CORRECTION OF DOPPLER-BROADENED RAYLEIGH-BACKSCATTERING EFFECTS IN H_2O DIAL MEASUREMENTS

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This paper describes and discusses a general method of solutions for treating effects of Doppler-broadened Rayleigh backscattering in H_2O DIAL measurements. Errors in vertical DIAL measurements caused by this laser line broadening effect can be very large (Ansmann, 1) and, therefore, this effect has to be accounted for accurately.

To analyze and correct effects of Doppler-broadened Rayleigh backscattering in DIAL experiments, a generalized DIAL approximation was derived starting from a lidar equation, which includes Doppler broadening:

$$(1) \qquad N(\bar{R}) = \frac{1}{2(\sigma_1(\bar{R}) - \sigma_2(\bar{R}))DR} \left\{ ln \left(\frac{P_1(R_1) \cdot P_2(P_2)}{P_1(R_2) \cdot P_2(R_1)} \right) + D_1(\bar{R}) - D_2(\bar{R}) \right\}$$

where $N(\bar{R})$ is the water vapor number density averaged over the range cell DR centered at $\bar{R} = (R_1 + R_2)/2$ and $P_1(R)$ and $P_2(R)$ are the on- and off-line laser signals backscattered from the range cell at R, respectively. The absorption cross section for wave number v_i ($i = 1$: on-line, $i = 2$: off-line) averaged over the range cell DR centered at $\bar{R}$ is given by

$$(2) \qquad \sigma_i(\bar{R}) = \frac{1}{2} \int_{-\infty}^{\infty} \sigma_i(v,\bar{R}) \cdot \left(\left(1 + \frac{\beta_M(R_2)}{\beta(R_2)}\right) h_i(v) + \frac{\beta_R(R_2)}{\beta(R_2)} g_i(v, R_2) \right) dv$$

and the Doppler broadening correction term D_i for wave number v_i is given by

$$(3) \qquad D_i(\bar{R}) = ln \left\{ \int_{-\infty}^{\infty} \left(\frac{\beta_M(R_2)}{\beta(R_2)} h_i(v) + \frac{\beta_R(R_2)}{\beta(R_2)} g_i(v, R_2) \right) \cdot exp\left(- \int_{R_o}^{R_1} N(r) \cdot \sigma_i(r, v)\, dr\right) dv \right\}$$
$$- ln \left\{ \int_{-\infty}^{\infty} \left(\frac{\beta_M(R_1)}{\beta(R_1)} h_i(v) + \frac{\beta_R(R_1)}{\beta(R_1)} g_i(v, R_1) \right) \cdot exp\left(- \int_{R_o}^{R_1} N(r) \cdot \sigma_i(r,v) dr\right) dv \right\}$$

where $\beta(R_j)$ is the total backscattering coefficient for range R_j, $\beta_M(R_j)$ and $\beta_R(R_j)$ are the Mie and Rayleigh backscattering coefficients for range R_j, $h_i(v)$ is the normalized laser line shape for wave number v_i, and $g_i(v, R_j)$ is the convolution of the incident laser profile $h_i(v)$ and the intensity distribution of an incident monochromatic frequency v_i backscattered by air molecules in the range cell at R_j.

The calculation of water vapor density $N(\bar{R})$ with Eqs. (1)-(3) includes the correction of Doppler broadened Rayleigh backscattering effects. For using this calculation scheme, laser and H_2O absorption line parameters, temperature and pressure have to be known as usual for H_2O DIAL retrieval. In addition, for the correction of effects of Doppler broadening, backscattering properties of molecules and aerosols have to be known. The backscattering properties of molecules can be determined from measured temperature and pressure profiles or approximated from model atmosphere data. The aerosol backscattering properties can be obtained from range normalized off-line signals $P_2(R) \cdot R^2$ using a numerical integration scheme (Fernald, 2; Sasano et al., 3). Here, in addition, Rayleigh backscattering coefficients, aerosol extinction/backscattering ratio and aerosol backscattering coefficient at calibration range R_c have to be known. To yield generally stable solutions of this integration scheme for $\beta_M(R)$ with respect to uncertainties in the signals and the other input parameters, backward integration mode with boundary value $\beta_M(R_c)$ for maximum range $R_c = R_{max}$ should be used (Klett, 4). For the evaluation of the integral in Eq. (3) giving the water vapor optical thickness up to the range R_1, values for N(r) calculated in the preceding steps $R_0 < \bar{R} < R_1$ can be used. The off-line Doppler broadening correction term D_2 can be neglected, if off-line absorption is approximately constant over the transmitted spectrum.

To evaluate the accuracy of H_2O DIAL measurements using Eqs. (1)-(3), computer simulations were performed using Gaussian laser line shape with HWHM of 0.0125 cm^{-1}, Voigt-H_2O absorption lines with Lorentz halfwidth of 0.09 cm^{-1}, profiles of temperature, pressure and H_2O density (5.9 g m^{-3} at ground level) for standard atmospheric conditions, aerosol scattering coefficients for clear atmosphere conditions (McClatchey, 5, ground level visibility of 23 km) with additional layers of enhanced aerosol backscattering, and realistic lidar and receiver parameters. Lidar signals needed for the determination of H_2O and aerosol backscattering were calculated with a lidar equation considering Doppler broadened Rayleigh backscattering. H_2O-DIAL number densities were calculated with Eqs. (1)-(3). To analyze only Doppler broadening effects, no errors in the profile $\ln(P_1(R)/P_2(R))$ used for solving the DIAL approximation (1) were assumed. The difference between the retrieved and the true or input H_2O is shown in the figures.

