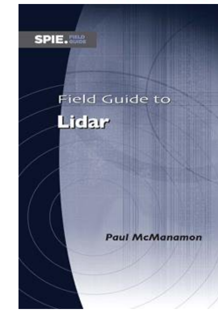
Lidar Technology and Systems

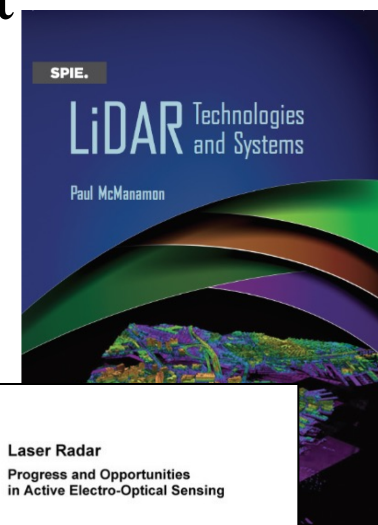
Dr. Paul McManamon

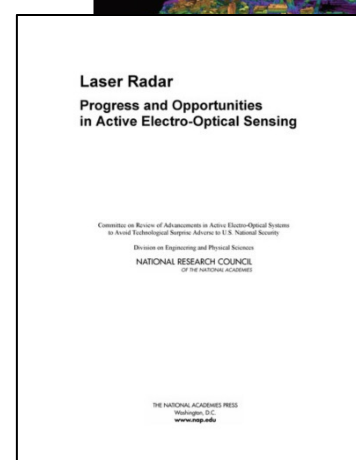
SPIE FELLOW OSA FELLOW MSS FELLOW IEEE FELLOW FELLOW FELLOW AIAA ASSOCIATE FELLOW

Some References (1)

- Lidar Technologies and Systems – Paul McManamon.
- Field Guide for Lidar – Paul McManamon
- National Academy of Sciences, NAS, Report
  - http://www.nap.edu/catalog.php?record_id=18733
  - Laser Radar: Progress and Opportunities in Active Electro-Optical Sensing (2014)
- Review article on ladar (Paul McManamon, June 2012, Optical Engineering)
- Introduction to Laser Radar by Al Jelalian
  - Older book, mostly CO_2 ladar







Some References (2)

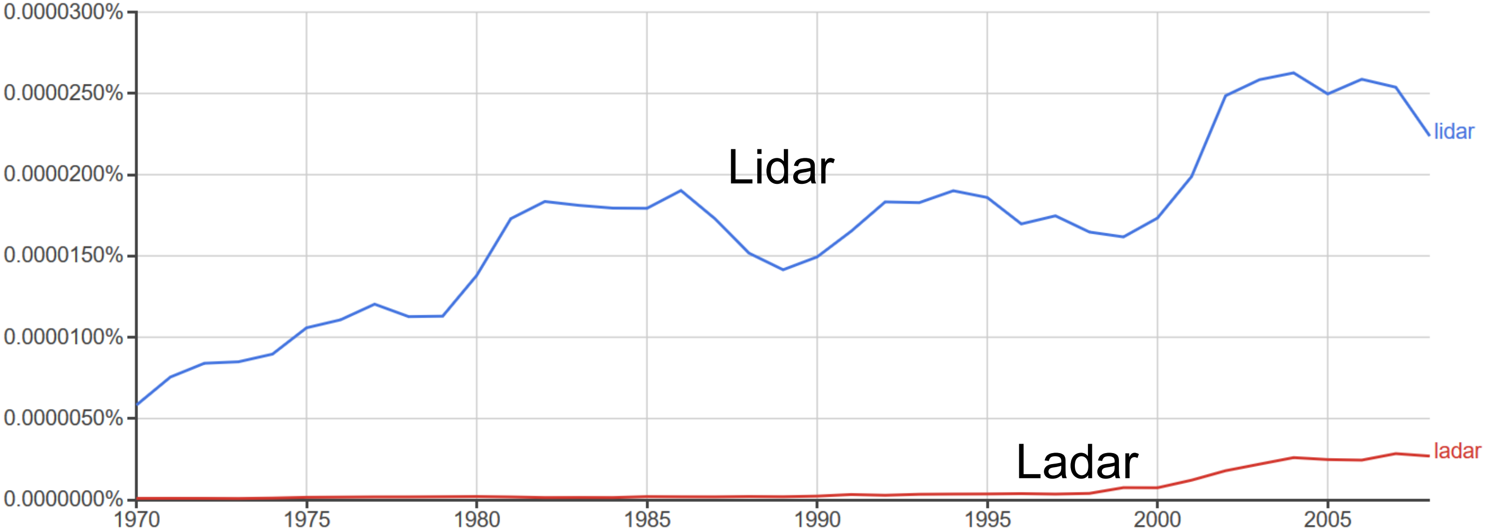
- InGaAs Avalanche Photodiodes for Ranging and Lidar Huntington, Andrew Huntington
  - Very good on LMAPDs
  - Optical Detection Theory for Laser Applications by Greg Osche
    - Fairly comprehensive on detection
- Laser Remote Sensing by Takashi Fujii and Tetsuo Fuluchi
    - Chapter 7 by Sammy Henderson is from p469 to p722
- Direct detection LADAR Systems
  - Richmond and Cain

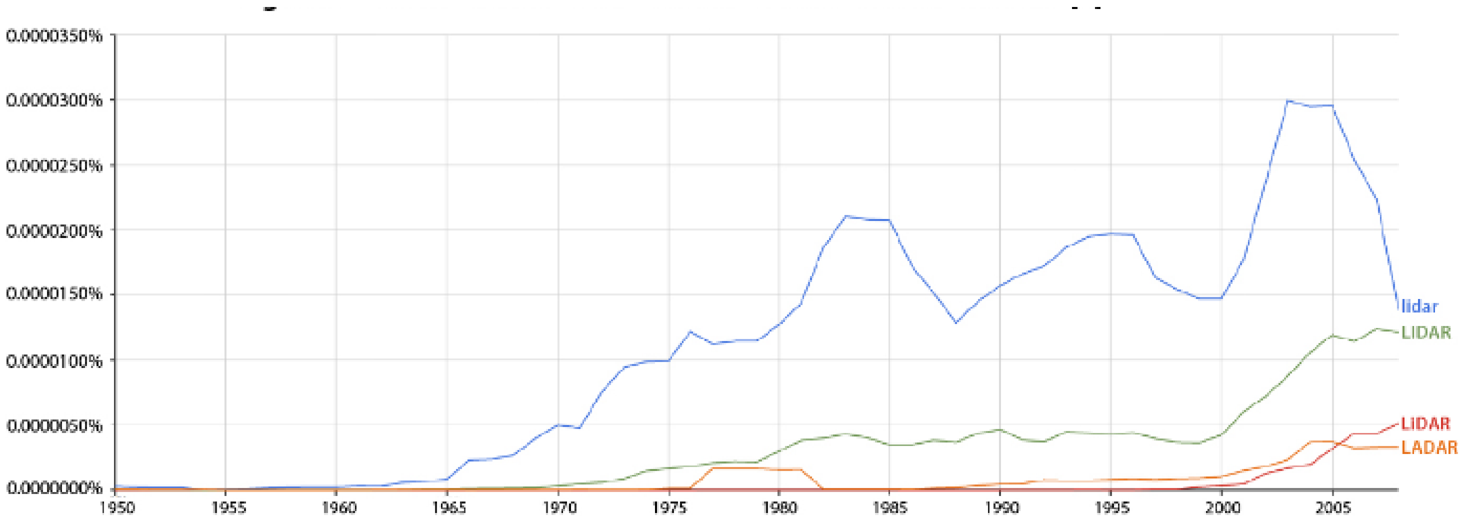
Ladar names

- LIDAR – Light Detection And Ranging
  - Generally used with atmosphere or chemical vapor detection
  - Used by the National Geospatial Intelligence Agency, NGA
  - Usually used for commercial applications
- LADAR – LAser Detection And Ranging
  - Historically used with hard targets
  - Adopted by NIST as the standard term for active EO Sensing
- Active EO Sensing, Laser Radar, Optical Radar, Laser Remote Sensing
- For Reference
  - RADAR – RAdio Detection And Ranging

Now I swim with the tide (lidar)

