IOCCG Summer Lecture Series

Principles of lidar

Davide Dionisi

Italian National Research Council- Institute Marine Sciences (CNR – ISMAR), Rome, Italy

14 July 2026

Summary

- Introduction
  - What is a lidar
  - Historical overview

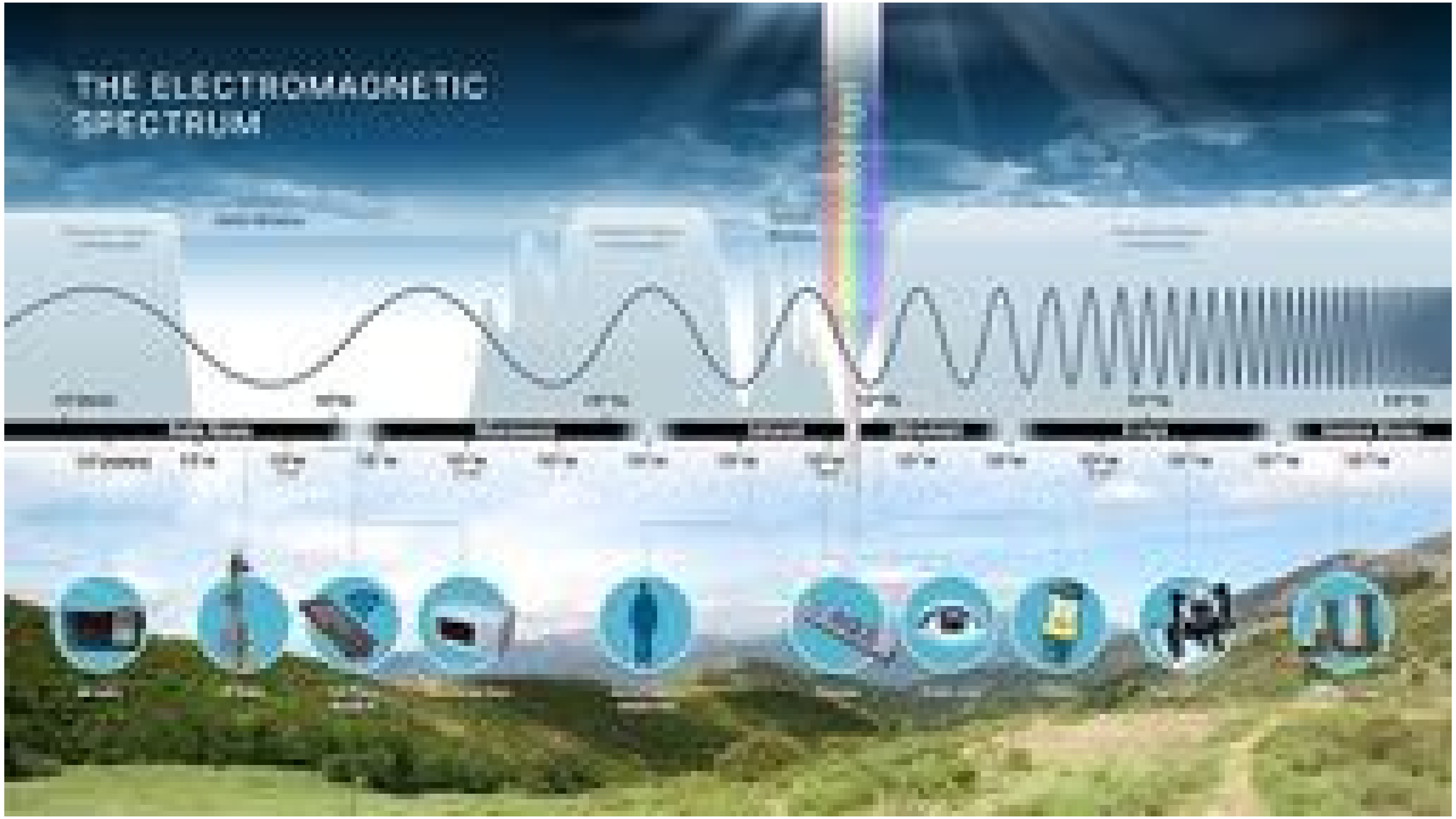
- Lidar basics
  - Description of the instrument
  - Lidar equation

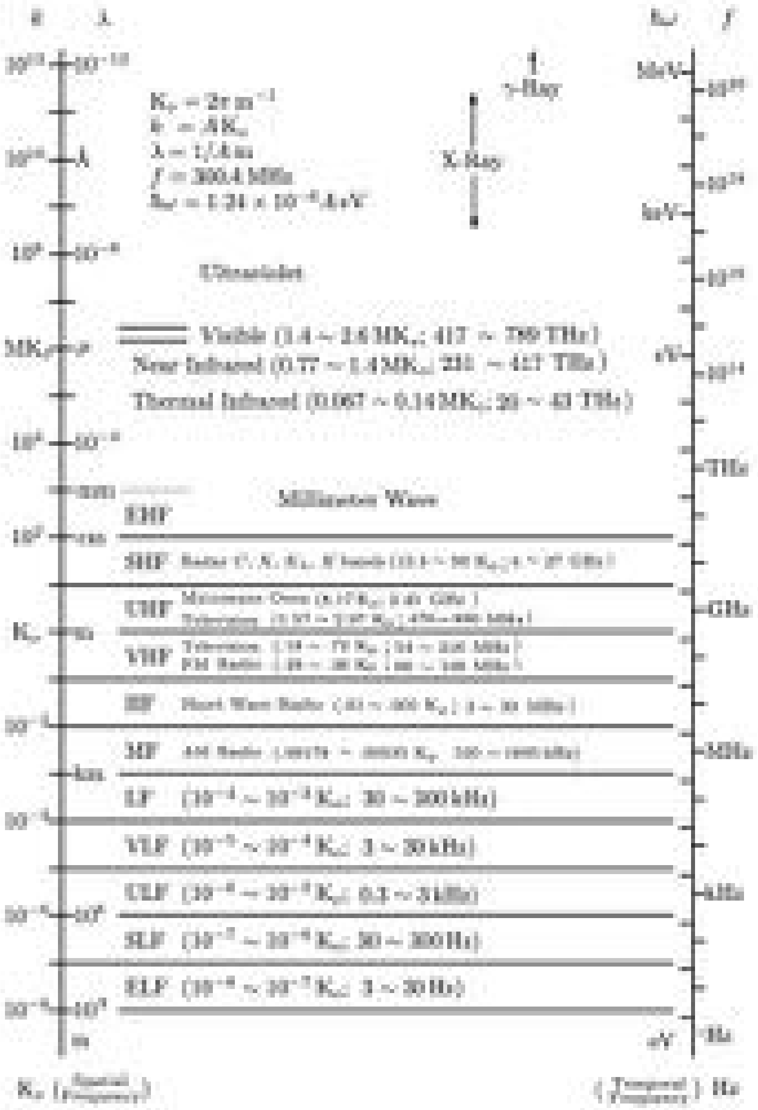
- Optical Interactions of Relevance to Lidar and oceanic lidar algorithms
  - Elastic: Rayleigh/Mie/Polarization;
  - Inelastic: Raman/Fluorescence/Brillouin;

- Lidar variables and OC products

- Uncertainties
  - Precision and Accuracy
  - Signal-to-noise ratio and calibration

Introduction – Electromagnetic spectrum

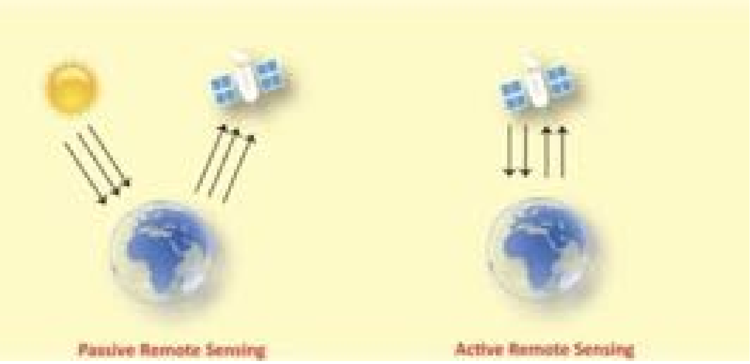




Introduction – What is a lidar

Lidar is an optical sensing technology that can measure the **distance to, or other properties of a target** by illuminating the target with pulsed **light** produced by a laser.

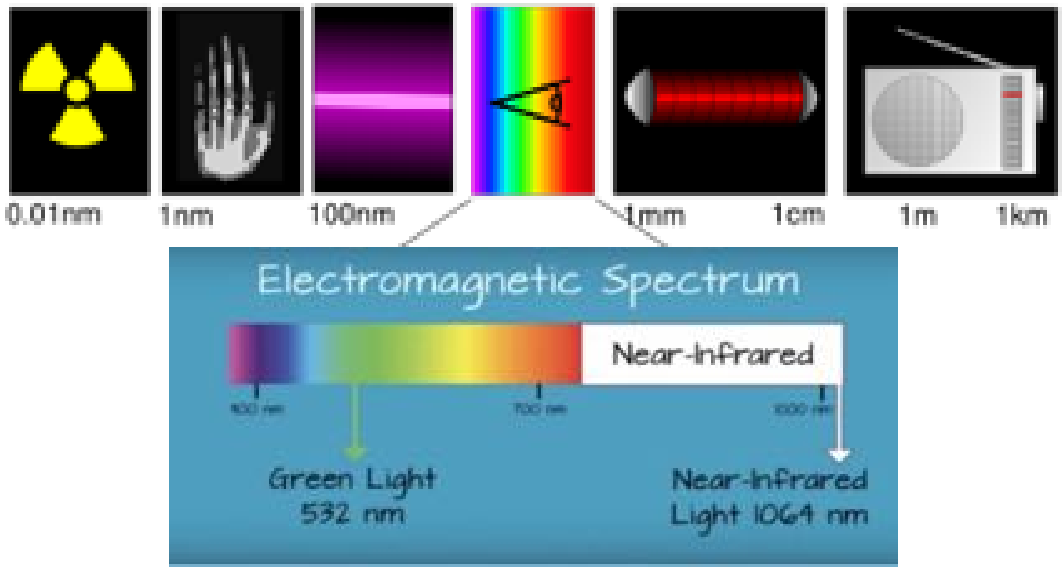
Active remote sensing technique



RADAR : Radio Detection and Ranging
LIDAR : Light Detection and Ranging

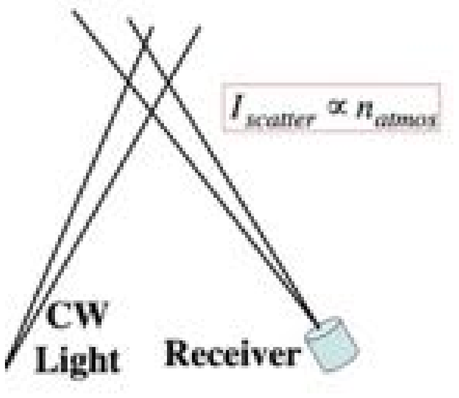
=> Same physical principle, except the wavelength.

Lidar mainly operates using electromagnetic (EM) waves in the optical and infrared spectrum



Introduction – Historical Overview

- 1930: E.H. Synge suggests to probe the atmospheric density using light source, « Searchlight» principle.



- 1946: First monostatic lidar system with pulsed light source to determine the base clouds altitude by R. Bureau.

- 1959: Laser invention by G. Gould (principle given by A. Einstein in 1917).

- 1962,63: First use of laser as lidar source to measure the distance from the moon and for stratospheric measurements by L.D. Smullins and G. Fiocco.

- 1980: First airborne lidars by E.V. Browell

- 1994: Lidar In-space Technology Experiment (LITE). First Earth-orbiting atmospheric lidar.

McCormick,

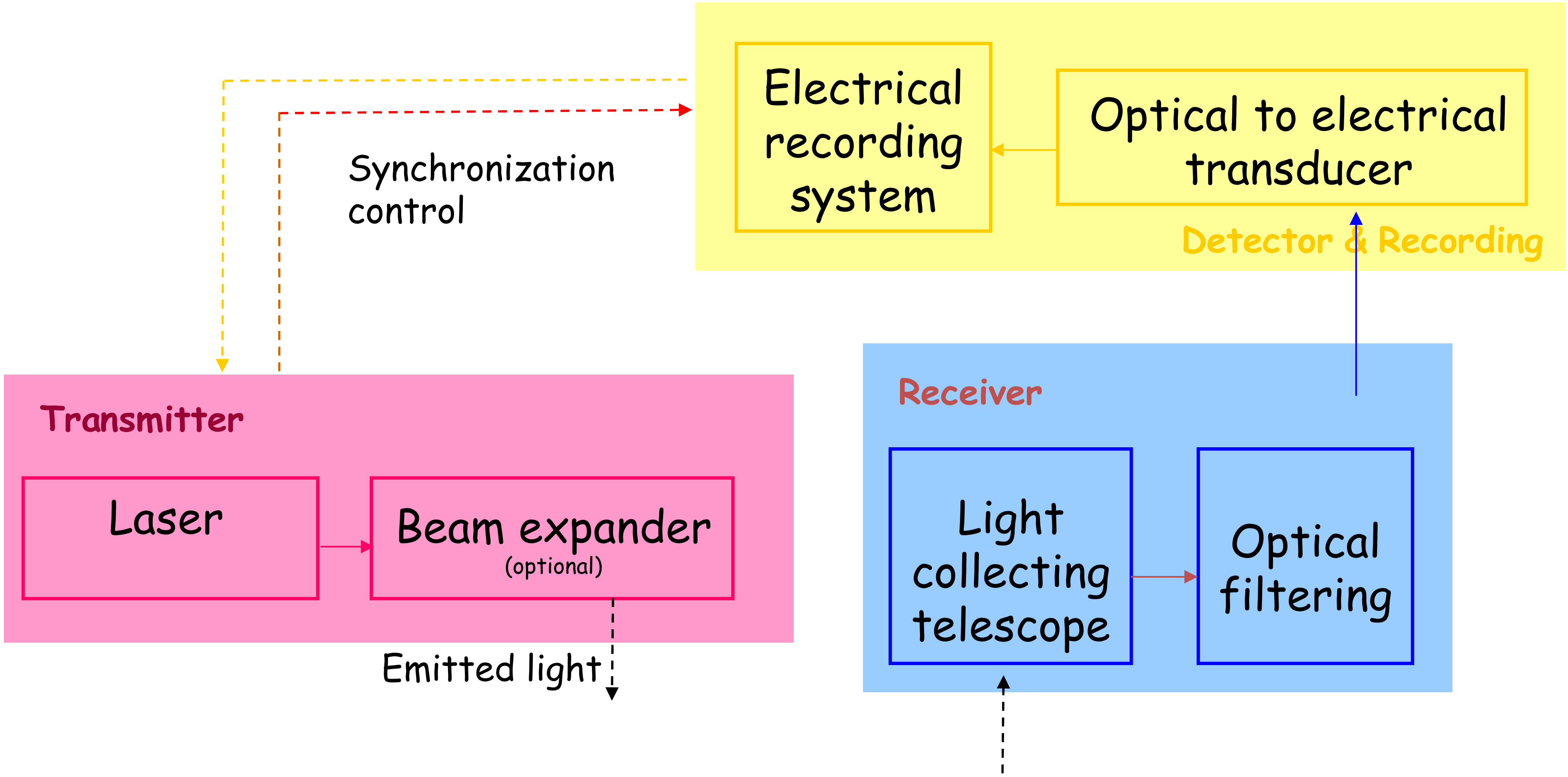
Introduction – Lidar applications

Lidar supports a wide range of applications

- Archaeology (uncovering hidden landscapes)
- Construction (high-resolution 3D models of construction sites and existing structures)
- Forestry and agriculture (forest structure and health; land's surface and soil conditions)
- Mapping and Surveying
- Transport (autonomous vehicles, aviation)
- Military and defense
- Urban Planning and risk assessment
- Energy (wind, bathymetry)
- Geology
- Environmental Monitoring (Land, Coastal, Atmosphere, Marine)

