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Signal-Induced Noise Effects in a Photon Counting System For Stratospheric Ozone Measurement

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Introduction

One very sensitive method of optical signal detection is called photon counting. Light falls on the photosensitive cathode of a photomultiplier tube (PMT), creating electrons that are multiplied through a dynode chain, resulting in an output pulse at the anode. Ideally, each photon received produces an electrical pulse at the anode of the PMT that is then sent through an amplifier and into a pulse discriminator. The discriminator has a set output pulse width and threshold setting. The threshold is set just above the noise level in the system; therefore only pulses above this level are counted. Each pulse sent by the discriminator has an equal pulse width and height set by the discriminator. These pulses are sent to a multi-channel scaler and averaging memory that counts the number of pulses received from the discriminator and stores them in typically one-microsecond bins (see fig. 1). The main advantages of photon counting are (1) more sensitive detection of very low light levels that do not produce analog signals and (2) elimination of electronic baseline effects. If the noise and light signal are properly distinguished, low light levels (single photon counts) can be detected.

In a typical DIAL (Differential Absorption Lidar) system, two laser pulses, separated in time, are emitted by the laser system. These pulses, one tuned to high ozone absorption (on-line) and the other tuned to a lower absorption (off-line), are backscattered by the atmosphere, creating a return light signal. This signal is received by a telescope, passed through a narrow band filter, and focused onto a photomultiplier detector. When ozone is present in the atmosphere, the on-line signal decay is faster than that of the off-line due to the absorption by ozone. The difference in the on-line and off-line decay rates of the returned signal yields the number density, n, of ozone as a function of altitude, shown in equation (1)

$$n = \frac{1}{2 \cdot \Delta\sigma \cdot \Delta R} \cdot \ln\left[\frac{P_{\text{off}}(R_2) \cdot P_{\text{on}}(R_1)}{P_{\text{off}}(R_1) \cdot P_{\text{on}}(R_2)}\right] \quad (1)$$

where $\Delta\sigma$ is the difference of on-line and off-line cross-sections, $\Delta R = (R_2 - R_1)$ is the range cell, and $P(R)$ are the powers of the on-line and off-line signals at altitude R (ref. 1).

It is usually assumed that the signal output of a PMT is linearly proportional to the input light intensity and that when no light is present there is only a small DC electrical output, known as dark current. While this is a good assumption for low light levels, the PMT output is nonlinear for high input light intensities. Also, when the PMT is exposed to momentary high light intensities, the output does not return to the dark current level immediately but instead decays slowly. The latter effect is called signal-induced noise (SIN), which can limit the range and accuracy of ozone measurements in a DIAL system unless it is compensated for in the data analysis.

Grant et al. (ref. 2) have noted that the airborne UV DIAL data are systematically lower than those of other instruments at higher altitudes. This discrepancy could be caused by signal-induced noise, which would tend to measure less ozone.

In this technical memorandum we will describe the effects of signal-induced noise on a stratospheric ozone photon counting system. The nature of SIN will be evaluated with respect to PMT type, voltage, incident wavelength, and incident intensity. These results have provided for a greater understanding of this problem and should lead to an approach for eventually neutralizing this effect.

The Effect of Signal-Induced Noise

SIN is a common effect resulting when a PMT is saturated, for a brief moment, with a high intensity light pulse. The effect is shown schematically in figure 2. After the laser pulse is sent into the atmosphere, a very large light return, from either the near field atmosphere or a cloud, causes the PMT to momentarily saturate. When the PMT gate is turned on, the far field light return from the atmosphere is observed, but when the gate is turned off, no signal is seen at the anode. This signal is distorted because of the addition of SIN to the received light signal, causing a slower than expected decay of the atmospheric signal return. The true signal return and SIN cannot be separated because they are both derived from the same laser pulse. The large number of electrons emitted from the photocathode during saturation appear to charge up some internal components, which then emit electrons very slowly, resulting in a long-decay SIN signal. The temporal characteristics of SIN typically follow those of decaying exponentials (refs. 3–6). If SIN is present, its decaying exponential baseline is added to the real lidar return signal, resulting in a longer signal decay than expected. This effect can cause large errors in DIAL measurements, particularly in the far field. For example, unless measured without a lidar return present, the unknown baseline cannot be subtracted from returned light signals. This can lead to unrealistic negative ozone measurements because the decay rate of the on-line signal may be slower than the decay rate of the off-line signal. Also, when the lidar is pointed in the zenith, the returned atmospheric light signal from high altitudes is extremely low. When the returned light level is low enough, the signal cannot be distinguished from the SIN; therefore the overall measurement range of the lidar system is limited. Electrical gating of the PMT has been shown to reduce SIN but not eliminate it (ref. 4).

