ORTEC®

AN51
APPLICATION NOTE
Revision 1

Pulse-Processing Electronics for Single-Photon Counting
with Counting Rates from 10 to 10^7 Counts/Second

Summary

Single-photon counting is a powerful measurement tool for quantitative measurements with low-intensity light sources. It provides excellent linearity and precision over a dynamic range of 100,000:1. This application note describes the instrumentation and methods suitable for single-photon counting with both steady-state and time-variant light sources. Simple explanations of how the systems work are provided along with a summary of the precision available under extreme operating conditions. Examples are provided for DIAL, LIDAR, Raman Spectroscopy, and Phosphorescence Decay applications.

Function and Purpose

Single-photon counting is a productive technique for measuring the intensity of light when the signal is weak. By using a fast photomultiplier tube to detect the light and equally fast electronics to process the signal, the arrival of individual photons can be detected and counted. Photon resolving times of the order of 10 ns accommodate counting rates ranging from a few counts per second up to 10^6 counts/s with less than 1% nonlinearity in the response to the photon rate. This is a dynamic range in excess of 10^5:1. The technique can be applied to steady-state signals, or to sources whose intensity varies as a function of time. In the latter case, the time scale of interest can range from nanoseconds to months.

The purpose of this application note is to provide a brief introduction to the techniques and instrumentation that are productive for single-photon counting.

Simply Counting Single-Photon Pulses

The counter/timer option in Figure 1 offers a simple system for counting single photons. This configuration is appropriate when the light intensity is constant during the measurement period and the photon counting rate from the signal is large compared to the counting rate from the noise generated within the photomultiplier tube (PMT). This system also provides a simple framework for describing the basic functions in single-photon counting.

The photomultiplier tube detects a single photon when the photon transfers all of its energy to an electron in the photocathode, causing the electron to be ejected from the cathode. The electron is accelerated towards the first dynode of the PMT by the applied bias voltage (Fig. 2). When the electron strikes the first dynode, it knocks out several secondary electrons, and these secondary electrons are accelerated towards the next dynode. This process of amplification is repeated at

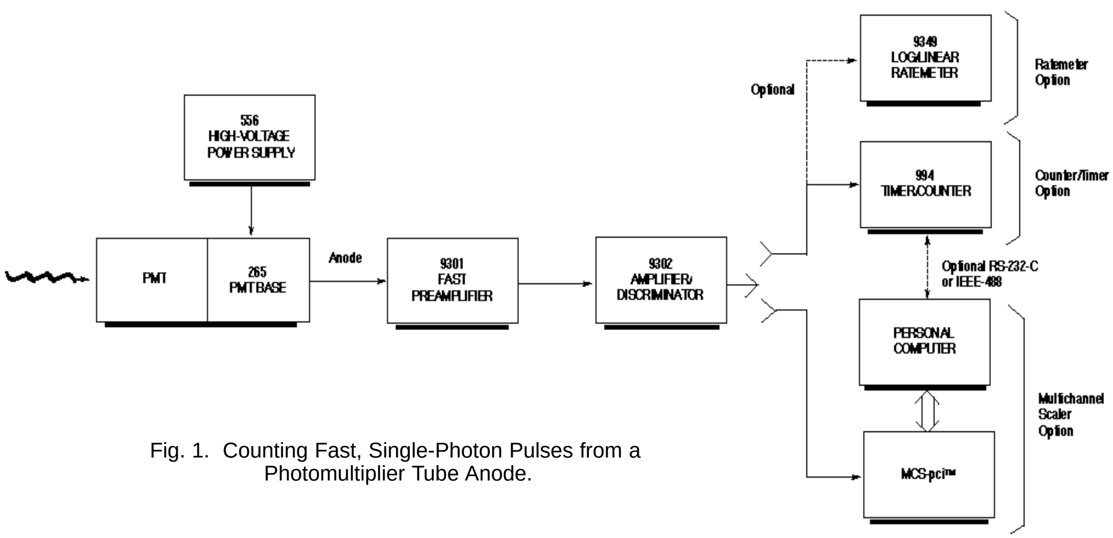

Fig. 1. Counting Fast, Single-Photon Pulses from a Photomultiplier Tube Anode.

successive dynodes, resulting in a pulse of electrons that grows in amplitude as it cascades from dynode to dynode. By the time the pulse of electrons is collected at the anode, the number of electrons has been amplified by a factor of about 10^7. Thus the negative pulse developed on the 25-Ω load at the anode typically has an amplitude of about 8 mV, a rise time the order of 3 ns, and a total duration of about 9 ns. These numbers will vary somewhat with choice of PMT and the applied bias voltage.