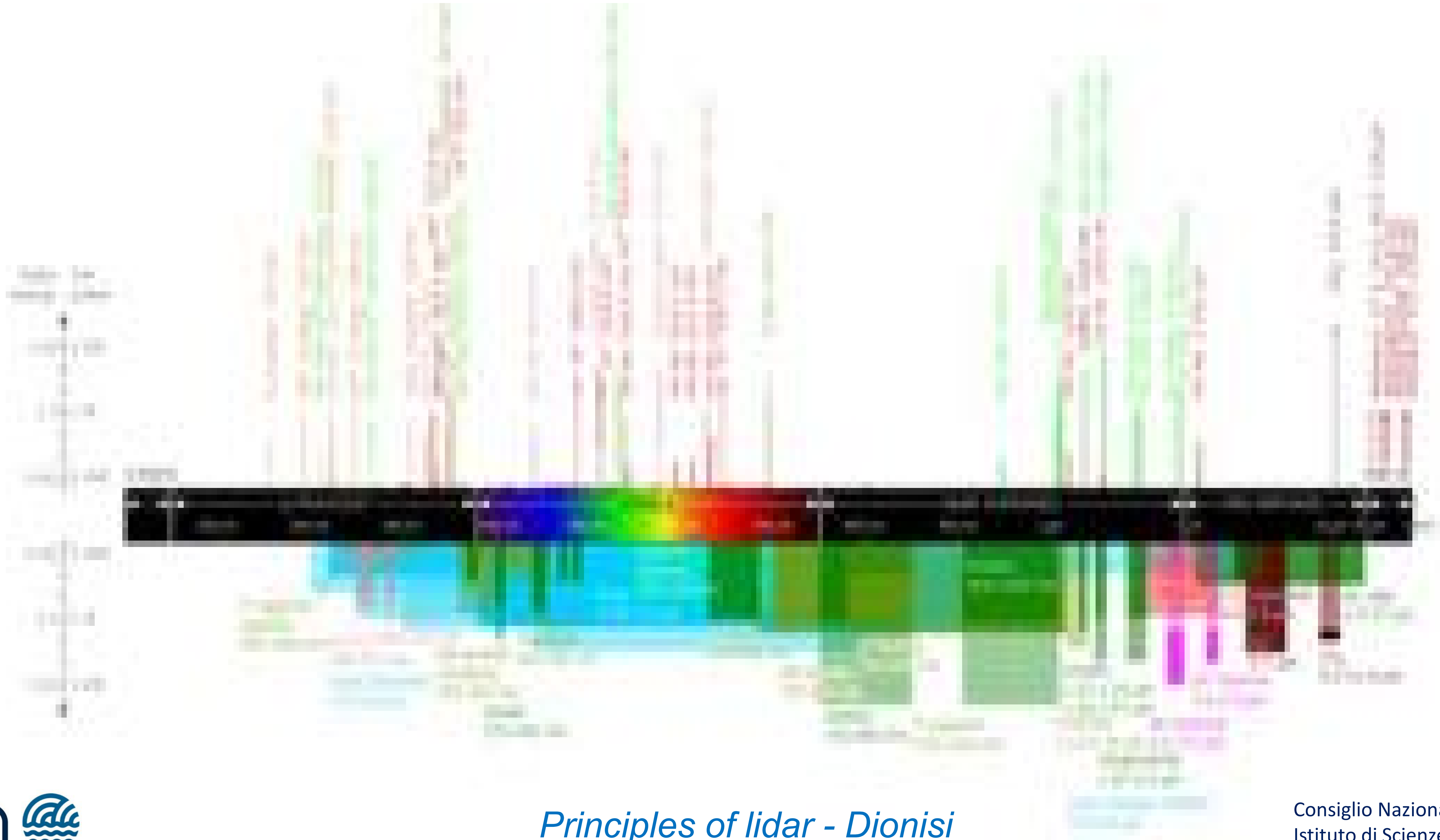
Lidar Basics

Block diagram of a generic lidar system



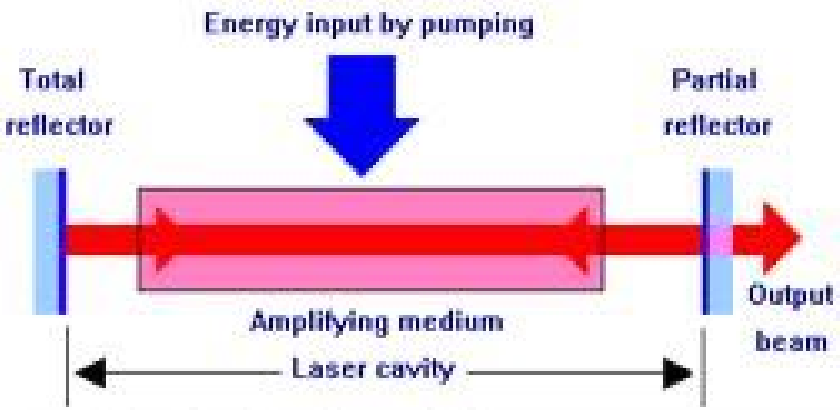
Consiglio Nazionale delle Ricerche
Istituto di Scienze Marine

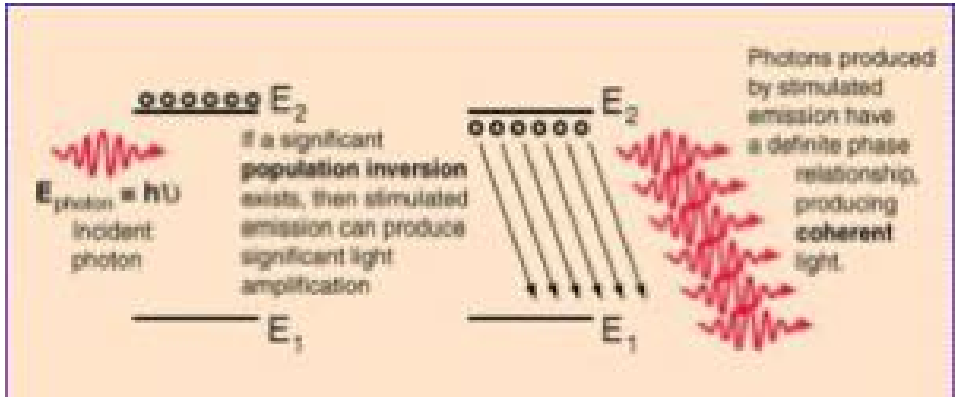
Lidar Basics – Transmitter



Lidar Basics – Transmitter

Laser = Light Amplification by Stimulated Emission of Radiation





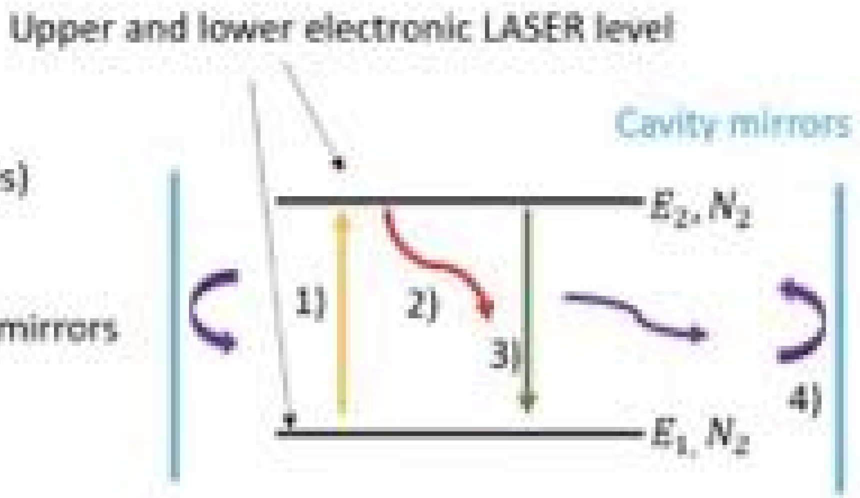
How does lasing work?

Two-level system

1) Pumping electron into higher energetic level (flashlamp, diodes)
2) Spontaneous emission of a photon
3) Spontaneously emitted photon **stimulates** next emission
4) Simulation of further emissions by photons reflected at cavity mirrors

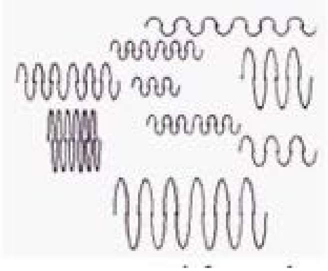
-> exponential increase of number of photons in cavity

-> **light amplification by stimulated emission**

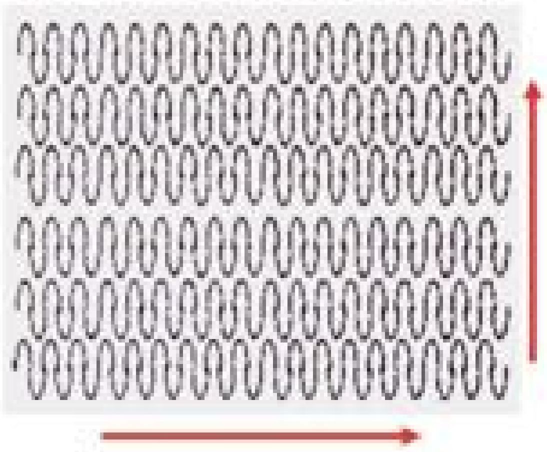


Lidar Basics – Transmitter

Incoherent emission: photons are emitted randomly, at different times and with different phases



Coherent emission: photons are emitted simultaneously and with the same phase



Spatial coherence: waves have the same phase at all points across the cross-section of the beam.

Temporal coherence: waves maintain the same phase over time.

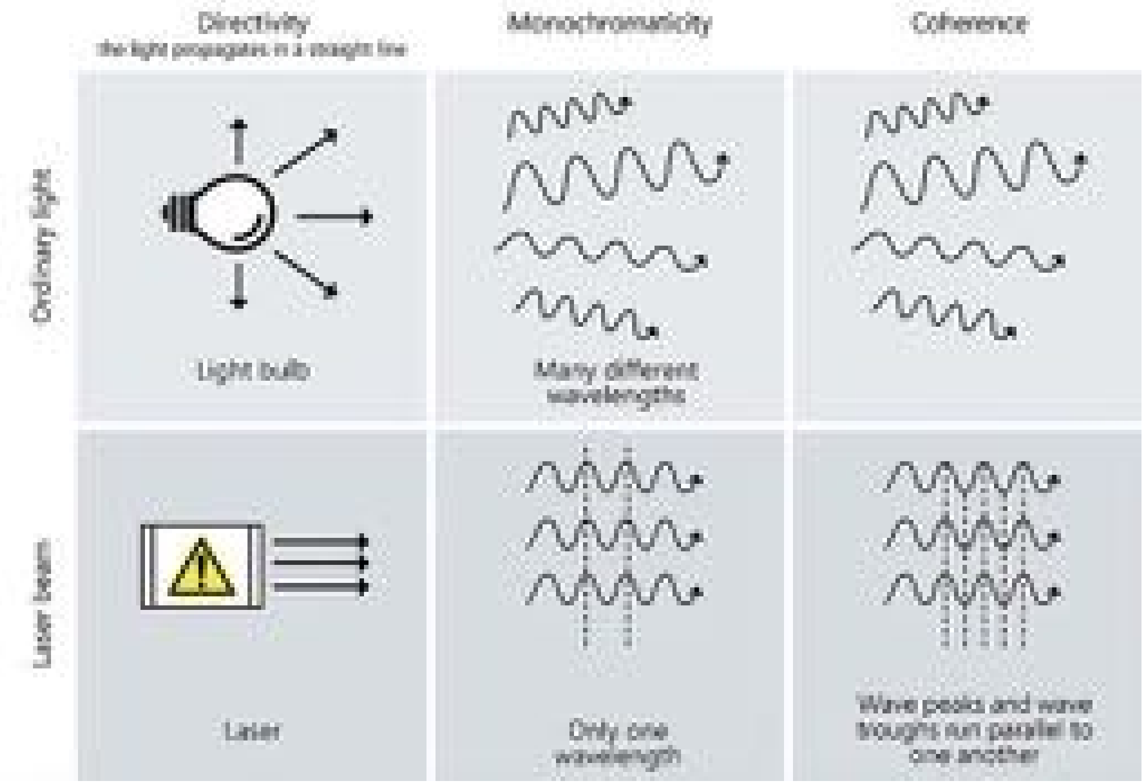
High directivity

Laser emits a collimated beam. Related to spatial coherence. Intrinsic divergence due to the diffraction limit

Monochromaticity: capability of laser to emit radiation beams in a narrow spectral range

$$\Delta t_c = \frac{1}{\Delta \upsilon} \qquad \Delta \upsilon = \frac{c}{\lambda^2} \Delta \lambda \qquad l_c = \frac{\lambda^2}{\Delta \lambda} = \frac{c}{\Delta \upsilon}$$

Lidar Basics – Transmitter

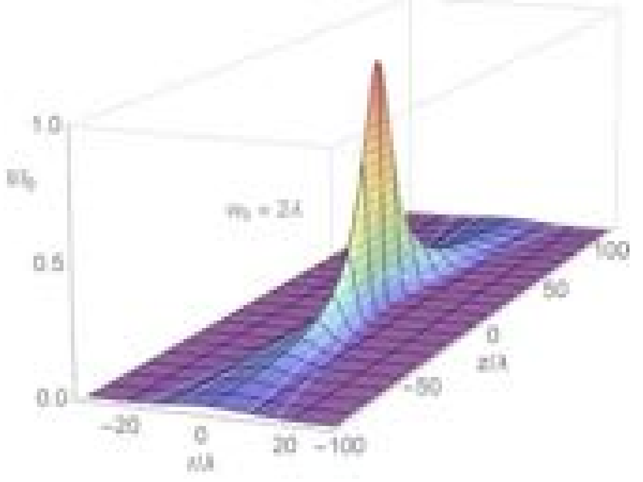


- Monochromaticity
- High directivity
- High coherence
- High energy density

Lidar Basics – Transmitter

Laser Properties

Irradiance (*I*) or power density [W/m²] is a consequence of the directivity



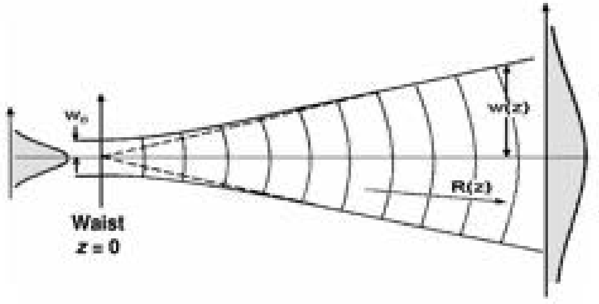
- For a gaussian beam (simmetric on x and y axes), the irradiance is:

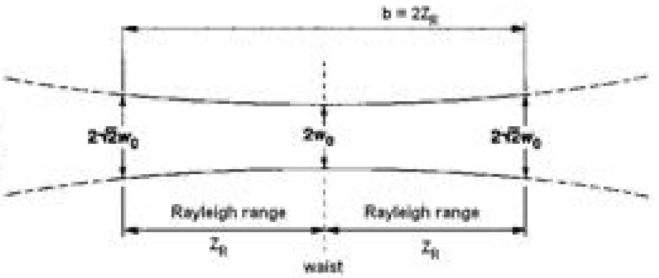
$$I(x,y,z) = I_0 exp\left[\frac{-2(x^2+y^2)}{w^2}\right]$$

$I_0 =$ max irradiance
$w(z) =$ radius of the laser beam
$z =$ coordinate for the beam direction

Propagation of a Gaussian beam

$$w^2(z) = w_0^2 + \left(\frac{w_0}{z_R}\right)^2 z^2 = w_0^2 + \left(\frac{\lambda}{\pi w_0}\right)^2 z^2 \rightarrow \sigma^2(z) = \sigma_0^2 + \theta_\sigma^2 z^2.$$



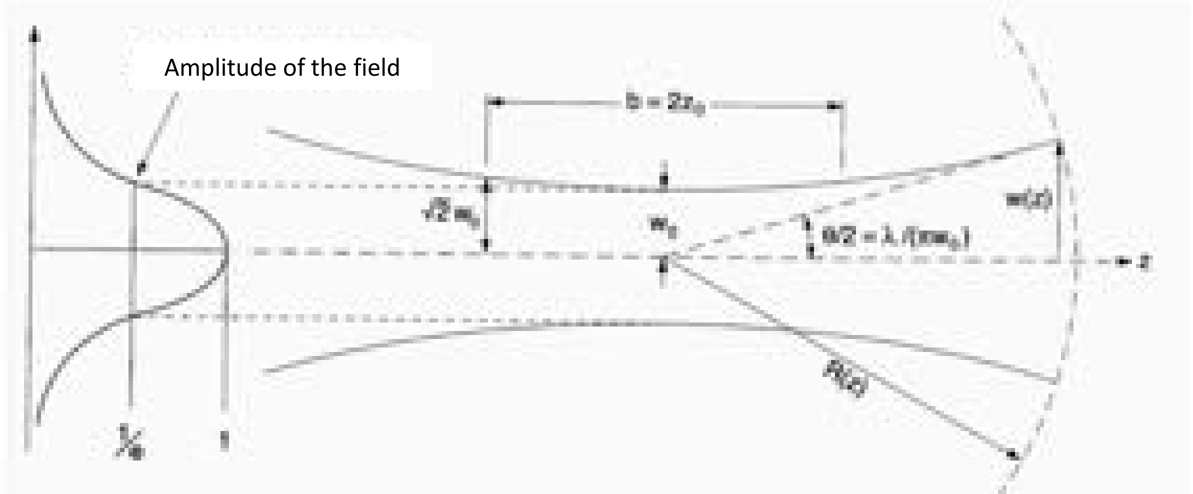


$$z_R = \frac{\pi w_0^2}{\lambda}$$

z_R = Rayleigh distance = distance at which the beam is considered collimated

Laser Properties

Divergence of a Gaussian beam



For $z > z_R$ the divergence angle is given by the asymptotes of the hyperbole

$$\theta = 2\lim_{z\to\infty}\frac{w(z)}{z} = 2\lim_{z\to\infty}\left[\frac{w_0^2}{z^2}+\left(\frac{w_0}{z_R}\right)^2\right]^{1/2}$$

$$\boxed{\theta = \frac{2w_0}{z_R} = \frac{2\lambda}{\pi w_0} = 0{,}64\,\frac{\lambda}{w_0}} \Rightarrow w_0\theta = 0{,}64\lambda$$

Lidar Basics – Emission geometry

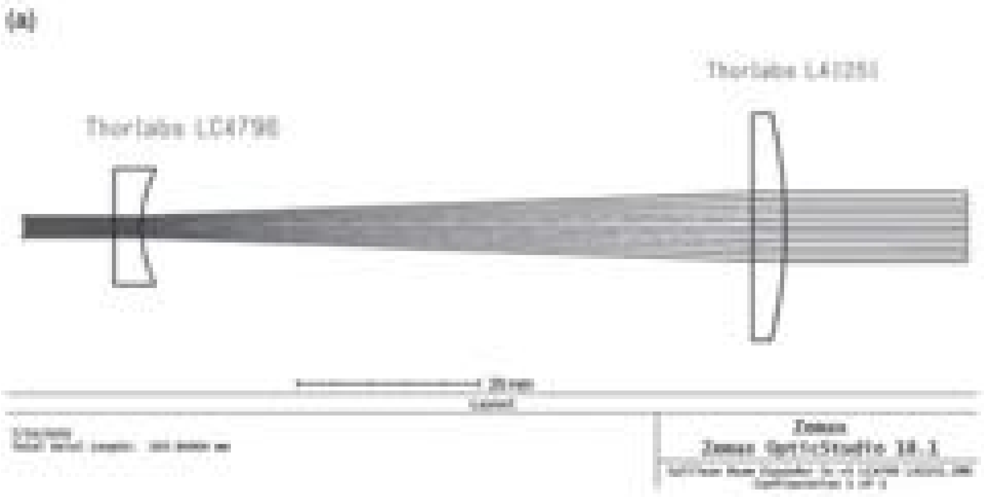
Beam expander

Beam quality quantified by the beam parameter product (BPP, conservative parameter):

$$BPP = w_0 \cdot \frac{\theta}{2}$$

By enlarging the beam size, the transmitting beam divergence angle is accordingly reduced due to conservation of BPP.