Since electrical gating of the PMT does not eliminate SIN, other methods of reduction and/or removal of the effect are necessary. Mechanically shielding the PMT with a chopper fan while the gate is off would seem to be the most effective way of eliminating SIN. The chopper needs to close for a few tens of microseconds to protect the PMT from the near field return from the on-line laser, open for typically 270 μsec (~40 km) to allow the lidar return from the on-line laser pulse to be detected, and repeat this process for the off-line laser pulse. This fast timing requires a very fast and stable chopper, which is difficult to implement because most choppers have a low stability. Another method would be to model the SIN response and try subtracting this from the lidar returns mathematically (refs. 3–6). This method has been shown to improve DIAL measurements, but it increases the complexity of the data analysis.

One way to see the effect of SIN is to range-correct the lidar return light signal and compare it to the standard molecular density profile of the atmosphere. The light backscattered from each cubic centimeter of atmosphere at a given altitude should directly follow the atmospheric density. Range-correction of a returned signal is done by mathematically compensating for the $1/R^2$ geometric decrease in collected backscattered signal with range and correcting for the atmospheric attenuation between the lidar and scattering range. The atmospheric attenuation results from aerosol scattering, Rayleigh scattering, and absorption at a given wavelength, which can be summed into a total extinction coefficient over a given optical depth. These total extinction coefficients have been estimated at many wavelengths by Elterman (ref. 7). The total range-corrected signal is then given by equation (2):

$$S(R)_A \cdot C = \frac{P(R)_A \cdot R^2}{\exp(-2 \times OD)} \qquad (2)$$

where $P(R)_A$ is the power of the received signal from altitude R, OD is the optical depth (ref. 7), $S(R)_A$ is the atmospheric backscattering coefficient (which at high altitudes is primarily molecular scattering), and C is a system constant.

Ideally, the corrected $S(R)_A$ signal should follow the decaying molecular density profile as a function of increasing altitude. If SIN is present or if the background is not properly subtracted from the return light signal, then the range-corrected signal will not follow the molecular density. Instead, at higher altitudes where the return signal is low, the SIN will cause the range-corrected signal to grow, as shown in figure 3.

The photon counting data in figure 3 resulted from a 20-minute measurement period performed at night. The measured background was negligible. The laser wavelength was 300 nm, and the receiver telescope was a 14 inch Cassegrian type. The laser beam was emitted from the system to the atmosphere along the outer edge of the lidar telescope. This configuration caused a large near field return to be seen by the telescope, enhancing the SIN effect. In this figure, the lidar return follows the molecular density to a range of 19.5 km where SIN dominates over the lidar return, causing the signal to depart from the atmospheric density. Below 19.5 km, the signal-to-noise ratio is high and the lidar return follows the molecular density. Above 19.5 km, the signal-to-noise ratio is low due to the fact that the actual lidar return signal follows the molecular density but the SIN does not. SIN was found to follow a much slower decay with time.

Experimental Setup

In order to understand the basic characteristic of SIN, an experiment was devised to determine the effect of PMT tube type, voltage, incident light wavelength, and incident light intensity on SIN. A pulsed light source would be used to saturate the PMT, and at some later time, the PMT gate would be turned on. The resulting SIN was measured with a two-minute accumulation period. In each case the pulse width and threshold of the discriminator were set at 5 ns and 30 mV, respectively.

Two different light sources were used to study the SIN-PMT response. The first light source for the experimental setup, shown in figure 4, was a 1000 W-xenon lamp with an adjustable current power supply. A 57 mm condenser lens, placed in the lamp housing's optical axis, allowed beam-focusing adjustments. The light was directed into a high intensity grating monochrometer that was adjustable from 180 to 800 nm. Adjustable slits on the input and output sides of the monochrometer allowed control of light intensity. The complete light source was attached to a "light" box that blocks out all unwanted light. The second experimental setup used a blue LED with a center wavelength at 470 nm, as shown in figure 5.

The light from either the LED or the Xe lamp was passed through a small aperture that was placed close to a chopper fan. The aperture hole and the two chopper fan slits were each approximately 2 mm in width. By using a chopper, it could be assured that no light fell on the PMT when the PMT gate was turned on. Neutral density filters were used to vary intensities of the incoming light pulses. The fiber-optic cable that joined the two light boxes was a 1 mm diameter UV grade quartz fiber. The PMT was mounted in the second light box, where the output of the fiber was placed near the PMT photocathode.

The entire photon counting system was triggered from a synchronization pulse coming from the chopper fan controller. The chopper fan rotated at 50 Hz providing a 100 Hz pulse rate from the two fan slits. The count rates were set to be 10, 1, and 0.1 times saturation by using corresponding neutral density filters. The saturation points for these tubes were experimentally determined by increasing the input light intensity while monitoring the PMT output. The saturation level was defined at the intensity level where the PMT output was no longer increasing linearly with the input light.

Signal-induced noise effects were studied for several PMT with similar physical structures. All the tubes used were linear focused with a 12 dynode chain. The characteristics of each tube are summarized in table 1. The 9214Q tubes are used in the ozone DIAL system because of their high quantum efficiency in the UV range and stable gain versus changing pulse rate. The 9954Q and 9817Q tubes were used for a comparison because of their similar physical structures with different photocathode and dynode chain materials.

