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INFLUENCE OF RAYLEIGH-DOPPLER BROADENING ON THE SELECTION OF H_2O DIAL SYSTEM PARAMETERS

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INTRODUCTION

Rayleigh Doppler broadening is a process that causes spectral spreading of backscattered laser energy due to the random motion of air molecules. Early lidar measurements[1] showed that, due to their lower mass, air molecules are more effective in Doppler broadening of the laser energy than aerosol particles. Assuming that the molecular velocity distribution is given, approximately, by the Maxwellian function, the Doppler broadening width $d\lambda$ (HWHM) is given by

$$d\lambda = \frac{2\lambda}{c}\sqrt{\frac{2kT(\ln 2)}{m}} \qquad (1)$$

where k is the Boltzman constant, T is the atmospheric temperature, m is the mean molecular mass, λ is the wavelength of the laser, and c is the velocity of light. The magnitude of $d\lambda$ defined in Equation (1), which arises due to the backscattering processes, is twice the normal Doppler broadening observed in absorption or emission. For $\lambda = 728$ nm, $T = 300^\circ$K and $m = 28.9$ amu, $d\lambda \sim 1.7$ pm, which is similar to the H_2O absorption linewidth[2] at $\sim$12 km altitude. Previous studies have shown that Doppler broadening has a significant influence on DIAL measurements[2-4]. Doppler broadening reduces the effective absorption cross section in H_2O DIAL measurements; however, this systematic effect is predictable and can be removed to first order. This aspect of the Doppler broadening effect has been well documented, but the influence of Doppler broadening on DIAL sensitivities to errors in other parameters has not been previously reported. Doppler broadening reduces the sensitivity of DIAL H_2O measurement errors due to the finite laser linewidth, laser position uncertainty and laser spectral resolution measured by a wavemeter. This effect also reduces errors due to an uncorrected pressure shift of the H_2O absorption line with altitude. Examples of these effects will be discussed after a description of the modeling assumptions.

MODELING

Computer simulations have enabled us to study the performance of a H_2O DIAL system by spectrally analyzing the forward propagating and backscattered laser energy. The assumed atmospheric, aerosol and H_2O

model profiles reflect an average mid-latitude summer-time condition[5] without clouds. Strong gradients in aerosol and H_2O profiles have been avoided so that the altitude variations of the DIAL parameters could be studied without interference due to gradient terms[4]. The simulations were done for a high altitude (21 km) DIAL system operating in a nadir-viewing mode. These results are directly applicable to the National Aeronautics and Space Administration's H_2O DIAL system currently under development[6], and they are also relevant to a spaceborne DIAL system. The laser spectral output is assumed to be composed of 3 equal-amplitude equally spaced modes over a 1 pm interval, which is typical of recently developed Alexandrite lasers operating in the 728 nm region. Unless otherwise stated, a nominal value for the H_2O absorption cross section of $\sigma_o = 20.9 \times 10^{-24}$ cm^2 at ground level is assumed.

SIMULATION RESULTS

The Rayleigh Doppler broadening effect on the measurements of H_2O concentrations can cause systematic underestimates[2] greater than 10% at altitudes $\gtrsim$ 10 km. While these errors are large, this systematic offset error can be calculated with the help of a model temperature profile and an aerosol scattering ratio profile (retrievable from the off-line DIAL signal). Our calculations show that with a 10% temperature error and 50% error in the aerosol scattering ratio, the worst case error in the calculated absorption cross section leads to only about a ± 1.5% error in the H_2O measurements in regions free of large aerosol gradients. Therefore, in effect, the Doppler broadening causes only about a 1.5% error in H_2O DIAL measurement and we will show that the Doppler broadening, at least in clean atmospheric regions, reduces sensitivity to measurement uncertainty caused by finite laser linewidth, laser position uncertainty, system spectral resolution of laser energy, and H_2O line pressure shift. Examples of these effects are given below.

