GENERALIZED CHARACTERISTICS OF LIDARS

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The paper presents analytical expressions which could be useful for estimating the efficiency of lidar systems in applications to laser remote sensing of the atmosphere. The quality of a lidar, in this approach, is determined by three generalized parameters.

It is shown, in the paper, that for any concrete lidar system, a single-parameter family of characteristics can be constructed, which allows one to completely describe the capabilities of the lidar system taking into account the influence of background noise.

The applicability of a lidar facility to solve some problem of atmospheric studies is .normally assessed by comparing the anticipated fluctuations of a signal plus noise and mean value of the signal calculated using lidar equation. Such an assessment is aimed at estimating the achievable accuracy of measurements during an acceptable time interval. If one needs to optimize the lidar parameters then there can appear necessity to involve large number of the parameters into the optimization procedure. But, as is shown below, any lidar system can be fully described with three generalized parameters only, if the problem of lidar measurements is formulated using the terms discussed below.

In any problem of lidar sensing of the atmosphere the object for studies is an ensemble of light scattering particles. The scattering properties of such an ensemble, required for lidar sensing, are described with the volume backscattering coefficient β_π.

The conditions for light propagation through the atmosphere to a target at a distance r and back to the lidar are described by the atmospheric transparency $T(r)$ along the path segment $[0, r]$.

It is natural to take sis a generalized target parameter ρ a combination of the foregoing parameters in the form in which they appear in the lidar equation, i.e.,

$$\rho(r,\lambda)=\beta_\pi(r,\lambda)T^2(r,\lambda)/r^2 \tag{1}$$

If scattering takes place at a wavelength λ_1 different from the wavelength of the transmitter, then the product $T(r, \lambda)$, $T(r, \lambda_1)$ must be used in (1) instead of $T^2(r, \lambda)$.

In many problems of lidar sensing of the atmosphere, the target is distributed along the sounding path and information about the spatial distribution of inhomogeneities constitutes a part of the useful information. The smallest detail of this structure discernible with a lidar is determined by the spatial resolution

$$\Delta r=c\Delta\tau/2, \tag{2}$$

where c is the speed of light, and $\Delta\tau$ is the integration time. The minimum integration time is determined by the laser pulse duration. For the detection of weak lidar signals, $\Delta\tau$ is essentially the instrumental integration time, amd is to a certain extent a compromise between the required spatial resolution and the desired measurement accuracy.

The signal measurement error is related to the signal-to-noise ratio ξ. By definition [1],

$$\xi^2=I_m^2/D(I_t), \tag{3}$$

where I_m is the mean signal current in the photodetector, and $D(I_t)$ is the variance of the total detector current, including both signal and noise. It is desirable, and very often the case, that in lidar experiments the mean noise current (or count rate) be measured; this usually take place between laser pulses. The mean signal current is then the difference between the total current and noise current $I_m = I_t - I_n$. The relative error of signal measurements $\delta I_m = (D(I_m))^{1/2}/I_m$ can then be written in terms of measured values as

$$\delta I_m=(D(I_t)+D(I_n))^{1/2}/(I_t-I_n) \tag{4}$$

In photon counting mode, when the signal is accumulated over k laser shots, I_t and I_n are given by $I_t = e\mu N_t/k\Delta\tau_s$, $I_n = e\mu N_n/k\Delta\tau_n$, where N_t and N_n are the number of photocounts obtained during the signal and noise gating times respectively; $\Delta\tau_s$ and $\Delta\tau_n$ are the durations of the signal and noise gates, respectively; μ is the gain of the PMT; e is the electron charge.

Equation (4) then becomes

$$\delta I_m=(D(N_t)/\Delta\tau_s^2+D(N_n)/\Delta\tau_n^2)^{1/2}/(N_t/\Delta\tau_s+N_n/\Delta\tau_n) \tag{5}$$

If one assumes Poisson statistics for the signal and noise fluctuations, and $\Delta\tau_s = \Delta\tau_n$, Eq. (5) is takes the

$$\delta I_m = (N_t + N_n)^{1/2}/(N_t - N_n). \tag{6}$$

One can readily see that for $\xi \gtrsim 1$ (for 4–6), we have the approximate relation $\delta I_m = \xi^{-1}$, and the signal-to-noise ratio describes the accuracy of signal measurements quite adequately.

