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# light sensors & detection methods for TLD

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## abstract

*Photomultipliers and APDs are preferred devices for the measurement of low light levels in non imaging applications. The quality of performance with regard to detectivity and resolution is limited by the statistical nature of both light and device gain. Photon counting is shown to be superior to the direct current detection method as a means of measuring low light levels. The performance of APDs and photomultipliers are compared in practical situations to show where each detector has distinct advantages.*

*The effect on photomultiplier performance because of changes in temperature, shock, vibration and magnetic fields are significantly reduced when using the photon counting method. The effects of dead time can be corrected, making photon counting superior to current measurement with regard to dynamic range. The benefits of using photon counting packages are presented.*

## 1 introduction

**matching the spectral emission spectrum to that of the detector.**

Whatever the application, but especially in TL, the first consideration in selectiving the detector is to get the best match between the emission spectrum and detector response. **Figure 1** illustrates the range of spectral responses available from silicon detectors and photomultipliers. The choise of detector response may be obvious from inspection but if not a simple folding of the emission curve and the sensitivity curve of the detector under consideration will readily show which detector provides the maximum output signal. It is important to include any heat blocking IR filters or visible filters in the process – it is the spectrum of light actually falling on the detector that is important. Allowance for the temperature dependence of emission from thermoluminescent materials compounds is an important consideration. The paper by Townsend$^1$ presents examples of TL emission for materials commonly used which illustrates the complex relationship between temperature and wavelength of light emitted.

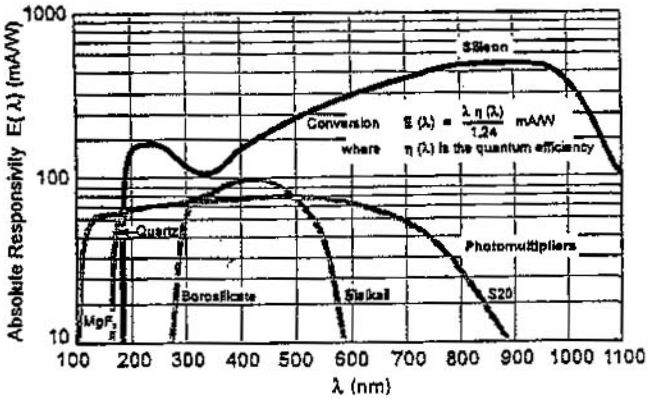

**figure 1** radiant sensitivity curves for silicon detectors and photomultipliers.

Deciding between using a silicon detector a photomultiplier is not easy and requires a careful analysis based on light levels and the proposed signal handling method. A TL signal is an emission of photons over a period of seconds or minutes. The signature of a measurement is embodied in the rate of emission of photons over time, which contains information on the intensity, time structure and total light output. Photon counting can capture all this information since the user has the choice over the sample time that is chosen to suit the particular glow curve under observation. Direct current detection is the alternative method and may be perfectly adequate in applications where light levels are high. The choice of detection method depends on the details of the application and a consideration of the basics of light detection will point to the approriate technique.

## 2 basic statistical considerations in the detection of light

### photon statistics

Light is detected in photosensitive devices through the generation of photocurrent. Electronic charge is quantised and hence this is an inherently noisy process.

Consider a steady light flux incident on the photocathode producing $m$ photoelectrons per second. Over a period of one second we expect $m$ photoelectrons on average with a standard deviation of $m^{1/2}$ as described by Poisson statistics. The S/N ratio is:

$$S/N = m/m^{1/2} = m^{1/2} \qquad \ldots(1)$$

The noise associated with photocurrent $I_k$, taking a system bandwidth, $B$, into account is given by the Shot noise formula

$$(i_k^2)^{1/2} = (2eI_kB)^{1/2} \qquad \ldots(2)$$

where $e$ is the electronic charge. The $S/N$ ratio is given by

$$S/N = I_k/((2eI_kB)^{1/2} \qquad \ldots(3)$$

**Example 1** Consider an ideal photomutliplier with a gain of 2 x $10^6$ and a dark current of 1 nA. What is the corresponding cathode current, number of electrons per second and the noise?

