Atmospheric Lidar

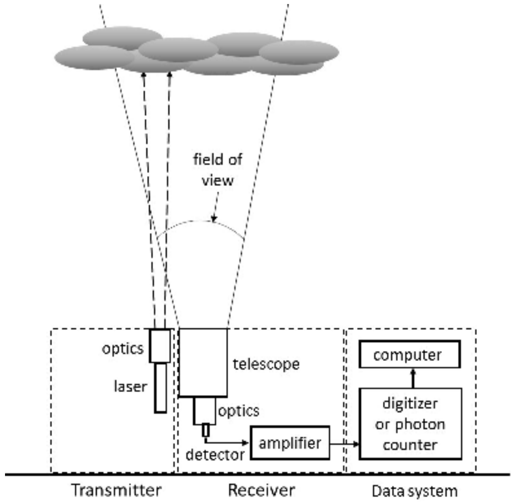
4. Lidar Transmitters, Receivers, and Data Systems

Lidar Tutorials

21st Coherent Laser Radar Conference

Three major components

- A direct detection lidar can be considered as three subsystems:
  - Transmitter
  - Receiver
  - Data system
- We will discuss the technology and technical challenges in each subsystem.



G.G. Gimmestad graphic

Transmitters

- Only two transmitter parameters appear in the lidar equation:

$$N_S(z) = N_0 k_T k_R\, G(z) \left(\frac{A}{z^2}\right)(c\tau/2)\, \beta(z) \exp\left[-2\int_0^z \alpha(z')dz'\right]$$

number of photons per laser pulse

transmitter optical efficiency

- However, often many other parameters of the laser beam must be tightly controlled.

Lasers for lidars

- Only a few types of laser are used in lidar systems.
- Nd:YAG, with its harmonics, is the “workhorse” laser.

Type	Wavelength	Comments
Ruby	0.694 µm	The original lidar laser; still in use but rare.
CO_2	9 - 11 µm (many lines)	10.6 µm strongest; used in coherent lidars.
Dye	0.39 – 0.64 µm	Tunable.
Nd:YAG	1.064 µm (+ 532, 355, 266 µm)	Also used as a pump laser.
Nd:YLF	1.047 µm (+ 523.5, 349, 262 µm)	Also used as a pump laser.
Er:YAG	1.550 µm	Eye safe, as laser rod or fiber laser
Excimer	0.193, 0.248, 0.308, 0.353 µm	Media such as XeF only exist in excited state.
$Ti:Al_2O_3$	0.650 – 1.100 µm	Tunable. Often pumped by Nd:YAG.
Tm:YAG	1.930 – 2.040 µm	Tunable (narrow range).
Ho:YLF	2.08 µm	Used in coherent lidars.
Alexandrite	0.700 – 0.820 µm	Tunable.
QCL	MWIR - LWIR	Fabricated for chosen wavelengths.
Ce:LiSAF, Ce:LiCAF	280 – 316 nm	Tunable, pumped with quadrupled Nd:YAG or excimer lasers. Used in ozone DIAL.

Changing the wavelength

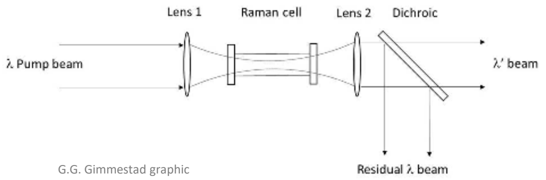
- Harmonic Generators
    - 2X, 3X, 4X fundamental frequency
    - 1/2, 1/3, 1/4 the fundamental wavelength
        - Nd:YAG fundamental is 1064 nm
        - Harmonics are 532, 355, 266 nm

https://picclick.com/Continuum-Quantel-SHG-T30-Second-Harmonic-Generator-YAG-Laser-254122078214.html

Harmonic generators are nonlinear crystals, usually packaged in ovens. Sensitive to temperature, angle, and polarization.

Wavelength shifters

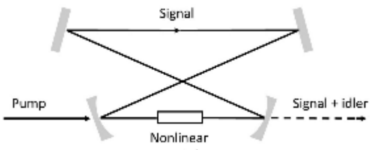
Stimulated Raman Scattering (SRS)



G.G. Gimmestad graphic

Lens 1 creates a beam waist inside the Raman cell. Lens 2 re-collimates the residual beam and the wavelength-shifted beam. The dichroic mirror separates the two beams.