Experimental Results

With saturating light pulses, we observed SIN responses that followed a combination of decaying exponentials over a 550 μsec observation time. The SIN effect was observed at different wavelengths, different PMT voltages, and different count rates (intensities). SIN response was also compared for three different tube types. The results are summarized as follows:

Table 1. PMT Tube Characteristics

PMT manufacturer-type-serial #	Photo-cathode material	Quantum efficiency @ 300 nm (%)	Dynode chain material	PMT voltage
EMI-9214Q, #5162	Bialkali Sb-K-Cs	25.2	CsSb	1200
EMI-9214Q, #5150	Bialkali Sb-K-Cs	31.5	CsSb	1200
EMI-9954Q, #5358	Bialkali Sb-K-Cs	26	BeCu	1800
EMI-9817Q, #3236	S20 Trialkali Na-K-Sb-Cs	23.2	BeCu	1850

A. Light Wavelength Effect on SIN

Figure 6 shows the first 50 μsec of the SIN PMT response for tube 9214Q #5162 at input light wavelengths of 300, 350, and 400 nm. The input light intensity was kept constant at 10 times saturation level. For all wavelengths of light, the time constant of the SIN effect was 35 μsec, as shown by the straight line in figure 6. This indicates that wavelength is not a major driver for SIN as long as the photocathode electron emission intensity is constant. SIN appears to be more a function of the number of electrons emitted from the photocathode. A higher quantum efficiency PMT would emit more electrons, resulting in a greater SIN effect.

B. SIN and PMT Voltage

Figure 7 shows the SIN PMT response at different PMT dynode chain voltages for tube 9214Q #5162. Once again the intensity was kept constant for each voltage. The amplitude of the SIN did increase as PMT voltage increased. This was expected due to the higher gain of the PMT at higher dynode chain voltages. The time constant differed by only 2 μsec for a PMT voltage range of 200 volts, which indicates that only the amplitude of SIN, and not the decay rate, is affected by changing PMT voltage.

C. Input Light Intensity and SIN

SIN response for the PMT 9214Q #5150 at three different 300 nm wavelength light intensities is shown in figure 8. The light intensities were 0.1, 1, and 10 times saturation level of the PMT. The response shows that SIN is a combination of three different decaying exponentials, with decay constants of 34 μsec, 49 μsec, and 525 μsec. This suggests that there are three different mechanisms causing SIN for this PMT. The third component of the 0.1 saturation level cannot be seen because it has already decayed into the dark count level of the PMT. The amplitude of the SIN increased linearly with increasing light intensity, but the decay constants at each intensity remained the same. This shows that the amplitude of SIN is affected by different light intensities, but the temporal behavior remains unchanged.

D. Different PMT Types and SIN

SIN response for three different PMT (9214Q, 9817Q, and 9954Q) with similar physical structures is shown in figure 9. The light intensity was set to 10 times saturation for each tube. The decay constants for the initial fast component and the slowest third component are similar in each tube. This indicates that tubes with similar physical structures should exhibit similar SIN responses. With a different PMT structure we would expect different SIN decay time constants.

Conclusions

Photon counting offers an extremely sensitive detection method for measuring stratospheric ozone with a DIAL system. However, the range of the system using this technique can be limited by signal-induced noise effects caused by high intensity near field or cloud returns.

This technical memorandum has characterized SIN responses to varying parameters of the incident light on the PMT. These varied parameters included incident wavelength, PMT voltage, incident intensity, and tube type. It was found that only the amplitude of the SIN and not the decay time constant was affected by varying PMT voltages and light intensities. The amplitude increased linearly as input light intensity increased. Different incident wavelengths at the same intensity did not affect the amplitude or the temporal behavior of the SIN response. Finally, different PMT with similar physical structures exhibited similar SIN responses, although with different amplitudes. The different amplitudes can be attributed to the different gains and operating voltages of each tube.

These results suggest that SIN is caused by photocathode electron dynamics such as charge accumulation on internal PMT surfaces. These surfaces then emit the electrons slowly, resulting in a long decay noise signal. With the SIN responses characterized, a method to reduce or eliminate SIN in DIAL systems can now be developed.

