

# Combined Raman–elastic backscatter lidar method for the measurement of backscatter ratios

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A variation of the conventional combined Raman–elastic backscatter lidar method, the 1-2-3 lidar method, is described and analyzed. This method adds a second transmitter wavelength to the conventional combined Raman–elastic backscatter lidar. This transmitter wavelength is identical to that of the Raman receiver. One can generate the transmitted beam at this wavelength by Raman shifting the laser radiation in molecular nitrogen or oxygen. Measuring a second elastic lidar signal at the Raman-shifted wavelength makes it possible to eliminate differential transmission effects that can cause systematic errors in conventional combined Raman–elastic backscatter lidar. © 1997 Optical Society of America

*Key words:* Raman lidar, elastic lidar, backscatter ratio.

## 1. Introduction

Conventional elastic lidar signals are a function of both atmospheric backscattering and extinction coefficients. The quantitative analysis for either coefficient depends on questionable assumptions and results should be used with some caution. The conventional combined Raman–elastic backscatter lidar uses one transmitted wavelength, but two receiver channels.<sup>1–3</sup> One channel detects the elastic backscatter signal, the other the vibrational Raman backscatter signal. The purely molecular Raman backscatter signal can be used to remove the extinction terms in the elastic signal and to retrieve a backscatter ratio profile. However, this removal is generally not complete as the Raman signal has a different wavelength from the elastic signal and therefore can be subject to different extinction.

Our new approach, the 1-2-3 lidar method, employs one laser, two transmitted wavelengths, and the observation of three different lidar return signals. It is a variation of the conventional combined Raman–elastic

backscatter lidar, adding an elastic lidar channel at the wavelength of the Raman return. The objective of this method is to separate the lidar backscatter and extinction functions and thereby to measure the range dependence of backscatter ratios accurately even when the situation is significantly complicated by the presence of aerosol or gaseous extinction. After an initial calibration, the 1-2-3 method can be used to measure the product (or geometric mean) of the backscatter ratios at two closely spaced wavelengths without contamination by transmission ratios. The basic concept has been described previously.<sup>4,5</sup>

## 2. Combined Raman–Elastic Backscatter Lidar

Conventional combined Raman–elastic backscatter lidar systems utilize a single-wavelength transmitter and a dual-wavelength receiver.<sup>1–3</sup> The receiver measures both the elastic backscatter signal at the transmitter wavelength  $\lambda_1$  and the Raman backscatter signal at a second wavelength  $\lambda_2 = (1/\lambda_1 - \nu_R)^{-1}$ , where  $\nu_R$  is the wave number of the molecular Raman shift. Raman scattering from the vibrational Raman  $Q$  branch of either atmospheric nitrogen ( $\nu_R = 2331 \text{ cm}^{-1}$ ) or oxygen ( $\nu_R = 1555 \text{ cm}^{-1}$ ) is commonly used for this purpose.

For single scattering, the range and overlap-corrected elastic lidar signal  $S_1(r)$  can be written as

$$\begin{aligned} S_1(r) &= \frac{r^2 S_1(r)}{O(r)} \\ &= C_1 [\beta_1^m(r) + \beta_1^p(r)] T_1^2(r_0, r) \\ &= C_1 R_1(r) \beta_1^m(r) T_1^2(r_0, r), \end{aligned} \quad (1)$$

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Received 8 May 1996; revised manuscript received 18 February 1997.

0003-6935/97/215144-04\$10.00/0

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where the subscript 1 refers to the wavelength  $\lambda_1$ ,  $s(r)$  is the uncorrected signal at range  $r$ ,  $O(r)$  is the lidar overlap function,  $C$  is the system constant that includes the laser pulse energy,  $\beta_1^m(r) = \beta^m(r, \lambda_1)$  and  $\beta_1^p(r) = \beta^p(r, \lambda_1)$  are molecular and particulate backscatter coefficients, respectively;  $R_1(r) = R(r, \lambda_1)$  is the wavelength-dependent backscatter ratio defined as

$$R_1(r) = \frac{\beta_1^m(r) + \beta_1^p(r)}{\beta_1^m(r)}, \quad (2)$$

and  $T_1(r_0, r) = T(r_0, r, \lambda_1)$  is the one-way transmission coefficient between the lidar locations  $r_0$  and range  $r$ ,

$$T_1(r_0, r) = \exp\left[-\int_{r_0}^r \sigma_1(x)dx\right], \quad (3)$$

where  $\sigma_1(r) = \sigma(r, \lambda_1)$  is the wavelength-dependent extinction coefficient at  $r$ .

