

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

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*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.<sup>1</sup> In addition, there are a number of interferences, such as the sky background, laser-induced atmospheric glow,<sup>2</sup> and dark-current noise of a photomultiplier.<sup>3</sup> 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.<sup>3,4</sup> 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<sup>5,3,2</sup> and we give no consideration to them here.

Let us consider the conventional lidar configuration<sup>1,2</sup> 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.<sup>1,2,6</sup> 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 form<sup>7</sup>

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

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  $\mu$ 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  $z = 1 + \kappa$ ,  $\xi_s$  and  $\xi_{bg}$  are the mean intensities of photon fluxes of the signal and background at the input of the photomultiplier of the first channel,  $\eta$  is the quantum efficiency,  $\xi$  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.<sup>8</sup> Let us take<sup>3</sup>

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

(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  $\eta_1$  and  $\eta_2$  and  $\xi_1$  and  $\xi_2$  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.<sup>9</sup> Let us take<sup>3</sup>

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

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  $\eta_1$  and  $\eta_2$  and  $\xi_1$  and  $\xi_2$  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.

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