Seeing the Air: An Overview of Atmospheric Lidar

by
Dr. Leda Sox
Senior Research Scientist
Georgia Tech Research Institute

With
Dr. Christopher R. Valenta, GTRI
Dr. Gary G. Gimmestad, GTRI/GTPE
Light Detection And Ranging (LIDAR)

Ranging from: \( R = \frac{ct}{2} \)

Lidar for Autonomous Vehicles
“Hard-target” Lidar

Bathymetric Lidar
Brown et al., 2019

Topographic Lidar
Moller & Fernandez-Diaz, 2019

Radiohead’s House of Cards music video
Using Atmospheric Lidar to “See the Air”
Soufriere (Montserrat – Caribbean) erupted on May 20. Its water droplet/sulfuric acid plume was tracked by OMI and seen crossing over Indonesia by CALIPSO on June 7.

From Dr. Irina Sokolik’s Remote Sensing of the Atmosphere and Oceans course
Overview

• Atmospheric Lidar Theory
• History of Lidar for Atmospheric Study
• Recent Developments
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• History of Lidar for Atmospheric Study
• Recent Developments
Basic Lidar system: The Elastic Backscatter Lidar
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Basic Lidar system: The Elastic Backscatter Lidar
Sky background

- Atmosphere
- Receiver FOV
- Pulsed Laser
- Telescope
- Detector
- Data System
- Electronics

![Signal vs. Time (Range)]
Components of the Lidar Equation

The power received from a range bin is proportional to:

- **Power** transmitted, $P_0$
- **Transmitter and receiver optical efficiency**, $k_t$ and $k_{rec}$
- **Receiver collecting area**, $A_{rec}$
- A range-dependent **geometrical overlap factor** (not shown in figure), $G(r)$
- The range bin **backscatter coefficient**, $\beta$
- The length of the **range bin**, $ct/2$
- The atmospheric **transmittance** to & from the range bin, $T_{path}$
The Elastic Backscatter Lidar equation

\[ P_L(R) = P_o \eta_T \eta_R G(R) \left( \frac{A}{R^2} \right) \left( \frac{ct}{2} \right) \beta(R) \exp \left[ -2 \int_0^R \alpha(R') dR' \right] \]

\( P_L(R) \) = Power received from range, \( R \)

\( P_o \) = Average power per laser pulse

\( \eta_T \) = Transmitter optical efficiency

\( \eta_R \) = Receiver optical efficiency

\( G(R) \) = Geometric overlap factor

\( \left( \frac{A}{R^2} \right) \) = Receiver solid angle (sr)

\( \left( \frac{ct}{2} \right) \) = Range bin length (m)

\( \beta(R) \) = Atmos. Volume backscatter coefficient (m\(^{-1}\)sr\(^{-1}\))

\( \exp \left[ -2 \int_0^R \alpha(R') dR' \right] \) = Two-way path transmittance

\( \alpha(R) \) = Atmos. extinction coefficient (m\(^{-1}\))
The Elastic Backscatter Lidar equation

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- **Power received per range bin**
- \( P_L(R) \) = Power received from range, \( R \)
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- **Power transmitted**
  - \( P_L(R) \): Power received from range, R
  - \( P_o \): Average power per laser pulse
  - \( \eta_T \): Transmitter optical efficiency
  - \( \eta_R \): Receiver optical efficiency
  - \( G(R) \): Geometric overlap factor

- **Other parameters**
  - \( \frac{A}{R^2} \): Receiver solid angle (sr)
  - \( \frac{ct}{2} \): Range bin length (m)
  - \( \beta(R) \): Atmos. Volume backscatter coefficient (m\(^{-1}\)sr\(^{-1}\))
  - \( \exp \left[ -2 \int_0^R \alpha(R') \, dR' \right] \): Two-way path transmittance
  - \( \alpha(R) \): Atmos. extinction coefficient (m\(^{-1}\))
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**System variables**

- \( P_L(R) \) = Power received from range, \( R \)
- \( P_0 \) = Average power per laser pulse
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**Variables**