Optical Parametric Oscillator (OPO)



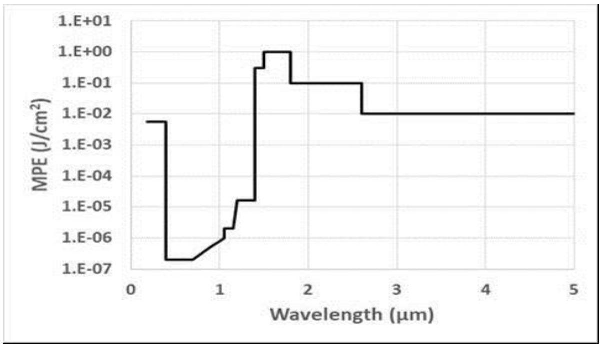
G.G. Gimmestad graphic

The cavity generates two frequencies.The sum of the two frequencies = the pump beam frequency. OPOs are tunable and efficient. They tends to have high beam divergence.

Laser eye safety & optical damage

- The greatest eye hazard is in the UV-Visible wavelength region.
- Any lidar depending on $1/\lambda^4$ or electronic levels must operate there:
  - Raman (all types)
  - Rayleigh
  - HSRL
  - Resonance scattering
  - High altitude wind sounders
- Eye safety can sometimes be achieved with a very large beam and very small pulse energy.
- UV photons are so energetic that they can damage optics!

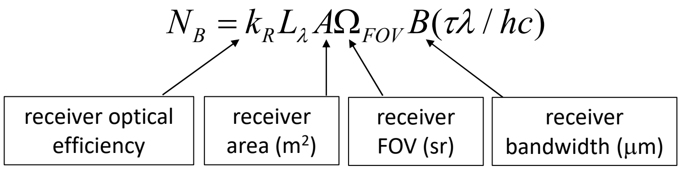
ANSI Z136.1 - 2014 Maximum Permissible Exposures for a single 10-ns pulse



G.G. Gimmestad graphic

Receivers

- Four receiver parameters appear in the sky background equation:



$$N_B = k_R L_\lambda A \Omega_{FOV} B(\tau\lambda / hc)$$

- Optical efficiency k_R and area A also appear in the lidar equation.
- Areas range from a few cm^2 to several m^2.
- FOVs (plane angle) range from a few mr (easy) to 18 µrad (difficult).
- Receiver optical bandwidths range from a few nm (easy) to 1.7 pm (difficult).

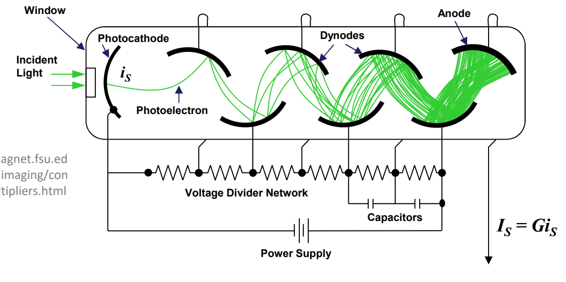
Detectors

- Detectors convert a stream of photons into a stream of electrons.
- Main measures of merit:
  - Quantum efficiency (the fraction of the incident photons that the detector responds to)
  - Dark count rate (how often the detector registers a photon when there isn't one)
  - Gain (yields a large output & less need for amplification)
  - Linearity (the electron stream is a faithful copy of the photon stream)

The photomultiplier

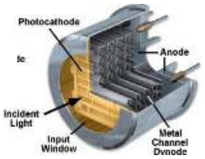
Output signal current = Current Gain X Input Signal Current

$I_S = Gi_S$



https://micro.magnet.fsu.edu/primer/digitalimaging/concepts/photomultipliers.html

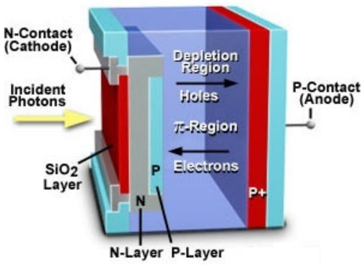
https://upload.wikimedia.org/wikipedia/commons/3/36/Pmside.jpg



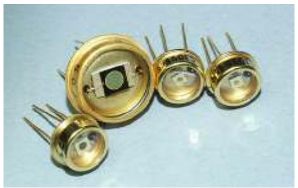
http://hamamatsu.magnet.fsu.edu/articles/digitalimagingdetectors.html

- A photon incident on the photocathode ejects a photoelectron.
- The photoelectron is accelerated to the first dynode where it causes 5-6 electrons to be ejected.
- The chain of 5-10 dynodes produces current gains G at the anode of $10^5 – 10^8$.
- Responds with a pulse for each detected photon.
- Electrons are also ejected thermally from the cathode and dynodes, causing dark counts.