Signal fluctuation and intrinsic detector noise are usually comparable to or greater than the noise due to extraneous light only under nighttime background conditions. The spectral brightness of the background B_λ must therefore be considered a parameter of an conditions under which the experiment is carried out.

As the last parameter characterizing the measurement process, let us take the sampling rate F. This quantity is the reciprocal of the integration time required to obtain a specified signal-to-noise ratio. This parameter can be convenient for use in assessing the Suitability of a lidar for studies of nonstationary or periodic processes in the atmosphere.

It also can be useful for aquantitative comparison of different lidar systems, since those Ildars are more efficient which provide a higher value of F for given ρ, Δr, ξ, B_λ.

These five quantities provide for a fairly complete characterization of a lidar problem.

An expression derived in Ref. 2 relates lidar and target parameters to the signal-to-noise ratio. This expression may be recast in the form

$$F = 2\ \Delta r\ \xi^{-2}\rho\ K_1[1+B_\lambda\ K_2/\rho + K_3/\rho\ ]^{-1} \tag{7}$$

where F, Δr, ξ, ρ, B_λ are described above, and K_1, K_2, K_3 are the generalized lidar parameters which depend solely on the lidar's components and universal physical constants.

The parameter K_1 in (7) can be called the energy potential of the lidar. It is defined by

$$K_1 = E\ f\ \eta\ S/h\nu(1 + \kappa^{-1}) \tag{8}$$

where E is the energy of the sounding pulse, f is the pulse repetition rate, S is the receiving area of the lidar, η is the total efficiency of the entire optical train, $h\nu$ is the photon energy, and κ is the quantum efficiency of the photodetector. The parameter K_1 determines the data sampling rate F for large values of ρ, provided that

$$B_\lambda K_2/\rho \ll 1; \qquad K_3/\rho \ll 1. \tag{9}$$

The factor K_2, which takes account of extraneous light, is given in terms of the lidar's parameters by

$$K_2 = \Omega\ \Delta\lambda/cE, \tag{10}$$

where Ω is the solid angle of -the lidar receiver directional pattern, $\Delta\lambda$ is the bandwidth of the lidar's optical train, and c is the speed of light. The smaller the value of K_2, the less the measurements are affected by extraneous light.

The factor K_3 takes into account the internal noise of the lidar, and is given by

$$K_3 = h\nu\ n_d/c(\kappa^2 + \kappa)E\ \eta\ S, \tag{11}$$

where n_d is the mean dark-count rate of the photodetector.

Consider the function

$$F'(\rho) = 2\ \rho\ K_1[1+B_\lambda K_2/\rho + K_3/\rho]^{-1}, \tag{12}$$

which is the data-sampling rate required to obtain unity signal-to-noise ratio and 1 m spatial resolution. One can construct, using Eq. (12), a parametric family of curves $F'(\rho,\ B_\lambda)$ which completely describes a lidar system using our newly specified parameters.

Figure 1 presents an example of such a family of $F'(\rho,\ B_\lambda)$ for a lidar system whose parameters are given in the figure caption. For clarity, we have provided an altitude scale corresponding to the generalized target parameter ρ, for which we have assumed a standard molecular atmosphere.

In order to find the data-sampling rate for an atmospheric target with characteristic ρ using a lidar system with generalized parameters K_1, K_2, K_3, one must find $F'(\rho,\ B_\lambda)$ for specified values of ρ and B_λ on the family of characteristics and calculate the quantity

$$F = \Delta r\ \xi^{-2}F'(\rho, B_\lambda). \tag{13}$$

Equations (7)–(12) enable one to clearly reveal the role of one or another parameter of a lidar system operating under extraneous light conditions. Thus, to maintain F constant while decreasing the target parameter, one must first of all increase the generalized system parameter K_1.

It is clear from Eq. (8) which parameters of the system must be improved to accomplish this. Special attention must be paid to the relationship between the mean power of a transmitter and its pulse energy. For any lidar system there exists a range of ρ values, given by (q), for which it is just as efficient to increase the mean power of a beam by increasing the pulse repetition frequency and the increase of pulse energy. To the extent that ρ decreases, however, it is preferable to increase the pulse energy.

The higher the extraneous light level and the larger the value of K_2, the sooner these situations sets in.

It is worth noting that, as follows from Eqs. (8), (10) and (11), the pulse energy is the only parameter of a lidar system whose increase provides for simultaneous improvement in all three generalized parameters, i.e., parameter K_1 increases, while K_2 and K_3 become smaller.