For Raman backscatter signals at wavelength  $\lambda_2$  an analogous equation can be written as

$$S_{1,2}(r) = \frac{r^2 s_{1,2}(r)}{O(r)} C_{1,2} \beta_{1,2}^m(r) T_1(r_0, r) T_2(r_0, r), \quad (4)$$

where  $\beta_{1,2}^m$  is the Raman backscattering coefficient for inelastic scattering from  $\lambda_1$  to  $\lambda_2$ . The backscatter ratio profile  $R_1(r)$  at  $\lambda_1$  can be calculated from the signal ratio  $S_1(r)/S_{1,2}(r)$  as

$$R_1(r) = \frac{C_{1,2} \beta_{1,2}^m(r) T_2(r_0, r_{\text{ref}}) T_2(r_{\text{ref}}, r) S_1(r)}{C_1 \beta_1^m(r) T_1(r_0, r_{\text{ref}}) T_1(r_{\text{ref}}, r) S_{1,2}(r)}. \quad (5)$$

The calibration factor contains the ratio of the system constants  $C_{1,2}/C_1$ , a molecular backscatter coefficient ratio  $\beta_{1,2}^m(r)/\beta_1^m(r)$  that is constant for much of the atmosphere because of the constant fractional abundance of  $\text{N}_2$  ( $\text{O}_2$ ), and a transmission ratio  $T_2(r_0, r_{\text{ref}})/T_1(r_0, r_{\text{ref}})$  between lidar location  $r_0$  and reference range  $r_{\text{ref}}$  that depends on atmospheric conditions. The calibration factor can be obtained from a lidar calibration if particle-free air [ $R_1(r_{\text{ref}}) = 1$ ] or some other known backscatter ratio is encountered at some reference range  $r_{\text{ref}}$ . The calibration ratio contains the transmission ratio  $T_2(r_0, r_{\text{ref}})/T_1(r_0, r_{\text{ref}})$  and remains valid only as long as this transmission ratio does not change significantly, i.e., the system has to be recalibrated periodically or continuously. The second factor is the transmission ratio  $T_2(r_{\text{ref}}, r)/T_1(r_{\text{ref}}, r)$  between reference range  $r_{\text{ref}}$  and measurement range  $r$ . Its value has to be estimated and errors can contaminate the local value of  $R_1(r)$  with the range-integrated transmission ratio. The third factor is the measured signal ratio  $S_1(r)/S_{1,2}(r)$ .

The interfering influence of the transmission ratio can be reduced by utilizing Raman scattering from atmospheric oxygen, with a Q-branch shift of 2/3 of that of nitrogen. However, the resulting Raman li-

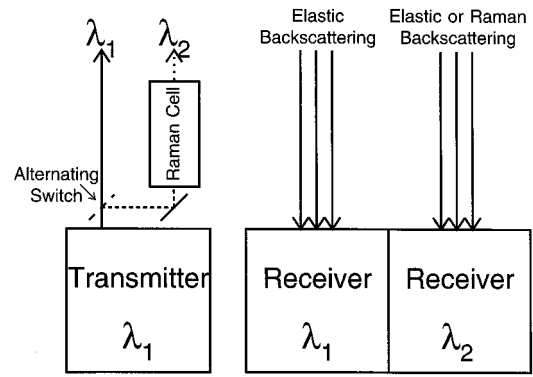


Fig. 1. Schematic diagram of the 1-2-3 lidar system.

dar signal is approximately a factor of 3 weaker than that from nitrogen.

