

# Optical Remote Sensing with DIfferential Absorption Lidar (DIAL)

## Part1: 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

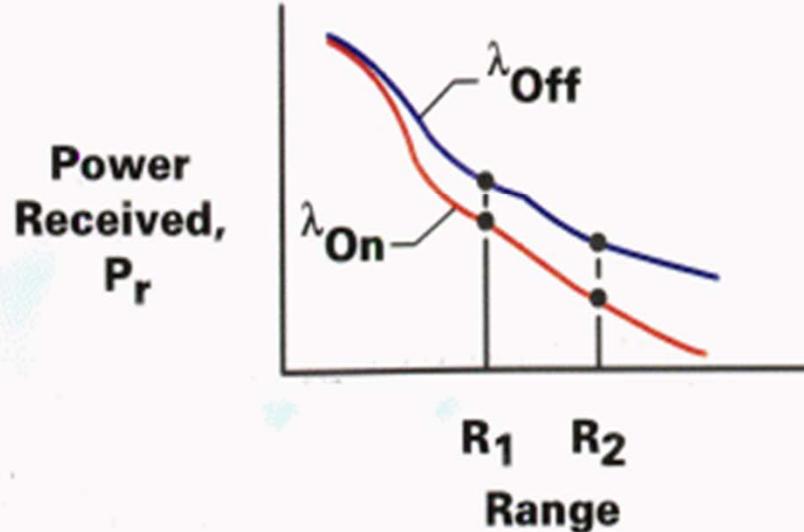
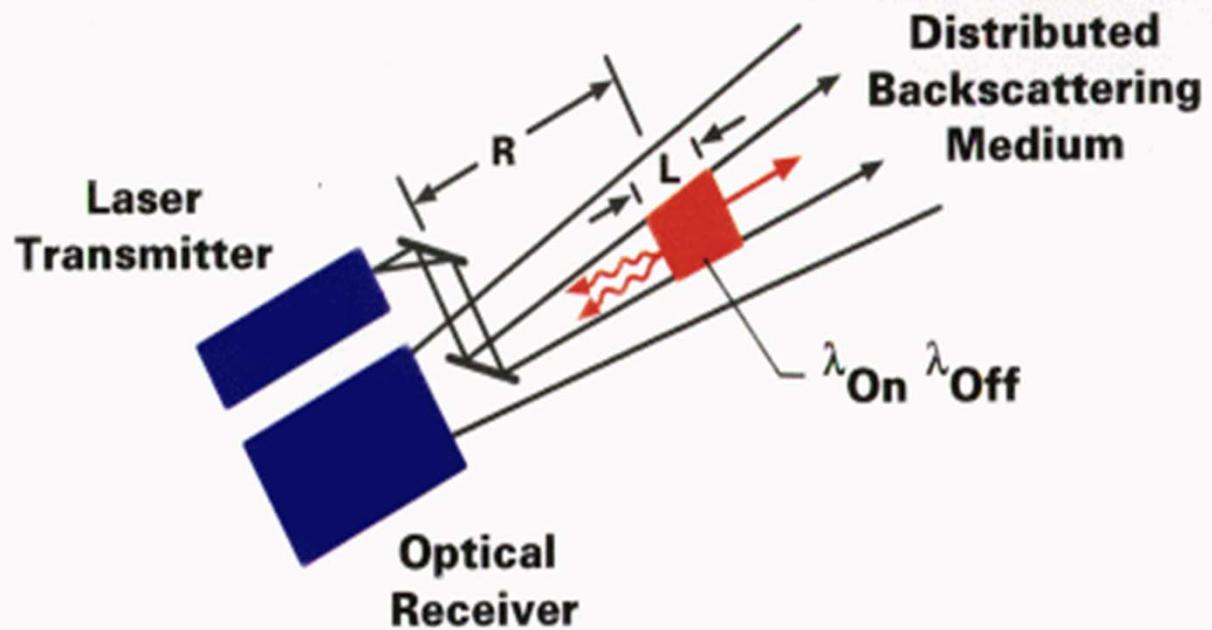
March 2, 2011