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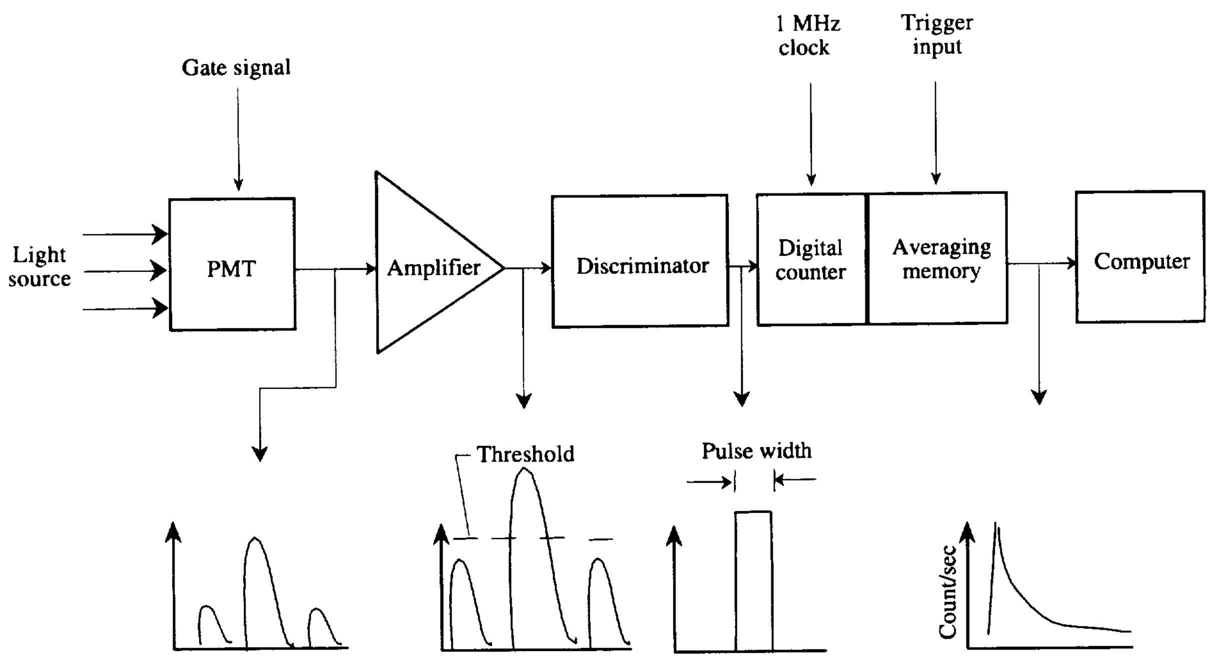
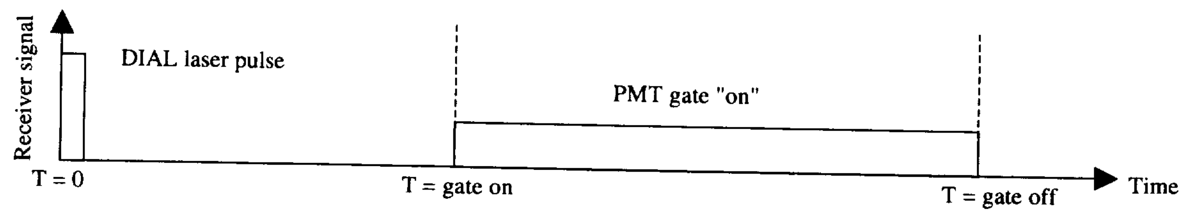
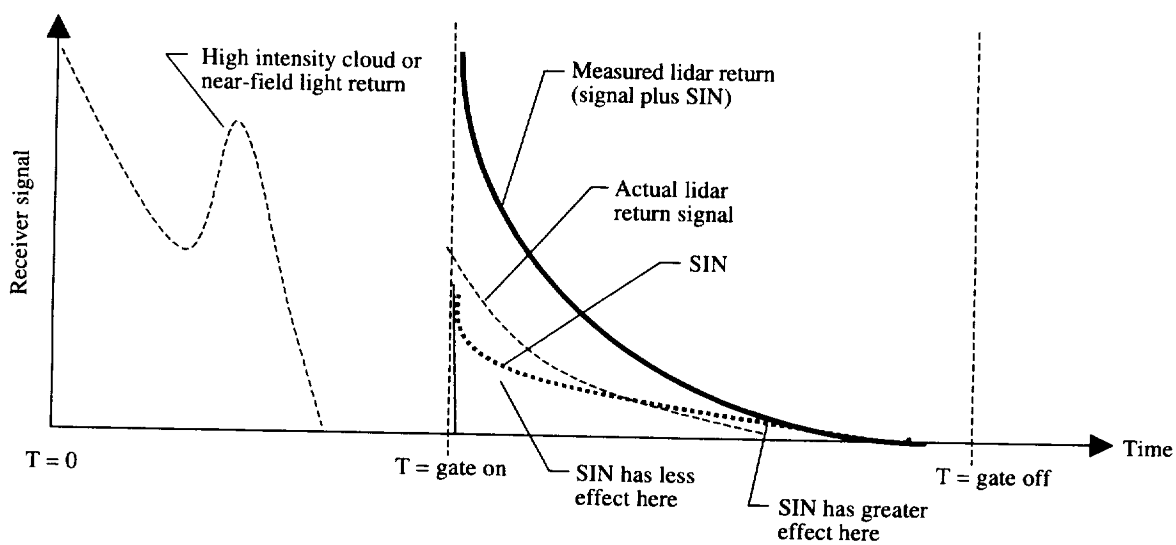


Figure 1. Block diagram of photon counting system.



(a) Laser pulse and PMT gate timing.



(b) Measured lidar return showing SIN effect caused by high intensity light falling on PMT while PMT is gated off.

Figure 2. Typical PMT timing showing SIN response.

