Optical Remote Sensing with Di|fferential Absorption Lidar (DIAL)

Part 1: Theory

Christoph Senff

CIRES, University of Colorado & NOAA/ESRL/CSD/Atmospheric Remote Sensing Group

http://www.esrl.noaa.gov/csd/groups/csd3/

Guest lecture for ASEN-6519 Lidar Remote Sensing
CU Boulder

October 8, 2012
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

Power Received, $P_r$

Absorption Cross Section

$\lambda_{On}$ $\lambda_{Off}$

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

Range $R_1$ $R_2$

Wavelength $\lambda_{Off}$ $\lambda_{On}$
Atmospheric gases measured with DIAL

- H$_2$O
- O$_3$
- SO$_2$
- NO$_2$, NO
- NH$_3$
- CH$_4$
- CO$_2$
- 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

- **Maiman:** Invention of the laser
  - 1960
  - 1964

- **Shumate & Menzies:** First Airborne DIAL (column O₃)
  - 1977
  - 1978
  - 1981

- **Schotland:** First H₂O DIAL measurements
  - 1977

- **Megie:** First O₃ DIAL
  - 1995

- **Browell:** First airborne H₂O DIAL
  - 1995

- **Browell:** First autonomous DIAL (LASE H₂O DIAL on ER-2 aircraft)
  - 2000
  - Present

- **Space-based DIAL**
  - ??
Single scattering, elastic backscatter LIDAR equation:

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

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

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

\[
\frac{N_S(\lambda_{\text{off}}, R) - N_B(\lambda_{\text{off}}, R)}{N_S(\lambda_{\text{on}}, R) - N_B(\lambda_{\text{on}}, R)} = \frac{N_L(\lambda_{\text{off}}) \, \eta(\lambda_{\text{off}}) \, G(\lambda_{\text{off}}, R) \, \beta(\lambda_{\text{off}}, R)}{N_L(\lambda_{\text{on}}) \, \eta(\lambda_{\text{on}}) \, G(\lambda_{\text{on}}, R) \, \beta(\lambda_{\text{on}}, R)} \times \exp \left[ -2 \int_0^R \alpha(\lambda_{\text{off}}, r) - \alpha(\lambda_{\text{on}}, r) \, dr \right] \times \exp \left[ -2 \int_0^R \left( \sigma_C(\lambda_{\text{off}}, r) - \sigma_C(\lambda_{\text{on}}, r) \right) n_C(r) \, dr \right] \times \exp \left[ -2 \int_0^R \sum_{i=1}^m \left( \sigma_{X_i}(\lambda_{\text{off}}, r) - \sigma_{X_i}(\lambda_{\text{on}}, r) \right) n_{X_i}(r) \right] \, dr
\]
DIAL equation (2)

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

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

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

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

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

G = differential geometrical factor  \ \ \ \ B = differential backscatter
E = differential extinction  \ \ \ \ 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.

Best precision in \( n_C \) when:

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

(Reinseberg & 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 \( R_{max} = 3 \text{ km} \):

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

![Ozone absorption in the UV](image-url)
Precision of DIAL measurements

Simple “back of the envelope” calculation:

\[
n_C = \frac{1}{2 \Delta \sigma_c(R) \Delta R} \ln \left[ \frac{N(\lambda_{\text{off}}, R + \Delta R) N(\lambda_{\text{on}}, R)}{N(\lambda_{\text{on}}, R + \Delta R) N(\lambda_{\text{off}}, R)} \right]
\]

with \( N = N_S - N_B \)

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

with \( \text{SNR} = \frac{N}{\delta N} \)

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

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

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

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

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

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

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

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

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: \[-\frac{1}{2\Delta\sigma_c (R)} \frac{d}{dR} \ln \frac{G(\lambda_{off}, R)}{G(\lambda_{on}, R)} \] \[G\]

Effect of differential geometrical factor on O\(_3\) retrieval
Accuracy of DIAL measurements (3)

Differential backscatter & extinction:

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

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

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

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)

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

\[ - \frac{1}{2 \delta \sigma_C(R)} \frac{d}{dR} \left[ \ln \frac{\beta(\lambda_{off1}, R)}{\beta(\lambda_{on1}, R)} - C \ln \frac{\beta(\lambda_{off2}, R)}{\beta(\lambda_{on2}, R)} \right] \quad \text{[B']} \]

\[ - \frac{1}{\delta \sigma_C(R)} \left[ \alpha(\lambda_{on1}, R) - \alpha(\lambda_{off1}, R) - C(\alpha(\lambda_{on2}, R) - \alpha(\lambda_{off2}, R)) \right] \quad \text{[E']} \]

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

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

- 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 9 - 10)


Aerosol correction & DUAL-DIAL (slides 14 - 18)