# Outline

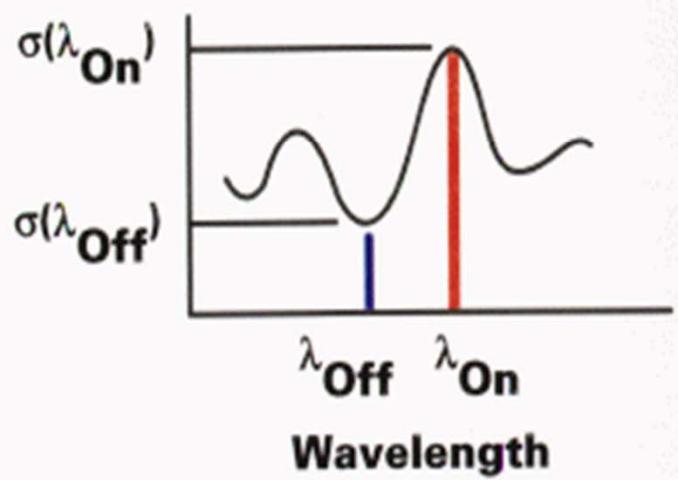
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- DIAL concept
- A short history of DIAL
- DIAL equation
- Precision & accuracy of DIAL retrieval
- Dual-DIAL technique

# Differential Absorption Lidar (DIAL) Concept



Absorption  
Cross  
Section



# Atmospheric gases measured with DIAL

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- H<sub>2</sub>O
- O<sub>3</sub>
- SO<sub>2</sub>
- NO<sub>2</sub>, NO
- NH<sub>3</sub>
- CH<sub>4</sub>
- CO<sub>2</sub>
- 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 !

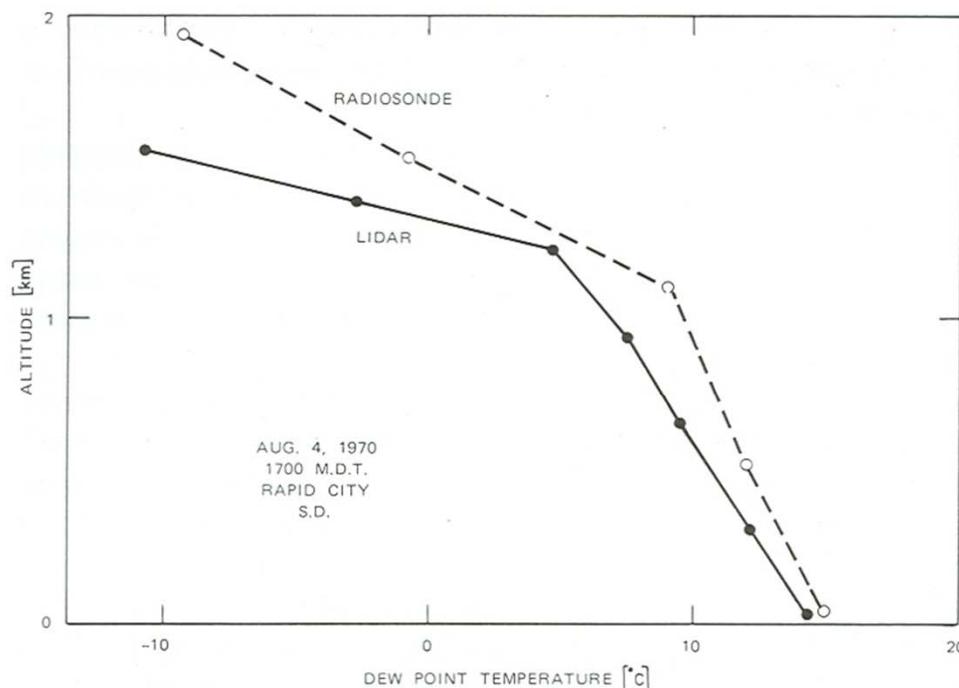
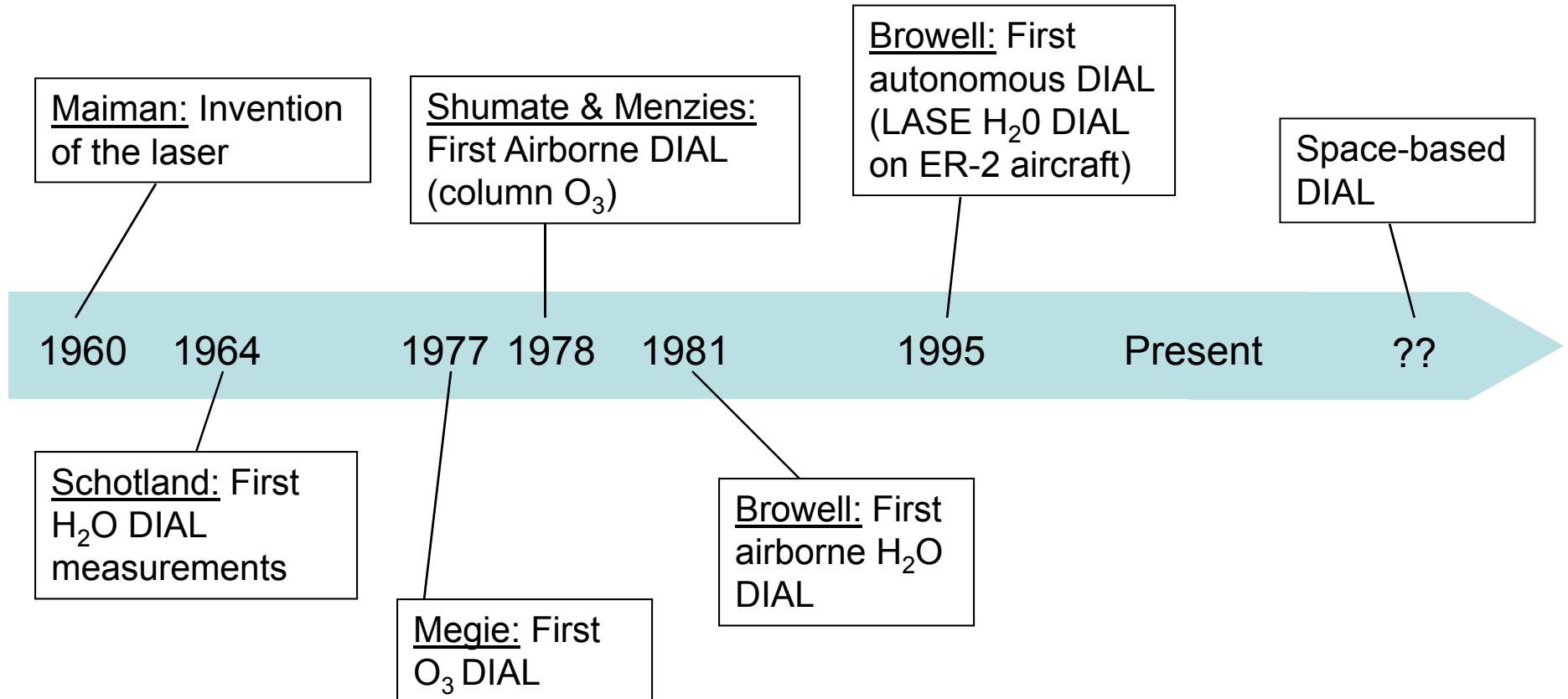


