Optical Remote Sensing with DIfferential Absorption Lidar (DIAL)

Part 1: Theory

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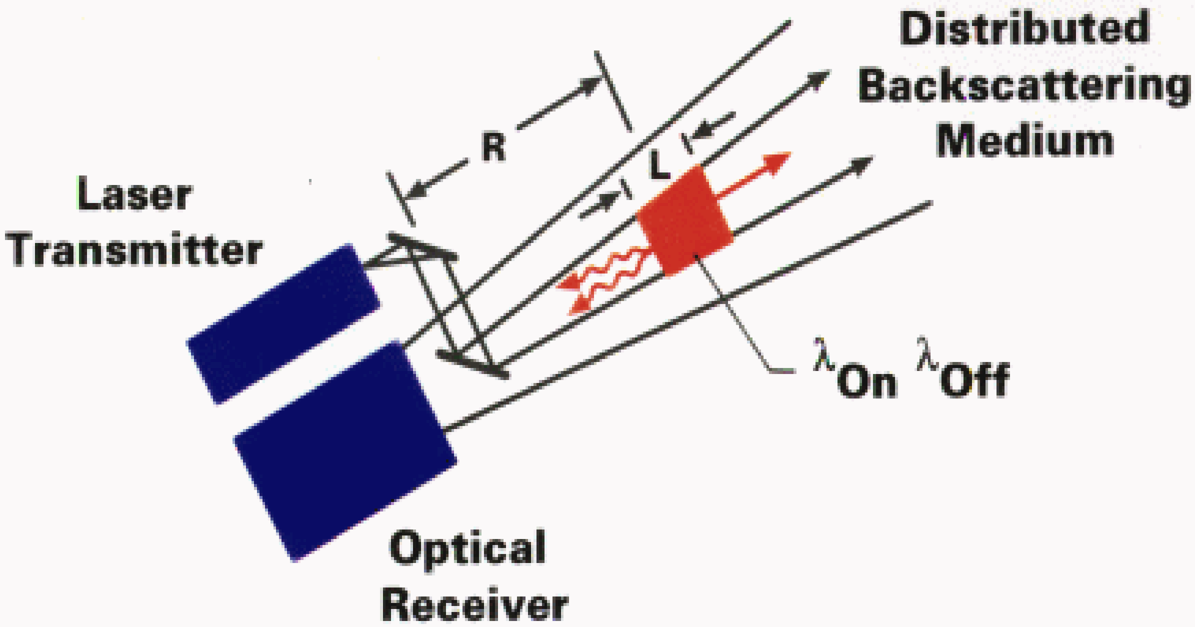
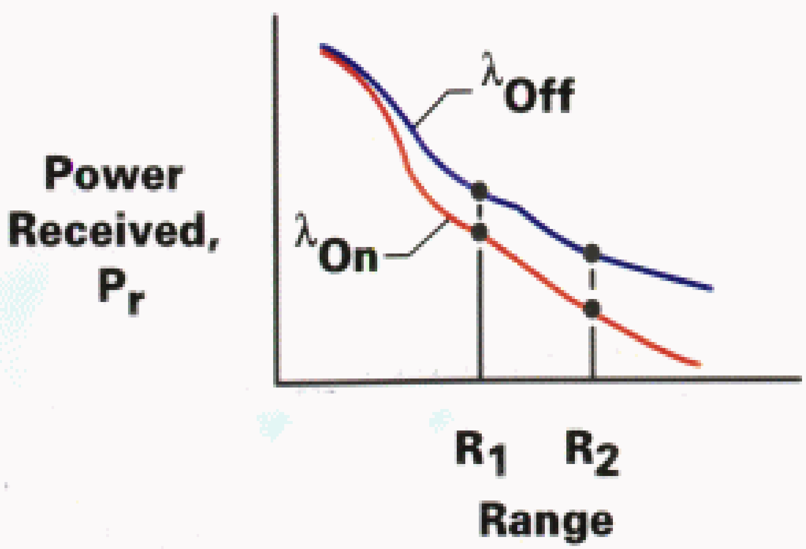
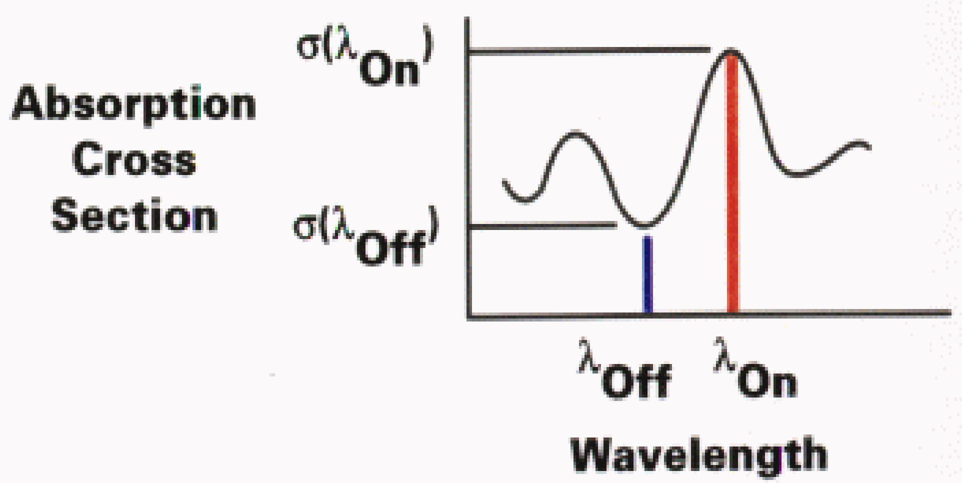
Outline