- \( \frac{A}{R^2} \) = Receiver solid angle (sr)
- \( \frac{ct}{2} \) = Range bin length (m)
- \( \beta(R) \) = Atmos. Volume backscatter coefficient (m\(^{-1}\)sr\(^{-1}\))

\[
\exp \left[ -2 \int_0^R \alpha(R')dR' \right] = \text{Two-way path transmittance}
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- \( \alpha(R) \) = Atmos. extinction coefficient (m\(^{-1}\))
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**System variables**

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- \( P_o \): Average power per laser pulse
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**Atmospheric variables**

- \( \frac{A}{R^2} \): Receiver solid angle (sr)
- \( \frac{ct}{2} \): Range bin length (m)
- \( \beta(R) \): Atmos. Volume backscatter coefficient (m\(^{-1}\)sr\(^{-1}\))
- \( \exp \left[ -2 \int_0^R \alpha(R') dR' \right] \): Two-way path transmittance
- \( \alpha(R) \): Atmos. extinction coefficient (m\(^{-1}\))
Elastic Backscatter Equation Assumptions

- The backscattered light is at the same wavelength as the transmitted light
- All range-dependent signal losses apart from the $1/R^2$ factor are due to the atmosphere, not the technology
- Photons experience a single scattering event during their trip through the atmosphere - no multiple scattering
- The entire laser pulse is contained within the range bin
- $\alpha$ and $\beta$ are constant within a range bin
- Only one laser pulse at a time is in the atmosphere
Extinction and backscatter coefficients have components from interactions with aerosols and molecules:

\[ \alpha(R) = \alpha_{aero} + \alpha_{mol} \]

\[ \beta(R) = \beta_{aero} + \beta_{mol} \]

Atmospheric extinction is due to absorption and scattering:

\[ \alpha(R) = \alpha_{aero, abs} + \alpha_{aero, sca} \]
\[ + \alpha_{mol, abs} + \alpha_{mol, sca} \]

- The terms \( \beta(z) \) and \( \alpha(z) \) are the range-dependent parameters of interest for atmospheric studies.
- The molecular scattering quantities are proportional to atmospheric number density (N\(_2\), O\(_2\), Ar).
- Unfortunately, they represent several unknowns in a single equation.
  - An underdetermined system (on its own!)
The Challenge

• The lidar equation describes one signal that depends on two atmospheric parameters, in different ways.
  – There is no unique solution
  – We must either reduce the number of parameters to one by:
    • Defining $S_a = \alpha / \beta$, (so $\alpha = S_a \beta$) or
    • Using Rayleigh $\beta$ in aerosol-free regions to calibrate, or
    • Working in the mesosphere where $\alpha \sim 0$,
  – Or add more information:
    • From other instruments
    • Using Two (or more) wavelengths, angles, polarizations, etc.
  – Much of the history of LIDAR describes efforts to overcome this challenge!
Rayleigh Lidar (Upper Atmospheric Lidar)

- **Rayleigh lidar** essentially bypasses the lower atmosphere and only receives useful signal from >30 km where aerosols are typically not present (Hauchecorne and Chanin; 1980)
  - Measurements include: temperature, density, dynamics (gravity waves, tides, planetary waves)

- **Resonance fluorescence lidar** transmitted light is matched to a specific atomic transition or electronic transition of a specific atom (Bowman et al., 1969)
  - Upper atmospheric species studied: sodium, iron, potassium, calcium/calcium ion, nickel

- Limits studies to upper atmosphere
Fernald-Klett Data Analysis Method

• The Fernald-Klett algorithm is a **data analysis** method for retrieving aerosol extinction from lidar signal (Fernald et al., 1972; Fernald, 1984; Klett, 1981)

• Inversion technique, which requires additional information:
  – Estimated or modeled molecular extinction profile
  – Initial value of aerosol extinction at maximum range
  – Initial guess of the lidar aerosol extinction-to-backscatter ratio, \( S_a = \frac{\alpha_a}{\beta_a} \)
  – Auxiliary measurement to constrain the inversion (e.g. sun photometer aerosol optical depth measurement)

• This method is still widely used in modern atmospheric lidar programs like NASA’s Micro-Pulse Lidar NETwork (MPLNET; Welton et al., 2001)

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*Figure 3. MPLNET V3 Cloud, Aerosol and PBL Products*  
Welton et al., 2018
Depolarization and Multi-Wavelength Lidar

• Can add further **hardware capabilities** to distinguish aerosol types

• Depolarization lidar measures degree to which the received light’s polarization state has changed from the transmitter laser light
  
  – Lower depolarization → atmospheric scatterers are spherical
  
  – Higher depolarization → atmospheric scatterers are non-spherical

• Adding multiple wavelengths gives more information about particle sizes

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**Fig. 1.** Time–height cross section of the range-corrected signal (upper panel, log-scale, a.u.) and the volume linear depolarization ratio (lower panel) at 532 nm derived from MULIS lidar measurements at Mässach from 16 April 17 UTC to 17 April 24 UTC.

