Pulse (Photon) Counting: Determination of Optimum Measurement System Parameters

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Pulse (Photon) Counting: Determination of Optimum Measurement System Parameters

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Linearity measurements and integral pulse height distributions have been used to evaluate the effects of electron multiplier voltage and discriminator coefficient (A_d) on the stability, sensitivity, and dynamic range of three pulse counting measurement systems. The data show that selection of the highest possible voltage has significant advantages for most experiments, but that the choice of an "optimum" value for A_d depends on the requirements of the particular experiment and requires careful evaluation of the trade-offs among stability, sensitivity, and dynamic range. Semiquantitative evaluation of these trade-offs on the basis of the experimental results is illustrated. The data also show clearly that measurements such as those reported here must be made on each system, since specific results for one system cannot be generalized to others.

Electron multipliers are widely used as particle flux transducers, whether incorporated into a photomultiplier (PMT) for measuring photon flux, or used "bare" for detecting ions, electrons, or vacuum ultraviolet photons. The particle flux can be determined either by measuring the average direct current output of the electron multiplier (the "dc" method) or by counting the individual charge pulses (*1*). The latter technique is often referred to as "photon counting", but the more general term "pulse counting" will be used throughout this paper.

When a pulse counting system is to be used for analytical measurements, several characteristics of the transfer function which relates measured count rate to incident particle flux may be important. Ideally, the transfer function would be a straight line (good linearity) which extends from zero to infinity (infinite dynamic range), would have a slope of one (high sensitivity), and would be invariant with time, temperature, etc. (high stability and freedom from noise).

Because of limitations inherent in the components of any real pulse counting system, such an ideal transfer function is unattainable. The extent to which the ideal is approached in practice is influenced not only by the limitations of the pulse counting system components, but also by the operating parameters of the system. For example, the accuracy with which a pulse counting measurement can be made is limited at high count rates primarily by pulse overlap counting losses (i.e., by nonlinearity of the transfer function). The percentage of pulses lost at a given count rate depends not only on the speed of the counter, the pulse arrival time distributions, and the pulse shape distributions (both amplitude and width) from the electron multiplier, but also on the discriminator coefficient, A_d (defined as the fraction of the pulses passed by the discriminator) (*1, 2*). Thus, the user can adjust A_d to optimize the linearity of the system. Unfortunately, A_d also influences the sensitivity and stability of the pulse counting system in such a way that optimum linearity often results in less-than-optimum stability and sensitivity (*1*). Since the relative importance of linearity, stability, and sensitivity will vary depending on the type of experiment, there is unlikely to be a universally optimum setting for A_d. Instead, the "optimum" setting of this and other measurement system parameters must be selected while keeping in mind the particular experimental conditions likely to be encountered. The relationships between the measurement system parameters and the desired transfer function characteristics cannot be predicted in advance, since they depend on the characteristics of the individual electron multiplier, the multiplier power supply, component temperatures, component history, and so on. A careful selection of the parameters for the "optimum" operation of any pulse counting system will require an effective determination of the system characteristics.

In this paper, we present the results of pulse height distribution and linearity measurements made on several different pulse counting systems. Although these measurements do not provide a complete characterization of these systems, they do allow many of the trade-offs involved in selecting operating parameters to be evaluated on at least a semiquantitative basis. These examples illustrate the importance of such characterizations in making sound selections of the operating parameters.

EXPERIMENTAL

Equipment. Three different electron multipliers were used in these studies, an RCA 8850 PMT, an RCA 1P28 PMT, and a Johnston MM1 electron multiplier. The 8850 was mounted in a thermoelectrically cooled housing and powered with a Hewlett-Packard 6110A power supply. The 1P28 was housed in a Heath (now GCA-McPherson) EU-701-30 photomultiplier module, and used the integral power supply of that module. The MM1 was used as the ion transducer in a photoionization mass spectrometer (*3*) and was powered with a Power Designs 1543A power supply. All of the measurements reported here were made with the electron multipliers at room temperature.