Fig. 4.20. Comparison of atmospheric water vapor vertical profiles (expressed as dew point temperature) measured by differential absorption lidar and radiosonde [4.82]

# Major milestones in the history of DIAL

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# DIAL equation (1)

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Single scattering, elastic backscatter LIDAR equation:

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

Ratio LIDAR equations for online and offline wavelengths  $\lambda_{on}$  and  $\lambda_{off}$ :

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

Number density  
of constituent C

## DIAL equation (2)

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$$\begin{aligned}
 n_C &= \frac{1}{2\Delta\sigma_C(R)} \frac{d}{dR} \ln \left[ \frac{N_S(\lambda_{off}, R) - N_B(\lambda_{off})}{N_S(\lambda_{on}, R) - N_B(\lambda_{on})} \right] \\
 &\quad - \frac{1}{2\Delta\sigma_C(R)} \frac{d}{dR} \ln \frac{G(\lambda_{off}, R)}{G(\lambda_{on}, R)} \quad [G] \\
 &\quad - \frac{1}{2\Delta\sigma_C(R)} \frac{d}{dR} \ln \frac{\beta(\lambda_{off}, R)}{\beta(\lambda_{on}, R)} \quad [B] \\
 &\quad - \frac{1}{\Delta\sigma_C(R)} [\alpha(\lambda_{on}, R) - \alpha(\lambda_{off}, R)] \quad [E] \\
 &\quad - \frac{1}{\Delta\sigma_C(R)} \sum_{i=1}^m \Delta\sigma_{X_i}(R) n_{X_i}(R) \quad [X]
 \end{aligned}$$