**Fig. 14.** Particle lidar ratio vs. particle linear depolarization ratio for different aerosol types at 355 nm (left) and 532 nm (right).

**Groß et al., 2012**
Differential Absorption Lidar (DIAL)

• Transmit two different wavelengths that have distinct absorption cross-sections ($\sigma$) for the interrogated trace gas
  – Identify “on” and “off” wavelengths for selected trace gas, difference of cross sections proportional to difference in atmospheric extinction:

$$\Delta \alpha = \rho_{\text{trace gas}} \Delta \sigma$$

$$\rho_{\text{trace gas}} = \frac{1}{2 \Delta \sigma} \left[ \frac{d}{dR} \ln \left( \frac{P_{\text{on}}}{P_{\text{off}}} \right) \right]$$

• Mostly used to measure trace gas concentrations: ozone, methane, water vapor, etc.

• Recent work has demonstrated DIAL system for temperature measurements (Stillwell et al., 2020)
Raman lidar

- Raman lidar creates a source at a new wavelength, in the scattering volume, by inelastic scattering molecular species
  - The Raman backscatter is much weaker than Rayleigh

- Raman lidars designed to receive two or more shifted wavelengths

- Raman lidar technique can be used to spectroscopically separate molecular and aerosol extinction

- Technique can also be used to measure:
  - Vibrational-rotational Raman: Trace gas concentrations (water vapor, methane, carbon dioxide)
  - Rotational Raman: Temperature

Fig. 14. Six-day time series of water vapor with 10 min time resolution. All data are shown, including data with a statistical error > 10%. The noisy zones above 5000 m (around noon) mark the increase in statistical error due to the solar background during the daytime. The white zones mark data gaps.
High Spectral Resolution Lidar (HSRL)

- HSRL technique optically separates Rayleigh (molecular) and Mie (aerosol) signals (Shipley, 1983)
- Spectral distribution of molecular signal is Doppler-broadened, aerosol spectral distribution is not broadened
  - An atomic-vapor filter is used to block the aerosol signal so that the molecular and aerosol signals can be separated
- Returned signal separated into two channels:
  - Molecular backscatter channel
  - Molecular + aerosol backscatter channel
- Profile of molecular density is modeled/measured from auxiliary instruments is required to calibrate
Doppler Wind Lidar

- Typically achieved with **coherent detection**: atmospheric backscatter signal, is mixed with a local oscillator reference beam (Pearson et al., 2009)

- Doppler shifts are determined from the spectrum of the mixed signal

- Most systems are built to scan and measure line-of-sight velocities at each pointing angle in the scan
  - LOS winds can be decomposed into 3D components

- Commercial systems widely available (Halo Photonics, Vaisala)

*Range/time/Doppler plot for a fixed LOS 40 m gates, 1-second average per ray, 6-minute record. The raw data were saved and re-processed as shown below.*

https://halo-photonics.com/lidar-systems/streamline-allsky-series/
Lidar Design

• There are many different types lidar to choose from!

• Lidar performance is affected by many atmospheric, optical, electronic, mechanical, algorithmic, and geometric factors

• High-fidelity atmospheric lidar simulator coupled with Monte Carlo analysis has been developed to aid in lidar system design and algorithm development (Valenta & Sox, 2022)
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Searchlight Lidar

- Lidar technique first proposed by Sygne, 1930 to measure atmospheric scatter from searchlight beams
- First measurements came from bistatic searchlight systems (e.g. Hulbert, 1937)
- Johnson et al., (1939) showed profile of atmospheric structure with respect to altitude using a “pulsed” system