The cathode current $I_k$ is the anode current divided by the gain

$$\begin{aligned} I_k &= 3.3 \text{ x } 10^{-16} \text{ A} \\ &= 3.3 \text{ x } 10^{-16} / 1.6 \text{ x } 10^{-19} \\ &= 2000 \text{ electrons/second} \end{aligned}$$

The standard deviation or noise on this is √2000 or 44 electrons per one second. The noise current is

$$\begin{aligned} (i_k^2)^{1/2} &= (2 \text{ x } 16. \text{ x } 10^{-19} \text{ x } 3.3 \text{ x } 10^{-16})^{1/2} \\ &= 1 \text{ x } 10^{-17} \text{ A} \\ &= 63 \text{ electrons/second} \end{aligned}$$

The shot noise formula is the analogue way of looking at noise in terms of the current and bandwidth while $\sqrt{m}$ is the digital or statistical interpretation. They are related through the Fourier transform and hence the associated electron noise numbers differ by √2 – but they are describing the same phenomenon. In most noise or resolution considerations it is best to think in terms of electrons rather than current.

Equations **(1)** to **(3)** represent best case and refer to ideal detectors. In practice the S/N obtained will always be worse than stated above.

## 3 gain noise factor, *F*

The gain of any active device is a statistical quantity. When we talk about gain we really mean average gain because of the associated noise. APDs rely on an avalachne process to provide gain and this is very noisy. Photomultiplier gain derives from secondary emission, the statistics of which can be shown to conform quite closely to Poisson. The gain noise factor $F$ is defined quite generally as

$$F = \langle g^2\rangle/\langle g\rangle^2 = 1 + var(g)/\langle g\rangle^2 \qquad \ldots(4)$$

$F$ may be determined experimentally for a photomultiplier by recording the single electron response, SER. That is, the output pulse height distribution derived from the illumination of the photocathode with single photons. An example of such a distribution for a photon counting quality photomultiplier is shown in **figure 2**. $F$ values vary from 1.2 to 2 for the range of photomultipliers commercially avialable.

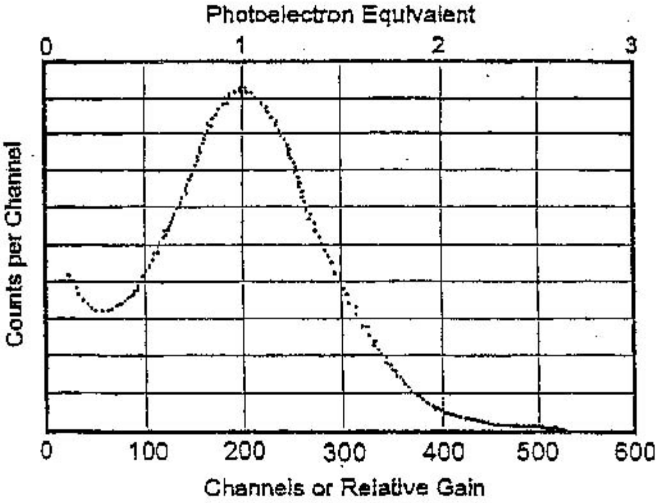

**figure 2** pulse height distribution for the output of a photon counting photomultiplier when excited with single photons. The peak is taken as one photoelectron equivalent.

Equations **(1)** and **(3)** when modified to allow for $F$, predict the noise behavour after the application of gain.

$$S/N = (m)^{1/2} \text{ from (1)} \qquad \ldots(5)$$

$$(i_k^2)^{1/2} = (2eI_kg^2FB)^{1/2} \text{ for signal} \qquad \ldots(6)$$

$$(i_d^2)^{1/2} = (2eI_{kd}g^2FB)^{1/2} \text{ for background} \qquad \ldots(7)$$

For avalanche photodiodes there is an analogous expression to **(6)** for signal, but for dark counts

$$(i_d^2)^{1/2} = (2e(I_{ds}+I_{db}g^2F))^{1/2} \qquad \ldots(8)$$

Measured values of $F$ are shown for APDs from three manufacturers in **figure 3**. Note the minimum value of 2 rising to 4 at gains of 100.

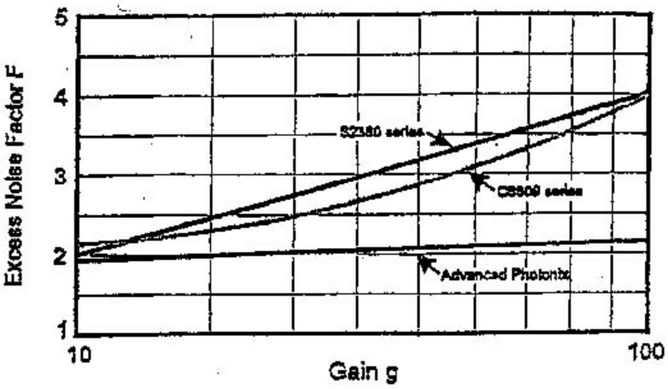

**figure 3** the excess noise factor, *F*, for a selection of APD's.

Noise equivalent power – NEP: The concept of Noise Equivalent Power is a useful one when comparing the detectivity of various different types of optical detector. The definition that will be used here is as follows: NEP is the optical power on the detector needed to produce a signal equal to the noise in the dark current $i_d$. Unit bandwidth is assumed and NEP has the units of $W/\sqrt{Hz}$

$$NEP \quad = (i_d^2)^{1/2} / g\, E(\lambda) \qquad \ldots(9)$$

Where $g$ is the gain of the device and $E(\lambda)$ is the radiant sensivity at unity gain.