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

G = differential geometrical factor  
 E = differential extinction

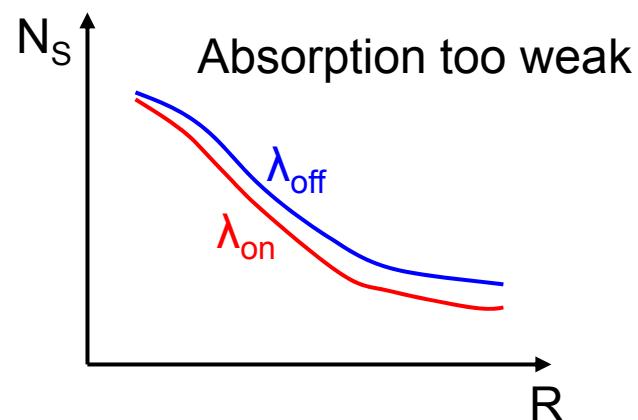
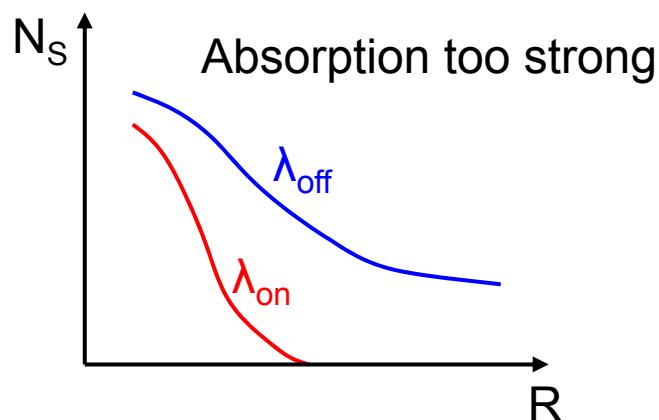
B = differential backscatter  
 X = interfering constituents

## How to choose an appropriate absorption line for DIAL (1)

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$$N_s(\lambda_{on}, R) \propto \exp \left[ -2 \int_0^R \sigma_c(\lambda_{on}, r) n_c(r) dr \right]$$

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)

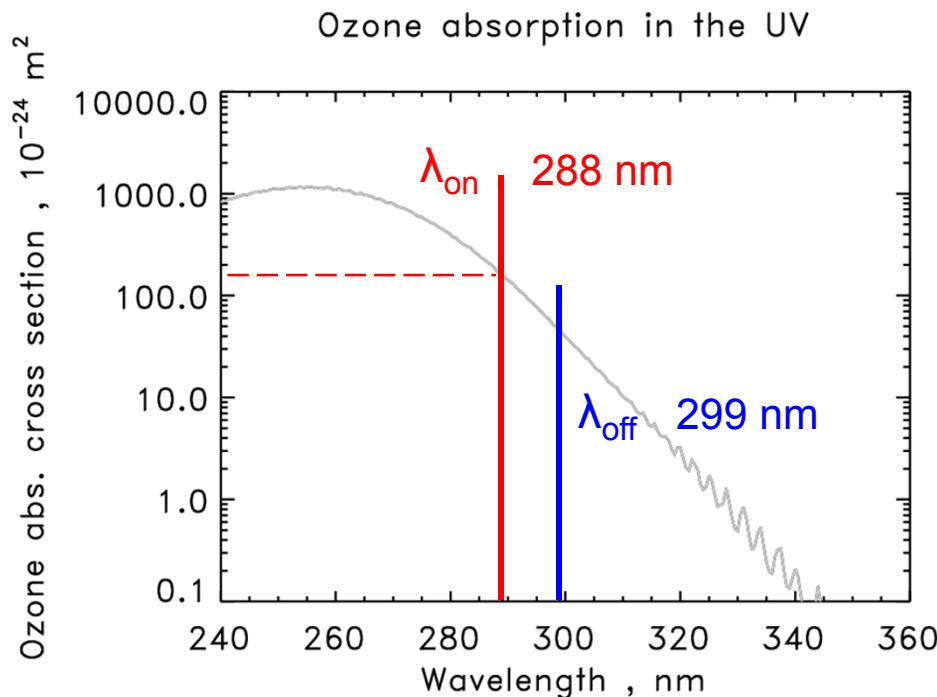
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Example: Ozone

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

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

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



# Precision of DIAL measurements

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Simple “back of the envelope” calculation:

$$n_c = \frac{1}{2\Delta\sigma_c(R)\Delta R} \ln \left[ \frac{N(\lambda_{off}, R + \Delta R) N(\lambda_{on}, R)}{N(\lambda_{on}, R + \Delta R) N(\lambda_{off}, R)} \right] \quad \text{with } N = N_s - N_b$$

$$\delta n_c = \frac{1}{2\Delta\sigma_c(R)\Delta R} \sqrt{\sum_{i,j} \frac{\delta^2(N(\lambda_i, R_j))}{(N(\lambda_i, R_j))^2}} \approx \frac{1}{\Delta\sigma_c \Delta R} \frac{\delta N}{N} = \frac{1}{\Delta\sigma_c \Delta R \text{ SNR}} \quad \text{with } \text{SNR} = \frac{N}{\delta N}$$

$$\frac{\delta n_c}{n_c} = \frac{1}{\Delta\sigma_c n_c \Delta R \text{ SNR}} = \frac{1}{\tau_{\Delta R} \text{ SNR}} \Rightarrow \boxed{\text{SNR} = \frac{1}{\tau_{\Delta R} \delta n_c / n_c}}$$

