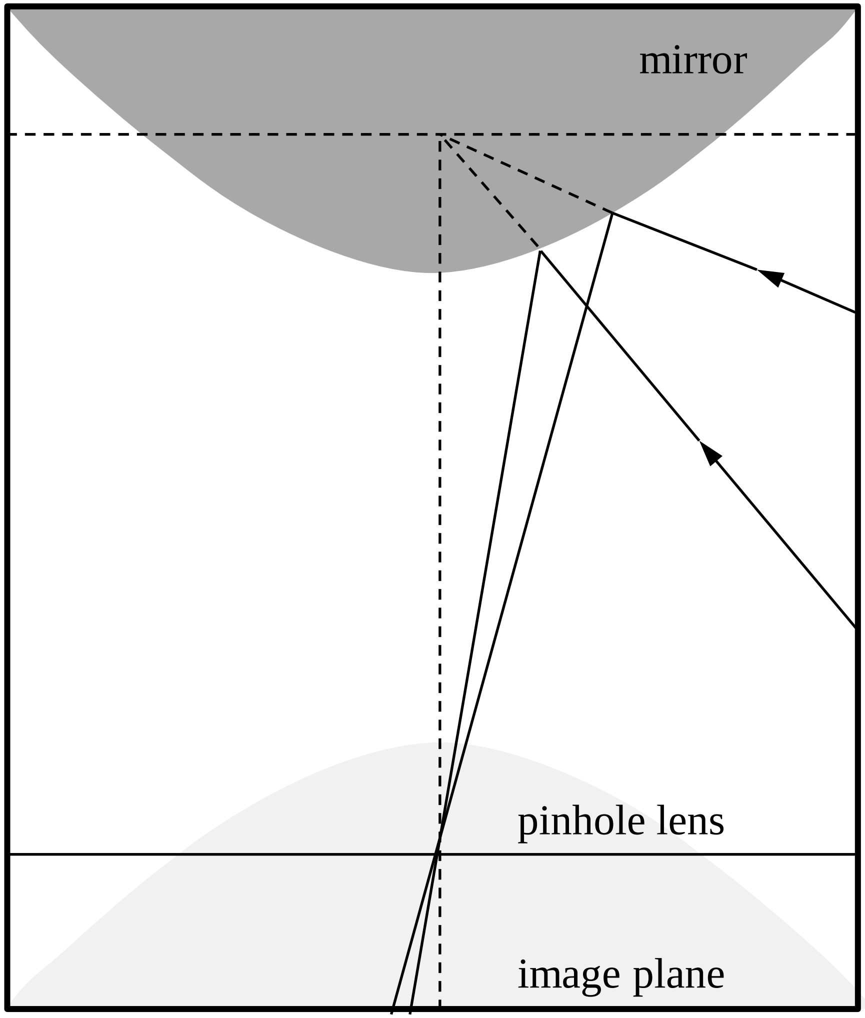
(Depth of Field)

- Objects at <u>different ranges</u> form images at <u>different distances</u> behind lens, so one or the other will be blurred.
- Depth of field is the motion of the image plane that produces a 1 pixel blur circle (on either side of perfect focus distance).
  - Larger depth of field means more of image is in focus.
  - Depth f field increases if you reduce aperture (and light entering lens).



8.2.4.3 Mirrors

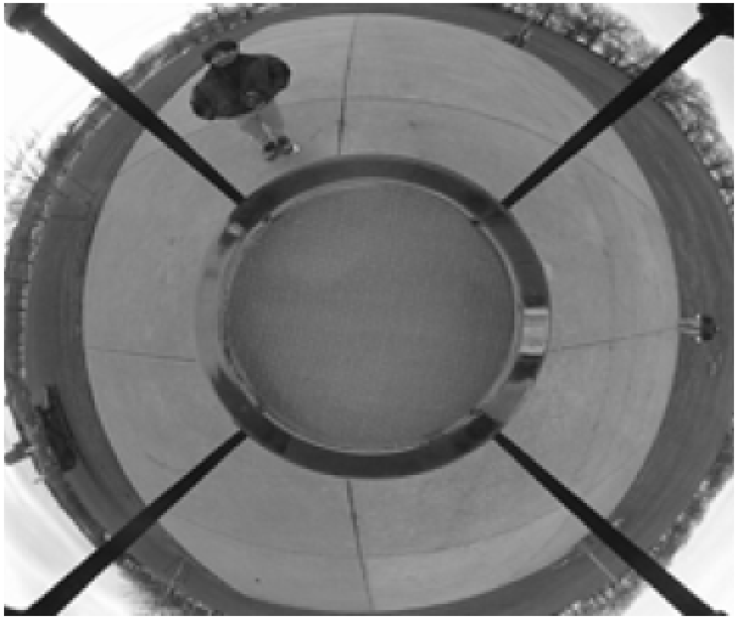
- These bend or distort the path of a laser or the field of view of a camera – which can be useful.
- Omnicams can be constructed from a camera and a hyperbloidal mirror.
  - Great for seeing in all directions.
  - Great for distinguishing translation from rotation in visual odometry.



8.2.4.3 Mirrors

(Omnicam Example)

Actual Image



Rectified Cylindrical Image

Outline

- 8.2 Physics and Principles of Radiative Sensors
  - 8.2.1 Radiative Sensors
  - 8.2.2 Techniques for Range Sensing
  - 8.2.3 Radiation
  - 8.2.4 Lenses, Filters, and Mirrors
  - <u>Summary</u>

Summary

- Radiative sensors are the basic mechanism by which mobile robots see what is around them.
- Processing sensor data involves inverting models of radiation, so the physics of radiation must be understood.
- Many effects including beam properties, medium and object physical properties, and geometry at all scales influence behavior of sensors.
- Proximity sensors are a simple and inexpensive means of ranging.