CORRECTION OF LIDAR SIGNALS FOR PHOTOMULTIPLIER AFTERPULSING NOISE

B.V. Kaul', O.A. Krasnov, and A.L. Kuznetsov

Institute of Atmospheric Optics,
Siberian Branch of the Academy of Sciences of the USSR, Tomsk
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The parameters of the excess noise produced in an FÉU-130 photomultiplier by the electron stream striking its elements were measured. It is shown that this noise, called afterpulsing, must be taken into account when processing lidar signals.

Noise in photomultipliers caused by thermal emission as well as by the interaction of the dark and signal currents with the residual gases and structural elements.[1] In a photomultiplier operating in the photon-counting mode the latter noise, called afterpulsing noise, is manifested in the form of pulses which are identical to the photoelectron pulses. The moment τ at which an afterpulse appears, measured from the moment at which the primary pulse passes, is a random quantity and is described by some probability distribution function:

$$\varphi(\tau) = P\psi(\tau), \tag{1}$$

where P is the probability that an afterpulse appears and the function $\psi(\tau)$ is normalized by the condition

$$\int\limits_0^\infty \psi(\tau)d\tau = 1 \tag{2}$$

If the flux of photoelectron pulses is described by the function $f(t)$, then the reaction to this flux $F(t)$ is described by the following equation:

$$F(t) = f(t) + P\int\limits_0^t F(t - \tau)\psi(\tau)d\tau \tag{3}$$

In lidar signals, whose dynamic range is large, the distortions caused by afterpulsing can play a significant role. This was already pointed out in Refs. 2 and 3. In Ref. 4 the characteristics of the afterpulsing of one type of photomultiplier (RCA 8852) were studied and it was shown by a computational method that in the case of vertical sounding the signal is equal to the slow afterpulsing component at an altitude of about 30 km and that above this altitude the afterpulsing noise is stronger than the signal. This example convincingly demonstrates the importance of correcting signals for afterpulsing when sounding the upper layers of the atmosphere. This is also true for sounding at short distances, where the signal has a large dynamic range over a time Interval that is comparable to the characteristic time of the strong fast afterpulse component.

To make the correction it is necessary to know the probability distribution for the appearance of afterpulsing. This distribution is determined by Eq. (1). Since it is not supplied as part of the specifications of the photomultiplier, it must be estimated experimentally for each photomultiplier used in the lidar.

We describe below a simple method for estimating the afterpulsing characteristics of detectors used in a lidar intended for sounding stratospheric aerosols and for investigating the polarization of backscattered radiation[5]. The detectors and the recording apparatus of the Ildar operate in the photon-counting mode. The counter speed is characterized by the maximum counting rate for a periodic sequence of pulses and is equal to 25 MHz. The minimum sample time (strobe pulsewldth) is equal to 40 ns. The delay in activating the counter relative to the starting pulse can be regulated from 0 to 100 μs.

Afterpulsing of the photomultiplier was studied directly on the measuring system of the Ildar. For this, the optical channel of the lidar was illuminated with a short (300 ns) pulse of light from a 1ight-emitting diode. By regulating the current pulse and introducing optical attenuation we were able to set the intensity of the light flux so that the light flux was recorded by the apparatus as a sequence of single-electron pulses arriving at an average rate of 1 MHz. This made it possible to neglect the misses which arise owing to the finite time resolution of the photon counter. The current-pulse generator, powering the light-emitting diode, and the photon counter were triggered by the same starting pulse. The delay in triggering the counter was set to zero. The source photons were recorded in the first four strobe pulses, each pulse being 80 ns wide. In subsequent strobe pulses the dark current pulses and excess noise pulses due to afterpulsing were recorded. The total duration of the strobe pulses was equal to 128 μs. The further analysis showed that within this time interval the rate of arrival of the afterpulses decreases to a value comparable to the rate of arrival of the dark pulses, which

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was of the order of $2 \cdot 10^2$ pulses/s for the two FÉU-130 photomultipliers investigated. To obtain statistically well-founded readings during each strobe pulse and especially during the last pulses, counts were accumulated for 10^5 flashes of the 1ight-emitting diode. The magnitude of the expected dark-current pulses $\Delta N_{d,i}$

$$\Delta N_{d,i} = \bar{n}_d \cdot m \cdot \Delta t_i ,$$

where $\bar{n}_d$ is the average rate of arrival of the dark pulses, m is the number of flashes of the light-emitting diode, and Δt_i is the width of the ith strobe pulse, was subtracted from the N_i counts obtained in the ith strobe pulse.

A problem arises in connection with the finite lifetime of the electron-hole pairs in the light-emitting diode. For this reason, sometime after the current pulse terminates relaxational recombination of non-equilibrium charge carriers accompanied by photon emission occurs. To take this factor into account, the characteristic relaxation time θ was estimated based on the trailing edge of a quite strong light pulse, such that the pulse could be observed on an oscilloscope. It was found that θ = 50 ns. When the results were analyzed the computed value of the expected illumination was subtracted from the counts of the ith strobe pulse

$$\Delta N_{i,i} = N_0 \Delta t_i \exp(-t_i/\theta)/\Delta t_0 ,$$

where N_0 is the number of photocounts accumulated in the first four strobe pulses (the strobe pulse regulating the Illumination), Δt_i is the width of the ith strobe pulse, and t_i is the position of the ith strobe pulse on the time axis. The effect of relaxational deexcitation becomes negligible within a time less than 1 μm.

The further processing of the results starts with a series of corrected counts

$$N'_i = N_i - \Delta N_{d,i} - \Delta N_{i,i} .$$

This series is a discrete representation of the function $F(t)$, appearing in Eq. (3), which is solved by means of successive approximations. For the zeroth-order approximation we take

$$P = \sum_{i=5}^{n} N'_i / \sum_{i=1}^{4} N'_i ; \quad \psi_j = N'_j / \Delta t_j \sum_{j=1}^{n-4} N'_j ,$$

where $j = i - 4$.

The computed series of values of the probability density for the two FÉU-130 photomultipliers studied can be approximated well by a sum of two exponentials:

$$\varphi\tau = P\left[c_1 \exp(-\tau/\tau_1) + c_2 \exp(-\tau/\tau_2)\right]$$

with the following parameters: $P = 0.052$, $c_1 = 0.48$ μs^{-1}, $\tau_1 = 1.49$ μs, $c_2 = 5.9 \cdot 10^{-3}$ μs^{-1}, and $\tau_2 = 51$ μs.

Our data qualitatively agree with the results of Ref. 4 from the standpoint that the fast and slow components of the afterpulsing noise can be separated. The characteristic decay times are different from the values given in Ref. 4. Thus, for the slow component we obtained $\tau_2 = 51$ μs, while in Ref. 4 $\tau_2 = 60$ μs. The total probabilities for the appearance of an afterpulse for the two photomultipliers studied were virtually identical (0.050 and 0.053). The rapidly decaying component includes about 70% of all afterpulses ($\tau_2 = 1.49$ μm). For sounding high layers of the atmosphere, when the width of the spatial probe is much greater than $c\tau_1/2$, and the dynamic range of the signal in two neighboring strobe pulses is small, the effect of the fast component is insignificant. It consists of the fact that the excess noise, which is proportional to the signal itself with a coefficient of proportionality of about 0.04, is added to the signal. The slow component significantly affects the accuracy of the measurement of signals returning from high altitudes and requires, in accordance with Eq. (3), that the measured flux $F(t)$ be corrected in order to estimate its true value $f(t)$. Neglecting the afterpulsing factor can result in errors equal to tens of percent.

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