Example:  $\tau_{\Delta R} = 0.05$ ,  $\delta n_c / n_c = 5\%$   $\Rightarrow$   $\boxed{\text{SNR} = 400!}$

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

# Accuracy of DIAL measurements (1)

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$$\begin{aligned} n_C = & \frac{1}{2\Delta\sigma_C(R)} \frac{d}{dR} \ln \left[ \frac{N_S(\lambda_{off}, R) - N_B(\lambda_{off})}{N_S(\lambda_{on}, R) - N_B(\lambda_{on})} \right] \\ & - \frac{1}{2\Delta\sigma_C(R)} \frac{d}{dR} \ln \frac{G(\lambda_{off}, R)}{G(\lambda_{on}, R)} \quad [G] \\ & - \frac{1}{2\Delta\sigma_C(R)} \frac{d}{dR} \ln \frac{\beta(\lambda_{off}, R)}{\beta(\lambda_{on}, R)} \quad [B] \\ & - \frac{1}{\Delta\sigma_C(R)} [\alpha(\lambda_{on}, R) - \alpha(\lambda_{off}, R)] \quad [E] \\ & - \frac{1}{\Delta\sigma_C(R)} \sum_{i=1}^m \Delta\sigma_{X_i}(R) n_{X_i}(R) \quad [X] \end{aligned}$$

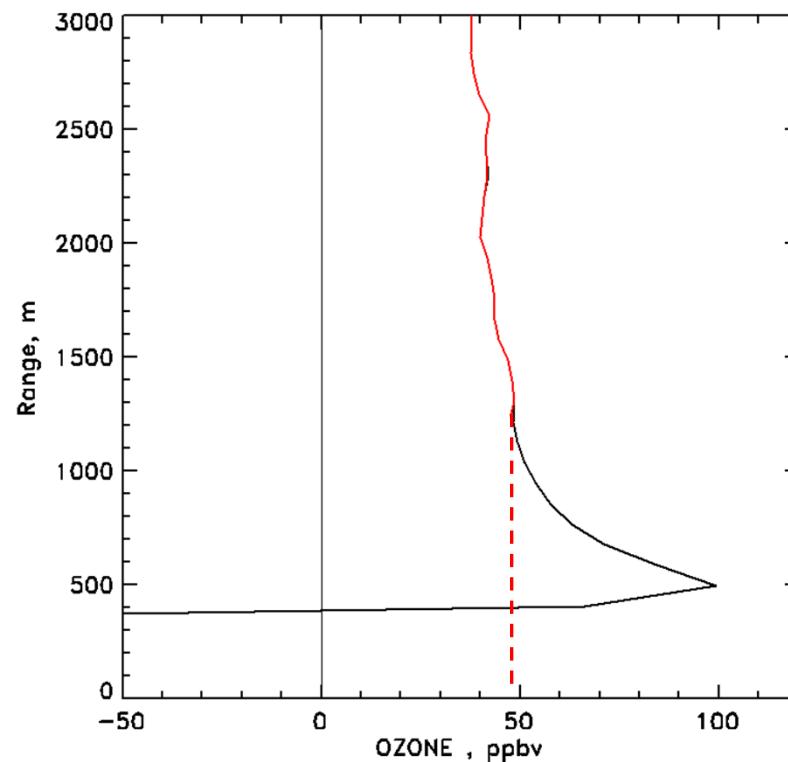
Accuracy affected by:

