An Experimental Determination of the Depolarization of Scattered Laser Light by Atmospheric Air

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ABSTRACT

The previously adopted values of the depolarization factor of clear atmospheric air are checked with the values obtained by lidar facilities, and with those obtained in laboratory measurements, using scattering of a He-Ne gas laser. These values and the importance of the depolarization factor in lidar measurements are discussed.

1. Introduction

The use of lidar (or laser radar) for the detection of clear air turbulence (CAT), temperature inversions, etc., is usually based on theoretical calculations which correlate such phenomena with intensity variations of the backscattered signal which are due to fluctuations in air density. On the other hand, fluctuations of the same or greater order of magnitude can be caused by the presence of small dust particles and aerosols. To resolve the question whether the variations in the measured backscatter are caused by changes in air density or by other factors, the depolarization factor (Atlas *et al.*, 1953) of the incident, linearly polarized, laser light can be measured. It is shown herein that the theoretical as well as the experimental value of the depolarization factor in clear air is ~0.015. In measurements of atmospheric turbulence, for example, while the backscattered intensity would vary (due to fluctuations in air density), the depolarization factor of backscattered light would not. Thus, the lack of a variation in the depolarization factor would be an indication that turbulence was being measured. On the other hand, if the depolarization factor was substantially different from 0.015, the measurements could not be attributed to turbulence since intensity variations might then be due to variations in aerosols which have also increased the depolarization factor. The depolarization factor, to some extent, discriminates among different mechanisms and, therefore, is an additional parameter useful in backscattering experiments. It can also play an important role in research dealing with coherence distance and phase shift along the path of a laser beam.

2. Theory

The four Stokes' parameters $I_{\parallel}$, $I_{\perp}$, U, V (van de Hulst, 1957) for laser light polarized perpendicular to the reference plane (which includes the directions of the incident and the scattered light), are 0, $I_{\perp 0}$, 0, 0. The transformation matrix **A** for the scattered light by a single particle is a function of the polarizability tensor α_{ij}, depending on the particles' symmetry, and on the scattering angle θ; thus,

$$\begin{bmatrix} I_{\parallel} \\ I_{\perp} \\ U \\ V \end{bmatrix} = \mathbf{A} \begin{bmatrix} 0 \\ I_{\perp 0} \\ 0 \\ 0 \end{bmatrix}. \tag{1}$$

For random orientation of many non-absorbing particles, having the same polarizability tensor and sizes much smaller than the laser wavelength λ, the matrix **A** has the form (van de Hulst, 1957)

$$\mathbf{A}=C\begin{bmatrix} (2a+3b)\cos^2\theta+a-b & a-b & 0 & 0 \\ a-b & 3a+2b & 0 & 0 \\ 0 & 0 & (2a+3b)\cos\theta & 0 \\ 0 & 0 & 0 & 5b\cos\theta \end{bmatrix}, \tag{2}$$

where

$$a=\frac{1}{15}\sum_{i=1}^{3}\alpha_{ii}^2,$$

$$b=\frac{1}{30}\sum_i\left(\alpha_{ii}\sum_{j\neq i}\alpha_{jj}\right),\quad i,j=1,2,3,$$

$$\alpha_{ij}=0,\quad i\neq j,$$

C = constant, depending on λ.

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TABLE 1. Polarizabilities and δ factors for atmospheric molecules*.

Molecule	Per cent per unit air volume	$\alpha_{\parallel}$ (10^{24} cm^3) Stuart (1952)	$\alpha_{\parallel}$ (10^{24} cm^3) Bridge (1966)	$\alpha_{\perp}$ (10^{24} cm^3) Stuart (1952)	$\alpha_{\perp}$ (10^{24} cm^3) Bridge (1966)	$\delta^{(1)}$ Stuart (1952)	$\delta^{(2)}$ Bridge (1966)	$\delta^{(3)}$ de Vaucouleurs (1951)
N_2	78.084±0.004	2.38	2.22	1.45	1.53	0.018	0.010	
O_2	20.946±0.002	2.35	2.32	1.21	1.23	0.033	0.030	
CO_2	0.033	4.01	4.03	1.97	1.93	0.037	0.040	
Dry air**	100					0.0205	0.0142	0.016

