AN INTEGRATED LIDAR TECHNIQUE FOR STUDYING THE LOWER ATMOSPHERE

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We suggest an integrated method for simultaneously determining vertical stratification of the optical, meteorological, and turbulent parameters in the lower layers of the atmosphere. We show that it is possible to construct an integrated Raman-scattering lidar for simultaneous determination of the vertical stratification in temperature, water content, and wind velocity between 250 m and 1000 m.

Over the course of the past two decades, researchers have been working on remote sensing techniques which make use of the spontaneous Raman scattering of laser light by major gaseous constituents of the atmosphere. Without going into any detail concerning the basic characteristics of Raman scattering (e.g., Glazov[1]), we should note that several papers published in recent ye airs (involving the development of a spontaneous-Raman-scattering for measurements the vertical temperature profile,[2] a spontaneous-Raman-scattering method for determining the optical parameters of the atmosphere,[3] measuring the vertical water-vapor profile and attempting to begin studying the statistical properties of the atmospheric parameters being measured,[4] and the possibilities for using correlation methods of wind measurement in spontaneous-Raman-scattering lidar – especially three-beam correlation for measurements carried out on simultaneous intervals of space and time) enable us to draw up the following list of problems which could be solved using an integrated Raman-scattering lidar system:

a) Studying the vertical structure of the optical and meteorological parameter fields;

b) Studying the dynamics of mechanical and thermal energy transfer in the boundary layer under various meteorological conditions.

Figure 1 shows a block diagram of the integrated spontaneous-Raman-scattering lidar system.

Treating the integrated Raman-scattering lidar as a multichannel spectroscopic instrument operating in a photon-counting mode where individual sections of the spectrum play the role of channels, the system of lidar equations describing the signal power received by the photodetectors in the signal-scattering approximation may be written in the following form:

$$\begin{cases} N(\lambda_0, H) = C_0 F_0(H)\left\{\beta^R_\pi(H) + \beta^M_\pi(H)\right\} T^2(\lambda_0, H) H^{-2} + N_{b,0}, \\ N^{RS}_1(\lambda, H) = C_1 F_1(H) \beta^{RS}_{\pi,1}(H) T(\lambda_0, H) T(\lambda, H) H^{-2} + N_{b,1}, \end{cases} \qquad (1)$$

where $N(\lambda_0, H)$ is the echo signal due to Rayleigh and Mie scattering; $N^{RS}_1(\lambda, H)$ is the signal from the section of the Raman-scattering spectrum; λ_0 is the wavelength of light from the laser; λ is the central wavelength of the spectral region selected by the monochromator; i = 1, 2, H_2O, O_2, N_2, CO_2 is a subscript which Indicates whether the channel belongs to one of two temperature-sensitive regions in the rotational spectrum or variational-rotational components, respectively, of various molecular constituents in the atmosphere; C is the instrumental constant for the channels, which includes the area of the detector telescope, the number of photons emitted, the transmission coefficients of the receiving and transmitting optics, the quantum efficiency of the photodetector, and the averaging interval ΔH; $\Phi(H)$ is the geometric factor for the corresponding spectral interval; H is the altitude; $\beta^M_\pi(H)$, $\beta^R_\pi(H)$, and $\beta^{RS}_\pi(H)$ are, respectively, the backscattering coefficients per unit volume for aerosol, Rayleigh, and ith molecular rotational or vibrational components of the various atmospheric components; $T(\lambda_0, H)$ and $T(\lambda, H)$ are the transition coefficients per unit volume, and $N_{b,1}$ and $N_{b,0}$ background signals.

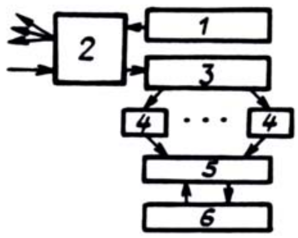

FIG. 1. Block diagram of integrated Raman-scattering lidar: 1) light source; 2) receiving and transmitting optics; 3) monochromator; 4) photomultiplier tube and discriminator; 5) multichannel integrator; 6) computer.

The selection of temperature-sensitive regions in purely rotational Raman spectra has been discussed by Cohen, et al.[S]

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Reconstruction of the profiles for the various atmospheric parameters is based on the assumption[6] that the optical parameters in the lower atmosphere are virtually independent of λ on an interval $\Delta\lambda$:

$$T(\lambda + \delta\lambda) \simeq T(\lambda);$$

$$\beta_{\pi}(\lambda + \delta\lambda) \simeq \beta_{\pi}(\lambda) \qquad (2)$$

Furthermore, we assume that the contribution to the molecular scattering coefficient per unit volume in each region of the purely rotational spectrum selected is due to the same atmospheric component and occurs in the same ratio as β_{π}^{R}, i.e.,

$$\beta_{\pi}^{R}(H) = \gamma\left[\beta_{\pi,1}^{RS}(H,\ T) + \beta_{\pi,2}^{RS}(H,\ T)\right], \qquad (3)$$

where γ and γ_k are constant and T is temperature.