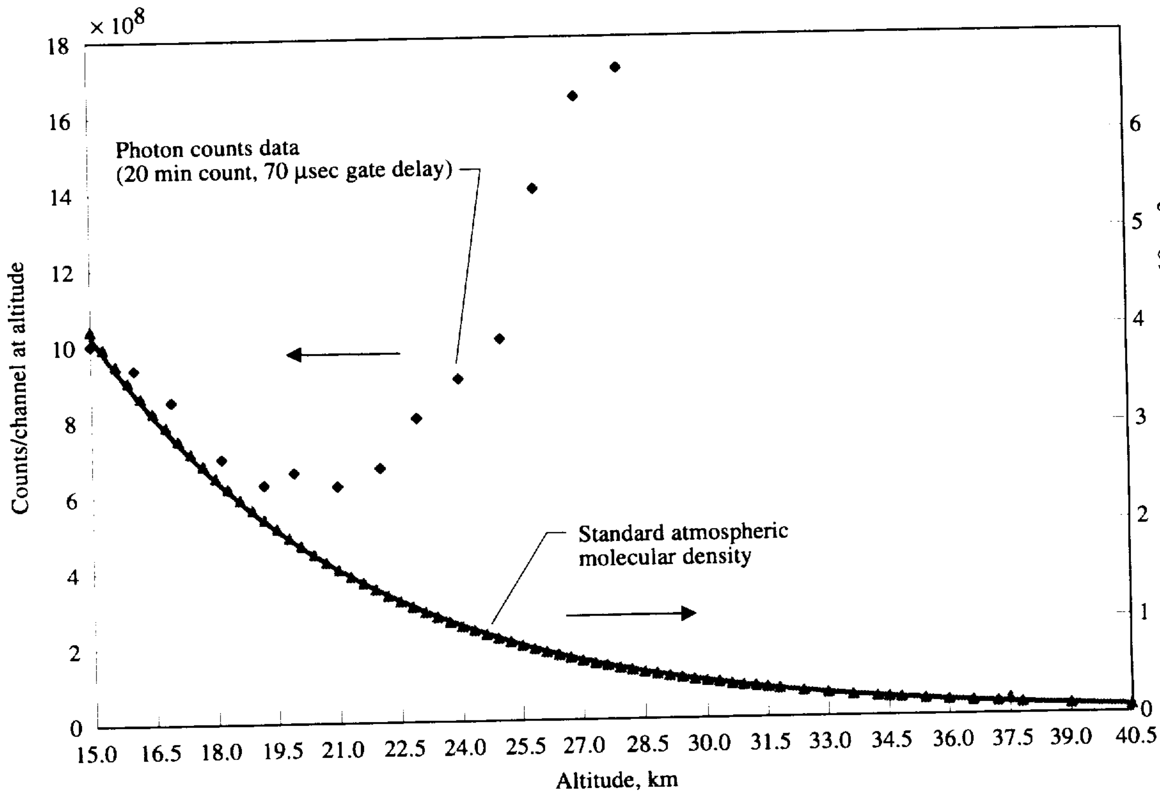


Figure 3. Range-corrected photon counts and atmospheric molecular density vs. altitude.

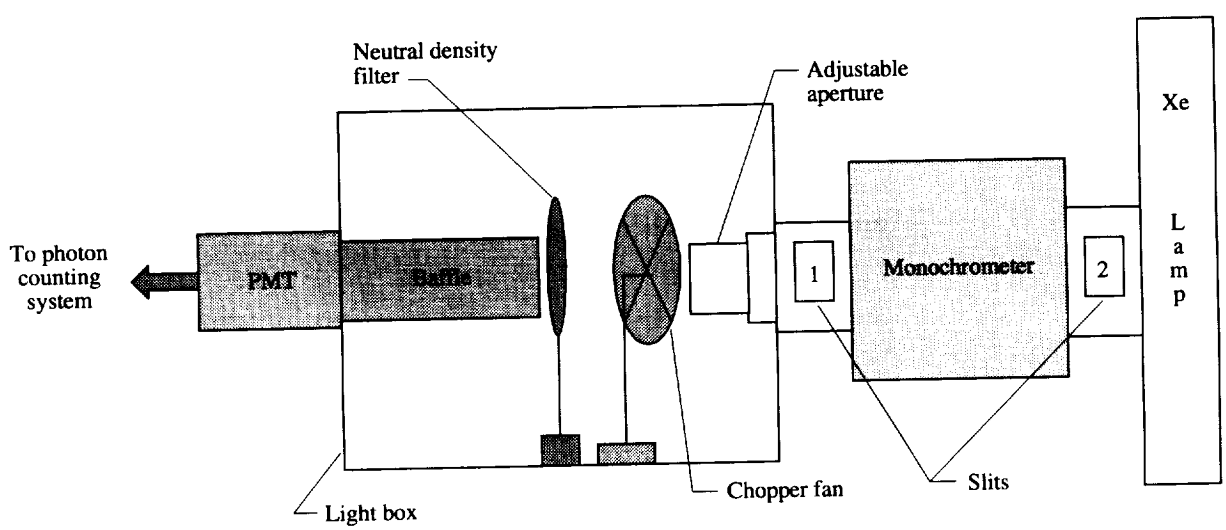


Figure 4. Experimental setup.