- DIAL concept
- A short history of DIAL
- DIAL equation
- Precision & accuracy of DIAL retrieval
- Dual-DIAL technique

Differential Absorption Lidar (DIAL) Concept







Atmospheric gases measured with DIAL

- H_2O
- 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 !

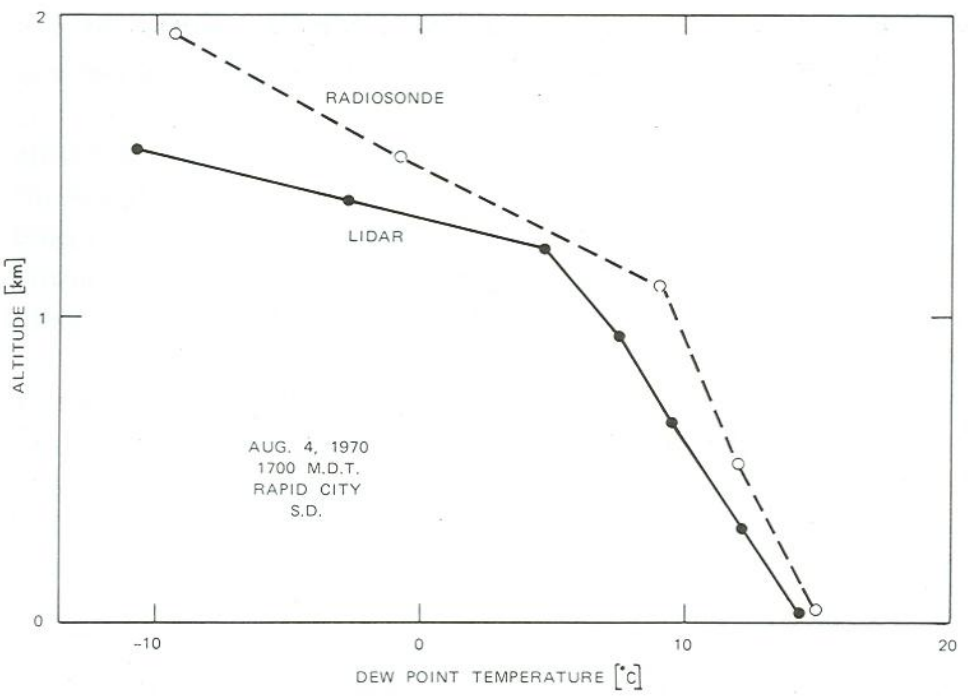
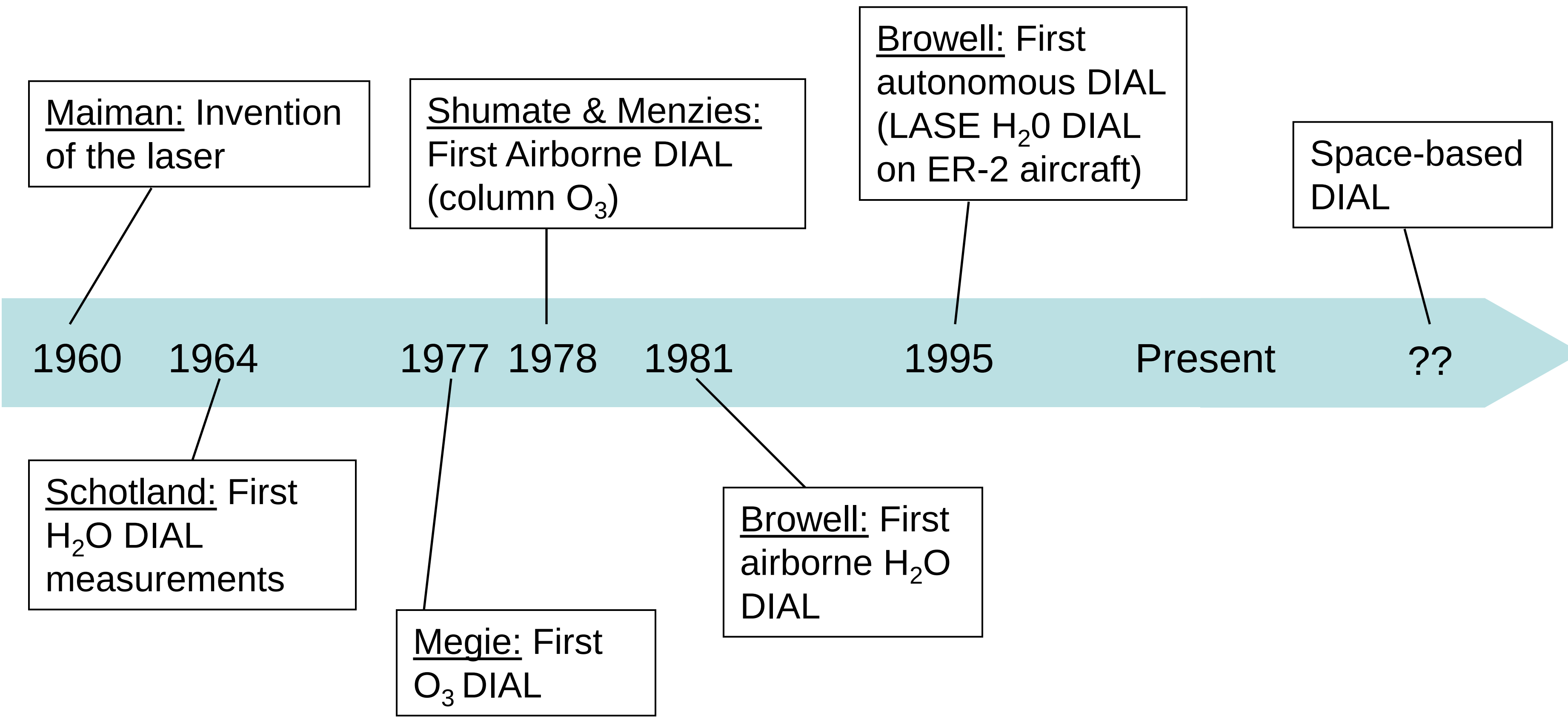