The Models 9301 and 9302 (Fig. 1) incorporate fast amplifier stages with rise times <3 ns. The fast rise time is critical for preserving the short duration of the anode pulse. After amplification the pulse is passed to a discriminator in the Model 9302 to separate the single photon pulses from the lower-amplitude noise inherent in the system. This noise discriminator is a comparator with an adjustable amplitude threshold. A pulse having sufficient amplitude to cross the threshold generates an output logic pulse of 5-ns duration. Thus, each logic pulse from the Model 9302 output corresponds to one photon detected by the photomultiplier tube.

In the simplest system the single-photon logic pulses from the Model 9302 are counted by the Model 994 Counter and Timer. The timer determines the interval during which the counter is allowed to count the photons. At the end of the counting period the counting rate is calculated by dividing the counts recorded by the time interval. This counting rate is proportional to the intensity of the light source.

The Measurement Error is Controlled by Counting Statistics

Predicting the Standard Deviation: For the typical case, in which dead-time losses are negligible, the statistics of counting single photons are defined by the Poisson Distribution.[1]

$$P_N(t) = \frac{(rt)^N e^{-rt}}{N!} \qquad (1)$$

where $P_N(t)$ is the probability of counting N photons in the time interval t, and r is the expected mean arrival rate of photons. If the measurement is repeated a large number of times and the measured values of N are averaged, that average will approximate the mean value of Equation (1), which is rt. Similarly, the standard error in the measured values of N will approximate the standard