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First Ruby Lidar

- First working laser in 1960 (Maiman, 1960)
- Fiocco & Smullin demonstrated first ruby laser-based atmospheric lidar in 1963

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Fiocco & Smullin, 1963
Many Lidar Techniques

- Many atmospheric lidar techniques were developed after the first system came online:
  - **Raman lidar** ~1960s-1970s: Leonard & Caputo, 1974; Cooney
  - **DIAL** ~ 1960s-1970s: Schotland, 1966
  - **HSRL** ~ 1980s: Shipley et al., 1984

- **Lidar with searchlights**
  - 1930s

- **First Laser**
  - 1960

- **First Lidar**
  - 1963

- **Lidar Techniques Developed**
  - **1960-1990s**
    - 1960s
    - 1970s
    - 1980s

- **Lidar Networks**
  - 2000s

- **NASA CALIPSO**
  - 2006

- **ESA Aeolus**
  - 2018

- **Measures, 1994**
Ground-based Lidar Networks

• NASA Micro-Pulse Lidar Network (MPLNET)
  – ~26 active Micro-pulse elastic backscatter lidars with depolarization functionality

• NASA Tropospheric Ozone Lidar Network (TOLNET)
  – ~6 DIAL Ozone lidars (Leblanc et al., 2018)

• European Aerosol Research Lidar Network (EARLINET)
  – 30+ elastic and multi-wavelength Raman lidars (Pappalardo et al., 2014)
Lidars in Space!

• NASA/CNES Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) onboard the CALIPSO satellite
  – Launched in 2006, ended 2023
  – Elastic backscatter lidar with depolarization and two wavelengths

• ESA Atmospheric Laser Doppler Instrument (ALADIN) onboard Atmospheric Dynamics Mission-Aeolus satellite
  – Launched in 2018, ended 2023
  – Doppler wind lidar for winds from 0-30 km

Lidar with searchlights | First Laser | First Lidar | Lidar Techniques Developed | Lidar Networks | NASA CALIPSO | ESA Aeolus
---|---|---|---|---|---|---

Fig. 4. (a) A 532-nm backscatter browse image, (b) cloud-aerosol mask, and (c) the corresponding aerosol subtyping plot showing vast smoke layer in southwestern Africa during the peak of the burning season, observed on 8 Aug 2006 and stretching across land into the South Atlantic. The relative scales are as in Fig. 3.

ESA/ECMWF:http://m.esa.int/SpaceInImages/Images/2018/09/Winds_imaged_by_Aeolus

Omar et al., 2009
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Commercialization of Lidar

• Elastic backscatter lidar →
  – Droplet Measurement Technologies
  Micro Pulse Lidar
  – Ceilometers from Vaisala, Campbell Scientific

• Doppler wind lidar →
  – Vaisala WindCube
  – Halo Photonics Streamline Series

• DIAL →
  – Vaisala DA10 water vapor DIAL
Earth Cloud, Aerosol and Radiation Explorer (EarthCARE)

- ESA/JAXA mission to better understand Earth’s thermal and solar radiation balance

- Expected launch date: May 2024

- Atmospheric lidar (ATLID)
  - HSRL
  - Depolarization lidar
  - For cloud-top, thin-cloud profiling, aerosol profiling

- Also includes:
  - Cloud profiling radar → penetrate clouds
  - Multispectral imager → wide-scene images
  - Radiometer → reflected & outgoing radiation

Modeled example data from Zadelhoff et al., 2023
Conclusions

• Light scattering interactions with molecules and particles have been employed as a method of atmospheric measurement for more than 90 years, with laser transmitters used in modern technology.

• Many different types of atmospheric lidar enable atmospheric studies of:
  – Temperature & composition $\rightarrow$ Rayleigh, Raman, & Resonance Fluorescence lidar
  – Dynamics $\rightarrow$ Doppler wind lidar
  – Aerosols & air quality $\rightarrow$ elastic backscatter, Raman, & HSRL
  – Trace gases $\rightarrow$ DIAL & Raman lidar

• Recent advancements have brought atmospheric lidar technology to the commercial sector and new lidar systems continue to be deployed on major satellite programs.
References


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MPLNET Data from March 18, 2024 @ El Arenosillo in Doñana National Park, Spain: https://mplnet.gsfc.nasa.gov/data-policy