Fig. 4.20. Comparison of atmospheric water vapor vertical profiles (expressed as dew point temperature) measured by differential absorption lidar and radiosonde [4.82]

Major milestones in the history of DIAL



DIAL equation (1)

Single scattering, elastic backscatter LIDAR equation:

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

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

Take ratio of LIDAR equations for online and offline wavelengths λ_{on} and λ_{off} :

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

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

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

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

Number density of constituent C

DIAL equation (2)

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

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

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

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

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

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

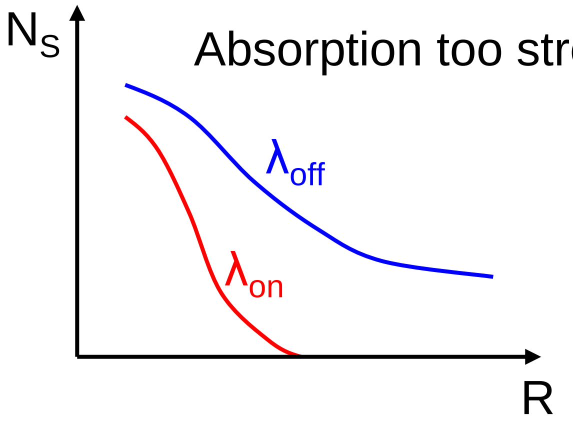
G = differential geometrical factor
E = differential extinction