The photon source used with the 8850 and 1P28 was made up of Heath (GCA/McPherson) 700 series components. The radiation from a tungsten lamp in an EU-701-50 light source module was dispersed by a model EU-700 monochromator. The monochromator slit width was used to control the photon flux. The MM1 detected a beam of Ar^+ ions which had an intensity determined by the Ar sample pressure in the ion source region of the mass spectrometer. For the linearity studies performed on the 8850 and 1P28 systems, a model EU-721-11 alternating cell module was inserted between the monochromator and PMT housing. This module contained a neutral density filter which was in the light beam whenever the sample cell carriage was in the sample position, but out of the beam in the reference position. The carriage position could be controlled by a computer. The shutter of the sample cell compartment was connected to a small solenoid so that it also could be computer controlled. All count rate data were acquired (under computer control) with an integrated-circuit based, dc-coupled pulse counter that has high sensitivity (130 μV) and a pulse pair resolution of $\sim$11 ns. This pulse counter is described in detail in a companion paper (*4*).

Pulse Height Distributions. Relative integral pulse height distributions were measured for all three pulse counting systems by measuring the dark count rate and the light count rate (dark counts subtracted) at a constant photon or ion flux as a function of the pulse counter discriminator level. These measurements were made at a sufficiently low count rate that negligible pulse overlap errors occurred. Thus, a plot of count rate vs. discriminator level is proportional to the integral pulse height distribution.

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Linearity Measurements. The linearity studies reported here were performed using a method similar to that described by Heroux (*5*). The apparent transmittance of a neutral density filter was measured with the pulse counting apparatus as a function of light intensity. It is useful to define the following terms:

- I_0 photon flux on the PMT without the filter, quanta s^{-1}
- I photon flux on the PMT with the filter, quanta s^{-1}
- T the actual transmittance of the filter, I/I_0, dimensionless
- N_0 measured count rate without the filter, counts s^{-1}
- N measured count rate with the filter, counts s^{-1}
- T' the apparent transmittance of the filter, N/N_0, dimensionless.

From these definitions, it can be seen that while T is independent of light intensity, T' will be independent of light intensity (and equal to T) only when pulse overlap counting losses do not occur in the measurement of N and N_0. When such losses do occur, they will affect N_0 more than N, and T' will deviate from T by an amount which is indicative of the amount of dead time loss or pulse overlap gain in the measurement of N_0.

This method of analyzing the data assumes that pulse overlap loss in the measurement of N is small. Providing that T is small, this will be a good assumption, except perhaps at the very highest photon fluxes used. In any case, the data can be used to check the validity of the assumption, and to correct the results to any desired accuracy if the assumption turns out not to be "valid enough". The linearity of a pulse counting system can therefore be determined even when no other type of system is available for comparison measurements (such as an accurate dc measurement system). Furthermore, this method avoids the not-insignificant difficulty of ascertaining the accuracy and linearity of an analog dc system over many orders of magnitude.

A reasonable test of the linearity of a pulse counting system is to measure the count rate at which 1.0% of the counts are lost because of pulse overlap. In order to do so, the transmittance of the filter (about 0.013) must be known to an accuracy considerably better than 1.0% of its value, i.e., to better than ±0.0001. Since none of the analog spectrometers available were capable of this accuracy, the transmittance of the filter was measured with the photon counting system at very low light levels (about 10 000 photons/s), where pulse overlap in the measurement of N_0 is certain to be negligible. However, the value of N then had to be measured at count rates of only 130 photons/s, which is comparable to the dark count rate for the 8850. Precise measurement of such low light intensities, especially in the presence of 1% light source instability, demanded the use of a synchronous measurement procedure similar to that of Arecchi et al. (*6*). Rather than measure N for sufficient time to accumulate a statistically significant number of counts and then measure N_0, both N and N_0 (as well as the dark count, D) were measured in rotation for periods of time (a few seconds each) much shorter than the period of the light source drift. The short integrations could be accumulated to produce an effective integration time of any desired duration. Errors caused by light source drift were found to be negligibly small with the above procedure, which was automated and controlled by a computer. After about 24 h of integration at low light levels, the value of T for the filter was determined to be 0.01304 ± 0.00004. This is an accuracy of ±0.3%, and thus the count rate for errors of 0.5% or greater could readily be determined.

RESULTS AND DISCUSSION

Pulse Height Distributions. In any real pulse counting system, there are several potential sources of instability. Any change in the discriminator setting relative to the mean pulse height at the discriminator input (or vice versa) may cause a variation in the measured count rate. Such a change may occur as a result of a change in the operating voltage or gain of the electron multiplier, in the gain of the preamplifier, or in the discriminator setting itself. These types of instability are the main sources of "excess noise" in the system (*1*).