Figure 1 shows the combined influence of laser spectral width and Rayleigh broadening (uncorrected) on the H_2O DIAL measurement errors. For these simulations we used a strong absorption line ($\sigma_o = 70.1 \times 10^{-24} cm^2$) which is suitable for measurements over the altitude region 2-10 km. The errors caused by the distortion of the laser spectral profile due to H_2O absorption are also included in these error estimates. At altitudes $\gtrsim$ 6 km the Rayleigh broadening offset error (indicated by the 0.3 pm curve) decreases as the laser spectral width increases. This is because, in this altitude region, with low aerosols and small H_2O linewidths, the Doppler broadening influence is more effective for smaller laser linewidths. Below 6 km, the Rayleigh broadening influence decreases and the distortion of the laser line shape becomes important. In this altitude region, the 3 pm line suffers from laser line distortion problem more severely (which can perhaps be corrected with an iterative H_2O DIAL solution). The difference in systematic errors between the 1 pm and 0.3 pm DIAL systems is $\lesssim$ 1%. Above 6 km the 0.3 pm line has larger error due to greater Doppler broadening influence and below 6 km the 1 pm linewidth produces larger error due to laser line distortion. Even when the Doppler broadening and laser line distortion effects are corrected, it is expected that the residual error difference between these two will be less than 1%

over the 0-15 km altitude range. These results suggest that H_2O DIAL systems having a total spectral width ∿ 1 pm would perform nearly as well as single-mode laser DIAL systems.

Figure 2 shows the sensitivity of laser tuning error with and without Doppler broadening influence. The profiles have been normalized to eliminate laser distortion error and it has been assumed that Doppler broadening is fully correctable. In the lower troposphere (< 5 km), the error due to a 0.5 pm detuning is comparable for the two cases but at high altitudes (> 5), this error is reduced by the Doppler broadening influence. It can be seen that at 15 km, this error is larger by about 45% in the absence of Doppler broadening. In Figure 3, overestimates of the H_2O density measurement due to wavemeter resolutions of 0.5 and 1 pm with and without Doppler broadening are compared. It shows that Doppler broadening when fully corrected reduces the sensitivity of the error due to wavemeter resolution.

Rayleigh Doppler broadening also reduces sensitivity to atmospheric effects. Zuev et al.[7] have shown that pressure shifts (uncorrected) can cause up to 30% error at 20 km altitude. They did not include the influence of Doppler broadening in their calculations. Figure 4 shows that without Doppler broadening, the errors would be larger by about 45% at 15 km altitude. Therefore, the presence of Rayleigh broadening reduces the sensitivity of error due to pressure shifts when the line positions are not properly selected.

We have evaluated the influence of Rayleigh Doppler broadening on DIAL measurement accuracies and have shown that the Rayleigh broadening influence, which can be corrected to first order in regions free of large aerosol gradients, reduces the sensitivity of DIAL H_2O measurement errors in the upper tropospheric regions ($\gtrsim$ 10 km). We discuss in this paper our ability to correct the Rayleigh broadening and the selection of H_2O DIAL parameters when all the systematic effects are combined.