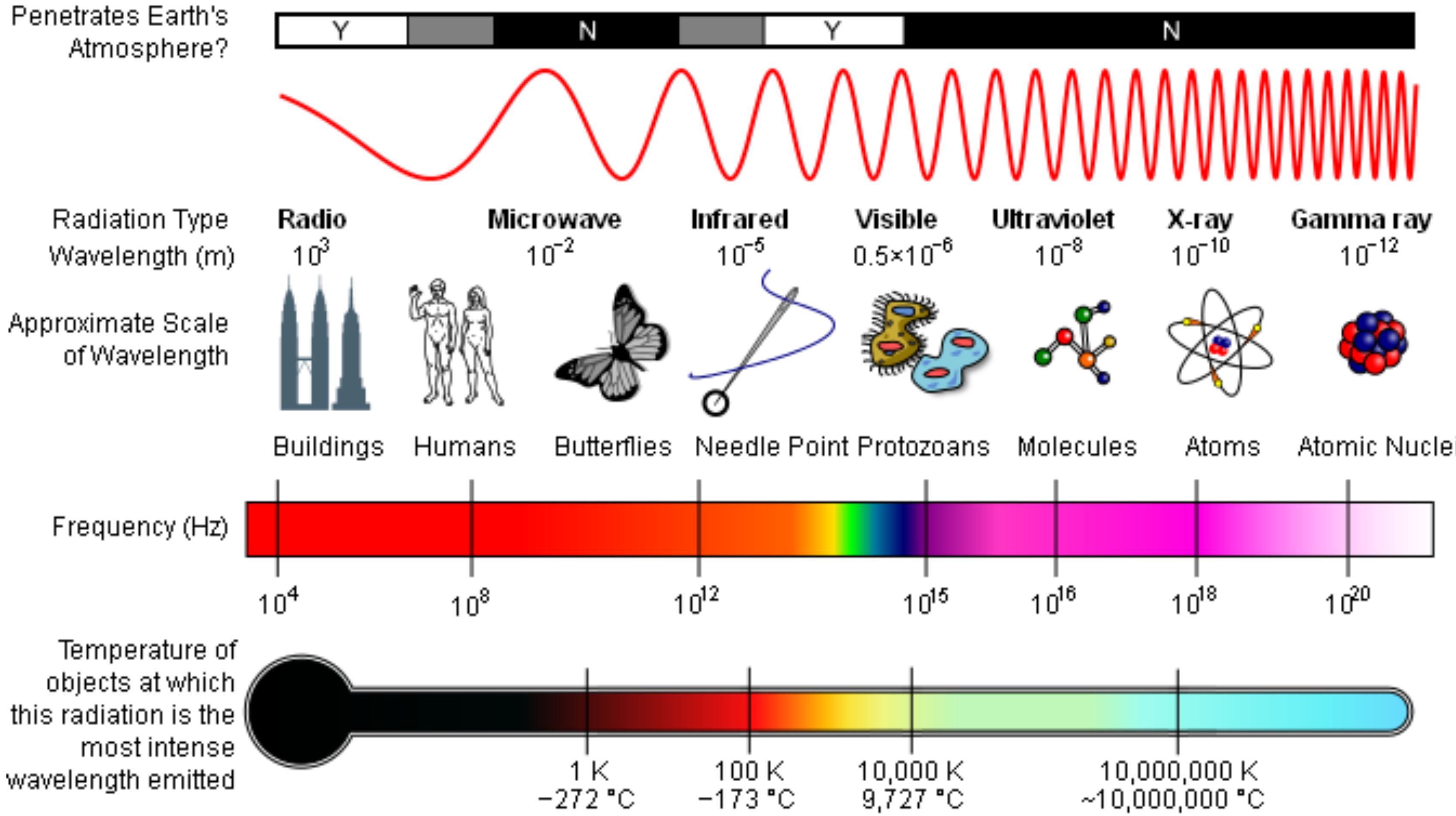
Google Ngrams up to 2008





I think LiDAR is most popular now

Electro-magnetic Spectrum



-1.5 μm wavelength is 200 Thz

-1.5 < fog or many aerosols

-10 Ghz is 3 cm wavelength

-3 cm is > rain drops

20,000 time difference

Why Ladar Instead of Passive EO or Radar?

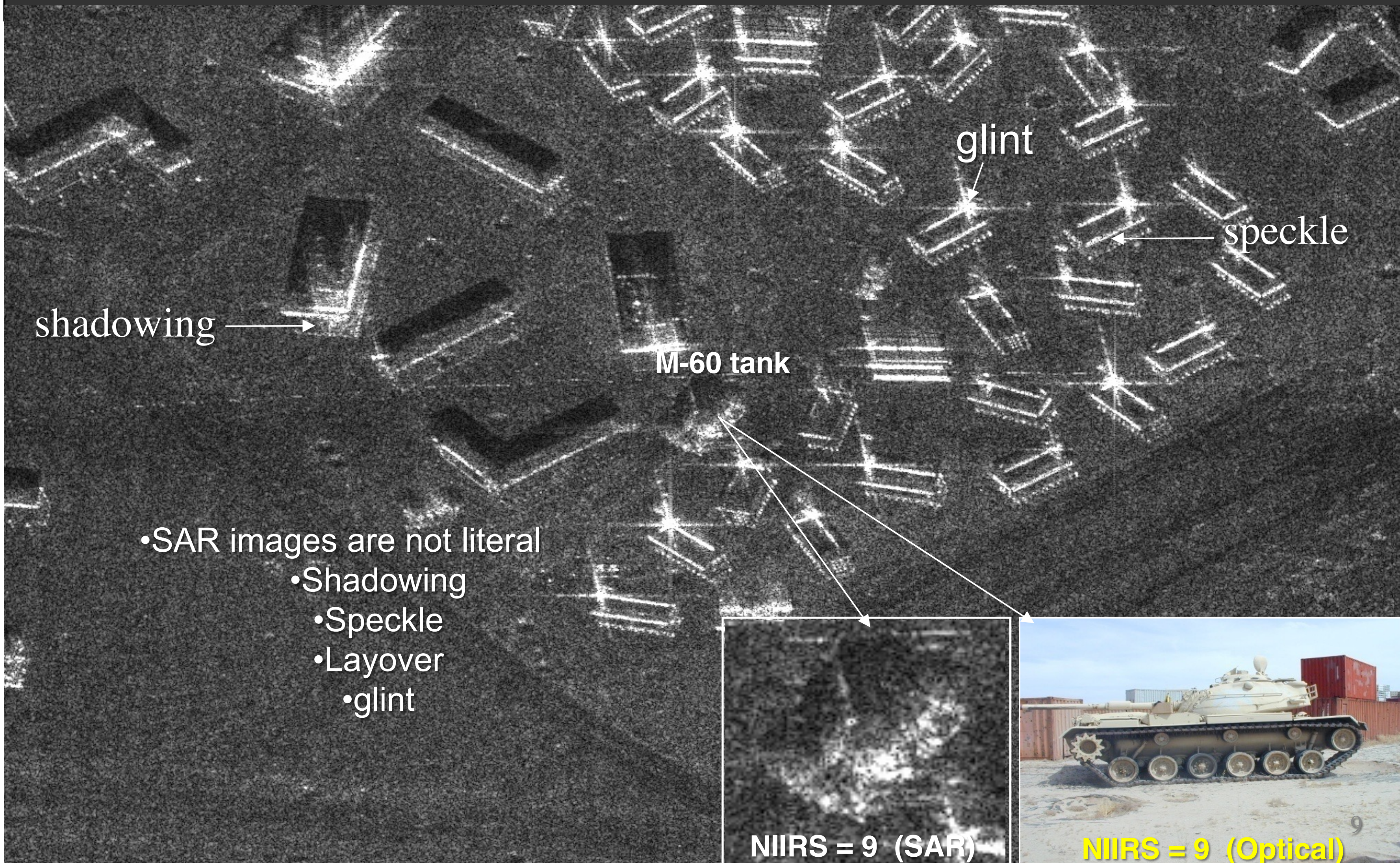
- EO has excellent real beam resolution
  - 20,000 time radar, comparing 3 cm, 10 Ghz, to 1.5 µm, 200 Thz
  - Lidar signature will look closer to natural
- Ladar controls the illumination
  - Can use Near IR wavelength at night
  - Can measure range and velocity
  - Can detect field.
  - Can structure illumination

Sensor Context Summary

- Radar is a great Search Sensor
  - Radar can see through clouds, but is a lousy ID sensor
- Hyperspectral Passive EO helps search as well
- Lidar has control of the illumination, similar to microwave radar
- Lidar is a great for ID
  - Lidar can go to longer range than most passive EO sensors
    - Bringing our own photons
  - Lidar can be 3D, for great hand off and re-acquisition
  - Lidar can provide many discriminates

SAR has good weather penetration, but SAR does not provide literal images required for weapons release authorization

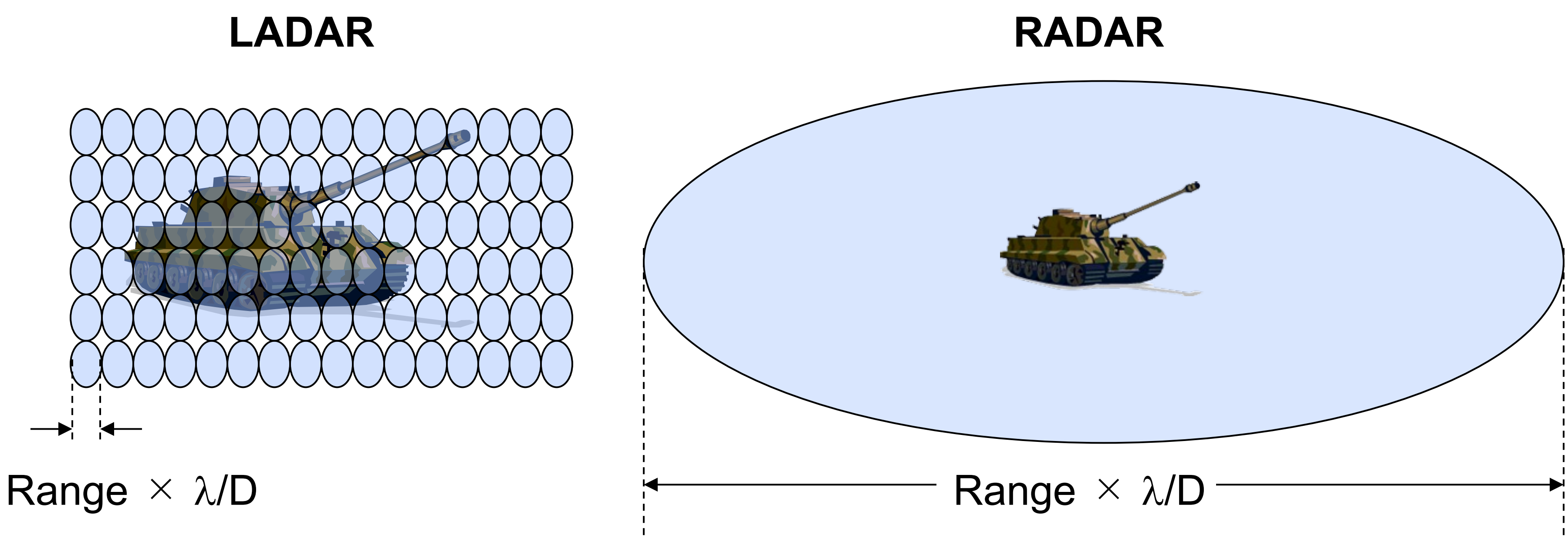
Lynx SAR: 4" Resolution Image of USMC Urban Warfare training site NIIRS = 9 (SAR)