**Example 2** A 9863/350 photomultiplier has a cathode radiant sensitivity of 10 mA/W at 800 nm. The dark current is typically 1 nA at the rated gain of 3 x $10^6$. Calculate the NEP assuming an *F* factor of 1.58. From **(9)** and **(7)**.

$$NEP=(2 x 1.6 x 10^{-19} x 1.58 x 10^{-9})^{1/2}/(\sqrt{3} x 10^3 x 10 x 10^{-3})$$
$$= 1.3 x 10^{-15} \quad W/\sqrt{Hz}$$

Note for the above example that at 400 nm, $E(\lambda)$ is 100 mA/W and consequently the NEP is 10 times lower.

**Example 3** An APD of diameter 17 mm has a dark current of 400 nA with noise of 10 pA√Hz at a gain of 200. Calculate the NEP at 400 nm where the radiant sensitivity is 0.2 A/W at unity gain.

$$NEP = 10^{-11}/0.2 x 200$$
$$= 2.5 x 10^{-13} W/\sqrt{Hz}$$

When comparing different types of detector it is important to make the comparison at the same wavelength and for the same sensitive area.

NEP values are shown in **table 1** for three types of detector using information supplied by the manufacturers. One must be careful about generalising from the data from **table 1** but an immediate conclusion that can be drawin is that photomulitpliers are the superior detectors for ultra low light level measurement.

**table 1** NEP values fro three types of detector

| **type** | | **PIN Diode S2387-8K** | **APD AP API**[1)] | **PMT ETL 9863/350** |
|---|---|---|---|---|
| Active area mm$^2$ | | 100 | 225 | 64 |
| Gain, *g* | | 1 | 200 | 3 x $10^6$ |
| Dark current | | 0.2 nA | 400 nA | 1 nA |
| $E(\lambda)$ A/W (g=1) | 400 nm | 0.2 | 0.2 | 0.1 |
| | 800 nm | 0.5 | 0.5 | 0.01 |
| NEP | 400 nm | 4 x $10^{-14}$ | 2.5 x $10^{-13}$ | 1.3 x $10^{-16}$ |
| | 800 nm | 2 x $10^{-14}$ | 8.0 x $10^{-14}$ | 1.3 x $10^{-15}$ |

1)see reference [10]

## 4 practical considerations

### PIN diodes

1) As they have unity gain, amplification is required for low light level applications and it is the noise performance of the amplifier that determines the lowest level of detection in dc applications.

2) The low dark current figures quoted in the specifications generally refer to zero or near zero bias. A faster time response is required where transient signals are to be measured and it will be necssary to speed up the diode by reducing its capacitance by the application of reverse bias voltage. This has the effect of increasing the dark current substantially.

3) Fast and low noise applications are generally restricted to the use of small pin diodes.

### avalanche photodiodes

1) The demands on the amplifier are less severe than with a pin diodes because an APD will have gain capability of up to 1000. However, this gain is noisy.

2) The application of bias voltage to provide gain has the desirable effect of increasing the speed of response and also reducing the capacitance.

3) Dark current increases rapidly with gain and for dc applications it is not practical to try measuring signals less than one tenth of the background. For low light level and low bandwidth signals pin diodes seem to be the preferred devices.

4) With a low noise amplifier and appropriate time constant it is possible to resolve pulsed signals

containing greater than about 1000 photons.

### photomultipliers

1) Photomultipliers have dark currents of the order of $10^{-15}$ – $10^{-17}$ Amps (referred to the photocathode). This is 6 decades less than pin diodes.

2) The multiplier provides wide bandwidth gain of up to $10^8$ with $F$ between 1.2 and 2.0.

These detector characteristics are summarised in **table 2**.