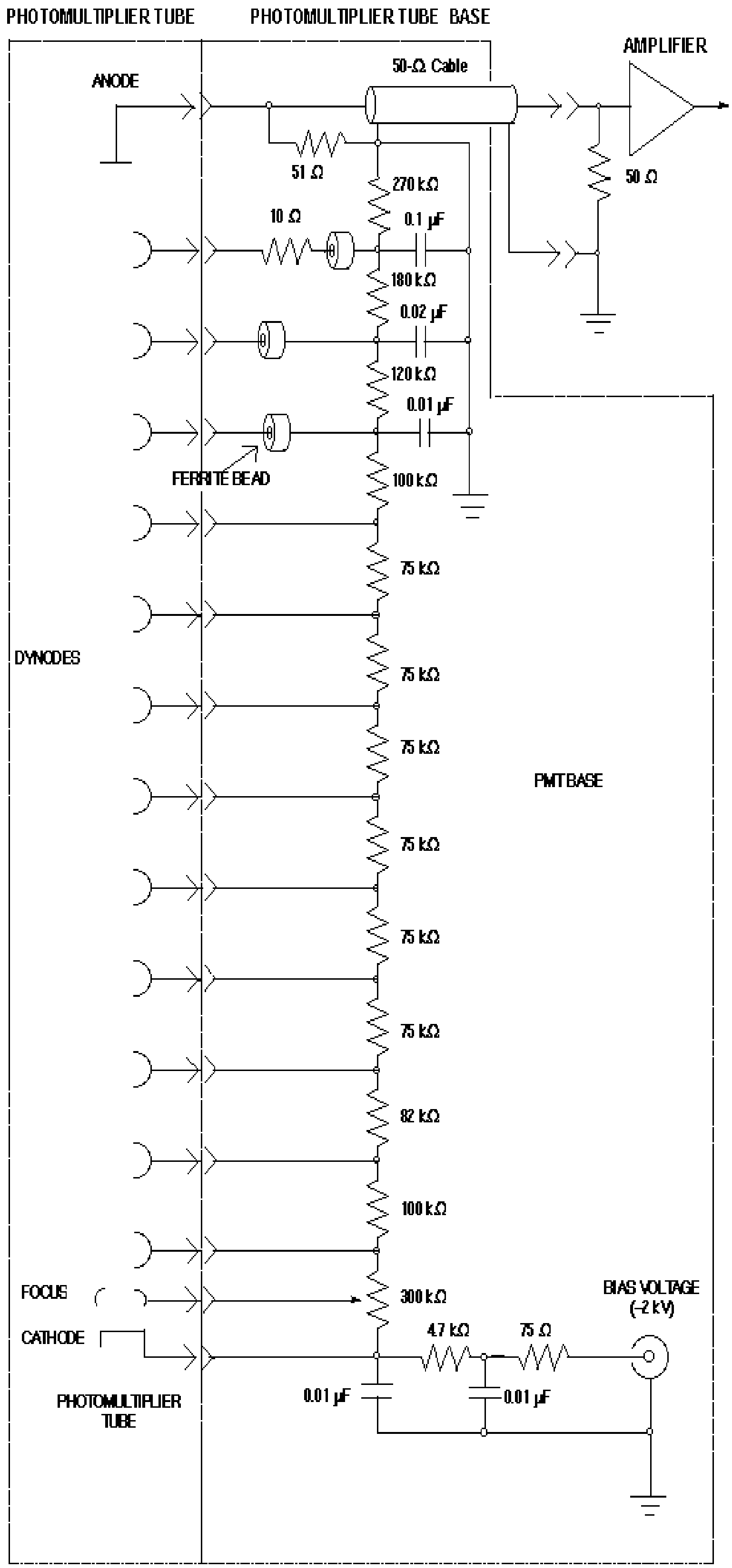

Fig. 2. Typical Photomultiplier Tube and PMT Base for Single-Photon Counting.

deviation of Equation (1), which is $(rt)^{1/2}$. Thus, if N is a moderately large number, a reasonably accurate estimate of the standard deviation in N is

$$\sigma_N = (N)^{1/2} \quad (2)$$

and this estimate can be based on a single measurement of N.

The Precision of the Measured Intensity: The photon intensity is proportional to the measured counting rate, which is calculated as

$$R = N/t \quad (3)$$

Since the time interval is not subject to significant statistical error, the precision in the measurement of R is given by

$$\frac{\sigma_R}{R} \times 100\% = \frac{\sigma_N}{N} \times 100\% = \frac{100\%}{N^{1/2}} \quad (4)$$

Consequently, a 1% statistical precision in the measurement requires at least 10,000 photons to be counted. This can be accomplished by choosing a sufficiently long time interval. Alternatively, one can measure the time required to record 10,000 photons in the counter, and divide this time into 10,000 counts to compute the counting rate. The Model 994 Counter and Timer supports either method.

Recording Varying Counting Rates

The Model 9349 Ratemeter with logarithmic and linear scales on its analog meter (Fig. 1) can be a convenient means of visually monitoring changes in counting rates during an experiment. For a precise record of counting rates that vary with time, the MCS-pci™ Multichannel Scaler is a much better solution.

The multichannel scaler (MCS) behaves like 65,536 sequential counters. When the measurement is started, the first counter counts the photons for the time t. (In a multichannel scaler, the time interval t is typically called the "dwell time".) When the first counter stops, the second counter counts the photons for the next time interval t. This sequential counting process continues until the last counter has completed its counting interval. At the end of the scan the contents of the 65,536 counters show the variation of counting rate with time over a total time period equal to 65,536t.

Although this same function could be achieved by computer automation of a single counter, the inevitable dead time caused by computer readout of the counter leaves significant gaps in the data when the counting intervals are short. The MCS-pci totally eliminates the dead time between counting intervals, and does so at a cost similar to that of a single, computer-interfaced counter and timer.

A multichannel scaler is an efficient solution for recording the spectrum of counting rate versus wavelength. For example, in Raman Spectroscopy the MCS scan can be synchronized with the scan of the monochromator. At the end of the scan the MCS contains the spectrum of counting rate versus wavelength.

Choosing the Photomultiplier Tube and PMT Base

A number of manufacturers (Burle, Hamamatsu, Philips, Thorn EMI) offer photomultiplier tubes suitable for single-photon counting; their literature should be consulted for choosing and operating the PMT. There are several important criteria for selecting a photomultiplier tube for single-photon counting:

1. Sensitivity to the intended wavelengths**.** If the light source is exceptionally weak, choose a PMT that exhibits a high quantum efficiency for the wavelength to be measured.

2. High gain**.** Single-photon signals are small. A gain of the order of 10^7 or more is needed in the PMT. This generally dictates a 12-stage PMT.

3. Fast rise time, followed by a rapid and smooth return to baseline. Total anode pulse widths are typically 2 to 3 times the stated rise time specification. A rise time <3 ns is desirable to achieve the pulse-pair resolving time needed at high counting rates. Excessive ringing upon return to baseline can cause erroneous multiple counting of a single photon. Choose a PMT that exhibits minimum ringing.

4. High gain at the first dynode. This reduces the pulse-amplitude fluctuations with single photons, thereby allowing better discrimination between single-photon pulses and noise.

5. Low dark counting rate. When the light source is weak, the dark counts generated within the PMT

determine the detection limit for the light signal. Cooling the PMT usually reduces the dark counting rate.

6. Low transit-time spread. This is important only if the PMT will be used in time-correlated measurements that require sub-nanosecond time resolution.

7. Compatibility with a PMT base designed specifically for fast rise time and a smooth pulse shape for single-photon applications.