Lidar vs. Radar: Many Similarities — and Many Fundamental Differences

- **Example: Single vs. multiple footprint patches**

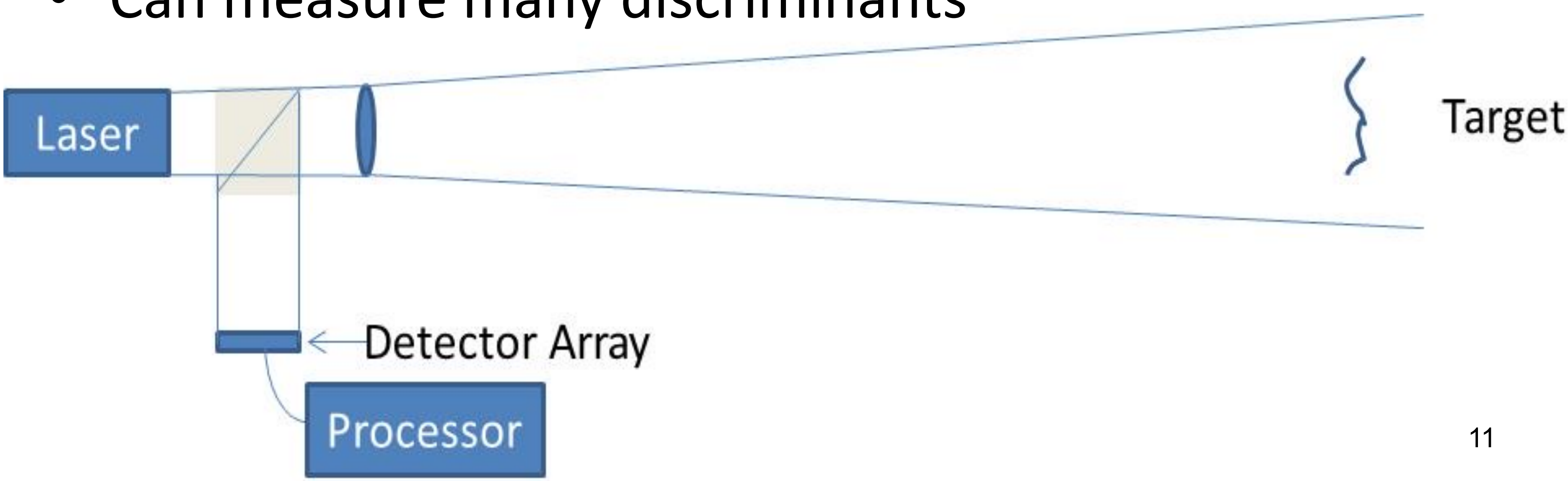
  In radar, a single real aperture patch covers a large area, usually large enough to cover the whole target area of interest. In ladar, the target area must be imaged by "mosaicing" real aperture patches together.



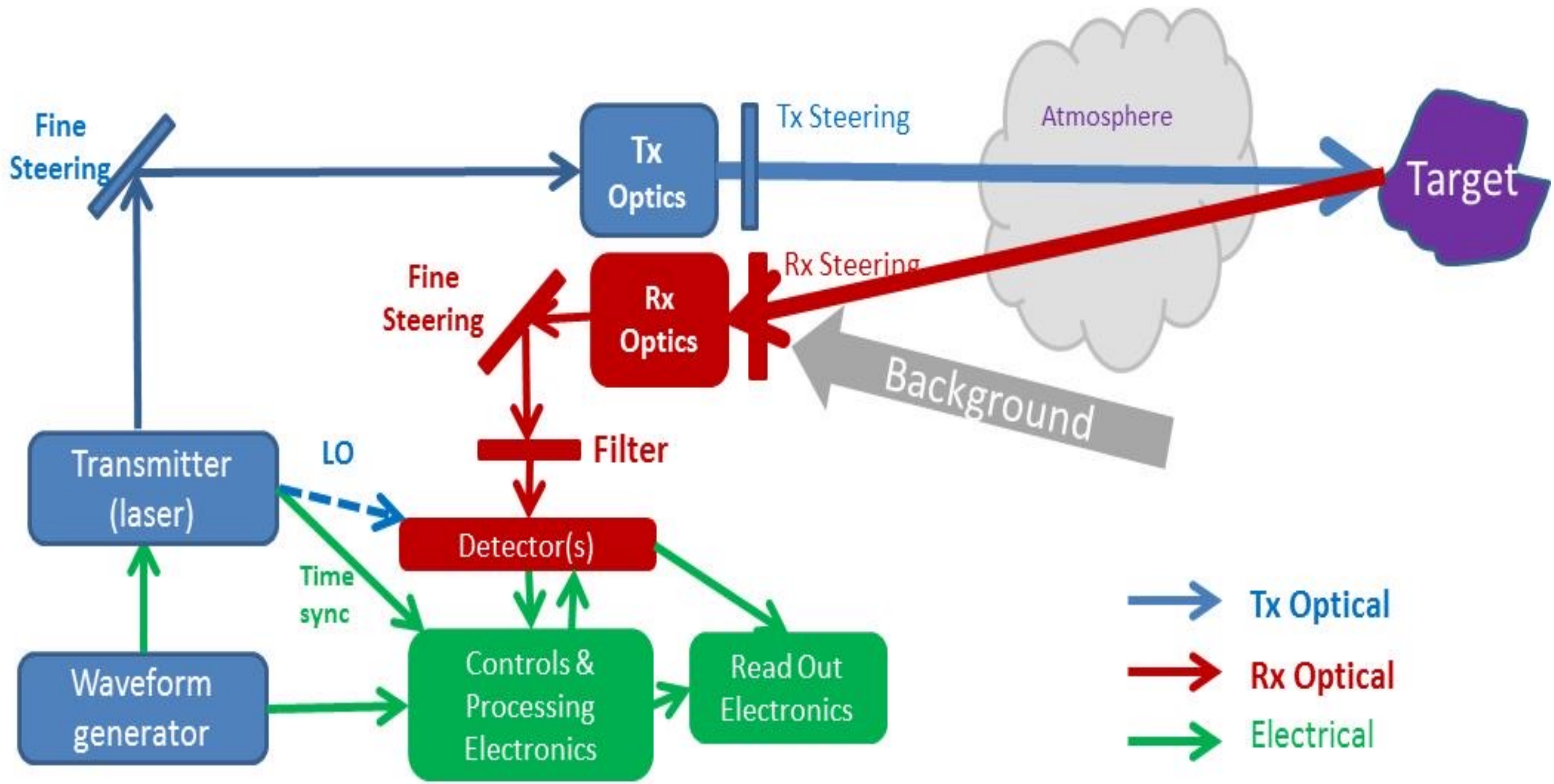
Real Aperture footprint = Range × λ/D

One simple Lidar Description

- Need a laser source, some optics, and a receiver
- Transmits through a medium
  - The atmosphere, water, space
- Bounces off of an object
- Have to process the received data
- Generally display an image (2D or 3D)
- Can measure many discriminants