* $\delta^{(1)}$, $\delta^{(2)}$ and $\delta^{(3)}$ are calculated according to Eq. (3), and therefore do not necessarily have the same values as in the original papers.
** The amounts of H_2 and N_2O, and their contribution to δ, are negligible, while δ for argon and other atoms present in atmospheric air is zero.

Substitution of (2) into (1), leads to the depolarization factor δ:

$$\delta=\frac{I_{\parallel}}{I_{\perp}}=\frac{a-b}{3a+2b}. \tag{3}$$

Since the experiments to be described involve values of θ of 90° and 180°, it is clear from the above matrix that the results should be equal, since δ is not dependent on the scattering angle.

For linear molecules like O_2, N_2 and CO_2, the polarizability tensor is $\alpha_{\parallel}=\alpha_{11}$ and $\alpha_{\perp}=\alpha_{22}=\alpha_{33}$ (Davies, 1965); δ thus becomes

$$\delta=\frac{(\alpha_{\parallel}-\alpha_{\perp})^2}{(\alpha_{\parallel}+2\alpha_{\perp})^2+2\alpha_{\parallel}{}^2+4\alpha_{\perp}}. \tag{4}$$

In Table 1 we list δ values for the most important components of air (Stuart, 1952; Bridge and Buckingham, 1966) as well as dry air (de Vaucouleurs, 1951) as found in the literature. It should be noted that:

1) The α_{ii}'s are functions of the incident wavelength λ. We assume, however, that δ does not change significantly from the He-Ne laser wavelength of 6328Å (with the use of which the $\delta^{(2)}$ values were determined) to the ruby laser wavelength of 6943Å (used in most of the lidar systems). One has to be careful to tune the ruby laser so that its wavelength does not fall within an absorption line of O_2 or H_2O.

2) Since the δ value for water vapor is 0.01 (Stuart, 1952), the presence of humidity in the atmosphere will result in a variation of from zero to a negative 5% in the dry air δ value. For a Rayleigh atmosphere, where no particles other than air molecules are present, this variation can, in principle, be used to determine the relative humidity. However, in the present paper, the theoretical values of the δ's for the air will be taken as in Table 1. The estimated error of 5% takes into account changes in the humidity.

3) Cloud droplets, spherical dust particles and other aerosols have values of $\delta=0$ at $\theta=180°$ (Eiden, 1966), essentially because $\alpha_1\approx\alpha_2\approx\alpha_3$. However, microscopic measurements made in Jerusalem for various samples of locally collected dust particles (E. Ganor, personal communication), indicated that in many cases the simplification of assuming spherical particles is not accurate. This will give rise to a depolarization factor for these dust particles. This has been observed with our lidar measurements (Cohen *et al.*, in preparation).

3. Measurements of clear air δ and results

a. The lidar

Our lidar, described in detail elsewhere (Neumann *et al.*, 1968), was directed horizontally in order to minimize standard vertical variations in air density as well as variations in the mixing ratio of the water vapor. In all cases, when measurements were made during daytime, the azimuth angle of the lidar was 180° with respect to the sun and its elevation angle was less than 20°, to avoid possible variations in the fluctuations of the background noise due to the polarization of solar diffused light (Sekera, 1957). Since the expected parallel and perpendicular (with respect to the incident linearly polarized ruby laser light) backscattered intensities differed by two orders of magnitude, the voltage on the EMI 9558 A photomultiplier was changed and its amplification curve calibrated. The photomultiplier was followed by an ac amplifier which cut the average background noise. The physical characteristics of the analyzer, situated in front of the photomultiplier, were determined by laboratory measurements. The experimental data were taken in 20 days. Each day at least 20 pictures were taken for the two polarizations, each picture containing over 10 points from which data can be evaluated. The δ's varied from 0.015 (for the clearest days) up to 0.7. There was a correspondence between the changes in visibility distances and the depolarization factors, the visibility distance being defined as $V=\text{constant}/\sigma$, where σ is the extinction coefficient. For the purpose of evaluating clear air δ's, we have only taken into account those pictures in which the visibility distance was large; that is, where $\sigma<0.02$ km^{-1}. The dependence of δ on visibility will be discussed separately (Cohen *et al.*, in preparation).