Beam expander = a small telescope with the placement of its objective and image lenses reversed.



Consiglio Nazionale delle Ricerche
Istituto di Scienze Marine

Telescope

Collection of the scattered return and deliver to a photon-counting detector.

Principal elements:

- mirror size
- Reflectivity
- f-number $$f = \frac{f_l}{d_a}$$
- Field of view $$FOV = \frac{r}{f_l}$$

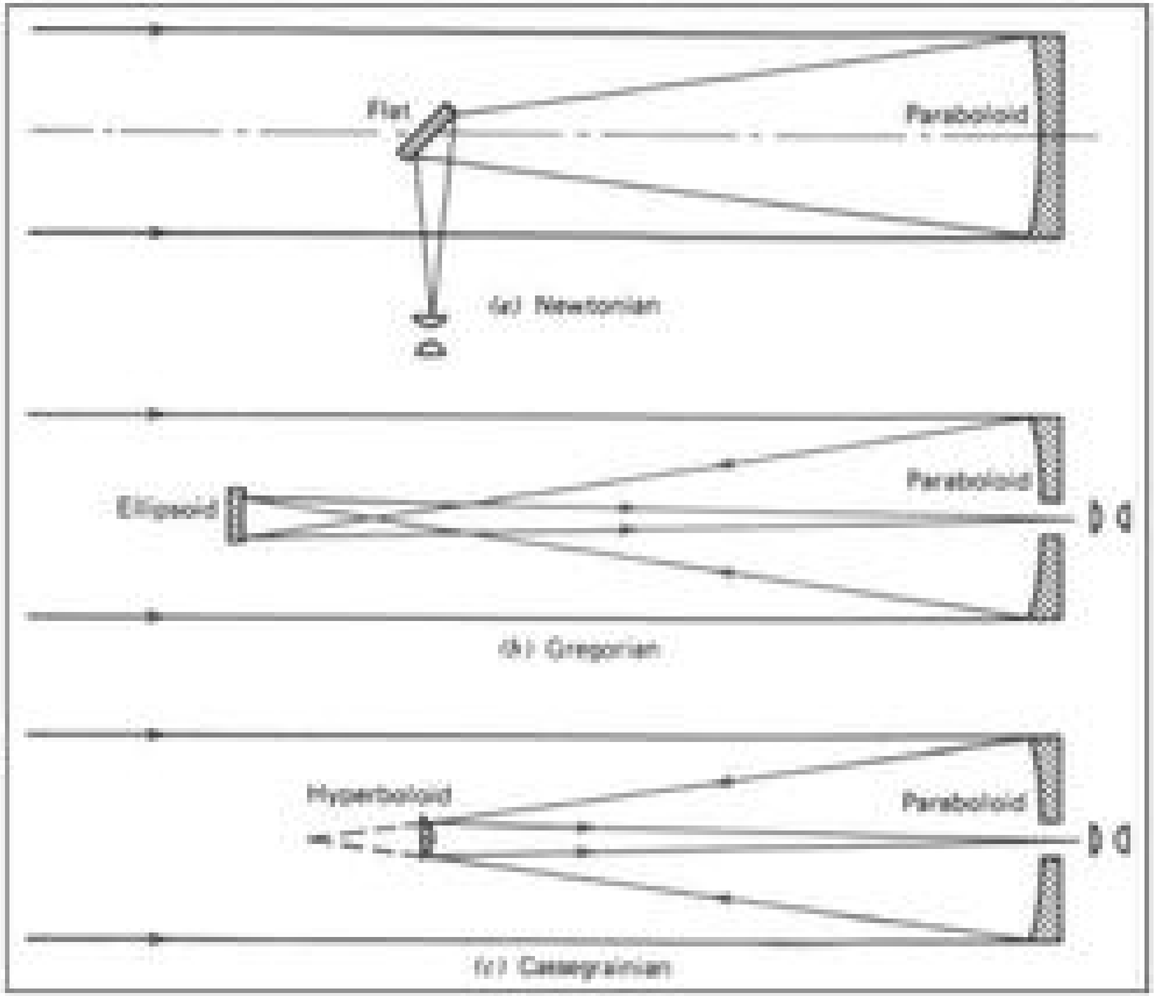


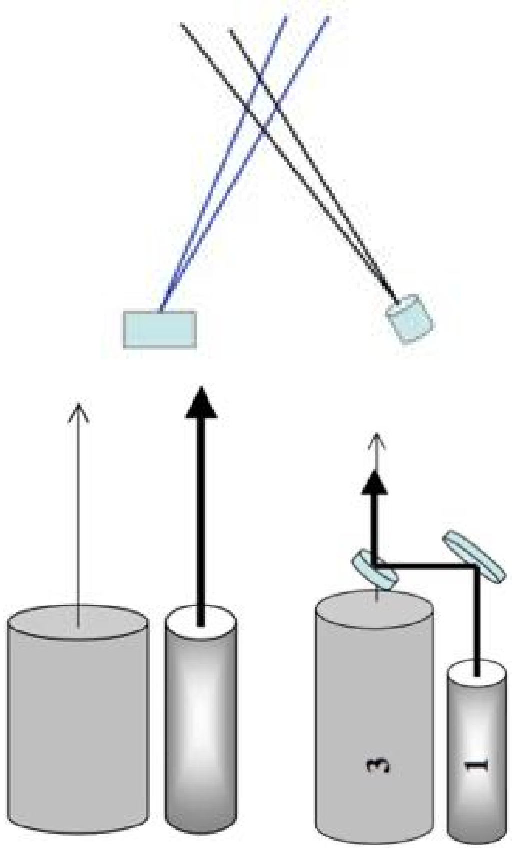
Fig. SOURCE: Measures (1992); R.M. Measures, "Laser Remote Sensing. Fundamentals and Applications". John Wiley & Sons, 1984. (Reprint de 1992, Krieger Publishing Company).

Lidar Basics – Emission-reception

Emission – reception geometry

Bistatic

Monostatic



Biaxial Coaxial

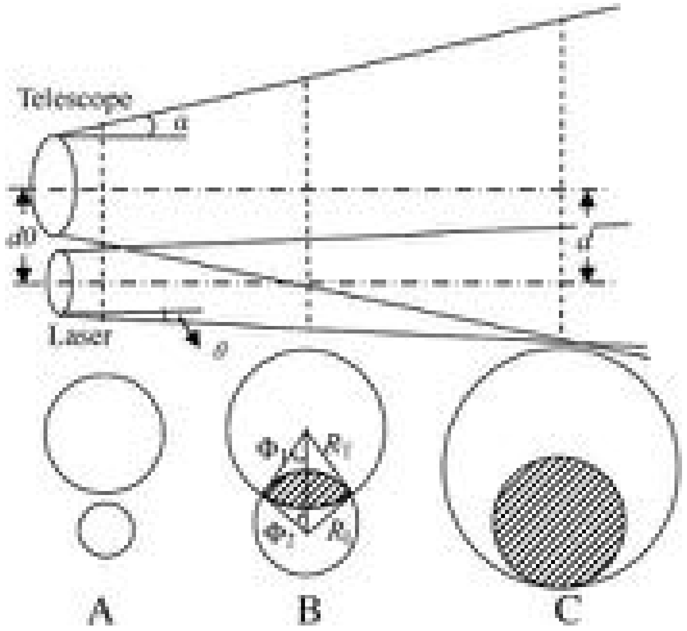
Laser Telescope

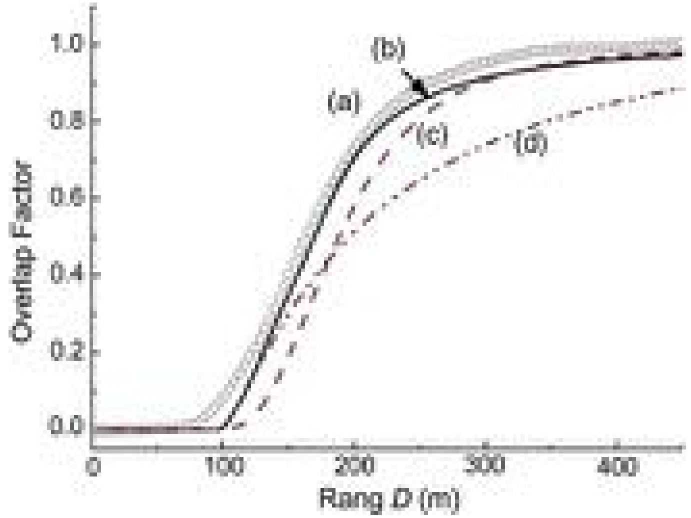
Background stray light is a major contributor to noise on the lidar signal and is a major challenge for daytime operations.
Reducing the field of view is the most effective way to mitigate this.

Consiglio Nazionale delle Ricerche
Istituto di Scienze Marine

Overlap factor

The telescope cannot “read” the full atmospheric cross-section illuminated by the laser beam (i.e., does not lie within its FOV).
The overlap function $O(z)$quantifies the fraction of the laser beam seen by the receiver. It increases from 0 (no overlap) to 1 (full overlap) as range increases.





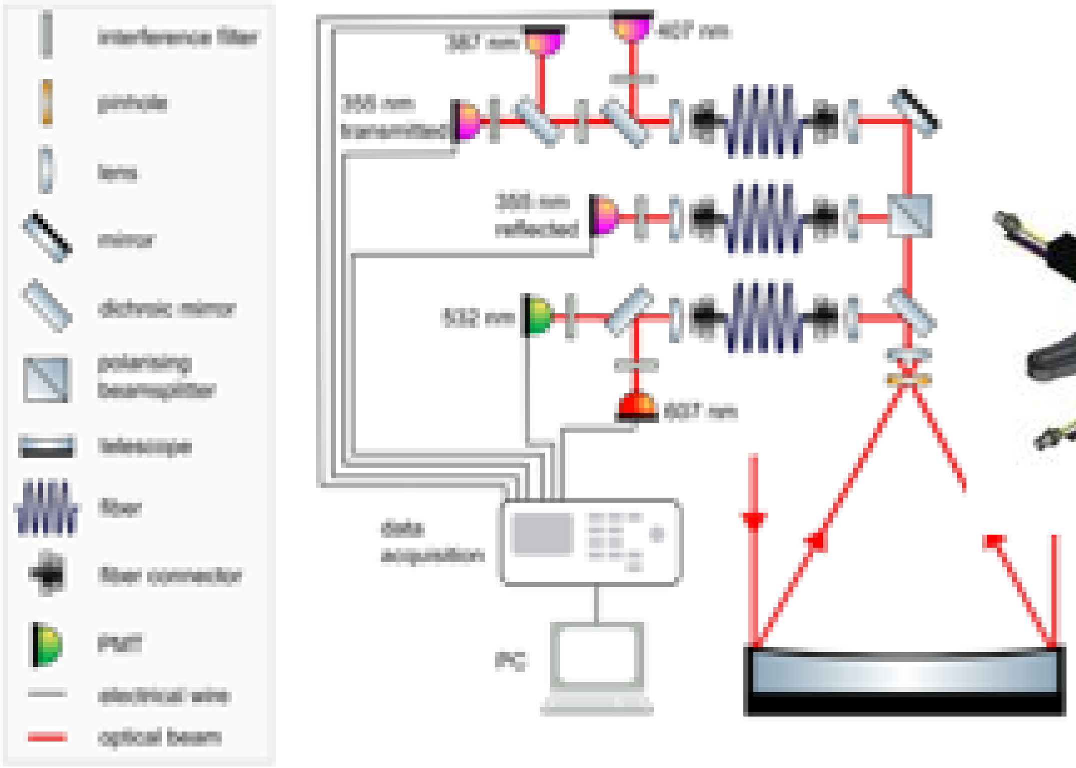
Gong et al., 2011 (https://doi.org/10.1016/j.optcom.2011.01.062)

It is a function of many geometrical and optical parameters of both the laser and telescope.

Lidar Basics – Optical selection

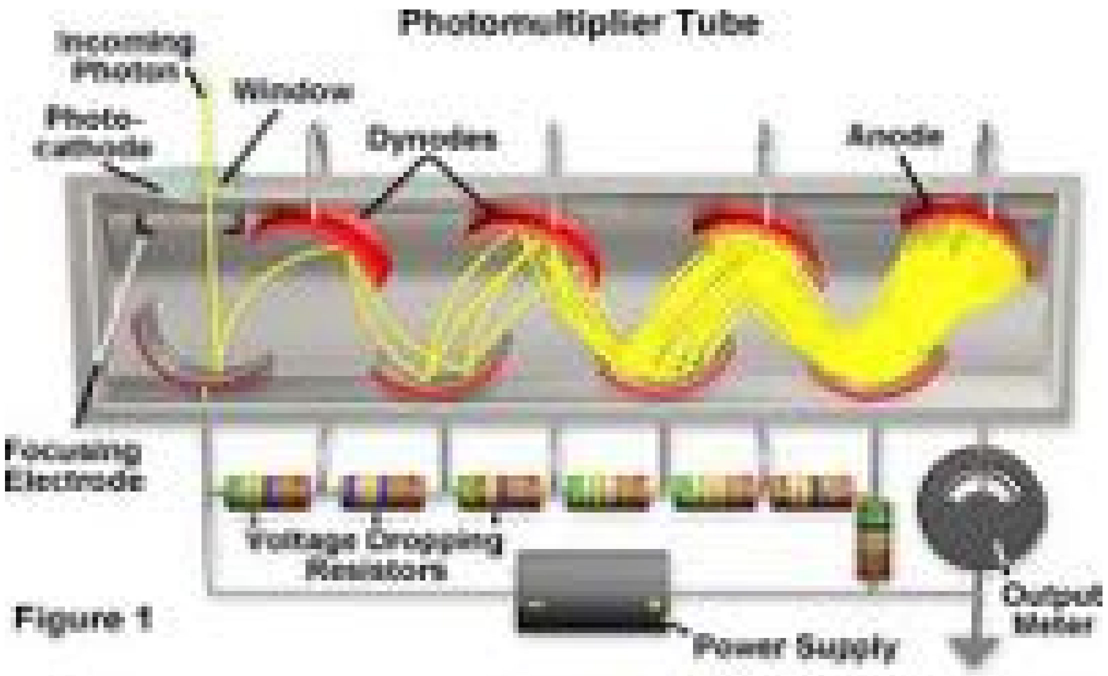
From Telescope Output to PMTs

The receiver uses a field stop and collimating optics to stabilize angular response and define field of view.



PMT

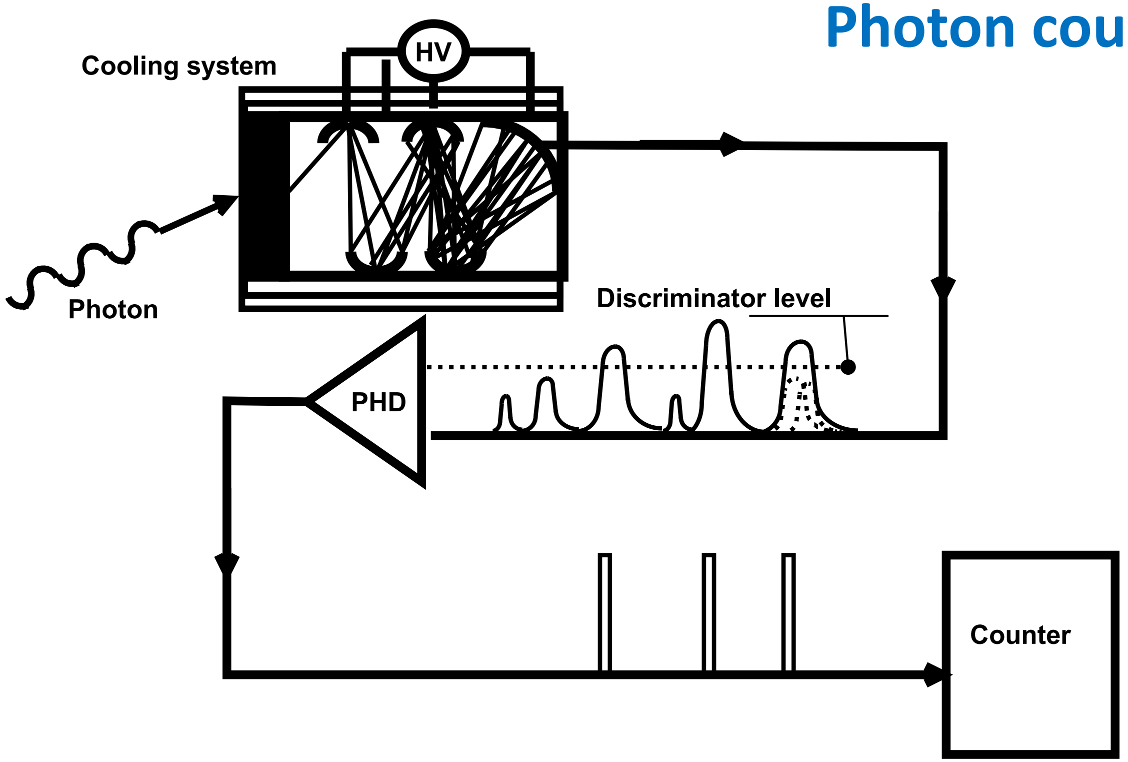
Photomultiplier tubes (PMTs) convert photons to an electrical signal



- Accelerate electrons within the chain of dynodes

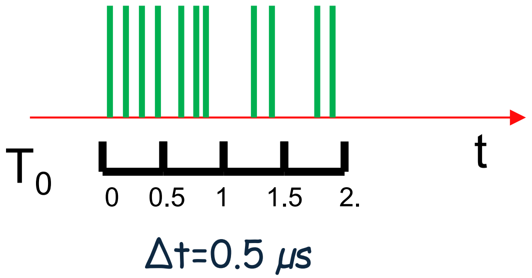
- The amplification depends on the number of dynodes and the accelerating voltage. This amplified electrical signal is collected at an anode at ground potential, which can be measured

Photon counting



Vertical resolution:

$$\Delta z = c\Delta t/2$$



Photon Counting Detection

Detects individual photons using devices like PMTs and SPADs to generate electrical pulses for weak signals.

