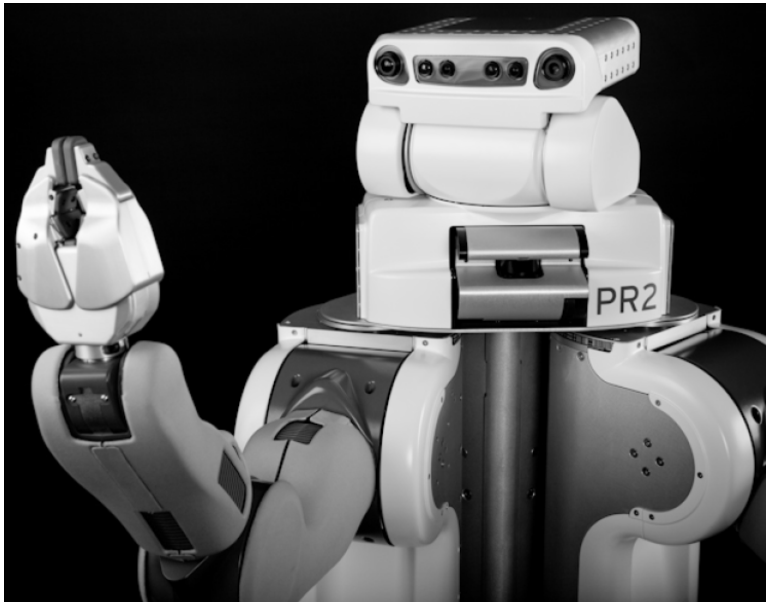
Chapter 8
Perception



Part 3

8.3 Sensors for Perception

Introduction

- Intelligent robots must know what is out there.
- Sensors may sense:
  - “appearance” (including IR and UV wavelengths)
  - geometric features.
- More esoteric applications might use
  - ground penetrating radar (to find buried land mines)
  - ambient sound (traffic)
  - chemical signals (smell).
- Real sensors are often:
  - well suited to some applications
  - poorly suited to others.

Outline

- 8.3 Sensors for Perception
  - 8.3.1 Laser Rangefinders
  - 8.3.2 Ultrasonic Rangefinders
  - 8.3.3 Visible Wavelength Cameras
  - 8.3.4 Mid to Far Infrared Wavelength Cameras
  - 8.3.5 Radars
  - Summary

Outline

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  - – 8.3.1 Laser Rangefinders
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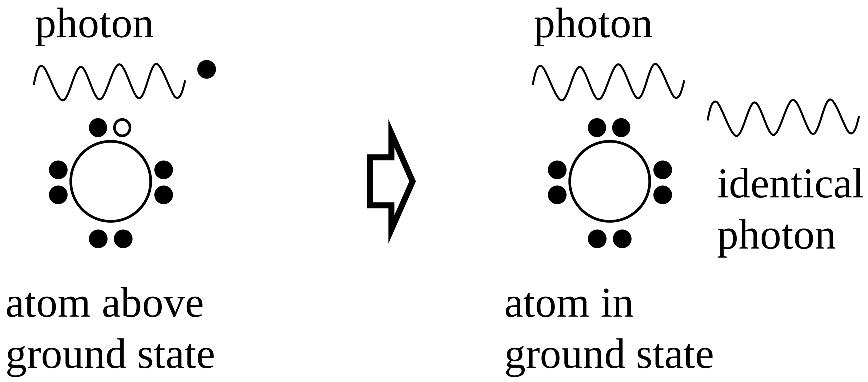
  - – 8.3.4 Mid to Far Infrared Wavelength Cameras
  - – 8.3.5 Radars
  - – Summary

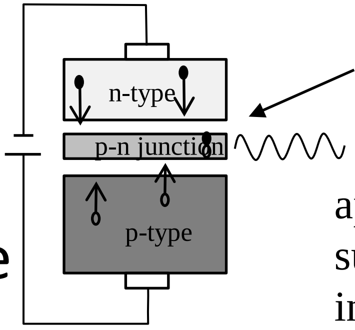
8.3.1 Laser Rangefinders

- LADAR, LIDAR (Light Detection and Ranging).
- Earliest application of the laser was rangefinding
  - Hughes Aircraft COLIDAR (1961)
  - pulsed ruby laser
- Apollo 11 (1969)
  - retroreflector used to measure range to moon
  - telescopic collimation used
  - spot in moon was 1 mile in diameter
  - recieved spot at earth 16 Km in diameter
  - 10**20 photons sent per pulse, 25 photons recieved
  - moon range (384,400km) measured to +/- 12 cm

8.3.1.1 Principles
(Semi-Conductor Lasers)

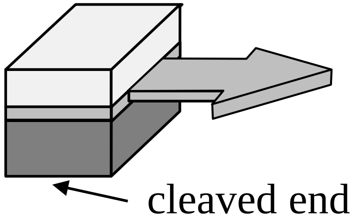
- All lasers are optical oscillators → two ingredients:
  - positive optical feedback
  - frequency filtering
- Positive Feedback
  - stimulated emission of a photon by an atom
- Frequency filtering
  - cavity resonance condition
- Semi-conductor: beams are not round
  - Junction dimensions imply beam is not well formed
  - Collimation optics used to fix this issue.



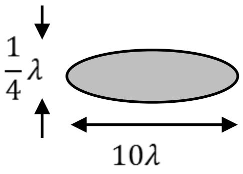


electron-hole recombination causes photon emission

applied voltage sustains population inversion

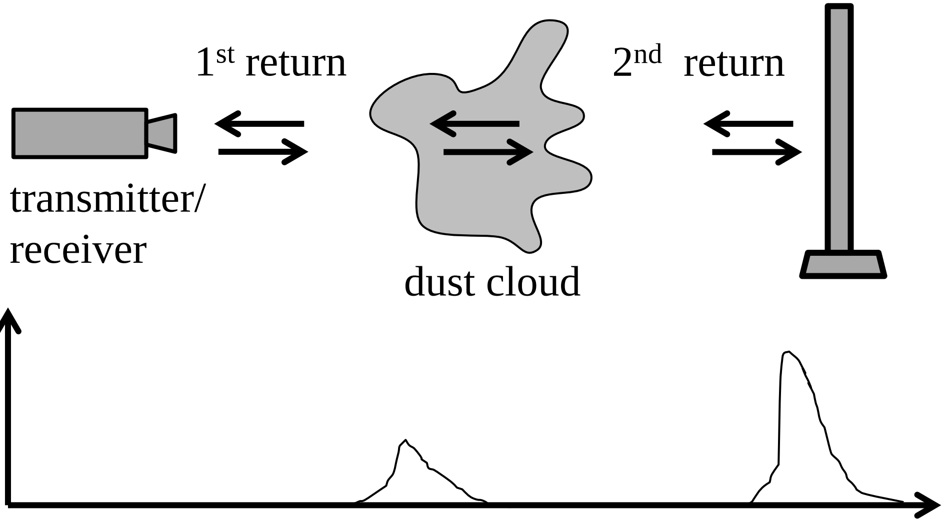


cleaved ends serve as mirrors



8.3.1.2 Signal Processing

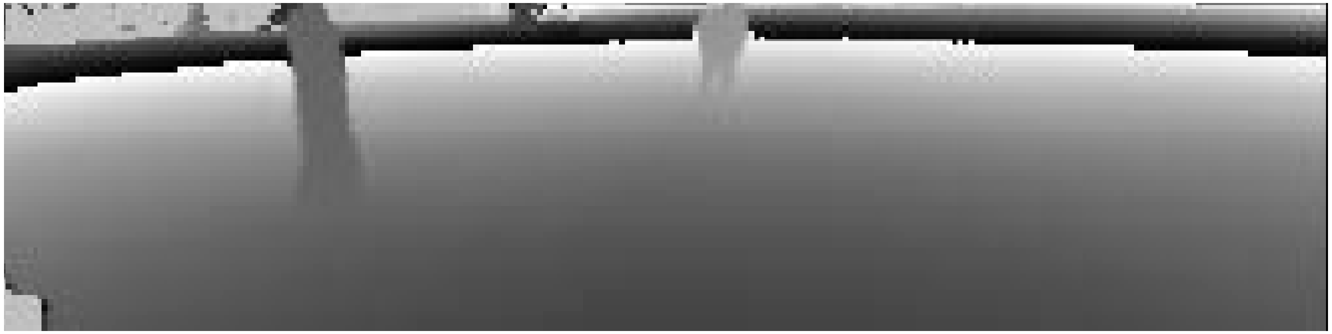
- Most contemporary devices are AM and pulsed.
  - FM exists, but is rare.
- Nominally, they "time" the return from the first reflecting surface ...
- Recording multiple returns is valuable in partially transparent environments.



8.3.1.2 Signal Processing

(Typical Images)

Range



Reflectance

8.3.1.4 Advantages and Disadvantages

Advantages

- Accuracy relatively <u>independent of range</u>.
    - depends on reflected power and surface orientation.
- Range is measured in hardware.
    - Shape can be obtained with very little processing.
- Performance relatively <u>independent of ambient lighting</u>.
    - Very bright ambient light reduces performance slightly.
- Can operate in the presence of moderate dust and fog.

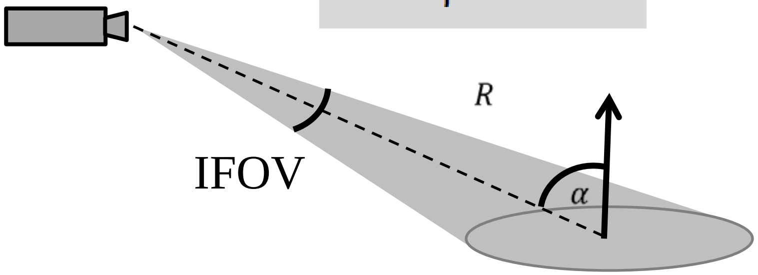
Disadvantages

- Most are physically scanned.
    - Complex mechanism
    - Sensor pose estimate required.
    - Precision system level timing required
- Angular resolution is limited by signal to noise.
- Minimum amount of surface reflectivity (albedo) is needed for an accurate range measurement.

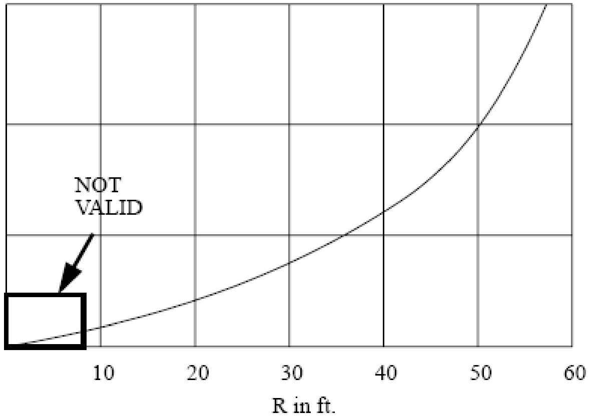
Performance: Precision

- Major source of error is reduction in returned signal levels with
  - Range
  - incidence angle
- 10 to 50 mm is a typical resolution.

$$\sigma_r \propto \frac{\lambda \cdot R^2}{\rho \cdot \cos\alpha}$$

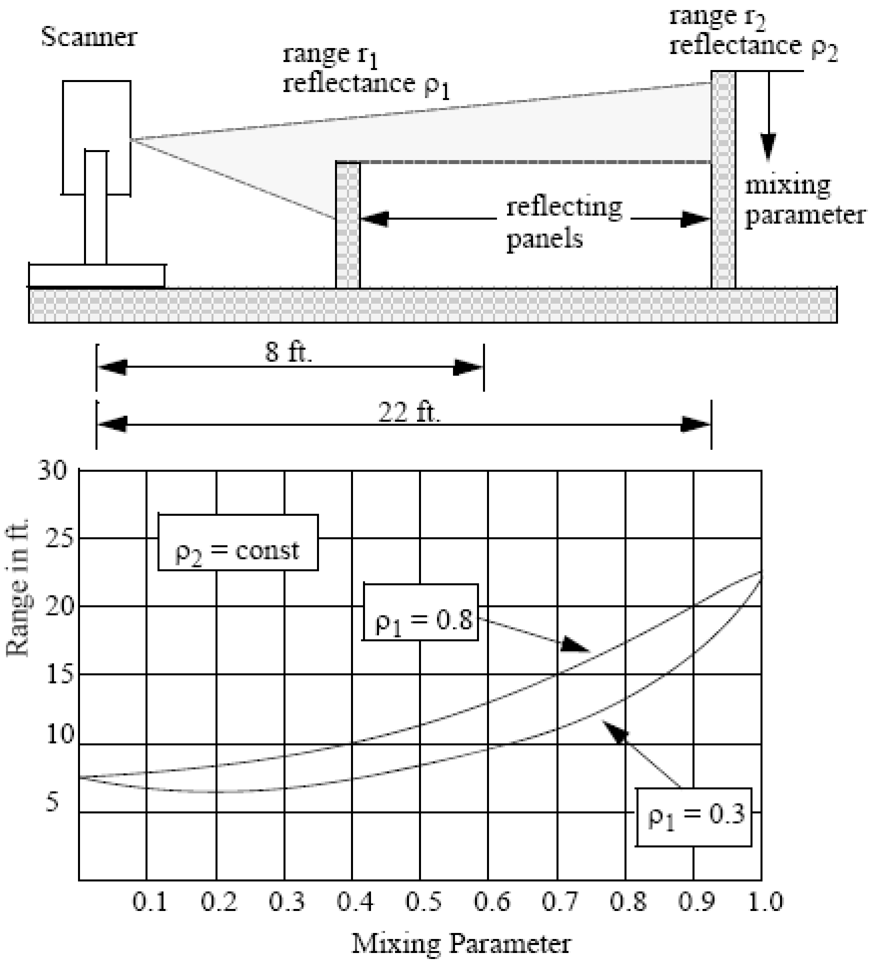


σ_r = range_std_dev
R = range
λ = wavelength
ρ = reflectance
α = angle_of_incidence



