EFFECT OF DOPPLER BROADENING OF RETURN SIGNALS ON THE ACCURACY OF RECONSTRUCTING THE H_2O PROFILES FROM LIDAR DATA

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The exact formulas are presented that allow for the effect of Doppler-broadened Rayleigh backscattering (DBRS) in DIAL humidity sensing. Numerical experiments have shown that the DBRS effect imposes limitations on the applicability of DIAL technique to sensing the humidity in the stratosphere with a ground–based lidar. As to a spaceborne lidar, the DBRS effect results in the error in H_2O *measurements no more than* 16% *within the altitude range* 0–20 km *with no aerosol layers.*

The Doppler broadening of an elastically backscattered signal is due to the motion of air molecules and aerosol particles. The speed of aerosol particle motion is some orders of magnitude lower than that of molecular thermal motion, therefore, in aerosol scattering the Doppler broadening can be neglected.

The effect of the Doppler–broadened Rayleigh backscattering (DBRS) on the accuracy of gas sensing by DIAL measurements was first considered in Ref. 1. In Ref. 2 the H_2O DIAL sensing from airborne and spaceborne platforms was modeled with the due regard for the DBRS effect. The influence of DBRS on the accuracy of H_2O sensing with a ground–based lidar was studied in Ref. 3. This problem was further discussed in a number of papers.[4–8]

In this paper, the exact formulas are presented for calculating the effective differential absorption coefficient and the errors in water vapor sensing with ground–based, airborne, and spaceborne lidars are estimated.

The lidar equation with regard to DBRS has the following form:

$$U(\lambda_i, z) = S_{\text{lid}}(\lambda_i)\,\frac{1}{z^2}\,T^2_{\text{atm}}(\lambda_i, z) \times$$
$$\times\,[\beta_{\text{a}}(\lambda_i, z)\int g(\nu_i-\nu)\,T^2(\nu, z)\,\text{d}\nu + \beta_{\text{m}}(\lambda_i, z)\,\times$$
$$\times \int\!\!\int g(\nu_i-\nu) f(z, \nu-\nu')T(\nu, z)T(\nu', z)\text{d}\nu\text{d}\nu']\,, \quad (1)$$

where $U(\lambda_i, z)$ are the return signals from the distance z at the wavelength λ_i; $S_{\text{lid}}(\lambda_i)$ is the lidar constant; $T_{\text{atm}}(\lambda_i, z)$ is the transmission of the layer $[z_1, z_2]$ of the gas–aerosol atmosphere (without regard for the absorption by a gas under study); $T(\nu, z)$ is the transmission of a gas under study; ν is the wavenumber, $\beta_{\text{a}}(\lambda_i, z)$ and $\beta_{\text{m}}(\lambda_i, z)$ are the coefficients of aerosol and molecular backscattering; $g(\nu_i-\nu)$ is the intensity spectrum of laser radiation $\int g(\nu_i-\nu)\text{d}\nu = 1$; $f(z, \nu-\nu')$ is the Doppler line profile of Rayleigh–backscattered signal, in general case it is a function of the scattering angle[9,10]:

$$f(\theta, z, \nu-\nu') = \sqrt{\frac{\ln 2}{\pi}}\,\frac{1}{\gamma(z, \theta)}\,\exp\left\{-\ln 2\,\frac{(\nu-\nu')^2}{\gamma^2(z, \theta)}\right\},$$

where $\gamma(z, \theta) = 2\sin(\theta/2)\gamma_{\text{D}}(z)$, $\gamma_{\text{D}}(z)$ is the Doppler half–width, θ is the scattering angle, and for $\theta = \pi$, γ equals $2\gamma_{\text{D}}$.

The volume coefficient of molecular scattering α_{m} is an integral value,

$$\alpha_{\text{m}}(\nu, z) = \int \text{d}\nu' \int \text{d}\Omega\,\beta_{\text{m}}(z, \theta, \nu-\nu'),$$

and it is independent of the line shape f. That is why in Eq. (1) T^2_{atm} can be factored outside the integral sign. Here $\beta_{\text{m}}(z, \theta, \nu-\nu')$ is the coefficient of backward scattering within the angle θ, $\text{d}\Omega$ is the element of solid angle.

According to the DIAL technique, the gas concentration is determined from the expression

$$\rho(z) = \frac{1}{2\,\tilde{K}_{\text{eff}}(z)}\,\frac{\text{d}}{\text{d}z}\ln\frac{U(\lambda_{\text{off}}, z)}{U(\lambda_{\text{on}}, z)}\,,$$

where λ_{off} and λ_{on} are the wavelengths lying off and on the absorption line of a gas, $\tilde{K}_{\text{eff}}(z)$ is the effective differential absorption coefficient determined by the equation

$$\tilde{K}_{\text{eff}}(z) = \frac{1}{2\,\rho(z)}\,\frac{\text{d}}{\text{d}z}\ln\frac{U(\lambda_{\text{off}}, z)}{U(\lambda_{\text{on}}, z)}\,. \quad (2)$$

