Optical Remote Sensing with Differential Absorption Lidar (DIAL)

Part 1: Theory

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Outline

- DIAL concept
- A short history of DIAL
- DIAL equation
- Precision & accuracy of DIAL retrieval
- Dual-DIAL technique
Differential Absorption Lidar (DIAL) Concept

Laser Transmitter

Optical Receiver

Distributed Backscattering Medium

\( \lambda_{On} \), \( \lambda_{Off} \)

Power Received, \( P_r \)

\( R_1 \), \( R_2 \)

Absorption Cross Section

\( \sigma(\lambda_{On}) \), \( \sigma(\lambda_{Off}) \)

\( \lambda_{Off} \), \( \lambda_{On} \)
Atmospheric gases measured with DIAL

- $\text{H}_2\text{O}$
- $\text{O}_3$
- $\text{SO}_2$
- $\text{NO}_2$, NO
- $\text{NH}_3$
- $\text{CH}_4$
- $\text{CO}_2$
- $\text{Hg}$
- VOCs (Volatile Organic Compounds)
- Toluene, Benzene
First DIAL measurements

Richard M. Schotland ("The father of DIAL")

1964 – Measured vertical profiles of water vapor by thermally tuning a ruby laser on and off the water vapor absorption line at 694.38 nm.

Only 4 years after invention of ruby laser!

Fig. 4.20. Comparison of atmospheric water vapor vertical profiles (expressed as dew point temperature) measured by differential absorption lidar and radiosonde [4.82]
Major milestones in the history of DIAL

- **1960** Maiman: Invention of the laser
- **1964** Shumate & Menzies: First Airborne DIAL (column \(O_3\))
- **1977** Schotland: First \(H_2O\) DIAL measurements
- **1978** Megie: First \(O_3\) DIAL
- **1981** Browell: First \(H_2O\) DIAL (LASE \(H_2O\) DIAL on ER-2 aircraft)
- **1995** Browell: First airborne \(H_2O\) DIAL
- **Present** Space-based DIAL

**??**
Extinction coefficient:

$$\alpha(R), \left[ m^{-1} \right]$$

Optical depth / thickness:

$$\tau(R) = \int_0^R \alpha(r) \, dr$$

Transmission:

$$T(R) = \exp[-\tau(R)] = \exp \left[ -\int_0^R \alpha(r) \, dr \right]$$
DIAL equation (1)

Single scattering, elastic backscatter LIDAR equation:

\[ N_S(\lambda, R) = N_L(\lambda) \left[ \beta(\lambda, R) \Delta R \right] \frac{A}{R^2} \exp \left[ -2 \int_0^R \alpha_{Tot}(\lambda, r) \, dr \right] \left[ \eta(\lambda) \, G(\lambda, R) \right] + N_B(\lambda) \]

with \( \alpha_{Tot}(\lambda, r) = \alpha(\lambda, r) + \sum_i \sigma_{mol,abs,i}(\lambda, r) \, n_i(r) \)

Take ratio of LIDAR equations for online and offline wavelengths \( \lambda_{on} \) and \( \lambda_{off} \):

\[ \frac{N_S(\lambda_{off}, R) - N_B(\lambda_{off}, R)}{N_S(\lambda_{on}, R) - N_B(\lambda_{on}, R)} = \frac{N_L(\lambda_{off}) \, \eta(\lambda_{off}) \, G(\lambda_{off}, R) \, \beta(\lambda_{off}, R)}{N_L(\lambda_{on}) \, \eta(\lambda_{on}) \, G(\lambda_{on}, R) \, \beta(\lambda_{on}, R)} \]

\[ \times \exp \left[ -2 \int_0^R \alpha(\lambda_{off}, r) - \alpha(\lambda_{on}, r) \, dr \right] \]

\[ \times \exp \left[ -2 \int_0^R \left( \sigma_C(\lambda_{off}, r) - \sigma_C(\lambda_{on}, r) \right) n_C(r) \, dr \right] \]

\[ \times \exp \left[ -2 \int_0^R \sum_{i=1}^m \left( \sigma_{X_i}(\lambda_{off}, r) - \sigma_{X_i}(\lambda_{on}, r) \right) n_{X_i}(r) \right] \, dr \]
DIAL equation (2)

\[ n_C = \frac{1}{2\Delta\sigma_C(R)} \frac{d}{dR} \ln \left[ \frac{N_S(\lambda_{\text{off}}, R) - N_B(\lambda_{\text{off}})}{N_S(\lambda_{\text{on}}, R) - N_B(\lambda_{\text{on}})} \right] \]

- \frac{1}{2\Delta\sigma_C(R)} \frac{d}{dR} \ln \frac{G(\lambda_{\text{off}}, R)}{G(\lambda_{\text{on}}, R)} \quad [GF]