### 3. The 1-2-3 Lidar Method

The conventional combined Raman–elastic backscatter lidar can be modified by adding a second transmitter wavelength  $\lambda_2$  and measuring its elastic backscatter signal with the already existing receiver channel at  $\lambda_2$ . A transmitted beam at this second wavelength can be generated efficiently from the laser output at wavelength  $\lambda_1$  by vibrational Raman shifting of this radiation in a  $\text{N}_2$  (or  $\text{O}_2$ ) gas cell.<sup>6–8</sup> The transmission of laser pulses alternates between  $\lambda_1$  and  $\lambda_2$ . When a pulse at  $\lambda_1$  is transmitted, both the elastic backscattering and the frequency-shifted Raman backscattering from atmospheric  $\text{N}_2$  are observed at  $\lambda_1$  and  $\lambda_2$ , respectively. For the interleaved laser pulses at  $\lambda_2$ , only the elastic backscattering at  $\lambda_2$  is observed. A schematic diagram of the 1-2-3 lidar system is shown in Fig. 1.

The second elastic backscatter signal at  $\lambda_2$  can be written equivalent to Eq. (1) as

$$\begin{aligned} S_2(r) &= \frac{r^2 s_2(r)}{O(r)} \\ &= C_2 [\beta_2^m(r) + \beta_2^p(r)] T_2^2(r_0, r) \\ &= C_2 R_2(r) \beta_2^m(r) T_2^2(r_0, r), \end{aligned} \quad (6)$$

and, together with the Raman backscattering signal  $S_{1,2}(r)$ , it yields the backscatter ratio  $R_2(r)$  at  $\lambda_2$ :

$$R_2(r) = \frac{C_{1,2} \beta_{1,2}^m(r) T_1(r_0, r_{\text{ref}}) T_1(r_{\text{ref}}, r) S_2(r)}{C_2 \beta_2^m(r) T_2(r_0, r_{\text{ref}}) T_2(r_{\text{ref}}, r) S_{1,2}(r)}. \quad (7)$$

Equation (7) is equivalent to Eq. (5), however, with inverse dependence on the transmission ratios. Therefore, the product of the two backscatter ratios  $R_1(r)$  and  $R_2(r)$  yields a local measurement of backscatter properties uncontaminated by range-integrated transmissions. The geometric mean

$R_{1,2}(r)$  of the backscatter ratios  $R_1(r)$  and  $R_2(r)$  can be written as

$$\begin{aligned} R_{1,2}(r) &= [R_1(r)R_2(r)]^{1/2} \\ &= \frac{[C_{1,2}\beta_{1,2}^m(r) S_1(r)S_2(r)]}{C_1C_2\beta_1^m(r)\beta_2^m(r) [S_{1,2}(r)]^2} \\ &= C \frac{S_1(r)S_2(r)}{[S_{1,2}(r)]^2}, \end{aligned} \quad (8)$$

where  $C$  is a constant. This simple analytical result is the basis of the 1-2-3 lidar method and can be interpreted as follows. The elastic backscatter lidar signals  $S_1$  and  $S_2$  each include a two-way transmission term at their individual wavelength,  $T_1^2$  and  $T_2^2$ , respectively. The Raman signal  $S_{1,2}$ , on the other hand, includes a transmission term  $T_1$  for the transmission of laser light at wavelength  $\lambda_1$  to range  $r$  and a transmission term  $T_2$  for the return transmission of scattered light at wavelength  $\lambda_2$ . Dividing the product of the elastic signals  $S_1$  and  $S_2$  by the square of the inelastic Raman signal  $S_{1,2}^2$  therefore completely removes the transmission terms and, in addition, normalizes the elastic scattering with the molecular Raman scattering, yielding a backscatter ratio  $R_{1,2}$ . This backscatter ratio  $R_{1,2}$  is the geometric mean of the backscatter ratios at the closely spaced wavelengths  $\lambda_1$  and  $\lambda_2$  and is a useful parameter to describe the atmospheric turbidity.