The quality of the PMT base controls the performance that can be extracted from the photomultiplier tube. Figure 2 is a simplified schematic of the ORTEC Model 265 PMT Base, which has been designed for high-resolution timing and single-photon counting with 12-stage photomultiplier tubes. The inter-electrode bias voltages are higher than average for the cathode and the first two dynodes. This increases the gain for the first two dynodes, which in turn reduces amplitude fluctuations on single-photon pulses. It also improves the time resolution by minimizing transit-time spreads in the critical early stages of the PMT. A network of capacitors, ferrite-bead inductors, and a damping resistor are applied to the last few dynodes in order to deliver an anode pulse with minimum distortion and ringing.

The cathode is operated at a negative high voltage, and this permits the anode to be dc-coupled to the external amplifier on a 50-Ω coaxial cable. The 50-Ω input impedance of the external amplifier prevents distorting reflections of the pulse by terminating the coaxial cable in its characteristic impedance. With the cathode at high voltage, conductors at ground potential should be kept at a safe distance from the PMT cathode. The entire assembly must also be shielded from extraneous light, RF interference, electrostatic fields, and magnetic fields. Appropriate shields are available for these purposes.

DC-Coupling for Exceptionally High Counting Rates

Amplifiers with ac-coupling between stages are generally simpler to design, and offer a baseline between pulses that is insensitive to temperature changes. AC-coupled amplifiers provide satisfactory performance for average counting rates up to about 10^6 counts/s in the typical single-photon counting system. This is well within the requirements of most applications.

At counting rates in excess of 10^6 counts/s, the performance is limited by baseline shifting across the ac-coupling. As the counting rate increases, the baseline between pulses at the amplifier output shifts so that the area circumscribed by the signal and baseline is equal on both the positive and the negative sides of ground potential. The baseline shift is negligible below 10^6 counts/s, but becomes significant at higher counting rates. For 10-ns pulse widths the baseline shift is about 1% of the pulse height at 10^6 counts/s, 10% at 10^7 counts/s, and 50% at 5 X 10^7 counts/s. At the noise discriminator, the baseline shift is equivalent to increasing the pulse amplitude required to cross the discriminator threshold. Consequently, a decreasing fraction of the pulses are counted as the counting rate increases above 10^6 counts/s, with a resulting severely nonlinear counting rate response.

This problem can be eliminated by dc-coupling the entire system, including the PMT, amplifier, and discriminator. This is implemented (Figure 3) with the Model 265 PMT Base, two of the Model 9305 Preamplifier, and the Model 9307 Discriminator. With complete dc-coupling, the counting rate can be increased until the pulse-pair resolving time of the PMT becomes the limiting factor.

Discriminators are available with pulse-pair resolving times less than 10 ns. Consequently, the 10-ns pulse length contributed by the photomultiplier ultimately limits the pulse-pair resolving time. When two photons arrive within 10 ns of each other, their pulses add in the PMT to form one composite pulse. The discriminator recognizes this as one photon instead of two. As a result, the measured counting rate, R, is related to the true photon rate, r, by the following equation

$$R = r\,e^{-rT} \qquad (5)$$

where T is the average pulse width at the discriminator threshold. The pulse pile-up losses cause the measured counting rate to fall short of the true photon counting rate. For T = 10 ns, the shortfall is 1% at r = 10^6 counts/s, 9.5% at 10^7 counts/s, and 39% at 5 X 10^7 counts/s. Fortunately, there are techniques for measuring the dead time, T, and mathematically correcting the measured counting rate to compute the true photon rate.[2] With such methods, dc-coupling can extend the upper limit on counting rate by an order of magnitude to about 10^7 counts/s.

If the pulse-pair resolving time of the discriminator is not smaller than the pulse width from the PMT, Equation (5) becomes more complicated,[2, 3, 4] and the counting losses are increased by the discriminator dead time. When the dead time losses exceed 10%, the counting statistics deviate significantly from Equations (1) and (2). In that case, slightly more complex equations are applicable.[5]