Performance: Mixed Pixels

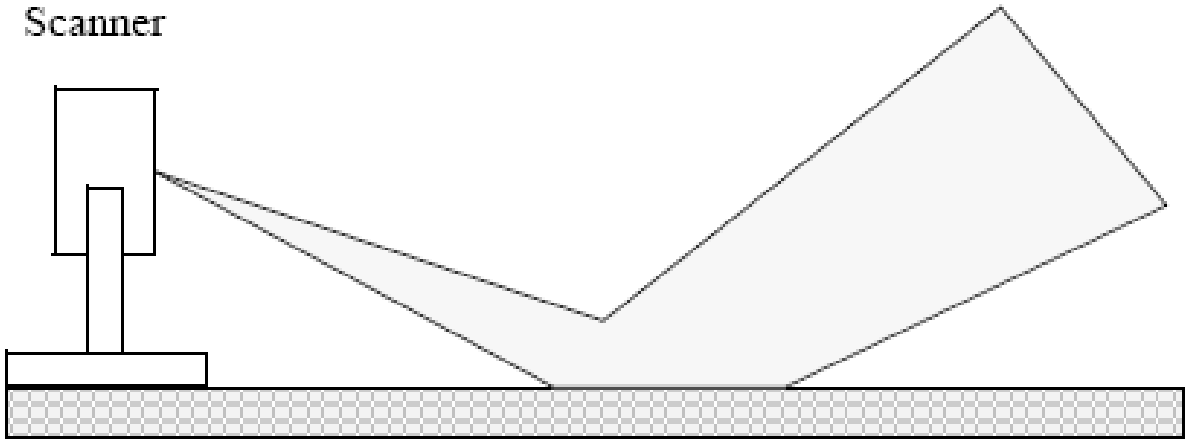
- Range measurements are potentially incorrect at edges in:
  - range
  - reflectance
- Depends on:
  - relative distances, r1, r2
  - instantaneous field of view
  - surface materials (reflection)



measured range depends on mixing parameter
it will NOT be a weighted average if r2-r1 > λ/4

Performance: Specularity

- Laser beam reflects specularly off of some surfaces
- Virtually no energy returned
- Occurs with water, ice and other very smooth surfaces



Performance: Other

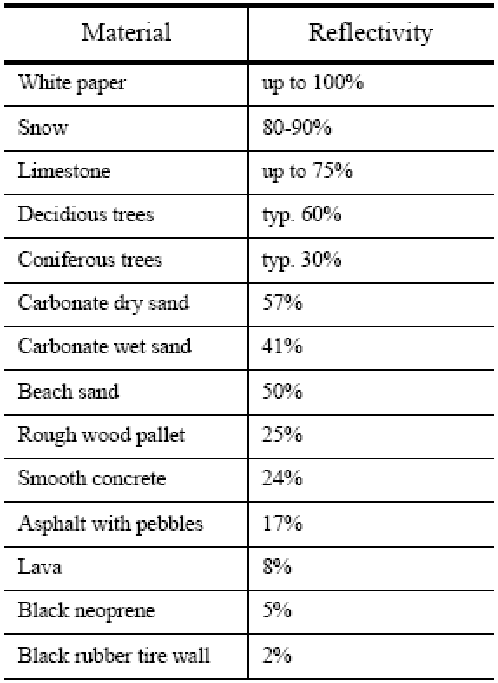
- Configuration:
  - 0D (spot laser)
  - 1D (line scanned)
  - 2D (azimuth, elevation)
- 2D case
  - a fast axis (5 to 75 Hz)
  - a slow axis (1-5 Hz).

- Angular Resolution:
  - Beam dispersions are in the range 0.1 mrad to 10 mrad.
  - This need not relate to pixel spacing but normally it does.
- Range resolution
  - Order of a cm is typical.
  - Some devices use two modulation signals to improve this by a factor of 10.

Performance: Other

- Max Range
  - Depends on reflectivity of “target”
  - Depends on surface roughness, incidence

Table 1: Reflectivities for Several Materials



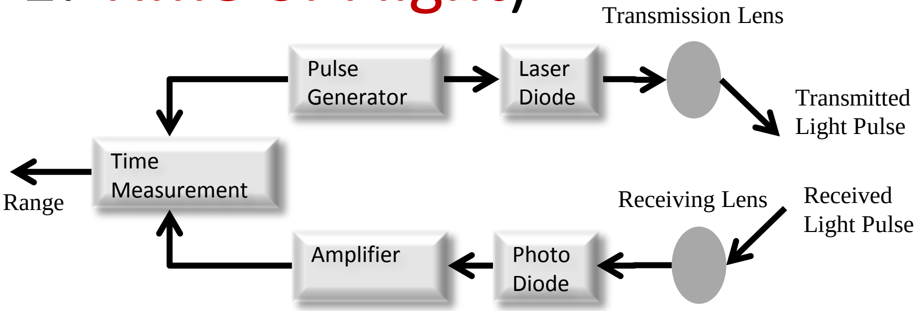
Material	Reflectivity
White paper	up to 100%
Snow	80-90%
Limestone	up to 75%
Decidious trees	typ. 60%
Coniferous trees	typ. 30%
Carbonate dry sand	57%
Carbonate wet sand	41%
Beach sand	50%
Rough wood pallet	25%
Smooth concrete	24%
Asphalt with pebbles	17%
Lava	8%
Black neoprene	5%
Black rubber tire wall	2%

- Pulse Rate:
  - Time-of-flight constraints would permit a pulse rate of 1.5 MHz for a 100 m target
  - Real pulse rates are in the range of 100 to 30,000 pulses/sec. in order to limit laser output power.
  - Maintaining compliance with Class-1 eye-safety regulations generally leads to a reduction in power.

8.3.1.5 Scanning Lidar Implementations

(Implementation 1: Time of Flight)

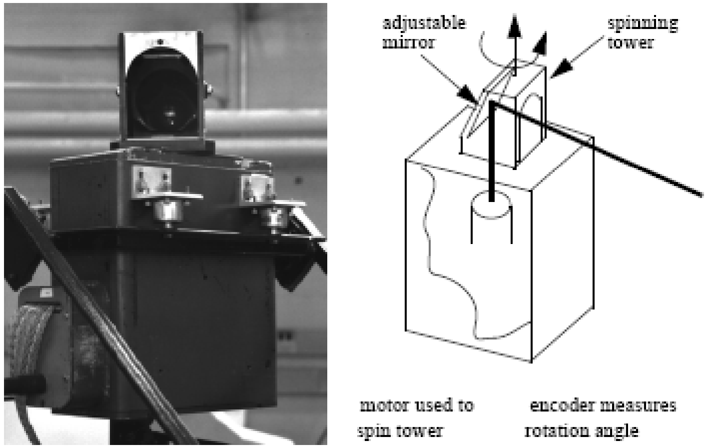
- **Range:** meters to kilometers depending of laser power and application.
- **Performance:** Better accuracy, speed. Improved response on some materials.
- **Limitation:** Detection electronics.
- **Imaging:** Mostly 1-D currently, some 2-D scanners available.
- Commercial systems include Reigl and Schwartz (gone).



Generic Time of Flight Laser Rangefinder

Table 2: Cyclone Performance

Range	up to 50 m
Scanning	1D radial
Resolution	10 cm
Accuracy	15 cm
Rotation Speed	15 scans/sec
Pulse Rate	7200 Hz
Beamwidth	2.5 mrad



Reigl sensor + Custom Mechanism

8.3.1.5 Scanning Lidar Implementations

(Implementation 2: AMCW)

- Reached theoretical performance limit
- Have an ambiguity interval, provide reflectance data
- Existing systems include ERIM, Perceptron, Acuity, Odetics

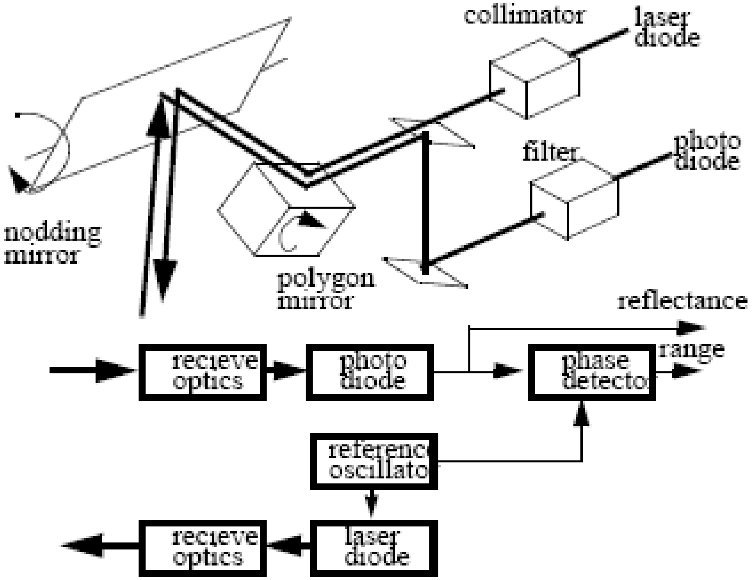
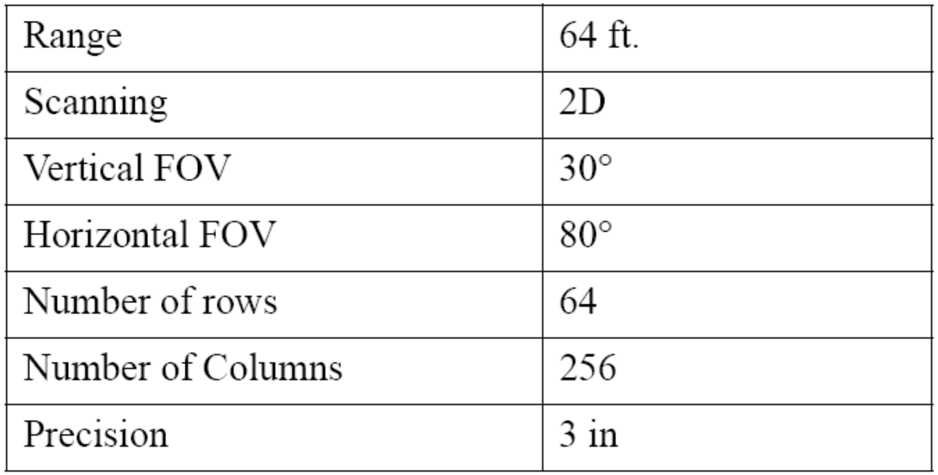


Table 3: ERIM Performance



Range	64 ft.
Scanning	2D
Vertical FOV	30°
Horizontal FOV	80°
Number of rows	64
Number of Columns	256
Precision	3 in

8.3.1.5 Scanning Lidar Implementations

(Implementation 3: FMCW)

- Similar to FM-CW radar
- High accuracy
  - – at cost of long dwell
- Limited depth of field
- High cost (now)
- Complex electronics
- Linearity of frequency ramp is major challenge

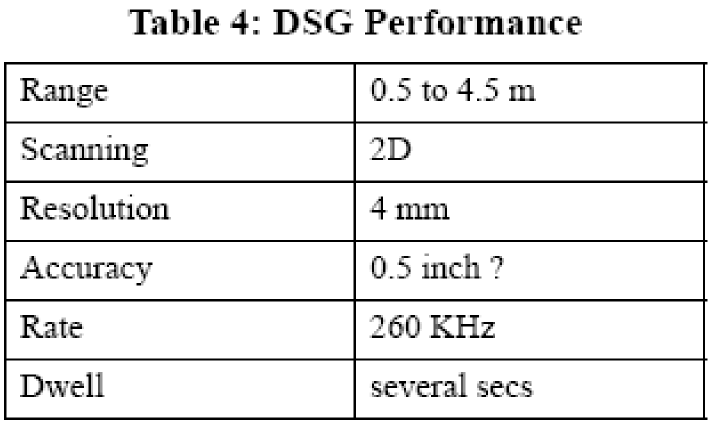


Table 4: DSG Performance

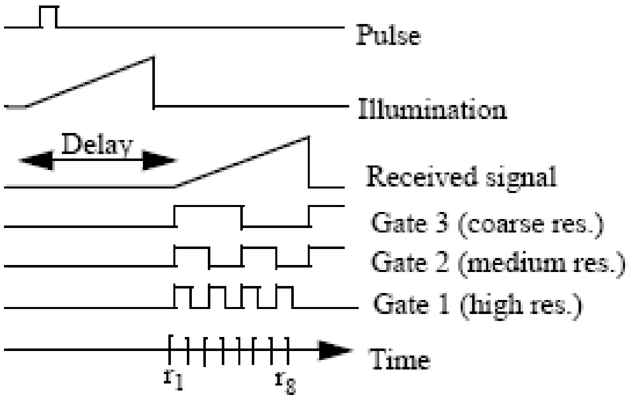
Range	0.5 to 4.5 m
Scanning	2D
Resolution	4 mm
Accuracy	0.5 inch ?
Rate	260 KHz
Dwell	several secs