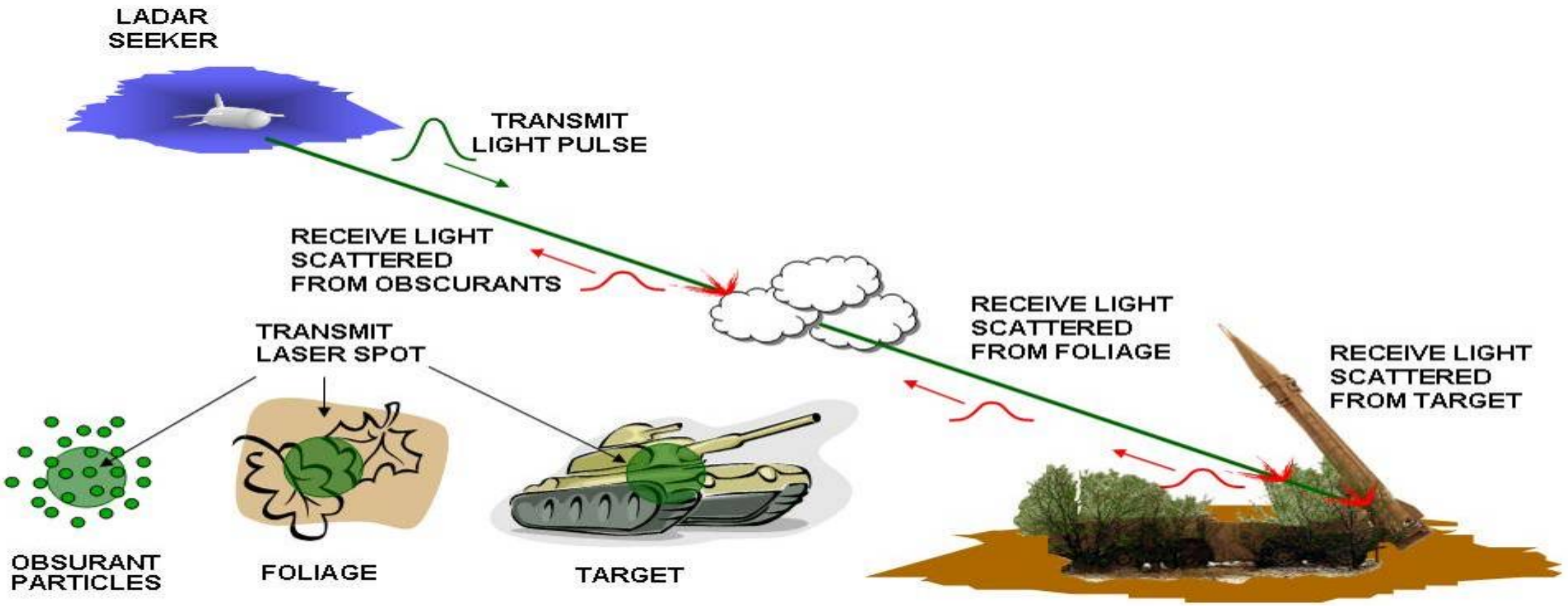


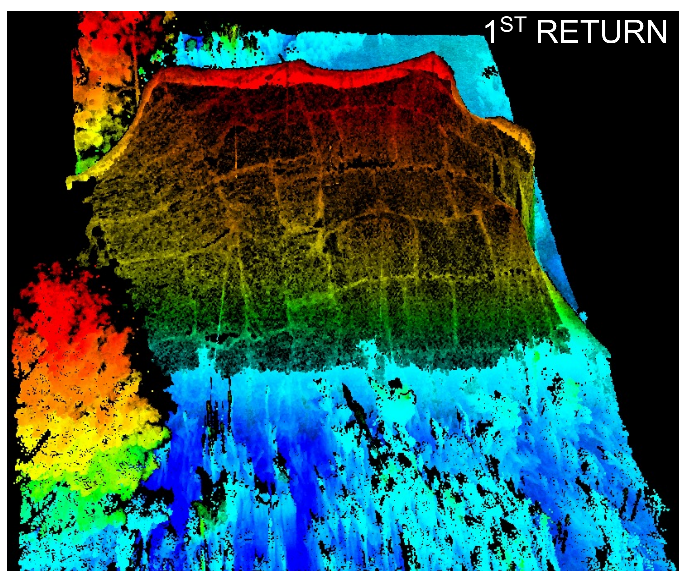
Lidar Block Diagram

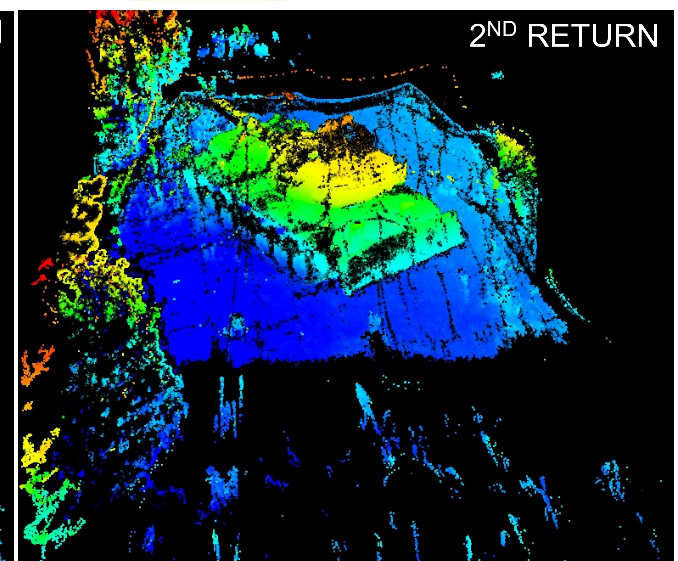


Lidar Overview

You can see through Obscurants







Major Components in Lidar

- Transmitter
  - Now days this is a laser
- Receiver
  - Can be one detector, or an array
- Optical Aperture(s), and beam steering
  - Need to point the transmitter and receiver at the object to be detected
- Processing
  - Gathering data does not make an image, or information.

What a lidar detects?

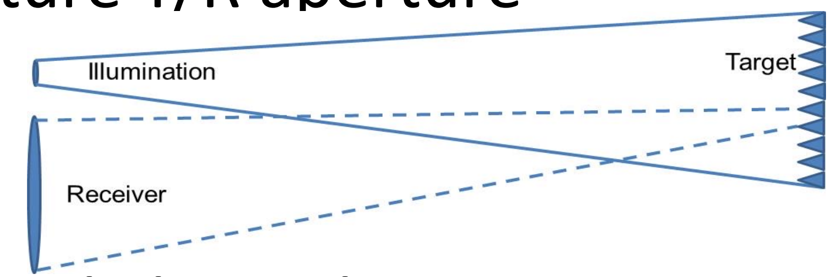
Direct Detection is currently focused on Geometry

- Geometry
  - 1D, 2D, 3D
- Surface characteristics
  - Color **– can be direct detection**
  - Roughness
  - polarization **– can be direct detection**
- Plant, or surface, noise
  - Vibration / sounds
  - signatures associated with piston or turbine engines
  - Electric transmission
  - Machine noise
- Effluents **– can detect effluents, but motion sensitivity will be limited**
  - exhaust air
  - Gases
  - waste heat
- Gross motion
  - translation
  - rotation
  - Can be motion of air or effluents

Coherent ladar adds a lot of functionality

Bi-Static Vs Monostatic

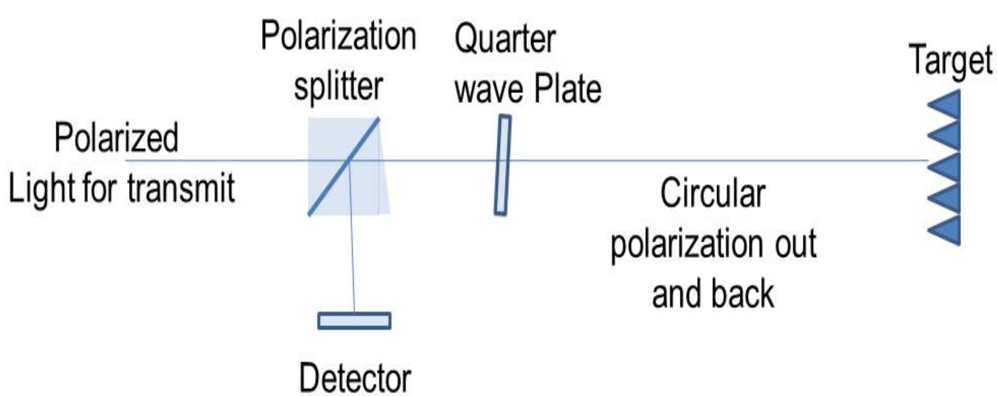
- Bi-static has separate transmit and receive apertures
- Monostatic a single aperture T/R aperture



- Monostatic can be smaller, lighter, cheaper
- For flash ladar the transmit aperture is much smaller, so does not have a big impact
- Multiple Input, Multiple Output, MIMO, ladars will be bi-static
- Bi-static has almost no isolation issues
  - Only atmospheric backscatter

Transmit/Receive Isolation

- A ladar can be bistatic or monostatic
- Bistatic lasers only have an isolation issue with backscatter from the air
- Temporal isolation can be used
  – For pulsed lasers you can turn of the detectors when the laser is emitted, eliminating backscatter
- Polarization is the baseline isolation approach



Lidars can Make Use of Volume Scattering

- Wind Sensing bounces laser energy off of aerosols or air.
- Chemical Sensing can bounce light off of the chemicals
  - Or can bounce light off of the ground, and measure absorption at different wavelengths while going through the air/material
- A LIBs, Laser-Induced Breakdown Spectroscopy, Lidar is in the Curiosity Spacecraft on Mars
  - Vaporizes some material, and then measures what it is

Surface Scattering

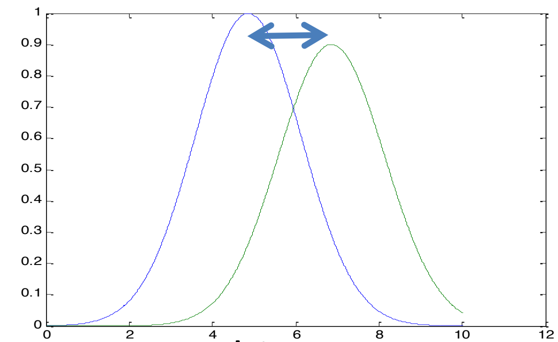
- Target ID for the military
- 3D lidar for driverless cars
- 3D mapping
  - Forestry lidar to measure the mass of trees
  - Archeology lidar to map
  - Utility line mapping
  - Transportation/road asset mapping
  - Urban infrastructure
  - Planets or space debris
  - Could be navigation
- Lidar for Robot, or UAVs
- Microsoft Kinect game machine
- Obtaining data for 3D printing

Current EO landscape

- Deployed Passive Thermal Imagers
  - 3-5 μm for newer systems
  - 8-12 μm for older systems
- Active EO
  - 2D range gated Active
  - **3D active**
    - **Commercial 3D mapping lidars are popular**
  - **Self Driving cars**
  - 3 companies have flown synthetic aperture lidars
  - Microsoft Kinect for gaming

Resolution and Accuracy

- Range Resolution
  - Quantifies the ability to detect two objects separated in range along a single line of sight.
  - Limited to c/(2×B) where c is the speed of light and B is the system bandwidth



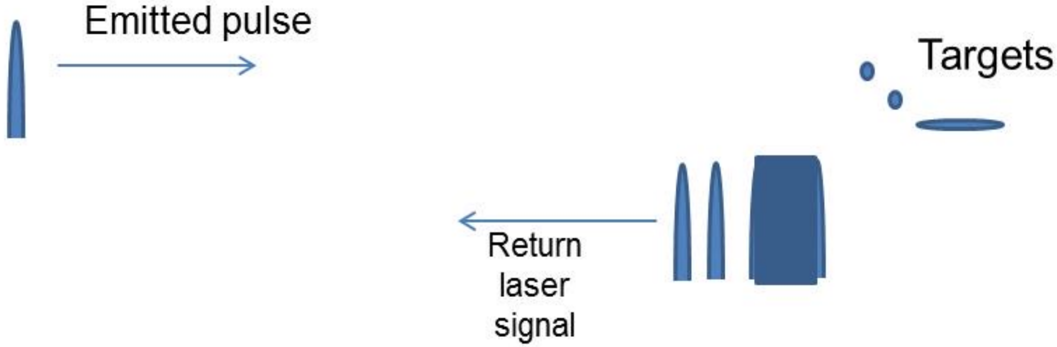
- Range Precision
  - Quantifies the relative uncertainty of a range measurement to an object
  - Limited by the range resolution and the signal-to-noise ratio of the measurement, and can be significantly better than the range resolution.
- Range Accuracy
  - Quantifies the degree to which a range measurement yields the "true value" of the absolute range.
  - Depends on range precision as well as systematic errors (e.g., clock rate, drift, timing offsets, etc.)
- This is always a big confusion

Range Resolution of Lidar

- Range is measured by the speed of light and time

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

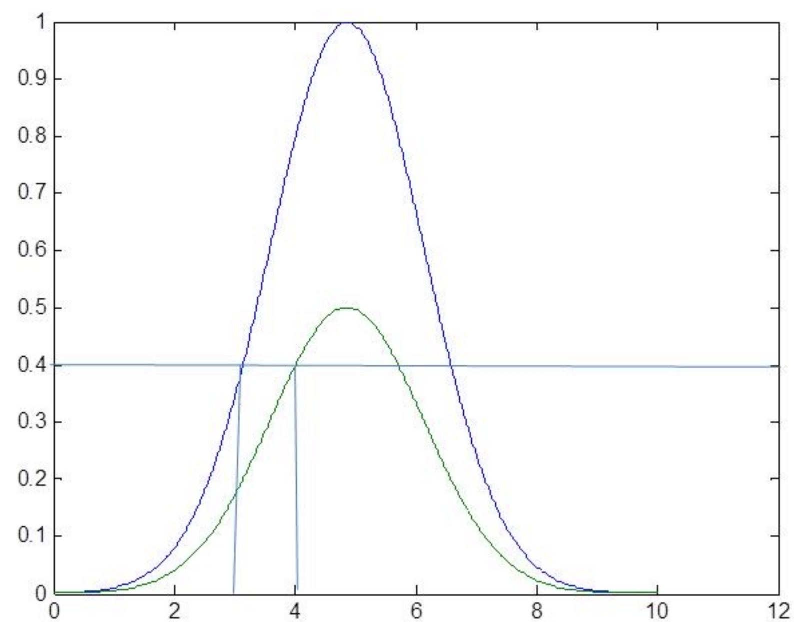
- Factor of 2 comes because light goes out and back
- Measurement precision has to do with a convolution of the "pulse" and the target



Is there a dip between targets?