Linear avalanche photodiodes



www.hamamatsu.com

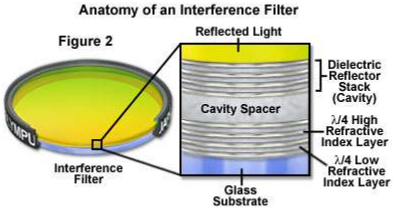


www.optoelectronics.perkinelmer.com

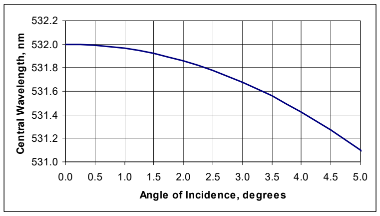
- A linear APD is the semiconductor analog of a photomultiplier.
- A photoexcited carrier produces electron-hole pairs through impact ionization as it moves through the depletion region.
- Pair creation occurs at fields strengths of ~10^5 V/cm.
- Gains are in the range 10 – 100.

Optical filters

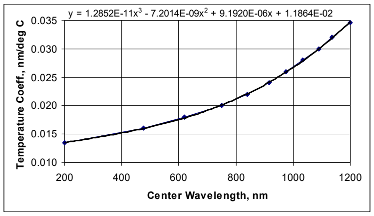
- The term *B* in the background equation is the optical bandwidth (μm).
- *B* is most often limited with interference filters.
- They are sensitive to both ray angle and temperature.



https://www.globalspec.com/learnmore/optical_components_optics/optical_components/optical_filters



Passband shift with angle

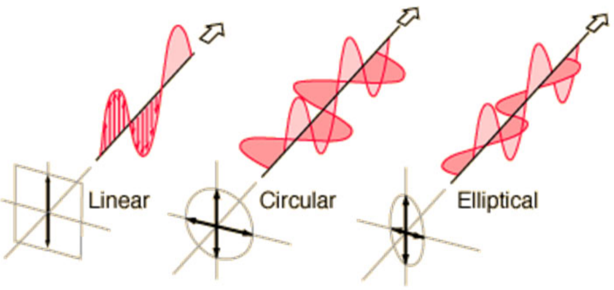


Passband shift with temperature

https://www.andovercorp.com/technical/bandpass-filter-fundamentals/

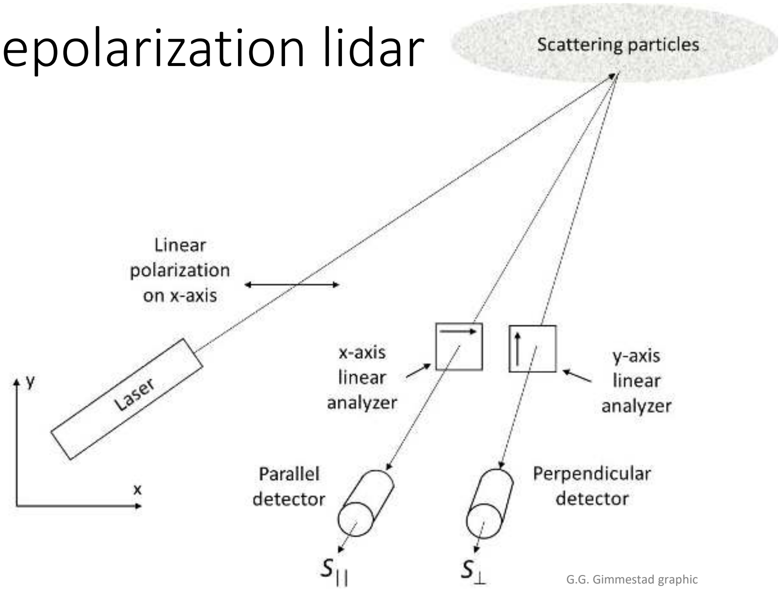
Polarization

- The *polarization state* of light is defined by the pattern traced out by the tip of the electric field vector in a plane perpendicular to the direction of propagation.