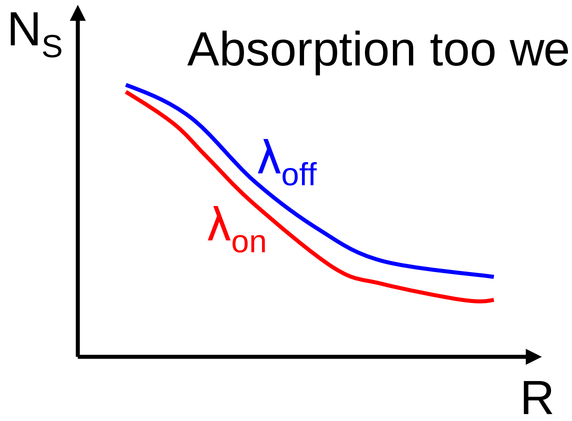
B = differential backscatter
X = interfering constituents

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

(Remsberg & Gordley, 1978)

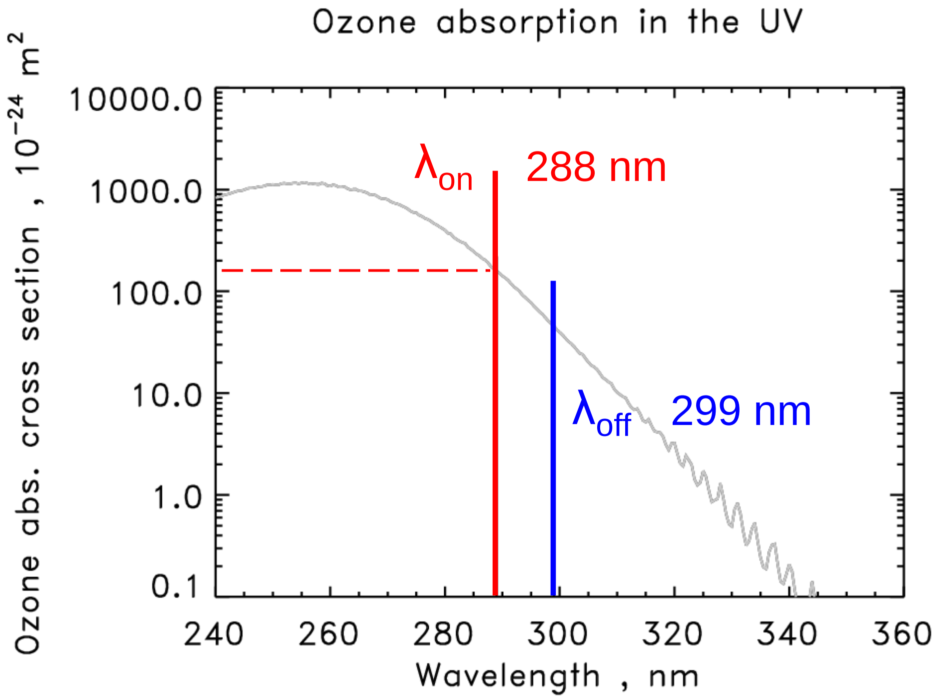
How to choose an appropriate absorption line for DIAL (2)

Example: Ozone

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

$$For \quad mr_{O_3} = 80\, ppbv \quad or \quad n_{O_3} = 2\times10^{18} m^{-3} \; and \; R_{max} = 3km:$$

$$\sigma_{O_3}(\lambda_{on})\, n_{O_3}\; R_{max} = 1.1 \quad \Rightarrow \quad \boxed{\sigma_{O_3}(\lambda_{on}) = 1.83\times10^{-22} m^2}$$



Precision of DIAL measurements

Simple “back of the envelope” calculation:

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

$$\delta n_C = \frac{1}{2\,\Delta\sigma_C(R)\,\Delta R}\sqrt{\sum_{i,j}\frac{\delta^2\left(N(\lambda_i, R_j)\right)}{\left(N(\lambda_i, R_j)\right)^2}} \approx \frac{1}{\Delta\sigma_C\,\Delta R}\,\frac{\delta N}{N} = \frac{1}{\Delta\sigma_C\,\Delta R\ \ SNR} \qquad with\ \ SNR = \frac{N}{\delta N}$$

$$\frac{\delta n_C}{n_C} = \frac{1}{\Delta\sigma_C\ n_C\,\Delta R\ SNR} = \frac{1}{\Delta\tau\ SNR} \quad \Rightarrow \quad \boxed{SNR = \frac{1}{\Delta\tau\ \ \delta n_C / n_C}}$$

$$Example: \quad \Delta\tau = 0.05,\ \ \delta n_C / n_C = 5\% \quad \Rightarrow \quad \boxed{SNR = 400\,!}$$

