

OPTIMIZATION OF THE PHOTOMULTIPLIER OPERATION IN A RAMAN-LIDAR GAS ANALYZER

V.M. Dubyagin

*Institute of Atmospheric Optics,
Siberian Branch of the Russian Academy of Sciences, Tomsk
Received March 27, 1992*

An algorithm for selecting the optimum mode of photomultiplier operation in a Raman-lidar gas analyzer is presented, which provides the minimum error in measuring the gas concentration. Concrete examples demonstrate the implementation of the algorithm for selecting the temperature and supply voltage of the photomultiplier.

Signals of the spontaneous Raman scattering (SRS) are very weak due to the small scattering cross sections and low concentrations of sounded gases.¹ In addition, there are a number of interferences, such as the sky background, laser-induced atmospheric glow,² and dark-current noise of a photomultiplier.³ Therefore, it is natural to increase the quantum efficiency and to decrease the dark current of the photomultiplier. But these parameters are interrelated and improvement in one of them may lead to deterioration of another.^{3,4} In this case an optimum may exist, which depends on the parameters of the photomultiplier, lidar, and conditions of sounding.

This paper suggests optimization against the immediate criterion of quality, namely, the rms error in estimating the gas concentration. Some questions of optimization against the indirect criteria, such as the threshold radiation flux, information content, and signal-to-noise ratio, were studied elsewhere^{5,3,2} and we give no consideration to them here.

Let us consider the conventional lidar configuration^{1,2} with two receiving channels, the first is tuned to the SRS frequency of a sounded gas, the second is tuned to the SRS frequency of nitrogen, and both operate in a photon-counting mode. The interference in the first channel is comparable to the signal and is limited by the sky background and dark current in the case of rational narrowing of the receiving bandwidth and suitable selection of spectral instruments.^{1,2,6} In the second channel the interference is negligible in comparison with the signal which is high due to the high nitrogen concentration M_2 . In each channel the signal is recorded from the sounded distance in the strobe T and between the sounding events in the strobe T_n (see Ref. 2).

In general, the estimated gas concentration has the form⁷

$$\hat{M}_1 = M_2 K \sum_{\mu=1}^N (n_{\mu 1} - \kappa n_{\mu 1}^n) / \sum_{\mu=1}^N (n_{\mu 2} - \kappa n_{\mu 2}^n), \quad (1)$$

where K is the calibration factor, $\kappa = T/T_n$, N is the number of sounding events in the measurement run, $n_{\mu i}$ and $n_{\mu i}^n$ ($i = 1$ and 2) are the numbers of photocounts in the μ th event and i th channel for the strobes T and T_n , respectively. The error of estimate (1) is

$$\delta(\hat{M}_1) = (NT)^{-1/2} [\xi_s \eta(U) + z \xi_{bg} \eta(U) + \xi(U)]^{1/2} / \xi_s \eta(U), \quad (2)$$

where $z = 1 + \kappa$, ξ_s and ξ_{bg} are the mean intensities of photon fluxes of the signal and background at the input of the photomultiplier of the first channel, η is the quantum efficiency, ξ is the intensity of the dark photoelectron flux, U is the generalized parameter of the operating mode of the photomultiplier of the first channel. We may select temperature, supply voltage, external magnetic field, etc. as the parameter U (see Ref. 3). The optimum value U_{opt} is obtained by minimization of Eq. (2).

Let us consider two cases:

(1) U is the temperature.⁸ Let us take³

$$\eta(U) = a_1 U + b_1, \quad \xi(U) = c_1 U^2 \exp(-d_1/U)$$

(the Richardson law), where a_1 , b_1 , c_1 , and d_1 are the coefficients. Then the optimum value U_{opt} is found by solving the equation

$$z c_1 \exp(-d_1/U) [U(a_1 d_1 + 2b_1) + b_1 d_1] - a_1 (a_1 U + b_1) (\xi_s + z \xi_{bg}) = 0. \quad (3)$$

For the known values of η_1 and η_2 and ξ_1 and ξ_2 at the points U_1 and U_2 ($U_1 < U_2$), we derive

$$a_1 = (\eta_2 - \eta_1) / (U_2 - U_1), \quad b_1 = \eta_1 - a_1 U_1, \\ d_1 = [\ln(\xi_2/\xi_1) + 2 \ln(U_1/U_2)] / (U_1^{-1} - U_2^{-1}), \\ c_1 = \xi_1 \exp(d_1/U_1) / U_1^2.$$

For example, for $T = T_n$, $\xi_s = 1.2 \cdot 10^3 \text{ s}^{-1}$, $\xi_{bg} = 0.6 \cdot 10^3 \text{ s}^{-1}$, $\eta_1 = 0.2$, $\eta_2 = 0.25$, $\xi_1 = 50 \text{ s}^{-1}$, and $\xi_2 = 200 \text{ s}^{-1}$ at $U_1 = 253 \text{ K}$ and $U_2 = 293 \text{ K}$ (Ref. 3) we obtain $U_{opt} = 256.3 \text{ K}$.

(2) U is the supply voltage.⁹ Let us take³

$$\eta(U) = a_2 \exp(b_2 U), \quad \xi(U) = c_2 U^2 \exp(-d_2/U),$$

where a_2 , b_2 , c_2 , and d_2 are the coefficients. Then the optimum value U_{opt} is found by solving the equation

$$z c_2 \exp(-d_2/U) [2U(1 - b_2 U) + d_2] - a_2 b_2 \exp(b_2 U) (\xi_s + z \xi_{bg}) = 0. \quad (4)$$

For the known values of η_1 and η_2 and ξ_1 and ξ_2 at the points U_1 and U_2 ($U_1 < U_2$) we derive

$$b_2 = \ln(\eta_2/\eta_1)/(U_2 - U_1), \quad a_2 = \eta_1 \exp(-b_2 U_1),$$

d_2 is analogous to d_1 , c_2 is analogous to c_1 (with d_2 instead of d_1).

For example, for $T = T_n$, $\xi_s = 1.2 \cdot 10^4 \text{ s}^{-1}$, $\xi_{bg} = 0.6 \cdot 10^4 \text{ s}^{-1}$, $\eta_1 = 0.2$, $\eta_2 = 0.25$, $\xi_1 = 10 \text{ s}^{-1}$, $\xi_2 = 10^4 \text{ s}^{-1}$, $U_1 = 1.5 \cdot 10^3 \text{ V}$, and $U_2 = 2 \cdot 10^3 \text{ V}$ (Ref. 3) we obtain $U_{opt} = 1621 \text{ V}$.

It should be noted that U_{opt} can be selected against the criterion of the signal-to-noise ratio, as it was done in Ref. 10 in which the optimum voltage of the FÉU-79 and FÉU-84 photomultipliers was determined through the maximum ratio of the count rate of valid pulses to the dark ones. However, the error in measuring the gas concentration may not reach its maximum in this case.

Thus, the criterion and algorithm suggested to optimize the photomultiplier operation enable us to increase the accuracy of the lidar gas-analyzer and to select the most suitable type and specimen of the photomultiplier and its necessary operating mode.

The author would like to acknowledge Dr. S.A. Danichkin for the idea of the paper and Dr. G.N. Glazov for his help.

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