Range Precision Issues

- Amplitude of return pulse
  - Higher amplitude can appear closer
  - Ratio processing can solve this issue
    - E.g half max to measure range
  - Measuring front and back of a pulse can also resolve this issue

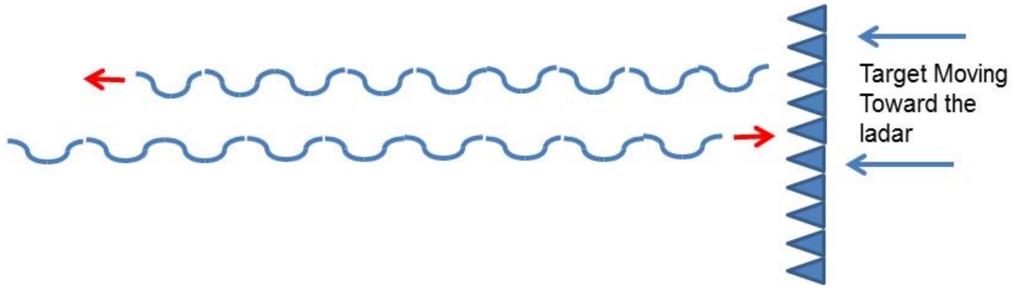


Velocity Resolution of lidar

- Can measure Doppler shift
  - Usually use a heterodyne ladar

$$\Delta f = \frac{2V}{\lambda}$$

- Can also measure range multiple times.
  - Police lidars are direct detection, and use multiple range measurements.

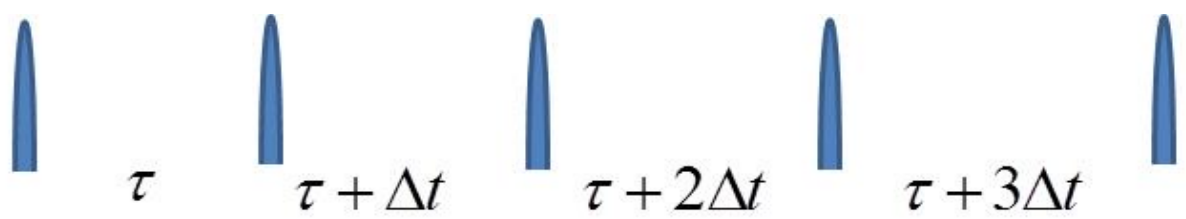


Unambiguous Range

- The range for which you only have one pulse in the air at a time.

$$R_{unambig} = \frac{c\tau}{2}$$

- Can extend the unambiguous range by slightly changing the pulse repetition frequency.



Diffraction

- There are multiple different conventions for beam width
- I tend to use the full width, half max, beam width

$$\vartheta \approx \frac{\lambda}{D}$$

- Where ϑ is the diffraction limited angle, D is the aperture diameter, and λ is wavelength
- Some people use
  - Half angle to zero

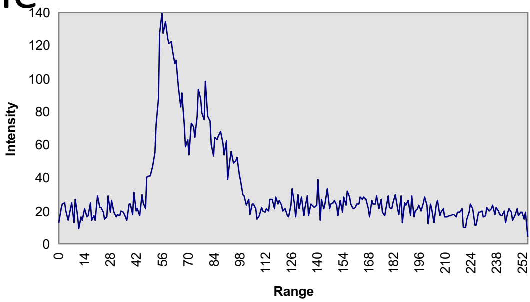
$$\vartheta \approx 1.22\frac{\lambda}{D}$$

- Where ϑ is the angular half beam width at the zeros for a circular aperture

EO systems not Limited by Diffraction

- Synthetic Aperture Lidar
  - Will be able to make a literal image at long range (goal of radar ranges)
  - No inherent range limitation
  - Very new
  - Currently not a small system
- High Range Resolution Lidar
  - 1D Lidar
  - For airplanes the nose is usually pointed where it is going
  - Might as well have 3D, with range limited angle/angle
- Vibration Lidar
  - Will be able to ID objects that are vibrating
  - No inherent range limitation
  - Not a literal image, but could "hear" the target
    - e.g hear a turbine vs. a hear a diesel
- Polarization & Color
  - Mostly limited by engineering and cost. It can mature relatively quickly

1-dimensional

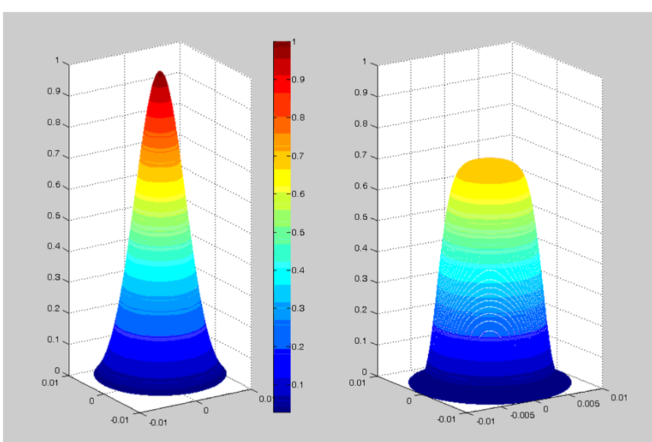


Can have clipping with a Gaussian beam transmitter

- Full width, half max

- 2x full width, half max
- Super Gaussian beams

Clip less



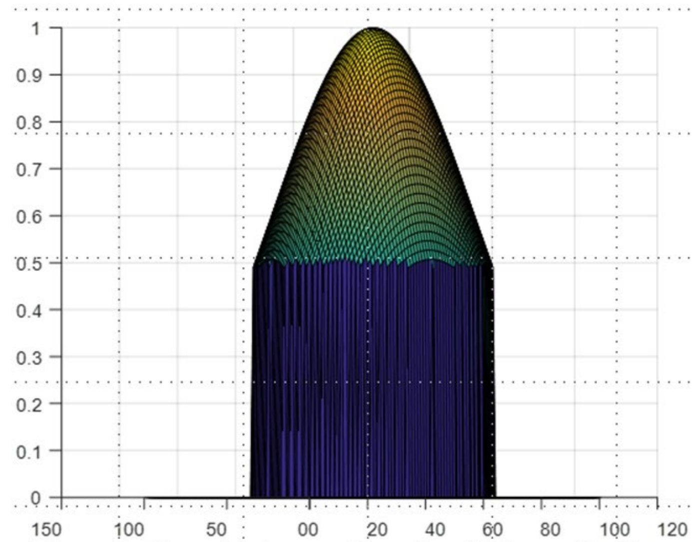


Figure 4: Gaussian beam clipped at 50% amplitude

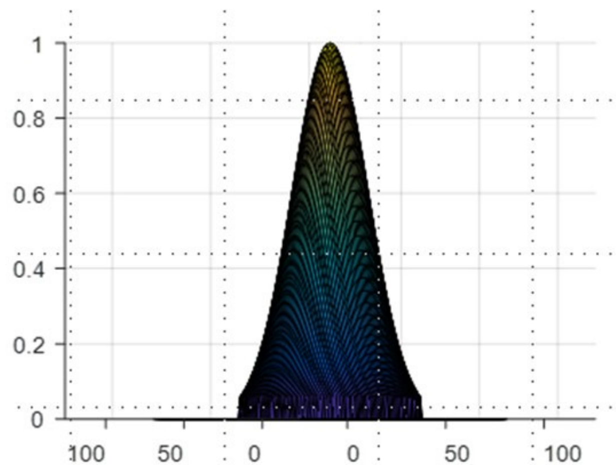
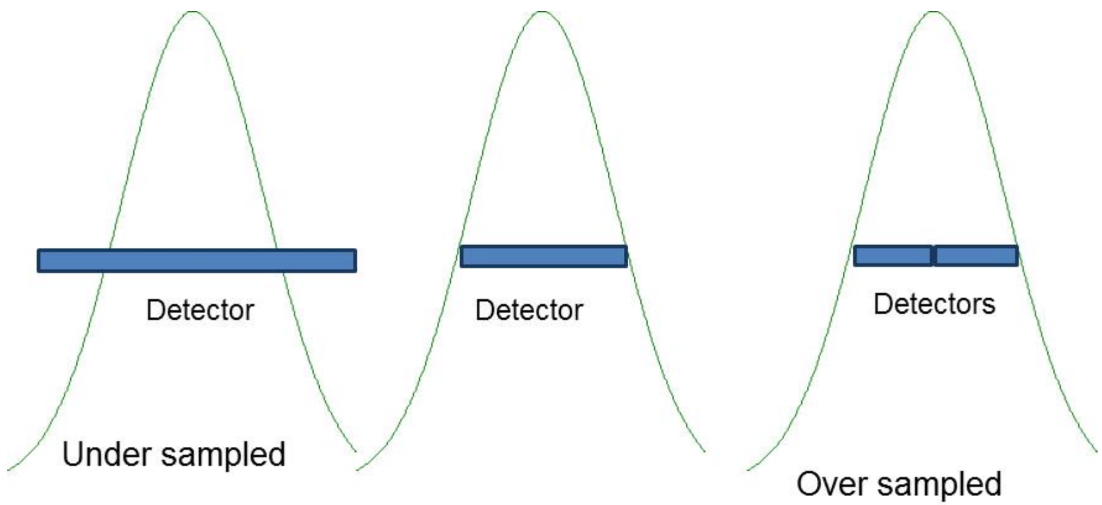