Digital System Corp. FM-CW Device

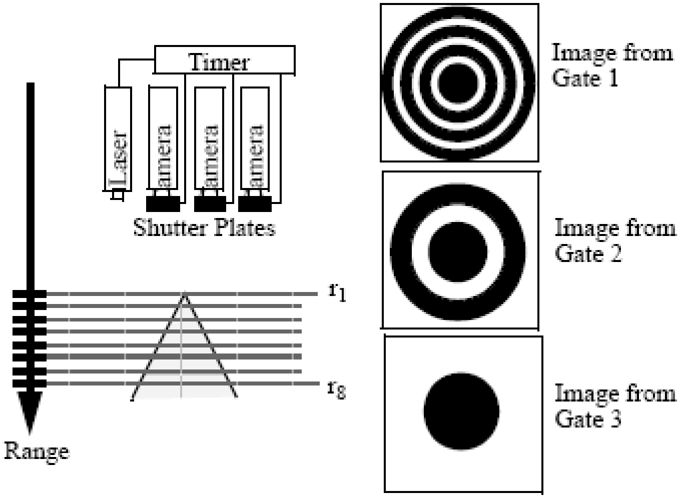
8.3.1.5 Scanning Lidar Implementations

(Implementation 4: Range Gating)

- Achieve imaging without scanning by:
  - Illuminating the whole scene with a narrow pulse
  - Measuring which pixels see a return at each time gate
  - Encoding range as a binary number
- Overcome scanning problems of:
  - synchronization
  - ruggedness
  - maximum scanning speed
  - accuracy
- E.g. Three cameras implementing three gates shown opposite:



Gate Drive Signals

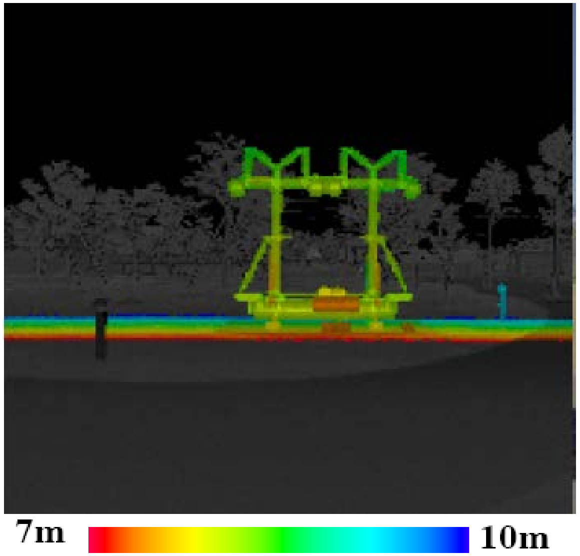


Imagery

8.3.1.5 Scanning Lidar Implementations

(Implementation 5: Colorized)

- Intrinsically registered color and range information.
- Laser pulse rates as high as 30KHz make the effective shutter speed very short.
- Color can only be measured effectively in very bright conditions.
- For LMS Z210, Ladar reflectivity is produced too as a third output



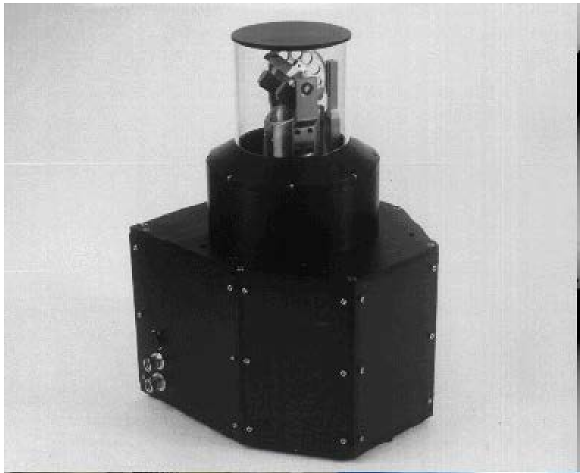
Color-Encoded Range Image (intensity overlayed)

Reigl LMS Z210

8.3.1.5 Scanning Lidar Implementations

(Implementation 6: Vernier)

- Precision mapping devices work hard to get good data slowly.
- The QuantaPoint ladar uses the Z+F vernier rangefinder to produce lots of high precision data.
- Image below is a museum model produced from textured point cloud data.



8.3.1.5 Scanning Lidar Implementations

(Implementation 7: Flash Lidar: Principle)

- A wide beam ("flash") of ladar light illuminates the entire scene, reflected from objects in the scene, and processed by an array of smart pixels in the sensor.
  - In detail, LED array illuminates scene with AM modulated light.
- Custom CMOS chip measures phase shift of returned light (different for each pixel).

8.3.1.5 Scanning Lidar Implementations

(Implementation 7: Flash Lidar: (Dis)Advantages)

Advantages

- First ladar class to be as immune to motion disortion as a visible light camera.
- Optics of typical light cameras can often be used.

Disadvantages

- Highly dispersed flash leads to very low signal levels in returns.
- Dramatic reduction in S/N means reduced maximum range and limited utility outdoors.

8.3.1.5 Scanning Lidar Implementations

(Implementation 7: Flash Lidar: Example: Swiss Ranger

Table 9: Swiss Ranger Specs

Spec	Value
Pixels	160 x 124
Field of View	40 degree FOV (lens dependent)
Dynamic Range	0 to 7.5 meters
Exposure control	electronic shutter
Modulation frequency	20 MHz
Resolution	1 cm
Accuracy	~ 5 cm
Frame Rate	30 fps
Weight	0.2 kg
Dimensions	13 cm x 4 cm x 3 cm
Interface	USB 2.0

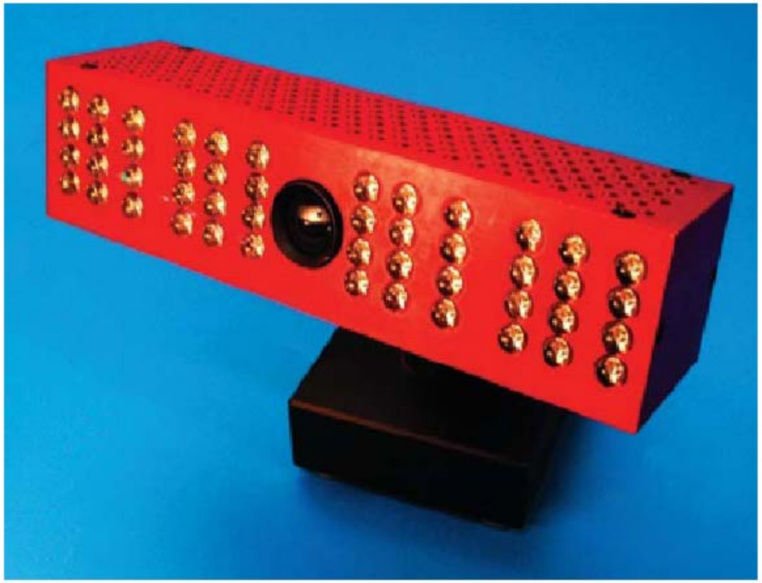


Figure 14 Flash Ladar: Swiss Ranger SR2 minature 3D time-of-flight camera.

Outline

- 8.3 Sensors for Perception
  - 8.3.1 Laser Rangefinders
  - 8.3.2 Ultrasonic Rangefinders
  - 8.3.3 Visible Wavelength Cameras
  - 8.3.4 Mid to Far Infrared Wavelength Cameras
  - 8.3.5 Radars
  - Summary

8.3.2 Ultrasonic Rangefinders
(SONAR)

- SOund Navigation and Ranging (SONAR)
- Originally developed for underwater applications
- Despite obvious biological success stories (bats, dolphins), progress with sonar use has been disappointing.
- Most commercial sonars are TOF devices despite theoretical availability of more sophisticated alternatives

8.3.2 Ultrasonic Rangefinders

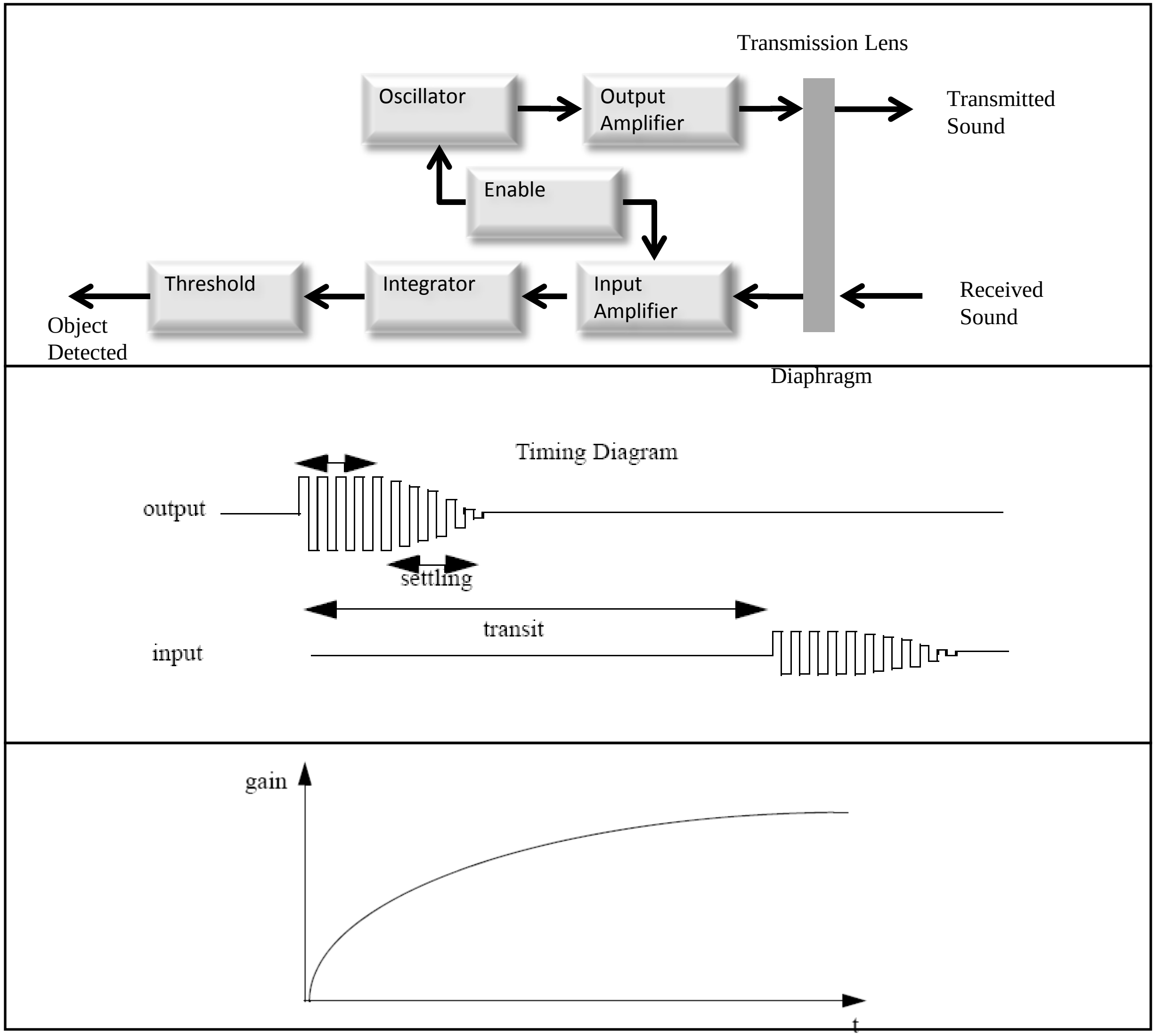
(SONAR)

- Difficult to use, problems include:
  - wide beamwidth (10-30 degrees) + sidelobes
  - slow wave speed
  - high attenuation
  - high standoff + reduced max range
  - specular reflections + multipath
  - environmental interference
- why use ‘em at all?
  - real cheap, simple, light weight, low power
  - good for obstacle avoidance
    - sometimes hi res data is more a burden

8.3.2.1 Principles

(Electrostatic Acoustic Transducer)

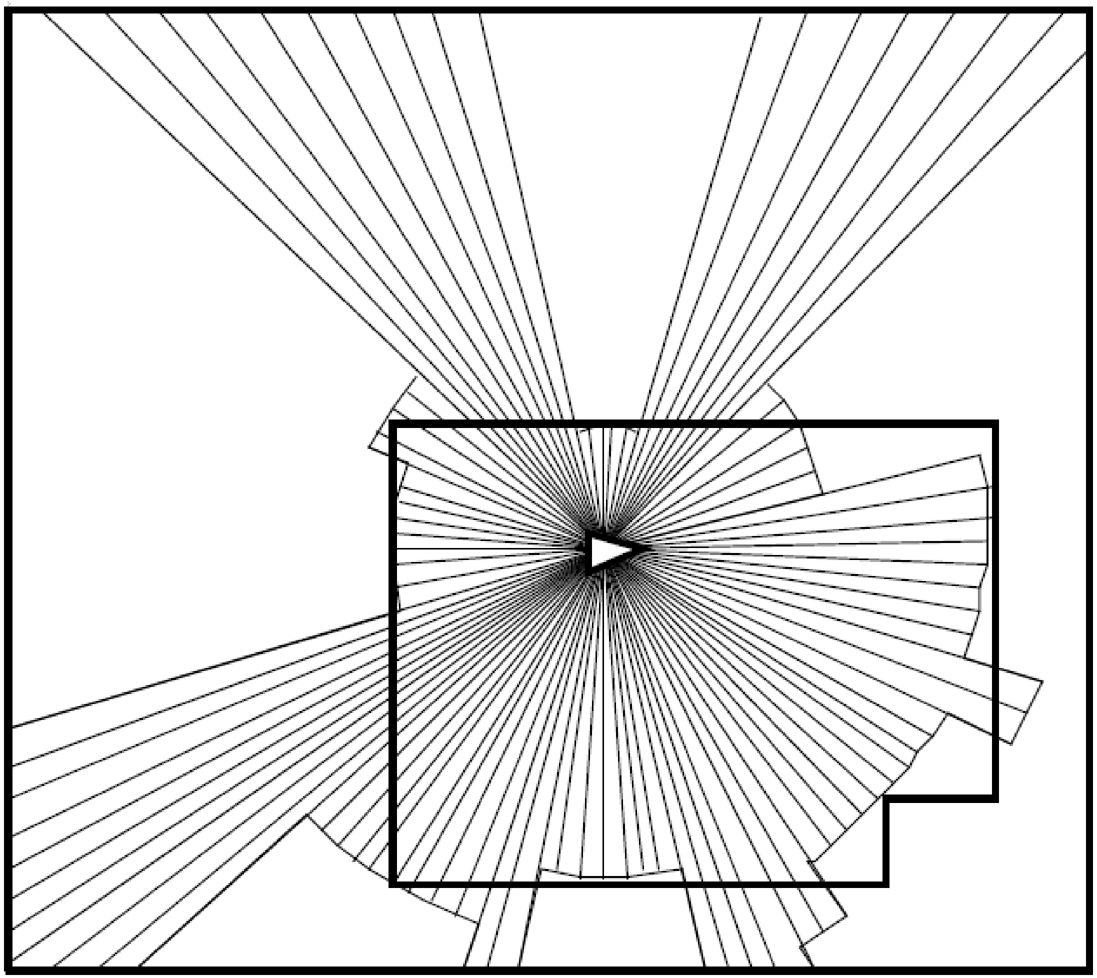
- Device operates as both loudspeaker and microphone
- Timing
- Functional block diagram …
- Input must be boosted in a predictable fashion to account for:
  - spreading loss
  - attenuation