Signal Processing Chain

Amplifies pulses, applies threshold discrimination, and converts signals into standardized digital pulses for counting.

Range Resolution and Profiling

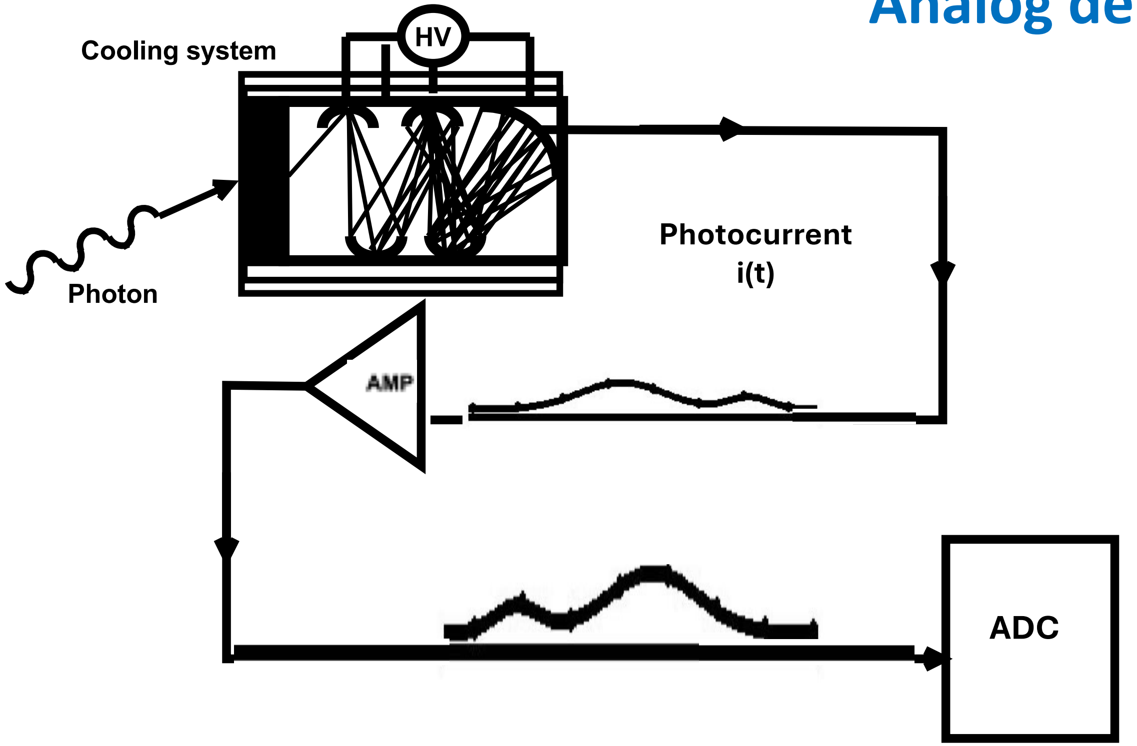
Time-binned photon counts enable calculation of range-dependent profiles with resolutions defined by bin width.

Statistical Sensitivity and Limitations

Photon counting follows Poisson statistics and excels at low signals but suffers saturation at high count rates.

Lidar Basics – Detection

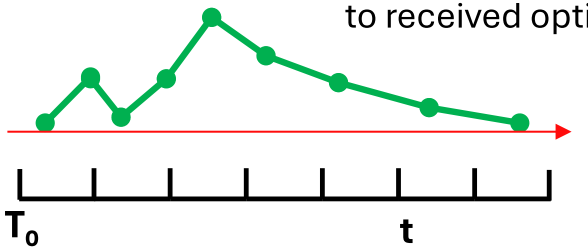
Analog detection



Digitized voltage proportional to received optical power

Vertical resolution:

$$\Delta z = c\Delta t/2$$



$\Delta t = 0.5\ \mu s$

Principle of Analog Detection

Analog detection converts photon flux into a continuous electrical signal proportional to optical power.

Signal Amplification and Digitization

Photocurrent is amplified by a transimpedance amplifier and digitized by an analog-to-digital converter.

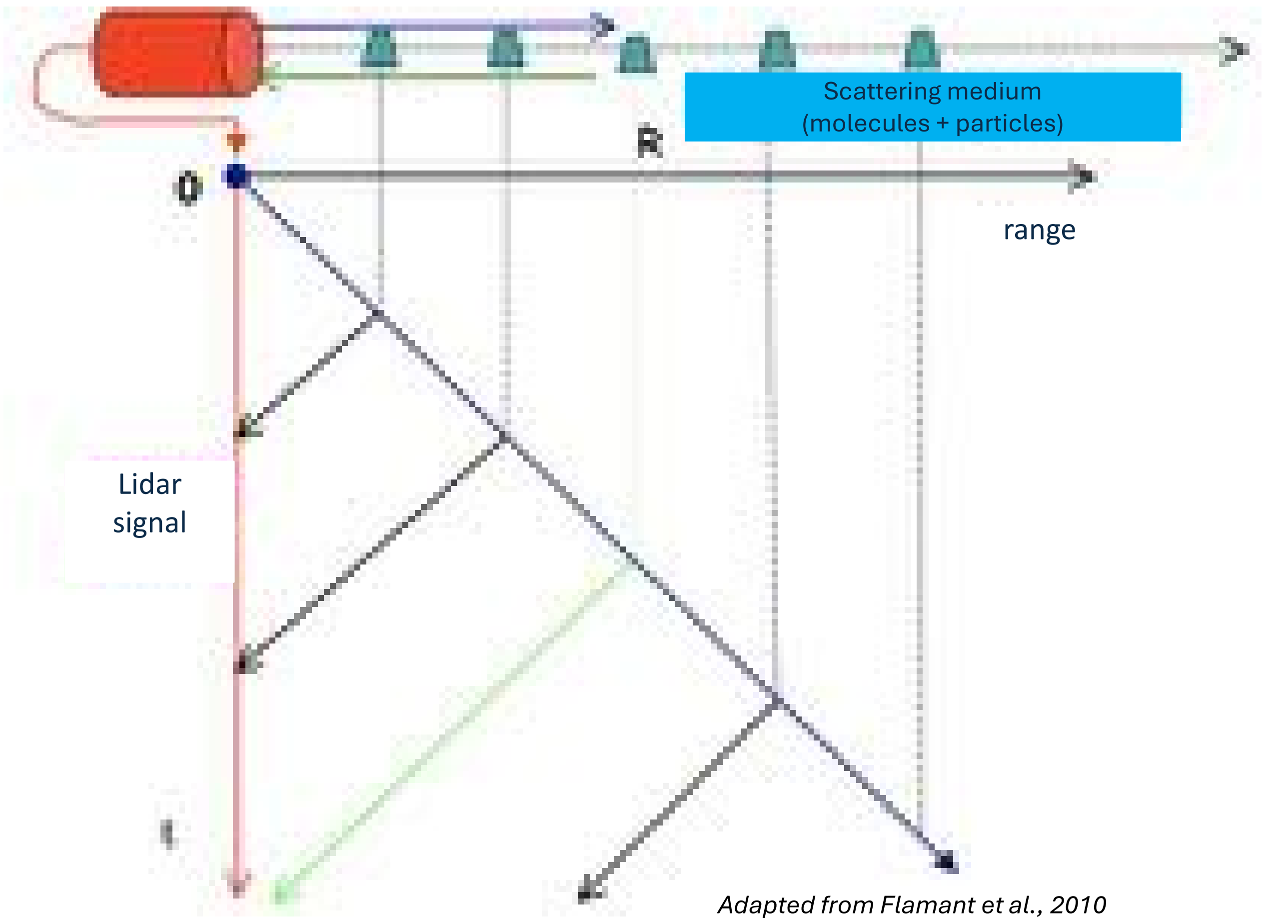
Advantages and Limitations

Analog mode handles high signals without saturation but suffers at low signals by electronic noise and shot noise.

Combined Use with Photon Counting

Analog detection is complemented by photon counting to cover wide dynamic ranges effectively.

Building a lidar profile



Adapted from Flamant et al., 2010

- The laser pulse is not stopped by the medium; it is progressively attenuated.
- Backscatter is received continuously along the line of sight.
- The output is a range-resolved atmospheric profile.

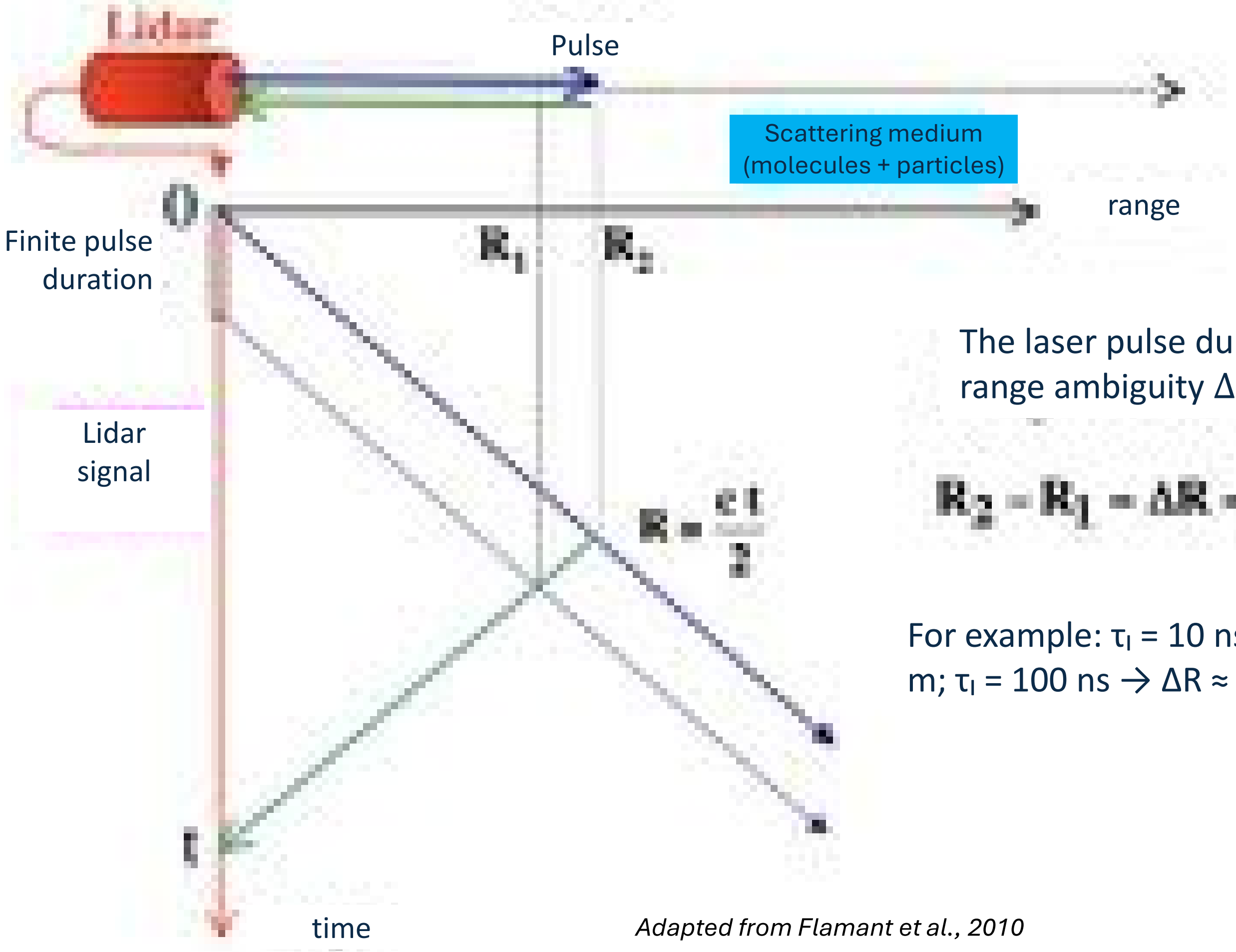
Each detection time corresponds to the range of the scattering volume.

$$R = c\,t\,/\,2$$

Lidar ranging is a time-of-flight measurement with a two-way path.

Lidar Basics – Ranging

Building a lidar profile



Adapted from Flamant et al., 2010

The laser pulse duration leads to a range ambiguity ΔR

$$R_2 - R_1 = \Delta R = \frac{c\,t_l}{2}$$

For example: τ_l = 10 ns → ΔR ≈ 1.5 m; τ_l = 100 ns → ΔR ≈ 15 m.

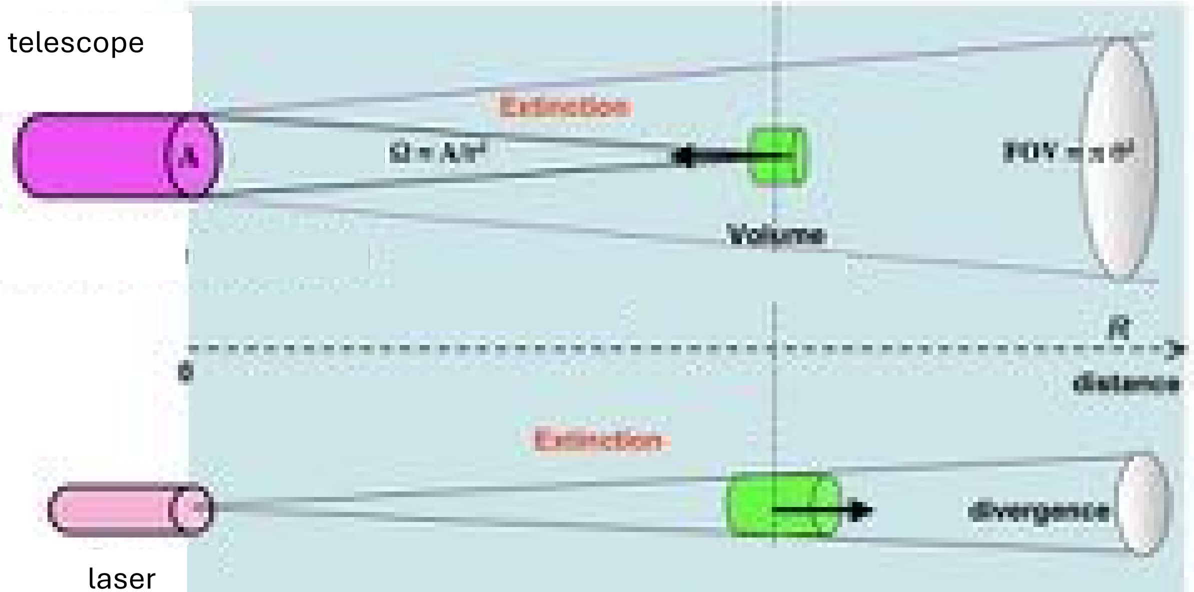
Lidar effective resolution is due:

- laser pulse duration
- detector/electronics response
- digitizer sampling interval
- range-bin integration time

Lidar Basics – Lidar equation

Elastic backscatter lidar

$$P(\lambda, r) = P_0(\lambda) \cdot K(\lambda) \cdot G(r) \cdot \Delta R \cdot \beta(\lambda, r) \cdot T^2(\lambda, r) + P_{bg}(\lambda)$$