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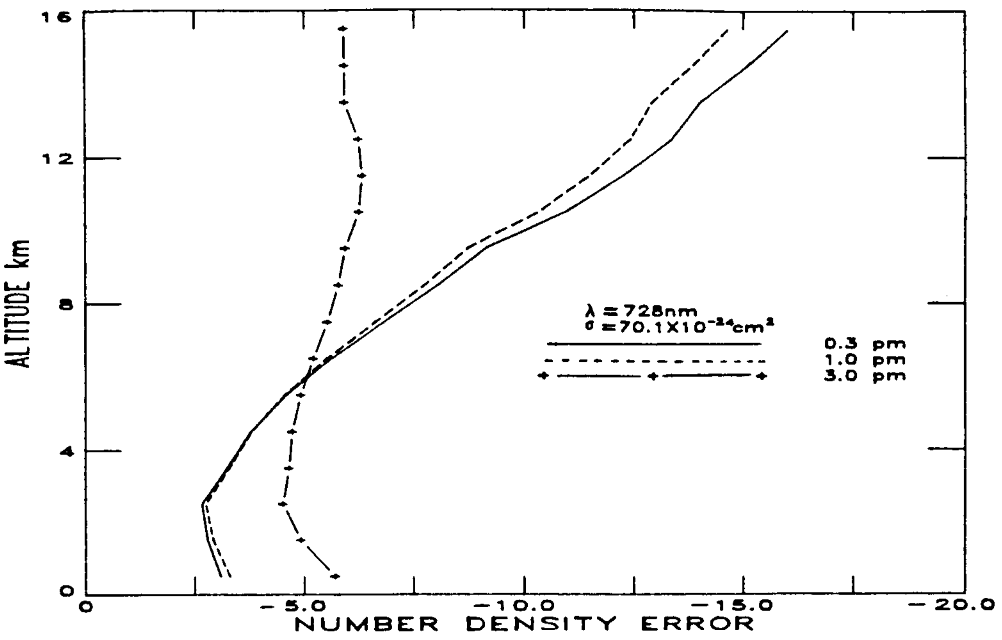

Figure 1. Influence of laser linewidth on Rayleigh Doppler broadening and laser line distortion error.

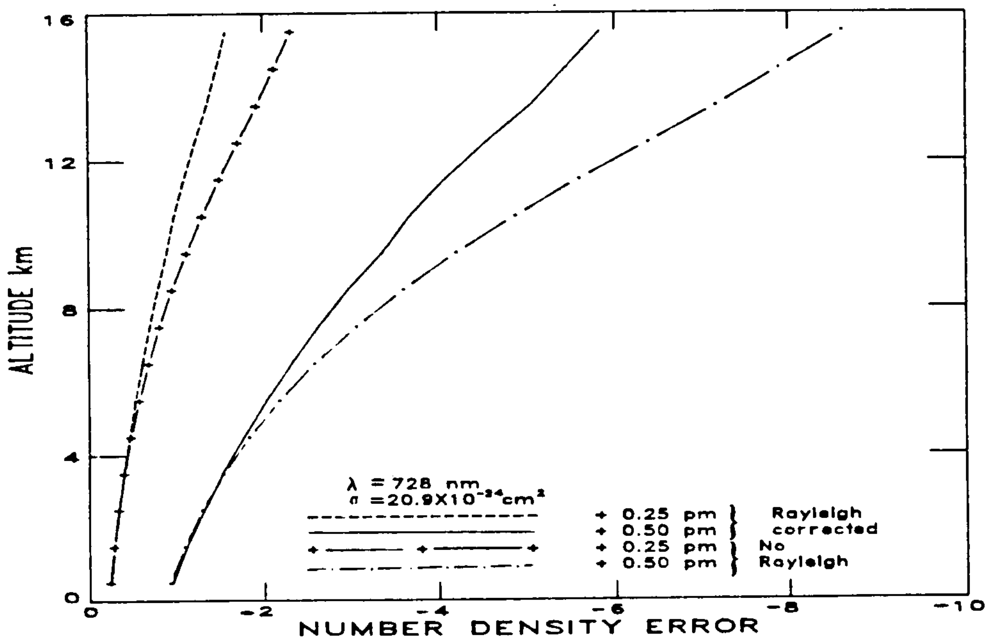

Figure 2. Laser shift (detuning) error with Rayleigh broadening (corrected) and in the absence of Rayleigh broadening influence.