8.3.2.2 Performance

(Typical Sonar Scan)

- Sonar distortion is a fact of life



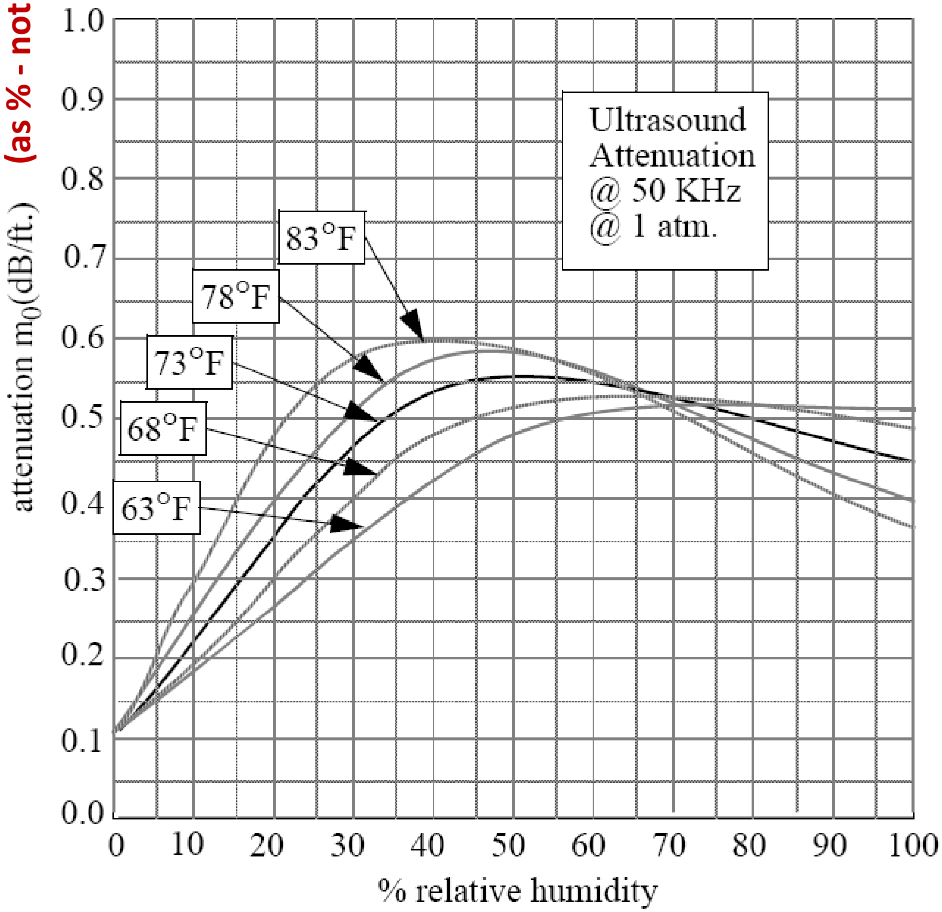
8.3.2.2 Performance

(Maximum Range)

- Governed by attenuation
- About 3 dB/ft (check graph) of total path length.
- This requires a 60 dB sensor dynamic range to measure 20 ft range.

$$I = I_0 e^{-m_0 r} \quad \text{(ignoring spreading)}$$

$$I = 10\log I_0 - 4.343 m_0 r$$



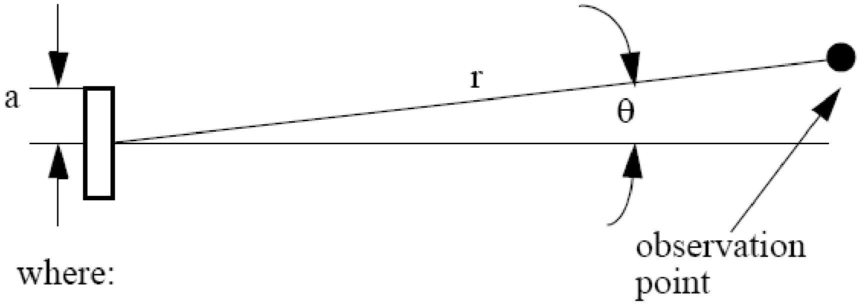
(as % - not in dB)

8.3.2.2 Performance
(Angular Precision)

- Governed by by aperture of sensor, and wavelength.
- Piston model tells the whole story; gives far field intensity produced by cylindrical piston set in infinite baffle.

$$I_s = \frac{P_0}{r^2} \times \left(\frac{J_1(ka\sin\theta)}{ka\sin\theta} \right)^2$$

$$P_0 = \frac{\rho_0 \times \omega^2 \times a^4 \times U_0^2}{2 \times c_0}$$



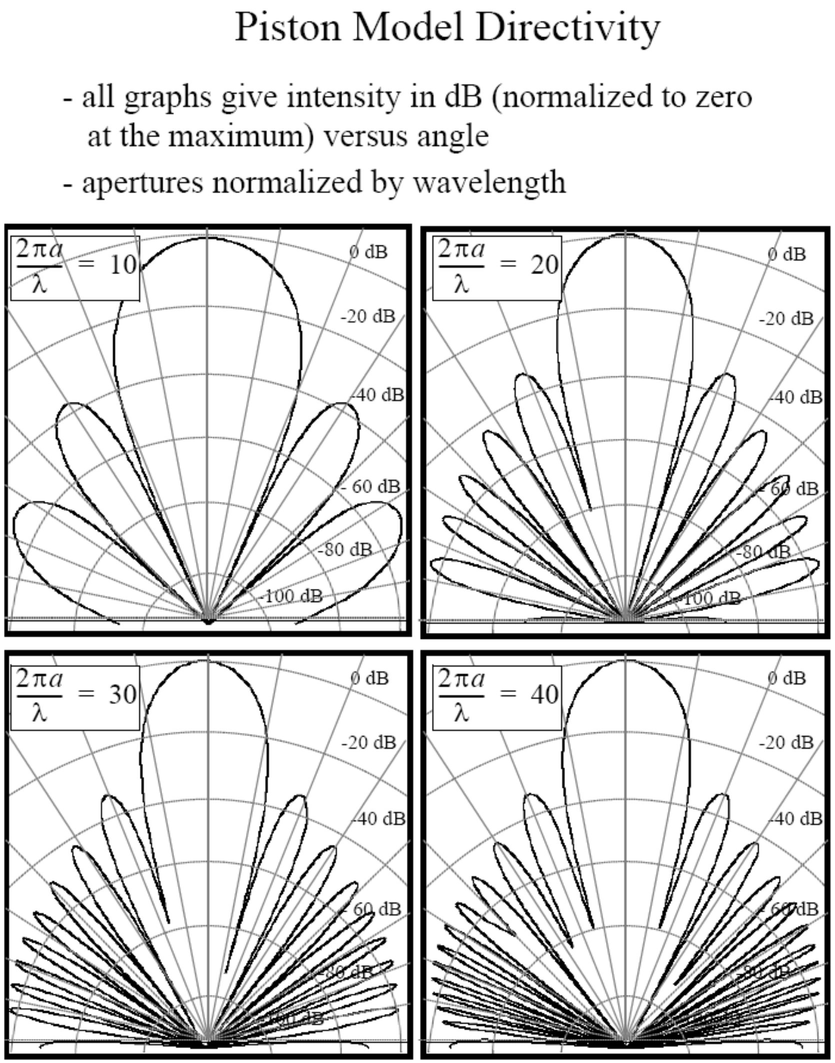
where:

J1 is the Bessel function of the first kind of order one
k is the wave number $k=2\pi/\lambda$
θ is the angle that the observer ray makes with acoustic axis
U_0 is the velocity amplitude of oscillation
a is the radius of the piston
ω is the frequency of oscillation
ρ_0 is the mean density
c_0 is the wave speed
r is the distance

8.3.2.2 Performance

(Angular Precision)

- Intensity versus angle for any antenna is typically given with a directivity plot as shown below



Piston Model Directivity

- all graphs give intensity in dB (normalized to zero at the maximum) versus angle
- apertures normalized by wavelength

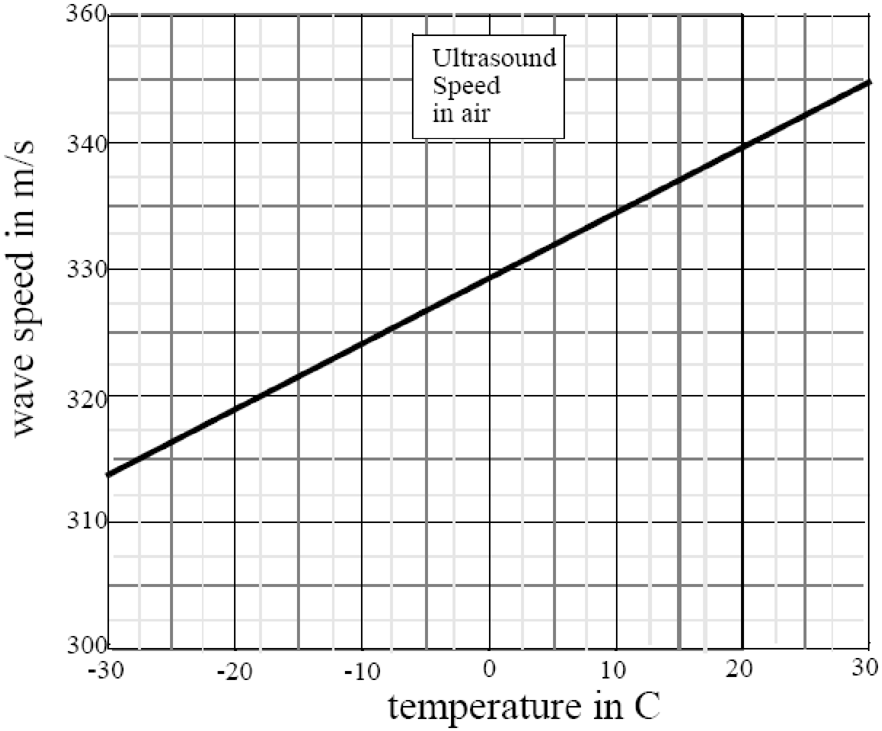
8.3.2.2 Performance

(Range Accuracy)

- Governed by speed of sound variation with environmental parameters and sensor electronics
- ±5 % speed variation over ambient extremes

$$c = 331.4\sqrt{T/273} \approx 331.4 + 0.607\Theta$$

c is speed of sound in m/s
T is ambient temp in K
Θ is ambient temp in C



8.3.2.2 Performance

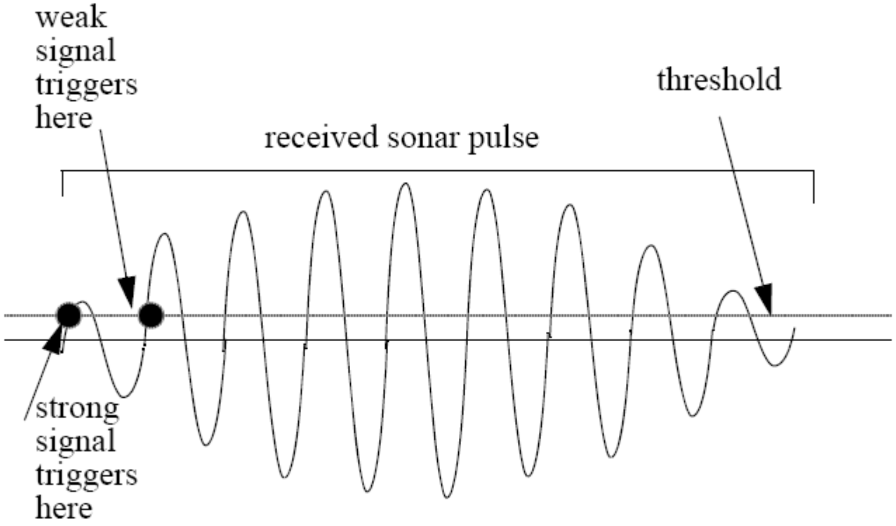
(Other)

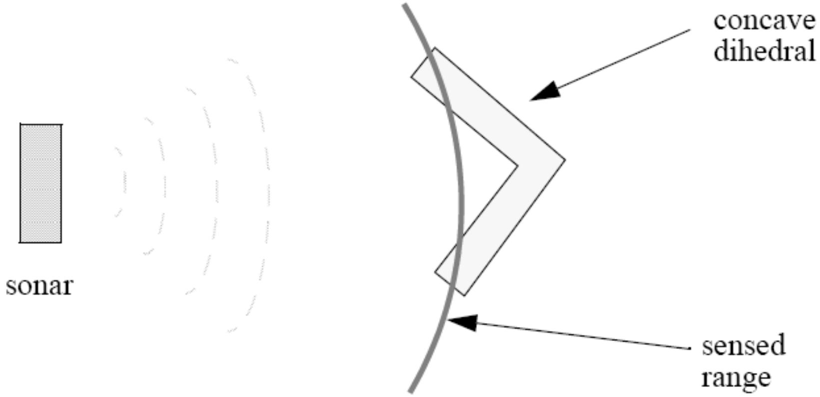
- Standoff
  - Governed by pulse width (1 ms typ.) and diaphragm/crystal mechanical damping (1 ms typ.); these numbers give 2 ft. standoff
- Measurement Frequency
  - Governed by speed of sound; for 20 m = 60 ft. depth of field, readings can be taken at about 8 Hz.