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

$$Poisson\ statistics: \quad \delta N = N^{0.5} \ \Rightarrow\ SNR = N^{0.5}$$

$$Since\ N \propto \Delta t\,\Delta R, \quad \boxed{SNR \propto \Delta t^{0.5}\Delta R^{0.5} \quad and \quad \delta n_C \propto \Delta t^{-0.5}\Delta R^{-1.5}}$$

Accuracy of DIAL measurements (1)

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

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

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

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

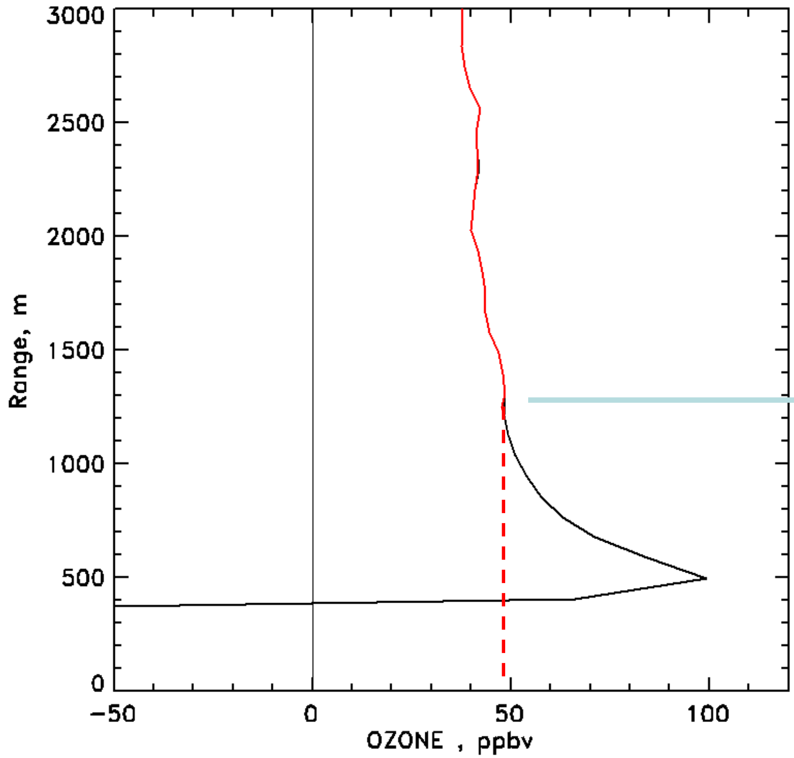
$$-\frac{1}{\Delta\sigma_C(R)}\sum_{i=1}^{m}\Delta\sigma_{X_i}(R)\,n_{X_i}(R) \qquad [X]$$

Accuracy affected by:

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

Accuracy of DIAL measurements (2)

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



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

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

Effect of differential geometrical factor on O_3 retrieval

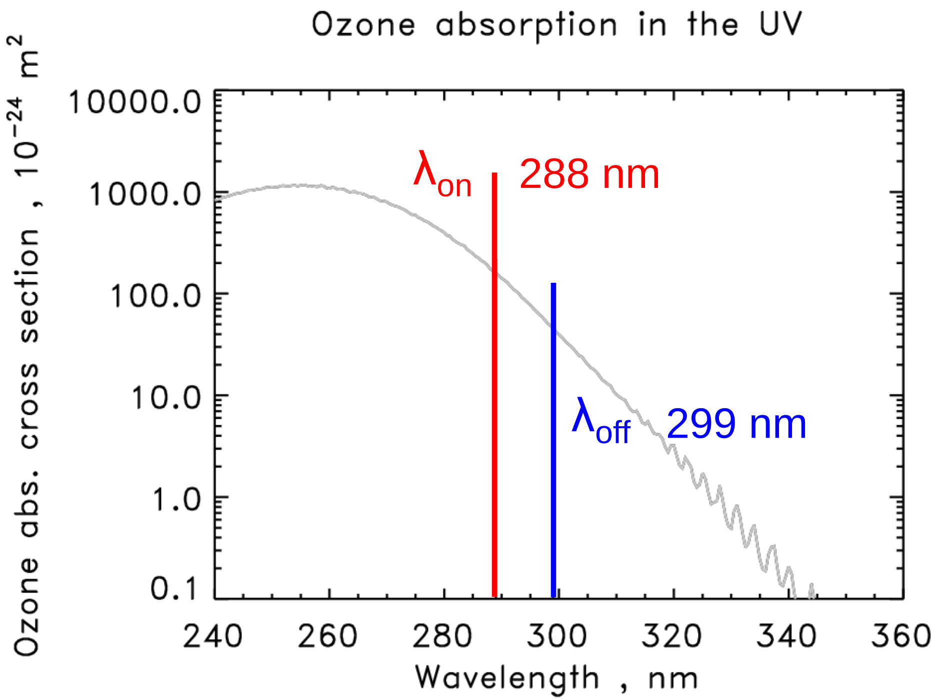
Accuracy of DIAL measurements (3)