The measurement of the vertical profile of the wind velocity involves the assumption that there are inhomogeneities in the atmospheric aerosol which move with the wind.[7] Using three spatially-separated scattering volumes and assuming the inhomogeneities to be horizontally and vertically isotropic as well as long-lived, we can determine the shift in the peak of the time correlation function (which is inversely proportional to the wind velocity) from the minimum condition

$$\frac{\partial\rho(H,\ l,\ \tau)}{\partial\tau} = 0, \qquad (4)$$

where the $\rho(H,\ l,\ \tau)$ are the two-point correlation coefficients at altitude H horizontal separation l and time shift τ.

The Raman-scattering coefficients are approximately four orders of magnitude smaller than the aerosol scattering coefficients (for a mean visibility range of 10 km or higher). Then, under the assumption that the echo-signal measurement in the aerosol channels requires four orders of magnitude less time than the echo-signal measurement in the inelastic-scattering channels, system of lidar equations (1) for the echo signals from a pulse of length ΔH at altitude H can be cast into the following form (talking Eqs. (2), (3), and (4) into account):

$$\begin{cases} R_{\beta} = \gamma_{\beta}\dfrac{\bar{N}_1 - N_b}{N_1^{Rs} - N_{b,1} + \gamma_k\left[N_2^{Rs} - N_{b,2}\right]}, \\ R_{TR} = \gamma_{TR}\left\{N_1^{Rs} - N_{b,1} + \gamma_k\left[N_2^{Rs} - N_{b,2}\right]\right\}, \\ R_1 = \gamma_1\dfrac{N_1^{Rs} - N_{b,1}}{N_{N_2}^{Rs} - N_{b,N_2}}, \\ R_T = \gamma_T\dfrac{N_1^{Rs} - N_{b,1}}{N_2^{Rs} - N_{b,2}} \end{cases} \qquad (5)$$

where $R_{\beta} = R_{\beta}(H) = \dfrac{\beta_{\pi}^{R}(H) + \beta_{\pi}^{M}(H)}{\beta_{\pi}^{R}(H)}$ is the profile of the scattering ratio; $R_1 = R_1(H) = \beta_{\pi,1}^{RS}(H)\ /\ \beta_{N_2}^{RS}(H)$ is the profile for the ratio of the ith atmospheric constituent relative to nitrogen; $R_{TR} = R_{TR}(H)$ is the profile of the atmospheric transmission at the wavelength of the laser; $\gamma_{\beta} = \gamma_{\beta}(H)$, $\gamma_{TR} = \gamma_{TR}(H)$, $\gamma_1 = \gamma_1(H)$, and $\gamma_R = \gamma_T(H)$ are the profiles of the normalization constants; and $R_T = R_T(H)$ is the temperature ratio profile.

Taking our assumptions concerning the ratio of the integration time for the elastic-scattering signals to that for the inelastic-scattering signals, the following equations can be added to system (5):

$$\begin{cases} \rho_{12}(\tau) = \sum\limits_{t}\sum\limits_{t'<t}\left\{\bar{N}_1 - N_1(t)\right\}\left\{\bar{N}_2 - \bar{N}_2(t')\right\}/\sigma_1\sigma_2, \\ \rho_{23}(\tau) = \sum\limits_{t}\sum\limits_{t'<t}\left\{\bar{N}_2 - N_2(t)\right\}\left\{\bar{N}_3 - N_3(t')\right\}/\sigma_2\sigma_3, \end{cases} \qquad (6)$$

where $\rho_{12}(\tau) = \rho_{12}(H,\ l,\ \tau)$, $\rho_{23}(\tau) = \rho_{23}(H,\ l,\ \tau)$ are matrices containing the normalized correlation coefficients for the three beams located at the vertices of a right triangle with sides $l = l(H)$; $\tau = t - t'$ is the time shift; and $N_1(t)$, $N_2(t)$, and $N_3(t)$ ($N_1(\lambda_0,\ H,\ t)$, $N_2(\lambda_0,\ H,\ t)$, and $N_3(\lambda_0,\ H,\ t)$, respectively) are the echo signals recorded from each of the three beams at time t; $\bar{N}_1$, $\bar{N}_2$, and $\bar{N}_3$, and σ_1, σ_2, and σ_3 are the means and standard deviations for the signals from each of the three aerosol channels at altitude H. The profiles of the normalization factors are determined using equations of the following form (taking (2) into account):

$$\begin{cases} \gamma_{\beta}(H) = \dfrac{C_1F_1(H)}{C_0F_0(H)}, \\ \gamma_{TR}(H) = \dfrac{\gamma H^2}{\beta_{\pi}^{R}(H_0)C_1F_1(H)}, \\ \gamma_1(H) = \dfrac{C_{N_2}F_{N_2}(H)}{C_1F_1(H)}, \\ \gamma_T(H) = \dfrac{C_2F_2(H)}{C_1\Phi_1(H)}. \end{cases} \qquad (7)$$

Under the assumption that the geometric factors are identical, the normalization profiles degenerate into constants which can be determined using the signals from the initial pulse. The situation becomes noticeably more complicated if the initial pulse is longer than 50 m (this is especially true of γ_{TR}, where the geometric factor appears explicitly), since it is difficult to monitor the initial parameters. The situations can be resolved if it is possible to operate in the horizontal direction to determine the geometric factor. Using the fact that the atmosphere is horizontally isotropic, we can determine both the initial parameters and the for» of the geometric factor.