8.3.2.2 Performance

(Range Precision)

- Intrinsic precision governed by <u>carrier wavelength</u>.
- Mixed pixels due to poor angular precision is a more real issue.
- At longer ranges, spreading and attenuation loss create limits.

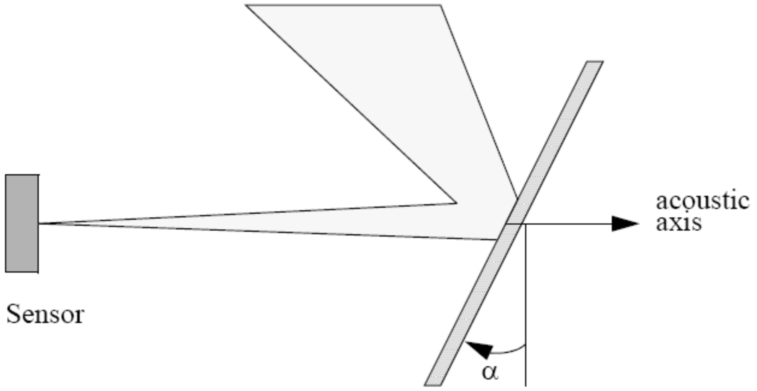




8.3.2.2 Performance

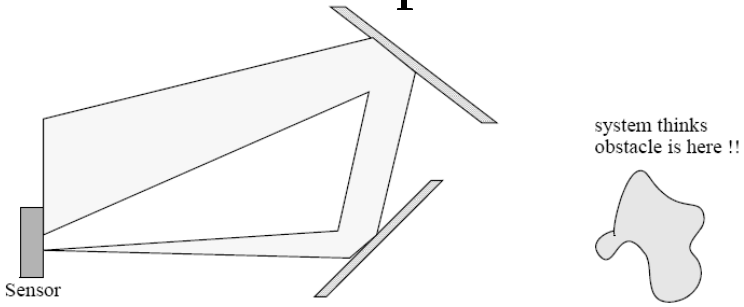
(Specularity and Multipath)

Specularity



- Most man-made objects reflect ultrasound specularly.
- Virtually no energy returned from specular reflectors unless aligned with normal.

Multipath



- Can give rise to hallucinations, and collisions - if you don’t account for it
- Corners can reflect sidelobes.

8.3.2.3 Implementations

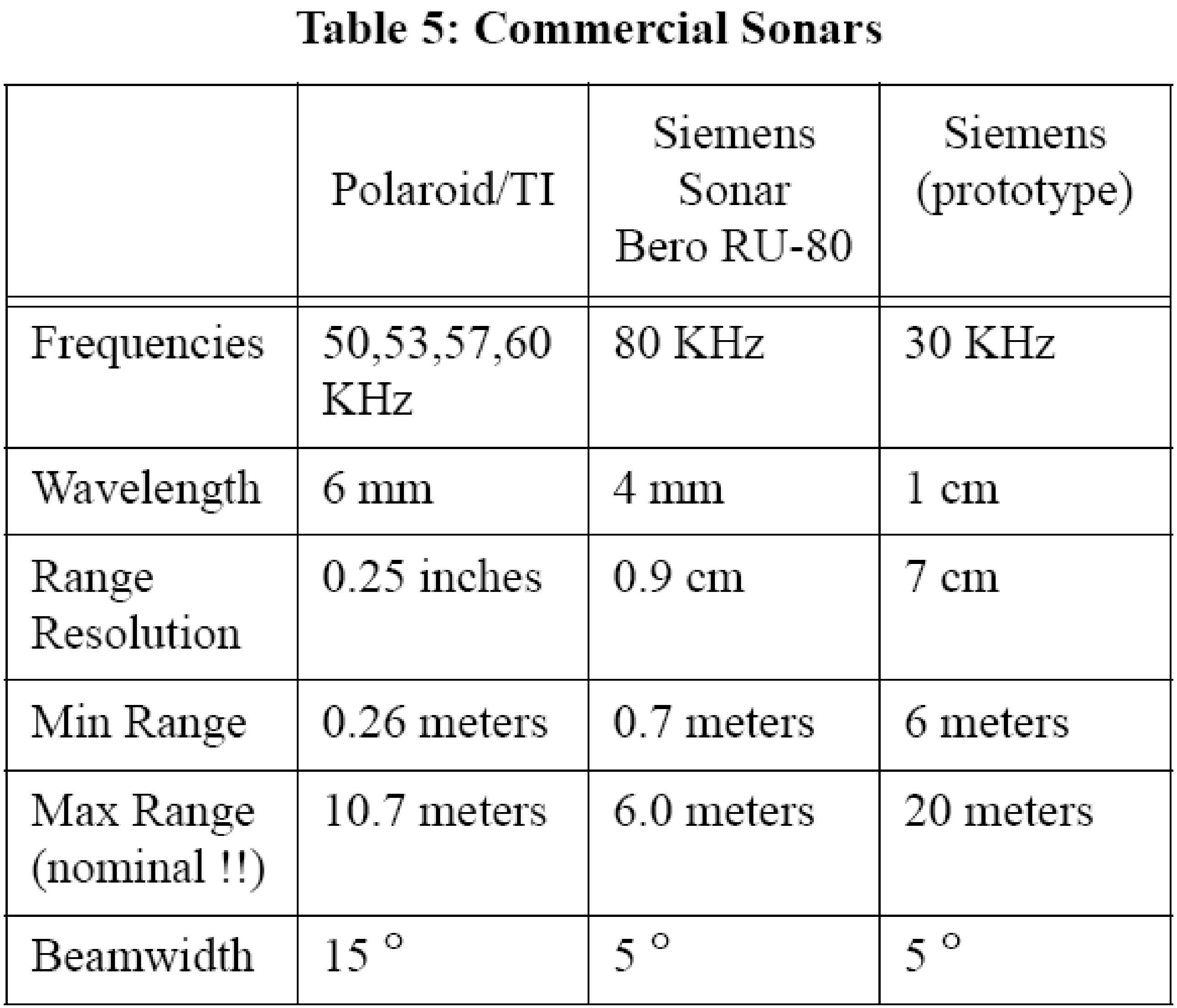


Table 5: Commercial Sonars

	Polaroid/TI	Siemens Sonar Bero RU-80	Siemens (prototype)
Frequencies	50,53,57,60 KHz	80 KHz	30 KHz
Wavelength	6 mm	4 mm	1 cm
Range Resolution	0.25 inches	0.9 cm	7 cm
Min Range	0.26 meters	0.7 meters	6 meters
Max Range (nominal !!)	10.7 meters	6.0 meters	20 meters
Beamwidth	15 °	5 °	5 °

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Visible Cameras

- Workhorse of computer vision.
- Most significant pragmatic issue is the quality (intensity, uniformity) of lighting.

8.3.3.1 Principles of Operation

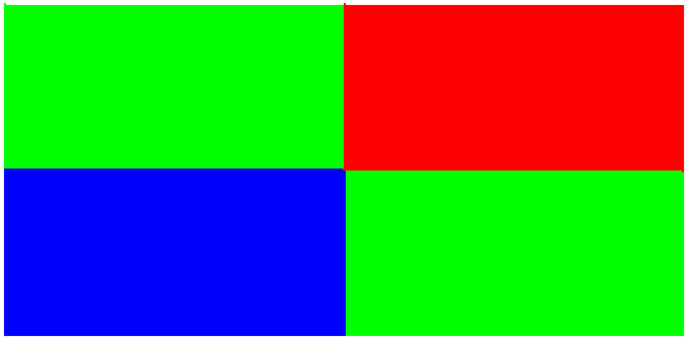
(Monochrome CCD)

- Overall process is:
  - Collection. Photons emitted by environmental objects are collected by an array of sensing elements.
  - Photoelectric effect. Sensing material emits an electron when struck by a photon.
  - Storage. The liberated electrons accumulate in capacitors in each pixel.
  - Readout. Pixel charges are shifted one at a time to a special capacitor whose voltage (proportional to charge) is read and amplified.
- Quantum Efficiency:
  - CCD Cameras respond to 70% of incoming light
  - Photographic films have an efficiency of 2%.
- Hence, astronomers like CCDs → so do night vision people.

8.3.3.1 Principles of Operation

(Color CCD)

- Digital color cameras generally use a Bayer mask (filter) over the CCD.
- Each square of four pixels has one filtered red, one blue, and two green.
- Because the human eye is most sensitive to green (forest dwellers?).



Beyer Mask

8.3.3.1 Principles of Operation
(CMOS)

- CMOS (Complementary Metal Oxide Semiconductor) camera technology uses the same manufacturing techniques as integrated circuits.
  - These device don’t even use metal anymore. They use a material called polysilicon but the name has stuck.
  - Makes it possible to incorporate signal conditioning (and computing) directly into the sensing elements.
  - Needed for increased noise of CMOS but situation is improving. Limits fill factor compared to what would otherwise be very high densities. 4 Megapixels is common today though.
- Low power consumption because power is only used when transistors switch between on and off states.
- They do the charge-to-voltage conversion at each pixel.

8.3.3.1 Principles of Operation

(CCD vs CMOS)

- Differences in technology lead to differences in responsivity, dynamic range, signal-to-noise ratio, shuttering, capture speed, and uniformity.
- CCD sensors tend to have:
  - a higher dynamic range
  - better signal-to-noise ratio
  - better shuttering
- CMOS sensors tend to have:
  - slightly better responsivity
  - significantly better capture speeds (order of magnitude).
- One other important difference is that most CMOS cameras have rolling shutters, which can lead to image distortion due to motion.

8.3.3.2 Optics and Sensor Control Features

(Auto Iris Lens)

- The iris of a lens is an adjustable diaphragm that controls the amount of light passing through the lens (i.e., controls the aperture size).
- Similar in principle to gain control but the iris directly alters the light level on the sensor array.
- An auto iris lens includes a circuit that enables automatic adjustment of aperture size according to varying light levels (intended to maintain a constant image).
- Two types:
  - Video Auto Iris: Lens takes a raw video signal and generates a dc signal to drive the aperture.
  - Direct Auto Iris: Lens takes a dc signal (which something else generated from video or other light level sensing).

8.3.3.2 Optics and Sensor Control Features

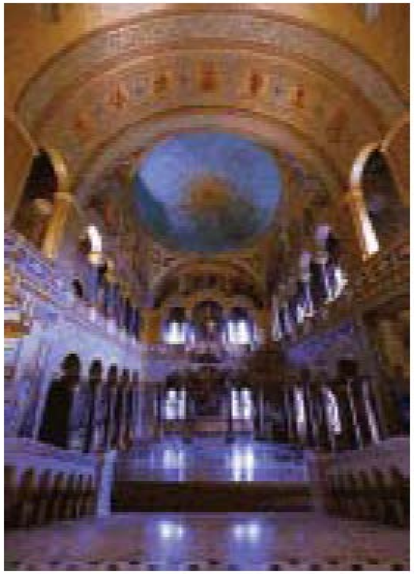
(Electronic Iris)

- Mimics the capabilities of an auto iris lens by adjusting the shutter speed rather than the aperture size to control the amount of light that strikes the sensor array.
  - Has implications for motion distortion.

8.3.3.2 Optics and Sensor Control Features

(Auto White Balance)

- Most light sources are somewhat colored. The off-whiteness is often called color temperature.
  - Color shifted toward the red is high color temperature.
  - Color shifted toward blue is low color temperature.
  - Candlelight produces light with a color temperature of 1500K, whereas sunny midday daylight is about 5500K
- Show the camera something white and toggle the auto white balance and it will compensate.
- In principle allows you to develop color aware algorithms independent of lighting but beware in practice.



Whites in left image are bluish.

Corrected in right image.