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

## Accuracy of DIAL measurements (2)

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



Effect of differential geometrical  
factor on  $O_3$  retrieval

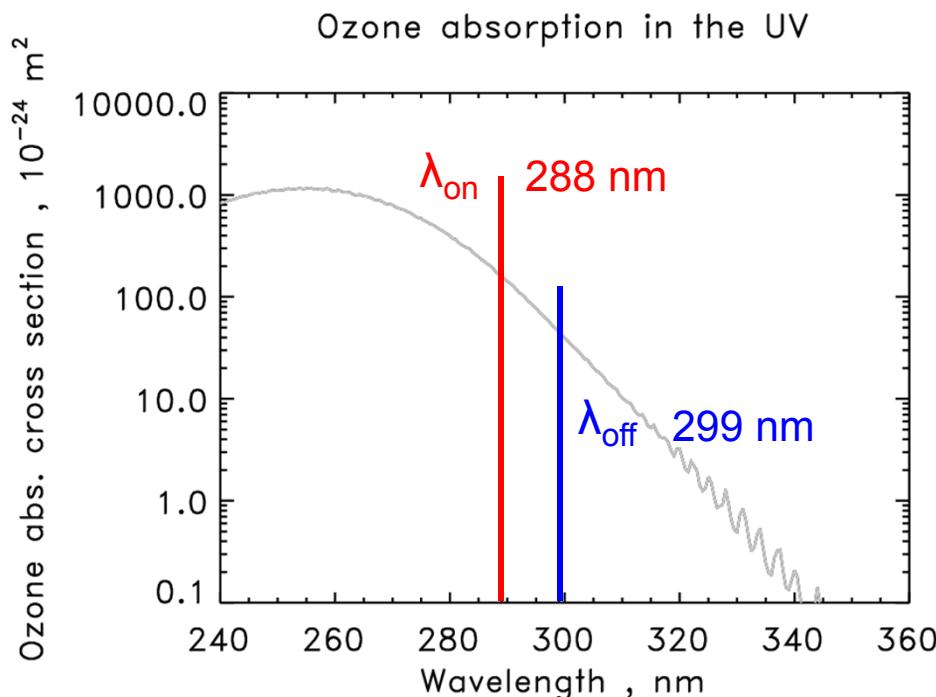
## Accuracy of DIAL measurements (3)

Differential backscatter & extinction:

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

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

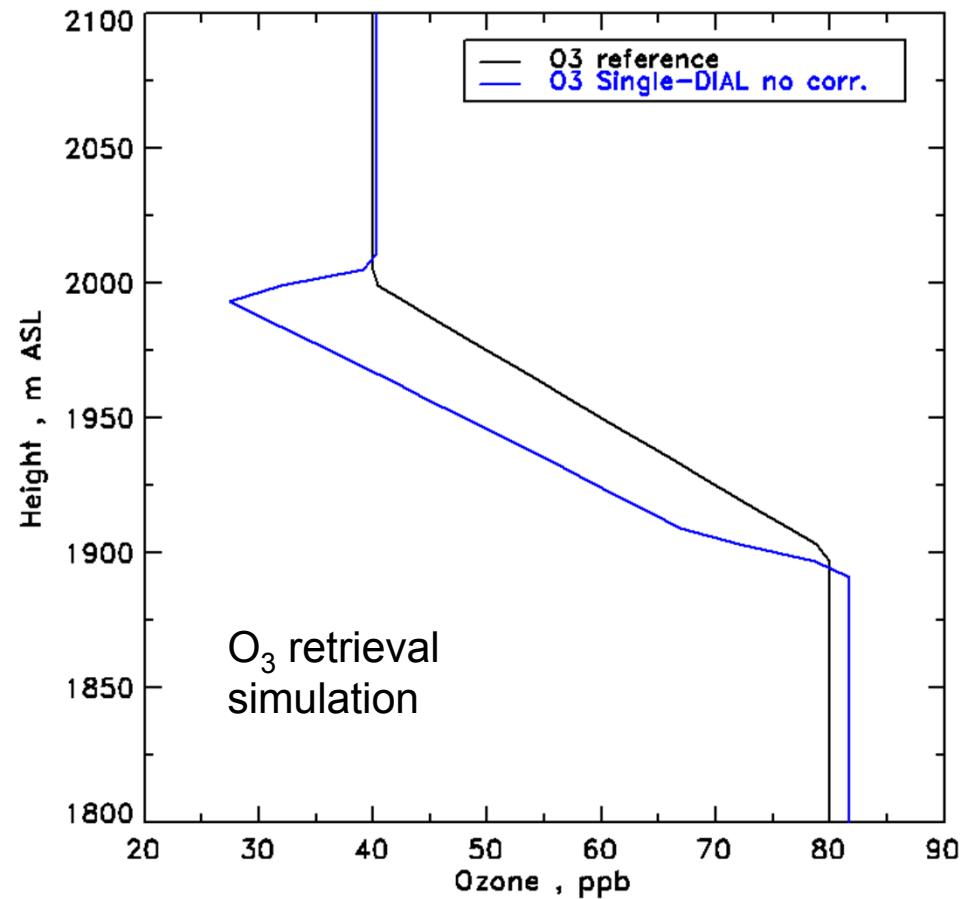
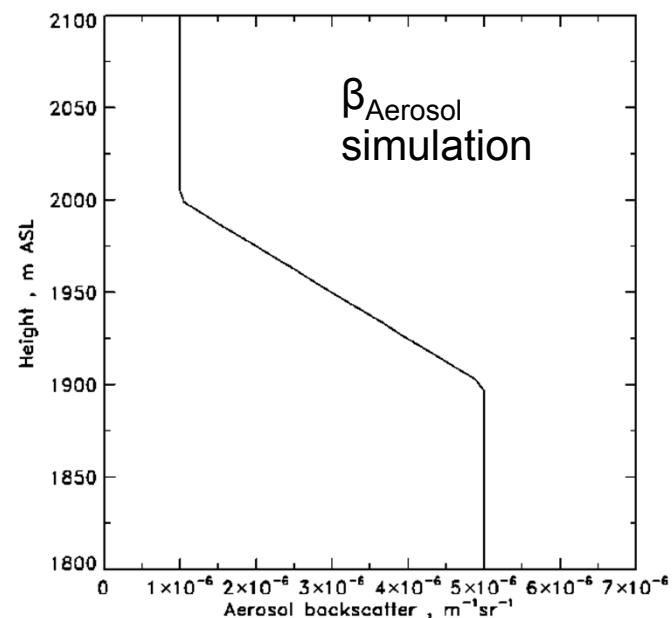
$$\beta = \beta_{Rayleigh} + \beta_{Aerosol}, \quad \alpha = \alpha_{Rayleigh} + \alpha_{Aerosol}$$