From these data we obtained $\delta=0.015\pm0.002$, in which the estimated error arises mainly from the visual definition (breadth) of the line of the scope.

Another method for the determination of δ was based on the assumption of a homogeneous horizontal atmosphere (defined as an atmosphere with constant extinction and backscattering coefficients). In this case, the lidar equation for the backscattered light from a distance R can be written as

$$I=A(\beta/R^2)e^{-2\sigma R}, \tag{5}$$

where I is the recorded intensity, A a constant of the system, β the backscattering cross section of the air, and σ the extinction coefficient. From (5) we obtain

$$\left.\begin{aligned} I_{\parallel}(R_i)&=A(\beta_{\parallel}/R_i^2)\exp[-2\sigma R_i] \\ I_{\perp}(R_j)&=A(\beta_{\perp}/R_j^2)\exp[-2\sigma R_j] \end{aligned}\right\}, \tag{6}$$

where $\beta_{\parallel}/\beta_{\perp}=\delta$. The distances R_i and R_j are determined by the time base of the recording oscilloscope.

By choosing experimental conditions so that $I_{\parallel}(R_1)=I_{\perp}(R_2)$, we have

$$\delta=\beta_{\parallel}/\beta_{\perp}=(R_1/R_2)^2\exp[2\sigma(R_1-R_2)], \tag{7}$$

where σ was determined using one set of measurements of $I_{\perp}(R_j)$ at two different distances, taken from the same picture; i.e.,

$$I_{\perp}(R_{j,1})/I_{\perp}(R_{j,2}) = (R_{j,2}/R_{j,1})^2\exp[2\sigma(R_{j,2}-R_{j,1})], \tag{8}$$

only σ being unknown. With the second method we obtain the same value of $\delta=0.015\pm0.002$, giving added confidence to the method and consistency of the results.

The experimental data in this case had better accuracy since all measurements were made at the same photomultiplier setting and only ratios of this setting were measured. However, the assumption of a constant σ is probably not quite correct and what is really measured is an average σ. This may introduce an error of 10–15%.

b. Laboratory measurements with the thermal diffusion cloud nuclei chamber system

A sample of air was pumped into the thermal diffusion cloud nuclei chamber (TDCNC; see Cohen, 1969) in which a high supersaturation condition ($e/e_s>1.01$) had been established. Under this condition, water droplets started to form over most of the nonmolecular particles. Upon reaching a certain size, the droplets fell out of the Ne-He laser beam. After a time period of 100 sec, the TDCNC was completely purged of aerosols and dust particles, resulting in clean air containing high amounts of water vapor. The 90° scattered light was collected by an 1P28 RCA photomultiplier, and recorded on an oscilloscope. A value of $\delta_{\text{dry air}}=0.0149\pm0.0005$ was obtained, the relative error of $\sim$4% being mainly instrumental. The results are contained in Table 2.

TABLE 2. Experimental δ values of atmospheric air.

Lidar	0.015 ± 0.002
TDCNC	0.0149 ± 0.0005

4. Conclusions

We have demonstrated that the depolarization factor measured by pulsed laser techniques over large distances in air (lidar techniques) is about the same as that evaluated from laboratory measurements of the different molecular species. Hence, the lidar technique can be used to measure deviations of the depolarization factor due to certain atmospheric conditions and determine in part the nature and the position of the particles which contribute to the depolarization.

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