8.3.3.2 Optics and Sensor Control Features

(Lenses and Mirrors)

- Lens is usually a separate module. Specifications of interest include:
  - Focal length (determines field of view)
  - CCD format supported (size of chip)
  - auto/manual iris
  - auto/manual focus
- Interesting part is the lens distortions and how to correct them.
- Panoramic imagery has a lot of good attributes for mobile robots

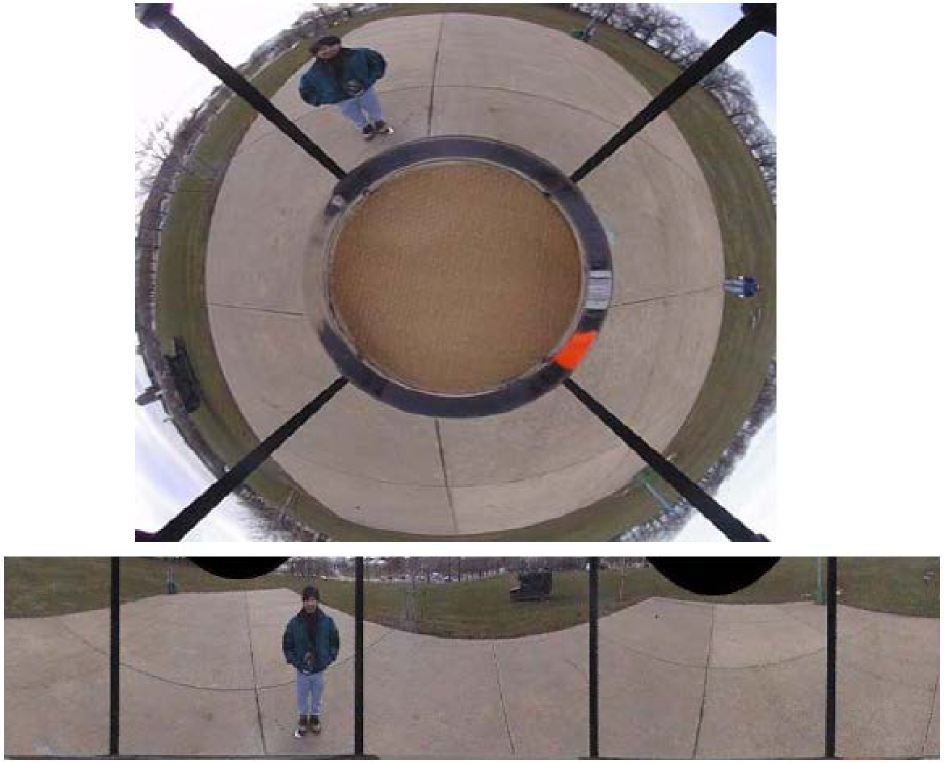


Figure 9 Panoramic Imagery. Using modes of the mirror geometry, the raw image at the top can be warped into a rectangular panorama as shown below.

8.3.3.4 Performance

(Minimum Illumination Level)

- Minimum level of light needed to achieve 50% or 100% video output level when the camera is set to maximum gain and the lens iris is completely open
- Usually measured in Lux, the SI unit of measure for the amount of light intensity at the surface that the light source is illuminating.

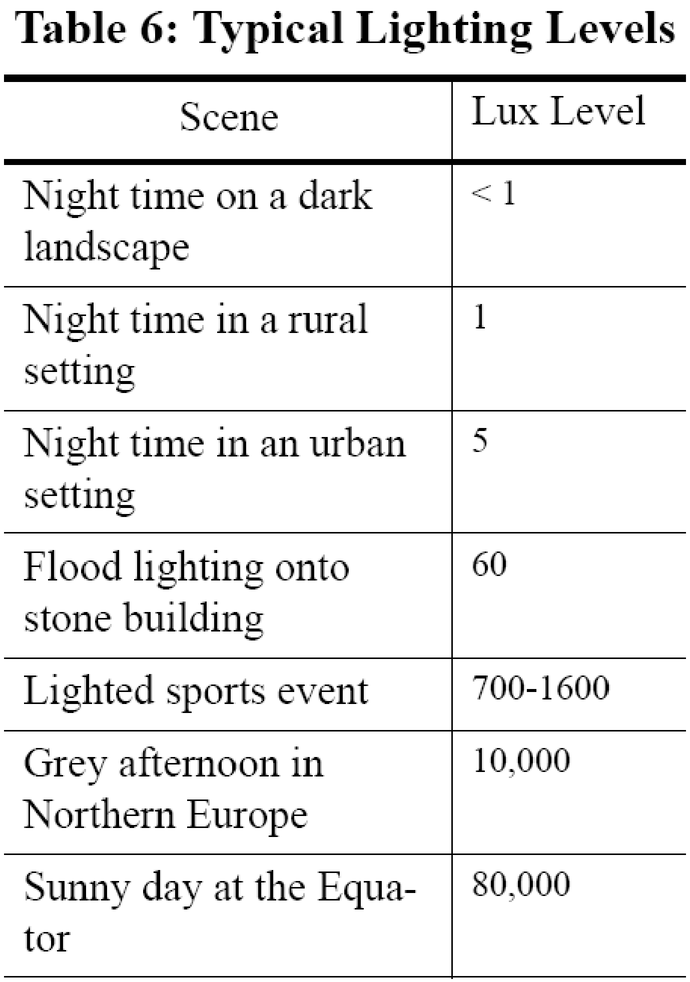


Table 6: Typical Lighting Levels

Scene	Lux Level
Night time on a dark landscape	< 1
Night time in a rural setting	1
Night time in an urban setting	5
Flood lighting onto stone building	60
Lighted sports event	700-1600
Grey afternoon in Northern Europe	10,000
Sunny day at the Equator	80,000

8.3.3.4 Performance

(“Resolution”)

- A measure of how fine of detail the camera can image, expressed in the number of horizontal and vertical pixels in an image.
- Standard values include:
  - 640 X 480 (VGA,Television)
  - 800 X 600 (SVGA)
  - 1024 X 768 (XVGA)
  - 1280 X 960 (1 Mpixel), 2048 X 1536 (3 Mpixel),
- There is a difference between the number of effective pixels and the resolution of the output of the camera.
- The latter can be constrained by how the data is transferred: for example, in the IEEE 1394 standard, there is no definition for an image of 1300 x 1030 pixels, so the nearest, smaller value would be used, i.e., 1280 x 960.

8.3.3.4 Performance

(Responsivity)

- The amount of signal the sensor outputs per unit of input optical energy.
- The responsivities of cameras are characterized by response curves, which plot the responsivity for different wavelengths of light.

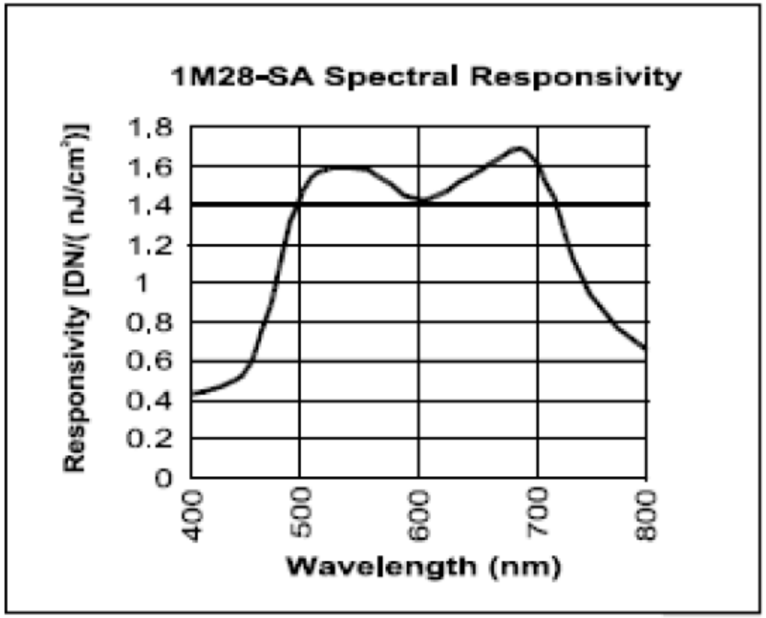
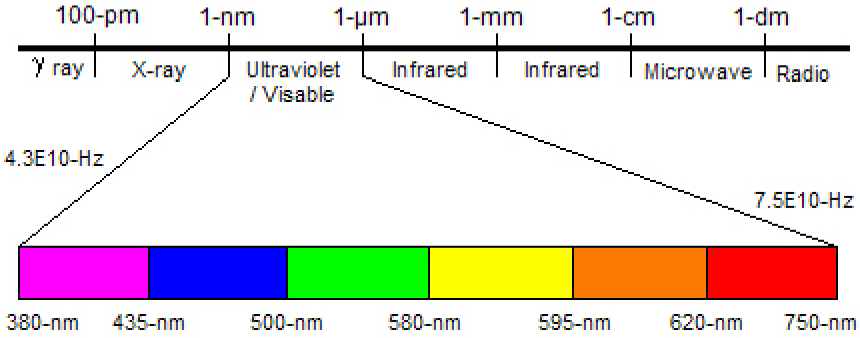


Figure 8 Responsivity. This is the responsivity curve for a modern megapixel CMOS camera.



8.3.3.5 Lighting and Motion Issues

(Lighting)

- S/N: Cameras generally do not have sufficient S/N to operate at night.
- Dynamic Range: Bright and dark patches cannot be viewed at once.
- Nonconstancy over time has several lines of attack.
  - Normalization algorithms. But they reduce S/N.
  - AGC amplifies noise as well as signal.
  - Electronic iris can introduce motion blur by slowing down the iris too much.
  - Autoiris is better than all above when you can get it.

8.3.3.5 Lighting and Motion Issues

(Motion Blur)

- Due to motion of the camera or of objects within the scene while the camera is collecting a snapshot.
  - Fast shutter speeds help to ameliorate this problem.
  - Interlaced cameras that collect an image one field at a time are more prone to motion blur (between the fields) regardless of shutter speed.
    - Dropping one field is an expedient in low res applications.

Other Issues

- High intensity regions in an image bleed charges outside their boundaries to adjacent pixels.
- CMOS sensors intrinsically handle blooming quite well, and CCDs are getting better.

Outline

- 8.3 Sensors for Perception
  - 8.3.1 Laser Rangefinders
  - 8.3.2 Ultrasonic Rangefinders
  - 8.3.3 Visible Wavelength Cameras
  - <u>8.3.4 Mid to Far Infrared Wavelength Cameras</u>
  - 8.3.5 Radars
  - Summary

8.3.4 Mid to Far IR Cameras

- Also known as IR cameras and FLIR (Forward Looking Infrared) cameras. The “forward looking” part does not mean much anymore.
- A recent technology breakthrough makes it feasible to generate thermal imagery at video rates in a handheld device running on a few AA batteries.
- Mainly developed by US defense researchers for use in missiles.
  - Expensive ($30K) and still sold by only a handful of companies.
  - US: TI, Raytheon
  - Britain: BAe
  - Japan: Mitsubishi, NEC
- Technology is evolving rapidly. 1/2 Million units per year sold in 2004.
- CCDs do not sense midrange and far IR energy, so exotic materials are used:
  - HgCdTe (Mercury-Cadmium-Telluride)
  - InSb (Indium Antimonide) - cooled
  - Platinum Silicide - cooled

8.3.4 Mid to Far IR Cameras

(IR Spectrum)

- Infrared region is defined as that region with wavelengths
  - longer than visible light
  - but shorter than microwave.
  - i.e. 1300 to 14,000 nm

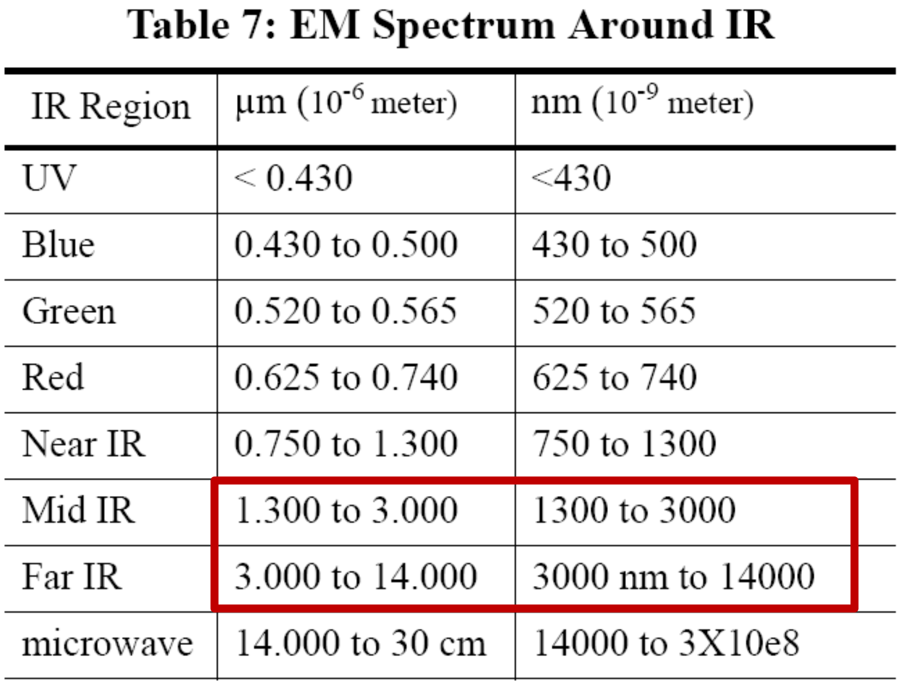


Table 7: EM Spectrum Around IR

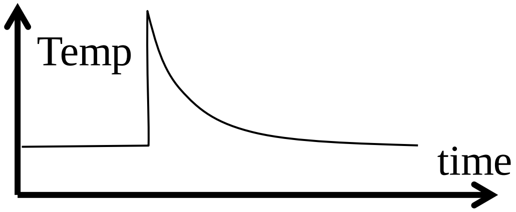
IR Region	μm (10^{-6} meter)	nm (10^{-9} meter)
UV	< 0.430	<430
Blue	0.430 to 0.500	430 to 500
Green	0.520 to 0.565	520 to 565
Red	0.625 to 0.740	625 to 740
Near IR	0.750 to 1.300	750 to 1300
Mid IR	1.300 to 3.000	1300 to 3000
Far IR	3.000 to 14.000	3000 nm to 14000
microwave	14.000 to 30 cm	14000 to 3X10e8

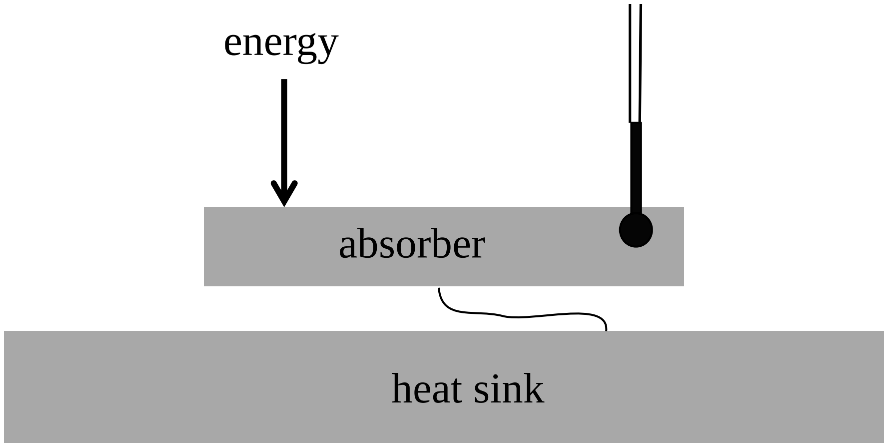
8.3.4.1 Principles

- A bolometer is a device for measuring thermal (or total) power. Invented in 1860 by American scientist Samuel Pierpont Langley.
- While cameras are based on the photoelectric effect, IR cameras are based on the photothermal effect - the production of heat in response to light absorption.
- This is the best known detector principle in the far-infrared to submillimeter wavelength range.
- Detectors often have at least two components:
  - A sensitive thermometer - usually a thermistor.
    - A resistor made of semiconductors having resistance that varies rapidly and predictably with temperature
  - A high cross section absorber.