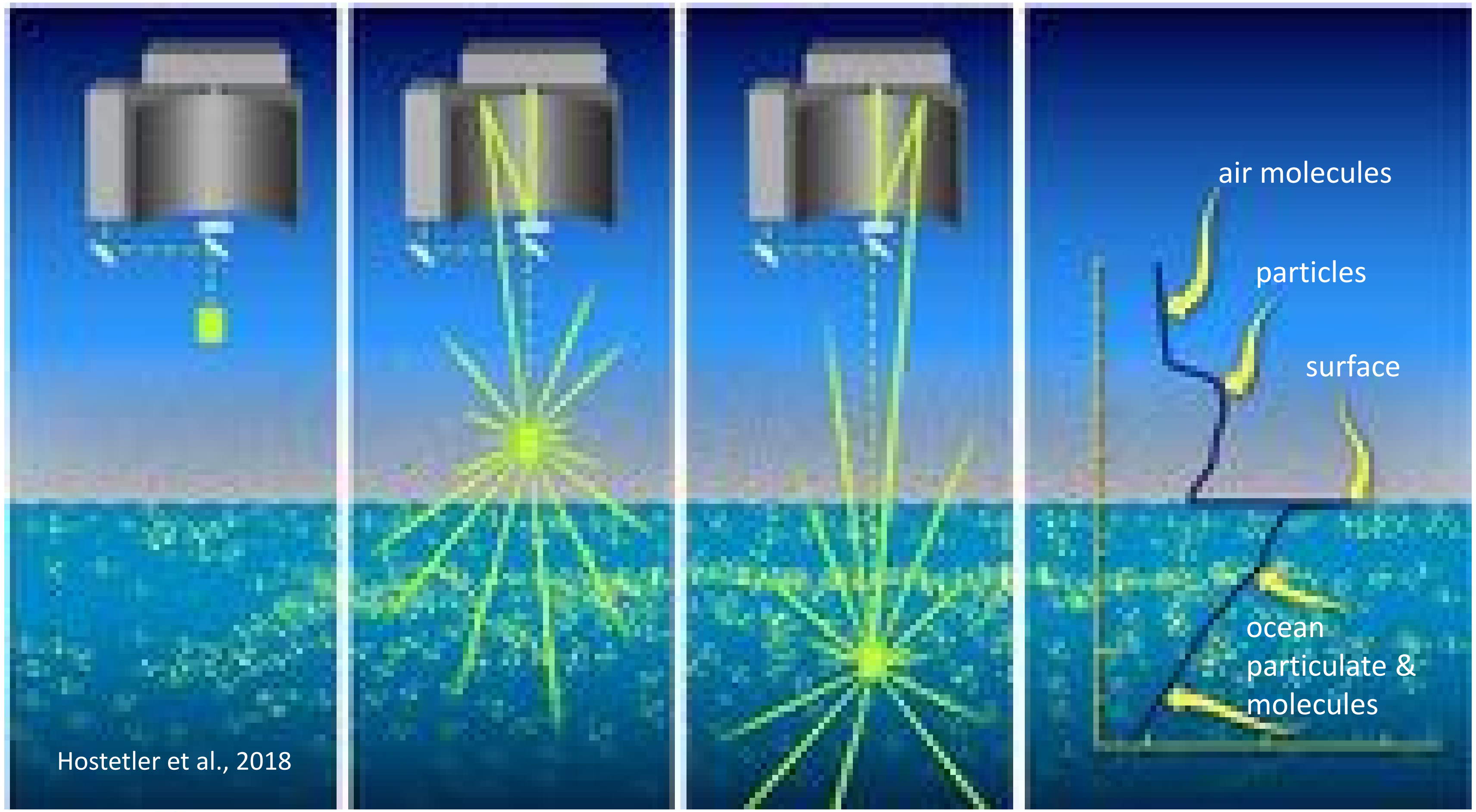
Adapted from Flamant et al., 2010

$P(\lambda, r)$ = power received from a distance r
$K(\lambda)$ = lidar instrument constant
$G(r) = \frac{A}{r^2}$ = telescope perception angle
$\beta(\lambda, r)$ = molecular plus particulate backscatter
$\Delta R = \frac{ct_l}{2}$. = lidar range resolution
$T(\lambda, r)$ = transmission terms
$P_{bg}(\lambda)$ = background power

Lidar Basics – Lidar equation

Ocean elastic backscatter lidar

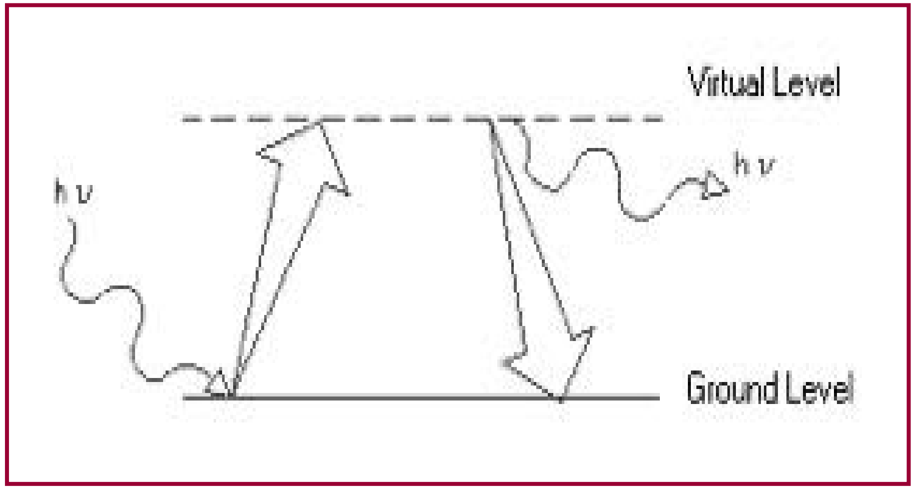
$$P(\lambda,r) = P_0(\lambda)\cdot K(\lambda)\cdot G(r)\cdot \Delta R\cdot \beta(\lambda,r)\cdot T^2_{atm}(\lambda,r)\cdot T^2_{surf}(\lambda,r)\cdot T^2_{ocean}(\lambda,r) + P_{bg}(\lambda)$$



Quasi-single-scattering approximation: light propagates through the water with a series of scattering events at small angles, undergoes a backscattering event, and then propagates back to the surface with only small-angle scattering events.

Lidar Basics – Optical Interactions of Relevance

Elastic interactions: Rayleigh scattering



Rayleigh Scattering

$$VSF = \sigma_{Ray} \cdot PSF$$

$$\sigma_{Ray} = \frac{\pi^5 \rho^6}{96\lambda^4}\left(\frac{m^2-1}{m^2+2}\right)^2$$

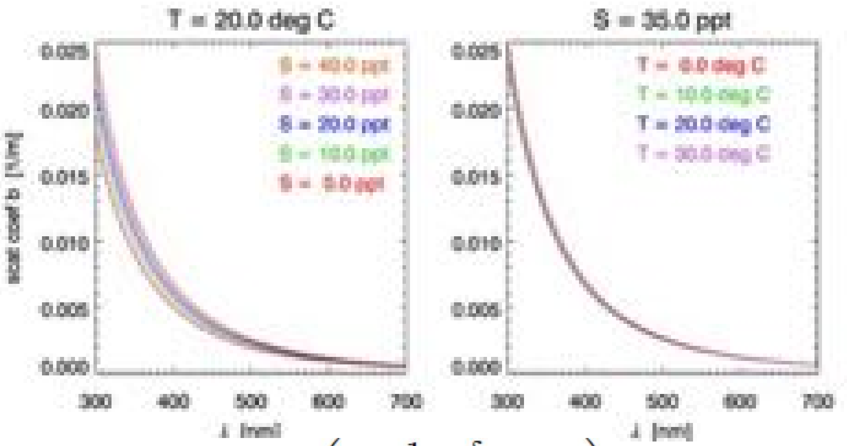
$$PSF = \frac{3}{16\pi}(1 + cos^2\psi)$$

size parameter = $\frac{2\pi\rho}{\lambda}$

- $\lambda >> \rho \rightarrow \sigma_{Ray} = C/\lambda^4$

Rayleigh for size parameters up to 0.5., $x=2\pi\rho/\lambda=0.5$ for $\lambda=500nm \rightarrow \rho=0.04\mu m$. Rayleigh scattering not valid for phytoplankton or other oceanographic particles (size $\rho \geq =0.5\mu m$)

Sea water VSF

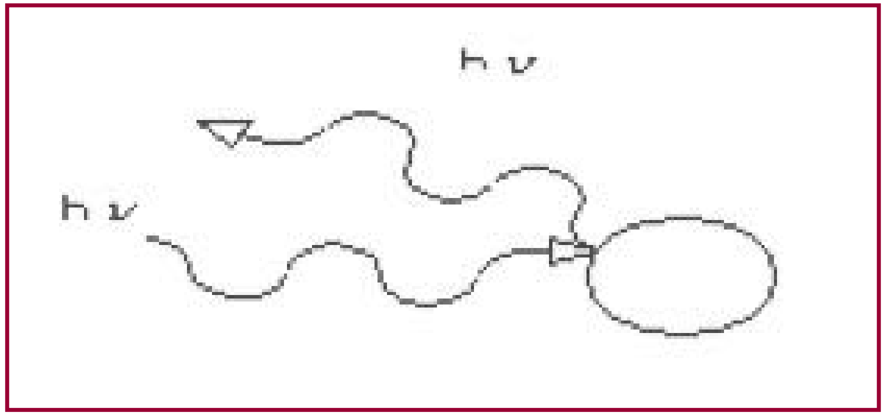


$$VSF = \beta(90)\left(1 + \frac{1-\delta}{1+\delta}\cos^2\psi\right)$$

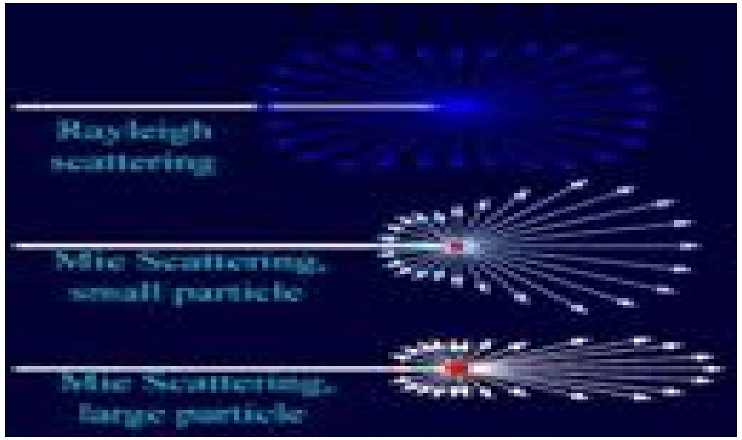
Zhang et al., 2009

Lidar Basics – Optical Interactions of Relevance

Elastic interactions: Mie scattering

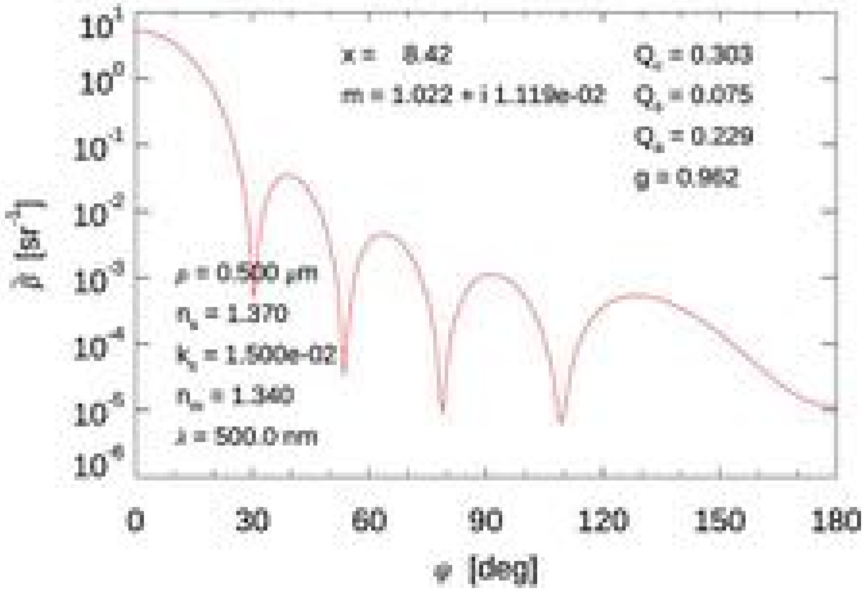


Mie Scattering



Mie theory is valid only for homogeneous spherical particles

- $\lambda \sim \rho \quad \rightarrow \quad \sigma_{Mie} = C/\lambda^a$



PSF for unpolarized light for phytoplankton with ρ=0.5μm.

Lidar Basics – Lidar equation

Elastic lidar

Emitted wavelength = 355 nm
Detection channels = 355 nm

$$S(z,\lambda) = C_L \frac{v}{2n}\left[\frac{A}{(nH+z)^2}\right]\cdot (T_A^2(\lambda))\cdot (T_S^2)\cdot \left[\beta_m(\pi,\lambda,z) + \beta_p(\pi,\lambda,z)\right]\cdot exp\left[-2\int_0^z K_L(z',\lambda)\,dz'\right] + S_B$$

- valid for quasi-single scattering approximation
- two unknowns: K_L and β_p

C_L= lidar instrument constant
A = telescope area
H = height of the lidar above the ocean
v = spped of light in vacuum
n = index o refraction of water
K_L= lidar attenuation coefficient
T_A= transmisssion of the atmosphere
T_S= transmission of the water surface
β_m= backscatter from water molecules
β_p= backscatter from suspended particles
S_B= background signal

Different inversion techniques to solve this equation:

1) Slope method: $\frac{d(lnS^{corr})}{dz} = \frac{1}{\beta}\frac{d\beta}{dz} - 2K_L$ If $\frac{d\beta}{dz} = 0$ $\Rightarrow$ $K_L = -\frac{1}{2}\frac{dS^{corr}}{dz}$

where: $S^{corr} = \frac{2nS(nH+z)^2}{vAC_L} - S_B$

Bukin et al., 1998
Collister et al., 2018

2) Klett method: If $\frac{d\beta}{dz} \neq 0$ $\frac{dS^{corr}}{dz} = \frac{k}{K_L}\frac{dK_L}{dz} - 2K_L$ $\Rightarrow$

$$K_L(z) = \frac{\exp\left[\frac{S(z)-S_m}{k}\right]}{\left\{\frac{S(z)-S_m}{k} + \frac{2}{k}\int_z^{z_m} exp\left[\frac{S(z)-S_m}{k}\right]dz\right\}}$$

$\beta = \text{const}\cdot (K_L)^k$

Klett 1981
Chen et al. 2021

Lidar Basics – Lidar equation

Elastic lidar

3) Perturbation method: $S^{corr}(z,\lambda) = C \cdot (T_A^2) \cdot (T_S^2)[\beta_0 + \beta'(z)] \cdot exp\left[-2K_{L0}z - 2\int_0^z K_L' dz'\right]$

If the varying part of the attenuation can be neglected $\beta(z) = \dfrac{S^{corr}(z)}{S_0^{corr}(z)}\beta_0$

where $S_0^{corr}(\mathrm{z})$, the homogeneous part of $S^{corr}(\mathrm{z})$, can be calculated from the following linear regression:

$S_0^{corr} = \ln(\mathrm{C_{trans}}\beta_0) - 2\mathrm{K_{L0}}$ where $\mathrm{C_{trans}} = C \cdot (T_A^2) \cdot (T_S^2)$

Churnside and Marchbanks, 2017

The combined use of Klett method and perturbation retrieval techniques (i.e. the 'Hybrid technique')

Chen et al. 2022

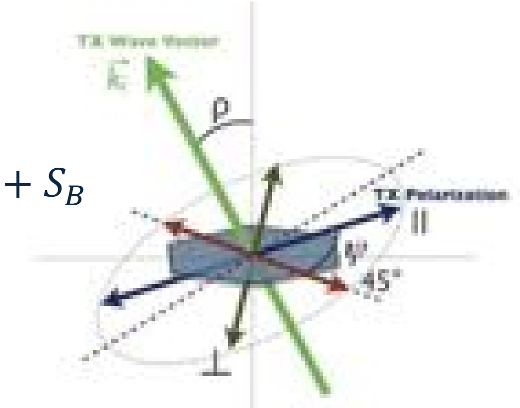
Appropriate elastic algorithm depends on the measurement conditions

Elastic polarization lidar

Emitted wavelength = 355 co nm
Detection channels = 355co nm,
355cross nm

$$S_C(z,\lambda) = C_L \frac{v}{2n}\left[\frac{A}{(nH+z)^2}\right] T_A^2(\lambda) T_S^2 f_C(\pi,z)\beta(\pi,\lambda,z) exp\left[-2\int_0^z K_L(z',\lambda)\,dz'\right] + S_B$$

$$S_X(z,\lambda) = C_L \frac{v}{2n}\left[\frac{A}{(nH+z)^2}\right] T_A^2(\lambda) T_S^2 \left[f_X(\pi,z)\beta(\pi,\lambda,z) + 2 f_C(\pi,z)\beta(\pi,\lambda,z)\int_0^z \gamma(z')\,dz'\right] exp\left[-2\int_0^z K_L(z',\lambda)\,dz'\right] + S_B$$



Neely et al. 2013

γ= rate of depolarization by multiple forward scattering
f_x= fraction of light co or cross polarized after scattering by π radians

Depolarization due to:
1) irregular oceanic particles (e.g. fish, zooplankton,and large phytoplankton)
2) multiple forward scattering

Depolarization ratio:

$$\delta(\pi,z,\lambda) = \frac{S_X(z,\lambda)}{S_C(z,\lambda)} = \frac{f_X(\pi,z)}{f_C(\pi,z)} + 2\int_0^z \gamma(z')dz' \Rightarrow$$

If the scattering properties of the water do not change with depth

$$\frac{d\delta(\pi,z,\lambda_0)}{dz} = 2\gamma(z)$$

Churnside, 2013

$$\Downarrow$$

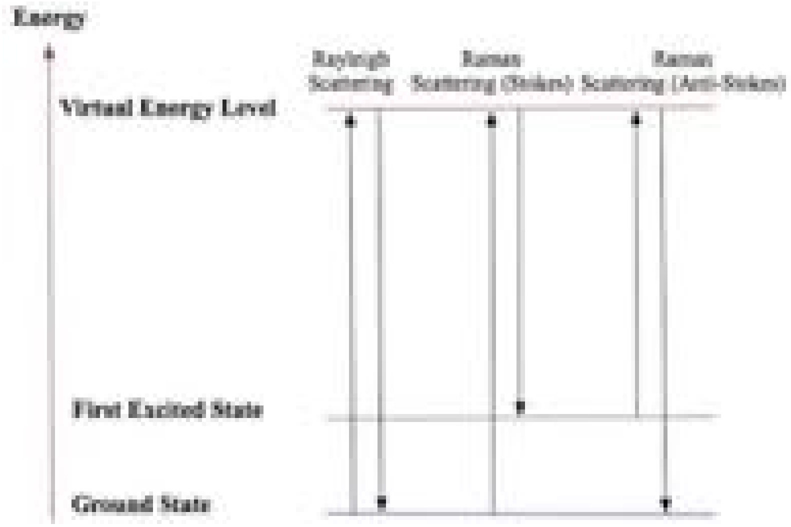
$$K_L = K_d \exp\left(f\left(\delta(\pi,z,\lambda)\right)\right)$$

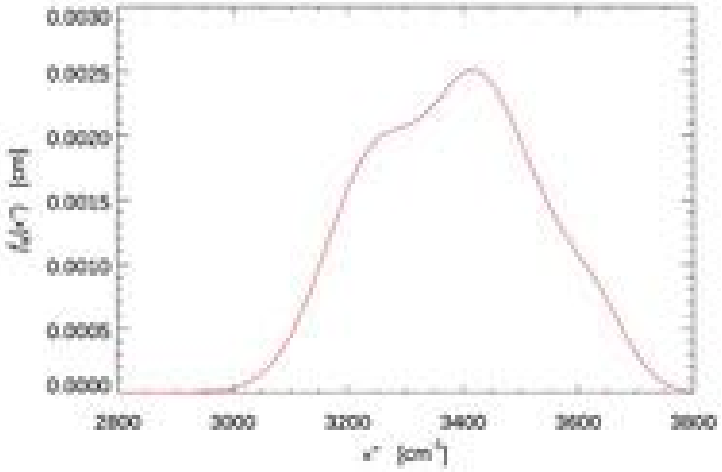
Hu, 2016

Lidar Basics – Optical Interactions of Relevance

Inelastic interactions: Raman scattering

- *Raman consists in a spectral shift of the returned wavelength characteristics of the considered molecule*
- *Raman signals that can be used to identify substances*

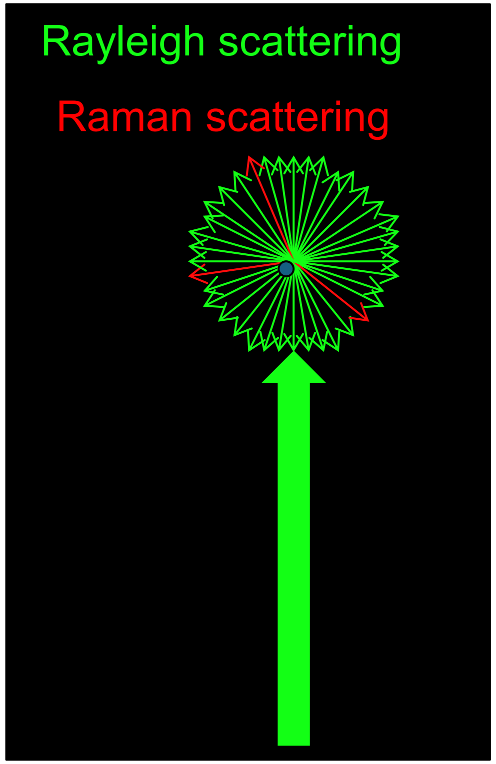




Raman wavelength distribution function for pure water at 25 C.