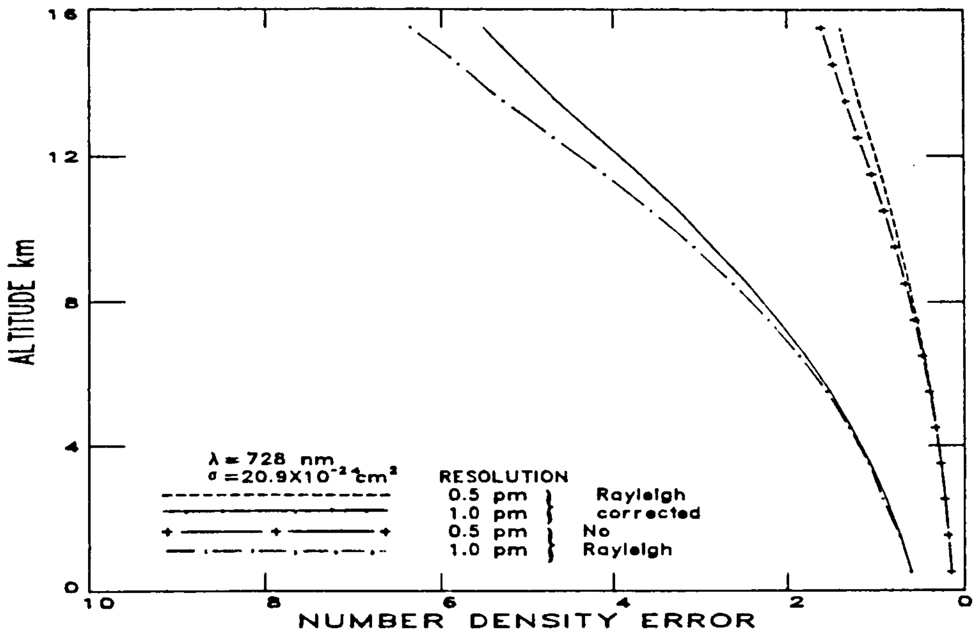

Figure 3. Wavemeter bandwidth errors with and without Rayleigh broadening (corrected).

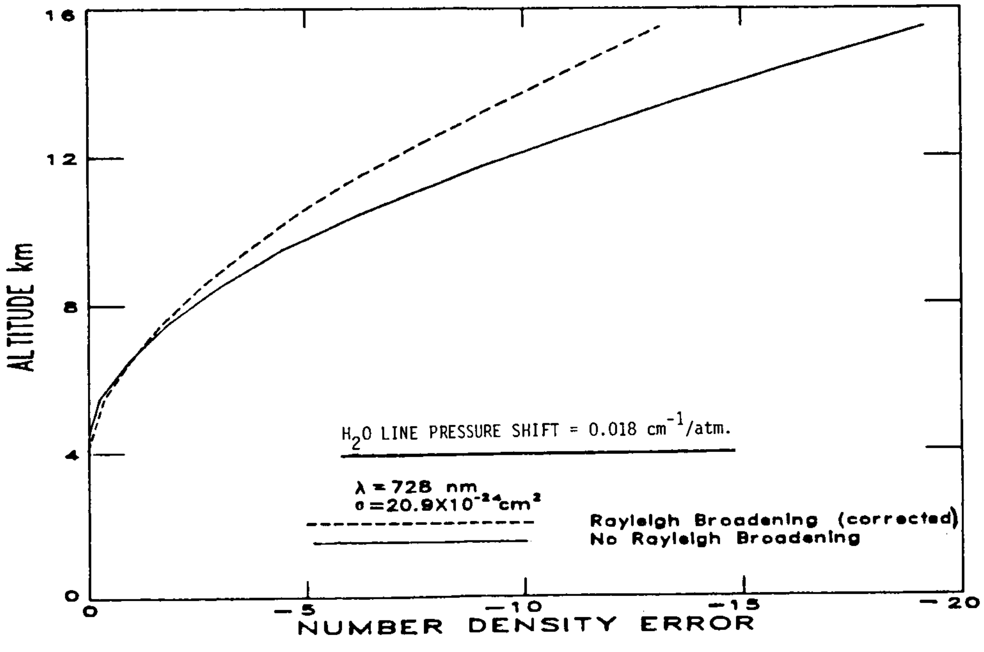

Figure 4. Errors due to pressure shift effects in H_2O absorption lines with and without Rayleigh broadening (corrected). The laser line is assumed to be at the center of the H_2O line at ground altitude.