**table 2** summary of detector characteristics

| **Characteristic** | **PIN** | **APD** | **PMT** |
|---|---|---|---|
| Dark current | high | very high | very low |
| Capacitance | serious | limiting | no problem |
| Magnetic suscep. | none | none | yes |
| Gain | 1 | 1-$10^3$, noisy | 1-$10^8$, noiseless |
| SER | no | yes | yes |
| Photons ($cm^{-2}$) | 1000 | 300 | 1 |
| Speed, $t_\tau$ | 1-$10^6$ ns | 0.2-100 ns | 0.5-20 ns |
| Temp Co, Gain | - | >1%°$C^{-1}$ | ~0.1% °$C^{-1}$ |
| Temp Co, $I_D$ | 2/(5°C) | 2/(5°C) | fig 4 |
| Temp Co, E(λ) | fig 5 | fig 5 | fig 6 |
| Max area, $cm^2$ | ~1 | ~2 | 2000 |
| Cost per $cm^2$ | $100 | $1000 | $3 - $300 |
| Dynamic range | $10^{10}$ | $10^8$ | $10^6$ |
| Rugged | very | medium | medium |
| Compactness | yes | yes | no |
| IR resp (fig 1) | high | high | low |
| UV resp (fig 1) | low | low | high |
| Temp max, °C | 80 | 60 | 200 |
| HV, V | 0-20 | 100-2500 | 500-3000 |

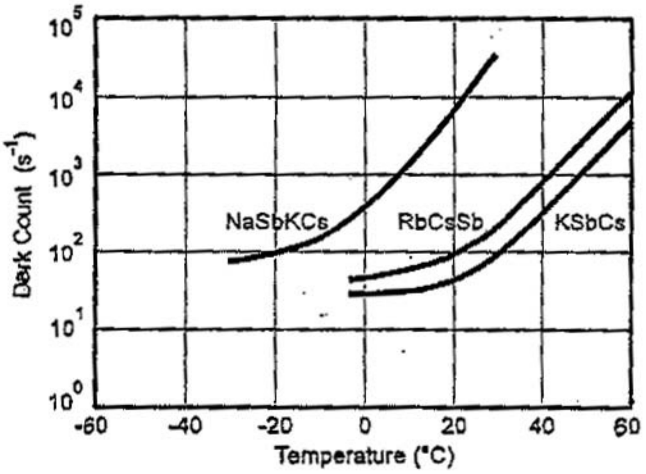

**figure 4** variation of dark counts with temperature in 30 mm photomultipliers, for the three most common photocathode types.

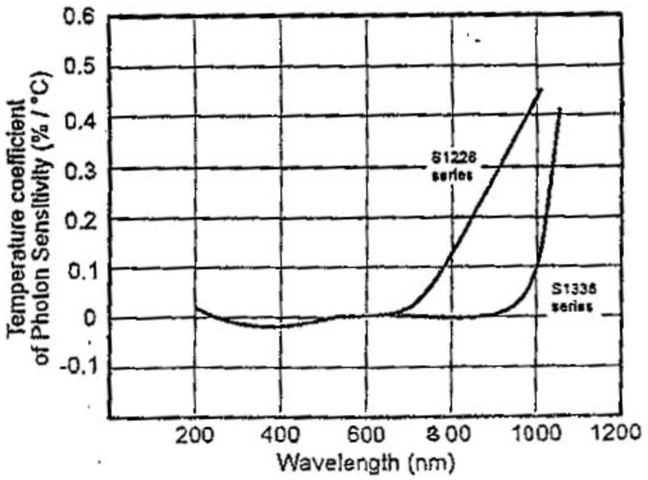

**figure 5** temperature coefficient for radiant sensitivity, $E(\lambda)$, for silicon devices. Note how the coefficient increases sharply at long wavelengths.

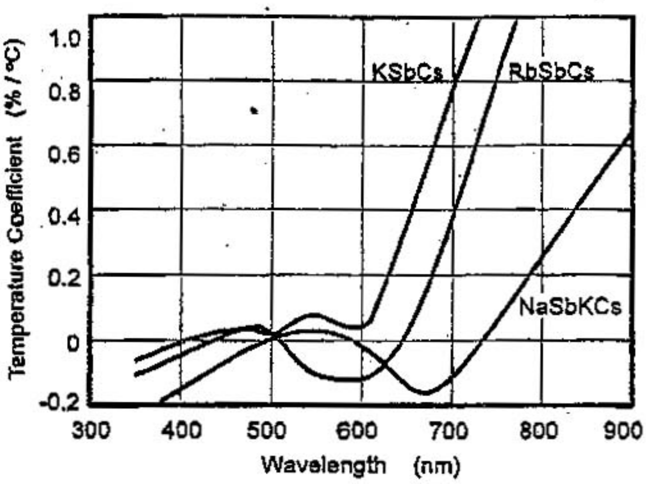

**figure 6** temperature coefficient for quantum efficiency, $\eta(\lambda)$, of various photocathode types. Note how the coefficient inreases sharply at long wavelengths.