8.3.4.1 Principles

- Radiation heats the active part of the bolometer (absorber) whose temperature increases.
- The temperature is measured by the thermometer.
- The absorbed heat is slowly drained to the heat sink





8.3.4.3 Implementations (Microbolometer)

- Microbolometers were developed by Honeywell on a classified MEMS project in the 1980s.
- Before this, IR imaging was based on photon detectors which typically operate at cryogenic temperatures (–200 C).
- The basic idea is to use silicon microfabrication techniques to make an isolated thermal structure with very little heat capacity.
- Ideally, to get the most sensitive possible instrument, you want:
  - A small heat input to cause a large temperature change.
  - A small temperature change to cause a large resistor change.

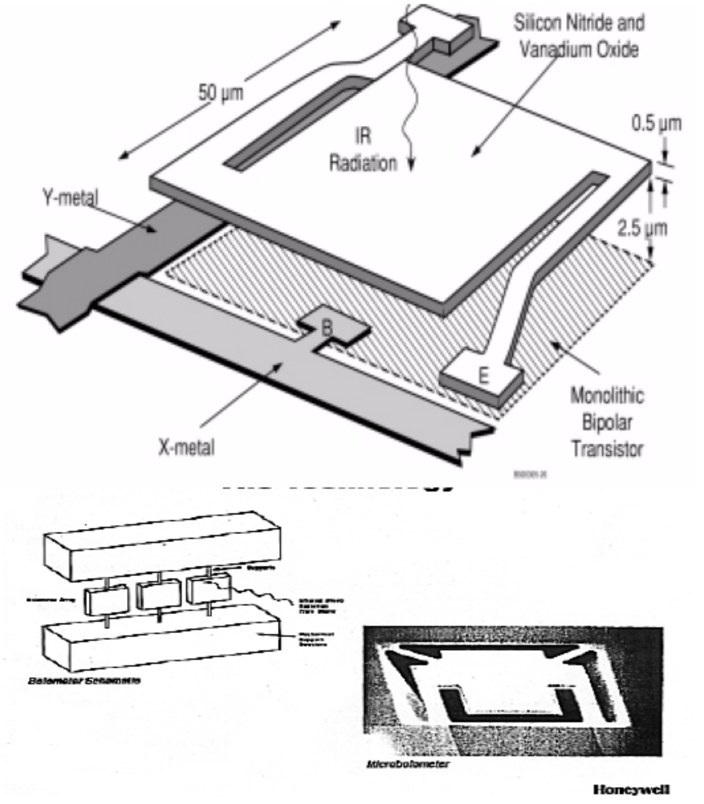


Figure 12 Microbolometer Pixel and Array. This one has a pixel pitch of 50 µm.

8.3.4.3 Implementations

(Focal Plane Arrays)

- A <u>matrix</u> of bolometer detectors is referred to as a focal plane array (FPA).
- FPA resolutions these days are:
  - low: 160 x120
  - med: 320 x 240
  - high: 640 x 480
- Resolution: Typically 10 to 14 bits.
  - Often the sensor S/N is the more limiting factor and the LSBs are just noise anyway.

8.3.4.2 Advantages & Disadvantages

- Operate in <u>total darkness</u> because they respond to thermal energy emitted by objects.
- Completely passive.
- In many situations, the heat sources are the objects of interest (vehicles, people).
- Very good discrimination of living plants (chlorophyl).

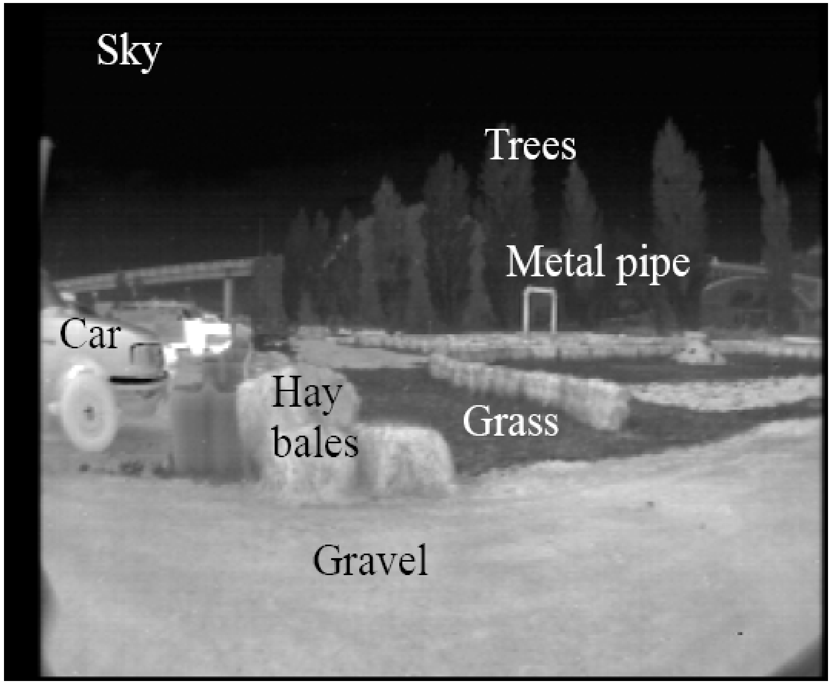


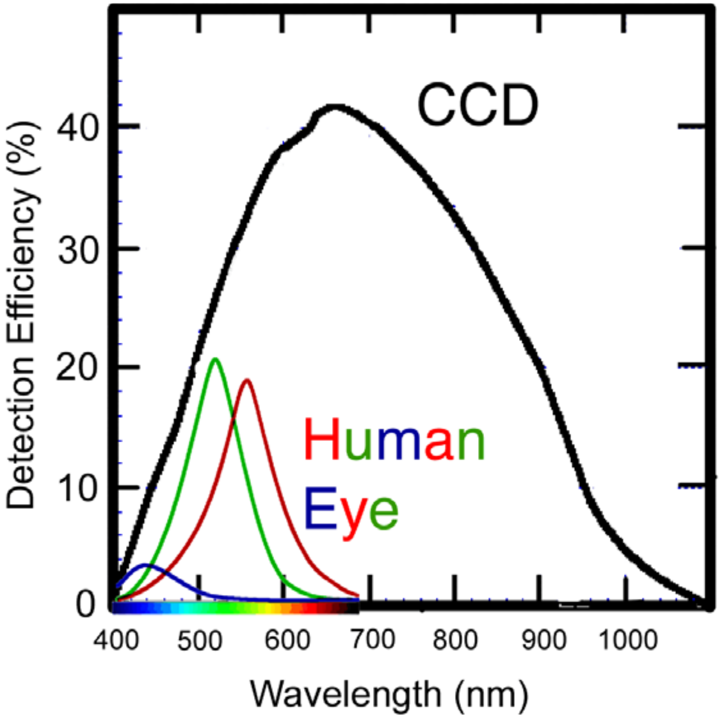
Figure 10 Thermal Imagery. An example of an infrared image taken in a total darkness using the Indigo Merlin Uncooled Far-Infrared Camera.

Cooled or Uncooled

- An important distinction is whether your bolometer is cooled or uncooled.
- Cooled sensors are much more sensitive because a small temperature change then produces a big change in resistance.
- However, cooled devices require a large package and a lot of power.
- Uncooled systems can be made very compact and low power.

Cameras as IR Sensors

- Silicon-based (CCD and CMOS) image sensors are equally sensitive to visible and NIR wavelengths out to about 1200 nm.
  - Remove the “IR cut” filter from a camera to get a near IR camera.
  - Add an “IR filter” to pass only the IR and get spooky imagery.



Real IR Cameras (Mid to Far IR)

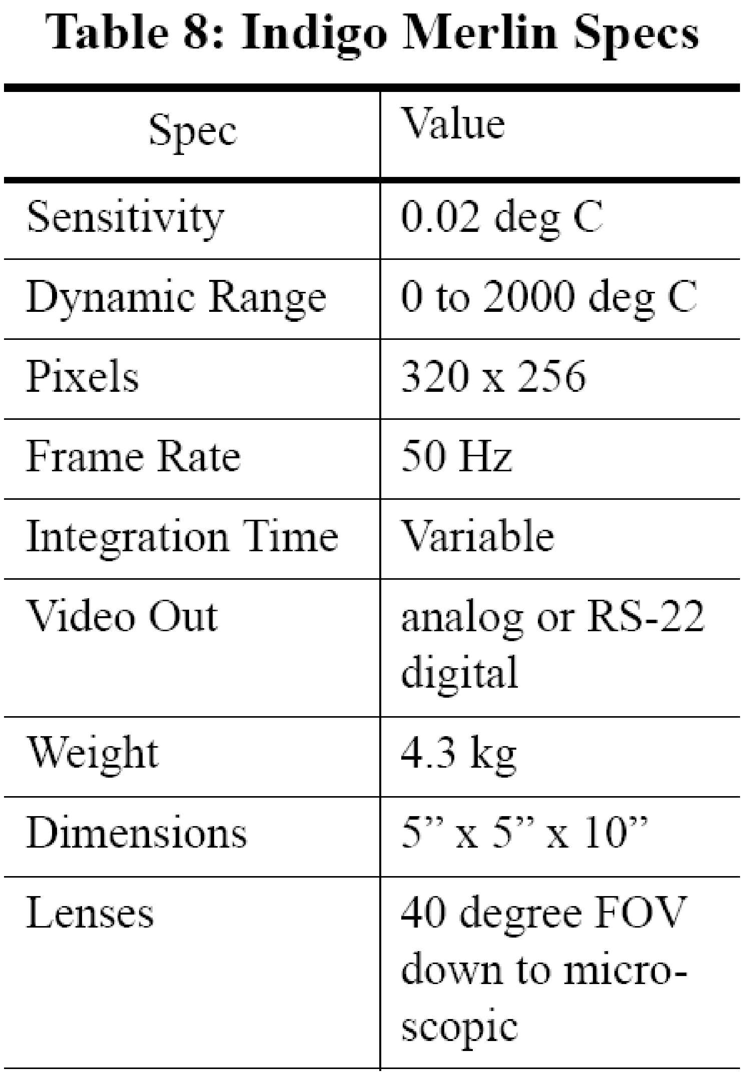


Table 8: Indigo Merlin Specs

Spec	Value
Sensitivity	0.02 deg C
Dynamic Range	0 to 2000 deg C
Pixels	320 x 256
Frame Rate	50 Hz
Integration Time	Variable
Video Out	analog or RS-22 digital
Weight	4.3 kg
Dimensions	5” x 5” x 10”
Lenses	40 degree FOV down to micro-scopic

Figure 13 Infrared Camera: FLIR Systems Indigo Merlin .

Disadvantages

- Motion distortion due to rolling shutter.
- Lower resolutions than visible light cameras.
- Require continuous calibration to get accurate temperatures.
- Depend on thermal contrast
  - Difficulty in an area where the whole scene has the same temperature.
  - Difficulty at the two times of day (diurnal crossovers) where temperatures of two scene spots are equal.
- Time constants in the 100 msec range.
  - This leads to motion blur (and associated loss of texture in imagery).