- \frac{1}{2\Delta\sigma_C(R)} \frac{d}{dR} \ln \frac{\beta(\lambda_{\text{off}}, R)}{\beta(\lambda_{\text{on}}, R)} \quad [B]

- \frac{1}{\Delta\sigma_C(R)} \left[ \alpha(\lambda_{\text{on}}, R) - \alpha(\lambda_{\text{off}}, R) \right] \quad [E]

- \frac{1}{\Delta\sigma_C(R)} \sum_{i=1}^{m} \Delta\sigma_{X_i}(R) n_{X_i}(R) \quad [X]

with \( \Delta\sigma_C(R) = \sigma_C(\lambda_{\text{on}}, R) - \sigma_C(\lambda_{\text{off}}, R) \)

GF = differential geometrical factor  \quad B = differential backscatter
E = differential extinction  \quad X = interfering constituents
How to choose an appropriate absorption line for DIAL (1)

\[ N_S(\lambda_{on}, R) \propto \exp \left[ -2 \int_{0}^{R} \sigma_C(\lambda_{on}, r) n_C(r) \, dr \right] \]

Extinction of online wavelength due to absorption by constituent C must be neither too small or too large.

![Graph showing absorption too strong and too weak](image)

Best precision in \( n_C \) when:

\[ \tau(\lambda_{on}, R_{max}) = \int_{0}^{R_{max}} \sigma_C(\lambda_{on}, r) n_C(r) \, dr = 1.1 \]

(Remsberg & Gordley, 1978)
How to choose an appropriate absorption line for DIAL (2)

Example: Ozone

\[
\tau(\lambda_{on}, R_{max}) = \int_0^{R_{max}} \sigma_C(\lambda_{on}, r) n_C(r) \, dr = 1.1
\]

For \( m_{r_{O_3}} = 80 \text{ppbv} \) or \( n_{O_3} = 2 \times 10^{18} \text{ m}^{-3} \) and \( R_{max} = 3 \text{ km} \):

\[
\sigma_{O_3}(\lambda_{on}) n_{O_3} R_{max} = 1.1 \quad \Rightarrow \quad \sigma_{O_3}(\lambda_{on}) = 1.83 \times 10^{-22} \text{ m}^2
\]
Precision of DIAL measurements

Simple “back of the envelope” calculation:

\[
n_C = \frac{1}{2\Delta \sigma_C(R) \Delta R} \ln \left[ \frac{N(\lambda_{off}, R + \Delta R) N(\lambda_{on}, R)}{N(\lambda_{on}, R + \Delta R) N(\lambda_{off}, R)} \right] \quad \text{with } N = N_S - N_B
\]

\[
\delta n_C = \frac{1}{2\Delta \sigma_C(R) \Delta R} \sqrt{\sum_{i,j} \delta^2(N(\lambda_i, R_j))} \approx \frac{1}{\Delta \sigma_C \Delta R} \frac{\delta N}{N} = \frac{1}{\Delta \sigma_C \Delta R \text{ SNR}} \quad \text{with } \text{SNR} = \frac{N}{\delta N}
\]

\[
\frac{\delta n_C}{n_C} = \frac{1}{\Delta \sigma_C n_C \Delta R \text{ SNR}} = \frac{1}{\Delta \tau \text{ SNR}} \quad \Rightarrow \quad \text{SNR} = \frac{1}{\Delta \tau \delta n_C/n_C}
\]

**Example:** \( \Delta \tau = 0.05, \ \delta n_C/n_C = 5\% \quad \Rightarrow \quad \text{SNR} = 400 \)

Even modest precision of 5% requires high SNR. SNR can be increased by averaging on/offline signals time- and range-wise.

**Poisson statistics:** \( \delta N = N^{0.5} \quad \Rightarrow \quad \text{SNR} = N^{0.5} \)

**Since** \( N \propto \Delta t \Delta R, \quad \text{SNR} \propto \Delta t^{0.5} \Delta R^{0.5} \quad \text{and} \quad \delta n_C \propto \Delta t^{-0.5} \Delta R^{-1.5} \)
Accuracy of DIAL measurements (1)

\[ n_C = \frac{1}{2\Delta \sigma_C(R)} \frac{d}{dR} \ln \left( \frac{N_S(\lambda_{\text{off}}, R) - N_B(\lambda_{\text{off}})}{N_S(\lambda_{\text{on}}, R) - N_B(\lambda_{\text{on}})} \right) \]

\[ - \frac{1}{2\Delta \sigma_C(R)} \frac{d}{dR} \ln \left( \frac{G(\lambda_{\text{off}}, R)}{G(\lambda_{\text{on}}, R)} \right) \] \hspace{1cm} [GF]

\[ - \frac{1}{2\Delta \sigma_C(R)} \frac{d}{dR} \ln \left( \frac{\beta(\lambda_{\text{off}}, R)}{\beta(\lambda_{\text{on}}, R)} \right) \] \hspace{1cm} [B]

\[ - \frac{1}{\Delta \sigma_C(R)} \left[ \alpha(\lambda_{\text{on}}, R) - \alpha(\lambda_{\text{off}}, R) \right] \] \hspace{1cm} [E]

\[ - \frac{1}{\Delta \sigma_C(R)} \sum_{i=1}^{m} \Delta \sigma_{X_i}(R) n_{X_i}(R) \] \hspace{1cm} [X]