## 5 the effect of photomultplier background on low light level measurements

All practical light detectors produce output signal in the absence of light stimulation. This unwanted signal, called background, is referred to as dark counts or dark current, depending on the application.

### pulse counting considerations

In all practical situations the signal rate relating to the phenomenon being observed is obtained by subtracting the background count rate from the measured signal plus background rate. The following generalisation applies to photomultipliers when comparing signal and background. Referring to the normalised curves of **figure 7**: there is a higher proportion of undersized pulses (region A) and of large pulses (regions C and D) in the background spectrum. In the photon counting mode of operation, a window may be set corresponding to the lower and upper boundaries of Region B, thereby eliminating the contributions of background signals that are not found in the spectrum of the signal alone. Note that in photon counting all pulses, regardless of size, but within the upper and lower threshold levels, contribute with equal weighting to dark count.

Since the proportion of pulses in region C of th espectrum is of the order of 10% or less of the total background, window discriminator techniques are seldom used in practical photon counting systems. Performance of accceptable quality can invariably be obtained by the use of a single, low level discriminator.

### signal to background considerations in current detection

Dark current $I_D$, is the sum of a pulse component and a leakage component (6). The pulse component is the integral of the background spectrum discussed above. Leakage is the major component of dark current at low gain but it always makes a contribution to dark current under low light level detection conditions. In the current detection mode all pulses in the spectrum contribute to dark current in proportion to their pulse heights. Those in region A make a reduced contribution, whereas those in regions C and D contribute significantly to $I_D$, because of their multi-photoelectron size.

Noise in dark current derives from the combination of statistical fluctuations in the background spectrum and from the noise factor $F_D$ acting on the amplifciation of the dark current. Note that $F_D$ is always greater than $F_S$ since the variance of the background spectrum exceeds that for signal – this is because there are relatively more counts in regions A and C of the spectrum of **figure 7**.

To summarise, the case against current measuring for low light level determinations is made from the following considerations:

a) noise Factors $F_S$ and $F_D$ enter into the signal current and dark current respectively and increase the noise.

b) dark current contains a leakage component.

c) multi-electron pulses contribute to dark current in proportion to their number and pulse height but only contribute to dark counts in proportion to their number.

In critical situations, the best signal to dark current ration, $I_S/I_D$, for a particular pmt can be determined experimentally by noting $I_S/\langle g\rangle$ as a function of $\langle g\rangle$. This curve has the typical shape of that shown in **figure 8** with a well-defined minimum. Most low light level applications are best satisfied at gains ~ $10^7$. More details are to found in (6) but note that it is sufficient to use relative gain, which is easily measured, for this purpose.

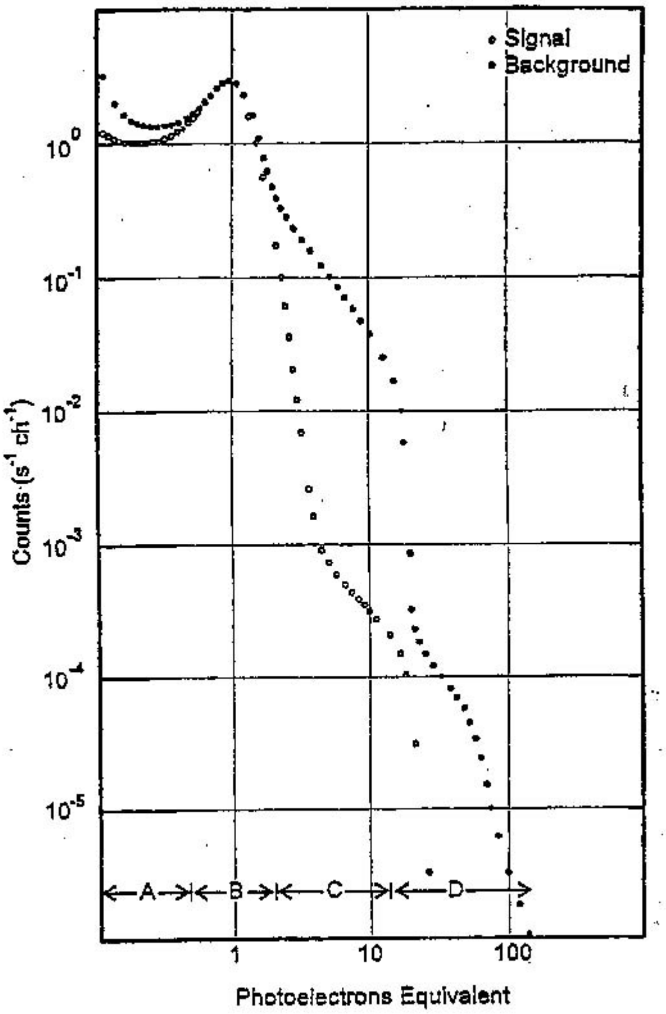

**figure 7** pulse height distributions for photomultiplier signal and background normalised to show the hgiher proportion of small and large pulses in the background.