➤ For ozone DIAL retrieval, backscatter and extinction correction is necessary due to large  $\Delta\lambda$ .

➤  $\beta_{Aerosol}$  and  $\alpha_{Aerosol}$  have to be determined from offline signal data and wavelength dependence of  $\beta$  and  $\alpha$  have to be guessed.

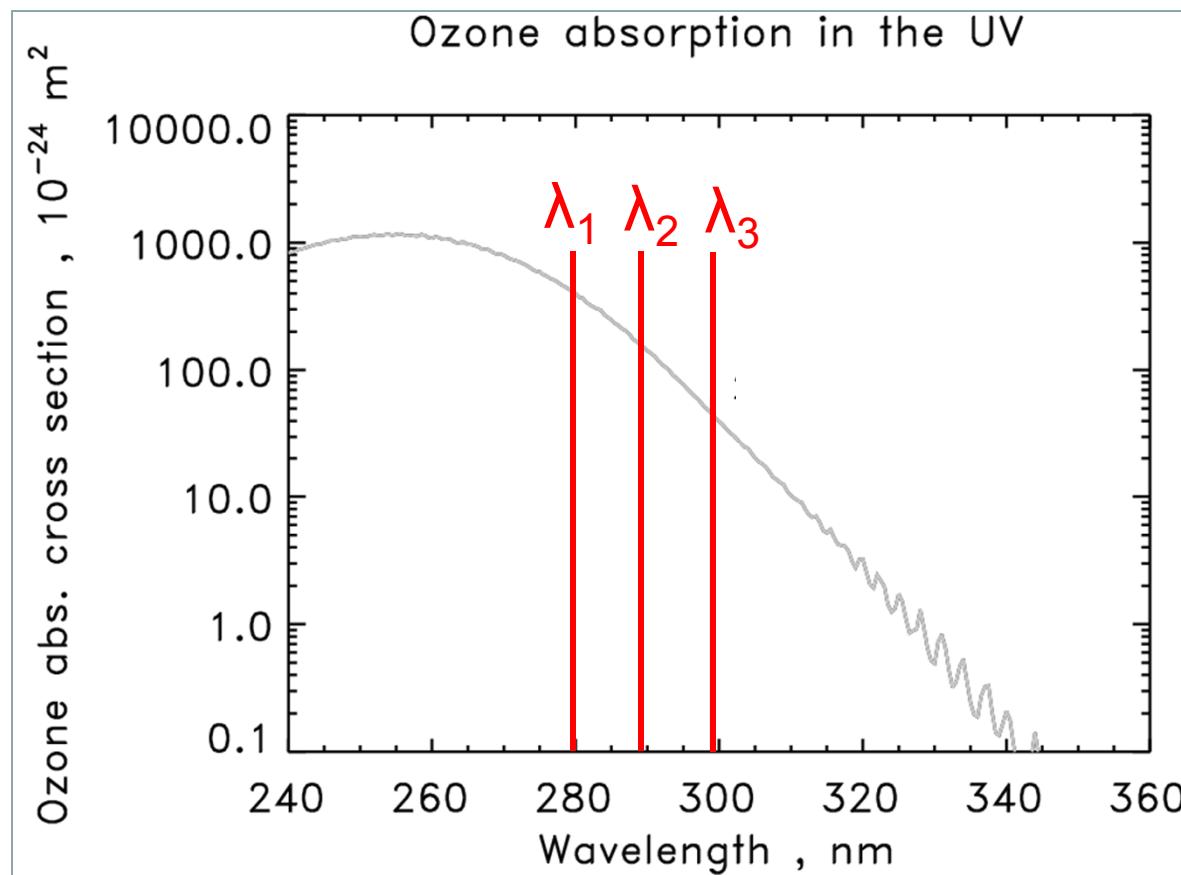
## Accuracy of DIAL measurements (4)



Wrong assumptions about aerosol parameters can introduce significant errors in O<sub>3</sub> retrieval !