The advantages of the 1-2-3 lidar method compared with the conventional combined Raman–elastic backscatter lidar can be deduced directly from Eq. (8). The calibration factor  $C$  is a true constant, independent of atmospheric conditions. Therefore, a one-time calibration with particle-free air at some reference range is sufficient. This calibration can be used for all atmospheric conditions as long as the system constants  $C_1$ ,  $C_2$ , and  $C_{1,2}$  remain constant. The ease of calibration is especially relevant for tropospheric measurements for which the measurement range often does not include an aerosol-free region. In addition, the measured backscatter ratio  $R_{1,2}(r)$  is a truly local property, not influenced by the transmission ratio  $T_1/T_2$  between the reference and measurement range. This can be an important advantage, especially for lidar systems that operate in the ultraviolet wavelength region where the wavelength-dependent absorption of ozone contributes to the transmission ratio.

A specific example for a solar-blind lidar system utilizing the fourth harmonic of a Nd:YAG laser as the transmitted wavelength ( $\lambda_1 = 266$  nm) and Raman shifting in nitrogen to generate the second wavelength ( $\lambda_2 = 284$  nm) is illustrated in Figs. 2(a)–2(c). A simple model profile is used with an aerosol-free region ( $R_1 = 1$ ) at and around the reference range  $r_{\text{ref}}$  used for the calibration of conventional combined lidar, followed by a homogeneous aerosol layer ( $R_1 = 3$  for  $r_{\text{ref}} + 600 \text{ m} \leq r \leq r_{\text{ref}} + 1200 \text{ m}$ ) and relatively clear air beyond this layer ( $R_1 = 1.2$  for  $r \geq r_{\text{ref}} + 1200 \text{ m}$ ). The model backscatter ratio  $R_2$  is calculated from  $R_1$  under the assumption of constant mo-