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Taking obvious approximations: $\beta_a(\lambda_{on}, z) = \beta_a(\lambda_{off}, z) = \beta_a(z)$ and $\beta_m(\lambda_{on}, z) = \beta_m(\lambda_{off}, z) = \beta_m(z)$, one obtains from Eqs. (1) and (2) that

$$\tilde{K}_{eff} = \tilde{K}_{on} - \tilde{K}_{off} + \Delta_1 + \Delta_2 ,$$

where

$$\tilde{K}_{on} = \tilde{K}^0_{on} \frac{\beta_a + 1/2\, \beta_m C_{on}}{\beta_a + \beta_m B_{on}} ,$$

$$\tilde{K}_{off} = \tilde{K}^0_{off} \frac{\beta_a + 1/2\, \beta_m C_{off}}{\beta_a + \beta_m B_{off}} ; \qquad (3)$$

$$\Delta_1 = \frac{1}{2\rho}\left[\frac{\beta'_a + \beta'_m B_{off}}{\beta_a + \beta_m B_{off}} - \frac{\beta'_a + \beta'_m}{\beta_a + \beta_m B_{on}}\right],$$

$$\Delta_2 = \frac{1}{2\rho}(\gamma'/\gamma)\,\beta_m\left[\frac{A_{off}}{\beta_a + \beta_m B_{off}} - \frac{A_{on}}{\beta_a + \beta_m B_{on}}\right];$$

$$A_i = \frac{\int\int g(\nu_i-\nu) f(\nu-\nu') T(\nu) T(\nu')\left[\frac{2\ln 2}{\gamma^2}(\nu-\nu')^2 - 1\right] d\nu d\nu'}{\int g(\nu_i-\nu')\, T^2(\nu')\, d\nu'},$$

$$B_i = \frac{\int\int g(\nu_i - \nu)\, f(\nu - \nu')\, T(\nu)\, T(\nu')\, d\nu\, d\nu'}{\int g(\nu_i - \nu')\, T^2(\nu')\, d\nu'},$$

$$C_i = \frac{\int\int g(\nu_i-\nu) f(\nu-\nu') T(\nu) T(\nu') [K(\nu)+K(\nu')] d\nu d\nu'}{\int g(\nu_i-\nu') T^2(\nu') K(\nu') d\nu'}; \qquad (4)$$

$$\beta'_a = \frac{d\beta_a}{dz}, \quad \beta'_m = \frac{d\beta_m}{dz}; \quad \gamma' = \frac{d\gamma}{dz}.$$

In Eq. (4), $K(\nu)$ is the monochromatic absorption coefficient of a gas, and $\tilde{K}^0_i$ in Eq. (3) is the effective absorption coefficient without Doppler broadening of Rayleigh backscattering signal. It is determined as

$$\tilde{K}^0_i = \frac{\int g(\nu_i - \nu)\, T(\nu)\, K(\nu)\, d\nu}{\int g(\nu_i - \nu)\, T^2(\nu)\, d\nu}. \qquad (5)$$

The Doppler broadening of a backscattered signal results in a systematic error of estimating the gas concentration from lidar data. It is equal to

$$\delta_\rho = \frac{\Delta\rho}{\rho} = \frac{|\tilde{K}_{eff} - \tilde{K}^0_{eff}|}{\tilde{K}^0_{eff}}, \qquad (6)$$

where $\tilde{K}^0_{eff}$ is the effective differential absorption coefficient calculated by Eq. (5) without the regard for DBRS effect.

In numerical simulation we used the following initial parameters: (a) the midlatitude summer[11] as the atmospheric model, (b) the background optical model of aerosol[12] (see Fig. 1), (c) the wavelength λ_{on} = 726.3425 nm and λ_{off} = 726.312 nm, (d) H_2O absorption line parameters taken from HITRAN–91 database,[13] (e) the width of the emission line $2\gamma_e$ = 1 pm, and (f) the Gaussian profile of the emission line.

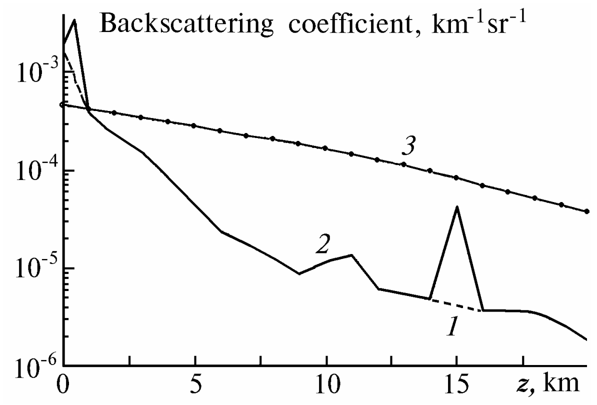

FIG. 1. Backscattering coefficients: β_a, *background model*[12] *(1),* β_a, *"perturbed" model (2), and* β_m *(3). Curves 1 and 2 differ at only two altitudes: z = 0.5 and 15 km.*

Shown in Figs. 2*a* and *b* are the values of δ_ρ (curves *1*) for two types of sensing paths. As seen, for the upward path the error δ_ρ exceeds 100% even for the background model of aerosol in humidity sensing with a ground–based lidar. In sensing with an airborne lidar, the error due to DBRS is no more than 16% (see curve *1* in Fig. 2*b*). In sensing with a spaceborne lidar, the error due to DBRS within altitude range 0–20 km is below 16% too.