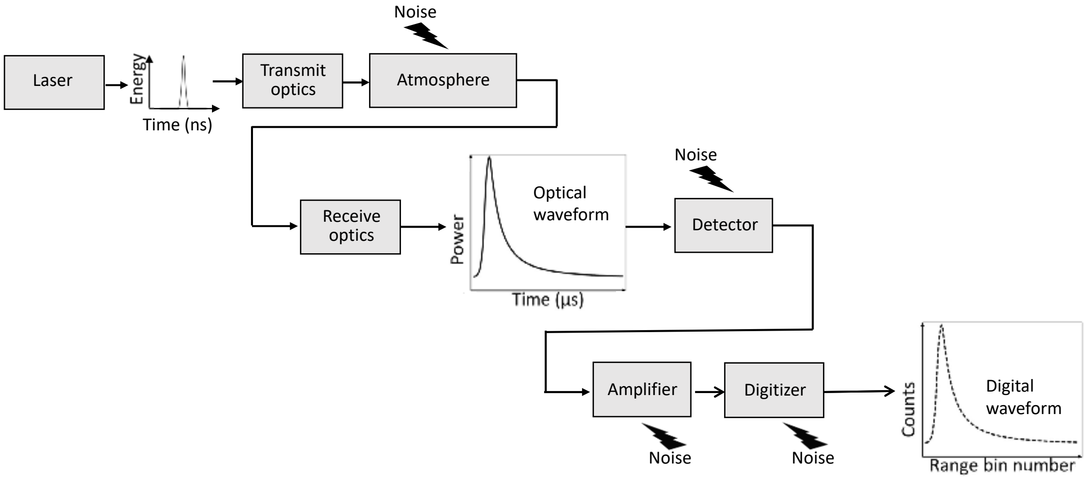
http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/polclas.html

Linear depolarization lidar



G.G. Gimmestad graphic

Data systems: analog signal processing



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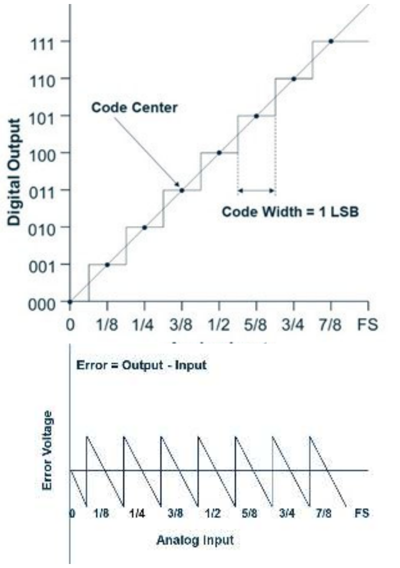
Quantization error

- The mere act of digitizing the signal into discrete levels adds uncertainty, which is a type of “noise”.
- For clarity, a 3-bit digitizer is illustrated here.



https://analogquantized.wordpress.com/2013/02/23/quantization/

Ideal signal-to-noise ratios due to quantization

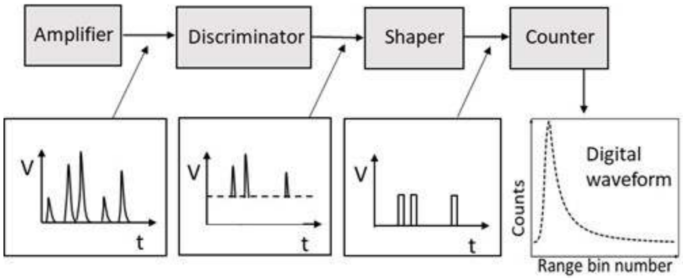
Resolution	Quantizing Levels	Signal-to-Noise Ratio (dB)
6 bits	64	37.9 dB
8 bits	256	49.9 dB
10 bits	1,024	62.0 dB
12 bits	4,096	74.0 dB
14 bits	16,384	86.0 dB
16 bits	65,536	98.1 dB

N = 1 in this table
(single pulse)

$$SNR_{ideal}(n, N) = 20 \log\left(2^n \sqrt{\frac{3}{2} N}\right)$$

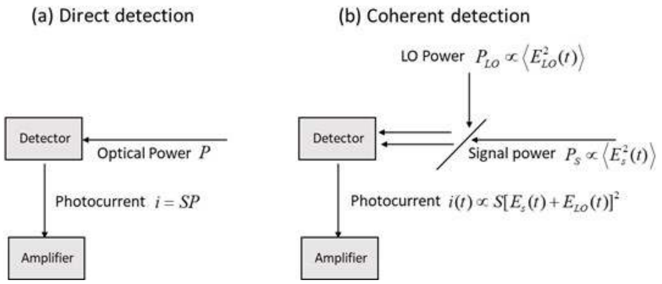
where *n* is the number of bits and *N* is the number of pulses averaged.