In designing an integrated three-beam Raman-scattering lidar system which operates in Photon-counting mode, we must attempt to find a common ground between the integration time required to obtain sufficient for the elastic-scattering signals and the integration time required for the faint inelastic-scattering signals. The required beam separation and integration time may by determined as follows. The relative error of measurement for the wind velocity V at altitude H for integration time t may be written in the form

$$\varepsilon_v \simeq \frac{\Delta l}{l} = \frac{tv}{l} .$$

The integration time may be estimated fro» Poisson photon-counting statistics, and if D is the dynamic range of the echo-signal envelope and f is the pulse repetition rate of the laser, assuming a forced reduction in the aerosol-channel echo signals to a level such that the probability of detecting a photoelectron from the near field in any given pulse approaches unity.

$$\nu + \varepsilon\nu^{1/2} \leq 1$$

where ν is the parameter in the Poisson distribution, ε is an estimate of the relative error of photoelectron accumulation during the integration time t, we then find that

$$\varepsilon \simeq \sqrt{D/ft},$$

and hence

$$l = vD/\varepsilon_v\varepsilon^2 f.$$

If we say that the level of fluctuations due to integration under Poisson statistics should be identical to the fluctuations in the aerosol level (which are equal to 0.05), an estimate for $\nu = 5–10$ m/s, $D = 10$, $f = 10$ kHz, $\varepsilon = 0.05$, and $\varepsilon_v = 0.1$ yields a minimum separation of order 20–40 m (without taking the noise in the light source and detector into account). Adopting an optimum separation of 40–150 m, we find that the measurements contain information on altitudes between 250 and 1000 m. The fraction of the main beam power used to create the additional beams is defined as

$$\frac{\delta U}{U} = \gamma_1\gamma_2\gamma_3,$$

where γ_1 is the ratio of the transmission in the aerosol detection channel to that in the Raman-scattering channel; γ_2 is the ratio of the Raman-scattering cross section to the aerosol-scattering cross section; γ_3 is the ratio of the integration time per profile in the aerosol channel to that in the Raman-scattering channel. For $\gamma_1 = 0.2$, $\gamma_2 = 0.00001$, and $\gamma_3 = 250$, the estimated upper limit on the fraction of the mean power removed from the main beam is 0.005, or 25–50 mW from the 5–10 W power source used for Raman-scattering lidar ranging.

Experimental results are beyond the scope of the present paper, but elements of this integrated method, such as normalization of the parameters from observations in the horizontal direction have been used in determining vertical profiles of the temperature, water-vapor mixing ratio, and the optical parameters of the atmosphere. Promising directions for future development in integrated Raman-scattering lidar include measuring the energy distribution in the atmosphere, as well as the profiles of wind velocity and the turbulence parameters.

Simultaneous measurement of the variation in the scalar temperature, water content, and aerosol fields, as well as the vector velocity field with 12–15 m resolution to altitudes of 1000 m on identical intervals of space and time will make it possible to study the statistics and interrelationships between the random fields on various scales from the microscale to the macroscale.

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REFERENCES

1. G.N. Glazov, *Statistical Problems in Atmospheric Lidar Ranging* [in Russian], Nauka, Novosibirsk (1987), 312 pp.

2. Yu.F. Arshinov, S.M. Bobrovnikov, V.E. Zuev, and V.M. Mitev, Appl. Opt. **22**, No. 19, 2984 (1983).

3. Yu.F. Arshinov, S.M. Bobrovnikov, V.E. Zuev, A.I. Nadeev, and K.D. Shelevoĭ, in: *Abstracts of Reports at the 13 th International Laser Radar Conference*, Toronto, Canada, August 11–15 (1986), p. 189.

4. Yu.F. Arshinov, S.M. Bobrovnikov, S.N. Volkov, V.E. Zuev, and V.K. Shumskiĭ, in: Laser and Optical Remote Sensing, Technical Digest Series **18**, 44 (1987).

5. A. Cohen, J.A. Cooney, and K.N. Geller, Appl. Opt. **15**, No. 11, 2896 (1976).

6. Yu.F. Arshinov and S.M. Bobrovnikov, in: *Abstracts of Reports at the 17th AU-Union Conference on Atmospheric Laser and Acoustic Ranging,* Tomsk (1982), p. 7.

7. G.G. Matvienko, Opt. Atmos. **1**, No. 6, 3 (1988).

8. Yu.F. Arshinov,S.M. Bobrovnokov, S.N. Volkov, V.E. Zuev, and S.M. Shumskiĭ, in: *Abstracts of Reports at the 14th International Laser Radar Conference*, Sec. 2, San Candido, Italy, June 20–22 (1988).