One of the advantages traditionally ascribed to pulse counting (as opposed to dc) measurements, however, is superior long-term stability (*1, 7*), which is especially important

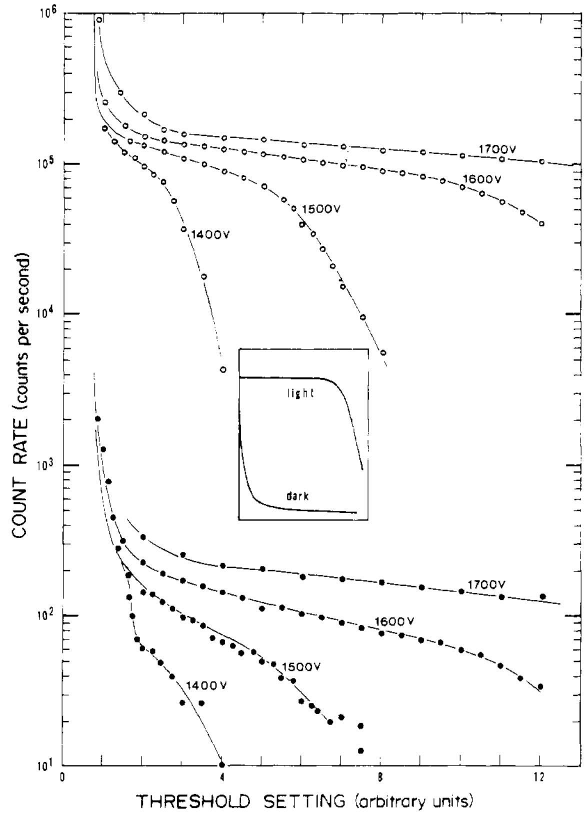

Figure 1. Integral pulse height distributions for the 8850 system at various PMT voltages. The open circles are light counts; the filled circles are dark counts. The inset shows the shape of "ideal" light and dark pulse height distributions

in low flux experiments. The reason usually stated to explain this stability is that it is possible to set the discriminator low enough that all "signal" pulses (those pulses originating at the first dynode of an electron multiplier or at the photocathode of a photomultiplier) have more than enough amplitude to be counted, while at the same time all of the (much smaller) "noise" pulses (those pulses originating at other dynodes or from other sources) are rejected. When this is the case (as it often is when bare electron multipliers are used at very high gains to detect electrons or high-energy ions), small fluctuations in the discriminator setting or mean pulse height will have no effect on the measured count rate, so that excess noise is usually assumed to be negligible compared to more fundamental noise such as quantum noise and signal and background flicker noise (*1*). Thus, the traditional "rule of thumb" in pulse counting is that the best stability is obtained when all the pulses are counted (i.e., when $A_d \simeq 1$), which is equivalent to operating on the "counting plateau" or on the horizontal portion of the integral pulse height distribution (see the "ideal" pulse height distribution in the inset of Figure 1). At the same time, counting all pulses ensures the best possible signal-to-noise ratio when shot noise is the main noise source (*8*). However, not all systems exhibit such ideal pulse height distributions. For example, pulse height distributions for the 8850 system at several different PMT voltages are shown in Figure 1. These data reveal a "plateau region" which is *not* flat, although it has a very shallow slope at higher voltages. Similar behavior for an RCA 8853 (a variant of the 8850) has been interpreted (*9*) as showing that there are very small signal pulses which are not counted at even the highest PMT voltage. The data of reference 9 were obtained with much higher PMT voltages than those used here, but with a much less sensitive pulse counter which had a fixed, 100-mV threshold. The data of Figure 1 do show a large number of noise pulses at the