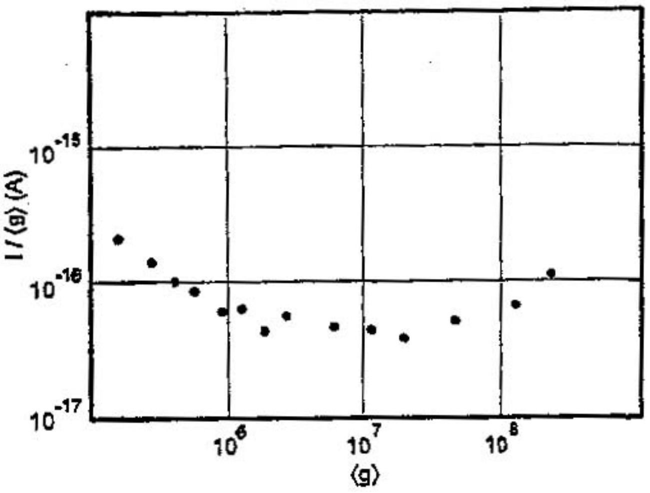

**figure 8** plotting signal current/gain vs gain is the best method for arriving at the conditions that will give the optimum S/B ratio.

# 6 the photon counting method – quality of performance

## plateau characteristic

In its simplest and most common form, practical photon counting instrumentation consists of a fast amplifier and a discriminator set to a low threshold of ~ -2 mV, referred to the input. This threshold has been shown, from experience, to correspond to the optimal compromise between susceptibility to electrical pick-up and operating the photomultiplier at excessive gain.

The signal plateau characteristic of **figure 9**, for a light source of fixed intensity, is obtained by varying the high voltage to the photomultiplier whilst noting the counts above threshold. The background plateau charactristic is measured in the same way but with the light removed. The ratio of the signal and background curves for this example suggests a choice of operating point between 1.35 to 1.45 kV, where S/B counts reach a maximum. The precise operating voltage of the photomultplier is best set with reference to the slope of the signal characteristic also. Electron Tubes set the operating point where the slope first becomes less than 0.1% per volt (at 1.40 kV in this example), which corresponds to counting all pulses which exceed a threshold of about ¼ photoelectron equivalent. Referring to **figure 2**, we see that about 90% of the single photon events are counted by selecting such a threshold. A note of caution is: operation at higher voltages to enhance the counting efficiency is done at the cost of hihger dark counts from Region A of the spectrum and increased afterpulses with consequent deterioration in counting statistics.

## temperature instability

Cathode quantum efficiency, $\eta$, and multiplier gain, $g$, are both sensitive to changes in temperature. The multiplier gain changes by approximately – 0.2 %°C$^{-1}$ but the photocathode sensitivity depends on wavelength in the manner shown in **figure 6**. The count rate, $n$, of a photomultiplier will thus be sensitive to temperature. For a given photomultiplier

$$n = n(g,\eta)$$

and the temperature coefficient of the count rate is given in 9).

$$\frac{1}{n}\frac{dn}{dT} = \left\{\frac{1}{n}\frac{\partial n}{\partial V}\right\}\left\{\frac{dV}{dg}g\right\}\left\{\frac{1}{g}\frac{dg}{dT}\right\} + \frac{1}{\eta}\frac{d\eta}{dT} \qquad \ldots(7)$$