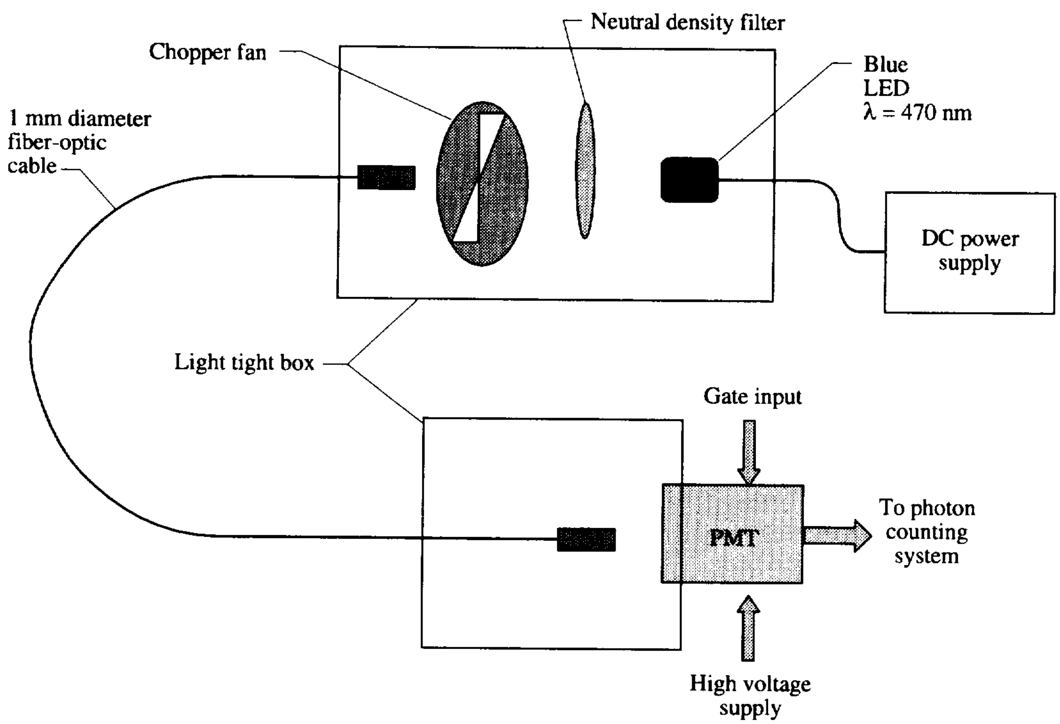


Figure 5. Experimental setup for intensity SIN measurements.