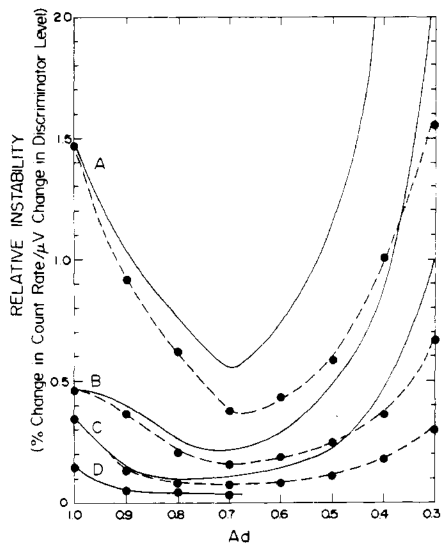

Figure 2. Relative light count instability of the 8850 system. The dashed lines are the unweighted curves, the solid lines are curves weighted by $1/A_d$ (see text). Curves A, B, C, and D were obtained at 1400, 1500, 1600, and 1700 V, respectively. Weighted and unweighted curves at 1700 V are virtually indistinguishable when plotted to this scale

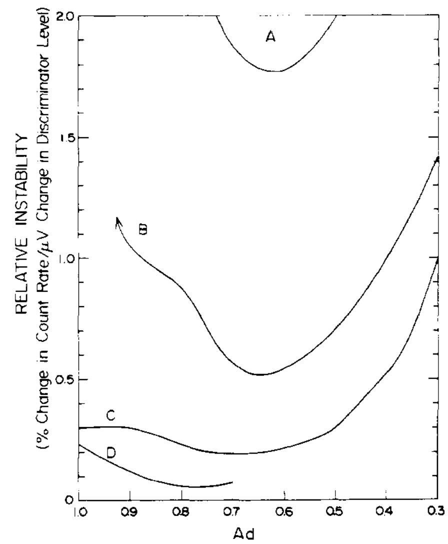

Figure 3. Relative dark count instability of the 8850 system. Only the weighted curves are shown. Curves A, B, C, and D were obtained at 1400, 1500, 1600, and 1700 V, respectively

lowest discriminator setting. However, since the "plateaus" observed in Figure 1 extrapolate to the same count rate (170 kHz) at all voltages, it is assumed that the extrapolated count rate represents "all the signal pulses". Therefore, this particular pulse counting system does have sufficient sensitivity to count virtually all of the pulses for PMT voltages above about 1500 V (half the recommended maximum of 3000 V). Rather than indicating a lack of sensitivity, these pulse height distributions indicate a fairly wide region of overlap between noise and signal pulses, with the smallest signal pulses being smaller than the larger noise pulses.

From a practical viewpoint, it is perhaps less important to understand the exact reasons for the shape of the pulse height distributions than to realize that a measured distribution can provide a great deal of information about the "best" operating parameters. For instance, since there is no portion of the pulse height distribution for the 8850 system which is completely horizontal, the excess noise contributed by discriminator instability, etc., may *not* be negligible, especially in experiments where long integration times are used (*4*). It is therefore important to evaluate the susceptibility of the pulse counting system toward such sources of drift for various operating conditions. This can be done by measuring the change in observed count rate for a unit change in either the mean pulse height or discriminator setting. The latter measure of "relative instability" is particularly convenient to use, since it is merely the slope of the integral pulse height distribution. It is important to note that relative instabilities measured in this way can be used to compare the susceptibility of a particular system to excess noise under different operating conditions, but that they cannot be used to compare different systems. This is because the actual change in measured count rate due to excess noise depends both on the susceptibility of the system and on the actual magnitude of drift in discriminator setting, amplifier and electron multiplier gain, and so forth.

The relative instability of the 8850 system (as measured from the light count pulse height distribution in Figure 1) is shown as a function of A_d in Figure 2 (dashed lines). These data show that in this case the best stability is not obtained at $A_d = 1$, but rather at $A_d \approx 0.6$–0.7, depending on the voltage. Unfortunately, at these lower discriminator coefficients, a large fraction of the signal pulses are lost (the slope of the transfer function is lower) so that longer integration times are required for a comparable signal-to-shot noise ratio. Therefore, these data should actually be weighted so as to show the changed susceptibility of the system to low frequency noise, due to the longer experiment duration, or decreased "noise equivalent bandwidth" (*1*). To do so accurately would require a detailed knowledge of the frequency distribution of the excess noise in the systems, which is difficult to measure. However, for low-flux experiments in which long integration times are used, high frequencies are averaged out quite well, and only low frequency ($1/f$) noise is much of a problem—the longer the integration time, the worse the drift problem. To illustrate the effect on the instability vs. A_d plots, the solid lines in Figure 2 show the same data as the dashed lines, but weighted by the relative integration time needed to reach a standard number of counts (i.e., by $1/A_d$). The point of best stability is indeed shifted toward higher values of A_d, but not very far. Similarly weighted dark count relative instabilities are shown in Figure 3.