Differential backscatter & extinction:

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

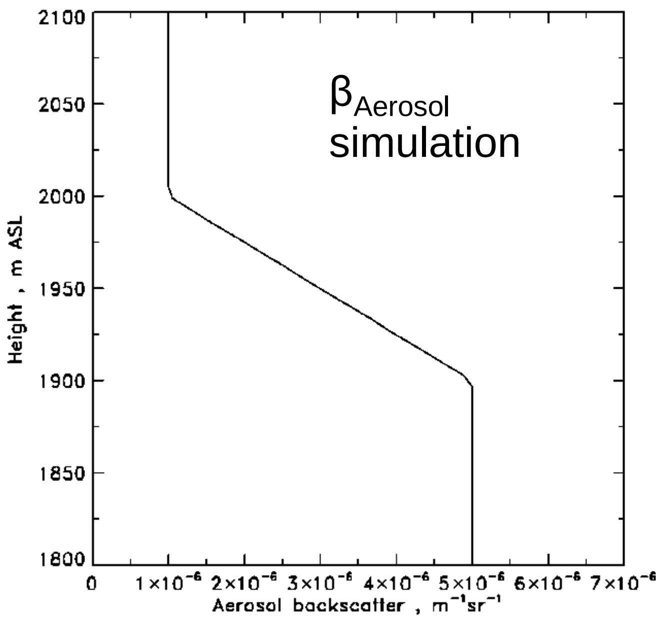
$$-\frac{1}{\Delta\sigma_C(R)}\left[\alpha(\lambda_{on},R)-\alpha(\lambda_{off},R)\right] \qquad [E]$$

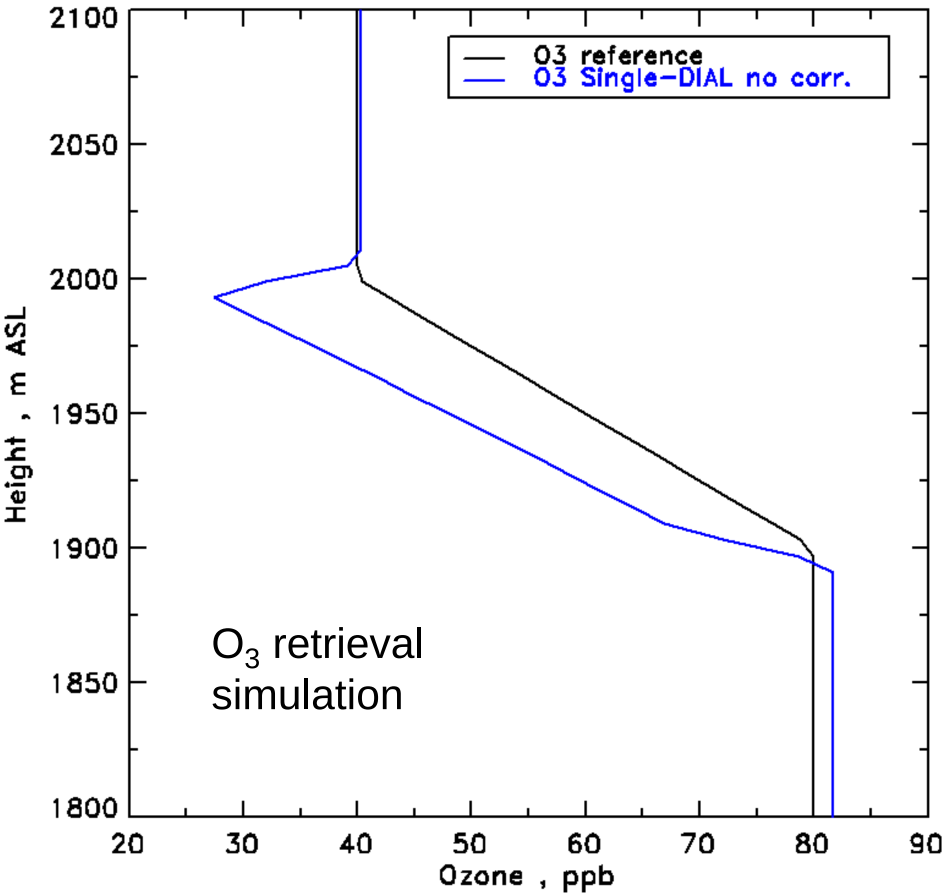
$$\beta=\beta_{Rayleigh}+\beta_{Aerosol}\,, \quad \alpha=\alpha_{Rayleigh}+\alpha_{Aerosol}$$