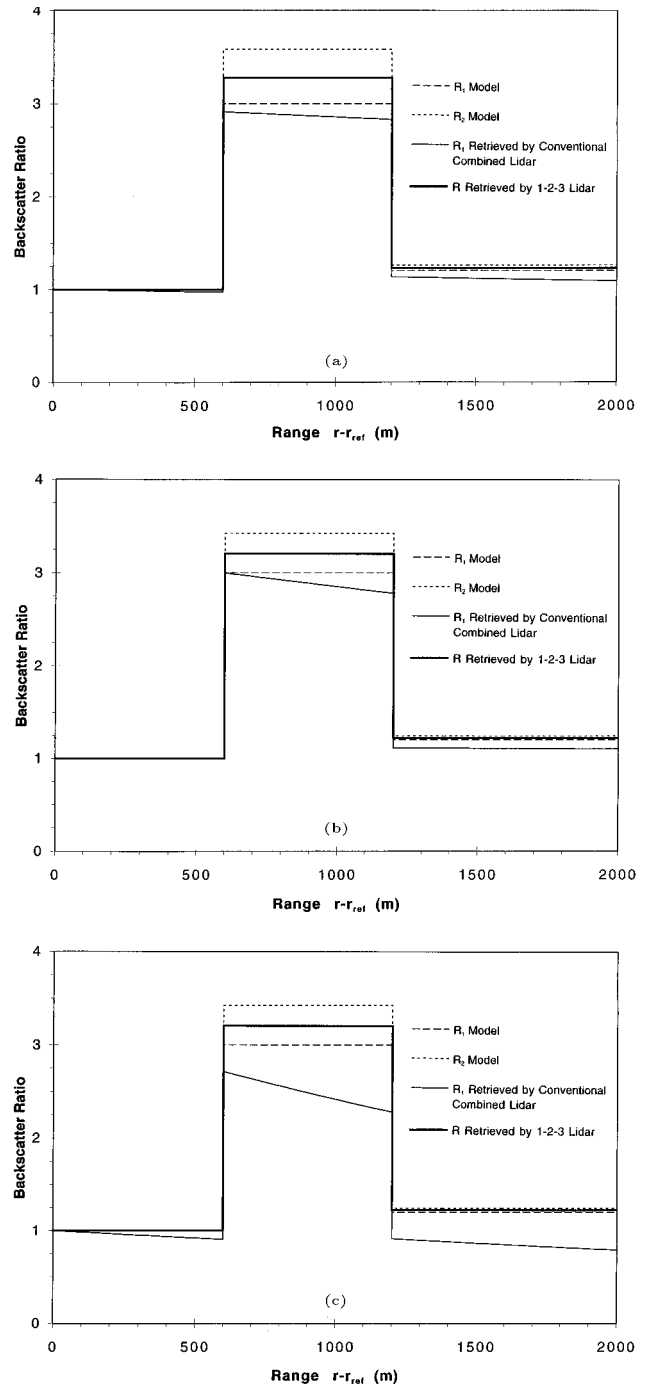


Fig. 2. Model atmospheric backscatter ratio profiles and profiles retrieved by conventional combined Raman–elastic lidar and by the 1-2-3 method for a solar-blind lidar utilizing a quadrupled Nd:YAG laser at 266 nm and Raman shifting in nitrogen. (a) The differential extinction between  $\lambda_1 = 266$  nm and  $\lambda_2 = 284$  nm is due to Rayleigh extinction. (b) The differential extinction between  $\lambda_1 = 266$  nm and  $\lambda_2 = 284$  nm is due to Rayleigh and aerosol ( $u = 1$ ) extinction. The retrieved  $R_1$  profile is corrected for differential Rayleigh extinction. (c) The differential extinction between  $\lambda_1 = 266$  nm and  $\lambda_2 = 284$  nm is due to Rayleigh, aerosol ( $u = 1$ ), and ozone (10 ppb) extinction. The retrieved  $R_1$  profile is corrected for differential Rayleigh extinction.

lecular density, corresponding to a near-horizontal path, and of a constant particulate backscattering phase function of  $0.025 \text{ sr}^{-1}$ . Each part of Fig. 2

shows model profiles of  $R_1$  and  $R_2$ , the  $R_1$  profile retrieved by conventional combined lidar, and the  $R_{1,2}$  profile retrieved by the 1-2-3 lidar method. In Fig. 2(a), the transmission ratio is due solely to Rayleigh extinction. However, the retrieved  $R_1$  profile could be corrected for the differential Rayleigh extinction as its magnitude is well known. In Fig. 2(b) differential aerosol extinction corresponding to the commonly used Ångström coefficient of  $u = 1$  [ $\sigma_2^p/\sigma_1^p = (\lambda_1/\lambda_2)^u$  for aerosol extinction] is added. The retrieved  $R_1$  profile in Fig. 2(b) is corrected for differential Rayleigh extinction. Correction of the retrieved  $R_1$  profile for aerosol extinction is more difficult as the Ångström coefficient  $u$  is generally not known. If an estimate  $\hat{u}$  is used to correct the retrieved  $R_1$  profile, Fig. 2(b) can be interpreted to show the error of the corrected  $R_1$  profile that is due to an error in estimating  $u$  of  $u - \hat{u} = 1$ . Figure 2(c) shows the added effect of 10 ppb of ozone. The retrieved  $R_1$  profile is again corrected for differential Rayleigh extinction. The effect that is due to 10 ppb of ozone corresponds to common errors in the measurement of a tropospheric ozone profile. If such measurements are not available the resulting distortion could be much worse. In summary, although the  $R_1$  profiles retrieved by the conventional combined lidar are distorted due to uncorrected differential absorption effects, the  $R_{1,2}$  profiles retrieved by the 1-2-3 lidar method are completely unaffected.

#### 4. Conclusions

The 1-2-3 lidar method is a straightforward concept that can be used to measure backscatter ratios uncontaminated by differential extinction. Especially in spectral regions affected by differential gaseous absorption, the 1-2-3 lidar method can yield significantly more accurate backscatter ratio profiles than

the conventional combined Raman-elastic lidar. However, this theoretical advantage will have to be evaluated experimentally in the future.

This research has been supported in part by an Institutional Project Assignment of the Desert Research Institute and by the CEDAR (Coupling, Energetics, and Dynamics of Atmospheric Regions) Program of the National Science Foundation.

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