The instability data of Figures 2 and 3 show not only that the best stability is obtained at values of A_d significantly less than 1, but also that operating at the highest PMT voltages has several advantages. Stability is better at higher voltages, and the slopes of the instability curves of Figures 2 and 3 are more gradual in the region of best stability. Thus, at the higher voltages, one could choose any A_d over a fairly wide range (e.g., to adjust for best linearity) without sacrificing too much stability. Furthermore, as seen from Figure 1, the counting "plateau" is broader at higher voltages (the change in A_d for a unit change in absolute discriminator level is lower) so that it is easier to adjust the discriminator to the desired A_d.

The data in Figure 1 also show that at equivalent light count rates (i.e., at equivalent A_d), there is a slightly higher dark count rate at the higher operating voltages. Thus, if one were to make measurements without background subtraction, a lower voltage would give a slightly wider dynamic range, since the dark count rate would determine the lower end of the dynamic range. However, if one does use some method of background subtraction, the lower end of the dynamic range can be well below the dark count rate (*10*). Then the important consideration is the amount of time which must be devoted to the measurement of the background. If the system is very stable, the background needs to be measured only once, just long enough to obtain the desired signal-to-noise ratio in the background measurement. If the system is not so stable, or if there is too much excess noise, then a synchronous

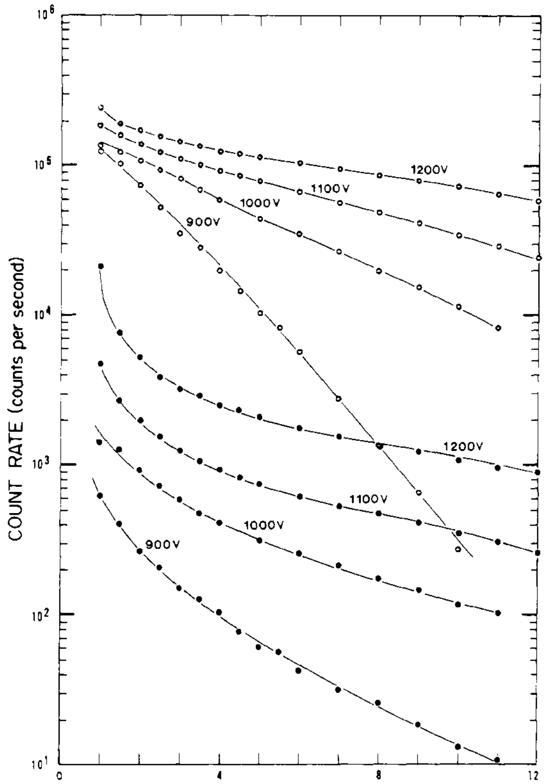

Figure 4. Integral pulse height distributions for the 1P28 system at various PMT voltages. The open circles are light counts; the filled circles are dark counts

demodulation technique must be used (*10*), and up to 50% of the time must be spent measuring the background count rate. The data of Figure 3 show that the excess noise in the dark count measurement associated with instability of the pulse counting system can be dramatically reduced by operating at higher voltages. This reduction in drift will far more than compensate for the slightly increased dark count rate. (Note that the dark count rate could be reduced considerably by cooling the PMT; whether the dark count rate and instability of a cooled PMT would behave the same as that of the room temperature PMT would have to be determined experimentally.)

Pulse height distributions for the 1P28 system, shown in Figure 4, contrast sharply with those of the 8850 system. There are again no noticeable plateaus at any voltage; even at the voltages indicated in Figure 4, which are near the maximum rating for the 1P28, stability is worse than for the 8850 system at voltages well below the recommended maximum for that PMT. Furthermore, the dark counts exhibited by the 1P28 system are higher than for the 8850 system, and the increase in dark count rate as a function of PMT voltage is more dramatic. Relative instabilities of the 1P28 system show roughly the same trends as those of the 8850 system, and are not shown here.