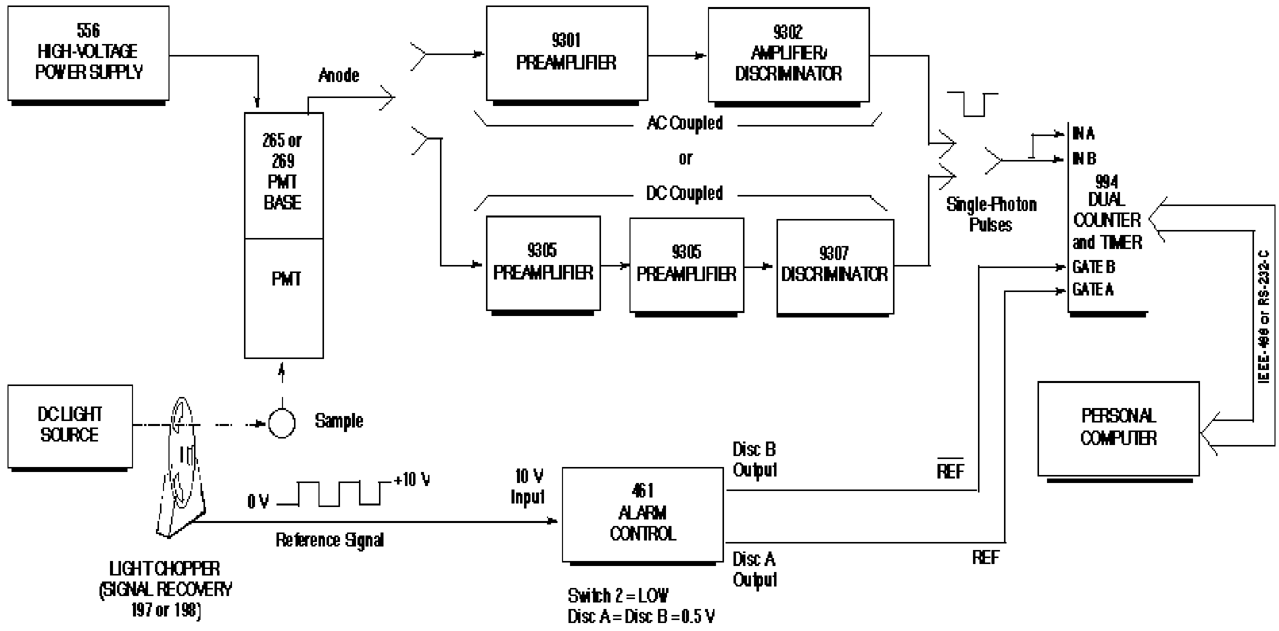

Fig. 3. Electronics for Single Photon Counting with a Light Chopper.

Measuring Exceptionally Low Photon Rates

At counting rates below 1,000 counts/s, the dark counts contributed by the photomultiplier tube must be considered. The dark counts are primarily caused by thermionic emission of electrons from the photocathode. In a tube designed for low dark counts, this background counting rate from the PMT can be as low as 10 to 50 counts/s. Cooling the photocathode can further reduce this rate.

When the dark counting rate is a significant fraction of the counting rate from the signal, the background from the dark counts must be measured and subtracted from the total counting rate in order to measure the true counting rate from the signal. Figure 3 shows how a light chopper can be added to accomplish this task. The rotating chopper wheel creates equal alternating periods when the light source illuminating the sample is turned on or off. A reference signal from the chopper designates when the light is passed through to the sample. The two discriminators in the Model 461 standardize the amplitude of this signal (REF) and create the complement of the signal ($\overline{REF}$). The REF signal is used to gate Counter A so that it counts the single photon pulses when the light is on. The $\overline{REF}$ signal gates Counter B to count the dark counts. At the end of the total measurement period the contents of Counter B are subtracted from the contents of Counter A to calculate the true signal from the sample. If the dark counts are N_B and the total counts in Counter A are N_A, then the true counts from the sample are computed as

$$N_S = N_A - N_B \tag{6}$$

and the standard deviation in the true counts from the sample is

$$\sigma_S = (N_A + N_B)^{1/2} = (N_s + 2N_B)^{1/2} \tag{7}$$

If the number of dark counts is negligible compared to the true counts, Equation (7) becomes identical to Equation (2). If the number of dark counts is large compared to the true signal, then the statistical error in the dark counts limits the detectability of the true signal. This is more obvious when the counting rates,

$$R_S = \frac{N_S}{t} \tag{8a}$$

$$R_B = \frac{N_B}{t} \tag{8b}$$

are substituted in Equation (7) and the precision is calculated. The result is:

$$\frac{\sigma_S}{N_S} \times 100\% = 100 \sqrt{\frac{1}{R_S\, t}\left[1 + 2\,\frac{R_B}{R_S}\right]} \quad (9)$$

When the dark counting rate is significant, the statistical precision in measuring the true signal N_S (or R_S) is controlled by three factors: the true signal rate R_S, the signal-to-dark-count ratio R_S/R_B, and the counting time t. To achieve 10% precision in a measurement with R_S = 5 counts/s and R_B = 50 counts/s, a counting time of at least 420 seconds would be required. If the dark counting rate can be reduced by a factor of 4 by cooling the photocathode, the required counting time is reduced to 120 seconds.