Outline

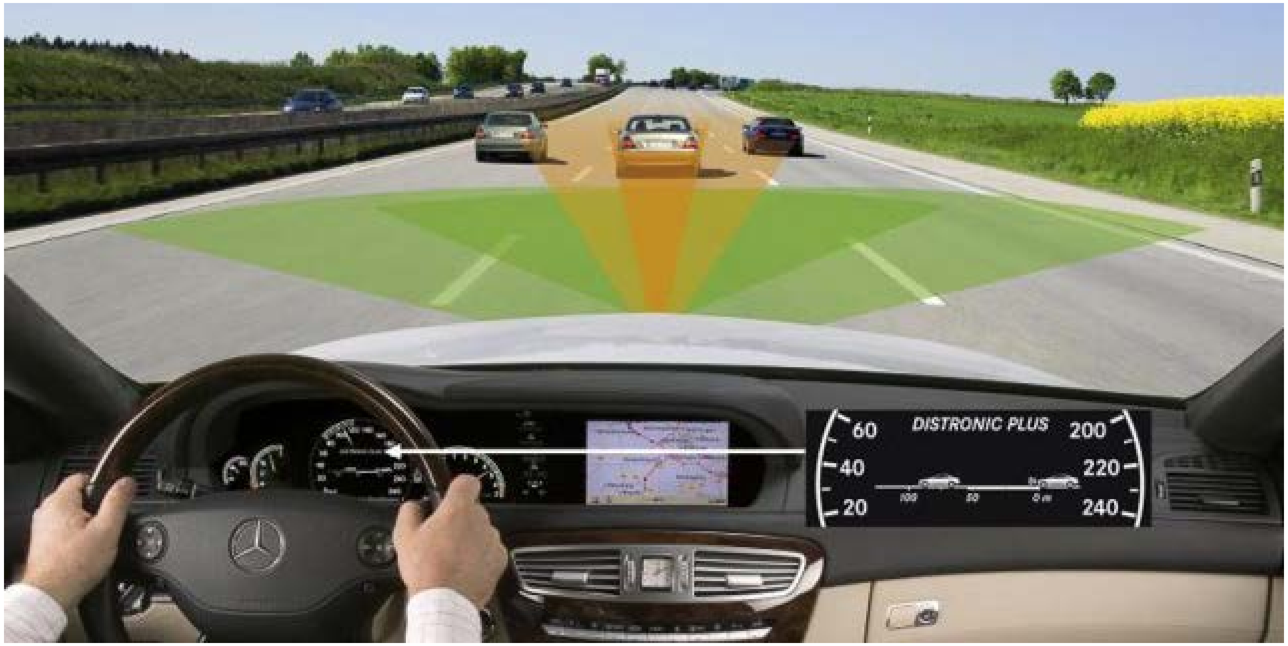
- 8.3 Sensors for Perception
  - 8.3.1 Laser Rangefinders
  - 8.3.2 Ultrasonic Rangefinders
  - 8.3.3 Visible Wavelength Cameras
  - 8.3.4 Mid to Far Infrared Wavelength Cameras
  - <u>8.3.5 Radars</u>
  - Summary

8.3.5 Radars

- Acronym for RAdio Detection And Ranging.
- Can be used for low resolution mapping, obstacle detection, and as landmarks in mobile robots.
- Similiar to sonar in terms of issues
  - wide angle beam
  - coarse range and angular resolution
  - (+) fast obstacle detection
  - many materials are absorbtive
  - specularity, side lobes, multi-path

8.3.5 Radars

(Automotive)



- The automotive industry is driving development and production of radar for use in advanced cruise control systems (blind spot monitoring and driver warning).
- These radar systems are low cost and physically robust.
- Commercial systems do not yet have the resolution and discrimination to work well as a human detection systems.

8.3.5.1 Principles

- Pulsed TOF and FM-CW are common.
- FM-CW are more common due to simpler circuitry.
- FMCW has the ability to measure the <u>velocity</u> of the target as well as the <u>range</u>.
- Specifically when c is the speed of light, f_0 is the center frequency, f_m is the modulation frequency and Δf is the maximum frequency deviation:

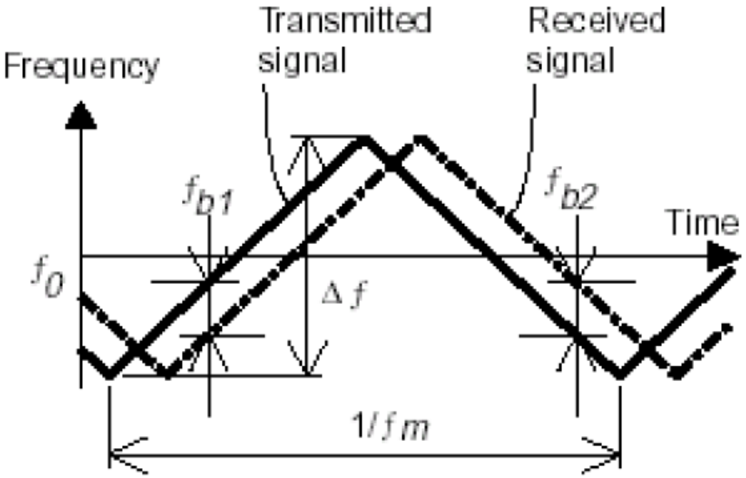


Figure 15 FM CW Radar frequency-time relationship.

$$R = \frac{(f_{b1}+f_{b2})c}{8f_m\Delta f}$$

$$V = \frac{(f_{b2}-f_{b1})c}{4f_o}$$

8.3.5.2 Performance

(Resolution)

- Angular:
  - 10-15 degrees beamwidth is typical.
  - Some millimeter wave radars are as thin as 2-3 degrees.
- Downrange:
  - Limited by pulsewidth. A large pulse width is easier to generate and detect, but it limits downrange resolution.
  - For FMCW, depends on ability to resolve small changes in beat frequencies, which requires a very stable and linear voltage controlled oscillator (VCO) and a low noise receiver.

8.3.5.2 Performance

(Effect of Frequency)

- Frequency affects penetration, resolution, and physical antenna size.
- Higher frequencies / smaller wavelengths lead to better downrange and angular resolutions and smaller packages at the expense of penetration capability.

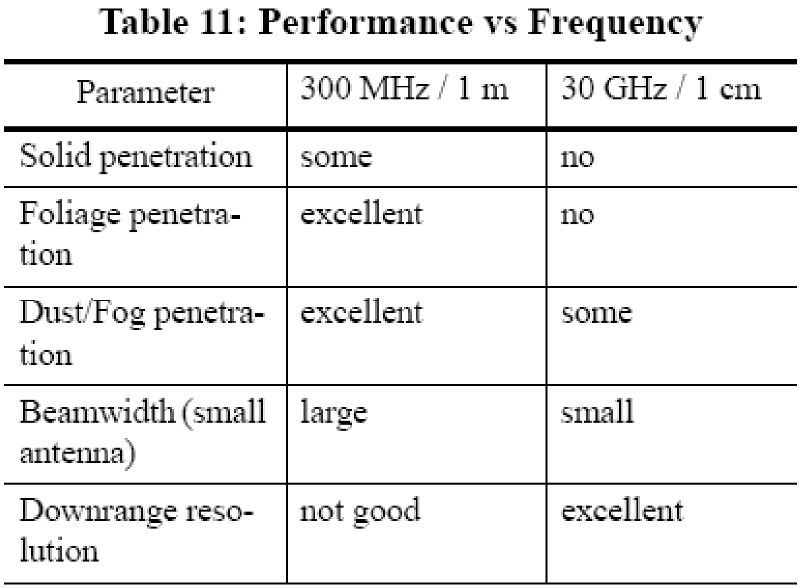


Table 11: Performance vs Frequency

Parameter	300 MHz / 1 m	30 GHz / 1 cm
Solid penetration	some	no
Foliage penetration	excellent	no
Dust/Fog penetration	excellent	some
Beamwidth (small antenna)	large	small
Downrange resolution	not good	excellent

8.3.5.2 Performance

(What is Visible to Radar)

- Reflected power depends on object properties:
  - – Radar cross section (RCS)
  - – Dielectric ratio
- The cross section is conceptually the projected area of the target onto a plane normal to the incident radar beam.
- In practice, it is more complicated. Real surfaces have texture which scatters the reflected wave in random directions.
  - – The RCS is low for a smooth metal surface at nonnormal incidence.

8.3.5.2 Performance

(What is Visible)

- Radar reflections happen at discontinuities in dielectric constant.
- The signal return ratio is proportional to the ratio of dielectric constants of the two media. It can be incorporated into the radar equation.
- Because most natural scenes do not contain metals, radar returns tend to be associated with changes in water content.
- Human tissues have a much lower dielectric constant (by 1-2 orders of magnitude) than metal.

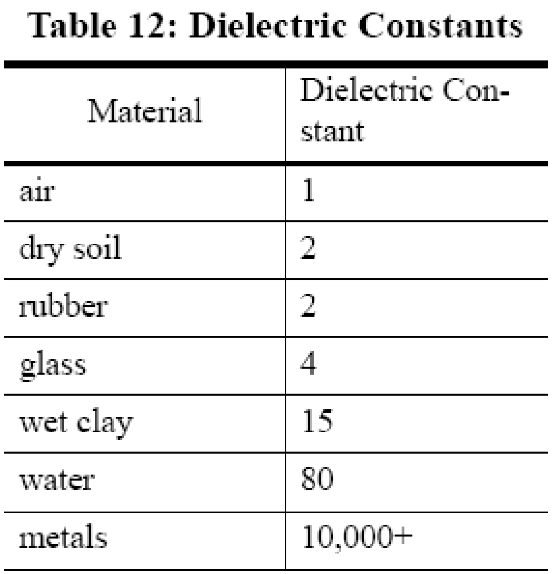


Table 12: Dielectric Constants

Material	Dielectric Constant
air	1
dry soil	2
rubber	2
glass	4
wet clay	15
water	80
metals	10,000+

8.3.5.3 Advantages and Disadvantages

(Advantages)

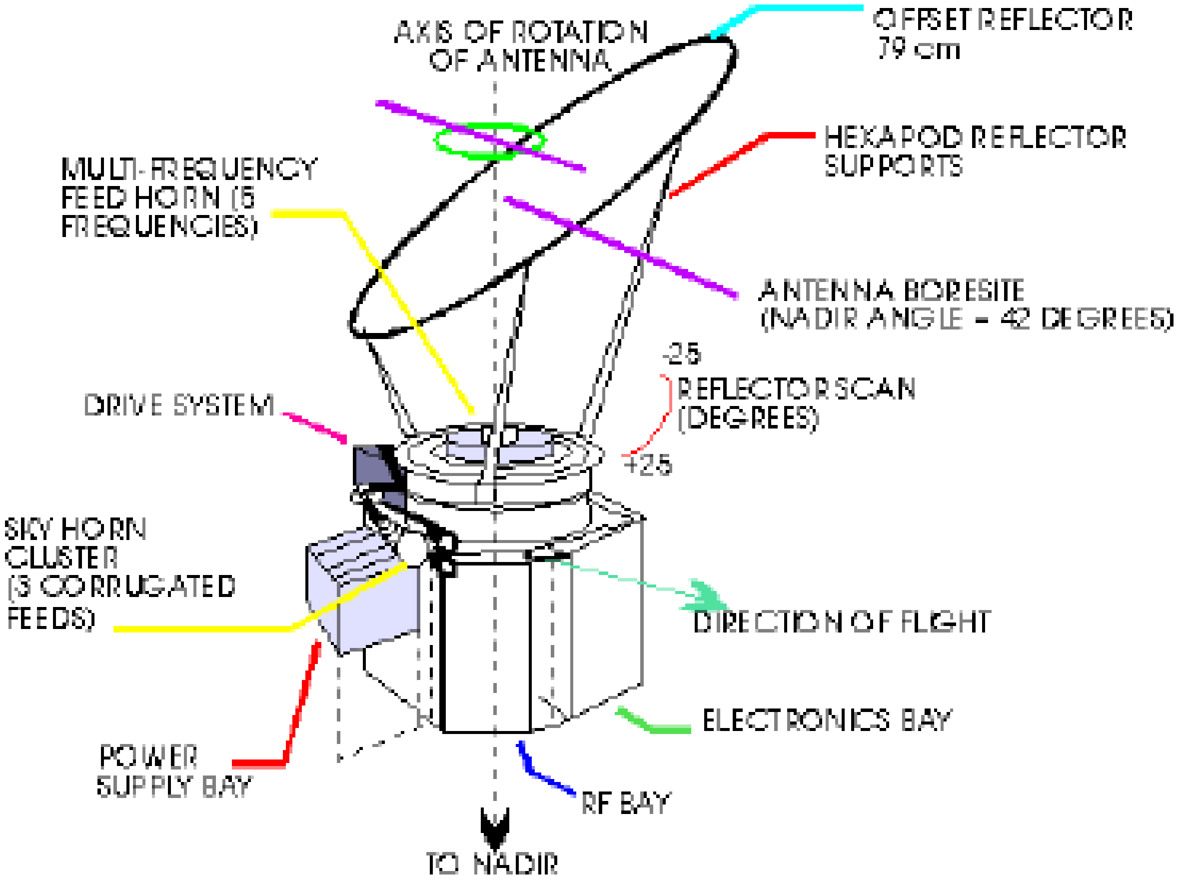
- Radar can be designed to be hard to detect (e.g wideband looks like noise).
- All-weather sensor.
  - Dust and fog penetration capability is excellent.
  - Performance doesn't depend on lighting conditions.
- Measures both range and range rate.
- Wide beams mean fast obstacle detection.
- Can use polarization measurements to discriminate different target characteristics.
- Transducers (antenna) can be made very robust compared to ladar transducers (optics).

8.3.5.3 Advantages and Disadvantages

(Disadvantages)

- Cross-range and down-range resolutions are relatively poor when compared with a ladar.
- Specularity:
  - Detection depends largely on the target's surface orientation and material.
  - Multipath problems if the target geometry is complex.
- Radar is an active device which can be detected using a suitable receiver.
- Large sized transducers (antenna) compared to ladar.
- Many materials are absorbtive

8.3.5.4 Implementations
(Radar Scanning)



JPL Nimbus 7 Scanning Radiometer

8.3.5.4 Implementations

(Example)

- Specs for General Microwave AM Sensor
  - Frequency: 10 GHz
  - Accuracy +/- 1 inch
  - Max Range: 50 ft
  - Beam: 30-80 degrees wide (antenna dependent)

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Summary

- Various forms of noncontact environmental sensors exist - ladar (lidar).
- Lidar is very narrow beam, great angular and range resolution, noninstantaneous scan. Its hard to generate more than 100KHz from a single transmitter-reciever. Nonscanning “Flash” ladar is coming along.
- Sonar is generally very wide beam. Sound propagation has unique properties and issues. Poor resolution is usually a difficulty but occasionally its useful. Same for radar.
- Today, both ladar and radar usually have complicted, slow, mechanical scanning systems.
- Although radar signals are notoriously hard to understand, they are almost all we have when the weather is bad.