The behavior of the pulse height distributions for the MM1 system (not shown) is quite different from that of the 8850 and 1P28 systems. Changing the voltage not only alters the slope of the pulse height distribution (as in the 8850 and 1P28 systems), but also alters its relative shape—there is no plateau at lower voltages, but at higher voltages a plateau is quite evident. The reason is probably that as the voltage on the MM1 is increased, not only is the gain of the electron multiplier increased, but so is the energy of the ions striking the first dynode, which is known to have a marked effect on the secondary electron emission coefficients and pulse height distributions (*11, 12*). Although at the highest voltage used (4700 V) the plateau was not quite flat, it is quite possible that higher ion impact energies would result in a nearly-ideal pulse height distribution, in which case the traditional rule of setting $A_d \simeq 1$ would be quite valid.

It should be emphasized that we do *not* claim that the characteristics observed in these systems are necessarily typical of the multiplier types employed. There is a great deal of variability in the behavior of different samples of the same type of multiplier, and the housing, power supply, pulse counter, and wiring details can drastically affect the performance of a given pulse counting system. Thus, any conclusions drawn here are expected to be valid only for the specific systems described. In fact, the most important point is not that the 1P28 system seems less suited to pulse counting than the 8850 system, or that even the 8850 system did not exhibit ideal behavior, but rather that the pulse height distributions must be measured to establish the actual behavior of a given system, and, once measured, they provide a great deal of information about the parameters affecting the relative stability of that system.

Linearity Studies. Pulse counting will always be limited at high particle fluxes by the inevitable count loss due to pulse overlap, either in the pulse counter electronics or in the electron multiplier itself. Thus, at very high particle fluxes, the dc method will be needed (*1*). However, if a dc system with high sensitivity and stability is not available, or if it is inconvenient to switch between pulse counting and dc techniques, it may be useful to extend the upper range of the pulse counting system as far as possible. For any given counter, this may be done in either of two ways: by employing some sort of "dead time compensation" (DTC) to make the system linear to higher count rates, or by employing appropriate count loss corrections (CLC) to the measured data to correct for the known nonlinearity of the system.

The CLC method has been discussed recently by Hayes et al. (*13, 14*), who find that the amount of count loss can be regarded as being controlled by an "effective deadtime", which can be far different from the pulse pair resolution of the counter, and which is affected by the discriminator coefficient. The basic approach used by Hayes et al. is to measure the pulse counting system transfer function and to fit this function to an appropriate count loss equation which includes the effective deadtime as a parameter. The effective deadtime so measured can be used in the same equation to correct later measurements made on the same system, which extends the effective accurate dynamic range of the system to the point at which the assumptions made in deriving the count loss formula are no longer sufficiently valid. When employing the CLC technique, it is found that the uncertainty in the measured effective deadtime becomes an important factor in limiting the precision at high count rates. In fact, at high count rates, better precision is obtained in a shorter time by intentionally *reducing* the particle flux, so that beyond some point dc techniques remain clearly superior (*13*).

There are several methods of including some sort of automatic correction for pulse overlap loss in pulse counters. In counters which have a single discriminator, this can best be accomplished by setting the discriminator so as to exclude some of the pulses at low count rates. At higher count rates, some of the excluded pulses will overlap and become large enough to be detected. It was first suggested by Smit and Alkemade (*15*) that if this "pulse overlap gain" could be adjusted to counterbalance the pulse overlap loss of larger pulses, enhanced linearity should result. A practical demonstration of the technique was first described by Ash and Piepmeier (*2*), who named the technique "deadtime compensation". Both Ash and Piepmeier (*2*), and later Ingle

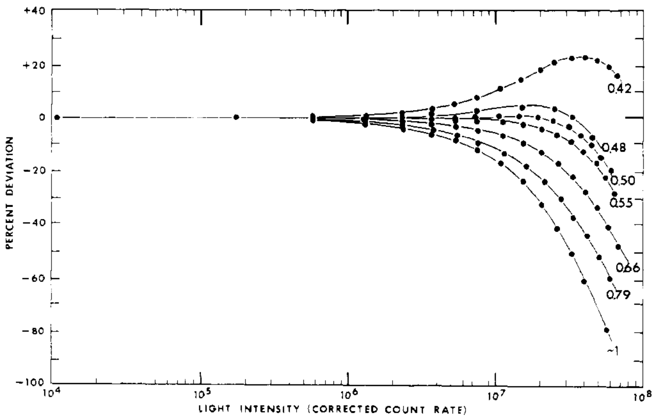

Figure 5. Linearity deviations of the 8850 system for various discriminator coefficients. The PMT was operated at 1500 V for these measurements

and Crouch (*1*, *8*), showed that the discriminator coefficient for "optimum" DTC should be about 0.5, although the precise value depends somewhat on the individual measurement systems.