Figure 5: Gaussian Beam clipping with an aperture 2x as wide as the full width, half max

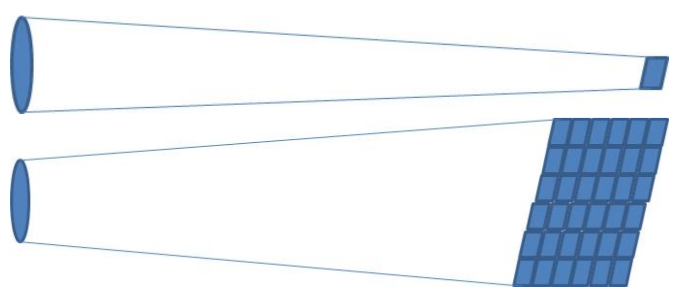
Angular Sampling

- Can under sample, as in the detector to the left
- Most EO systems are designed for the detector Angular Sub-tense (DAS) to match the Point spread function (middle)
- We can over sample (as on the left)



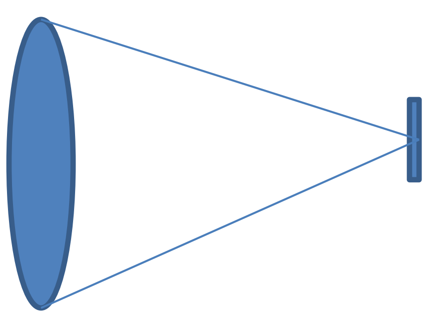
Lidar Image Stabilization

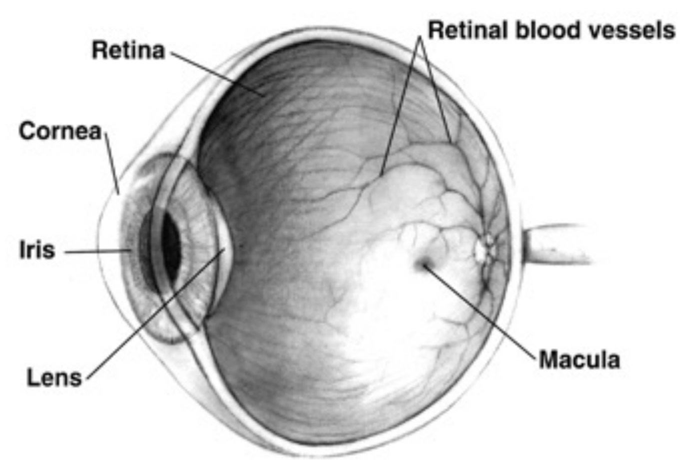
- Have to stabilize the image to a fraction of
  - The detector Angular Sub-tense (DAS) for single detectors
  - The array size in angle space for flash detectors
- True flash ladars do not need as much stabilization
- GMAPDs a sort of flash, but require as many as 50 pulses in coincidence detection



Eye Safety

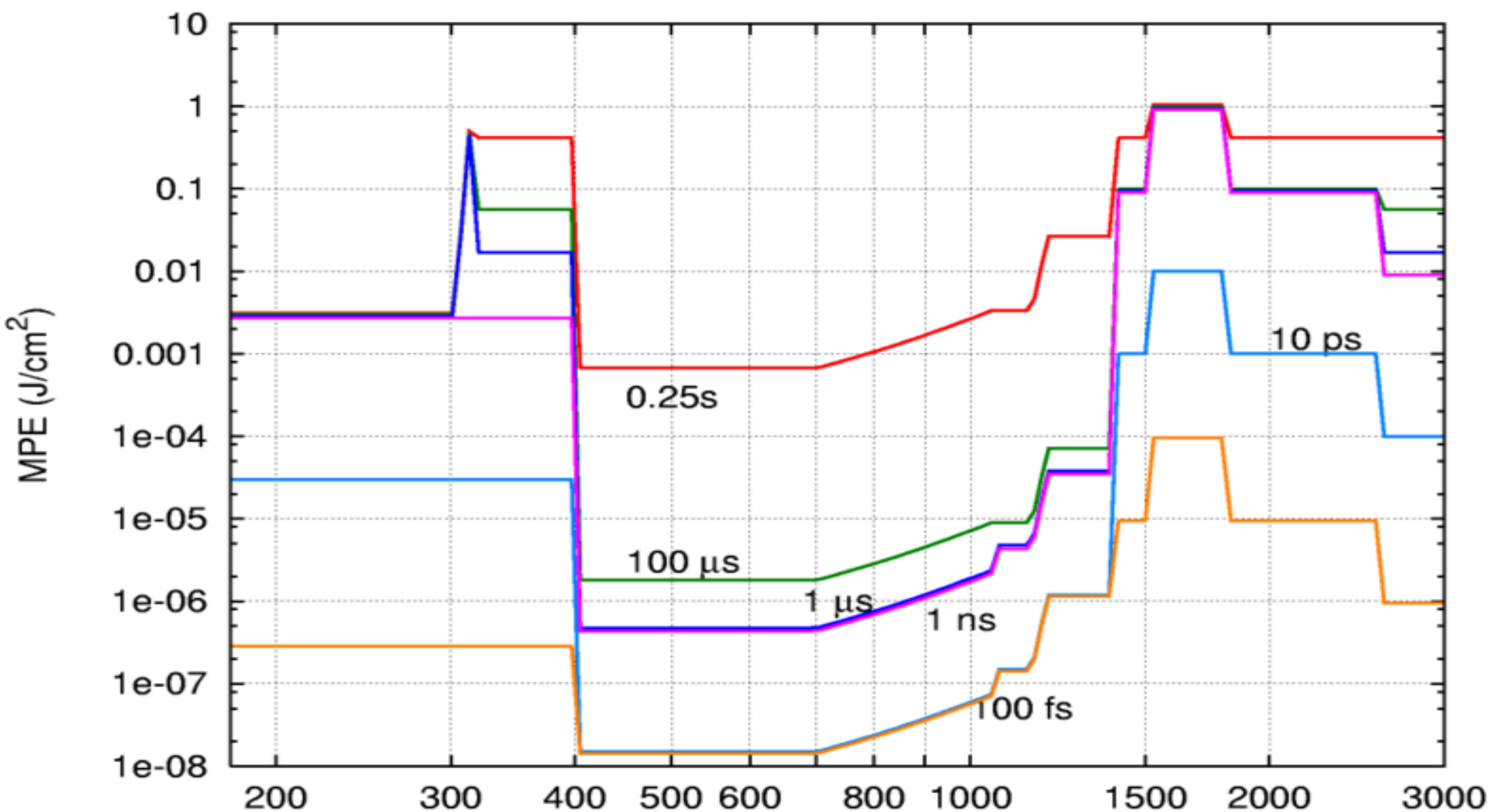
- Water absorbs light < 400 nm and > ~ 1400 nm
- Damage threshold much lower if the light can be concentrated on the retina
  - If a laser does not focus well it is not as dangerous
  - Focusing can magnify intensity 1000 to 10,000 times
- Usually use energy in 10 seconds for calculations of eye safety
  - Scanning reduces energy hitting the eye





Eye Safety

- Chart shows relative Eye safety threshold
  - 1 j/cm^2 @ 1.5 µm, and 1E-6 j/cm^2 @ .9 µm for nsec to µsec pulse width

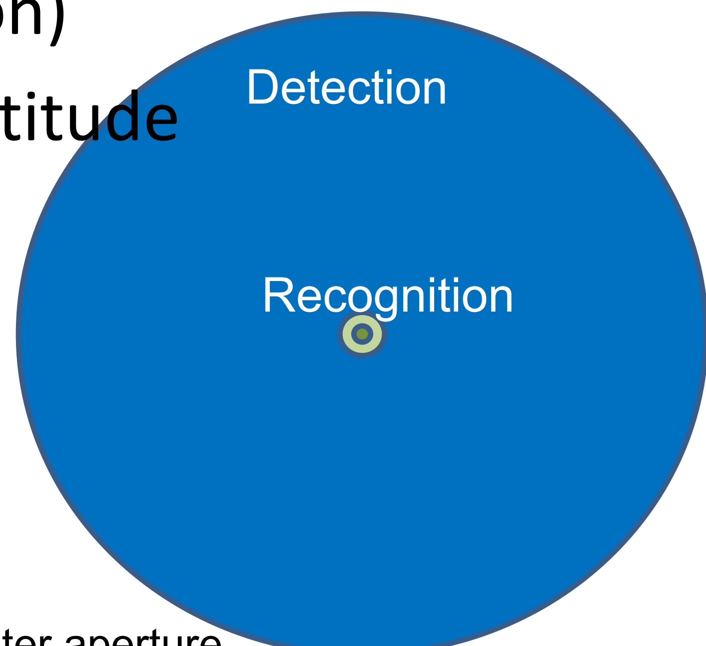


Laser Safety Classes

- Class 1
  - Safe, unless magnified
- Class 2
  - 400-700 nm only
  - Safe because of blink reflex. Won’t blink if you don’t see it
  - 1 mw cw or less
- Class 3
  - 5 mw cw or less – many laser pointers
  - Safe if handled properly
  - Class 3B may need goggles. Can be up to 30 mw
- Class 4
  - Can burn the skin, as well as damage the eye
  - Some laser pointers are more then 5 mw – a lot of them you order on the web are. **Be careful !!**