- Interaction with the quantized vibrational & rotational energy levels of the molecule

$$\Delta\tilde{\nu} = \tilde{\nu}_1 - \tilde{\nu}_s = \frac{\Delta E}{hc_0}$$



Consiglio Nazionale delle Ricerche
Istituto di Scienze Marine

Lidar Basics – Lidar equation

Elastic – Raman lidar

Emitted wavelength= 355 nm
Detection channels= 355 nm, 405 nm

$$S_{rmn}(z,\lambda,\lambda_{rmn}) = C_L \frac{v}{2n}\left[\frac{A}{(nH+z)^2}\right] \cdot T_A(\lambda) \cdot T_A(\lambda_{rmn}) \cdot (T_s^2) \cdot \beta_{rmn}(\pi,z,\lambda) \cdot exp\left[-\left(\int_0^z [K_L(z',\lambda) + K_L(z',\lambda_{rmn})]\, dz'\right)\right] + S_B$$

$$S(z,\lambda) = C_L \frac{v}{2n}\left[\frac{A}{(nH+z)^2}\right] \cdot (T_A^2(\lambda)) \cdot (T_s^2) \cdot \left[\beta_m(\pi,\lambda,z) + \beta_p(\pi,\lambda,z)\right] \cdot exp\left[-2\int_0^z K_L(z',\lambda)\, dz'\right] + S_B$$

$$K_L(z,\lambda) + K_L(z,\lambda_{rmn}) = \frac{d}{dz} ln \frac{\beta_{rmn}(z)}{S^{corr}_{rmn}(z)} \Rightarrow K_L(z,\lambda) = \frac{\frac{d}{dz} ln \frac{\beta_{rmn}(z)}{S^{corr}_{rmn}(z)}}{1+\left(\frac{\lambda}{\lambda_{rmn}}\right)^{k(z)}}$$

If density of seawater molecules is relatively constant (e.g. near-surface ocean):

$$\Rightarrow K_L(z,\lambda) = \frac{-\frac{d}{dz} ln S^{corr}_{rmn}(z)}{1+\left(\frac{\lambda}{\lambda_{rmn}}\right)^{k(z)}}$$

where: $\frac{K_L(z,\lambda)}{K_L(z,\lambda_{rmn})} = \left(\frac{\lambda_{rmn}}{\lambda}\right)^{k(z)}$ $\quad k(z)$ is the wavelength dependence of K_L

Coupling Elastic and Raman channel:

$$\frac{S^{corr}(z)}{S^{corr}_{rmn}(z)} = \frac{(\beta_m(\pi,z,\lambda) + \beta_p(\pi,z,\lambda))}{\beta_{rmn}(\pi,z,\lambda)} \cdot \frac{T_A(\lambda)}{T_A(\lambda_{rmn})} \cdot \Delta K_L(\lambda,\lambda_{rmn},z') \Rightarrow \beta_p(\pi,z,\lambda) = \beta_{rmn}(\pi,z,\lambda) \cdot \left[\frac{S^{corr}(z)}{S^{corr}_{rmn}(z)} \cdot \Delta T_{atm}(\lambda_w,\lambda) \cdot \Delta K_L(\lambda_{rmn},\lambda,z') - 1\right]$$

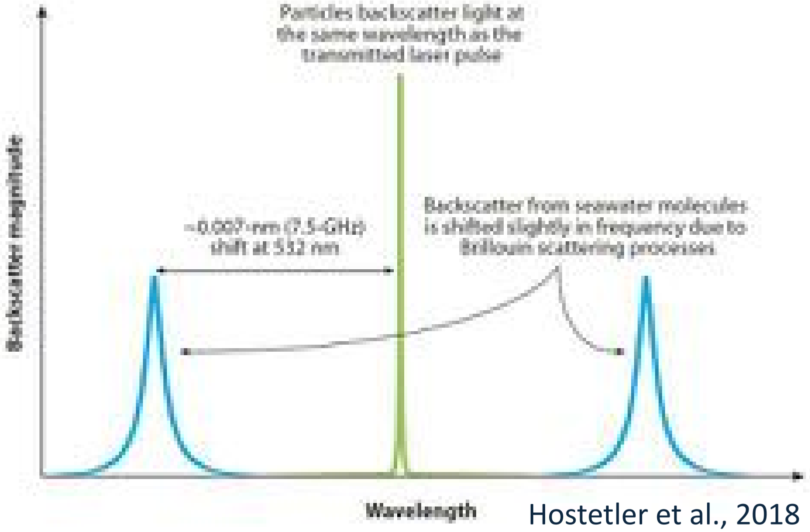
where: $\Delta K_L(\lambda,\lambda_{rmn},z') = exp\left(-\int_0^z [K_L(z',\lambda) + K_L(z',\lambda_{rmn})]dz'\right)$

$$\frac{T_{atm\_\lambda_w}}{T_{atm\_\lambda_0}} = \Delta T_{atm}(\lambda_w,\lambda_0)$$

Consiglio Nazionale delle Ricerche
Istituto di Scienze Marine

Lidar Basics – Optical Interactions of Relevance

Inelastic interactions: Brillouin scattering



Hostetler et al., 2018

Brillouin light scattering is the result of the interaction between a photon of light and the acoustic phonons of a material.

Spontaneous Brillouin scattering occurs as a consequence of density or refractive index fluctuations in the optical properties of the medium.

Frequency shift $$\Delta\nu_L = \pm\frac{nV_L}{\lambda}\sin\left(\frac{\Theta}{2}\right)$$

- ❖ Raman scattering: photons scattered by the effect of vibrational and rotational transitions in the bonds between first-order neighboring atoms
- ❖ Brillouin scattering: the scattering of photons caused by large scale, low-frequency phonons.

Lidar Basics – Lidar equation

High Spectral Resolution Lidar

Emitted wavelength= 355 nm
Detection channels= 355mol nm
355par nm

$$S_m(z,\lambda) = C_m \frac{v}{2n}\left[\frac{A}{(nH+z)^2}\right]\cdot(T_A^2(\lambda))\cdot(T_s^2)\cdot[\beta_m(\pi,\lambda,z)]\cdot exp\left[-2\int_0^z K_L(z',\lambda)\,dz'\right] + S_B$$

$$S_p(z,\lambda) = C_p \frac{v}{2n}\left[\frac{A}{(nH+z)^2}\right]\cdot(T_A^2(\lambda))\cdot(T_s^2)\cdot[\beta_p(\pi,\lambda,z)]\cdot exp\left[-2\int_0^z K_L(z',\lambda)\,dz'\right] + S_B$$

$$\beta_P = \beta_m \frac{\left(C_m S_p(z)\right)}{\left(C_p S_m(z)\right)} \qquad K_L(z) = -\frac{1}{2}\frac{d}{dz} ln[(nH+z)^2 S_m(z)]$$

Depending of the instrument design, cross-talk can affect the molecular and particulate channels:

$$S_m^{corr}(z,\lambda) = C_m\left(C_1\beta_m(\pi,\lambda,z) + C_2\beta_P(\pi,\lambda,z)\right)\cdot(T_A^2)\cdot(T_s^2)\left[exp\left(-\int_0^z K_L(z')dz'\right)\right]^2$$

$$S_p^{corr}(z,\lambda) = C_P\left(C_4\beta_m(\pi,\lambda,z) + C_3\beta_P(\pi,\lambda,z)\right)\cdot(T_A^2)\cdot(T_s^2)\left[exp\left(-\int_0^z K_L(z')dz'\right)\right]^2$$

$$\beta_P = \beta_m \frac{(C_m . C_1 - S_R C_P C_4)}{(S_R C_P C_3 - C_m C_2)}$$ where: $$S_R = \frac{S_p^{corr}}{S_m^{corr}}$$

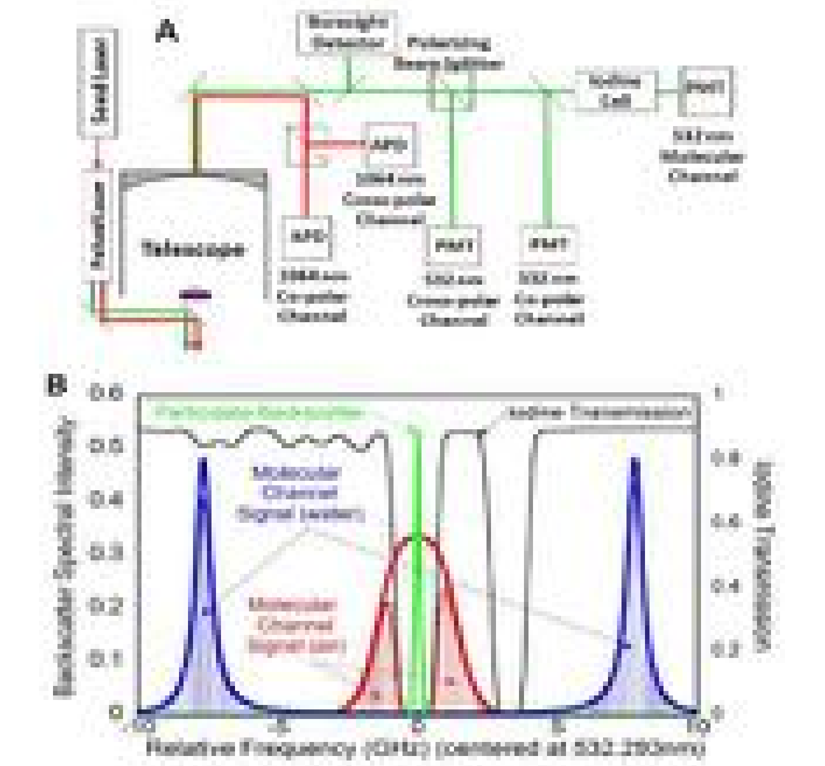


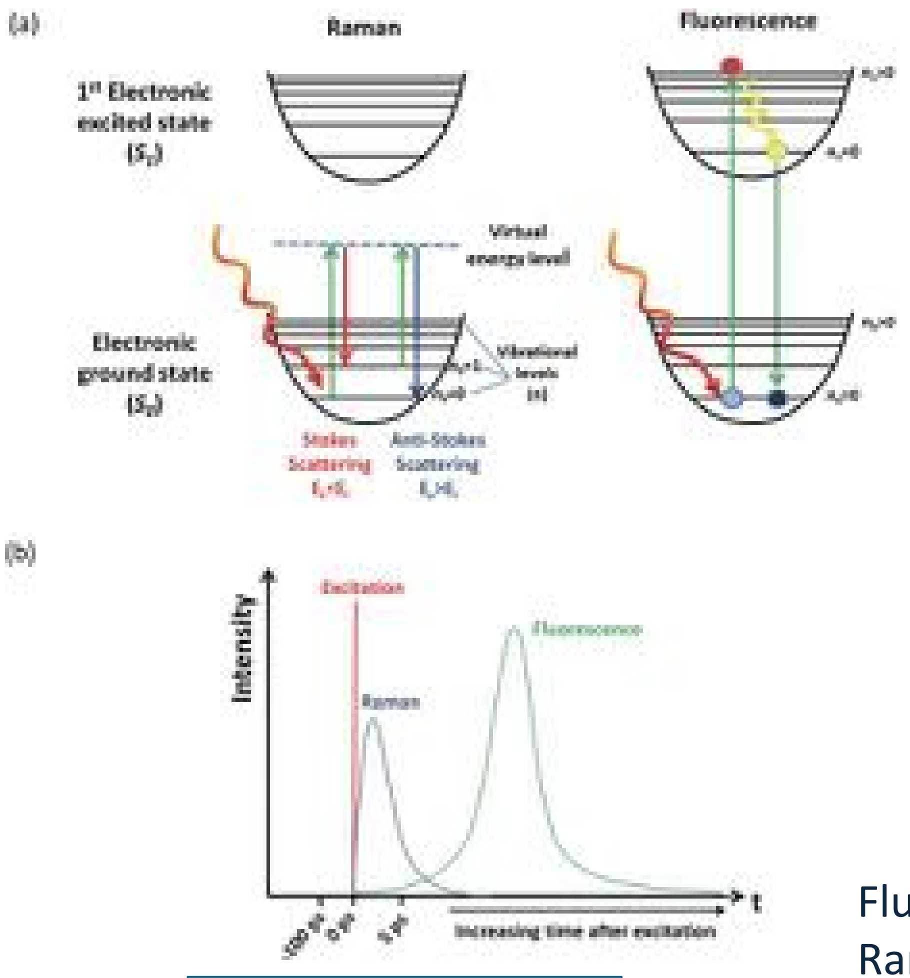
Figure 1. (A) Block diagram of the HSRL-1 instrument and (B) the spectra of backscatter signals at 532 nm relative to the iodine vapor filter absorption features.

Hair et al., 2016

Consiglio Nazionale delle Ricerche
Istituto di Scienze Marine

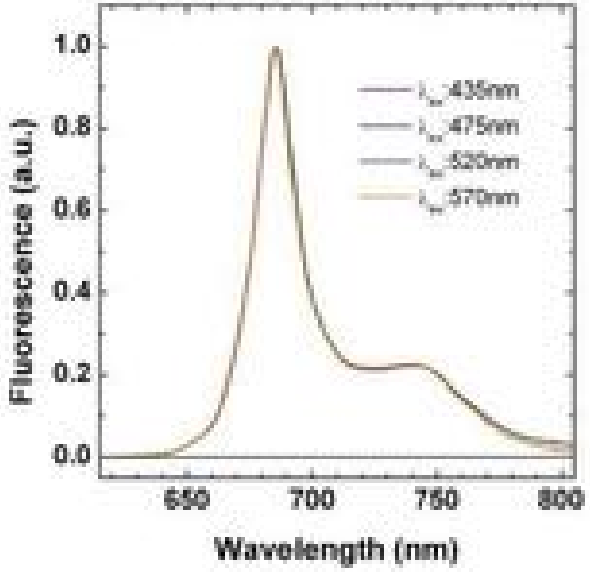
Lidar Basics – Optical Interactions of Relevance

Laser induced Fluorescence



Cabo-Fernandez et al., 2019

Typical chlorophyll fluorescence emission spectrum



Santabarbara et al., 2020

Fluorescence lifetime in the order of hundreds of ps to ns
Raman scattering is instantaneous (within ps or fs)

Lidar Basics – Lidar equation

Fluorescence lidar

Emitted wavelength= 532 nm
Detection channels = 650 nm
685 nm

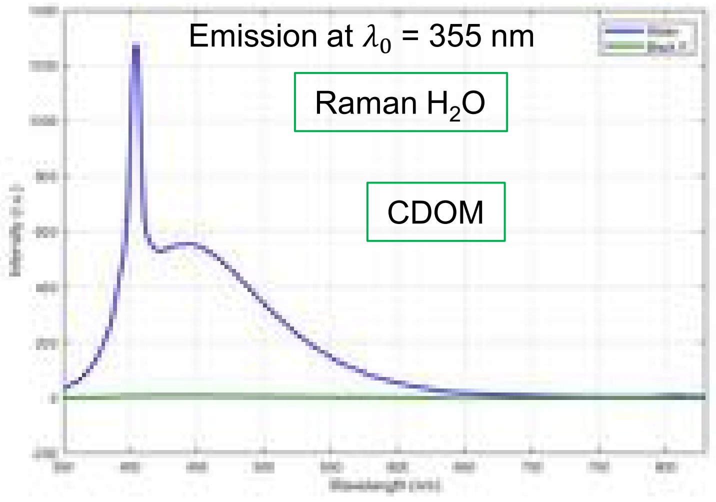
$$S_{FL}^{corr}(\lambda_{FL}, z) = T_S^2 T_A(\lambda) T_A(\lambda_{FL}) \beta_{FL}(\pi, z, \lambda) \left[exp\left(-\int_0^z [K_L(z', \lambda) + K_L(z', \lambda_{FL})] dz' \right) \right]$$

$$S_{rmn}^{corr}(z, \lambda, \lambda_{rmn}) = T_S^2 T_A(\lambda) T_A(\lambda_{rmn}) \beta_{rmn}(\pi, z, \lambda) \left[exp\left(-\int_0^z [K_L(z', \lambda) + K_L(z', \lambda_{rmn})] dz' \right) \right]$$

where: $\beta_{FL}(\pi, z, \lambda) = \int_{rmin}^{rmax} \frac{dN(r)}{dr} \sigma_F(r) dr$ $\quad \sigma_F(r) = \int_{\lambda min}^{\lambda max} \frac{d\sigma_F(\lambda, r)}{d\lambda} d\lambda$