Figure 5 shows the results of the linearity studies performed on the 8850 system at several discriminator settings (and at 1500 V). Results for the 1P28 system are similar and are not shown; no linearity studies have yet been performed on the MM1 system, which is used for very low flux experiments. This figure is a plot of the deviation from linearity vs. light intensity, which shows pulse overlap losses (and gains) much more clearly than the conventional plot of count rate vs. light intensity. The ordinate is the percent deviation from the correct count rate, calculated as

$$\text{percent deviation} = ((T/T') - 1)(100)$$

so that −50 corresponds to loss of half the pulses due to pulse overlap. The corrected count rate used as a measure of light intensity for the abscissa of Figure 5 is essentially the count rate that would be obtained for N_0 if there were no pulse overlap gain or loss, and the discriminator coefficient were 1.0. Its calculation requires knowledge of the actual discriminator coefficient which is measured from the pulse height distribution of Figure 1. The corrected count rates were then determined from N and the known value of T as

$$\text{corrected count rate} = N/((T)(A_d))$$

The count rates at which various amounts of pulse overlap loss occurred for different discriminator settings are summarized in Table I. These results can be used to establish the upper limit of the dynamic range of the system for a given accuracy. An accuracy exceeding ±0.5% is obtained at all count rates up to 200 kHz for all discriminator settings. The linearity is even better at values of A_d less than 1.0. For instance, at A_d = 0.5, the linear range is more than two orders of magnitude higher than with A_d = 1.0, which demonstrates clearly the effectiveness of deadtime compensation. The corrected count rate of 24 MHz corresponds to a measured count rate of 12 MHz, and a measured photocurrent of 3×10^{-6} A. While this current is still below the upper limit of linearity for dc measurements (which can be extended to even higher light intensities by lowering the photomultiplier voltage), it is nonetheless a significant gain in the upper range of the pulse counting system.

The increased linearity obtained with DTC comes at a price, however. Since a large fraction of the pulses are thrown away to begin with, the signal-to-noise ratio of the measurement will be lower for a given integration time. This can be compensated for if it is possible to integrate for longer periods,

Table I. Limits of Linearity for Different Discriminator Coefficients

discriminator coefficient, A_d	upper limit of corrected count rate for indicated degree of linearity, MHz				
	±0.5%	±1%	±2%	±5%	±10%
~1	0.20	0.50	1.1	3.3	≃6.0
0.79	0.40	0.72	1.4	4.2	8.0
0.66	1.1	1.8	3.3	9.0	14.0
0.55	3.7	6.6	13.0	25.0	33.0
0.50	24.0	26.0	30.0	36.0	45.0
0.48	1.8	3.3	7.5	42.0	48.0
0.42	≃0.70	1.2	2.3	5.8	≃10.0

but that may not be possible since the stability of the system is decreased under optimum DTC conditions, as shown in Figure 2. In this particular case, the stability is worse by a factor of 2 compared with the optimum; at higher operating voltages, the decrease in stability would not be as great. However, for systems which exhibit a flatter counting plateau, the loss of stability could be much worse. A final criticism of DTC (which applies also to CLC) is that its use requires that linearity measurements be performed in order to select the discriminator setting. This is not a very severe drawback, however, since the linearity should properly be checked whether or not one plans to use either DTC or CLC. Furthermore, the time to make such measurements is not as great as it might first appear. Once the transmittance of the neutral density filter has been measured, only measurements at high light fluxes are required, and since they can be made quickly with good precision, finding the optimum A_d will typically require less than an hour for a new system.