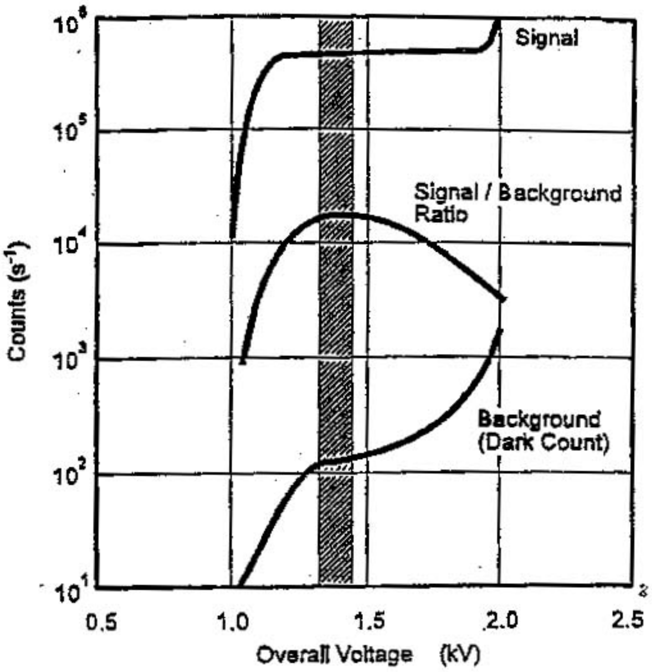

**figure 9** photon counting plateau characteristics for single photons and for background. The plot of the ratio of the two curves suggests an optimal operating point within the hatched area.

The relationship between gain and applied voltage follows the power law $g = aV^m$ where $m$ is 8 for the photomultiplier of **figure 9**.

$$\frac{dV}{dg}g = \frac{V}{m} = \frac{1400}{8}\text{ Volts}$$

$$\frac{1}{n}\frac{\partial n}{\partial v} = \text{relative plateau slope} = 10^{-3}\text{ per volt}$$

$$\frac{1}{g}\frac{dg}{dT} = -\ 0.2 \times 10^{-2}\ °C^{-1}$$

$$\frac{1}{\eta}\frac{d\eta}{dT} = \text{quantum efficiency temperature coefficient}$$

The temperature coefficient of the photocathode depends on the wavelength of interest, as shown in **figure 6**. It is typically – 0.1°C$^{-1}$ at 400 nm.

Combining the numberical values for all the terms in equation 7, we have

$$\frac{1}{n}\frac{dn}{dT} = -0.035 - 0.1\ \%°C^{-1}$$
$$= -0.135\ \%°C^{-1}$$

In current mode of operating the temperature sensitivity is

$$\frac{1}{I}\frac{dI}{dT} = \frac{1}{g}\frac{dg}{dT} + \frac{1}{\eta}\frac{d\eta}{dT} \qquad \ldots(8)$$
$$= -0.2 - 0.1\ \%°C^{-1}$$
$$= -0.3\ \%°C^{-1}$$

The above treatment shows that the effect of gain change is much reduced in photon counting compared with current detection at 400 nm, for example.

Note that at 500 nm, where the temperature coefficient of the photocathode is close to zero, the overall temperature coefficient is a factor of six different for the two methods.

### improved performance by cooling

**Figure 4** shows how dark counts vary with temperature in the three most common photocathode types. Although there is considerable variation amongst photomultipliers of the same type, the curves have a characteristic shape. For the KSbCs bialkali, for example, dark counts are substantially constant up to a temperation of 20 °C, beyond which the counts double per 5 °C temperature rise. If the background is a significant proportion of the signal, or indeed exceeds the signal, then taking a background measurement immediatley before or after a signal-plus-background determination, helps in reducing this source of error. Best performance will always result whenever the photomultplier is maintained at constant temperature. In very low light level measurements, further improvements in precision and accuracy can both be realised by maintaining the photomultiplier at a constant, cooled temperature, as is clear from **figure 4**.

In some instances it may be necessary to compromise between the benefit of dark current reduction versus a possible reduction in cathode sensitivity. **Figure 6** illustrates that there is a serious loss in cathode sensitivity, in the S20 cathode for example, at wavelengths beyond 700 nm. Hence the recommendation: ‘cool no more than necessary’.

### other sources of instalibity

Multiplier gain is sensitive to all of the following:

- photomultiplier ageing
- power supply instability
- rate effects
- magentic fields
- shock and vibration

The same reasoning used in termperature instability considerations tells us that photon counting will provide better performance than current detection agains these sources of gain instability.

Magnetic fields affect the gain and the collection efficiency of a photomultiplier. A change in collection efficiency is equivalent to a change in quantum efficiency, $\eta$. Conventional, open-ended, mu-metal shields are least effective against the field component directed along the axis of a photomultplier.

Vibration caused by rotating equipment such as vacuum pumps and shock, caused by sudden impulses, are the main causes of microphonic effects in photomultpliers. Resonant vibrations in the dynode structure generate a measurable current analogue at the anode. The spectrum exhibits frequency components centred around 1 kHz (8). In photon counting these signals can be discrimnated gainst by suitable high-pass filtering, but no such solution is available in current mode.