Military Object Identification Landscape

- Radar can detect objects at long range
- Radar imagery cannot be used to make kill decisions in restrictive rules of engagement
  - Radar can ID under liberal rules of engagement
- EO is usually used for ID (a kill decision)
- 278 Km line of sight from 20,000 ft altitude
  - Radar can detect out to the LOS
  - 3-5 mm FLIR ID range is 6.4 Km*
  - 1.55 mm ID range is 14.5 Km*

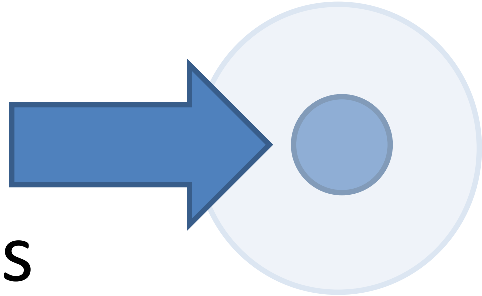


*Assume 15 cm resolution required for ID, and 15 cm diameter aperture

Major disconnect between detection & decision level ID ranges

Cross Section Definitions

- Traditional Optical Cross Section
  - scattering is near Lambertian, and reflected light is reflected into π steradians.
  - π steradians as the effective solid angle of reflected light by assuming a cosine distribution reflecting light over a hemisphere (2π steradians)
- Radar Cross Section
  - Scattering of light over 4π steradians from a small round gold ball
  - Radar will flow around a small ball
- Factor of 4 difference in definitions

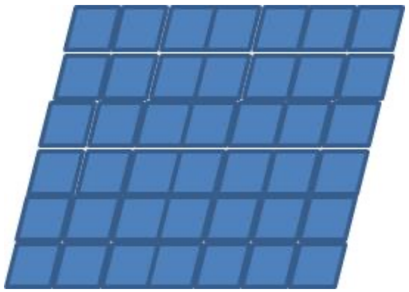


Lambertion Cross Section

- Cross section for a given receiver pixel is limited by the area of a pixel

$$\sigma = \rho_t * DAS_{az} * DAS_{el} * R^2$$

  - where d = cross range resolution, ρ_t is the reflectance of the area
  - Higher spatial resolution will mean each detector sees a smaller area and a smaller cross section.

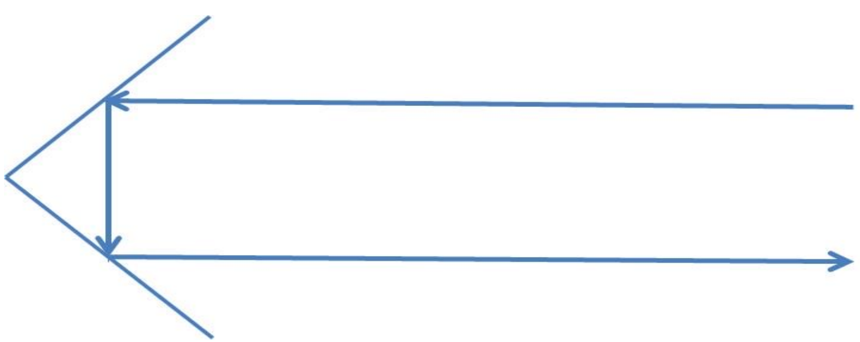


$$\frac{A_{illum}}{\sigma} = \frac{\eta_{illeff} N_{Det}}{\rho_t}$$

Corner Cubes

- The cross section of a corner cube is much larger than other surfaces because light hitting the corner cube is reflected back toward the source.
  - It is like an antenna with gain.
  - Dihedral, two planes meeting
  - Trihedral, concentrating light in two dimensions.

$$\sigma \approx \frac{4a^4}{\lambda^2}$$



Coherence

A word to avoid if by itself !

- **Spatial coherence**
  - Has to do with beam spread
  - Diffraction limited is the best you can do
    - Means a single laser mode
  - M^2 of laser is relevant
  - Has to do with how your resonator is built
    - Does it favor the 0,0 mode or not?
- **Temporal Coherence**
  - Temporal coherence tells us how monochromatic a source
    - Has to do with laser bandwidth
  - Coherence length of laser is a measure of temporal coherence
    - How far does the laser have to travel before there is a full wavelength of phase shift between the extreme frequencies in the laser?
    - Coherence length is speed of light divided by bandwidth
    - Phase is lost after one coherence length
      - No interference anymore
  - Need narrow line width for heterodyne laser radar
  - Have Speckle when use narrow line width
    - Speckle is interference!

Coherence Length

Has to do with Temporal Coherence

Coherence length Is one over the Line width time the Speed of light

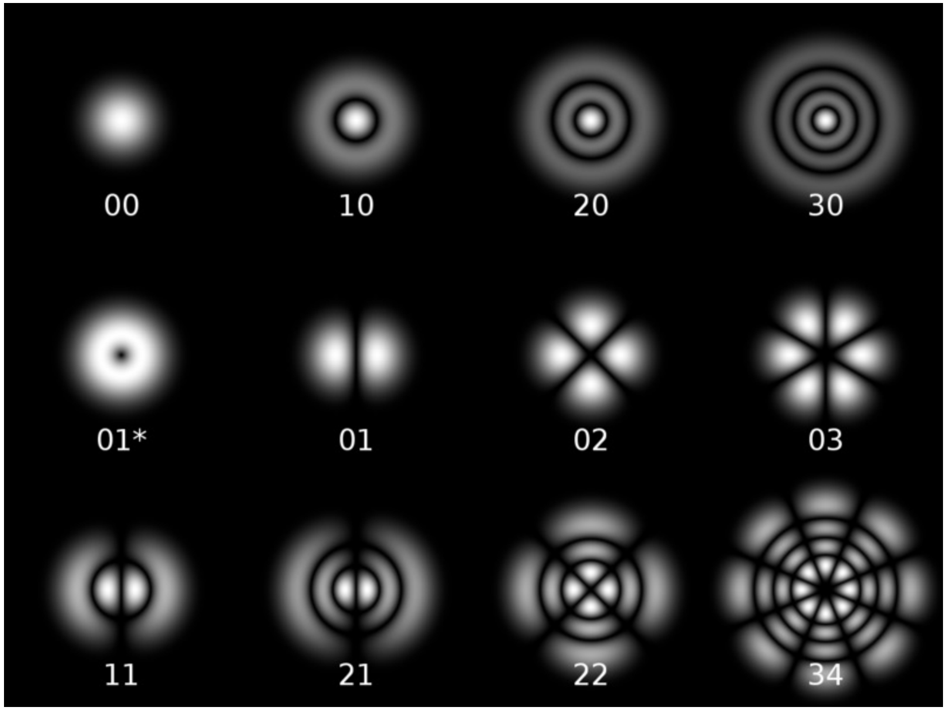
$$C_l = \frac{c}{B}$$

Laser bandwidth	Laser Coherence length
1 Khz	300 Km
10 Khz	30 Km
100 Khz	3 KM
1 Mhz	300 meters
10 Mhz	30 meters
100 Mhz	3 meters
1 Ghz	30 cm
10 Ghz	3 cm

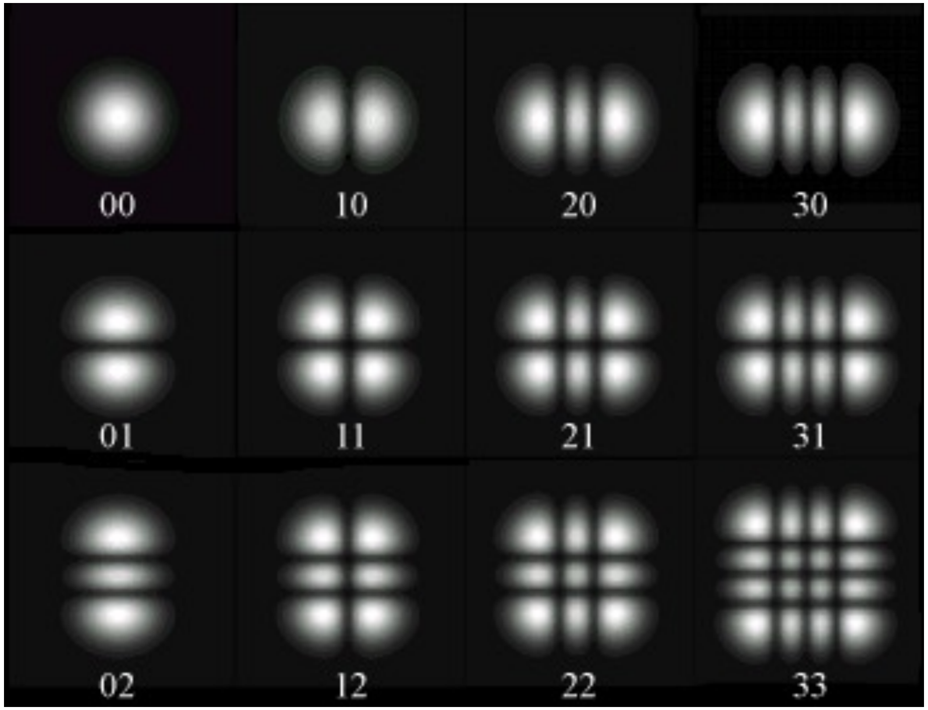
Laser Spatial Modes

Equation is p 330 of Siegman

Cylindrical modes -Laguerre-gaussian



Rectangular Modes



Most ladar Apertures are round

Line width in frequency

- In frequency lasers are very broad band
  - For 1.55 µm

Δ λ (nm)	Δf (Ghz)
0.1	13
1	126
10	1265
100	12650

$$B = -\frac{c}{\lambda^2}\Delta\lambda$$

The Far Field is just a Fourier Transform Away

- We receive in the pupil plane.
- We use a lens, and the focus is the image plane
  - If you know phase and angle you can focus the image electronically by imposing a phase parabola
- The far Field can be far away
  - Fresnel parameter $S = D^2/(4\lambda)$

D (cm)	lambda (microns)	far field(Km)
10	1.55	1.61
15	1.55	3.63
20	1.55	6.45
50	1.55	40.32