Accuracy affected by:

- How well is absorption cross section known?
- Improper correction of signal offsets, e.g. background light
- Geometrical factor different for \( \lambda_{\text{on}} \) and \( \lambda_{\text{off}} \)
- Differential backscatter & extinction not properly corrected
- Interfering species not taken into account
Accuracy of DIAL measurements (2)

Differential geometrical factor: $$\frac{-1}{2\Delta \sigma_c(R)} \frac{d}{dR} \ln \frac{G(\lambda_{off}, R)}{G(\lambda_{on}, R)} \quad [GF]$$

$$G(\lambda_{on}, R) = G(\lambda_{off}, R) = 1$$

$$G(\lambda_{on}, R) \neq G(\lambda_{off}, R); \ G < 1$$

Effect of differential geometrical factor on $O_3$ retrieval
Accuracy of DIAL measurements (3)

Differential backscatter & extinction:

\[ B = -\frac{1}{2\Delta\sigma_c(R)} \frac{d}{dR} \ln \frac{\beta(\lambda_{\text{off}}, R)}{\beta(\lambda_{\text{on}}, R)} \]

\[ E = -\frac{1}{\Delta\sigma_c(R)} \left[ \alpha(\lambda_{\text{on}}, R) - \alpha(\lambda_{\text{off}}, R) \right] \]

\[ \beta = \beta_{\text{Rayleigh}} + \beta_{\text{Aerosol}} \quad \alpha = \alpha_{\text{Rayleigh}} + \alpha_{\text{Aerosol}} \]

➢ For ozone DIAL retrieval, backscatter and extinction correction is necessary due to large \( \Delta\lambda \).

➢ \( \beta_{\text{Aerosol}} \) and \( \alpha_{\text{Aerosol}} \) have to be determined from offline signal data and wavelength dependence of \( \beta \) and \( \alpha \) have to be guessed.
Wrong assumptions about aerosol parameters can introduce significant errors in O$_3$ retrieval!
Dual-DIAL concept

2 DIAL wavelength pairs: $\lambda_1 / \lambda_2$ and $\lambda_2 / \lambda_3$
Dual-DIAL minimizes aerosol interference (1)

\[
n_C = \frac{1}{2 \delta \sigma_c (R)} \frac{d}{dR} \left[ \ln \frac{N_s^* (\lambda_{off1}, R)}{N_s^* (\lambda_{on1}, R)} - C \ln \frac{N_s^* (\lambda_{off2}, R)}{N_s^* (\lambda_{on2}, R)} \right] \\
- \frac{1}{2 \delta \sigma_c (R)} \frac{d}{dR} \left[ \ln \frac{\beta (\lambda_{off1}, R)}{\beta (\lambda_{on1}, R)} - C \ln \frac{\beta (\lambda_{off2}, R)}{\beta (\lambda_{on2}, R)} \right] \\
- \frac{1}{\delta \sigma_c (R)} \left[ \alpha (\lambda_{on1}, R) - \alpha (\lambda_{off1}, R) - C (\alpha (\lambda_{on2}, R) - \alpha (\lambda_{off2}, R)) \right]
\]

[B']

\[
E' = \left[ \frac{\lambda_{on1} - \lambda_{off1}}{\lambda_{on2} - \lambda_{off2}} \right] C
\]

with \( \delta \sigma_c (R) = \Delta \sigma_{C1} - C \Delta \sigma_{C2} \), DIAL pair 1: \( \lambda_{on1} / \lambda_{off1} \), DIAL pair 2: \( \lambda_{on2} / \lambda_{off2} \)

\[B' = E' \approx 0 \text{ for } C = \left[ \frac{\lambda_{on1} - \lambda_{off1}}{\lambda_{on2} - \lambda_{off2}} \right] \]

- No correction of differential aerosol effects needed and residual errors are small.
- However, precision of DIAL retrieval is degraded.
Dual-DIAL minimizes aerosol interference (2)
Selected References

**DIAL history (slides 5 - 6)**


**How to choose a DIAL absorption line? (slides 10 - 11)**


**Aerosol correction & DUAL-DIAL (slides 15 - 19)**