Chlorophyll fluorescence–to–water Raman ratio ∝ phytoplankton absorption coefficient

Hoge et al., 1995

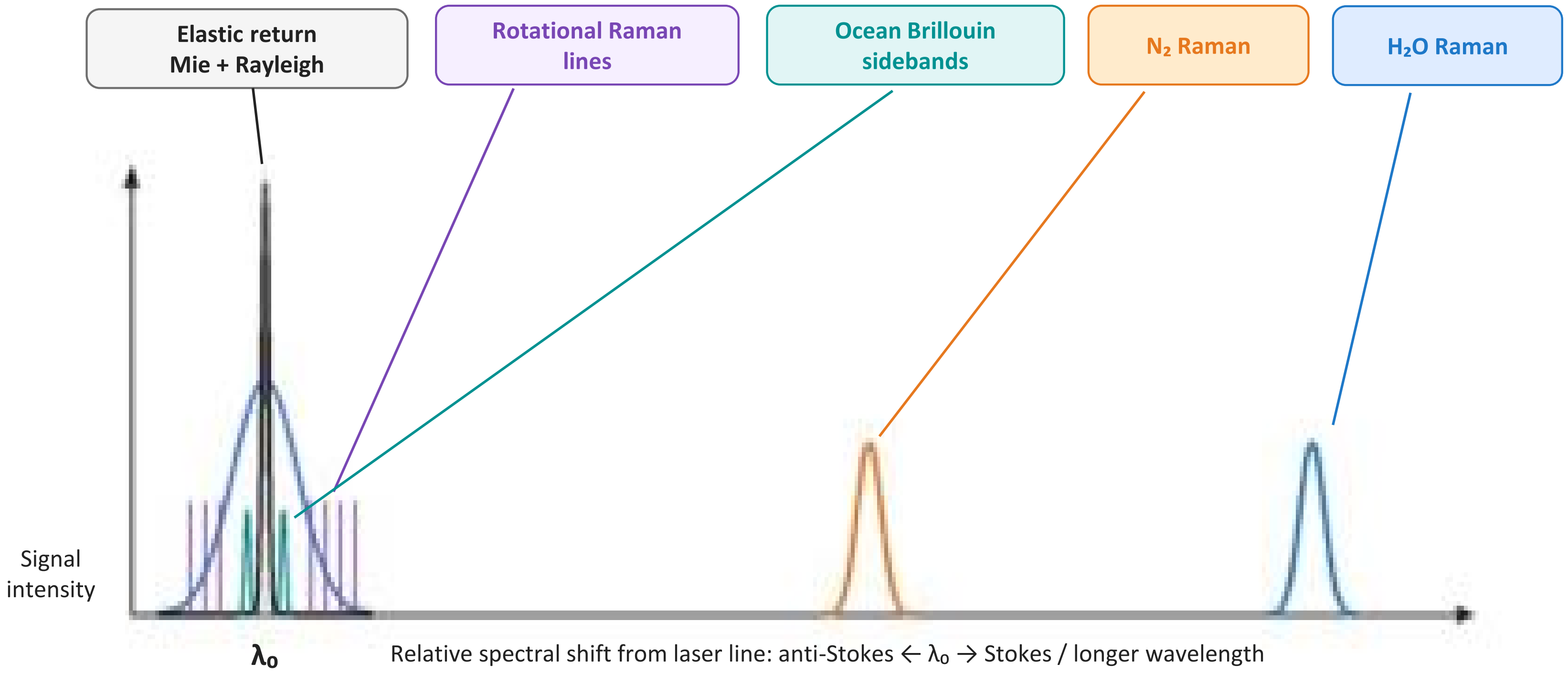


Applications: CDOM, Chlorophyll, Oil spills

Consiglio Nazionale delle Ricerche
Istituto di Scienze Marine

Lidar Basics – Optical selection

Wavelength selection



Indicative spectral width

Approx. $\Delta\lambda$ at λ_0 = 532 nm

- Mie / elastic particle ≈ laser-limited < 10^{-3}–10^{-2} nm
- Rayleigh molecular Doppler broadened ≈ 0.002–0.005 nm
- Rotational Raman comb envelope ≈ 1–5 nm individual lines ≪ 0.01 nm
- Ocean Brillouin shift ±0.005–0.010 nm linewidth ≈ 0.001–0.003 nm
- Vibrational Raman N_2/H_2O channel IF ≈ 0.3–2 nm FWHM

Order-of-magnitude values; instrument and T/P dependent.

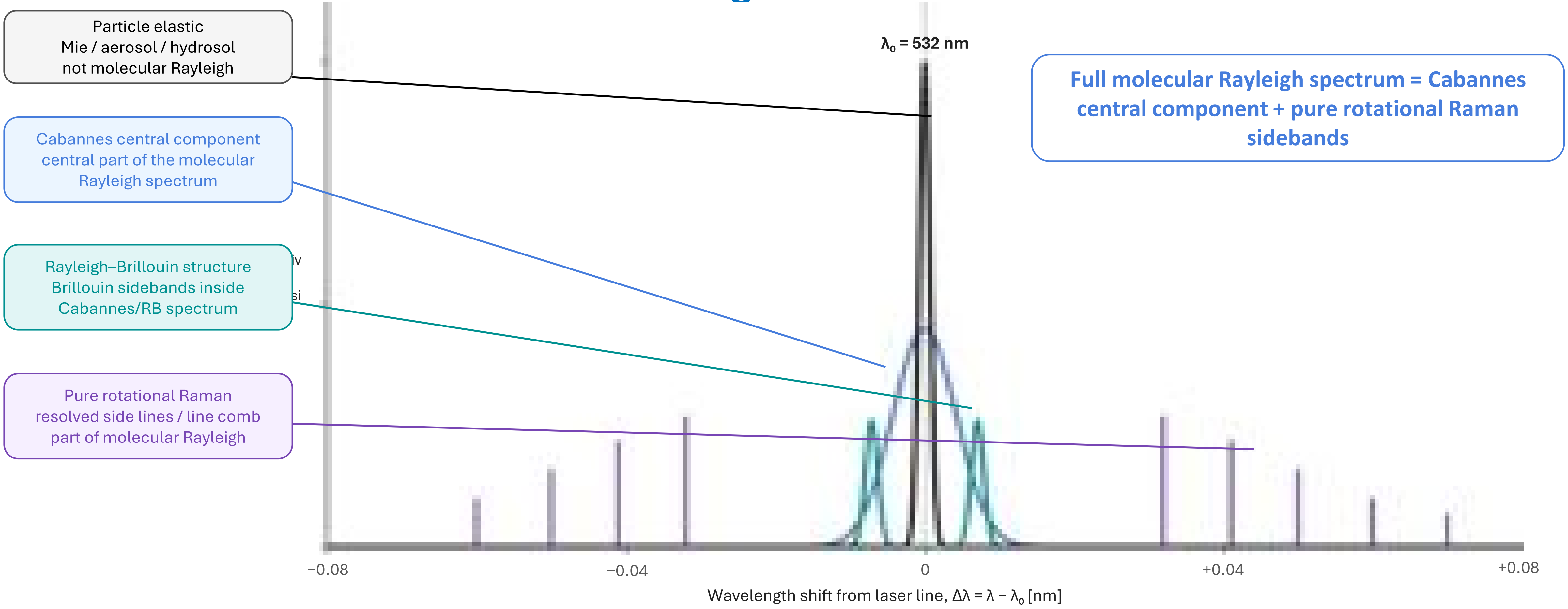
Typical spectral selectors

Elastic / Mie / Rayleigh	HSRL	Rotational Raman	Brillouin ocean	Vibrational Raman
Narrow IF; optional PBS	I_2 cell or FPI	FPI comb / IF pair	Fizeau / FPI / ASH	Dichroics + narrow-band IF

Far-shifted Raman bands can be isolated with dichroics and interference filters; near-λ_0 signals require high-resolution spectral discrimination.

Lidar Basics – Optical selection

Wavelength selection



Indicative scales at 532 nm: Cabannes/Rayleigh Doppler width ~10^{-3} nm scale; ocean Brillouin shift ±~0.007 nm; rotational Raman extends over nm scale; Mie elastic is laser-line limited.

Lidar Basics – Optical selection

Wavelength selection

Interaction	Spectral feature	Typical selector	Selected signal
Rayleigh	Elastic λ_0; molecular broadened	Narrow IF; optional etalon	Molecular backscatter
Mie	Elastic λ_0; particle return	Narrow IF + PBS for depol.	Aerosol / particles
Vibrational Raman	Large Stokes shift	Dichroics + narrow IF	N_2, O_2, H_2O channels
Rotational Raman	Small line comb near λ_0	IF pair or Fabry–Perot	Temperature-sensitive RR
Brillouin ocean	GHz-shifted sidebands	Fizeau / Fabry–Perot / ASH	Temperature, salinity, sound speed, liquid water
HSRL	Molecular vs aerosol line shape	I_2 absorption cell or Fabry–Perot	Extinction and backscatter

Examples: 532 nm elastic; N_2 Raman ≈607 nm; H_2O Raman ≈660 nm.
For 355 nm systems: N_2 ≈387 nm and H_2O ≈407 nm.

Consiglio Nazionale delle Ricerche
Istituto di Scienze Marine

Relationship between lidar products and ocean color products

Lidar products

$\mathbf{K_L}$ $\boldsymbol{\beta_p}$

OC products

$\mathbf{K_d}$ $\mathbf{b_{bp}}$

$$K_d = -\frac{d \ln E_d}{dz}$$

$$b_{bp} = 2\pi \int_{\pi/2}^{\pi} \beta_{wat}^{par}(\theta) \sin(\theta)\, d\theta$$

The described retrieval techniques assume quasi-single scattering approximation (i.e. most scattering in the ocean is at very small scattering angles) and are valid as long as the appropriate relationships between lidar and ocean products are used:

- $K_L \rightarrow K_d$ or c ?
- $\beta_p \rightarrow b_{bp}$

Relationship between lidar products and ocean color products

What values should be used for K_L?

K_L varies as a function of both the lidar viewing geometry and the optical properties of the sensed water.

- Gordon (1983) proposed: $\boxed{K_L = K_d + (c - K_d)\exp(-0.85cD)}$ for $\lambda_0 = 532$ nm

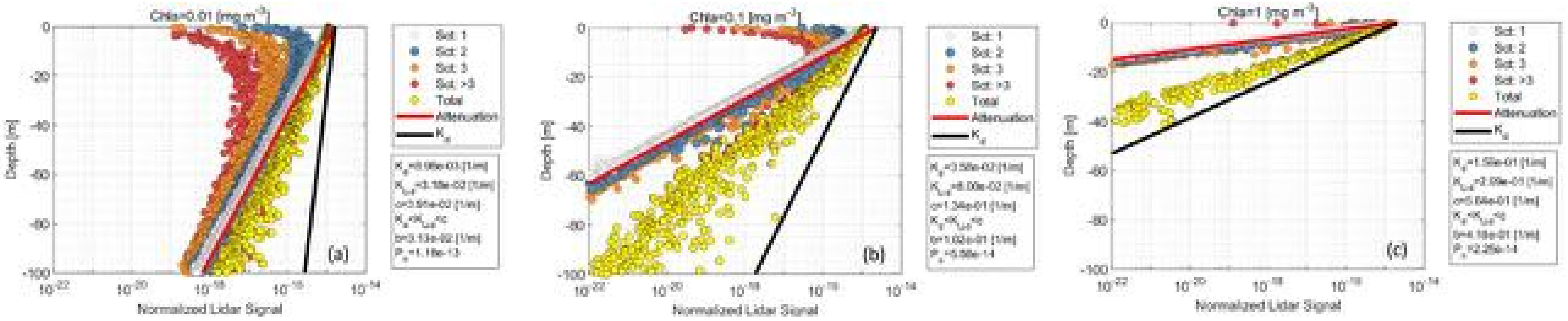
The ratio of the radius of the spot on the sea surface viewed by the lidar receiver optics to the mean free path of photons in water is a significant parameter related to K_L. When this ratio is near zero, K_L is given by c. If the ratio is greater than 5, K_L is given by K_d.

- Phillips and Koerber (1984) proposed that the upper and lower limits of K_L are given by c and the water absorption coefficient a, respectively, depending on the receiver FOV

Lidar Basics – Lidar and OC

Relationship between lidar products and ocean color products

AEOLUS case (D'Alimonte et al., 2024)

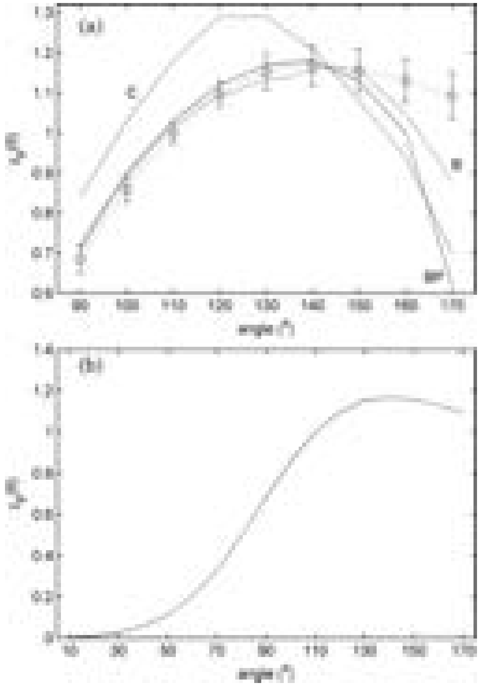


K_L varies close to c and K_d at low and high Chl-a values, respectively with different single and multiple scattering contributions.

Relationship between lidar products and ocean color products

What values should be used for χ_p?

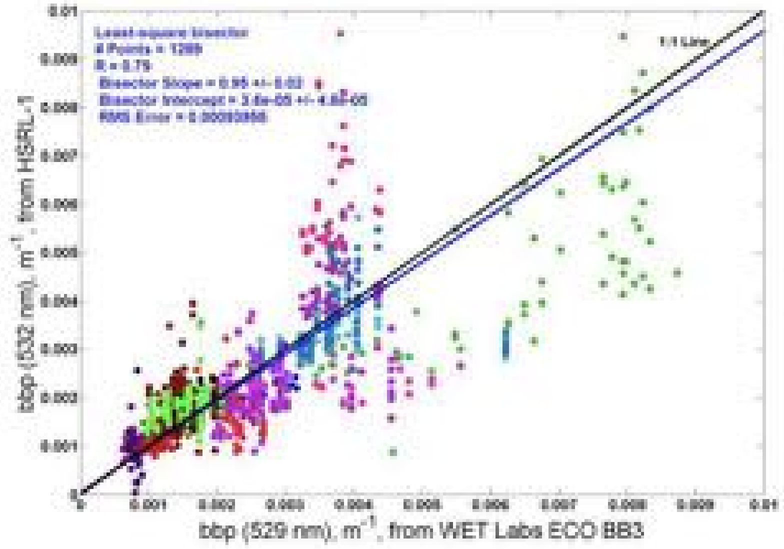
$$b_{bp}(z, \lambda_0) = 2\pi \boldsymbol{\chi_p} \beta_p(\pi, z, \lambda_0)$$



$\chi_p = 1.06$ (Sullivan and Twardoski, 2009) - in-situ VSF measurements

-

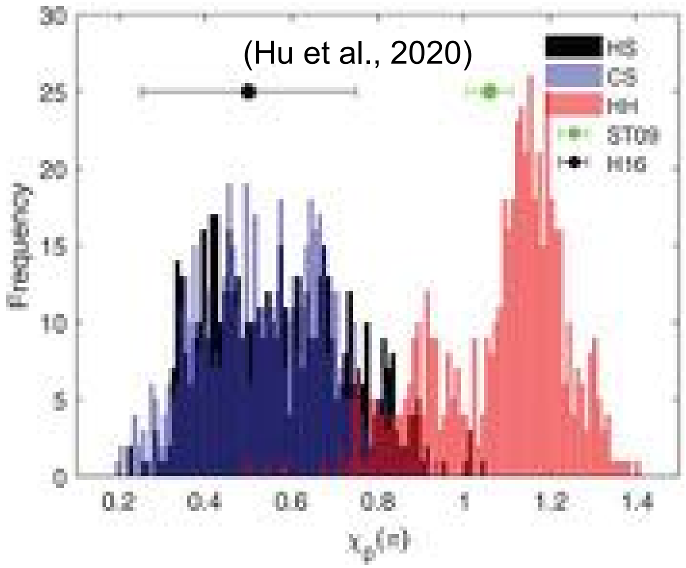
The conversion factor χ_p varies depending on size, shapes, and composition of the particle assemblage.