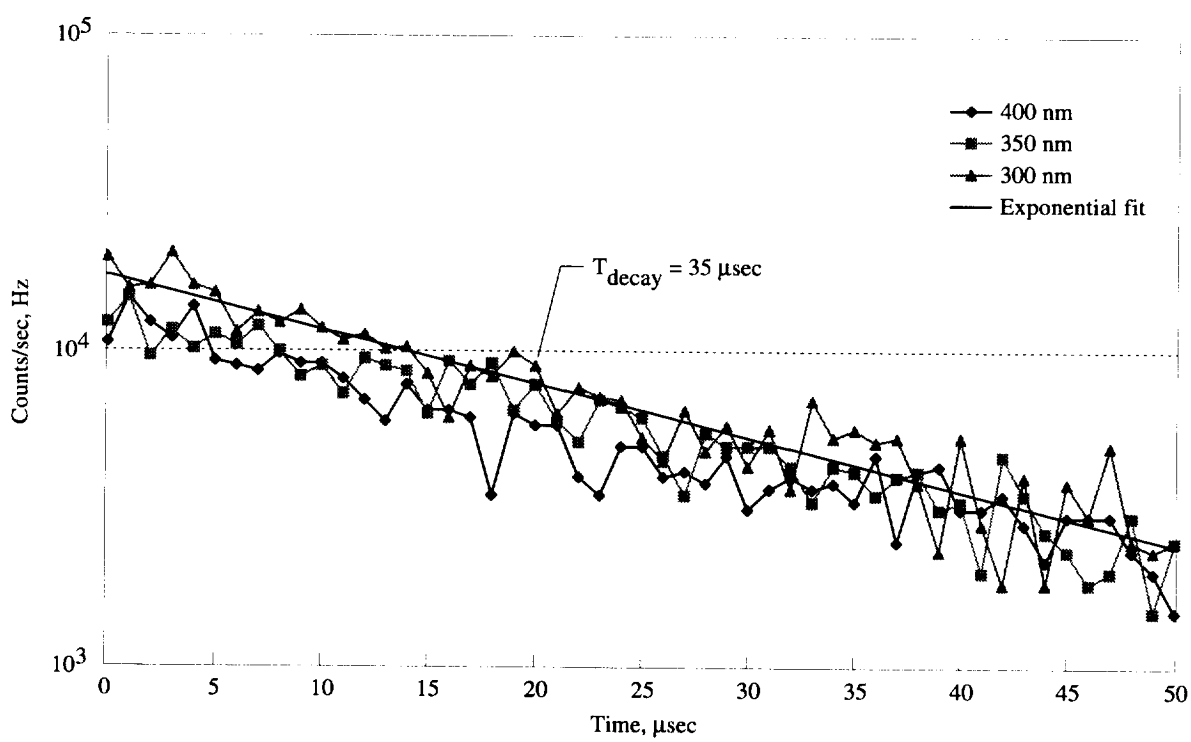


Figure 6. Signal-induced noise at different wavelengths with same count rate (10 × saturation) for PMT (EMI-9214Q, #5162).

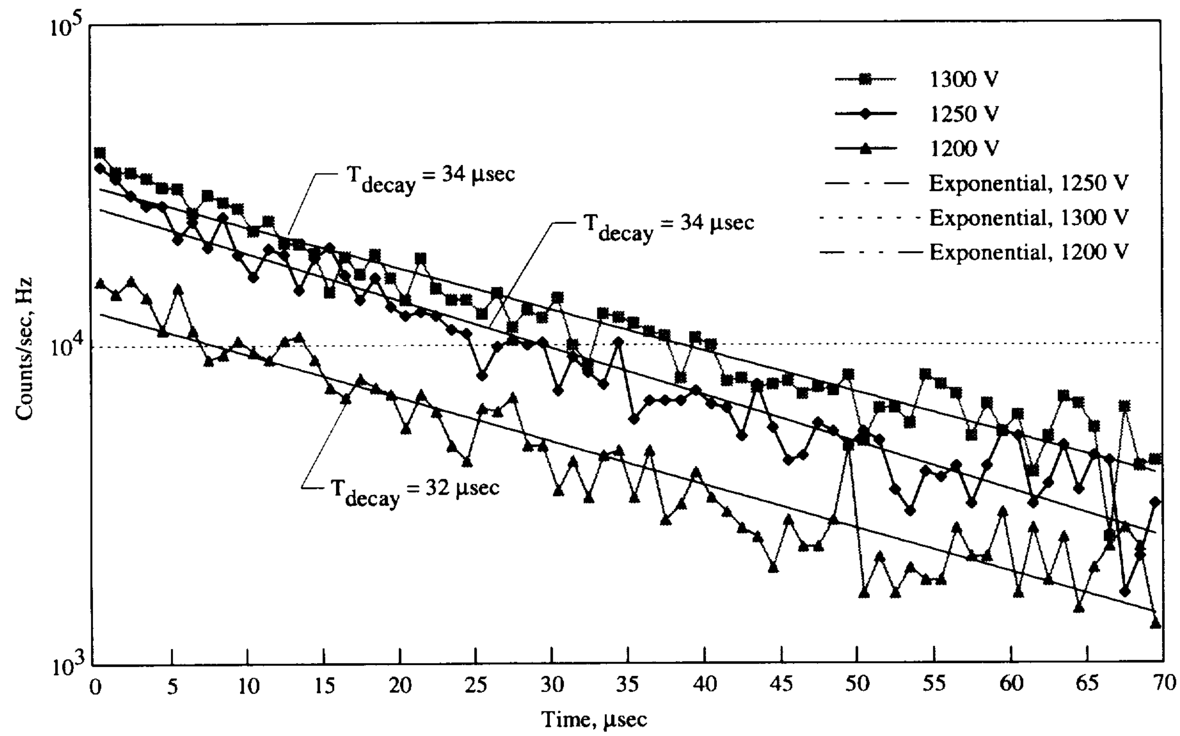


Figure 7. Signal-induced noise for different PMT voltages using PMT (EMI-9214Q, #5162).