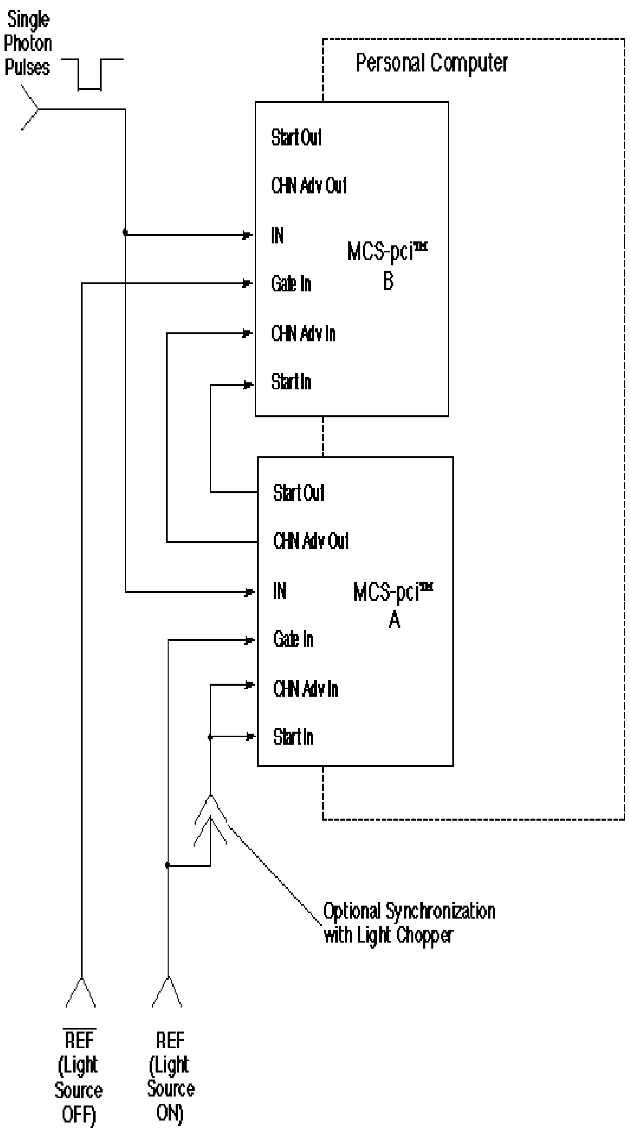

Fig. 4. Recording the Time Profiles for the Signal and Dark Counts (A) and the Dark Counts (B) Utilizing a Synchronized Pair of Multichannel Scalers for Single-Photon Counting.

If the counting rate is expected to change as a function of time, the Model 994 Dual Counter and Timer in Figure 3 should be replaced with two multichannel scalers (Figure 4). Multichannel Scaler A counts photons when the light is transmitted by the chopper wheel, and MCS B records the dark counts when the light is blanked by the wheel. The start of the scan and the dwell times in MCS B are controlled by MCS A. (MCS B is operated in the External Start and External Channel Advance modes.) Consequently, the time scale for the dark counts profile in MCS B matches the time scale for the signal plus dark counts in MCS A. After data acquisition, the time profile recorded in B can be subtracted from the profile in A to yield the true counts from the signal.

Under normal circumstances, MCS A is operated in the Internal Channel Advance mode, which allows the operator to choose the length of the dwell time. If channel-by-channel synchronization with the chopper wheel is desired, the optional External Start and External Channel Advance modes should be selected for MCS A. This option will limit data acquisition to 65,536 cycles of the chopper wheel in a single scan. If the data is time invariant, the MCS can be programmed to add multiple scans to improve the statistical precision. The statistical precision can also be improved by adding together data from a large group of channels in the MCS memory.

Pulsed Excitation Reveals Decay Times

A flash lamp or a laser can be used to excite the sample with a brief pulse of light, and the subsequent decay of the excited states can be tracked by time-correlated single-photon counting, using the instrumentation in Figure 5. The MCS-pci provides 65,536 channels of data with a minimum dwell time of 100 ns per channel, whereas the Turbo-MCS™ Multichannel Scaler offers 16,384 channels and a minimum dwell time of 5 ns. In both cases the start of the MCS scan is triggered by the light pulse, and the multichannel scaler records the decay curve for the counting rate based on the dwell time selected by the operator. Typically, the pulsed excitation and scan are repeated numerous times, with the data from each scan being added to the previous scans to improve the statistical precision.