Let us consider the influence of aerosol layers on the error in humidity sensing. Depicted by curve *2* in Fig. 1 is the profile β_a for the atmosphere with artificial aerosol layers at 15 km altitude (β_a is fivefold magnified) and 0.5 km altitude (β_a is fourfold magnified) whereas curves *2* in Figs. 2*a* and *b* show δ_ρ for this profile. As seen, the error in sensing increases essentially within the aerosol layers, and the oscillating behavior of δ_ρ is observed at altitudes adjacent to aerosol layers. However, in this situation, the accuracy of sensing the humidity of the stratosphere with an airborne lidar is well above that obtained in sensing with a ground based lidar (the error is below 40%, see curve *2* in Fig. 2*b*).

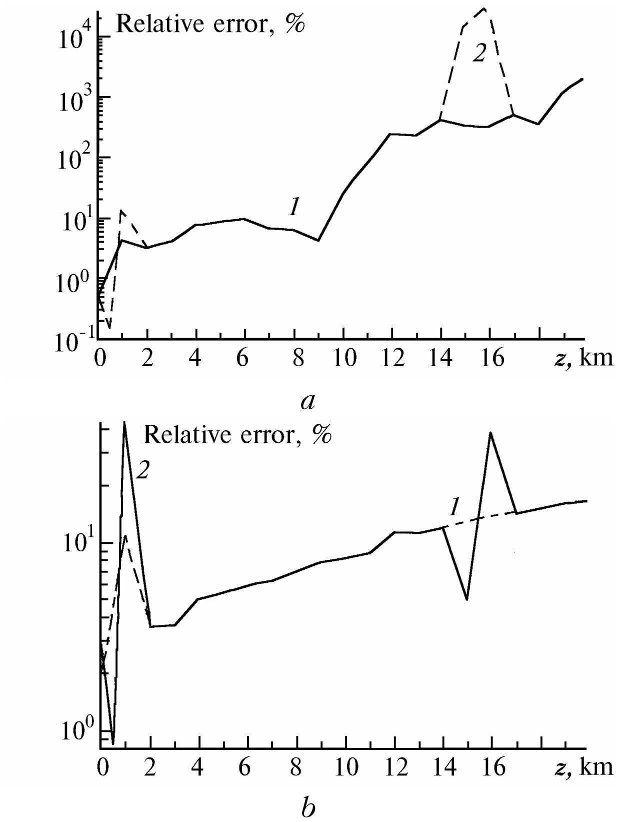

FIG. 2. Error in humidity sensing calculated by Eq. (6) for λ_{on} = 726.3425 nm *and* λ_{off} = 726.312 nm: *background aerosol model*[12] *(1) and "perturbed" aerosol model (2); upward (a) and downward path (b).*

The Doppler broadening of Rayleigh backscattered signal results in systematic error in humidity estimation from lidar data. To eliminate completely the influence of DBRS, the profiles of aerosol and molecular absorption coefficients must be known. However, it can be reduced if we will take the wavelength λ_{on} at a distance about $\gamma_a/2$ from the absorption line center rather than the line center itself, where γ_a is the absorption line width. A twofold and even more decrease of the error in 0–7 km layer is seen from Fig. 3 (curve *2*) with λ_{on} shifted by 2.6 pm.

It should be noted in conclusion that the error due to DBRS effect should be reduced simultaneously with the signal error and the error due to instability of radiation source. The latter two errors may increase with the shift of the wavelength toward the line wing.

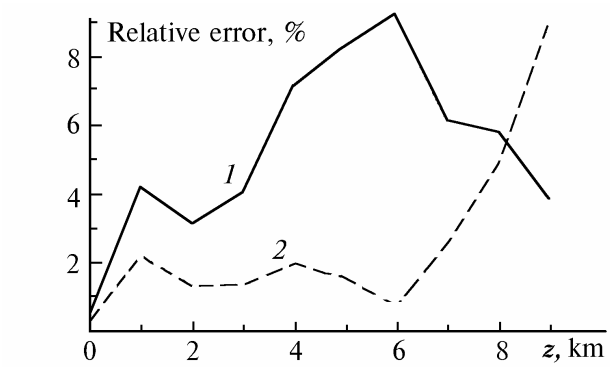

FIG. 3. The DBRS effect reduction for the upward path, λ_{off}=726.312 nm, $2\gamma_e$=1 pm: λ_{on}= 726.3425 *(1) and* 726.3451 nm *(2).*

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