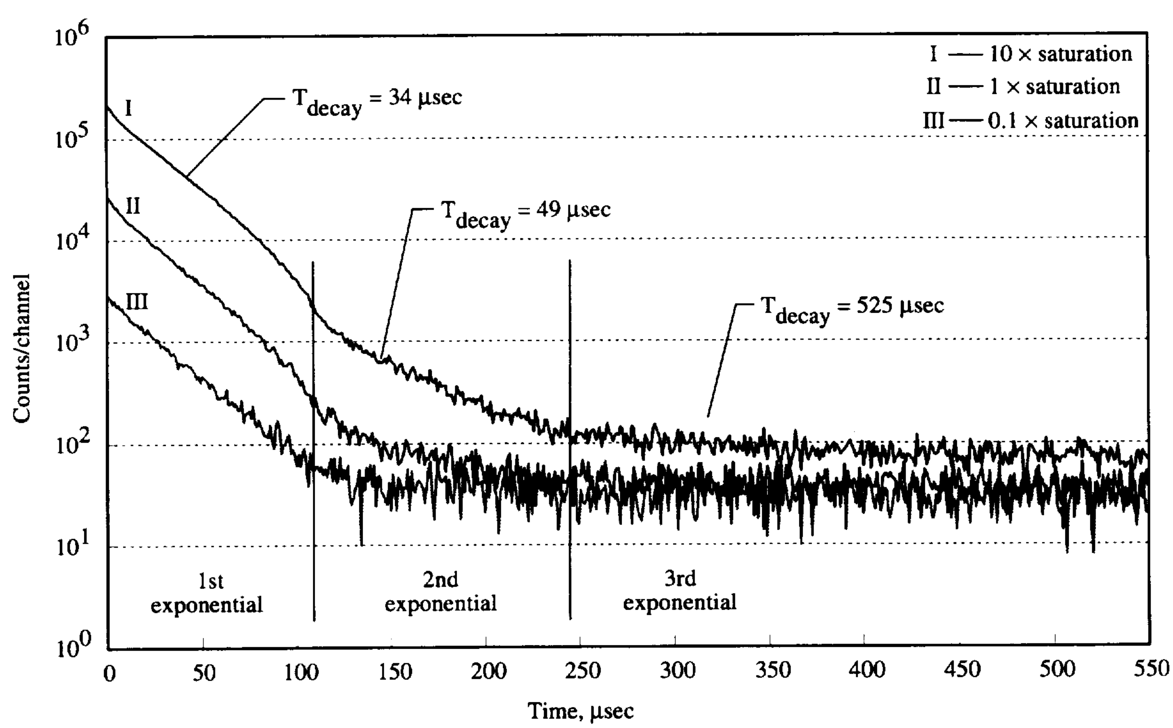


Figure 8. SIN response at different light intensities (defined as factor times saturation level) for PMT tube 9214Q, #5150.

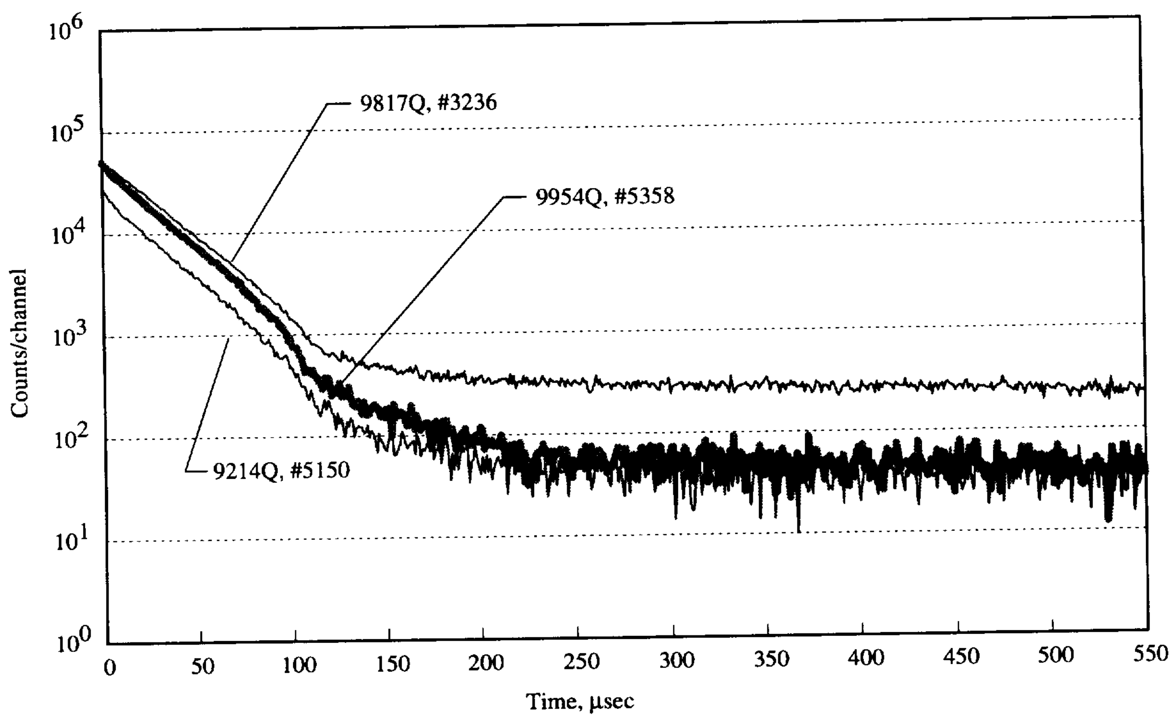


Figure 9. SIN response for three different PMTs.

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13. ABSTRACT *(Maximum 200 words)*
A significant source of error in making atmospheric differential absorption lidar ozone measurements is the saturation of the photomultiplier tube by the strong, near field light return. Some time after the near field light signal is gone, the photomultiplier tube gate is opened and a noise signal, called signal-induced noise, is observed. Research reported here gives experimental results from measurement of photomultiplier signal-induced noise. Results show that signal-induced noise has several decaying exponential signals, suggesting that electrons are slowly emitted from different surfaces internal to the photomultiplier tube.

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