On the Use of Ultraviolet Lidar for Observing Atmospheric Constituents by Raman Scattering

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1. Introduction

Leonard (1967) has made observations of Raman scattering by oxygen and nitrogen in the atmosphere using a pulsed nitrogen ultraviolet laser. He notes that

the Raman scattering technique can be of importance to the field of meteorology because, unlike ordinary scattering techniques, it can isolate the scattered signal from a specific atmospheric constituent and therefore

be used to determine the concentration of the constituent. Leonard chose to use a 3371 Å pulsed nitrogen laser in preference to the more commonly used 6940 Å ruby laser for two reasons: 1) the photo-efficiency of photocathodes is ~25 times greater for ultraviolet, and 2) the Raman scattering cross section is inversely proportional to the fourth power of the incident wavelength. According to Leonard, the wavelength dependence of the Raman scattering cross section makes the nitrogen lidar more effective than the ruby lidar by a factor of $(6940/3371)^4 = 17.96$. The foregoing treatment does not take into account, however, the attenuation of the lidar pulse by air molecules, which deplete the pulse by Rayleigh scattering. Since the Rayleigh scattering cross section is also inversely proportional to the fourth power of the incident wavelength, use of an ultraviolet wavelength would also result in increased attenuation of the lidar pulse. The purpose of this note is to examine the net effect of these two counteracting factors.

2. Development

The power P returned to a lidar from backscattering by an atmospheric constituent at range R may be expressed as (Barrett and Ben-Dov, 1967)

$$P = \frac{1}{2} P_t \delta c A R^{-2} K F, \quad (1)$$

where P_t is the transmitted power, δ the duration of the pulse, c the speed of light, A the aperture of the receiver optics, K the backscattering function, and F the attenuation loss factor. The backscattering function for Raman scattering may be expressed as (Eckhardt and Wagner, 1966)

$$K = E(\lambda_0^{-1} - \lambda_v^{-1})^4, \quad (2)$$

where E is a parameter which is independent of wavelength λ_0 of the incident light, and λ_v is the characteristic wavelength of the scattering molecule. At the wavelengths under consideration here, c may be considered to be independent of wavelength (Johnson, 1954). Under the assumption of a constant c , the Raman scattering wavelength λ for the more intense Raman lines is given by Richtmyer *et al.* (1955) as

$$\lambda^{-1} = \lambda_0^{-1} - \lambda_v^{-1}. \quad (3)$$

The attenuation factor due to scattering by air molecules as the lidar pulse travels a distance R and returns is given by

$$F = \exp[-R(k_0 + k)], \quad (4)$$

where k is the scattering coefficient (Johnson, 1954),

$$k_0 = \left(\frac{32\pi^3}{3n\lambda_0^4} \right) (m-1)^2 = B\lambda_0^{-4}, \quad (5)$$

in which n is the number of molecules per unit volume and m the index of refraction for air. At sea level,

$n = 2.66 \times 10^{19} \text{ cm}^{-3}$, and $m-1 = 293 \times 10^{-6}$, which through use of (5) yield a value of $B = 1.067 \times 10^{-24} \text{ cm}^3$.

Use of (2), (4) and (5) in (1) gives

$$P = D(\lambda_0^{-1} - \lambda_v^{-1})^4 \exp[-RB(\lambda_0^{-4} + \lambda^{-4})], \quad (6)$$

where D is a parameter which is independent of wavelength. The condition under which the increased backscatter due to use of a shorter λ_0 would be offset by increased attenuation is expressed by

$$\partial P / \partial \lambda_0 > 0. \quad (7)$$

Differentiation of (6) yields $\partial P / \partial \lambda_0$ which when substituted into (7) gives

$$R > [B(\lambda^{-4} + \lambda_0^{-3}\lambda^{-1})]^{-1}. \quad (8)$$

Hence, if a ruby lidar is being used to observe an atmospheric constituent like nitrogen, (8) yields a value of 163 km as the distance within which one can shift to shorter wavelengths to achieve an increase in the backscattered signal. Whereas, at the nitrogen lidar wavelength, the distance given by (8) is lowered to 7.4 km. It is interesting to note that if just Rayleigh scattering were being considered (i.e., $\lambda = \lambda_0$), the result $R > (2B)^{-1}\lambda_0^4$ would be obtained in place of (8). This formula would yield 109 km and 6.1 km, respectively, for the ruby and nitrogen lidar wavelengths.

The effectiveness of the nitrogen lidar over the ruby lidar, due only to the difference in wavelength, is given by the ratio of the backscattered power at each wavelength, i.e.,

$$P/P_r = (\lambda_r/\lambda)^4 \exp[RB(\lambda_{0r}^{-4} + \lambda_r^{-4} - \lambda_0^{-4} - \lambda^{-4})], \quad (9)$$

where the subscript r refers to the ruby lidar quantities. Thus, Leonard's estimate of the effectiveness is modified by the exponential term in (9). At ranges of 1, 5 and 10 km, this exponential term has the values 0.87, 0.51 and 0.26, respectively. Its value does not diminish to 1/17.96 until a range of 21.3 km is reached; hence, for ranges < 21.3 km, the increased attenuation does not offset the increased backscatter, and it is advantageous to use the ultraviolet lidar.

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