$\chi_p = 0.5$ (Hair et al., 2016), for $\lambda_0 = 532$ nm - HSRL and in-situ measureme

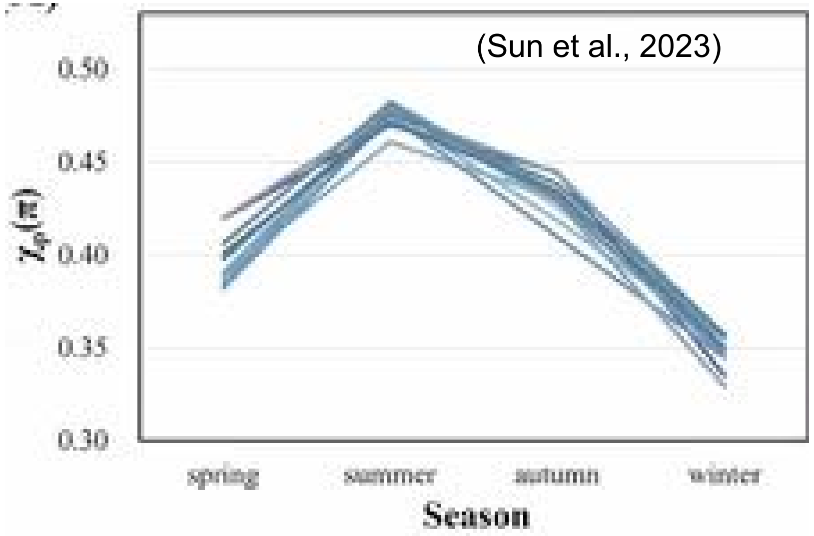
Relationship between lidar products and ocean color products

- χ_p VSF-inversion and forward modeling approach to the VSFs measured in a wide range of waters (Hu et al., 2020)



Depending on the particle model used, χ_p varies from 0.22 to 1.45
No spectral dependence

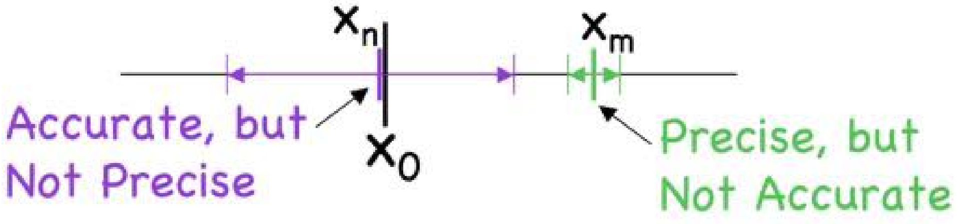
- χ_p comparison between the CALIPSO-retrieved b_{bp} products and the BGC-Argo floats (Sun et al., 2023)

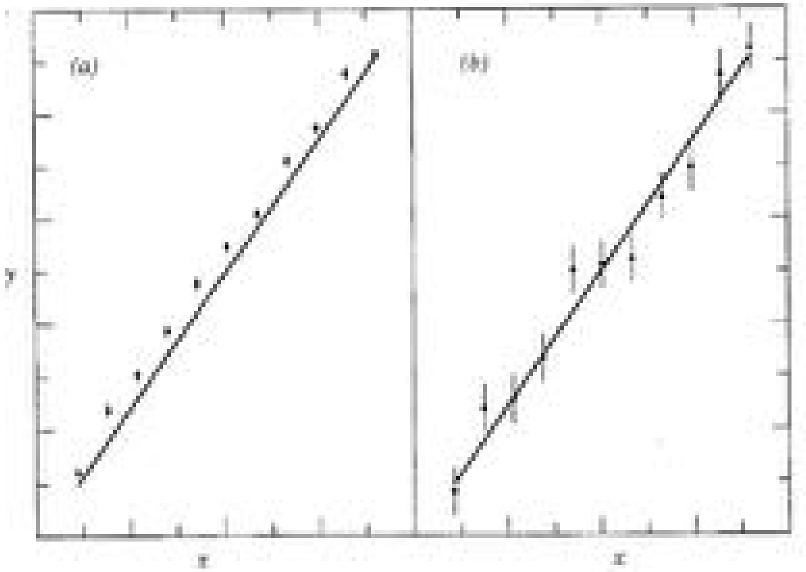


Lidar Basics – Uncertainties

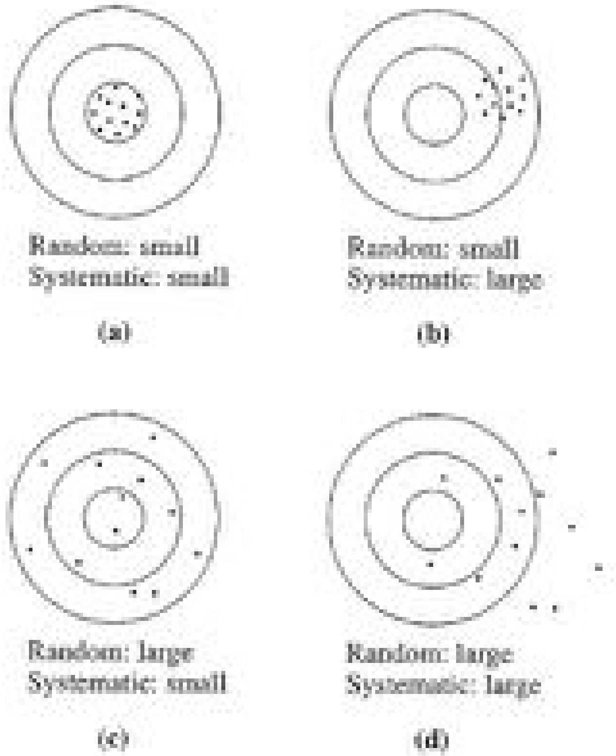
Random errors and bias (systematic) errors

Two major types of uncertainty in lidar observations





Data Reduction and Error Analysis, Bevington and Robinson (2003)



Random errors

Random errors determine the measurement precision.

Random errors: caused by random fluctuations (or noise) inherent in the measurement from:

(a) **shot noise**
(b) thermal noise
(c) excess noise introduced in the multiplication process

Photon counts obey Poisson distribution ➔for a given photon count N, the corresponding uncertainty is $\Delta N = \sqrt{N}$

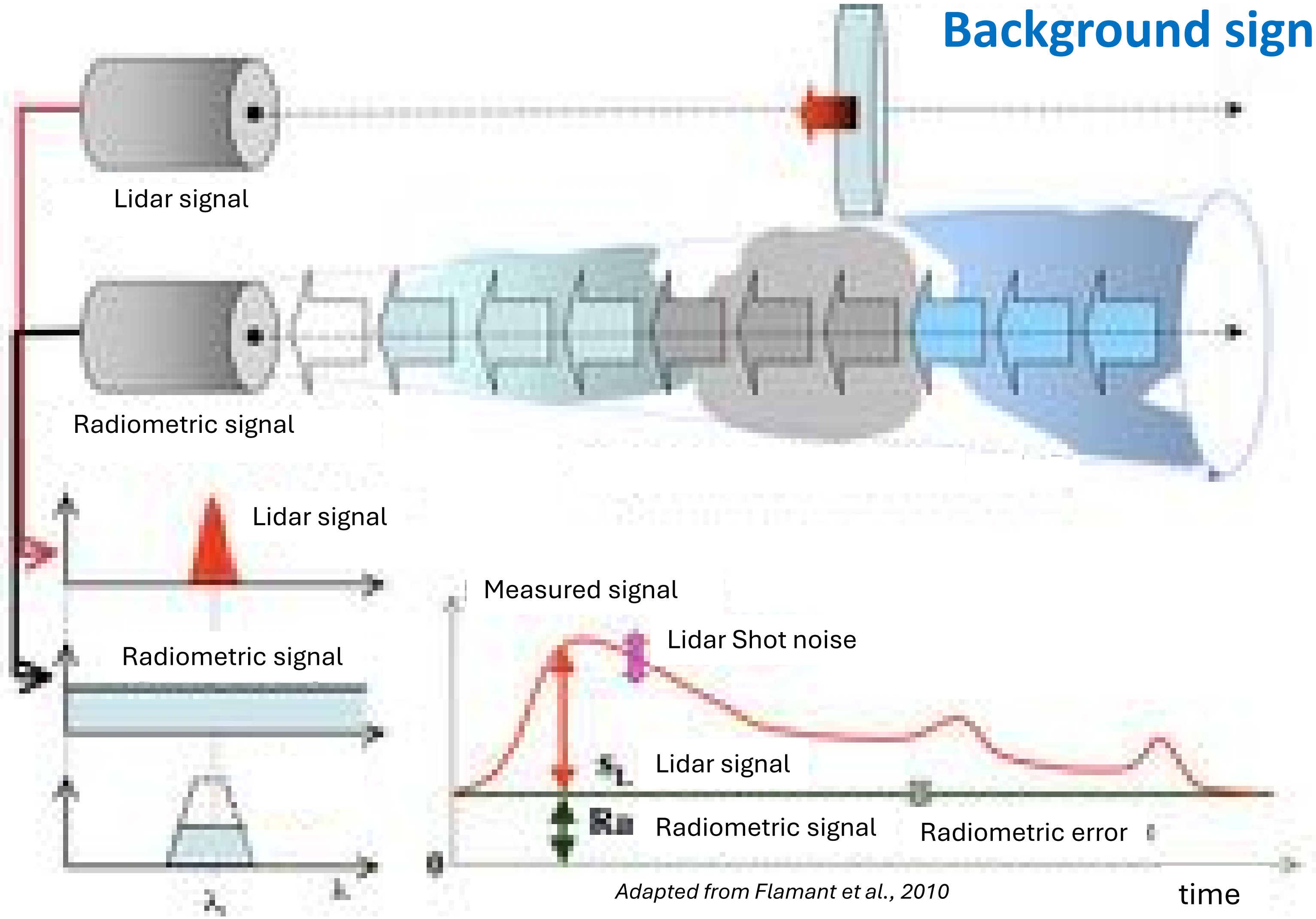
When many (m) shots are integrated together:

$$\frac{\Delta(mN)}{mN} = \frac{\sqrt{mN}}{mN} = \frac{1}{\sqrt{m}}\frac{\sqrt{N}}{N} = \frac{1}{\sqrt{m}}\frac{\Delta N}{N}$$

Random errors can be reduced by averaging or by repeating the measurement sacrificing temporal or spatial resolutions.

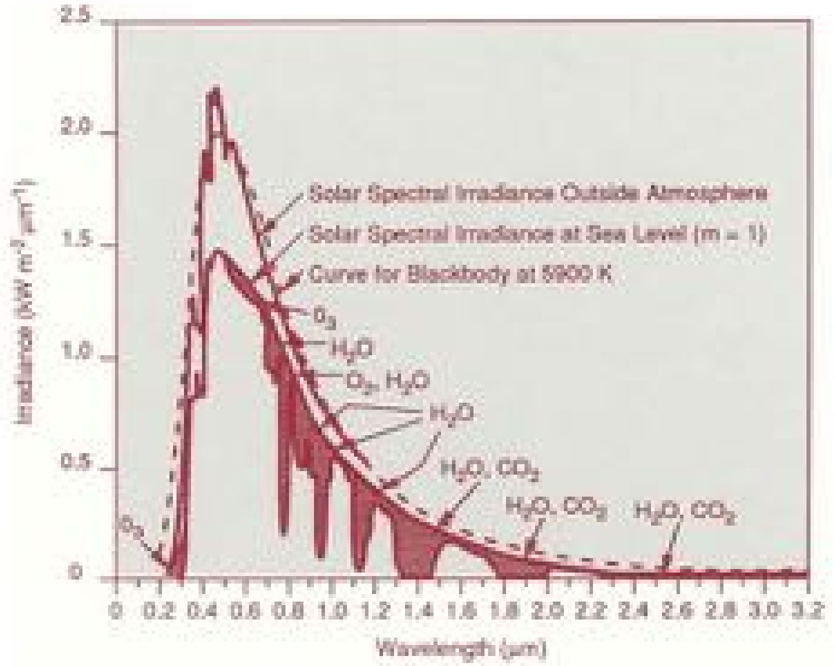
Lidar Basics – Uncertainties

Background signal



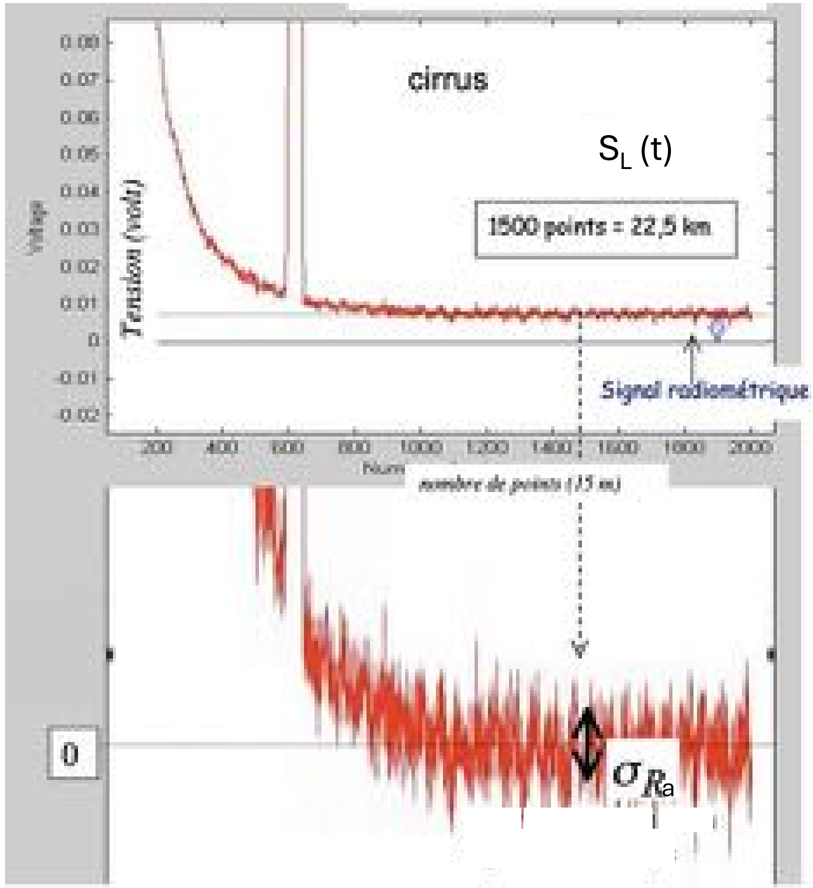
Adapted from Flamant et al., 2010

Solar constant = 1367 W m^{-2}



Lidar Basics – Uncertainties

Signal-to-noise ratio (SNR)



SIGNAL

- Laser energy
- Telescope area
- Optical efficiency
- Backscatter coefficient
- Averaging / repetition rate

NOISE

- Solar background
- Detector dark counts
- Shot noise
- Electronic noise
- Surface reflection / stray light

SNR(z) = Signal / Noise

$$SNR = \sqrt{\frac{(S_L - R_a)^2}{\sigma_L^2 + \sigma_{Ra}^2}}$$

Consiglio Nazionale delle Ricerche
Istituto di Scienze Marine

Signal-to-noise ratio (SNR)

Improving SNR: Design Choices and Trade-off

Strategy	Effect	Trade-off
Increase laser pulse energy	Higher signal	Eye safety, power, thermal load
Increase repetition rate	More averaging	Data volume, system complexity
Larger telescope	More collected photons	Size, weight, cost
Narrower field of view	Less background	More demanding alignment/overlap
Narrower spectral filter	Less background	Lower throughput; wavelength stability
Longer averaging	Lower random noise	Lower temporal/spatial resolution
Night operation	Lower solar background	Limited operational flexibility

Consiglio Nazionale delle Ricerche
Istituto di Scienze Marine

Bias (systematic) errors

Systematic errors determine the measurement accuracy.

Accuracy is mainly determined by:

(1) How much we understand the physical interactions and processes involved in the measurements or observations: e.g., scattering and absorption cross-section, transmission/extinction, interference absorption, etc.

(2) How well we know the lidar system parameters: e.g., laser central frequency, laser linewidth and lineshape, photo detector/discriminator calibration, receiver filter function, overlapping function, inaccurate calibration, nonlinearities in the photodetector response, defects in optical components, and/or a systematic electronic noise

➔ Inter-instrument comparison to assess the lidar measurement accuracy

Lidar Basics – Uncertainties

Lidar calibration

$$P(\lambda,r) = P_0(\lambda) \cdot K(\lambda) \cdot G(r) \cdot \Delta R \cdot \beta(\lambda,r) \cdot T^2(\lambda,r) + P_{bg}(\lambda)$$

- Lidar signal contains both geophysical information and instrumental response.
- $G(r) = 1$ at high range
- $K(\lambda)$ converts relative signals into quantitative products.
- $K(\lambda)$ describes **laser energy, optical alignment, optics transmission and detector gain** (may vary with time).
- $K(\lambda)$ uncertainty propagates into geophysical products.

Laser energy

Atmosphere / Ocean target

Telescope collection

Optical transmission

Detector response

Digitized signal

From Signal to Quantitative Products: without calibration, lidar is mostly relative; with calibration, it becomes quantitative.

Lidar Basics – Uncertainties

Lidar calibration

Element	Calibration target	Why it matters
Laser	Pulse energy; wavelength; repetition rate	Controls emitted power and spectral channel definition
Receiver optics	Transmission; alignment; field stop	Affects signal amplitude, FOV and background rejection
Telescope geometry	Overlap function O(z); FOV	Critical at short ranges and for near-surface ocean
Detector	Gain; linearity; dead time; dark counts	Affects photon-counting and analog accuracy
Polarization optics	Relative gain; cross-talk; extinction ratio	Needed for depolarization ratio δ
Spectral selector	Central wavelength; bandwidth; out-of-band rejection	Needed for Raman, HSRL, Brillouin channels

Lidar Basics – Photons to Geophysical Products

$$\mathrm{P}(\lambda, r) = P_0(\lambda) \cdot \mathrm{K}(\lambda) \cdot \mathrm{G}(r) \cdot \Delta R \cdot \beta(\lambda, r) \cdot T^2\,(\lambda, r) + P_{bg}(\lambda)$$

Raw signal
counts or voltage vs time

Background subtraction
solar/background level removed

Detector correction
dead time, analog offset, non-linearity

Range correction
two-way geometrical spreading

Overlap correction
near-range geometry

Averaging / smoothing
precision ↑; resolution ↓

Lidar equation inversion and calibration
retrieval assumptions

Ancillary data

Optical products
K_L, β_p, b_{bp}, δ, fluorescence