In Fig. 1 examples of error profiles to be expected in ground based H_2O DIAL experiments due to realistic uncertainties in input parameters for backscattering retrieval are shown. It can be seen that correction of Doppler broadening effects is generally necessary. The accuracy of this correction mainly depends on the accurate determination of aerosol backscattering coefficients. Analysis of the influence of each input parameter for aerosol backscattering retrieval shows that it is especially important to have a proper estimate of the boundary value $\beta_M(R_c)$ at $R_c = R_{max}$ as a starting value for iterative aerosol backscattering retrieval. Error peaks at the upper layer boundaries in Fig. 1 are mainly due to errors in $\beta_M(R_c)$. The influence of errors in backscattering calculation is most important, when Mie and Rayleigh backscattering coefficients are of the same order of magnitude and, in addition, layers with steep gradients of aerosol backscattering are present. This is the case in the figures for the layer regions in the middle and upper troposphere. The relative water vapor error due to uncertainties in Doppler broadening correction is proportional to DR^{-1} so that the shown effects decrease with increasing DR.

In conclusion, correction of Doppler broadened Rayleigh backscattering is possible with good accuracy in most cases of tropospheric H_2O DIAL measurements, but great care has to be taken when layers with steep gradients of Mie backscattering like clouds or inversion layers are present.

References

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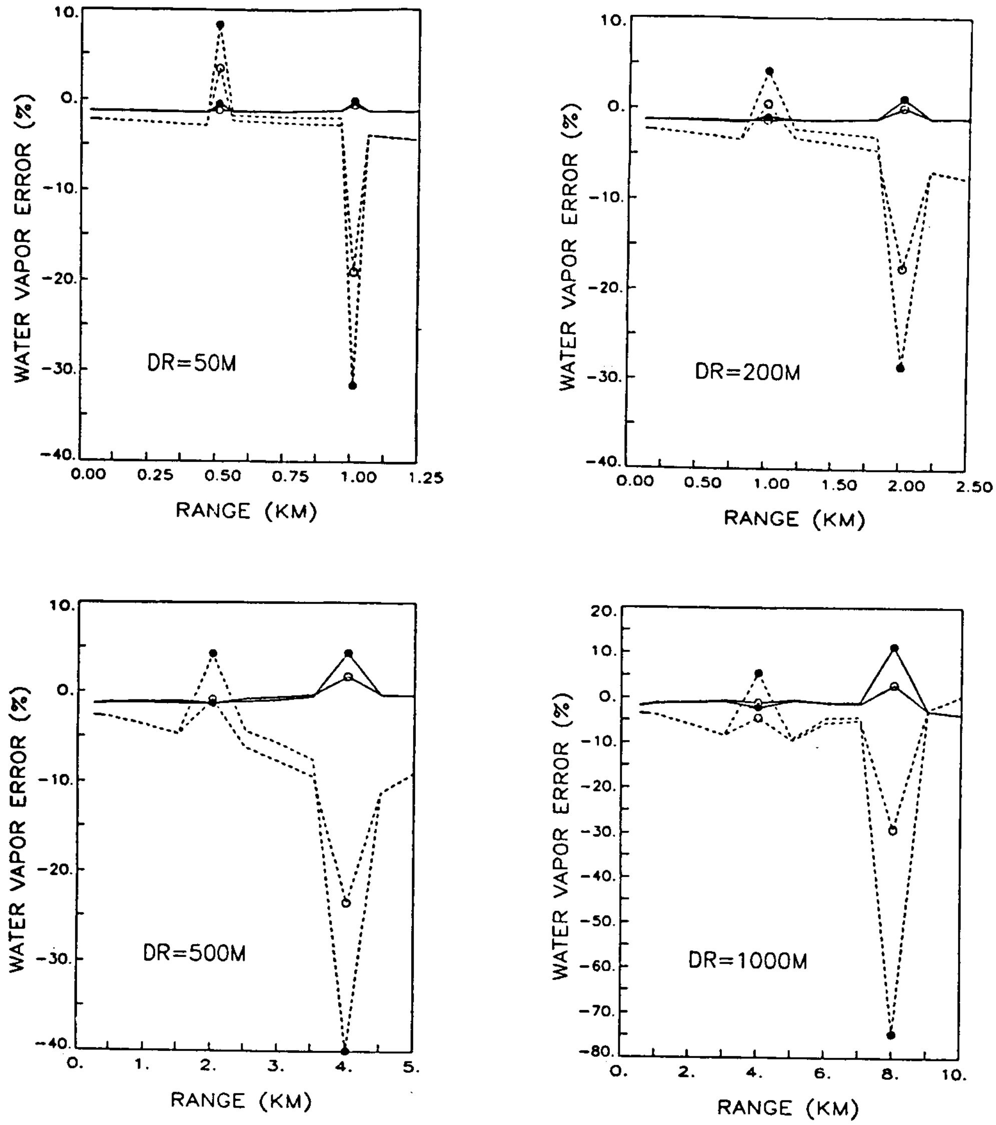

Fig. 1: Errors in H_2O DIAL measurements due to Doppler-broadened Rayleigh backscattering. Dashed lines: without correction of Doppler broadening; solid lines: correction applied. Errors in input parameters assumed for retrieval: 3K in temperature, -10 hPa in pressure; aerosol extinction/backscattering ratio assumed for retrieval: 60 sr, true value: 80 sr; Mie/Rayleigh backscattering ratio at R_{max} assumed for retrieval: 0, true value: 0.18. Aerosol layers with an aerosol concentration a factor 2 (o) and 5 (●) higher than the aerosol concentration of the clear air model between 0.5-1 km (DR = 50 m), 1-2 km (DR = 200 m), 2-4 km (DR = 500 m), and 4-8 km (DR = 1000 m).