Data systems: photon counting



1. A photodetector produces narrow current pulses in response to incident photons and internal noise
2. The output pulses are amplified (and inverted if necessary) by a preamplifier
3. A discriminator blocks pulses below a specified amplitude to filter out noise
4. A pulse shaper converts the analog pulses from the discriminator into digital pulses
5. A counter counts the pulses

Direct vs. coherent detection



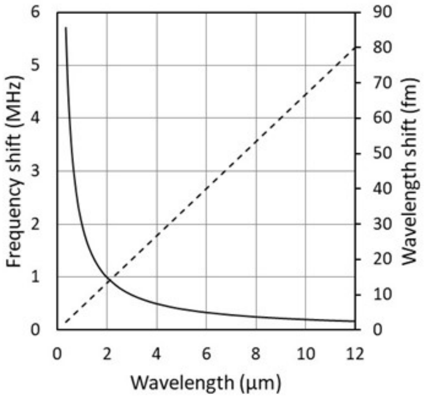
S = detector responsivity (A/W)

- Coherent has three advantages:
  - Highest SNR
  - Background discrimination
  - Doppler wind speed
- However, atmospheric turbulence limits the receiver aperture to ~10 cm for ground-based lidars.

Doppler wind sensing

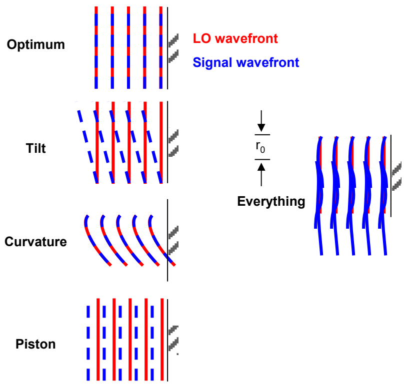
$$\Delta \nu = -2\frac{\mathrm{v}}{\lambda}$$

$$\Delta \lambda = 2\frac{\mathrm{v}}{c}\lambda$$



- v is wind speed, positive for motion away from lidar
- Plot is for -1 m/s wind.
- Solid line is frequency shift.
- Dashed line is absolute value of wavelength shift.
- Frequency shifts are MHz per m/s
- Wavelengths shifts are tens of fm!

Mixing efficiency & refractive turbulence



- The analysis described previously assumed
  - Flat LO and signal wavefronts
  - Parallel LO and signal wavefronts
- If the wavefronts are tilted relative to one another, the mixing efficiency is reduced
- Refractive turbulence adds local wavefront piston, tilt, and curvature to the signal wavefront
- The result is that increasing the receiver aperture much beyond the coherence diameter r_0 does not increase the signal

Summary

- Transmitters
  - What can be achieved in lidar depends on the laser
  - UV-VIS lasers are eye hazards and can cause optical damage
  - Many types of lidar must operate in the UV-VIS region
- Receivers
  - Sky background is maximal in the UV-VIS region
  - Narrow FOV and small optical bandwidth both reduce sky background
  - Detectors need linearity, internal gain, high quantum efficiency, and low dark count rate
- Data Systems
  - Photon counting SNR is better than analog, but maximum count rate is fairly low
  - Good digitizers are available
  - Coherent detection has three advantages but relies on aerosol backscatter and has small receiver due to atmospheric refractive turbulence.

Resources

V. Kovalev and W. Eichinger, *Elastic Lidar: Theory, Practice, and Analysis Methods*. Hoboken: Wiley-Interscience, 2004.	Written as a handbook of elastic backscatter lidar and a guide to the lidar literature. Includes some lidar instrumentation, but more focused on lidar techniques and analysis.
C. Weitkamp, Ed., *Lidar: Range-resolved optical remote sensing of the atmosphere.* New York: Springer, 2005.	Has 14 chapters on all major types of atmospheric lidar, with different authors for each chapter. Highly recommended as a general resource.
T. Fujii and T. Fukuchi, Eds., *Laser remote sensing*. New York: Taylor & Francis, 2005.	Has 9 chapters with different authors. Complementary to the Springer book described above, and chapters on resonance fluorescence lidar and wind lidar much more comprehensive.
C.-Y. She and J.S. Friedman, *Atmospheric Lidar Fundamentals: Laser Light Scattering from Atoms and Linear Molecules*. New York: Cambridge University Press, 2022.	Covers the physics of laser light scattering and atomic/molecular spectroscopy as well as the underlying optical and electro-optical technologies required for lidar.
G.G. Gimmestad and D.W. Roberts, *Lidar Engineering: Introduction to basic principles*, New York: Cambridge University Press, 2022 (in press).	A textbook, covering all aspects of lidar engineering at the advanced undergraduate level, with worked examples, homework problems, and many references. In press.

Coming Soon!

- How to build an eye safe lidar from scratch, operate it, and process the data, plus more!
- Chapters on
  - lidar performance models
  - atmospheric optics
  - Transmitters and receivers
  - Optomechanics
  - Optical detection
  - Data systems
  - Data analysis
  - Applications
- Cambridge University Press ISBN 9780521198516