## Dual-DIAL concept

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2 DIAL wavelength pairs:  $\lambda_1 / \lambda_2$  and  $\lambda_2 / \lambda_3$

## Dual-DIAL minimizes aerosol interference (1)

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

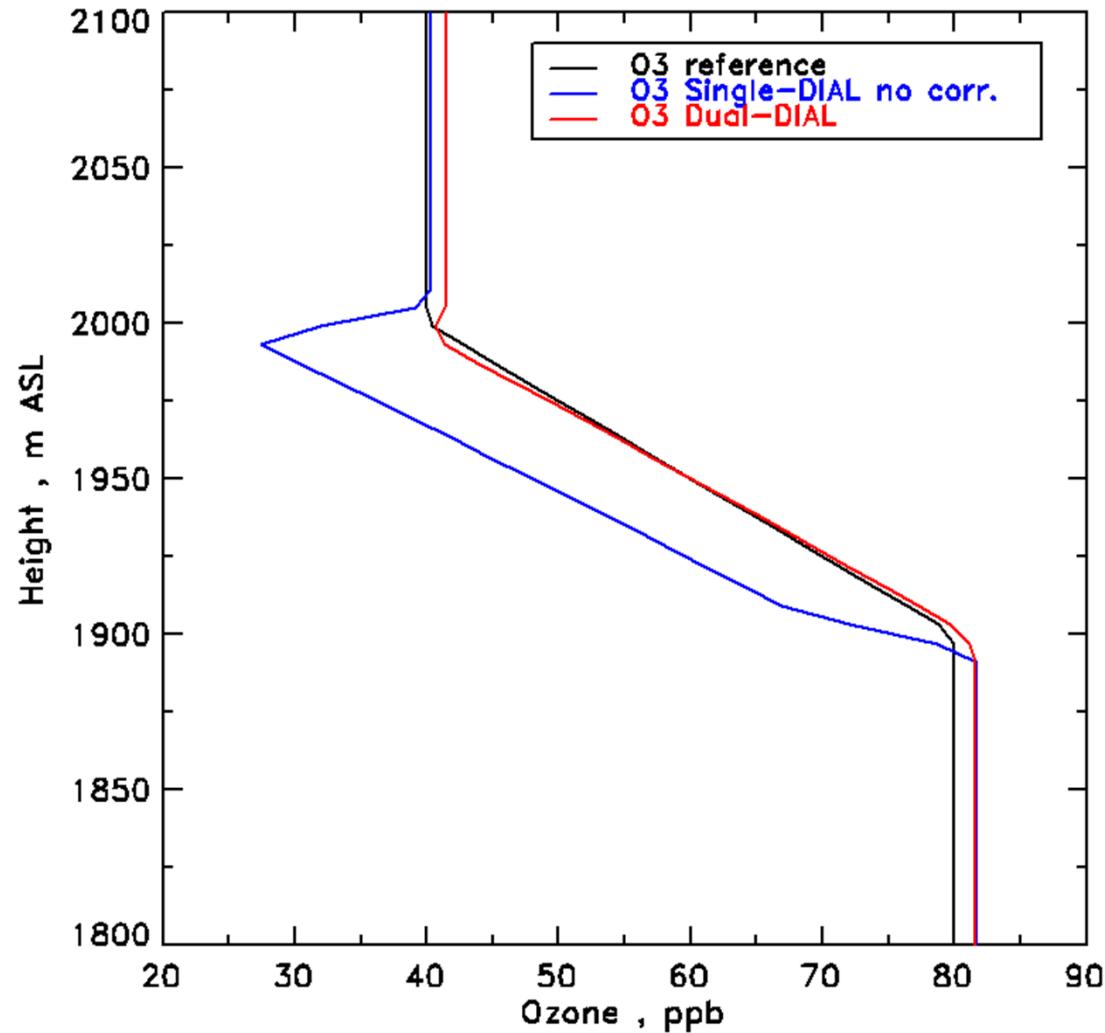
with  $\delta\sigma_c(R) = \Delta\sigma_{c1} - C \Delta\sigma_{c2}$ , DIAL pair 1:  $\lambda_{on1} / \lambda_{off1}$ , DIAL pair 2:  $\lambda_{on2} / \lambda_{off2}$

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

- 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)

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$O_3$  retrieval simulation

# Selected References

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## 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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