- For ozone DIAL retrieval, backscatter and extinction correction is necessary due to large Δλ.
- $\beta_{Aerosol}$ and $\alpha_{Aerosol}$ have to be determined from offline signal data and wavelength dependence of β and α have to be guessed.

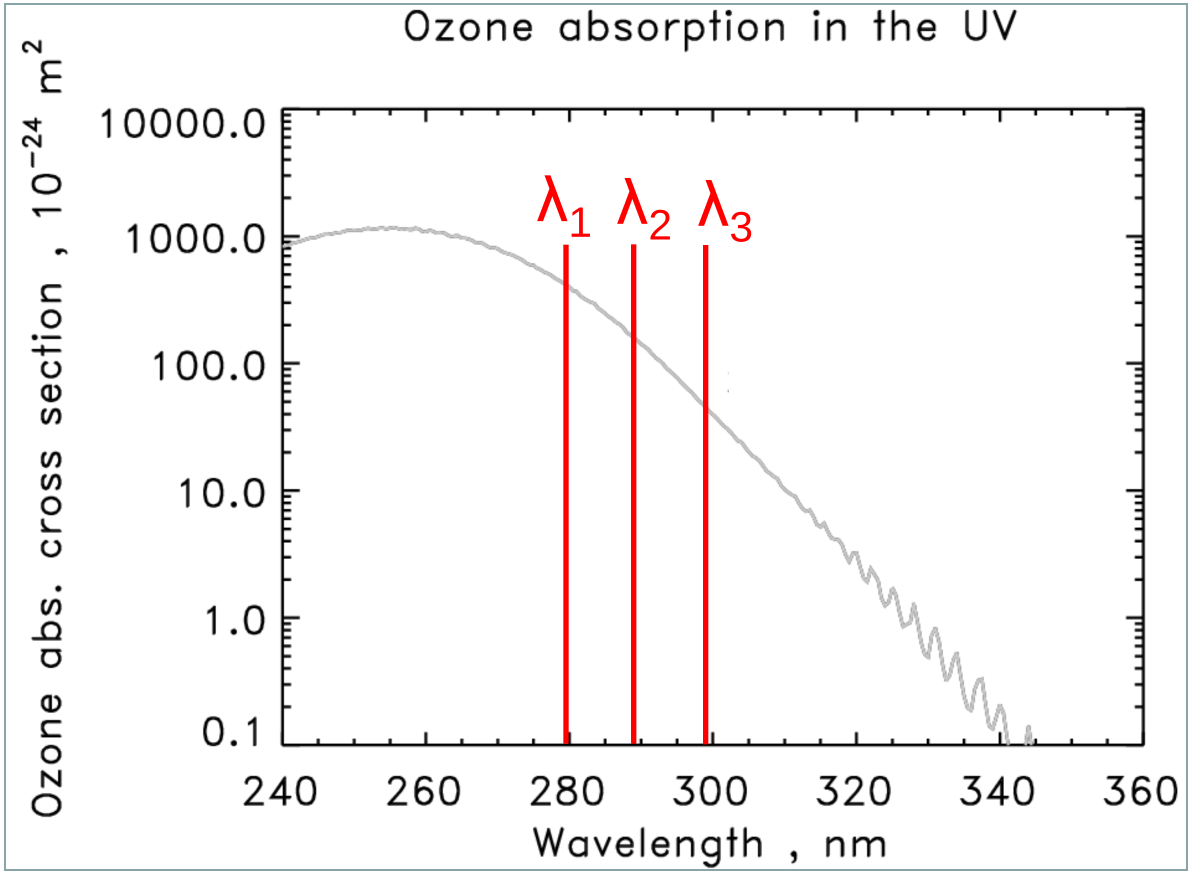
Accuracy of DIAL measurements (4)





Wrong assumptions about aerosol parameters can introduce significant errors in O_3 retrieval !