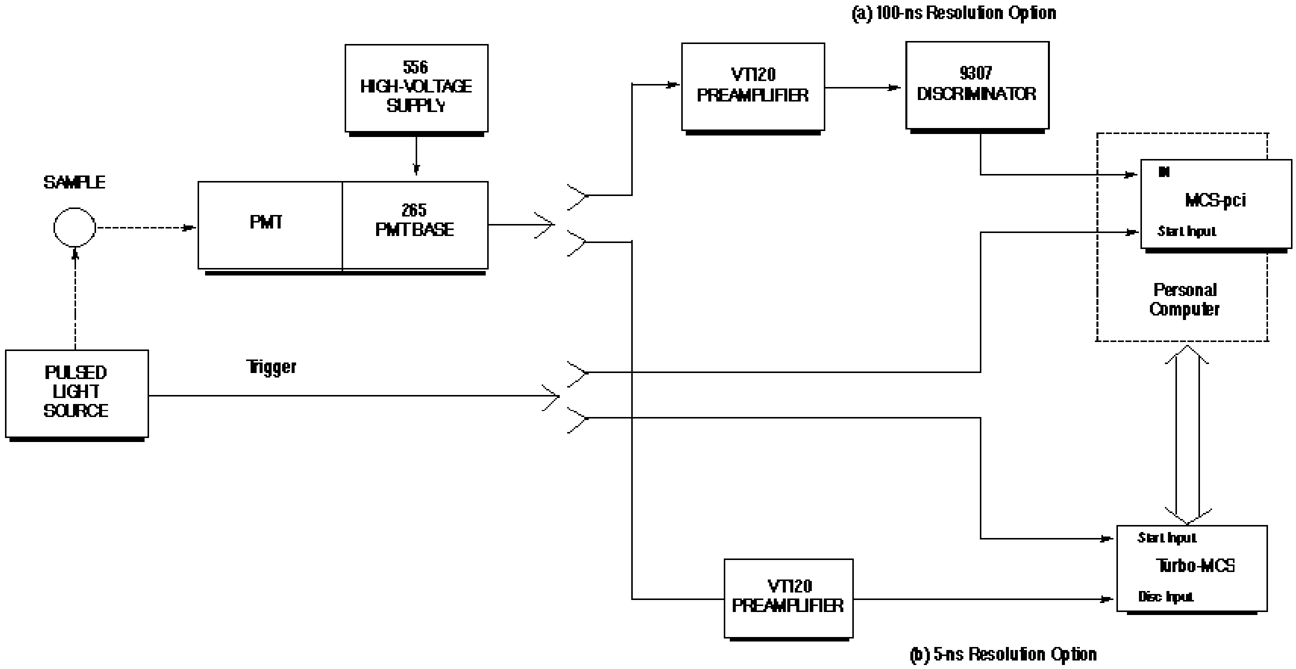

Fig. 5. Time-Correlated Single-Photon Counting with a Pulsed Light Source.

With the instrumentation in Figure 5, decay time constants down to 250 ns can be measured. This covers the time range of interest for phosphorescence decay. For fluorescence decay time constants ranging from 250 ns down to 10 ps, a timing system based on a time-to-amplitude converter and a multichannel pulse-height analyzer is the appropriate solution (Fig. 6). For an in-depth description, please consult the ORTEC AN50 Application Note: "Instrumentation for Fluorescence Lifetime Spectrometry."