The foregoing is illustrated by the data in Fig. 2 where the characteristic $F'(\rho,\ B_\lambda)$ is calculated for $\rho = 10^{-20}\ \text{m}^{-3}$ (Rayleigh scattering at 80 km altitude). All lidar parameters are the same as in Fig. 1, but the pulse energy and repetition rate are such that the product $E_f = 1$ W remains constant. The upper scale on the figure represents K_2, which varies in concert with E. We see from these data that only at the lowest level of background noise ($B_\lambda = 10^{-6}$ W/m^2 μm sr corresponding to a moonless night) is the data-sampling rate F almost independent of the sounding pulse energy. Thus, for $E = 10^{-3}$ J, F is only 20% lower than for higher energy values.

For higher background levels, the differences become very significant. It can even turn out that a for measurements than one with lower if the first condition of (9) is satisfied for the latter over a larger range of ρ values. A comparison of these two conditions enables one to find the range over which the intrinsic detector noise is dominant.

This noise can be insignificant in lidars with large receiving apertures, even under nighttime conditions, if the quality of the optics used cannot provide for high enough spatial and spectral resolution of the background light.

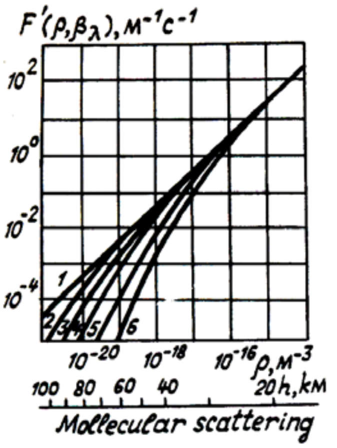

Fig. 1. The data-sampling rate F' at spatial resolution $\Delta r = 1$ m and unity signal-to-noise ratio as a function of ρ and spectral brightness of the background light B_λ for a lidar with parameters $\lambda = 532$ nm, $E = 1$ J, $f = 1$ Hz, $S = 1$ m^2, $\kappa = 0.05$, $\eta = 0.1$, $\Delta\lambda = 1$ nm, $\Omega = 8\times10^{-7}$sr ($\varphi = 1$ mrad), $n_d = 2\times10^2$ sec^{-1}. Generalized parameters of the lidar: $K_1 = 1.36 \times 10^{16}$ m^{2}sec^{-1}, $K_2 = 2.1 \times 10^{-18}$ W^{-1}sr × μm× m^{-1}, $K_3 = 4.7 \times 10^{-23}$ m^{-3}. Curves 1 to 6 are for B_λ values 10^{-6}, 10^{-3}, 10^{-2}, 10^{-1}, 10^0, 10^1 W/m^{2}sr×μm, respectively

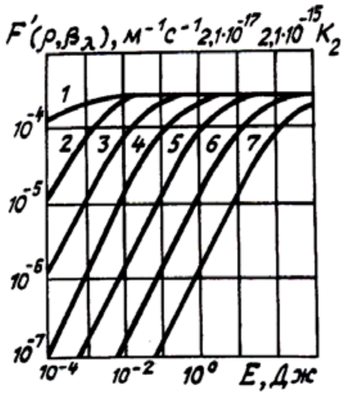

Fig. 2. $F'(\rho, B_\lambda)$ as a function of laser pulse energy at constant average power. Curves 1 to 7 are for B_λ values 10^{-6}, 10^{-5}, 10^{-4}, 10^{-3}, 10^{-2}, 10^{-1}, 10^0 W/m^{2}sr × μm, respectively. K_2 has dimensions sr × μm/W^{-1}m^{-1}. The lidar parameters are the same as in Fig. 1

We note in conclusion that in our opinion the relationships discussed above provide a basis for the simple and convenient evaluation of newly designed lidar systems, as well as for categorizing systems already in routine use.

Of course, these considerations do not deal with the distortions of the lidar signal that can occur in the recording electronics, due, for example, to miscounts. Also we have not analyzed the excess noise in a detector (for example, afterpulsing) produced by detector overloading by optical signals from the near layers of the atmosphere.

These distortions depend on the signal level, and they are therefore not additive noise. It is therefore difficult to describe them in terms of a signal-to-noise ratio. A separate investigation would be required to find an adequate way to take them into account and to assess their influence on measurement accuracy.

REFERENCES

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