Dual-DIAL concept



2 DIAL wavelength pairs: λ_1 / λ_2 and λ_2 / λ_3

Dual-DIAL minimizes aerosol interference (1)

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

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

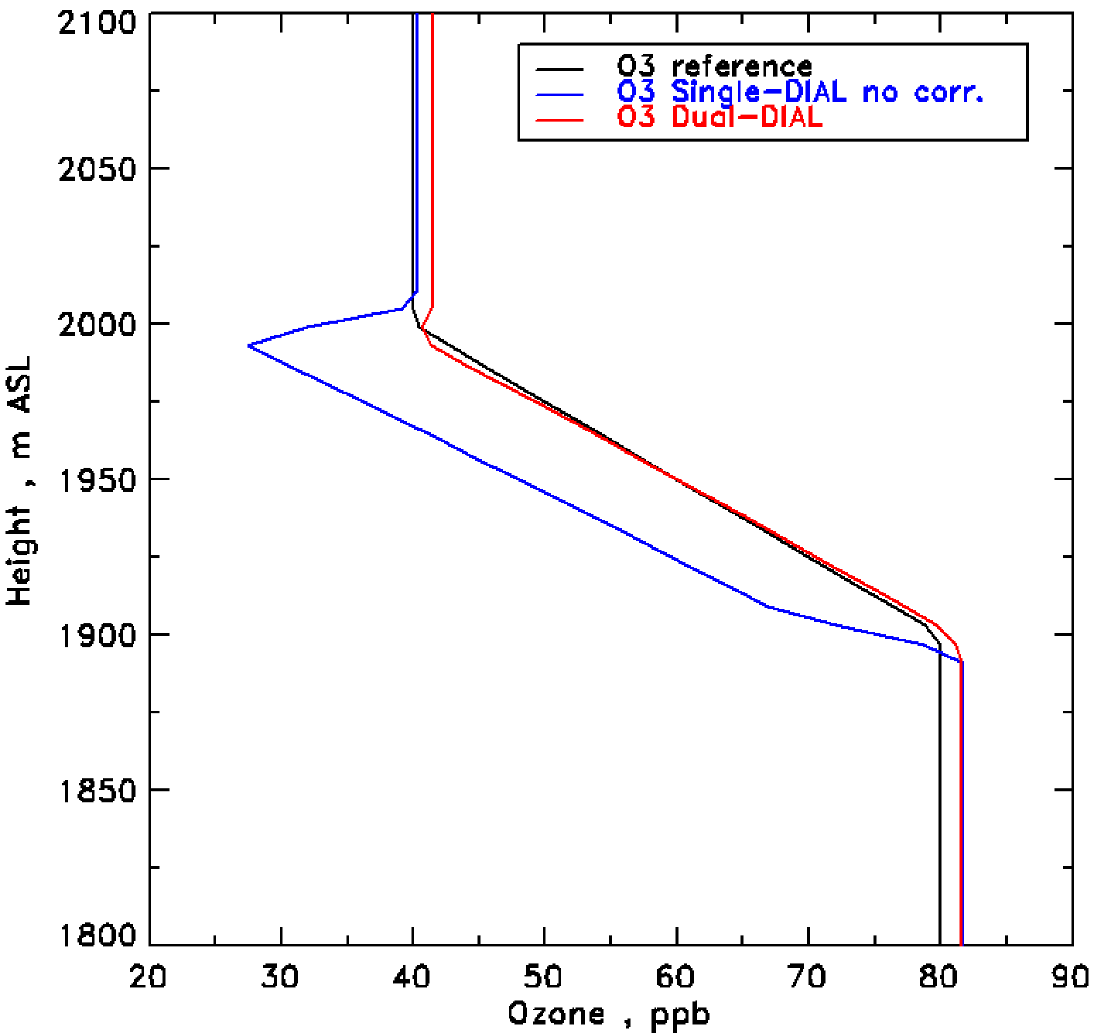
$$-\frac{1}{\delta\sigma_C(R)}\left[\alpha(\lambda_{on1},R)-\alpha(\lambda_{off1},R)-C\left(\alpha(\lambda_{on2},R)-\alpha(\lambda_{off2},R)\right)\right] \qquad [E']$$

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

$$B' = E' \approx 0 \quad for \quad C = \frac{\lambda_{on1}-\lambda_{off1}}{\lambda_{on2}-\lambda_{off2}}$$

- 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)



O_3 retrieval simulation

Selected References

DIAL history (slides 5 - 6)

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How to choose a DIAL absorption line? (slides 9 - 10)

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

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