Types of Lidar (Direct Detection)

- 1D lidar (range only)
- Tomographic lidar
- 2D lidar – Range Gated Active Imaging
- 3D lidar
  - Scanning
  - Flash
- Active Multispectral
- Polarization
- Laser-Induced Breakdown Spectroscopy, LIBs
- Laser-Induced Fluorescence (LIF)

Types of Lidar (Coherent Lidar)

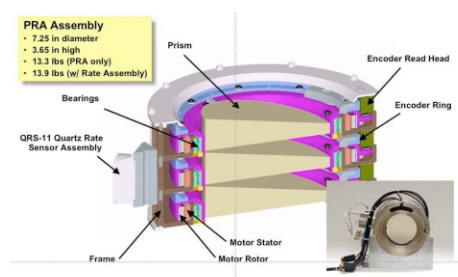
- Laser Vibrometers
- Range Doppler Imaging Lidar
- Speckle Imaging Lidar
- Aperture Synthesis based Lidar
  - Synthetic Aperture Lidar, SAL
  - Inverse Synthetic Aperture Lidar, ISAL
  - Multiple Input, Multiple Output, lidar, MIMO

Hard Target Laser Radar Modes

- High range resolution, 1D Ladar
- 2D Laser Radar
- 3D Laser Radar
  - –Scanning can cover more area
  - –Flash imaging (freeze motion)
- Vibration Laser Radar
- Synthetic Aperture Laser Radar
  - –High resolution at radar type ranges
- Can add discriminants to any of the above
  - –Polarization
  - –Multi-spectral
  - –Maybe even speckle characteristics

How is steering done today, and what are the limits of current practice?

- Gimbals are used for many military systems
  - They are expensive, bulky, heavy, and complex
- Risley Prisms are smaller, and can be flush
  - Pointing is complicated (easy to make Lissajous figures). Risley devices can be heavy, and have low optical quality
- Often Optical Satellites are body pointed using reaction mass
  - Can take 10s of seconds, & uses limited reaction mass
- DARPA has pursued chip scale OPAs, but scaling is a huge issue
- Small apertures may use MEMS, fast steering mirrors, or polygons



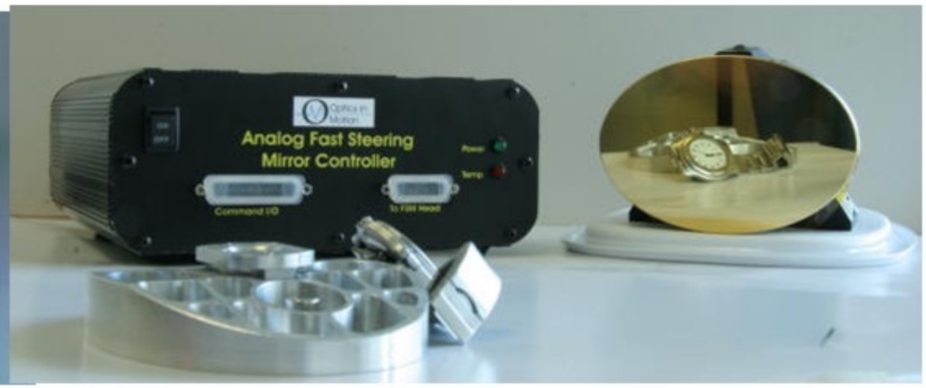
Common Mechanical Beam Steering Approaches

- Gimbals
- Fast Steering Mirrors (FSMs)
- Risley Prisms / Risley Gratings
- Rotating Polygons
- Small motion based beam steering
  - MEMs devices
  - Lenslet based beam steering
- Decentered lens Based Beam steering

Mechanical Beam Steering

- Many good mechanical approaches
  - Non-mechanical approaches will have to replace mechanical

a



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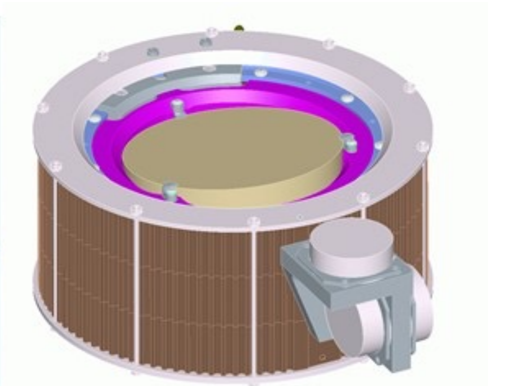

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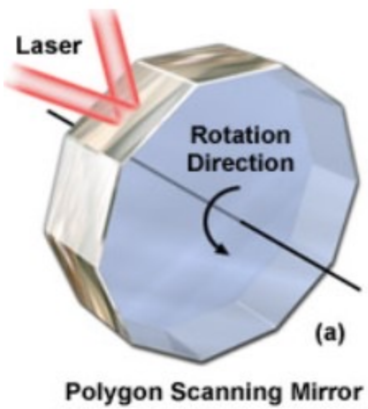

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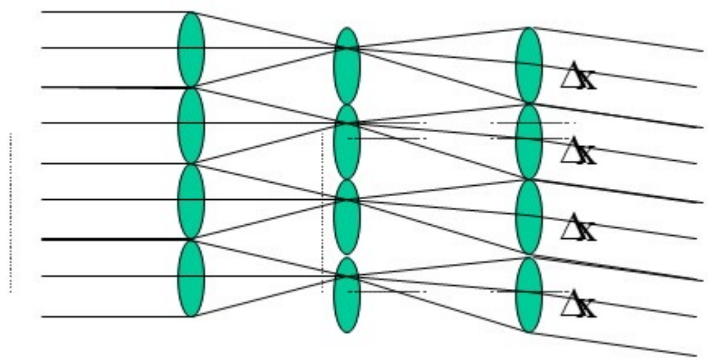

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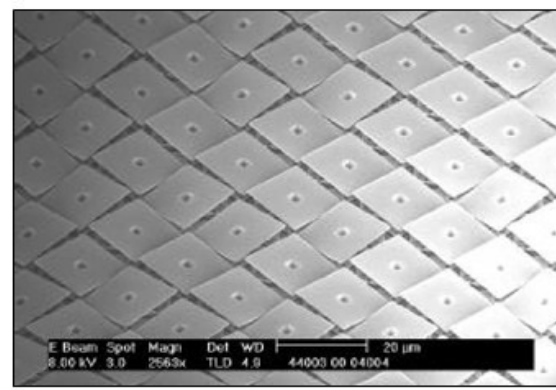


f

Optical Phased Arrays

The Vision
(a 35 year old chart)

- Eliminate Gimbals
  - Heavy
  - Expensive
  - Slow
- Solid state solution
  - Fast
  - Conformal
  - Cheap
  - New capabilities
    - Focus / defocus
    - Multiple beams
    - Random access
- Steer Active & Passive Sensors

Some History of Non-mechanical Beam Steering

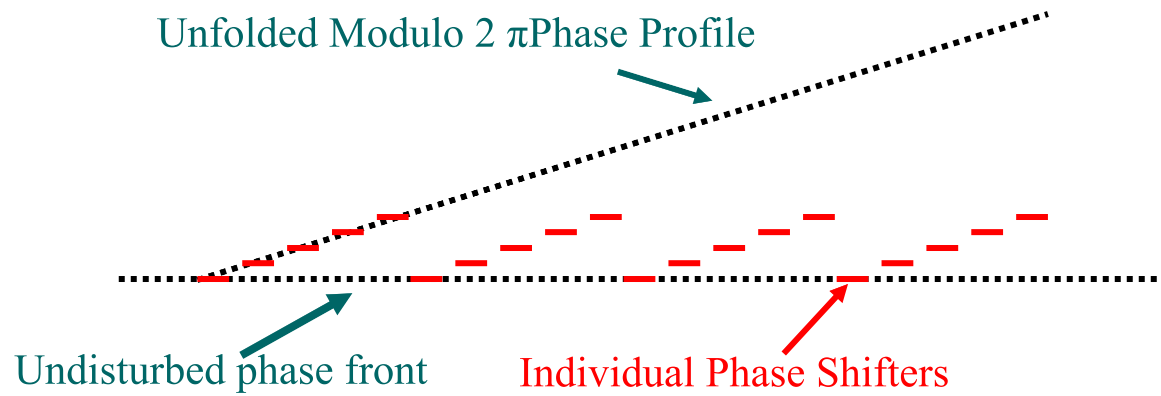
- I started pursuing non-mechanical beam steering in 1985
  - Had our 1st 3 contracts in 1987
    - Two using liquid crystals (Raytheon and HRL)
    - One using acousto-Optical (Westinghouse)
- Raytheon made a 4cm device on 1 micron centers about 1990
- BNS started selling commercial devices in late 90's
  - 1x4096 OPA, on 1.8 micron pixel pitch. The device is .74 cm x .74 cm , won 2000 circle of excellence award
  - 1x 12,228 on a 1.6 micron pitch. It took up to 13.2 volts to address it, and was 19.2 by 19.2 mm in size in 2003
- In 2005 Raytheon used Holographic Gratings with LCs to steer in a 45 degree cone
- I wrote a 2009 review article with LCs, MEMs, electro-wetting, Polarization Birefringent Gratings, and VCOPA
- Polarization Birefringent Gratings are at 15 cm in size

My Review Papers

- 1996 - Optical phased array technology: PF McManamon, TA Dorschner, DL Corkum, LJ Friedman, DS Hobbs, ...Proceedings of the IEEE 84 (2), 268-298 (885 citations)
- 2009 - A review of phased array steering for narrow-band electrooptical systems, PF McManamon, PJ Bos, MJ Escuti, J Heikenfeld, S Serati, H Xie, ...Proceedings of the IEEE 97 (6), 1078-1096 (510 citations)
- 2019 - Review of ladar: a historic, yet emerging, sensor technology with rich phenomenology: P McManamon: Optical Engineering 51 (6), 060901

Two Fundamentally Different methods of Non mechanical Beam Steering

- Create an Optical Path Delay, OPD



- Create a Phase Delay. Pancharatnam Geometry rotates phase, so no resets are required