### linearity

This refers to the degree of linarity between the intensity of the light stimulus and the output of the photomultplier. In photon counting, at sufficiently high light levels, the output rate will deviate from the photoelectron detection rate because of electronic dead-time effects caused by pulse pile-up. Pulses that arrive while the discriminator is busy are ignored. The type of discrimator used by Electorn Tubes is the non-paralizable type where the measued count rate can be corrected according to the following formula.

$$N = n/(1-n\tau) \qquad \ldots(9)$$

Where $N$ is the true count rate, corresponding to a measured rate of $n$ and $\tau$ is the dead-time of the discriminator. The value of $\tau$ that gives the best linearity is that determined experimentally from a set of counting rates of known ratios. **Figure 10** shows an example of dead time correction that provides linear response to better than ±0.5 % up to $20\ x10^6 s^{-1}$, based on $\tau = 23.5\ ns$.

Anode current is the intergral of pulse height and rate and is unaffected by pulse pile-up. However, it is easily verified by substitution into the signal analogue of equation (5) that operation at gain of ~ $10^7$, required for photon counting, implies an anode current of 32 µA at a count rate of 20 x $10^6$s$^{-1}$. To obtain linearity of performance at this level of anode current demands careful photomultplier selection and proper voltage divider design.

At the low count rate end of the dynamic range the arguments already given show that photon counting can offer another decade of performance over current detection through superior signal to background performance.

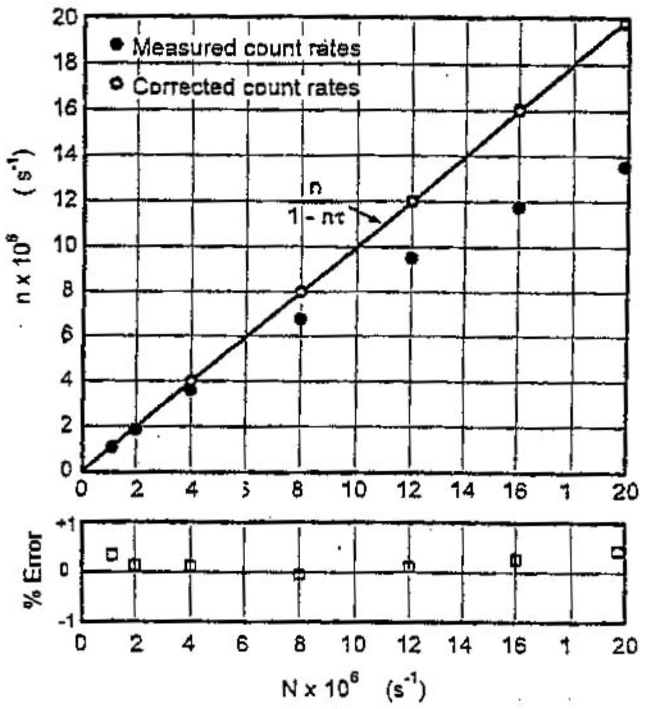

**figure 10** showing an example of dead-time correction applied to the measured count rate, $n$, extending linear performance up to 20 x 10$^6$s$^{-1}$ to within ±0.5 %.

## 7 summary of detector selection and mode of operation

Where low light levels are to be measured or where a large detection area is required, it has been shown that photomultplers offer superior performance over silicon detectors. Silicon detectors have far superior quantum efficiency, for $\lambda \gtrsim$ *450 nm* than photomultpliers but their low, noisy gain is a limiting factor.

The signal recovery peformance offered by photon counting has been shown to be superior to the current detection method over the entire dynamic range of photomultiplier operation. In photon counting terms this corresponds to rates of a few photons per second to ~10$^8$ per second., equiavlent to ~1 pA to ~ 100 μA in output current.

Photon counting is preferred over current detection because

- the gain process is noisy and introduces a factor $F$ into current detection measurements.
- dark current in current detection always exceeds the dark current equivalent of dark counts in photon counting because of leakage. Also, none of the component of the dark current can be eliminated by discrimination as in photon counting.
- it is less sensitive to temperature effects, ageing, high voltage stability, rate effects, magnetic effects and microphonics.
- the dynamic range is superior at fixed gain.
- the photon counting method preseves the temporal structure of the signal.

## 8 photon counting modules

Commercially available photon counting modules containing a selected photomultiplier, electromagnetic screening, high voltage supply and a fast amplifier-discriminator are aimed primarily at both the experimentalist and at the instrument manufacturer. The benefits of using a photon counting module are:

- complete, rugged, integrated assembly
- compact, lightweight, low power consumption
- fully enclosed high voltage
- simplicity of installation – only low voltage input and signal output to connect
- simplicity of operation – no set-up or adjustment
- preset operating conditions for optimised performance
- can be customised to suit specific applications

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