IMPLICATIONS FOR OPTIMIZING PULSE COUNTING SYSTEM PARAMETERS

If the 8850 system were to be used in low-light flux experiments, the implications of the data discussed above are fairly clear: one should use the highest voltage (1700 V or higher) and an A_d of about 0.8. Under these conditions, the system will exhibit the best possible stability (of utmost importance in low flux experiments) along with a fairly high sensitivity and a linear range extending to 400 kHz (±0.5% accuracy). At higher count rates, however, linearity becomes a worse problem than stability. If the experiment to be performed is fairly "slow", then DTC could be used to extend the linear range of the system more than an order of magnitude, using increased integration times to make up for the lower sensitivity. However, if the experiment is "fast" (for instance, monitoring the course of a fast reaction), then the decreased sensitivity may rule out the use of DTC so that the only choices would be to use CLC (if within the range of its applicability) or to switch to a dc measurement system. In any case, high flux pulse counting experiments should still be performed with the highest PMT voltage. Finally, if the experiment is likely to encompass both very low and very high count rates, one will be forced to make some sort of compromise in the choice of a discriminator coefficient, unless the voltage programmability of the discriminator setting of the pulse counter is exploited to allow a computer to select a high A_d for low count rate date acquisition and automatically switch to a lower A_d when the count rate becomes sufficiently high that DTC is needed.

CONCLUSIONS

We have shown how two relatively simple measurements (pulse height distributions and linearity studies) can provide valuable information about the optimum operating parameters for pulse counting measurement systems under different experimental conditions. The specific parameters found to be best for the particular systems studied are, however, not to be generalized; rather, they serve to demonstrate than even systems which use the same pulse counting electronics can behave quite differently, and that it is extremely important to characterize the behavior of any give pulse counting system to ensure that it does in fact satisfy the measurement requirements.

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Pulse (Photon) Counting: A High-Speed, Direct Current-Coupled Pulse Counter

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An amplifier/discriminator/prescaler module which forms a complete, high-performance pulse counter when combined with any standard TTL counter is described. It is constructed with readily-available integrated circuits and costs less that $150, yet has high sensitivity (130 μV) and is capable of very high count rates (>90 MHz with periodic input pulses; pulse pair resolution $\simeq$ 11 ns). The entire circuit is dc coupled so that there is no base-line shift at any count rate. The discriminator level is voltage programmable and the amount of prescaling can be selected remotely. Extra precautions taken to ensure drift-free operation of the electronics result in a pulse counter with excellent long-term stability.

It is widely recognized that pulse counting is the best method for measuring the output signal from electron multipliers used as particle (photon, ion, electron, etc.) detectors when the incident particle flux is very low (*1–8*). Likewise, it is recognized that pulse overlap counting losses inherent in the pulse counting technique limit its accuracy at higher particle fluxes, so that direct current (dc) techniques are best used at these higher fluxes (*5–9*). In spite of the fact that dc measurement systems which are adequate for medium- and high-flux measurements are readily available, there are several practical reasons for the continued interest in developing pulse counting systems which can operate at ever higher count rates. For example, pulse counting systems may have significant signal-to-noise ratio and stability advantages over dc systems at equivalent fluxes (*3–8*). Furthermore, pulse counting is an inherently digital technique; pulse counting measurements require fewer data domain conversions (*10*) than dc measurements, and are thus less susceptible to the inevitable errors which accompany such conversions (*8, 10*). The development of faster pulse counting systems not only extends these advantages to measurements made at higher fluxes, but also has important consequences in terms of cost and convenience. The availability of a pulse counting system which is as fast as possible increases the probability that all necessary measurements (or at least an entire series of measurements) can be made without resorting to dc techniques. Thus, in some applications, the cost of a dc system may be eliminated entirely. Even when dc measurements must be made, a fast pulse counting capability will reduce the sensitivity requirements for the dc system.

The pulse counter described here has performance characteristics approaching the practical limits, but it can be built for a small fraction of the cost of present commercial pulse counting systems. The pulse counter has high sensitivity as well as stable and easily adjusted gain and discriminator levels, which are independent of pulse rate. The discriminator level is voltage programmed, and the amount of prescaling can be selected remotely. These features allow the possibility of real-time computer control of the measurement system parameters, which could be automatically optimized to meet changing experimental conditions (*11*).

PULSE COUNTER DESIGN

A block diagram of the pulse counter is shown in Figure 1. The digital counter is a standard TTL design, interfaced to a PDP8/I minicomputer, and the clock is the real-time clock of the computer (*12*). These units are not described in this paper. For the sake of brevity, the remainder of the circuitry (amplifier, discriminator, prescaler, and line driver) will henceforth be termed the "pulse counter", although it should be realized that some sort of frequency meter (or digital counter and clock) are also necessary to make a complete pulse counter.

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