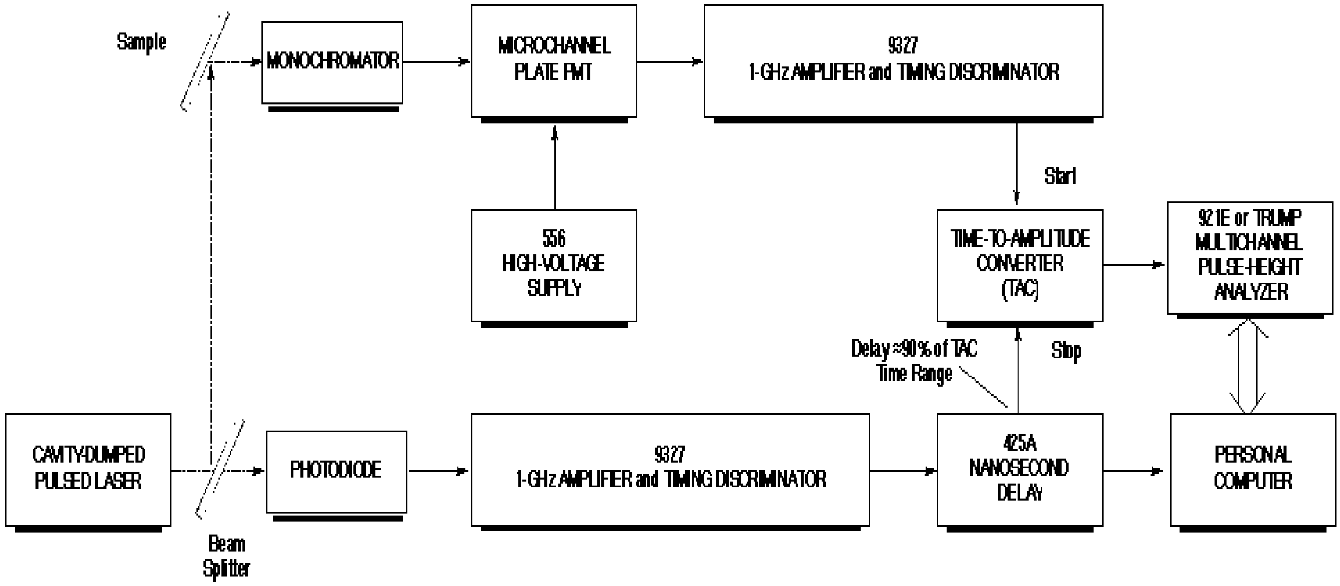

Fig. 6. Typical Block Diagram for a Fluorescence Lifetime Spectrometer.

LIDAR Measures Composition Versus Distance

Figure 7 shows the application of time-correlated single-photon counting to a LIDAR system for studying the concentration of compounds as a function of altitude in the atmosphere. Each laser pulse triggers the start of a scan in the Turbo-MCS Multichannel Scaler. Laser pulses scattered by molecules in the atmosphere are detected by a photomultiplier tube and counted by the MCS in a memory location that corresponds to the time of detection. The round-trip flight time of the photons, as recorded by the Turbo-MCS, measures the altitude at which the scattering took place. The counting rate of the detected photons from a particular altitude can be used to calculate the concentration of specific compounds at that altitude.[6] In practice, the laser and the photomultiplier tube are incorporated into a system of lenses, designed to limit the field of view and to guarantee overlap between the volume excited by the laser and that viewed by the PMT. Typically, two parallel systems are used to measure the response at different wavelengths. This allows differential absorption corrections to be applied. The latter technique is called Differential Absorption LIDAR (DIAL).

Further Details

Additional information is available on the instruments described above. Simply contact the closest ORTEC sales representative and ask for the ORTEC catalogs, data sheets, or brochures on the specific products.

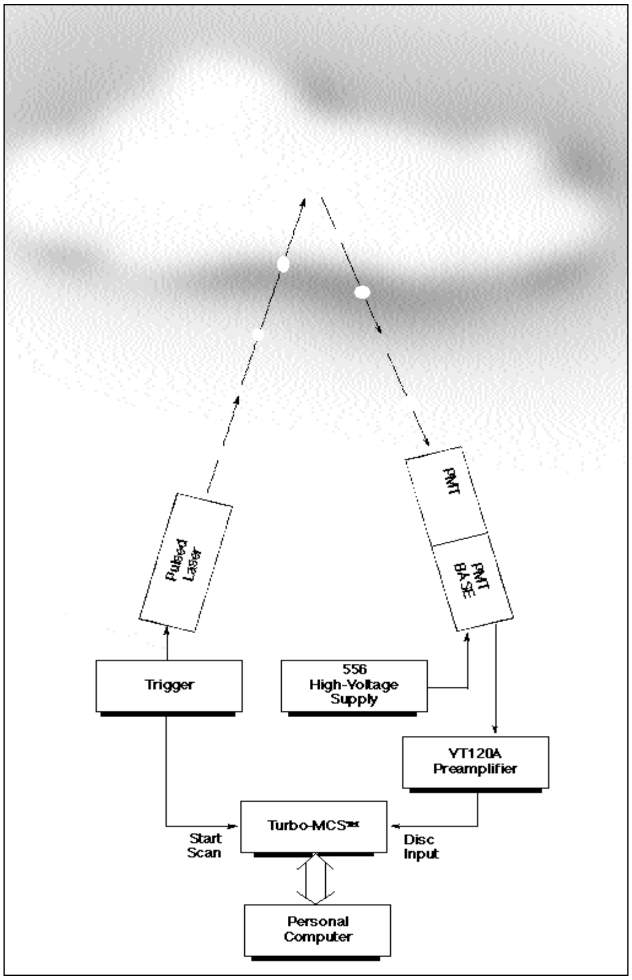

Fig. 7. A Simplified Diagram of the Application of Turbo-MCS™ to Atmospheric Measurements by LIDAR.

References

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3. D. R. Beaman, J. A. Isasi, H. K. Birnbaum, and R. Lewis, J. Phys. E: Sci. Instrum., 5, (1972), p 767.

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